



Universidad de Oviedo
Universidá d'Uviéu
University of Oviedo

Programa de Doctorado en Materiales

Estudio de procesos más allá del Modelo Estándar en estados
finales leptónicos con el detector CMS en el Run 2 del LHC

Study of beyond the Standard Model processes in leptonic final states with the CMS
detector at the Run II of the LHC

TESIS DOCTORAL

Carlos Francisco Erice Cid

Junio 2021





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La tesis presentada por D. Carlos Francisco Erice Cid titulada *“Estudio de procesos más allá del Modelo Estándar en estados finales leptónicos con el detector CMS en el Run 2 del LHC”*, dirigida por los Dres. D. Francisco Javier Cuevas Maestro y D. Santiago Folgueras Gómez, cumple con los requisitos para ser presentada a la Comisión de Doctorado y para optar al doctorado internacional.

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1.- Título de la Tesis	
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RESUMEN (en español)

El trabajo presentado en esta tesis está dedicado al estudio de la física de altas energías en estados finales con dos o más leptones (multileptónicos). Medidas del comportamiento del Modelo Estándar de la física de partículas (ME) y de procesos más allá del ME han sido estudiados con datos obtenidos por el experimento CMS durante el Run 2 del LHC.

Las primeras medidas del comportamiento del sector electrodébil del ME se corresponden con el estudio de procesos de producción asociada de dos bosones vectoriales masivos (WW, WZ, y ZZ). Se presentan las primeras medidas de la sección eficaz de estos procesos a una energía en el centro de masas de 5 TeV, incluida la primera observación del proceso WW en este rango de energía. También se presenta una detallada serie de medidas del proceso de producción asociada WZ a una energía en el centro de masas de 13 TeV. La sección eficaz total de producción de WZ ha sido medida con una incertidumbre relativa del 4%. La asimetría de carga en WZ, incluida una interpretación de la misma en términos de las funciones de distribución partónicas, ha sido medida con una precisión del 2.5%. Se han realizado estimaciones de las fracciones de polarización de los bosones W y Z, lo que ha conducido a la primera observación de bosones W polarizados longitudinalmente en estados finales dibosónicos. Finalmente se ha realizado una búsqueda de procesos de nueva física en forma de teorías de campo efectivas (TCE) dando lugar a nuevas restricciones en los posibles valores de cinco parámetros TCE de dimensión seis. Para corroborar todos los procedimientos anteriores, se han medido secciones eficaces diferenciales a nivel de partícula, libres de los efectos del detector, con respecto a todos los observables de alto nivel relevantes.

El acoplamiento de Yukawa entre el quark top y el bosón de Higgs ha sido estudiado a través del proceso de producción ttH. El procedimiento de análisis se ha basado en la optimización de un discriminante basado en requisitos sobre una única variable de cara a aumentar la sensibilidad final de la medida mientras se mantiene la reinterpretabilidad de la misma. Los resultados incluyen la evidencia de la existencia del proceso ttH a una significancia de 4 desviaciones típicas.

Se ha realizado una búsqueda de producción electrodébil de supersimetría (SUSY) en estados finales multileptónicos. Esta se ha basado en una estrategia exhaustiva que examina un total de doce estados finales divididos en función del número de leptones, su sabor y su carga. Se han diseñado dos criterios de búsqueda para la definición de regiones enriquecidas en señal: el primero se basa en una serie de requisitos sobre variables individuales para la definición de regiones de señal (RS), y el segundo utilizando una red neuronal paramétrica (RNN). Si bien no se ha observado un exceso en los datos compatible con la presencia de SUSY, los resultados han sido interpretados en términos de modelos simplificados para determinar límites en las secciones eficaces de producción y las masas de las partículas supersimétricas. Dependiendo de las hipótesis del modelo, los resultados dan lugar a los límites más estrictos hasta la fecha en las



masas del chargino y el neutralino.

De cara a preparar el funcionamiento del experimento CMS para la Fase II del LHC, nuevos métodos han sido desarrollados y estudiados. Los diferentes algoritmos presentados en la tesis se corresponden con nuevos métodos para que el sistema de trigger de L1 de muones sea capaz de adaptarse a las duras condiciones del LHC de alta luminosidad con igual o mejor desempeño que el que ha mostrado durante la toma de datos del Run 2.

RESUMEN (en Inglés)

The work presented in this thesis explores high energy physics in final states with two or more leptons (multileptonic). Data taken by the CMS experiment, corresponding to the Run 2 of the LHC, is used to explore both the physics of the Standard Model of Particle Physics (SM), and possible models of new physics beyond the Standard Model (BSM).

The electroweak sector of the SM is first probed through the study of processes involving the production of two massive gauge bosons (WW, WZ, and ZZ). The first measurements of the cross sections for all three processes at a center-of-mass energy of 5 TeV are presented, leading to the first observation of WW production at this energy regime. A detailed set of studies on WZ production at a center of mass energy of 13 TeV is also discussed. The results are lead by the most precise measurement of the WZ production cross section, with an overall relative uncertainty of 4%. The charge asymmetry in WZ production, including an interpretation in terms of parton distribution function constrainings, is measured at the 2.5% precision level. Estimations of the boson polarization fractions for both the W and Z bosons lead to the first observation of longitudinally polarized W bosons in diboson production. A search for BSM physics modelled through effective field theory (EFT) operators lead to constraints in five different dimension six components. All measurements are confirmed through the production of detector-free differential cross section measurements with respect to all relevant high level observables.

The Yukawa coupling of the top quark is studied through the ttH production mechanism. A dedicated single variable-based signal extraction criteria has been developed to optimize the sensitivity of the measurement while keeping the result easily reinterpretable. The results correspond to evidence for the ttH production mode with a significance of 4 statistical deviations.

A final set of measurements corresponding to searches for electroweak supersymmetry (SUSY) in multileptonic final states is also performed. An exhaustive strategy is followed in which twelve final states consisting on different lepton flavours, charges and multiplicities are explored in detail. Both a simple signal region (SR), approach based on single variable selection requirements, and a multivariate approach based on parametric neural networks (PNN) are designed to look for BSM physics. While no significant presence is found, limits are set in SUSY particle masses and production cross sections through the usage of simplified models (SMS). Depending on the model assumptions, these limits are up to the most stringent in chargino and neutralino masses up to date.

In order to prepare for the next operating years of the LHC, several improvements developed for the Phase II upgrade of the CMS detector are introduced. The different algorithms presented correspond to different upgrades to the current L1 trigger strategy so it can cope with the harsher running conditions of the High Luminosity LHC with equal or better performance that the current ones did for the Run 2.

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Ser miembro de una colaboración experimental como CMS significa que todo trabajo se realiza en mayor o menor medida en equipo. No implica, sin embargo, que ese equipo tenga que gustarte o que te haga la vida más fácil. He tenido la suerte de que en mi caso si haya sido así, lo que me ha permitido desarrollar mi trabajo en un entorno a la vez agradable a nivel personal y desafiante a nivel intelectual. Creo necesario dedicar al menos unas palabras a las personas que con su trabajo y apoyo han hecho esto posible.

El grupo de Oviedo ha sido mi casa desde que empecé en esto de la ciencia allá en 2016. El consejo de mis directores, Javier y Santi, ha sido crucial para evitar dar vueltas por callejones sin salida, si no fuera por ellos o bien seguiría escribiendo este documento o, más probablemente, puede que ni siquiera habría llegado a empezarlo. Javi e Isidro fueron dos de mis grandes motivaciones para emprender esto del doctorado después de la carrera y a día de hoy siguen siendo un ejemplo al que aspirar de cara al futuro. Kike y Bárbara han sido un apoyo constante en estos últimos años, espero puedan perdonarme lo pesado que soy a veces con mis ruegos y preguntas. Xuan y Sergio (quién, pese a lo que se diga, sigue siendo parte del grupo) han sido mis mentores en esto de ser estudiante de doctorado, el hecho de que sobreviviese a mi primer año es en un 66% culpa suya. He intentado transmitir algo de lo que me ofrecieron a Victor, Andrea, Clara, Alejandro y Carlos, espero no haberles dado muchos dolores de cabeza. Nicolás ha llegado un poco tarde al grupo, pero me ofrece una enorme tranquilidad saber que esta última tarea queda en buenas manos. No puedo evitar decirles una última cosa a Xuan, Sergio y Victor en recuerdo de varios memorable momento de estos últimos años: ¡Kubor!

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1

Introduction

Particle physics aims to describe the constituents of the universe at its most fundamental level. Such an ambitious objective produces the challenge of both developing a powerfully predictive theoretical model and the experimental tools for its experimental verification.

Developed during the twentieth century, the Standard Model of particle physics (SM), proved to be a remarkably accurate description of reality. It was not until 2012, though, when the final piece of the SM puzzle was finally found experimentally through the discovery of the Higgs boson by the ATLAS and CMS experiments [1, 2] with the data provided by the Large Hadron Collider (LHC). The story of particle physics, however, has not yet been finished as several questions are yet to be answered. How does gravity mix with quantum theory? Why is the Higgs mass so small? Is dark matter composed of elementary particles? Why is the observable universe made of matter and not antimatter? Why do neutrinos have non-zero mass? The answers to these questions will necessarily lie beyond the Standard Model (BSM), and are one of the driven forces of research on the field.

The LHC and its experiments have been invaluable tools in the study of elementary particles at the high energy level. The data collected has so far been used to push the common knowledge of the SM from the era of discovery to that of precision physics. Not only that but, with collisions happening at centre-of-mass energies of 13 TeV, they are prime candidates to produce and detect the so far elusive sign of new physics at the high energy regime.

Due to the non perturbative nature of the strong interaction, charged leptons are, arguably, the fundamental particles which are measured with the highest precision in collider experiments. Isolated leptons naturally appear in the decay of the W, Z, and H bosons, and never through the action of the strong interaction. As a consequence, multileptonic final states are one of the most powerful experimental signatures in the study of the electroweak sector of the SM and, usually, of its BSM counterparts.

The work presented in this thesis focuses on exploiting final states with two or more charged leptons in order to study different phenomena related to the electroweak sector of the SM. The associated production of massive vector boson pairs (WW, WZ, and ZZ), so called diboson production, is one of the main topics covered by these studies. They are processes that are intrinsically linked to the Higgs mechanism through the existence of triple gauge couplings, and the high quantity of data provided by the Run

2 of the LHC has shifted their study into the era of precision measurements of their properties, no longer limited by statistical uncertainties. Studies on WZ production at a centre-of-mass energy of 13 TeV are presented, corresponding to several publications I have contributed towards [3, 4]. A unique opportunity to study all diboson production modes at a centre-of-mass energy of 5 TeV was presented thanks to a preparation run for heavy ion studies taken by the LHC. The results that will be presented correspond to the first analysis of 5 TeV data for diboson production [5], which I have developed. They are a sharp example of the physics potential of the LHC at broad ranges of energies beyond the usual data taking conditions.

The Yukawa coupling of the top quark plays a leading role in the quantum corrections to the Higgs mass, making the t -H interaction a prime probe in the search for answers to the hierarchy problem. As the low peak mass of the Higgs boson inhibits the presence of a $H \rightarrow t\bar{t}$ decay, the $t\bar{t}H$ production mode provides a way to study indirectly this coupling that, coincidentally, also produces multileptonic final states. Studies on multileptonic $t\bar{t}H$ production will be presented corresponding to several published papers I have taken part of. [6–8]. Their combination with results obtained on other final states lead to the first observation of the $t\bar{t}H$ process in 2018 [9].

A third topic in the analysis of data in this thesis is the direct search for BSM physics within the framework of Supersymmetry (SUSY). Properly formulated SUSY models can provide answers to several of the open questions on the field, most notably the hierarchy and dark matter problems, and produce a broad range of experimental signatures that might be reachable at the LHC energies. While the Run 1 and Run 2 program of the LHC has already established quite stringent bounds on the energy scale of strongly produced SUSY particles at the TeV scale, the lower overall cross-sections of the electroweak SUSY sector have made their detailed study more difficult until the Run 2. Inspired by the multileptonic signatures studied before, direct searches for SUSY in the electroweak sector producing multileptonic final states are presented, corresponding to the results I developed and that can be found in References [10–12].

All the aforementioned publications rely on the great performance of the CMS experiment, which can only be achieved through the group efforts of the whole CMS collaboration in maintaining and improving both the physical parts of the detector, and the different algorithms used for triggering, and particle reconstruction and identification. I’ve taken part of these tasks as developer of the muon reconstruction for the Level 1 (L1) trigger in preparation for the Phase II upgrades of the CMS detector towards the High Luminosity operation of the LHC (HL-LHC). My contributions lay within the field of locally reconstructed muons within the CMS muon spectrometers, and were part of the collaboration effort published in [13]. In the non-trigger related world, I’ve also took charge of muon reconstruction, as coordinator of the development and maintenance team of muon reconstruction in the muon object group of the CMS collaboration.

A collaborative effort such as that of the CMS experiment relies on the group expertise in data analysis techniques as well, even if it doesn’t directly lead to new published results. Inside the SUSY group I have performed the role of expert on the widely used combine tool [14] for statistical treatment of data. During my tenure I’ve reviewed and helped get to fruition around 30 different publications from the group. More recently, I’ve also become involved on the Monte Carlo (MC) generation step, coordinating the MC efforts of the whole SUSY group. A summary of these and all the other main activities done during the period of this thesis are shown in Figure 1.1.

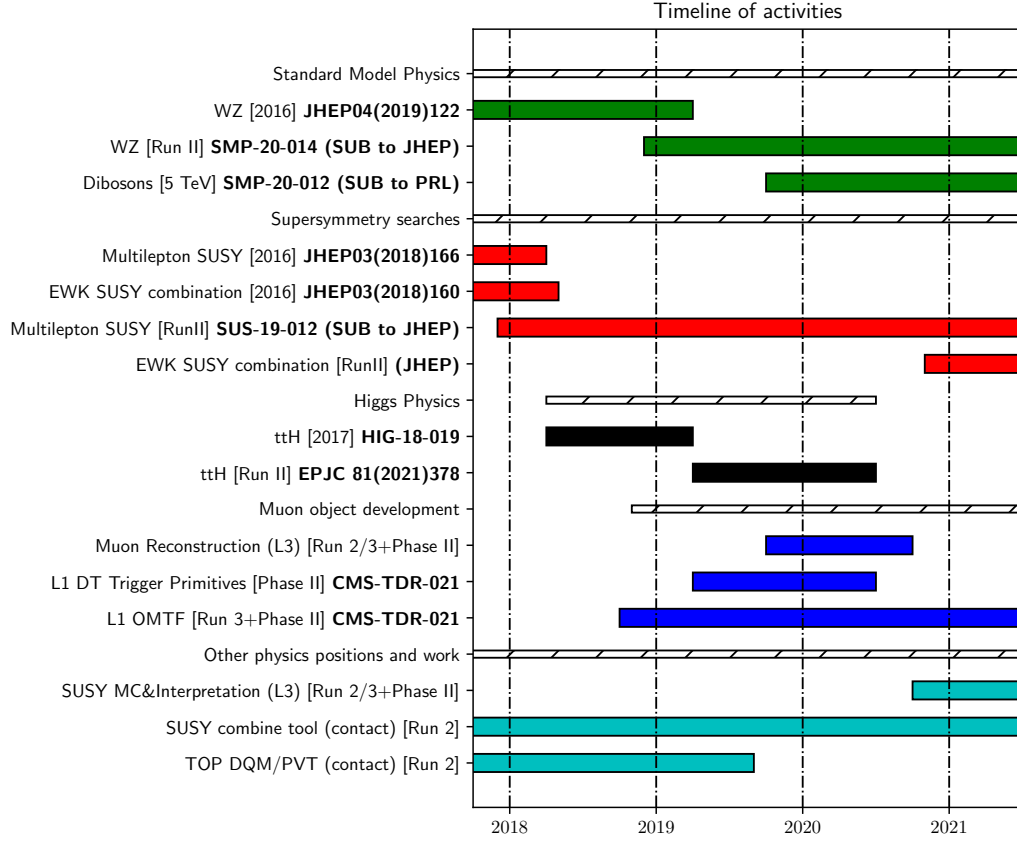


FIGURE 1.1: Timeline of the main analysis and service work developed during the thesis elaboration. Articles are split based on the internal CMS subgroup in which they were developed, and the timeline includes from start of the developing phase to the publishing of the results. Service work timelines correspond to either the official time from appointment to resignation in a position (for L3/contact positions) or time of active involvement in development otherwise.

This document is organized as follows. Chapter 2 provides a brief introduction to the SM, its particles and their interactions, the inherent limitations on its formulations, and several possible ways in which BSM physics might appear. Chapter 3 provides a description of the experimental setup, including a brief description of the LHC collider, a more detailed one of the CMS detector and its different constituents, and the introduction of the reconstruction techniques used to build up the particle kinematics from the detector information. Chapter 4 introduces several general purpose techniques in data analysis with specific emphasis on multileptonic final states. Results on the application of these techniques are provided through the discussion of the results on diboson cross-sections at 5 TeV and $t\bar{t}H$ production at 13 TeV. Chapter 5 provides a detailed view of the measurements on multiple properties of WZ production at 13 TeV. Chapter 6 discusses the search for electroweak SUSY in multileptonic final states and the bounds obtained using data corresponding to the Run 2 of the LHC. Chapter 7 discusses the improvements on the L1 muon trigger targetting the Phase II of the LHC. Finally, Chapter 8 provides a wrap-up of the results obtained.

2

Theoretical framework

Any description of reality which attempts to provide a complete picture of particle physics needs to accommodate the successfully predictive theories of quantum physics and special relativity, both of which apply at the realm of elementary particles. Quantum field theories (QFTs) provide a theoretical framework that fulfils such a request, describing particles and their interactions as quantized excitations of Lorentz invariant objects extended to the whole space–time known as quantum fields. However, not all possible formulations of QFTs correspond to theories that could describe fundamental interactions. Predictability, the ability to provide quantitative predictions that can be matched to experimental observations is a basic requirement that is not trivially fulfilled by all possible QFTs due to the numerical divergences that can appear when computing most physical observables. Renormalizability, the property of a theory that produces cancellations of these divergences is a usual criteria imposed to realistic QFTs that can be applicable to any energy. Additionally, experimental observations of the elemental interactions point towards the existence of quantities that are conserved, such as the electric charge, a phenomena that needs to be explained itself by the theory. The successful concept of gauge theories is able to encode such preserved quantities as fundamental properties of the underlying QFTs, making it derive from local symmetries of the fields.

The Standard Model of Particle Physics (SM) is a renormalizable QFT that describes all known fundamental particles and their interactions. Such interactions derive from a local gauge symmetry of the SM corresponding to transformations from the $SU_C(3) \times SU_L(2) \times U_Y(1)$ group, where $SU(X)$ denotes the special unitary group of dimension X and $U(X)$ denotes the unitary group of dimension X . The first group, $SU_C(3)$, relates to the strong interaction and the colour property of particles. The second and third $SU_L(2) \times U_Y(1)$ correspond to the electroweak interaction and the weak isospin and hypercharge of particles.

The predictive power of the SM is a fundamental tool of modern Particle Physics and has been found to agree with observations to astonishing precisions in most measured phenomena up to date. A very complete compilation of its success is presented in Reference [15]. References [16] and [17] provide more complete descriptions of both general QFTs and the SM. The following chapter briefly summarizes the underlying theoretical formulation of the SM, as well as more detailed descriptions related to the studies presented in this whole document.

2.1 Fermionic content of the SM

Fermions are particles with half integer spin. In the SM all fundamental fermions have spin 1/2 and can be roughly classified into two groups depending on which of the fundamental interactions they suffer.

Leptons are fundamental particles that have no colour and so only suffer the electroweak interaction. Depending on their electric charge, measured in units of the electron's, there are two kinds of leptons: charged leptons with electric charge 1 (generically e) and neutrinos with no electric charge (generically ν).

Quarks do have colour and so can also suffer the strong interaction. As in the case of the leptons, quarks come in two different kinds: up-like quarks with charge 2/3 (generically u) and down-type quarks with charge $-1/3$ (generically d).

A set composed of a fermion from each of the four aforementioned kinds is called a generation, with the particles of the first generation (the electron, the electron's neutrino, the up quark and the down quark) being the building bricks of ordinary matter. A total of three generations appear in the SM, with each one containing particles that interact the same way as the previous but have increased mass. The second and third generation charged leptons are the muon and the tau. The second and third generation up (down) type quarks are the charm and the top (the strange and the bottom). For simplicity, unless otherwise stated we will discuss the following sections with a single generation of fermions, knowing that interaction-wise all others are replicas of the first. Each of these kind of fermions, varying on their quantum numbers and generations, is known as a fermion flavour.

In QFT, fermions are associated to quantum fields called spinors, objects that transform under the spinor representation of the Lorentz group. As such, their dynamics are described by Dirac's equation. As usual in QFT, the properties of such fields are encoded into a Lagrangian density that describes the whole dynamics. For a non-interacting massless fermion field ψ such quantity is

$$\mathcal{L}_{Dirac} = \bar{\psi}\gamma^\mu\partial_\mu\psi \quad (2.1)$$

where γ^μ are the Dirac matrices, ∂_μ is the spacial derivative and Einstein's summation criteria is assumed. $\bar{\psi}$ denotes the Dirac adjoint of the field ψ defined from the more usual Hermitian adjoint as $\bar{\psi} = \psi^\dagger\gamma^0$ in order to make the Dirac Lagrangian Lorentz invariant. Spinors can be projected onto the so called left (ψ_L) and right (ψ_R) handed spinors as

$$\psi_L = \frac{1 - \gamma^5}{2}\psi \quad \psi_R = \frac{1 + \gamma^5}{2}\psi \quad \gamma^5 = i\gamma^0\gamma^1\gamma^2\gamma^3 \quad (2.2)$$

which provides the option to write an explicit mass term in the Lagrangian density for fermions as

$$\mathcal{L}_{Dirac}^{mass} = -m(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L) \quad (2.3)$$

A well known rule of thumb to ensure renormalizability, is that it can be achieved as far as all the non field coefficients in the Lagrangian density terms are either adimensional or have a dimension of a positive power of the energy. This rule, coupled with the Lorentz invariance of the theory means that terms 2.1 and 2.3 are the only allowed terms for a theory that explains free fermions on nature, meaning that three or four fermion interactions can not be explained except for the existence of additional items on the theory.

2.2 Electroweak interactions

The first set of gauge symmetries in the SM correspond to the $SU_L(2) \times U_Y(1)$ symmetry group and are those responsible for the electroweak (EWK) interactions. They were initially described by the Glashow-Weinberg-Salam model [18, 19].

The three fields corresponding to the $SU_L(2)$ group are vector fields denoted as W_μ^i where $i = 0, 1, 2$ denotes the field index and μ denotes the Lorentz vector coordinate. The associated Lagrangian density for these as massless free fields is

$$\mathcal{L}_W = -\frac{1}{4}W_{\mu\nu}^i W_i^{\mu\nu}, \quad W_{\mu\nu}^i = \partial_\mu W_\nu^i - \partial_\nu W_\mu^i + g\epsilon_{ijk}W_\mu^j W_\nu^k \quad (2.4)$$

where ϵ_{ijk} is the completely antisymmetric symbol and g refers to the coupling constant of the $SU_L(2)$ group. The final term of the field strength tensor $W_{\mu\nu}^i$ appears due to the non Abelian nature of the $SU_L(2)$ group and is responsible for one of the sources of triple gauge couplings.

As vector fields, each of W_μ^i has an associated vector boson of spin 1. One could consider such bosons to have masses, but the transformation rules of the W_μ^i fields under the gauge group $SU_L(2)$ do not allow the explicit presence of mass terms for the W_μ^i fields such as

$$\mathcal{L}_W^{mass} = \frac{m^2}{2}W_\mu^i W_i^\mu \quad (2.5)$$

thus, the three bosons associated to this W_μ^i fields remain massless.

Under transformations from this first group, right handed fermions behave as scalars (singlets), while left handed fermions are transformed simultaneously (doublets) both for quarks $q_L = (u_L, d_L)$ and leptons $l_L = (\ell_L, \nu_L)$. The associated conserved quantity, the weak isospin I_3 is 0 for singlet states, 1/2 for u_L and ℓ_L , and $-1/2$ for d_L and ν_L . Due to this configuration the explicit mass term in 2.3 is prohibited as it is not $SU_L(2)$ invariant.

The $U_Y(1)$ group has an associated vector field B_μ for which a free Lagrangian similar to the W_μ^i

$$\mathcal{L}_B = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu}, \quad B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu \quad (2.6)$$

Similarly, mass terms for the B^μ field are forbidden by the gauge invariance of the theory under $U_Y(1)$. The boson associated to the B^μ field is, again, massless. All fermions are singlets under transformations of the $U_Y(1)$ group. The associated conserved quantity is the hypercharge Y which is $-1/2$ for left handed leptons, -1 for right handed charged leptons, 0 for right handed neutrinos, $1/6$ for left handed quarks, $4/6$ for right handed up type quarks and $-2/6$ for right handed down type quarks.

Interactions of fermions and the gauge bosons are introduced through the usage of the covariant derivative, as usual in gauge theories, such that the total Lagrangian of the EWK sector is

$$\begin{aligned} \mathcal{L}_{EWK} = & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W_{\mu\nu}^iW_i^{\mu\nu} + \\ & + \bar{e}_R\gamma^\mu D_\mu^{e_R}e_R + \bar{u}_R\gamma^\mu D_\mu^{u_R}u_R + \bar{d}_R\gamma^\mu D_\mu^{d_R}d_R + \bar{q}_L\gamma^\mu D_\mu^{q_L}q_L + \bar{l}_L\gamma^\mu D_\mu^{l_L}l_L \end{aligned} \quad (2.7)$$

Do notice that right handed neutrinos do not interact with either the W_μ^i or B_μ field and, in fact, do not interact at all in the SM, so they are usually not included in its description. The covariant derivative for fermion flavour X with weak isospin I_3^X and hypercharge Y^X is defined as

$$D_\mu^X = \partial_\mu - igI_3^X\sigma_iW_\mu^i - ig'YB_\mu \quad (2.8)$$

where σ_i are the three generators of the $SU_L(2)$ group, g is the coupling constant of the $SU_L(2)$ group already introduced in Equation 2.4 and g' is the coupling constant of the $U_Y(1)$ group.

Again, the renormalizability criteria means that no additional terms can be added to the Lagrangian density of Equation 2.7. With the addition of gauge symmetry, not only the one described in Equation 2.5 is forbidden, but also explicit fermion mass terms, such as 2.3, meaning that a theory of fermions interacting through the $SU(2)$ and $SU(1)$ gauge fields only contains massless fermions.

2.2.1 Electroweak symmetry breaking and boson masses

Although explicit mass terms for fermions and the electroweak gauge bosons are forbidden due to gauge invariance, experimental evidence points towards both of these kinds of particles having masses. The mechanism that provides this property is, incidentally, the same one that relates the W^i and B bosons with their observable counterparts, the $W^\pm$, Z and γ bosons. It is the Higgs-Brout-Englert mechanism or spontaneous symmetry breaking of the electroweak sector [20, 21].

In order to introduce new dynamics to the electroweak sector, a new pair of complex scalar fields (ϕ^+, ϕ^0) is introduced with both hypercharge and weak isospin equal to $1/2$ that transform as a spinor doublet under $SU_L(2)$. The fact that the field is a scalar means that additional self interacting terms can be added to the Lagrangian density without breaking Lorentz invariance, gauge invariance or the renormalizability criteria. This leads to obtain a generic form

$$\mathcal{L}_\phi = D_\mu \phi D^\mu \phi - \mu^2 \phi^\dagger \phi + \frac{\lambda}{2} (\phi^\dagger \phi)^2 \quad (2.9)$$

where μ^2 and λ are free parameters of the model. In the most interesting case of $\mu^2 > 0$, the potential term $V(\phi) = -\mu^2 \phi^\dagger \phi + \frac{\lambda}{2} (\phi^\dagger \phi)^2$ will have a global minima outside the origin at the value of $\langle \phi \rangle = \sqrt{\frac{\mu^2}{\lambda}} = \frac{v}{\sqrt{2}}$. Such value is called the vacuum expectation value (vev) of the field.

Additionally, the local gauge $SU_L(2)$ symmetry can be used to eliminate one degree of freedom from this scalar field by using the *unitarity gauge* such that only the real component of the ϕ^0 field is non-zero. Coupled with an expansion of the field around its vev, one can obtain the transformed field relation $\phi^+ = 0$, $\phi^0 = v + H$, where H is the new physical field which will ultimately relate to what we call the Higgs boson. Plugging this expression and Equation 2.8 into Equation 2.9, several interesting terms arise. It is specially relevant to point the following ones:

$$\mathcal{L}_\phi = D_\mu H D^\mu H - \frac{\mu^2}{2} H^2 + \sqrt{\lambda} \mu H^3 + \frac{\lambda}{2} H^4 + o(vH) + o(v^2) \quad (2.10)$$

where the Higgs field acquires a mass and presents both triple and quadruple self-coupling interactions. Additionally, couplings with the electroweak gauge bosons through the covariant derivatives and the $o(vH)$ terms that involve either one or two Higgses and either one or two additional gauge bosons -with at least three total bosons- appear. The additional terms that are independent of the Higgs field and of order v^2 can be regrouped into what might be better visualized in a matrix operation

$$\mathcal{L}_{o(v^2)} = \frac{v^2}{2} \begin{pmatrix} W_\mu^1 & W_\mu^2 & W_\mu^3 & B_\mu \end{pmatrix} \begin{pmatrix} \frac{-g^2}{4} & 0 & 0 & 0 \\ 0 & \frac{-g^2}{4} & 0 & 0 \\ 0 & 0 & \frac{-g^2}{4} & \frac{-gg'}{4} \\ 0 & 0 & \frac{-gg'}{4} & \frac{-g'^2}{4} \end{pmatrix} \begin{pmatrix} W_\mu^1 \\ W_\mu^2 \\ W_\mu^3 \\ B_\mu \end{pmatrix} \quad (2.11)$$

Notably, mass terms for the W_μ^1 and W_μ^2 fields for masses of $m_W = \frac{gv}{2}$ are generated. Instead of using directly such fields, a usual redefinition is to take $W_\mu^+ = \frac{1}{\sqrt{2}} (W_\mu^1 + iW_\mu^2)$ and $W_\mu^- = \frac{1}{\sqrt{2}} (W_\mu^1 - iW_\mu^2)$ which correspond to the observed W^+ and W^- bosons. Additionally, by diagonalizing the lower part of the matrix it can be found that two different mass eigenstates appear: $Z_\mu^0 = \frac{1}{\sqrt{g^2 + g'^2}} (gW_\mu^3 + g'B_\mu)$ with mass $m_Z = \sqrt{g^2 + g'^2} \frac{v}{2}$ corresponding to the Z boson and $A_\mu^0 = \frac{1}{\sqrt{g^2 + g'^2}} (g'W_\mu^3 - gB_\mu)$ which is massless and corresponds to the photon. Rewriting the covariant derivative of Equation 2.8 in terms of the mass eigenstates it can be observed what quantities each field are coupled to

$$\begin{aligned}
D_\mu^X = & \partial_\mu - i \frac{g I_3^X}{2\sqrt{2}} \left[W_\mu^+ \sigma^+ + W_\mu^- \sigma^- \right] \\
& - i \frac{1}{\sqrt{g^2 + g'^2}} Z_\mu \left[g^2 I_3^X \sigma_3 - g'^2 Y^X \right] - i \frac{gg'}{\sqrt{g^2 + g'^2}} A_\mu \left[I_3^X \sigma_3 + Y^X \right]
\end{aligned} \tag{2.12}$$

with $\sigma^+ = \sigma_1 + i\sigma_2$ and $\sigma^- = \sigma_1 - i\sigma_2$ defined from the usual Pauli matrices. Noticeably, the W bosons only couple to particles with weak isospin, right handed fermions, while the Z boson also can couple to left handed fermions through their hypercharge. The combination $Q = I_3 + Y$, which the photon couples to, is the well known electric charge and appears for both left and right handed leptons.

As a final note, notice that, while the μ and λ parameters of the Higgs potential are not determined by the SM and so the Higgs mass and its vacuum expectation value have to be determined by experiments, once those are fixed the masses of the gauge bosons and the interaction strengths of the electroweak fields are dependant. In fact, the masses of the W and the Z are related by the relation

$$\frac{m_W}{m_Z} = \frac{g}{\sqrt{g^2 + g'^2}} = \cos(\theta_w) \tag{2.13}$$

where θ_w is known as the Weinberg Angle.

2.2.2 Boson polarization

In classical electrodynamics, the electromagnetic field in the vacuum can only have two different polarization states corresponding to the two spacial degrees of freedom that are orthogonal to the trajectory of an electromagnetic wave. Similarly, in QFT real massless bosons, like the photon, only have two allowed helicity states. A sketch of a proof of such phenomena is discussed here.

A generic quantum vector field A_μ can be written as a superposition of solutions to the Klein Gordon equation, plane waves such as¹

$$A_\mu(x) = \int \frac{d^4p}{(2\pi)^3} \sum_{i=0}^3 \epsilon_\mu^i(p) a_p^i e^{-ipx} + \epsilon_\mu^{i*}(p) a_p^{i\dagger} e^{ipx} \tag{2.14}$$

where p is the -integrated over- four momentum, and x is the time space coordinates. a_p^i and $a_p^{i\dagger}$ are the annihilation and creation operators that create a boson of momentum p and polarization state i . The four different four vectors ϵ_μ^i represent the polarization states in which bosons might be created. Any physical observable, such as the amount of independent polarization states, can not depend of the chosen gauge, so for simplicity let us take the Lorentz gauge: $\partial_\mu A^\mu = 0$. Applying this condition on Equation 2.14 and making it hold for any value of x , leads to the relation

¹See Equation (4.131) in Reference [16].

$$p_\mu \epsilon^\mu(p) = 0. \quad (2.15)$$

If the space–time coordinates are rotated such that the four momentum is fixed to $p = (E, 0, 0, p_z)$, where E is the total energy and p_z the momentum along the Z axis, the three independent solutions of Equation 2.15 are

$$\epsilon_L = (0, 1, -i, 0) , \quad \epsilon_R = (0, 1, i, 0) , \quad \epsilon_O = (p_z, 0, 0, E) \quad (2.16)$$

which are respectively called the left, right and longitudinal polarization states of the boson. Consider now any physical process producing a final state vector boson in a generic polarization state ϵ and with fixed momentum p . Ward’s identity points that if the associated matrix element is decomposed as $\mathcal{M} = \epsilon_\mu \mathcal{M}^\mu$ then

$$p_\mu \mathcal{M}^\mu = 0 \quad (2.17)$$

The space–time rotation that leads to Equation 2.16 can always be applied once the boson momentum is fixed so, without loss of generality operations can be done with the boson’s momentum along the Z axis.

If the boson is massless, notice that $p_z = E$, so the longitudinal polarization state is parallel to the photon’s momentum. Then, from Equation 2.17, $\mathcal{M} = \epsilon_{O,\mu} \mathcal{M}^\mu \propto p_\mu \mathcal{M}^\mu = 0$. Thus, the amplitude for the production of longitudinally–polarized massless bosons is zero for any given production mode, and so they can’t interact and thus, effectively, they don’t exist. The consequence is that the additional longitudinally–polarized mode only appears for massive bosons which, in turn, are a consequence of the spontaneous symmetry breaking mechanism. The usual interpretation is that the massive vector boson absorbs an additional polarization degree of freedom by from the original ϕ scalar field, the Goldstone boson associated to the broken symmetry.

Experimentally, most processes involving the production of W and Z bosons from collisions of unpolarized particles, end up producing all three polarized states. A handle to separate the different contributions is specially useful when dealing with studies of vector boson polarization. The usual description of the polarization in a sample of W or Z bosons relies on the definition polarization fractions f_L , f_R , and f_O , the proportion of bosons in the left, right or longitudinally–polarized state in the sample. A useful tool can be obtained by defining the polarization angle θ^W (θ^Z), as the angle between the W (Z) boson and the charged (negatively charged) lepton on its decay. The following relations for the differential cross sections hold before the outgoing charged lepton produces additional radiation:

$$\frac{d\sigma}{\sigma d \cos \theta^{W\pm}} = \frac{3}{8} \left[(1 \mp \cos(\theta^{W\pm}))^2 f_L^W + (1 \pm \cos(\theta^{W\pm}))^2 f_R^W + 2 \sin^2(\theta^{W\pm}) f_O^W \right] \quad (2.18)$$

$$\frac{d\sigma}{\sigma d \cos \theta^Z} = \frac{3}{8} \left[(1 + \cos^2(\theta^Z) + 2c \cos(\theta^Z)) f_L^Z + (1 + \cos^2(\theta^Z) - 2c \cos(\theta^Z)) f_R^Z + 2 \sin^2(\theta^Z) f_O^Z \right] \quad (2.19)$$

where σ represents the production cross section of a generic process involving the vector boson. It has to be noted, however, that polarization fractions are frame-dependant quantities so the measuring frame needs to be fixed first before performing such measurements to properly ensure the interpretability of the resulting polarization fractions.

2.2.3 Fermion masses

Up until now no comment has been made on the coupling of the ϕ field to fermions. The most general Lagrangian density that fulfils the criteria of Lorentz and gauge invariance, and renormalizability for a single generation of fermions is

$$\mathcal{L}_{Yukawa} = -y_l \bar{l}_L \phi e_R - y_d \bar{q}_L \phi d_R - y_u \bar{q}_L \epsilon \phi^\dagger u_R \quad (2.20)$$

where, again, ϵ is the completely antisymmetric symbol in the $SU_L(2)$ space. The y_l, y_d and y_u couplings are called Yukawa couplings and are free parameters of the model. Expanding this result around the vev of the scalar field, mass terms and couplings to the Higgs boson are obtained for the fermions as

$$\mathcal{L}_{Yukawa} = -\frac{y_l v}{\sqrt{2}} \bar{e}_L e_R - \frac{y_d v}{\sqrt{2}} \bar{d}_L d_R - \frac{y_u v}{\sqrt{2}} \bar{u}_L u_R + o(Hff) \quad (2.21)$$

where the mass of fermions equals $m_f = \frac{y_f v}{\sqrt{2}}$ for charged leptons and quarks, while neutrinos remain massless due to the non existence of right handed neutrinos which they can couple to.

The problem of the lepton masses becomes more complex when several generations are involved as in the more general approach the Yukawa couplings are promoted to Yukawa matrices Y_l, Y_d and Y_u which are not necessarily diagonal leading to possible flavour mixings between generations. This, in turn, would introduce the problem of fermion flavours being objects without either well defined masses. The solution is to redefine the fermion fields to be the eigenstates of the Yukawa matrices. For the case of the quarks a basis of fermion fields which are simultaneously eigenstates of the Yukawa matrices and of the electroweak interactions is not achievable. In fact, it has been measured that the electroweak interaction connects the quark mass eigenstates from different families. This phenomena is parametrized through the Cabibbo-Kobayashi-Maskawa (CKM) matrix [22]

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \quad (2.22)$$

which encodes the strength of the coupling of the W bosons to a pair of the corresponding quarks. The CKM matrix is not entirely diagonal, but the V_{tb} term has been measured to be big enough to ensure that most top quarks produce b quarks on their decays. The mixing of the first and second generation quarks is significantly more pronounced leading to a more complex set of decay relationships.

For the case of the charged leptons, thanks to the massless property of the neutrinos, this effect can be absorbed by redefining the three flavours of neutrinos and so no additional criteria needs to be applied. In models where neutrinos are not massless and such redefinition is not possible, an analogous to the CKM matrix, the PMNS (Pontecorvo-Maki-Nakagawa-Sakata) matrix exists [23].

The Yukawa couplings, including the mixing terms between generations, are free parameters in the SM that need to be determined by experiments, meaning that the SM does not fix the masses of its fermionic content, neither the mass of one elemental fermion can be used to predict the mass of another. This result completely separates the nature of fermion masses from that of boson masses which are fixed by the strength of the gauge fields as discussed in Equation 2.13.

2.3 Quantum chromodynamics

The remaining gauge fields that appear in the SM correspond to a $SU_C(3)$ symmetry. The associated interaction is the so called strong interaction and the corresponding theory is known as Quantum Chromodynamics (QCD). Analogous to Equation 2.23, a free field Lagrangian for the $SU_C(3)$ fields can be written as

$$\mathcal{L}_g = -\frac{1}{4}G_{\mu\nu}^a G_a^{\mu\nu}, \quad G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a + g_s f_{bc}^a G_\mu^b G_\nu^c, \quad [T^a, T^b] = i f^{abc} T^c \quad (2.23)$$

where f_{bc}^a are the structure constants corresponding to the relations of the eight generators of the $SU(3)$ group, T^x , and g_s is the strong coupling constant. As the $SU_C(3)$ group has eight generators, a total of 8 new vector bosons, known as gluons, arise from the corresponding gauge fields.

The preserved quantity associated to the interactions of QCD is known as colour, a property that only quarks amongst the SM fermions have, so Equation 2.8 only needs to be modified for quarks with colour charge C for which it would read as

$$D_\mu^X = \partial_\mu - ig I_3^X \sigma_i W_\mu^i - ig' Y B_\mu - ig_s C T^a G_\mu^a \quad (2.24)$$

Several peculiarities separate QCD from EWK interactions and introduce relevant consequences to experimental particle physics. First, gluons do not interact with the Higgs field, neither with any other scalar field which might provide them with mass through spontaneous symmetry breaking, so they remain massless particles. Together with Equation 2.23 this introduces a relevant problem of QCD. Not only gluons do self interact, but the fact that they are massless means that processes in which a freely

propagating gluon emits another gluon are not kinematically forbidden by the conservation of energy and momentum. Thus, a single freely propagating gluon constantly emits more gluons that can end up producing showers of strongly charged particles.

Second, the evolution of the strong coupling g_s has a very distinct behaviour. Computations performed with the renormalization group equations show that the evolution of g_s follows²

$$\frac{dg_s}{d\log(Q)} = -\frac{33 - 2n_f}{48\pi^2} \quad (2.25)$$

where Q is the energy scale of the interaction, and n_f is the number of fermion flavours which are coupled to the strong interaction under that energy scale. The consequence of solving Equation 2.25 is that the strong coupling increases as the total energy of the system decreases. In fact, at an energy scale generically known as Λ_{QCD} , the coupling constant becomes big enough that QCD can no longer be considered a perturbative theory. Under this scale, coloured particles group into bound states known as hadrons, a phenomenon that is known as confinement. Only the top quark, which, as a consequence from its high mass, has a mean lifetime orders of magnitude smaller than the typical hadronization timescales, does not hadronize. Conversely, as the energy of the interaction increases g_s becomes smaller and the strong interaction is weaker, leading to the existence free quark states at very high energies.

With the addition of QCD, the complete picture of the SM is obtained. A depiction of the elementary particle content, both fermions and bosons, of the SM is presented in Figure 2.1.

2.4 Limitations and extensions to the SM

Within its realm of applicability, the SM has proven to be an incredibly successful theory. Most phenomena observed in particle physics experiments can be explained within the framework of the SM and, in fact, all the particles of the SM have been observed experimentally, the latest of them being the Higgs boson (H) that was observed by the ATLAS and CMS collaborations in 2012 [1, 2]. However, several measurements from both inside and outside the field of particle physics can't be fully described by the SM and might point towards the existence of a more complex underlying theory that has not been found so far. Such theories are collectively known as Beyond the SM (BSM) physics.

The hierarchy problem, or the naturalness of the Higgs boson mass [25] appears when loop corrections to the propagator of the Higgs boson are computed with the SM. Such corrections can be summed up through renormalization into an additional correction to the Higgs bare mass and are computed to be at the order of the Planck scale, $\Delta(m_H)^2 \sim Y_x^2 \Lambda_P^2$, around seventeen orders of magnitude greater than the measured mass of the Higgs boson, and proportional to the Yukawa couplings of the SM fermions. The bulk of the correction comes from the top quark, as it has the greatest of the fermion masses of the SM by a wide margin. As both the bare mass of the

²Reference [16], Equations (17.12) and (17.13).

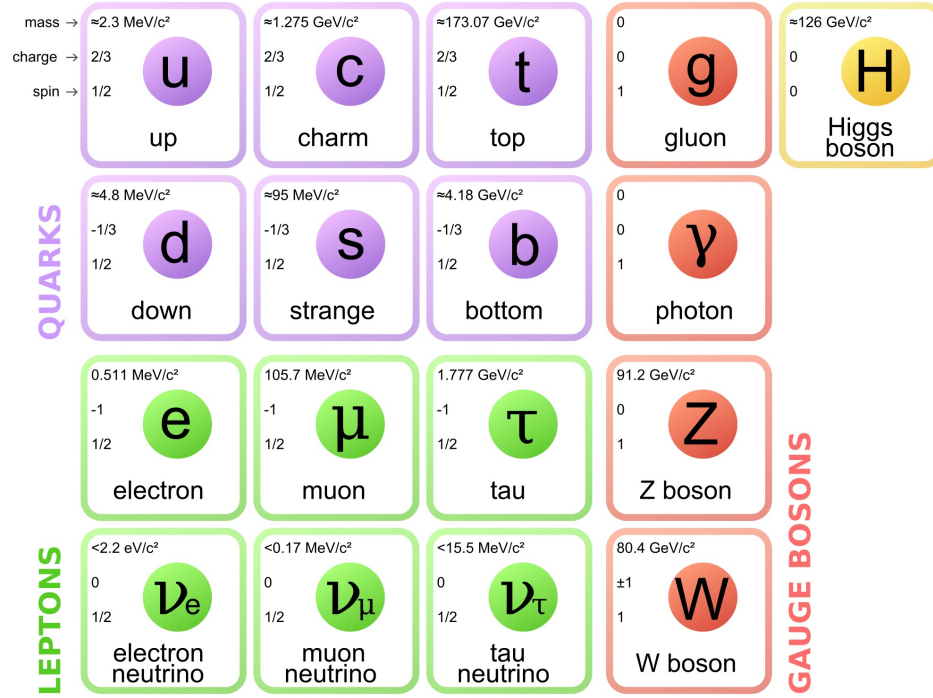


FIGURE 2.1: Schematic view of the particle content of the SM and several of the fundamental properties of each particle. Picture is available publicly in Reference [24].

Higgs and the Yukawa couplings of the fermions are free parameters of the model, it is feasible that these corrections cancel out with an equally big bare mass to lead to the observed Higgs mass value of around 125 GeV. However, such a fine tuning of constants of up to seventeen figures of merit points towards the possibility of a simpler explanation, possibly under a yet unknown symmetry of the system that is only slightly broken.

Neutrinos have been found to show a behaviour of oscillation between flavours [26]. Such an effect can only be understood if different masses are assigned to the neutrinos of each generation in the SM and a PMNS mixing matrix is included to the leptonic sector of the SM. While the absolute values of the masses and their assignment to each neutrino flavour are not completely understood, the small mass splittings have been measured accurately enough to proof they are different from zero. As right handed neutrinos would be non-interacting in the SM, neutrinos can't gain mass as other SM fermions. Either an additional set of interactions explaining how right handed neutrinos could be produced or additional mechanisms to explain the left handed neutrino mass would need to be introduced.

Gravity is widely known as one of the fundamental interactions, and its description by general relativity has been found as successful and predictive in cosmological processes as the SM has been for the elemental particle world. However, reconciliation of gravity with the SM poses a yet unsolved problem both theoretically and experimentally, as neither a consistent QFT of gravity has been developed and proven, nor a hint for a hypothetical gauge carrier -the graviton- has been found. The existence of super dense massive cosmological objects such as neutron stars and black holes, which incorporate both extreme gravity and quantum effects, would point to the need for such a unified theory for their description at close enough distances.

Cosmological observations provide yet another challenge to particle physics in the form of dark matter. Since several decades ago [27], observations of galaxies point that the speed at what they rotate at the outer edges is way bigger than would be expected by the amount of ordinary matter observed inside them. Measurements have since been validating by alternative experimental measurements, for example gravitational lensing ones [28]. The presence of a new kind of matter of yet unknown nature, called dark matter as it doesn't interact electromagnetically, is hypothesized as a possible explanation for the phenomena. No hints of new elementary particles that could compose this new matter have been found.

Yet another observation of cosmological origin is the apparent asymmetry of matter and antimatter in the universe, as most SM processes tend to produce both in equal terms. Phenomena that originate an excess of matter over antimatter break the charge-parity (CP) symmetry and are relatively rare. A few SM process are known to do so through the effect of a CP-odd phase in the CKM matrix, such as some types of meson decays [29], but their effects are too small to explain the level of asymmetry observed in the universe.

2.4.1 Supersymmetric theories

Supersymmetry (SUSY) is the general idea, which was first introduced in 1974 [30, 31], of extending the Lie algebra structure of the Lorentz group into a Lie superalgebra. In SUSY, the Lorentz group generators corresponding to the space-time translations, rotations, and boosts, are expanded with a set of new generators $\{Q_i\}$ that obey the Jacobi identity through commutation relations rather than anticommutation ones. As a consequence, all SM particles are part of multiplets where such new transformations apply. As the new transformations would commute with the existing SM symmetries other entries in said multiplets will have the same quantum numbers under the Lorentz group and the gauge field transformations. This leads to the appearance of new SUSY particles corresponding to the new transformed states.

2.4.1.1 Phenomenology and particle content

In the most simple realization of SUSY, each SM fermion pairs with a new BSM boson and each SM boson with a new BSM fermion, which are usually called their supersymmetric partners or superpartners. More complex theories which offer some mathematically desirable properties can be formulated by adding additional supersymmetric generators. Although they offer interesting new properties, the phenomenologically complex final state that they introduce, with the addition of great quantities of new particles, makes studying such theories experimentally quite challenging. In this document studies are restricted to the Minimal Supersymmetric Standard Model (MSSM) [32–34] which is the smallest extension that accommodates all SM particles and a minimal number of four supersymmetric operators. In the MSSM all fermions and gauge bosons have their corresponding superpartner, and two new doublets of Higgs fields are introduced instead of the usual one. The fermion's masses are generated through the mechanism described in Section 2.2.3 but up-type quarks and leptons only couple to an *up-type Higgs* while down-type quarks couple to the *down-type Higgs*.

In the MSSM the partners of the SM fermions are named by adding an additional “s” before their SM partner name and denoted with an additional tilde on top. Thus, the selectron is the SUSY partner of the electron and is denoted as $\tilde{e}$. The partners of the SM bosons are named by adding an “ino” suffix to their name. Thus, the gluino ($\tilde{g}$) is the SUSY partner of the gluon (g).

The additional freedom introduced by the extended MSSM Higgs sector means that the relations between the Higgs and electroweak gauge bosons’ fermionic superpartners are not fixed by the SM couplings, so they can freely mix into new mass eigenstates. In the most general case, the SUSY fermions that could be observed experimentally would correspond to mass eigenstates known as neutralinos (with zero electric charge) and charginos (with non zero electric charge), mixings of the interaction eigenstates corresponding to Higgsinos, Binos and Winos. Neutralinos and charginos are respectively denoted as χ_i^0 and $\chi_j^\pm$, where i and j are integers which refer to their order in mass, with χ_1^0 and $\chi_1^\pm$ being the lightest ones of each kind.

2.4.1.2 Consequences and properties of the MSSM

The main success of SUSY as a general framework is its ability to answer several of the issues pointed at the start of Section 2.4. As the properties of the supersymmetric partners match the ones of their SM counterparts, it can be proven that the loop corrections that cause the hierarchy problem for the Higgs boson mass cancel out between the fermions and sfermions, meaning that no fine tuning is needed to stabilize the Higgs mass [35, 36]. As such, studies related to the top superpartner (stop) are expected to provide further insight into the Higgs hierarchy problem that complements those that research on the properties of the top Yukawa coupling. This has lead to an extended effort in searching for the stop squark in the LHC experiments [37].

An usual restriction imposed to the MSSM is the conservation of an additional quantity known as R charge, or R -parity. This charge is computed multiplicatively for all particles in a given state, and assigns a value of 1 for SM particles and -1 for their superpartners. As a result, the decays of the lightest SUSY particle (LSP) are not kinematically allowed and it has to be a stable particle. Neutralino LSPs in R -parity conserving MSSM theories are prime candidates for Dark Matter candidates, as their expected mass values and interaction strengths, both at the level of the electroweak scales, match expected properties which could explain current measurements of the properties of dark matter [38]. As such, a discovery of R parity conserving (RPC) SUSY would lead to a natural particle candidate which would explain the dark matter problem.

As SUSY partners haven’t been found at the masses of their SM counterparts, the symmetry corresponding to SUSY has to have been broken at a given energy scale, originating what would be observed as a different mass spectra for the SM and the SUSY partners. As a consequence, the cancellations that lead to the *solution* of the hierarchy problem can not be exact, but would rather be at the order of the energy scale of the SUSY breaking mechanism. Thus, SUSY at the energy scales of the Higgs mass is still an specially appealing theory to be studied for at the LHC, which is specially suited to produce physical events at such momentum regimes.

2.4.1.3 Simplified models

The MSSM introduces relations between some of the SM free parameters but also introduces some new ones which need to be fixed by experimental measurements. As an experimental hint of MSSM is yet to be observed, a complete search for MSSM would need to simultaneously probe all possible free parameters of the theory, a daunting task from the experimental point of view due to the curse of dimensionality. As such, simplified models (SMS) [39] are introduced. An SMS is a projection of the MSSM parameter space into final states that contain only a handful of new BSM particles which can be parametrized by a small set of two or three parameters, normally using for convenience as the masses of the new particles. The branching fractions of such particles are usually set such that no additional SUSY partners need to be introduced.

While an SMS does not represent the full power of the MSSM, it provides a clearly defined template which can be used to probe the new interactions predicted by BSM physics. As such templates are agreed upon by the experimental collaborations and the theory community, SMS are useful tools to simultaneously probe for similar signatures in different analysis and experiments, ensuring a fair comparison and the joint reinterpretability of the results.

2.4.2 The effective field theory approach

An alternative way of searching for the presence of new physics is to use the formalism of Effective Field Theory (EFT) [40]. The underlying idea is that new physics might only appear at energies that are too high to directly produce the resonances associated to the BSM particles. Thus, at low energies BSM physics appear as an *integrated out* theory with a limited range of applicability in the energy scale of the interaction. The resulting effect is either the appearance of a new interaction vertex that was previously not allowed in the SM, or a modification of an already existing coupling. In practice, the EFT approach might be sensitive to many kinds of phenomena that could answer the different questions posed in Section 2.4, as most models will have an integrated out effect at low energy values.

2.4.2.1 Example: Fermi's theory of four fermion couplings

EFT can't only be applied to new interactions, in fact most QFTs can be reduced to an EFT in the appropriate low regime level. One of the most well known EFT is Fermi's theory of the beta decay [41], which models the flavour changing currents of what was later known as the action of the electroweak interaction at the low energy regime. Even if in Fermi's day the existence of the W and the Z boson were not known, we know today that this is the low energy EFT corresponding to exchanges of the W boson. It also happens to be a classical example of the first point, EFT parametrizations that lead to previously not existing couplings, so we will briefly review it as an example of an EFT model.

Fermi worked out its theory for the process of β decay, but the fundamentals are represented as well in terms of the $\mu\nu_\mu \rightarrow e\nu_e$ process. At the SM, the perturbative leading order (LO) diagram corresponding to such a process can be observed in Figure

2.2 (left). In a very low energy world, only fundamental fermions and the photon would be known to exist as elementary particles. As such, a modern formulation of such knowledge would be QED, the restriction of the SM to the $U_Y(1)$ symmetry with no Higgs mechanism and neither W or Z bosons. Thus, at very low energies, the puzzling process corresponding to the Feynman diagram on Figure 2.2 (right) is what it is effectively observed.

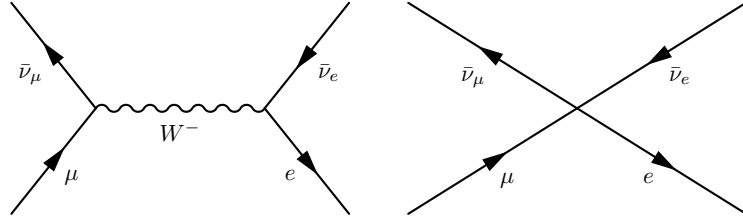


FIGURE 2.2: Feynman diagrams corresponding to the tree level effects in the $\mu\nu_\mu \rightarrow e\nu_e$ process for the SM (left) and Fermi's theory (right). The diagram on the right is an EFT variation of the one of the left with the intermediate W boson integrated out in a four fermion coupling.

According to Fermi's theory, a four fermion Lagrangian term is introduced. In modern notation it would appear as

$$\mathcal{L}_{Fermi} = -\frac{4G_F}{\sqrt{2}} (\bar{\nu}_\mu P_L \mu + \bar{\nu}_e P_L e) (\bar{\mu} P_L \nu_\mu + \bar{e} P_L \nu_e) \quad (2.26)$$

where P_L is the left handed projector $(1 + \gamma^5)/2$ and G_F is a new coupling known as the Fermi constant. Note that dimensional analysis shows that G_F has dimensions of inverse squared energy, and so the Fermi Lagrangian does not describe a renormalizable theory unless an upper energy cut-off is applied. The resulting matrix term for the four fermion term on Figure 2.2 is then

$$\mathcal{M}_{\mu\nu_\mu \rightarrow e\nu_e}^{Fermi} = \frac{iG_F}{\sqrt{2}m_W^2} \bar{\nu}_\mu(q_1)\gamma^\alpha(1-\gamma^5)\mu(q_2)g_{\alpha\beta}\bar{\nu}_e(p_1)\gamma^\beta(1-\gamma^5)e(p_2) \quad (2.27)$$

where q_1, q_2 are the momentum of the initial state particles, and p_1, p_2 the ones of the final state particles.

Alternatively, the EFT coupling can be derived from the SM one by computing the overall the matrix element. Mathematically, the diagram corresponding to the SM can be condensed into a matrix term composed of two Wff couplings plus the W boson propagator such as

$$\mathcal{M}_{\mu\nu_\mu \rightarrow e\nu_e}^{SM} = \frac{-ig}{\sqrt{2}} \bar{\nu}_\mu(q_1)\gamma^\alpha \frac{1-\gamma^5}{2} \mu(q_2) (i) \frac{g_{\alpha\beta} - \frac{q_\alpha q_\beta}{m_W^2}}{q^2 - m_W^2} \frac{(ig)}{\sqrt{2}} \bar{\nu}_e(p_1)\gamma^\beta \frac{1-\gamma^5}{2} e(p_2) \quad (2.28)$$

where the quantity $q = p_1 + p_2 = q_1 + q_2$ is the total exchanged momentum of the system that matches the momentum of the W boson exchanged. If the later quantity is small enough $q \ll m_W$, Equation 2.28 can be simplified to

$$\mathcal{M}_{\mu\nu\mu \rightarrow e\nu_e}^{Fermi} = \frac{ig^2}{8m_W^2} \bar{\nu}_\mu(q_1) \gamma^\alpha (1 - \gamma^5) \mu(q_2) g_{\alpha\beta} \bar{\nu}_e(p_1) \gamma^\beta (1 - \gamma^5) e(p_2) \quad (2.29)$$

which is just equivalent to Equation 2.27 if $G_F = \frac{\sqrt{2}g^2}{8m_W^2}$. Thus, at low enough energies Fermi's theory is equivalent to the exchange of a W boson in the SM.

Several notable observations can be made on this example. First, as discussed before, Fermi's theory introduces a new four fermion interaction that does not appear in the world of QED. The new Lagrangian is not renormalizable so our modern knowledge points towards the fact that it needs to break at a new energy for the theory to make finite predictions. Second, once the EFT is matched to the new physics at a low energy scale, the EFT parameters can be expressed on terms of physically meaningful scales (the W boson mass) of the complete theory. The EFT parameter G_F , however, is completely free in the EFT theory and it needs to be measured to fix it. Last, the complete theory provides the scale at what the EFT breaks, when q is closer to m_W^{PDG} but this quantity is unknown to the EFT. Thus, the EFT by itself is unable to describe its range of applicability.

2.4.2.2 Parametrization and limitations of the EFTs

The power of EFTs is rooted on the generalization that can be achieved once the EFT is not directly derived from the asymptotic behaviour at low energy of a fixed new physics model, but rather in a completely general approach. The SM EFT approach (SMEFT) is to build all possible Lagrangian density terms with the SM fields that are allowed by the SM symmetries and assign then arbitrary coupling constants. Then they can be ordered according to the dimensionality of their couplings in terms of powers of energy

$$\mathcal{L} = \mathcal{L}_2 + \mathcal{L}_3 + \mathcal{L}_4 + \mathcal{L}_5 + \mathcal{L}_6 + \dots \quad (2.30)$$

where $\mathcal{L}_X$ has a coupling constant with dimensions $4 - X$ (the 4 appearing due to the space-time integration of the Lagrangian density) and is called a dimension-X term. All terms of dimension 4 or lower are renormalizable and present in the SM³. Just one dimension 5 operator appears, coupling the Higgs boson and two left handed fermion doublets [42]

$$\mathcal{L}_5 = \frac{c_5}{\Lambda} \bar{L}_L H H^T L_L^c \quad (2.31)$$

where the c_5 coupling is suppressed by an arbitrary but fixed energy scale of Λ . In this notation, the adimensional coupling c_5 is known as the Wilson coefficient and is

³With the exception of the CP-breaking term involving a cross product of the QCD field tensors. It is renormalizable but not present at the SM. This is known as the strong CP issue and is related to axion theories.

a free parameter of the theory. Similarly, higher order Lagrangian densities can be written as sums over Wilson operators times new Wilson coefficients. Generically it can be written as

$$\mathcal{L}_X = \sum_{i=1}^{N_X} \frac{c_i}{\Lambda^{4-X}} \mathcal{O}_X^i \quad (2.32)$$

Starting at dimension 6, a lot of possible additional operators $-\mathcal{O}_6^i$ appear, its number depending on whether CP conservation and flavour universality of the different couplings are to be conserved or not. Several basis of independent operators are available in the literature depending on their better suitability for different computations or experimental measurement in concrete final states. Notice that if the Λ scale is fixed for all the appearing terms, at sufficiently low energies the energy scale suppression will be greater for operators of higher dimensions, so the lower dimension ones, corresponding to dimensions 6 to 8, are assumed to be the dominant ones.

An interesting relation appears if only dimension six operators are considered. If the matrix element for the presence of both the SM and a set of dimension six operators represented by the set of Wilson coefficients c_i , it can be proven that at LO the dependence of the cross-section on the matrix element for a given process is obtained by

$$\begin{aligned} \sigma_{SM+EFT} &\sim \left| \mathcal{M}_{SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{M}_i \right|^2 = |\mathcal{M}_{SM}|^2 + \sum_i \frac{2c_i}{\Lambda^2} \text{Re}(\mathcal{M}_{SM} \mathcal{M}_i^*) + \sum_{i,j} \frac{c_i c_j}{\Lambda^2} \text{Re}(\mathcal{M}_j \mathcal{M}_i^*) \\ &= |\mathcal{M}_{SM}|^2 \left(1 + \sum_i \frac{2c_i}{\Lambda^2} \frac{\text{Re}(\mathcal{M}_{SM} \mathcal{M}_i^*)}{|\mathcal{M}_{SM}|^2} + \sum_{i,j} \frac{c_i c_j}{\Lambda^2} \frac{\text{Re}(\mathcal{M}_j \mathcal{M}_i^*)}{|\mathcal{M}_{SM}|^2} \right) \\ &= |\mathcal{M}_{SM}|^2 \left(1 + \sum_i c_i b^i + \sum_{i,j} c_i c_j a^{ij} \right) \Rightarrow \\ &\Rightarrow \frac{\sigma_{SM+EFT}}{\sigma_{SM}} = \left(1 + \sum_i c_i b^i + \sum_{i,j} c_i c_j a^{ij} \right) \end{aligned} \quad (2.33)$$

meaning that, as the SM cross section doesn't vanish, the variations in the cross section with respect to the SM one follow a quadratic dependence on the EFT parameters. Moreover, this relation also holds for differential cross-sections, which makes it quite a powerful tool to provide a modelling of the EFT parameter effects without needing to simulate the possible continuous value each Wilson coefficient might take.

Several limitations have to be taken into account when studying the effect of BSM physics in terms of EFTs experimentally. First, the applicability of the theory needs to be restricted to a fixed energy range. As detailed before, when the energy scale that is being probed starts to get close by to the scale of the new physics the EFT approximation becomes unreliable. Moreover, as the value of such new scale is unknown, the only possibility is to scan for possible variations of its values to obtain a full picture of the discriminant power from any experimental measurement.

Second, the fact that dimension 6 operators are the ones that should be expected to have the greater effects does not mean that dimension 8 and over can be safely ignored. In fact, contributions at the cross section computation level can be pretty much comparable between the two, depending on the *real* value of the Wilson coefficients. As an example, assume that a SM process has a matrix element from SM-only hypothesis of $\mathcal{M}_{SM}$, another one from a dimension six operator of $\frac{c_6}{\Lambda^2}\mathcal{M}_6$, and yet another one from a dimension 8 operator $\frac{c_8}{\Lambda^4}\mathcal{M}_8$. Then, the total cross section ordered by powers of Λ would be proportional to

$$\begin{aligned} \sigma \sim \left| \mathcal{M}_{SM} + \frac{c_6}{\Lambda^2}\mathcal{M}_6 + \frac{c_8}{\Lambda^4}\mathcal{M}_8 \right|^2 &= |\mathcal{M}_{SM}|^2 + \frac{2c_6}{\Lambda^2}\text{Re}(\mathcal{M}_{SM}\mathcal{M}_6^*) + \\ &+ \frac{1}{\Lambda^4} \left(c_6^2 |\mathcal{M}_6|^2 + 2c_8\text{Re}(\mathcal{M}_{SM}\mathcal{M}_6^*) \right) + \frac{2c_6c_8}{\Lambda^6}\text{Re}(\mathcal{M}_6\mathcal{M}_8^*) + \frac{c_8^2}{\Lambda^8} |\mathcal{M}_8|^2 \end{aligned} \quad (2.34)$$

It should be noticed that the $1/\Lambda^4$ term contains both a contribution that appears purely due to the dimension 6 EFT but also the interference of the dimension 8 term and the SM which is not guaranteed to be neither smaller nor bigger than the first. Thus, complete studies of EFT effects either have to take into account several orders of the EFT approach or apply a cut-off to considered contributions to the cross-section up to lower values, such as considering only contributions up to the $1/\Lambda^4$ presence.

2.5 The SM at hadron colliders

At hadron colliders, like the LHC, the nature of QCD has a significant impact in how physical collisions are both produced and measured. The whole description of any physical process has two clearly separated energy regimes depending on whether QCD is perturbative (for scales over Λ^{QCD}) and can be treated as a weakly interacting theory in which free quarks exist, or it is not (scales under Λ^{QCD}) and hadronization of coloured particles inevitably occurs. Moreover, as the colliding beams are not composed of elementary particles but composite states bound by the strong interaction such as protons, any computation related to the high energy beam-beam interaction needs to be completed with the description of such bound states in ultrarelativistic conditions. At such energies not only the protons can interact, as the interaction of their components (partons) are usually the ones that do produce the most relevant physical processes. When this happens, a beam-beam collision is called inelastic as it ultimately breaks the proton into its constituents.

The description of an inelastic collision in the LHC can be roughly divided in several steps. Exemplified by proton-proton collisions they can be summarized as follows:

1. The description of the incoming protons, specifically an understanding of the kinematic properties of the colliding partons.
2. The collision itself (hard scattering), in which the two partons interact to generate a new state composed of different SM particles.
3. Radiation emitted by coloured final states resulting from the previous steps, which at some step will enter the regime of non perturbative QCD and produce

bounded states through hadronization. This includes the lower energy remnants of the incoming protons and their evolution after the hard scattering.

At collider experiments, measurable properties of the SM are studied in terms of production cross sections. Even if differential cross sections could be theoretically computed with respect to all degrees of freedom of a final state, the complexity of the most physically interesting ones makes such approach unpractical in reality. The simulation of collision processes using Monte Carlo (MC) methods, is a computationally affordable alternative that has been proven a key tool in experimental measurements. The need for this simulation to provide answers to the issues outlined before means that each of the discussed steps are usually treated by different interconnected tools.

2.5.1 Proton structure and parton distribution functions

Protons are hadrons, composite states resulting from the nature of QCD at low energies. In the quark model [15] the proton is a baryon, meaning that its quantum numbers under the SM interactions are given by the sum of those of its three main constituents, or valence quarks. Explicitly, such quarks are of flavours u , u and d . As quarks are coloured particles, the description of a proton needs to incorporate the presence of additional particles arising from the interactions of its valence quarks. These interactions can produce additional gluons or quarks which are known as sea quarks or sea gluons. Together with sea gluons, valence and sea quarks are the constituents of the proton known as partons. At low energies external interactions treat the proton as a elementary object, interacting with it as a whole. Whoever, as for any composite object, at sufficiently high energies the nature of the proton becomes evident and external interactions with its parton constituents will start to appear.

A Parton Distribution Function (PDF) $f_i(x, q^2)$ is an object that represents the probability to find a parton of a given flavour i with a fraction of the proton's momenta x when interacting at an energy scale q^2 . Effectively, the PDFs are parametrizations that represent the proton structure as it is seen from any external particle that interacts with it at a given energy regime. The power of the PDFs lies in its usage to summarize the structure of the proton which can't be computed by perturbative QCD computations in terms of quantities represented at the partonic level. For a generic observable Z that depends on the PDF of two initial state partons –like a cross section– its value in a pp collision can be computed as

$$Z = \sum_{i,j=0}^{N_f} \int dx_i dx_j f_i(x_i, \mu_F) f_j(x_j, \mu_F) Z_{ij}(x_i, x_j, \mu_F)(x_i x_j) \quad (2.35)$$

where $Z_{ij}(x_i, x_j, \mu_F)$ refers to the value of the same observable computed only with partons of flavour i and j at the given fractions of energy. The energy scale at what the PDFs are evaluated, the factorization scale μ_F is a somewhat arbitrary quantity introduced to regularize the effect of infrared divergences. It separates the regime in which additional radiation of particles are included -factored- into the PDF description or through some of the methods outlined later. For computations that are able to

incorporate all perturbative orders in QCD and EWK theories in the estimation of $Z_{ij}(x_i, x_j, \mu_F)$, the summed up predictions should be independent of μ_F .

Even if PDFs depend on the energy scale, once their values have been measured at a fixed value their evolution with respect to this parameter can be predicted using the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) equations [43]. Thus, they can be measured at lower energies than the LHC that are reachable in much cleaner electron–proton colliders and later extrapolated to the colliding energies of the LHC using the DGLAP equations. Thanks to this procedure, the results from the electron–proton HERA collider obtained by the ZEUS and H1 collaborations [44] are the foundation of modern PDF estimations.

Of course, measurements that rely on experimental data will incorporate additional uncertainties related to the precision with which that data is measured. Luckily, the possibility of extrapolating measurements from one energy regime to another means that results from different experiments that are sensitive to the PDFs can be combined into one to reduce these uncertainties. Combining different sets of measurements with slightly distinct methodologies, several modern collaborations provide different representations on PDFs and their uncertainties known as PDF sets. Even if the environment of the LHC is relatively noisy due to the involvement of two different protons in the collisions, the great amount of data obtained from its collisions has been started to be used for PDF determination into several of those. Explicitly, the PDF sets that will be used through this document, derived by the NNPDF [45], CT [46], MMHT [47] and PDF4LHC [48] collaborations do so.

An example of the PDFs from the NNPDF30_nlo_as_0118_mc set at relatively low energies corresponding to the HERA measurements ($Q^2 = 10 \text{ GeV}^2$) and the electroweak scale probed at the LHC ($Q^2 = m_Z^2$) is shown in Figure 2.3. It can be noticed how, as energies grow, the PDF of the valence quarks is progressively more similar to that of the sea quarks. Moreover, at higher energies the gluons start to take the majority of the proton’s momentum.

2.5.2 Hard scattering description, matrix element generators

The process in which a parton from each of the incoming hadrons interacts inelastically is known as the hard scattering process, and usually contains the physical coupling that is of more interest for LHC measurements. Usually both the two incident partons have a big enough fraction of the proton’s momentum to remain in the energy regime in which QCD is perturbative, so the whole SM QFT described in the previous sections can be used to perform hard scattering predictions perturbatively in the QCD and EWK couplings.

A mathematical description of the hard scattering provides the probability of finding a given set of final state particles with given momenta known the initial state particles and their kinematic properties. Explicitly, for the case of a cross section the usual description would replace the $Z_{ij}(x_i, x_j, \mu_F)$ term in Equation 2.35 by

$$d\sigma(ij \rightarrow f; x_i, x_j, \mu_F) = \delta^4(p_i + p_j - p_f) I(p_i, p_j) |\mathcal{M}_{ij \rightarrow f}(\mu_F)|^2 dF(p_f) \quad (2.36)$$

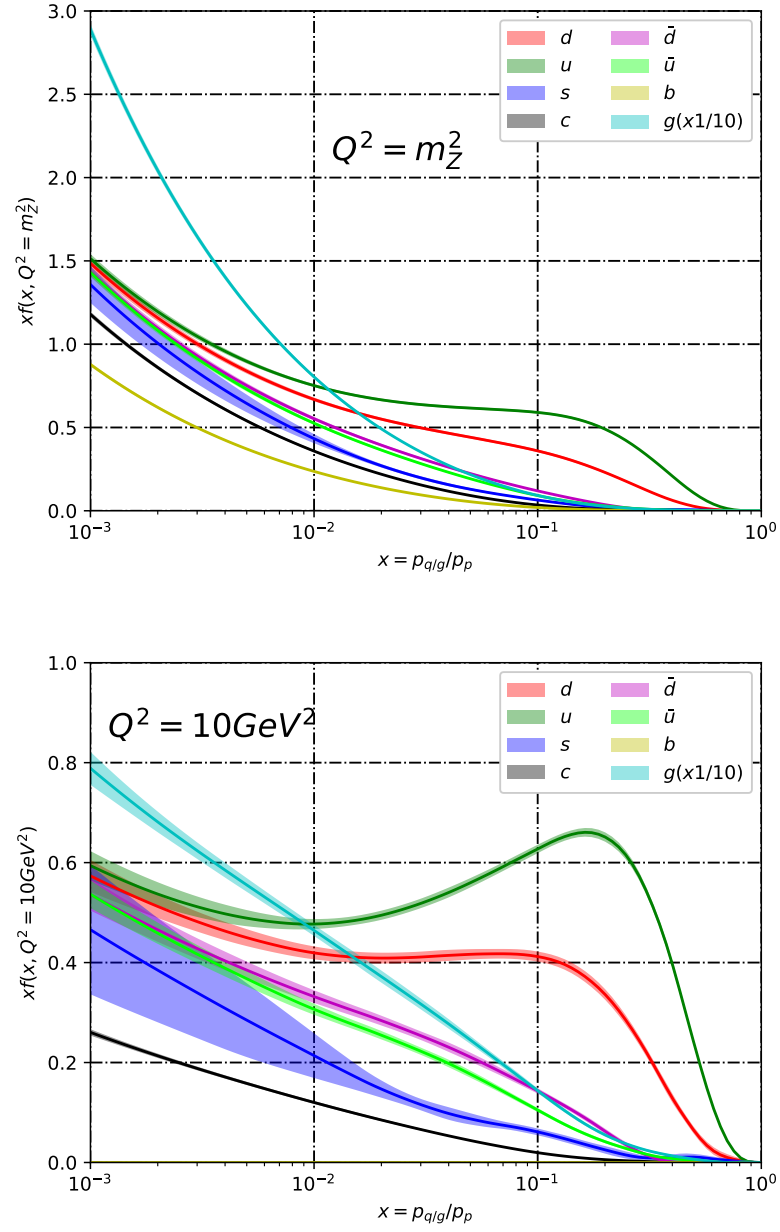


FIGURE 2.3: Parton distribution functions from the NNPDF30_nlo.as.0118_mc set at $Q^2 = m_Z^2$ (top) and $Q^2 = 10 \text{ GeV}^2$ (bottom). The gluon PDF is scaled downwards by a factor of 10 to better fit the plot range. The LHAPDF framework [49] was used to produce these plots.

where p_i, p_j are the four momentum of the initial partons and p_f is the four momentum of the –possibly many– final state partons. $I(p_i, p_j)$ represents normalization factors depending on the energy of the initial state, and $dF(p_f)$ an additional factor that accounts the differential phase space occupied by final state particles at the fixed momenta p_f . The $|\mathcal{M}_{ij \rightarrow f}|^2$ in the middle is known as the matrix element term and encodes the probability as obtained from the underlying QFT that a scattering of initial particles i, j produce final particles f based on the interactions it describes. The matrix element terms are usually estimated in QFT through the usage of Feynman diagrams (and rules) representing all possible transitions from the initial to the final states and their associated amplitudes. A summary of the Feynman diagrams and their associated rules for matrix element computations in the SM can be found in [16].

MC generator programs that are capable of using the matrix elements and perform phase space integration to provide an accurate description of differential cross sections from generated MC events are known as matrix element generators. A priori, a complete cross section computation requires producing matrix elements at arbitrarily high perturbative orders, each one suppressed by an additional power of the coupling constant α_s/α_{ew} which would add up to finite physical observables. However, such approach is impossible in practice, and computations are usually truncated to a limited –fixed– perturbative order. Thus, the explicit dependence of the coupling constants $\alpha_s(\mu_R)$ and $\alpha_{ew}(\mu_R)$ at a given energy scale, the renormalization scale μ_R , is not cancelled. MC computations need to choose the μ_R scale and several recipes are available to study the effects of the *missing* higher order computations as additional theoretical uncertainties. Expectations from the perturbative hypothesis are that the higher the perturbative order, the smaller the correction becomes, but this criteria needs to be validated in a case by case basis as cancellations might appear at lower orders that no longer apply at higher ones.

Going from computations at leading order (LO) to next-to-leading order (NLO) and further towards next-to-next-to leading order (NNLO) in QCD has been one of the triumphs in MC simulation. Depending on the final state particles, the incorporation of NLO and NNLO computations can introduce processes that were previously not considered in cross section computations. For example, at LO in QCD, WZ production can only be produced from two quark partons ($q\bar{q}'$) initial states, as both initial and final state need to have the same total electric charge. At NLO in QCD, an additional quark can be emitted and so initial states involving a quark and a gluon ($q\bar{g}$) should also be considered.

Nowadays MC generators at LO and NLO in QCD are available for most SM processes, and even matrix element computations for arbitrary final states are available. Through the work presented in this document the POWHEG [50–52] and MADGRAPH+aMC@NLO [53] generators are used extensively to represent different kinds of SM and BSM physics at LO and NLO in QCD. Minor usage of MCFM [54] and the matrix element capabilities of Pythia [55] are also included. As the strong coupling constant is usually quite bigger than the electroweak ones, the quoted matrix element computations contain only approximations at LO in EWK. Additionally, the simulations of generators producing predictions at higher orders, up to next-to-next-to leading order (NNLO) in QCD and NLO in EWK are considered through the introduction of the MATRIX framework [56].

2.5.3 Showering and hadronization

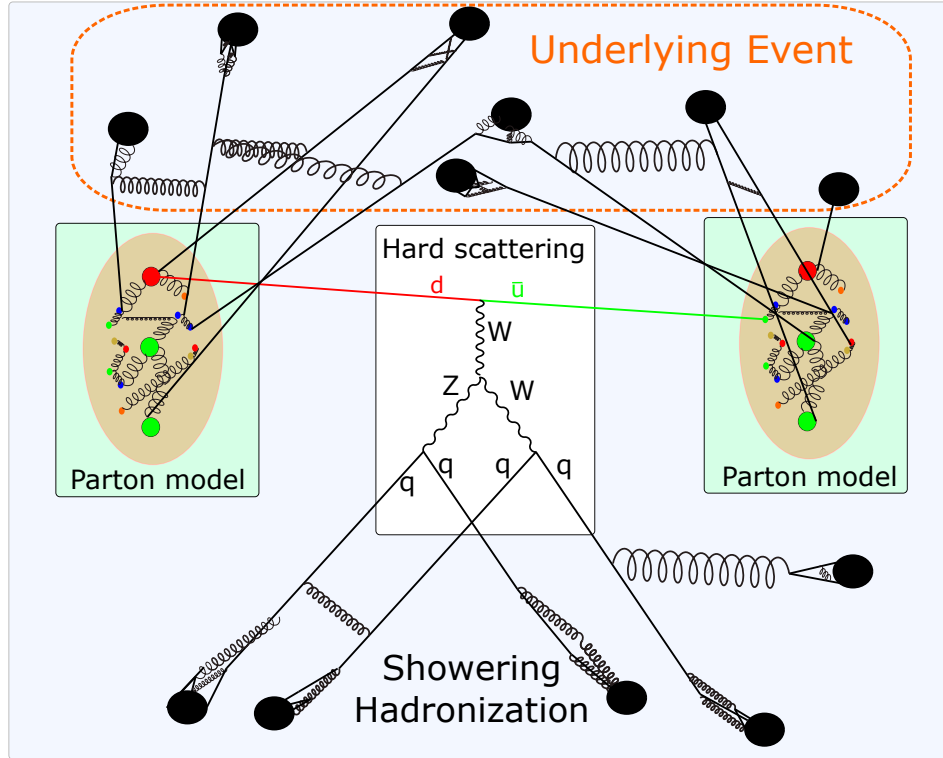


FIGURE 2.4: Schematic description of an inelastic proton proton collision. Each shaded background colour corresponds to the different models used to describe the associated physical phenomena depending on the energy regime and the associated behaviour of QCD.

Even if matrix element generators can provide accurate descriptions of the hard scattering at the partonic level, the resulting particles can either decay further or produce additional radiation. In fact, all charged particles might radiate photons and all coloured particles are likely to radiate gluons. Furthermore, this gluons can radiate additional coloured particles that interact between themselves, this process is known as parton fragmentation, and the structure of consecutive radiations from the initial parton state is a shower. On each radiation step the energy available decreases up to the point when hadronization kicks in, meaning that the results from parton fragmentation end up producing hadrons. The whole process contains a transition from perturbative to non perturbative QCD and is usually described by phenomenological models known as Parton Showers (PS).

A PS generator describes the effects of parton fragmentation by emission of gluons from coloured particles and gluon splitting into quark-antiquark pairs. Once low enough energies are reached, it also simulates the hadronization of the resulting particles. Moreover, the remnants of the colliding proton that are not the interacting parton also produce several, relatively low energy coloured particles, the underlying event (UE). Constituents of the UE suffer the same evolution process composed of showering and hadronization and are also modelled through Parton Showers. A depiction of an inelastic proton proton collision describing the ranges of applicability of the parton model, the hard scattering, and the showering and hadronization steps is presented in Figure 2.4.

MC simulations used on this paper use Pythia [55] as a PS generator, with different parameter tunes depending on the physics studied on each case. The simulation obtained by the hard scattering generators described in Section 2.5.2 is matched with the PS to provide a final description that correspond to the real physical states that later interact with the detector. Different procedures, merging, exist to complement the ME and PS simulations while avoiding double counting the radiation phase space for QCD emissions around the cut-off energy used to separate them.

3

The Large Hadron Collider and the CMS experiment

All studies presented in this thesis are performed with data corresponding to collisions performed with the Large Hadron Collider (LHC) and recorded with the Compact Muon Solenoid (CMS) experiment. The following sections aim to provide a quick description of both of them, as well as several key concepts later used in the rest of the thesis. Section 3.1 contains a description of the LHC and its more basic working parameters. Section 3.2 includes a description of the CMS experiment, including its component subdetectors, methods for object reconstruction, and triggering system. Section 3.3 includes a brief description of data taking conditions corresponding to both the LHC and CMS working parameters that will later characterize the different measurements presented through this document.

3.1 The Large Hadron Collider

The LHC is the largest particle collider ever built. It is a circular accelerator located in the frontier between France and Switzerland, close to the city of Geneva, 100 m underground and with its main accelerating ring covering a total circumference of 27 km. A general purpose facility, the LHC is capable of accelerating different types of particle beams, with the most common ones being proton–proton (pp) and lead–lead (PbPb) beam pairs, up to the energy scale of the TeV. Four different collision points are presented through the LHC circumference corresponding to the current positions of the A Large Ion Collider Experiment (ALICE), A Toroidal LHC Apparatus (ATLAS), CMS, and Large Hadron Collider beauty (LHCb) experiments. A detailed description of the LHC structure can be found in Reference [57].

A chain of accelerators is used to supply energetic particle beams to the LHC [58]. For pp collisions, protons are extracted from a hydrogen gas and accelerated up to 50 MeV in the LINear ACcelerator 2 (LINAC2). The Proton Synchrotron Booster (PSB) further enhances their energy up to 1.4 GeV and splits the continuous beams from the LINAC2 into bunches of protons. Two increasingly bigger circular accelerators, the Proton Synchrotron (PS) and Super Proton Synchrotron (SPS) further accelerate the protons to 26 GeV and then 450 GeV sequentially, at which moment they are injected

into the LHC main ring. Inside the LHC ring, the two proton beams circulate in opposite directions and are accelerated through the usage of electric fields presented in 16 cavities around the ring, each providing a voltage of around ~ 2 MV. A superconducting set of magnets is used to provide a magnetic field that keeps the protons inside the accelerator ring, and magnetic quadrupoles, sextupoles and octupoles are used to preserve the bunch coherence and shape. After the beams have been accelerated up to the colliding energy, they are deviated slightly such that collision of proton bunches or bunch crossings (BX) occur at the collision points. On each BX more than a proton pair can interact simultaneously, leading to the appearance of multiple interaction vertices (pileup) in registered collisions. An schematic view of the whole acceleration and colliding system can be found in Figure 3.1.

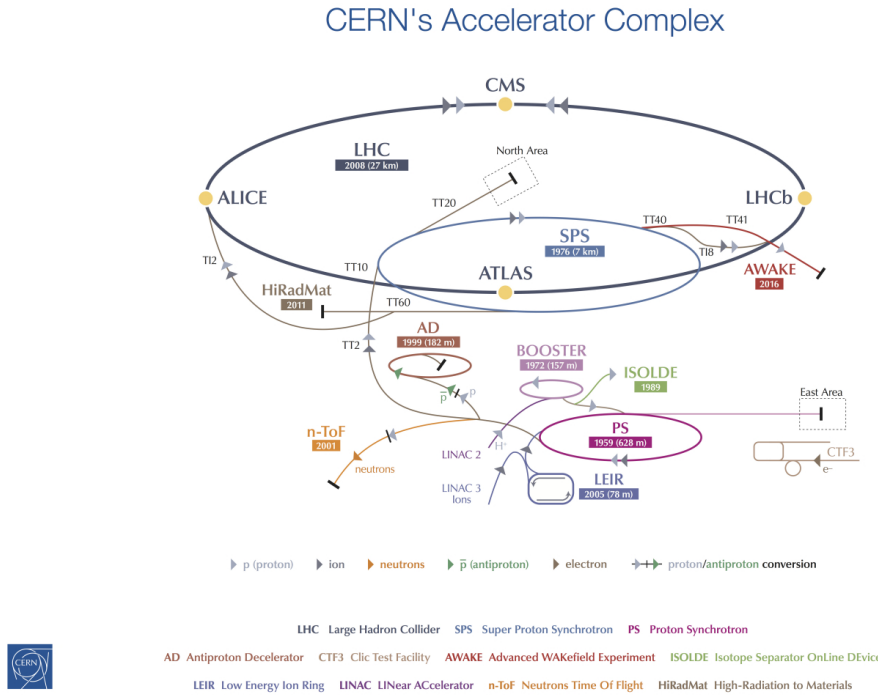


FIGURE 3.1: Depiction of the chain of accelerator complex leading to the LHC central ring, and the main set of experiments presented around its circumference. This picture is publicly available in Reference [59].

Several of the working parameters of the LHC are of special interest to the discussions presented through this document. First, the energy provided to each proton will determine the total energy available to the colliding system and so the behaviour of the physics produced during LHC operations. Such parameter is quantified through the Mandelstam variable $s = \sqrt{(P_1 + P_2)^2}$, where P_1 and P_2 are the four momentum of the incoming protons. The equivalent centre of mass energy, $\sqrt{s}$, is more commonly used as it is directly presented in units of energy. The LHC was designed to work with proton beams of up to 7 TeV energy each ($\sqrt{s} = 14$ TeV) but so far the higher energy collisions have been produced at 6.5 TeV beam energy ($\sqrt{s} = 13$ TeV).

Second, the potential of the LHC is also limited by the possibility of generating the interesting physics processes enough times so they can be properly measured. The amount of data produced by the LHC is quantified through the instantaneous luminosity quantity (L_{inst}), such as

$$\frac{dN}{dt} = \sigma L_{inst} \quad (3.1)$$

where $\frac{dN}{dt}$ is the differential rate, with respect to time, of produced events of a given physical process, and σ is its production cross section. As the cross-section is fixed in time, the total number of events is directly proportional to the total luminosity provided by the LHC (L), or the integration in time of the instantaneous luminosity. L_{inst} only depends on the LHC operation parameters and can be defined as

$$L_{inst} = \frac{n_b N_{p1} N_{p2} f}{4\pi\sigma_x\sigma_y} R \quad (3.2)$$

where n_b is the number of colliding bunches (up to around 3000), N_{p1} and N_{p2} are the number of protons per bunch in each colliding beam (around 10^{11} by design), f is the revolution frequency of the LHC (fixed at 40 MHz), σ_x and σ_y are the effective sizes of the bunches in the two transversal directions on collision, and R is a calibrated factor that accounts for the slight inclination introduced into the beams to produce the collision. Technical limitations due to the design of the LHC restricted its intended working parameters to a peak of $L_{inst} = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, but this quantity has been doubled during the peak performance days on the last years of pp collisions corresponding to the 2017 and 2018 years, by modifying the interaction parameters. In turn, in each bunch crossing the pileup multiplicity has increased correspondingly, which poses a greater challenge to detector operations. A depiction of the evolution in time of the accumulated CMS luminosity since the start of the LHC program in 2010 is shown in Figure 3.2.

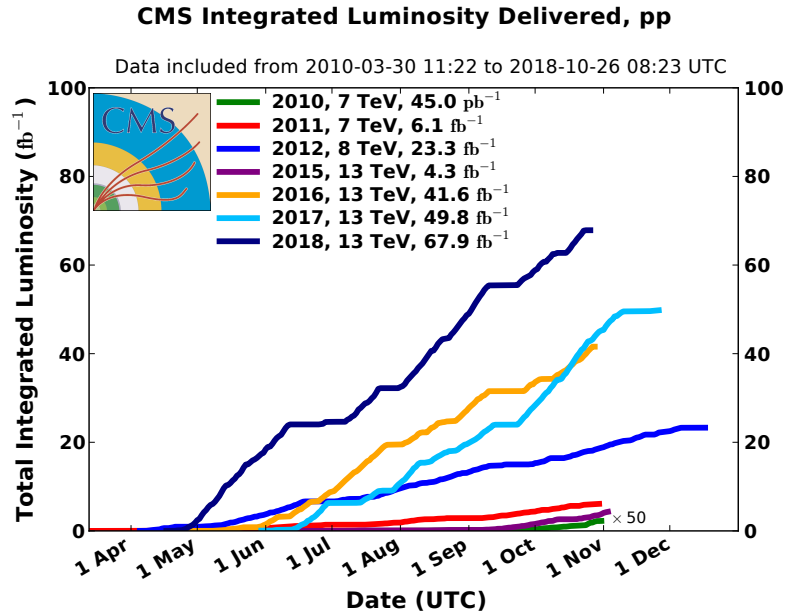


FIGURE 3.2: Evolution in time of the luminosity accumulated by the CMS experiment between the 2010 and 2018 data taking years. Figure is available in Reference [60]. Results are not accumulated across years.

3.2 The Compact Muon Solenoid experiment

The CMS detector has been constructed to serve as a general purpose experiment with large coverage over the different physics produced in the LHC collisions. A brief description of its structure is presented in the following pages, more details of which can be found on References [61, 62].

The shape of the CMS detector is roughly cylindrical, with a total length of around 20 m, and a diameter of roughly 15 m. The CMS experiment is designed based on a layered design in which several smaller subdetectors based on different technologies are placed sequentially one after the other. Combining the information from these subdetectors the different kinds of particles produced in an LHC collision and their properties can be properly measured. The different subdetectors roughly have a similar cylindrical shape to CMS, with a distinction usually being made between the barrel detectors (the lateral surface of the cylinder) and the endcap detectors (the bases of the cylinder). From innermost to outermost, the subdetectors are: the pixel detector, the silicon tracker, the electromagnetic calorimeter, the hadronic calorimeter, and the muon spectrometers. A solenoid magnet, which provides a magnetic field of 3.8 T along the central axis of the CMS detector, is present between the barrel layers of the last two subdetectors. A feature that even lends its name to the CMS experiment, its duty is to bend the trajectories of charged particles to improve the estimation of their momentum through measurements of their curvature. An open view of the CMS experiment and its subdetectors is presented in Figure 3.3.

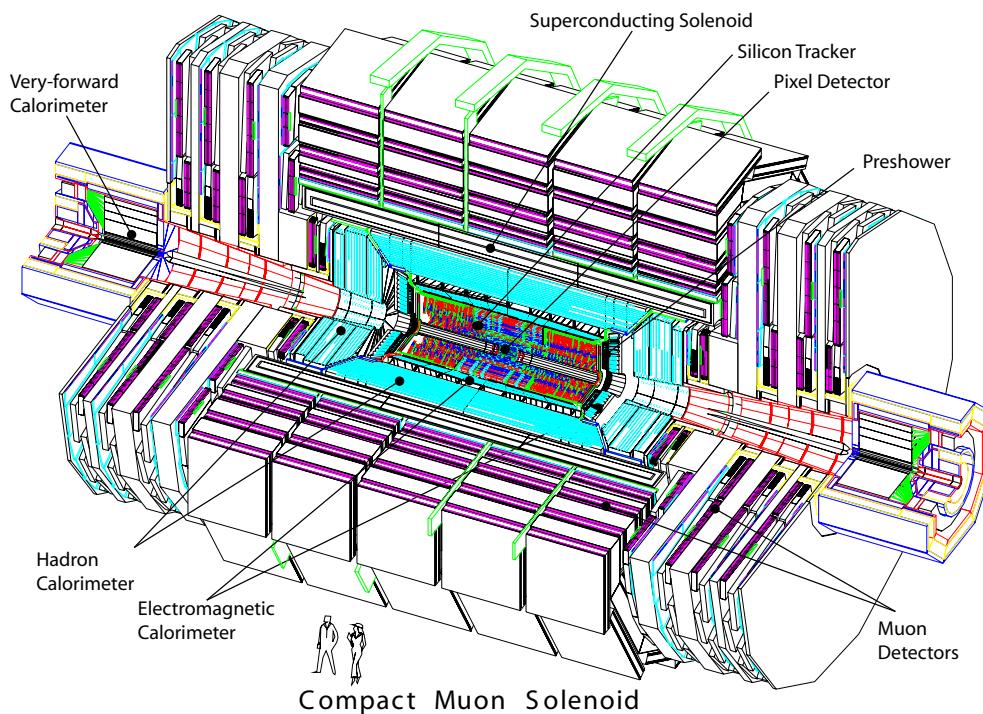


FIGURE 3.3: Schematic view of the CMS experiment and its subdetectors. Figure is available in Reference [62].

The CMS experiment is aligned in such a way that the incoming beams are perpendicular to the endcap surfaces and pass through the centre of the detector. A coordinate

system centred in the beam crossing spot is defined with the Z axis along the beam direction and pointing towards the Jura mountains, roughly to the west. The Y axis points perpendicular to the earth surface upwards and the X axis parallel to it towards the centre of the LHC. The symmetries of the collision process, in which both initial state particles have negligible momentum along the X and Y axis makes a separation between the Z axis (longitudinal axis) and the $X - Y$ plane (transverse plane) a natural division to describe the produced physics, as the overall sum of momenta in the later in collisions equals to 0.

A non-Euclidean coordinate system is used in order to describe the four-momenta of particles inside the detector. In the transverse plane, a polar parametrization is used with the transverse momentum (p_T) corresponding to the magnitude of the transversal momentum and the azimuthal angle ϕ defined counting from the x axis. In the few times that positions are used through this thesis, the transverse magnitude coordinate is described using the R character. The polar angle θ is measured with respect to the Z axis, but it is not used directly. Instead, the pseudorapidity η , a transformation of θ , is used. The pseudorapidity is equal to 0 at the transverse plane and tends to infinity towards directions parallel to the beam axis. Its most beneficial property is that differences in pseudorapidity are invariant under Lorentz' boosts along the longitudinal axis. The explicit transformations from the usual Euclidean coordinates (p_x, p_y, p_z) to the (p_T, η, ϕ) coordinates are given by the relations:

$$\begin{aligned} p_T &= \sqrt{p_x^2 + p_y^2} \\ \phi &= \arctan\left(\frac{y}{x}\right) \\ \eta &= -\log\left[\tan\left(\frac{\theta}{2}\right)\right] = \frac{1}{2} \log\left(\frac{\sqrt{p_x^2 + p_y^2 + p_z^2} + p_z}{\sqrt{p_x^2 + p_y^2 + p_z^2} - p_z}\right) \end{aligned} \tag{3.3}$$

An angular distance metric in the $\eta - \phi$ coordinates is defined as $\Delta R(p_1, p_2) = \sqrt{(\eta_1 - \eta_2)^2 + (\phi_1 - \phi_2)^2}$. This quantity is commonly used to define the angular separation between two different particles with momenta p_1 and p_2 as it has the interesting property of being Lorentz invariant under boosts along the Z axis.

3.2.1 Tracking systems, silicon detectors

The innermost of the CMS subdetectors are based on silicon sensors. Their duties is the precise reconstruction of charged particle tracks (tracking) through the measurement of energy depositions close to the interaction vertex. The good determination of the tracks is crucial both to obtain a precise estimation of the particle track parameters and its association with one or other interaction vertex, avoiding the wrong assignation of a particle to one vertex originated due to pileup interactions. The resilience of the silicon material against degradation due to ionizing radiation is crucial, as the beam radiation activity is the highest in positions closest to the beam axis. A more thorough description of the tracking system is described in Reference [63].

The closest subdetector to the beam axis is the pixel detector which was recently upgraded in 2017 [64]. In order to provide position measurements with very high precision, around 124 millions of silicon sensors of microscopic length are disposed into four different layers in the barrel region ($|\eta| < 1.5$) and three layers in the endcap –forward– region ($1.5 < |\eta| < 2.5$). After the latest upgrade, the innermost barrel pixel layer is around 2.9 cm far from the beam axis and the outermost at 16 cm. In the endcap, the pixel detector covers up to approximately 50 cm in the Z axis. The pixel subdetector provides position measurements with resolutions at the 10 μm level in the transversal plane and 20 μm in the longitudinal one.

The second part of the tracking system is based on several layers of thin silicon strips. They have a much bigger length than the silicon pixels, up to 10 cm, and relay on redundancy across different strip layers to provide precise position estimations. A total of 10 layers are present in the strip barrel region, up to a 110 cm distance from the beam, and where strips are parallel to the Z axis. On the endcap, 12 disks where strips are disposed in a radial way are disposed up to a longitudinal distance of 270 cm. The barrel layers are slightly rotated in an alternating pattern in order to increase the resolution in the Z axis direction. The typical resolutions along the Z axis are of around 200 μm , while those of positions on the transverse plane are around 20 μm .

Thanks to the presence of the solenoid magnet, the trajectories of charged particles are bent, a property that can be used in the tracking systems to estimate their transverse momentum. This measurement improves at lower values of the p_T , where the bending is noticeably higher. Resolutions in the track transverse momentum estimation from the tracking systems can reach relative precisions of up to 0.5% for low momentum tracks. This performance is close to optimal at the energy ranges later studied in this thesis, leptons with momenta in the 20–50 GeV range. Extrapolations of the tracks measured in the pixels also provide precise estimations of their impact parameter with resolutions at the 50 – 100 μm level, which is of special use when trying to reconstruct slightly displaced vertexes such as those produced by B mesons or hadronic τ decays. Example performance plots showing the resolution of the tracking systems on the impact parameter measurements are shown in Figure 3.4.

3.2.2 Calorimetry

The second set of subdetectors corresponds to the electromagnetic calorimeter (ECAL) and the hadronic calorimeter (HCAL). Each one is designed to absorb the majority of electromagnetically (ECAL) and hadronically (HCAL) interacting particles through the usage of high density material environments. The resulting radiation propagates as particle showers through the calorimeters which are then detected and absorbed, preventing their propagation to later stages of the CMS detector. These showers can later be used to reconstruct the properties of the original interacting particle through combination of measurements in adjacent calorimeter cells, or clustering. A thorough description of the ECAL is presented in Reference [66], while the same can be said for the HCAL in Reference [67].

The ECAL is a compact system built with around 70000 lead tungstate (PbWO_4) crystals. These crystals present an scintillating property which can be used to record the absorption of electromagnetically interacting particles through the ECAL. Moreover, a dense material with small radiation length and Moliere radius is specially suitable to

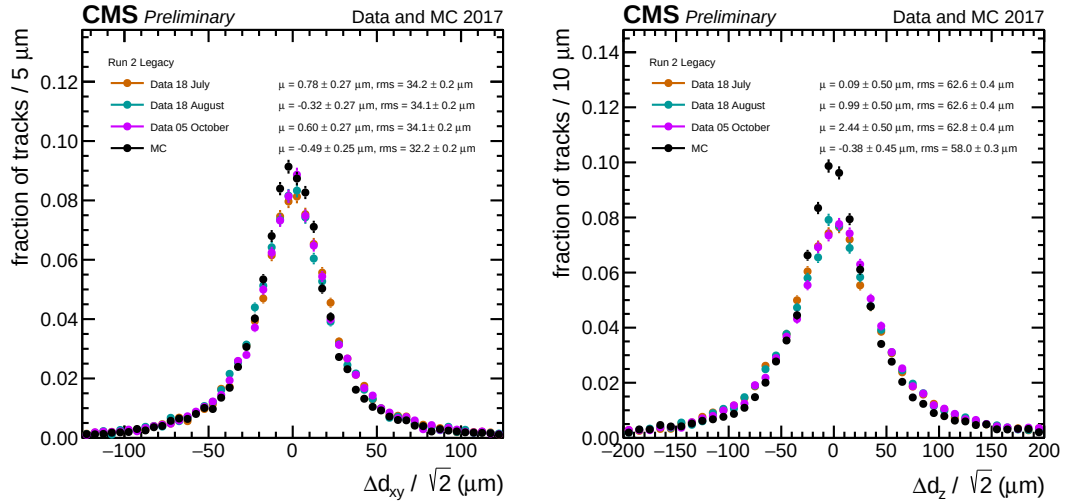


FIGURE 3.4: Resolution in the measurement of the transversal (left) and longitudinal (right) impact parameter of tracks as measured by the CMS tracking system. Measurements are performed in cosmic muon data and simulation in 2017 data taking conditions by comparing the estimations of the impact parameters obtained with the upper and lower parts of the tracking detectors. The figure is publicly available in Reference [65].

quickly absorb the produced electromagnetic showers before they reach the next sub-detector. The scintillating radiation produced in the crystals is absorbed by Avalanche Photodiodes connected to each ECAL crystal that provide the measurement of the deposited energy. The ECAL covers up to $|\eta| < 1.4$ and up to 160 cm in the barrel region and $1.4 < |\eta| < 3$ and up to 4 m in the endcap one. Before the endcap ECAL crystals, a preshower detector composed of two plates of lead and a silicon detector is present. Measurements of the overall particle energy can be performed in the ECAL through the aggregation of closeby channels into energy clusters. The resolution of such measurements tends to improve at higher energies, where the effect of noise is proportionally smaller, which complements the properties of the tracking systems. These measurements tend to be better at the barrel section of the detector than in the endcap, as depicted in Figure 3.5.

The HCAL is designed with alternating layers of absorbing and detecting material. Brass is used as absorbing material, due to its relatively small hadronic length, and the resulting low energy hadronic particles produced are then absorbed and detected through the usage of plastic scintillators. Two different sections compose the HCAL, including the barrel (up to $|\eta| < 1.3$ and a 2.8 m distance), and endcap ($1.3 < |\eta| < 3.0$ and 1 5.6 m distance) regions that cover the same phase space as the ECAL. To detect hadronic activity at higher values of pseudorapidity, and additional forward HCAL, where the absorbing material is replaced by the more radiation resilient steel, is present at the $3.0 < |\eta| < 5.0$ region up to a distance of 11.2m in the Z axis. An additional outer layer of HCAL scintillators is mounted on top of the solenoid, in order to absorb possible residual hadronic radiation before it reaches the latest set of subdetectors. As with the ECAL, the HCAL offers the possibility of estimating the energy of the incoming strongly interacting particles, but its resolution is typically worse than all other subdetectors of the CMS experiment.

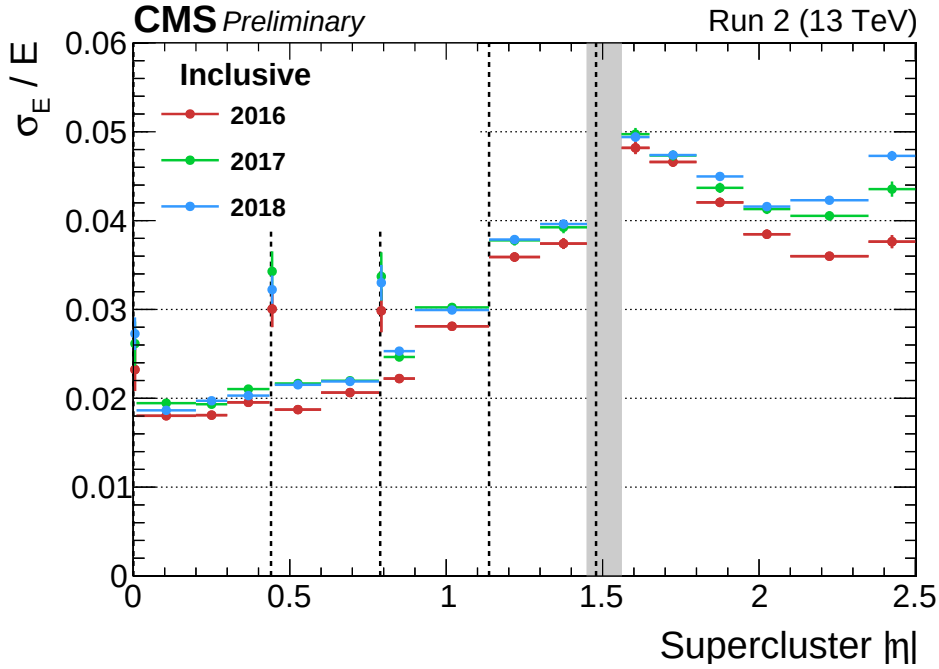


FIGURE 3.5: Relative resolution on the electron energy measured in the ECAL of CMS as a function of SC η for the different data taking years considered in this thesis. Measurements are performed using data composed with electron pairs from Z decays and fitting the invariant mass of the double electron pair to obtain the overall energy resolution on the Z boson peak. The figure is publicly available in Reference [68].

3.2.3 Muon spectrometers

The set of outermost subdetectors in the CMS experiment are collectively known as the muon spectrometers, and cover an area ranging up to $|\eta| < 2.4$ and distances of 7.4 m in the transverse plane and 10.6 m in the longitudinal axis. All the muon spectrometers are situated outside the solenoid magnet. Due to the minimum interacting particle (MIP) nature of muons, they are expected to be the only kind of SM particles reaching this part of the detector by design. Thus, the objective of the muon spectrometers is to provide a precise estimation of the properties of such muons at long distances from the beam axis. Different detecting technologies are used complementarily to improve spatial and temporal resolution while ensuring resilience against radiation in the harsher regions of the detector. Further details on the muon spectrometers can be found in Reference [69] and will be discussed in Chapter 7. A depiction of the muon spectrometers is presented in Figure 3.6.

The barrel region of the detector, up to $|\eta| < 1.2$, is covered by the drift tube (DT) detectors. The DT system is divided into five wheels along the Z axis with roughly the same width. Each of the wheels is further subdivided into 12 sectors corresponding to 30° divisions in the ϕ coordinate. Each of the sectors contains 4 different DT stations at increasing distances from the beam axis. Inside each of the stations, a few detecting layers are disposed. For the innermost three stations, 8 layers contain drift tube cells perpendicular to the beam axis, and 4 parallel to it, while the outermost station only contains the perpendicular layers. Each layer is composed of tens to hundreds of DT cells, a metallic prism with base size of 2.3×4.2 cm and variable length. The metal prism works as a cathode with an anode wire passes through its length at its middle.

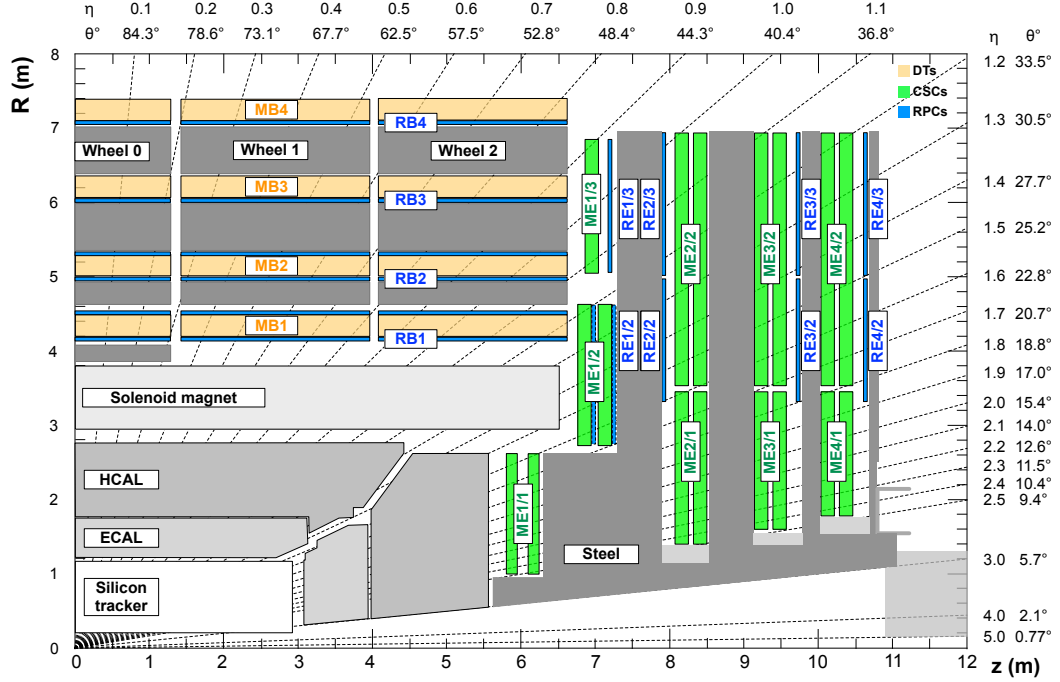


FIGURE 3.6: Schematic view of the CMS experiment with a detailed description of the different muon spectrometers and their disposition through the detector. A cross section of a quarter of the detector in the $R - z$ plane is shown. Non detecting material is shown in dark grey, the DT stations are depicted in yellow, the CSC rings are shown in green and the RPC layers are presented in blue. Figure is available in Reference [70].

The prism is filled with gas, and a voltage difference of around 3300 V is kept between anode and cathode, such that the passage of any ionizing particle through the gas would produce an avalanche effect that facilitates detection. Drift tubes provide precise estimations of the momentum track, with spatial resolutions between 70 and 120 μm in the transversal plane and in the 100 – 300 μm range for the longitudinal axis using information from a single DT station.

The endcap region, in $0.8 < |\eta| < 2.4$, can not be instrumentalized with the usage of DT technology due to the higher amount of irradiation received from the collisions. Instead, cathode strip chambers (CSC) are used. They are based on the presence of multiple anode wires placed radially between segmented metallic cathode planes that detect the passage of ionizing radiation through a similar avalanche process as in the DTs. The CSCs are placed in four disks perpendicular to the beam line at increasing distances in the Z axis, that are themselves divided between two to three rings at increased R distances from the beam. Most of the CSC rings are duplicated to improve the spatial resolution through the increased redundancy of the measurements. The CSC offer similar resolutions as those of the DT system for spatial measurements, with measurements using a single CSC ring providing a spatial resolution in the 60 – 120 μm range.

The DT and CSC systems are complemented by the presence of resistive plate chambers (RPCs), of which one to two are present surrounding each DT station and several of the CSC rings up to $|\eta| < 1.8$. The RPCs follow the idea of a gas detector used in the DT and CSC systems but use segmented metallic plates for both the anode and

cathode. Their spatial resolution is, thus, around an order of magnitude worse than that of the DTs and CSCs, at the level of 1 cm. However, they offer the best resolution in time of the muon systems, up to 1 – 2 ns, which complements the measurements obtained from DTs and CSCs.

3.2.4 Triggering on CMS

As discussed in Section 3.1, the LHC collides proton bunches at a rate of 40 MHz. Unfortunately, the amount of information produced by the depositions in the detector can not be saved at such a rate, due to the restrictions imposed by currently available hardware which can save slightly more than 1 kHz worth of bunch crossings. Thus, a triggering system that quickly operates with this information is used to decide whether to save the full data corresponding to a given bunch crossing or not. The trigger system of the CMS experiment is divided in two steps: the Level 1 (L1) Trigger and the High Level Trigger (HLT). Further details in the original design of the triggering system can be found in Reference [71]. Additional details on the L1 trigger will be discussed in Chapter 7.

The L1 trigger is based on information from the muon spectrometers and the calorimeters, with no information from the tracker used for this step. Its objective is to reduce the initial 40 MHz rate to around 100 kHz. First, the information from each subdetector is used to build locally reconstructed objects. Muons are first reconstructed as single segments or hits in the different DT stations, CSC rings or RPC chambers and quick track finding algorithms provide a combined reconstruction of the L1 muon candidate with a rough estimation of its kinematics. L1 electron, photon, jet, and hadronic τ candidates are reconstructed through clustering of the energy in the calorimeters and similarly quick reconstruction algorithms mimicking simplified versions of the offline object reconstruction that will be discussed in Section 3.2.5. All of these algorithms are directly implemented in dedicated hardware which operates under a latency time of 4 μ s, during which a snapshot of the detector information is still retained for the corresponding bunch crossing. A global L1 algorithm receives information from all L1 candidates and decides whether to pass it to the HLT or not, based on a previously designed set of decisions that depend on object multiplicity and kinematics. These decisions have been designed beforehand to target physics of interest to the CMS experiment based on the expected performance of the L1 and HLT systems.

If the L1 trigger decision is to select the event, the HLT takes over by using the whole detector information as well as the L1 reconstructed candidates in order to make a final decision. The HLT uses object reconstruction algorithms similar to the ones later used offline, described in Section 3.2.5, but is restricted to specific zones of the detector and final state topologies through the definition of several predefined sequences known as HLT paths (or simply triggers). If a suitable related set of L1 candidates is found in the collision event, the computations from an HLT path are started, which sequentially run alternating reconstruction and filtering steps. The reconstruction steps use only a limited set of information corresponding to the involved subdetectors, and if a filter requirements are failed, the corresponding HLT path computations are stopped in order to improve the speed of the HLT algorithm. The set of HLT paths present during a given data taking period are known as an HLT menu, and are defined with the objective of obtaining high efficiency towards the physics the CMS collaboration desires to study while avoiding surpassing the final output rate. At least one HLT path

needs its requirements to be fulfilled until its end for a collision to be finally saved. The HLT reconstruction and selection algorithms are run in a CPU farm outside the CMS detector.

In occasions, an additional criteria is applied in some HLT paths such that only one event out of a given number is allowed to pass its selection. These criteria are known as prescales, as they effectively scale down the effective luminosity of the corresponding HLT path by this value. While they are complex to use for measurements due to the difficulties in combining datasets with different effective luminosities, prescaled paths are useful for calibrations and auxiliary measurements that rely on relatively low p_T objects which can't otherwise be saved due to the inherent higher associated HLT rates.

3.2.5 Event reconstruction in CMS

For each bunch crossing registered by the CMS experiment, or collision event, the registered local measurements performed through the detector are combined to extract information on the underlying properties of the collision. This process, event reconstruction, aims to provide a complete description of the kinematic properties of the particles produced in the hard scattering and all other subsequent evolution processes. The Particle Flow (PF) algorithm [72] combines the information from all subdetectors to provide a set of candidates corresponding to reconstructed muons, electrons, photons, charged hadrons and neutral hadrons.

In a first step, tracks corresponding to charged particles are reconstructed from the signals in the tracking system. An iterative algorithm is employed to provide an efficient and pure set of reconstructed charged tracks. Each iteration of the algorithm employs a Kalman Filter [73] (KF) algorithm to find energy depositions (hits) in the tracker consistent with a given initial deposition (seed). On each iterative step, the requirements on the seeding and track quality criteria are loosened, but hits contained in successfully reconstructed steps are removed from posterior iterations. The resulting set of charged tracks is used to reconstruct interaction vertices, corresponding to the coincidence of several charged tracks in the same region of space. The vertex with the highest quadratic sum of charged track p_T in each event is assumed to be the one corresponding to the primary interaction (primary vertex), while the rest appear due to either the presence of long lived particles or pileup interactions.

Depositions in each of the calorimeters are clustered separately for the barrel and endcap regions. Cluster seeds are identified as cells in the calorimeter with energy depositions surpassing fixed thresholds and greater than neighbour cell measurements. A first set of clusters are then grown starting from the seeds by adding the contributions from their neighbour cells while their measured energy levels are incompatible enough with the noise only hypothesis. This first set of N candidate clusters is then refined by fitting the distributions of energy in the calorimeters to an analytic model in which N new seeds produce each a Gaussian response in the calorimeters. The positions of these new seeds in the η - ϕ plane are then fitted to provide the final set of clusters corresponding to their Gaussian-like signals. Additional dedicated seeds destined to electron reconstruction in both the ECAL and tracking systems are presented in more detail in Section 3.2.5.2.

Signals in the muon spectrometers can either correspond to tracks reconstructed across several of the muon stations (standalone tracks), or to those reconstructed in only a DT station or CSC ring (muon segments). More details on muon reconstruction are provided in Section 3.2.5.1.

Tracks and clusters are then associated through an association algorithm (linking). Elements that are the closest in the η - ϕ plane are considered candidates to linking and different criteria are used to define the likelihood of a match between two PF elements by extrapolating the measurements from one subdetector to another and checking their geometrical compatibility. PF blocks are built as sets of elements that are associated by the linking algorithm either directly or through an intermediate link. The resulting blocks are then classified depending on the observed set of depositions. Muons correspond to signals in the muon spectrometers and a reconstructed track. Electrons appear as blocks linking a charged track with an ECAL cluster. Photons are then extracted as single clusters in the ECAL. Charged hadrons correspond to a charged track, and clusters in the ECAL and HCAL. Neutral hadrons to a cluster in the HCAL alone. Further information on the definition of usage of these objects is provided in the Sections below. This set of relations between the candidate particles and the observed depositions are depicted in Figure 3.7.

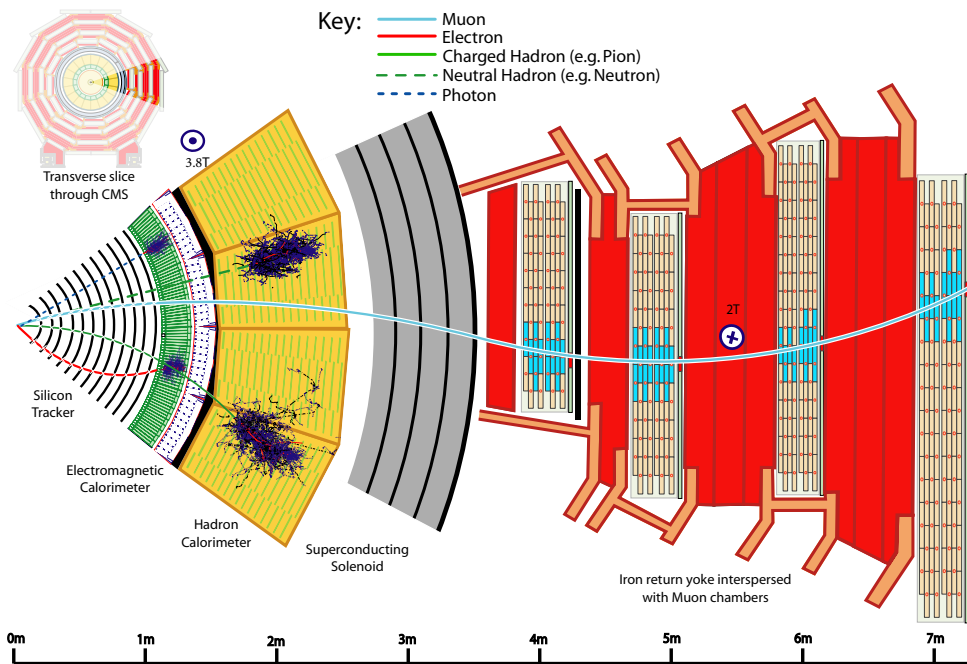


FIGURE 3.7: Schematic depiction of the energy depositions produced by each of the particles considered as possible output candidates from the PF algorithm over an slice of the CMS detector. The figure is taken from Reference [72].

3.2.5.1 Muon reconstruction

Reconstruction of muons is based on the presence of reconstructed tracks on either the muon spectrometers, the tracking volume, or both. Three main algorithms are used to perform such reconstruction depending on the seeding and kind of reconstructed deposition on each one [74].

A first kind of muon is based on signals on the muon spectrometers only. Local reconstruction of a track with only signals from a single DT station or CSC ring is known as a muon segment. A standalone muon candidate is one that is reconstructed with the combination of DT and CSC segments plus additional depositions on the RPC detectors. A KF algorithm is used to perform the combination of geometrically compatible segments into the standalone muon candidate [73].

Tracks reconstructed in the tracking system are extrapolated to the muon chamber under realistic assumptions on the existing magnetic field and the energy losses corresponding to the typical number of muon interactions with the material. Tracks that are found to be consistent geometrically with at least a locally reconstructed segment are known as tracker muons.

Finally, standalone muons are propagated inwards up to the tracker material under similar assumptions. If a tracking track is found that matches the standalone propagation geometrically, a new global track including the joint set of hits is built. An additional KF algorithm is run in this new global track to define a final muon candidate known as a global muon. By construction, global tracks can overlap with both standalone and tracker muons. In the cases in which this happens, they are merged into a single candidate which still retains references to the three individual reconstruction algorithms for identification purposes.

The estimation of the muon p_T is dominated by the measurements on the tracking system, as the spatial resolution it offers surpasses that of the muon spectrometers unless the muon p_T is high enough for its track to be near straight. Muons with p_T on the 3 – 200 GeV range, which appear in most of the contributions to the studies presented in this thesis, fall within this regime. These low momentum muons interact scarcely with the detector and so don't usually exhibit the showering problem observed from electrons and their bremsstrahlung effects. At higher values of the momentum, however, muon showering in the muon spectrometers starts to become a problem, for which dedicated reconstruction and fitting algorithms have been developed [74].

3.2.5.2 Electron reconstruction

Electrons are reconstructed as combinations of charged tracks and compatible depositions in the ECAL. As they are propagating through a material medium, electrons inside CMS will emit bremsstrahlung photons through the detector with an expected significant energy loss even before reaching the ECAL. Thus, electron reconstruction needs to recover the emitted radiation in order to measure the kinematics of the electron as it was produced in the hard scattering.

To tackle the radiation problem, three different dedicated PF elements for electron reconstruction are considered. Clusters from the ECAL are further grouped into superclusters (SC) representing both the initial electron and all its accompanying bremsstrahlung radiation. On the tracking side, reconstructed charged tracks that pass minimal consistency criteria are passed through a Gaussian Sum Filter (GSF) [75] algorithm more suited to reconstructed the trajectory of radiating particles than the KF used in the PF reconstruction. To recover the overall reconstruction efficiency, a third type in which the extrapolation of two compatible tracker hits is matched to an ECAL cluster is also included as a PF element which might work as a link between the GSF tracks and the reconstructed ECAL SC.

Resulting PF candidate blocks that include a matching set of a GSF track and an ECAL SC are the final reconstructed electrons. The kinematics of the electron are then derived from a joint fit to the GSF track and SC properties. At low values of the electron p_T , the estimation from the tracking measurement dominates the overall combined measurement, while at higher momentum the ECAL estimation is more precise.

Photon candidates are reconstructed in a similar way to electron SC, with an explicit veto in the presence of a GSF track.

3.2.5.3 Hadron and jet reconstruction

Due to the nature of QCD discussed in Section 2.5.3, any strongly charged particle will produce a cascade of multiple strongly interacting particles along its propagation through the detector. From the experimental point of view, reconstructing such cascades is needed in order to recover the original properties of the quark or gluon. This objective is achieved by clustering the resulting PF candidates into extensive objects known as hadronic jets. Electrons and muons are included into the jet clustering as heavy flavoured mesons, such as the B and D mesons, decay in a significant proportion of cases through leptonic channels. Photons are also considered as neutral pions near always decay to a photon pair.

In the studies presented in this thesis, the PF objects are clustered using the anti- k_T algorithm [76, 77] which is known to be both infrared (robust with respect to low energy emissions) and collinear (robust with respect to very collimated emissions) safe. The distance d_{ij} between two objects i and j , and d_{iB} of object i with respect to the beam axis are defined as

$$d_{ij} = \min \left(\frac{1}{p_T(i)^2}, \frac{1}{p_T(j)^2} \right) \frac{\Delta R(i, j)}{R_0^2} \quad d_{iB} = \frac{1}{p_T^2(i)} \quad (3.4)$$

where R_0 is a fixed parameter which will usually be taken as $R_0 = 0.4$. The algorithm proceeds iteratively by first computing the d_{ij} and d_{iB} for all combinations of candidate objects in the event and ordering them in increasing order. If the lowest value correspond to a d_{iB} , its associated object is defined as a jet and taken out of the algorithm. If not, the corresponding i and j objects are combined into one and the algorithm is repeated.

3.2.5.4 Hadronic tau reconstruction

Tau leptons have small enough lifetimes that they usually decay before any kind of interaction with the detector is possible. Those that decay through the muon or electron channels produce an identifiable final state charged lepton plus additional invisible particles that escape detection, so they effectively are reconstructed as either muons or electrons following the description of the Sections above. However, a high proportion of taus decay through hadronic channels in which is collectively known as hadronically decaying taus (τ_h).

Hadronically decaying taus, τ_h , produce final state jets that can easily be confused with those originating from quarks or gluons. The hadron-plus-strips algorithm [78] aims to tag reconstructed jets as τ_h candidates by reconstructing the possible τ_h decay chains for each case. Depending on the number of charged hadrons on the final state, τ_h decays are classified in one-, two-, or three-pronged. In each of them, additional neutral pions can be produced as well. The algorithm reconstructs such neutral pions from their decay products -low energy photons and electrons found inside the jet- and combines such information with the charged tracks presented inside the jet which are combined to build possible groups of particles corresponding to the resonances on each τ_h decay. The reconstructed mass of such resonances is then required to be consistent with the known decay modes of the τ lepton. If multiple groups fulfil the mass constrain criteria, the one with the highest p_T is selected as the τ_h candidate associated to the jet.

3.2.5.5 Missing transverse momentum

Not all elemental particles that are produced in an inelastic collision will necessarily be detected. In fact, both SM neutrinos and some hypothetical BSM particles, such as the neutralino, are expected to only interact through the weak interactions and so will likely not produce any energy deposition in the detectors, they are effectively invisible particles. While these kind of particles can not be fully reconstructed, some information can still be deduced from the measurements of the rest of the reconstructed objects and the application of energy-momentum conservation laws.

As the initial state of the inelastic collision involves two partons with momentum along the Z axis, the overall transverse momentum of the system in the laboratory frame is expected to be zero. Thus, if the sum of the p_T for all observed particles is different from zero it can be assumed that this recoiling quantity corresponds to the momentum of the invisible particles. The missing transverse momentum ($\vec{p}_T^{\text{miss}}$) is defined as the negative vector sum of all reconstructed particle momenta as

$$\vec{p}_T^{\text{miss}} = - \sum_p \vec{p}_T(p) \quad (3.5)$$

In most occasions through this document, however, the expression missing transverse momentum will be equivalently used to refer to the scalar quantity corresponding to its modulus (p_T^{miss}).

As it depends on the reconstruction of all other event particles, the p_T^{miss} quantity is sensitive to near all measurements and calibrations of the detector. Unfortunately, this means that all limited resolution effects for individual object reconstruction will be propagated to the p_T^{miss} estimation. As a consequence, p_T^{miss} tends to be specially sensitive to the jet energy calibrations and the relatively worse, in comparison with other energy measurements, estimation of the hadronic energy performed in the HCAL. As a secondary consequence, the presence of additional pileup interactions also tends to worsen the p_T^{miss} resolution. In case of malfunctioning detectors or failure of reconstruction, anomalously high values of p_T^{miss} might appear. This issue is solved by the introduction of additional mitigating selections or filters in all selected data as described in Reference [79].

3.3 Data taking conditions

The conditions of the LHC and the response of the CMS detector vary as data taking progresses. Upgrades of the detector, changes in the collision parameters of the LHC and detector degradation all play a role in its non homogenous response in time. While some of these effects can be mitigated through recalibrations of the detector, others still retain a sensitive effect on the obtained physics and so motivate the splitting of the data taking process into separate data taking periods.

With respect to the studies presented of this thesis, two main sets of data (datasets) corresponding to pp collisions at different centre of mass energies of $\sqrt{s} = 5$ TeV and $\sqrt{s} = 13$ TeV are considered. The 5 TeV dataset was obtained during the 2017 year during a week of data taking and corresponds to a luminosity of roughly 300 pb^{-1} , while the 13 TeV one corresponds to data obtained during the most part of the 2016, 2017 and 2018 years and corresponds to around 140 fb^{-1} .

In addition to the centre of mass energy, a fundamental condition that separates the two is the different profile of average pileup interactions that they present. The 5 TeV dataset was taken at relatively mild beam injection conditions which, paired with the smaller centre of mass energy, greatly reduces its average pileup to 2 or 3 mean interactions per bunch crossing. In contrast, data taken at 13 TeV has around an order of magnitude greater pileup as a consequence of modifying the injection parameters to reach higher instantaneous luminosities. As a result, data taken at 13 TeV has significant more statistical power and generally better reach in terms of BSM searches, but suffers from the need for tighter criteria in the HLT menu and potentially less resolution when measuring quantities that depend on energy depositions through the whole detector such as p_T^{miss} . A depiction of the pileup conditions for both datasets is shown in Figure 3.8.

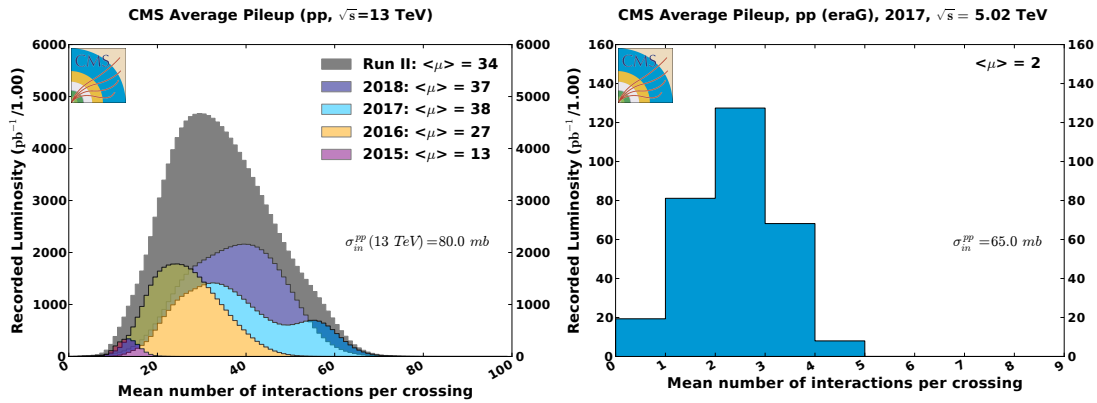


FIGURE 3.8: Pileup multiplicity profiles of the data taken during the Run 2 operations of the LHC for pp collisions at 13 (left) and 5 TeV (right). Data taken in 2015 at 13 TeV is also shown in the left figure although it was not used for the studies presented in this document. Figures are taken from the publicly available Reference [60].

As the 13 TeV dataset was taken during an extended period of time, additional differences also appear inside of it that sometimes motivate its splitting onto the different data taking years, or even smaller segments known as eras. The first of those, as shown in Figure 3.8, the different pileup conditions between the 2016 and the rest of the years. Partially as a consequence from this effect, the HLT requirements were

redesigned to accommodate both the higher rate from the 2017 and 2018 data taking years, producing slightly tighter criteria on the data selection during this year. More details will be discussed in Section 4.1.

The other significant change is the a partial upgrade of the detector that was performed between the 2016 and 2017 data taking years. The most notable modification is the introduction of an additional layer of pixels in both the barrel and endcap pixel tracker, positioning the innermost layer closest to the interaction vertex. Such an upgrade is expected to provide higher resolution towards the reconstruction of charged particles that produces depositions on such detectors, particularly on their compatibility with different production vertices through the precise estimation of impact parameters.

3.3.1 Performance and quality issues

The CMS detector does not maintain its properties completely stable through the data taking periods, as the radiation hard environment produced by the LHC collisions and the own running of the subdetectors will introduce degradation effects. Several notable ones that were found to affect data taking in the analysed datasets, as well as the strategies followed for their mitigation are described below. Higher radiation density is expected in the innermost detectors, as depicted in Figure 3.9, meaning that the innermost detectors with less resilient materials are susceptible to ageing effects that affect data taking and so the calorimeters, build in a much less resilient material than the tracking systems, are the source of most of these performance effects.

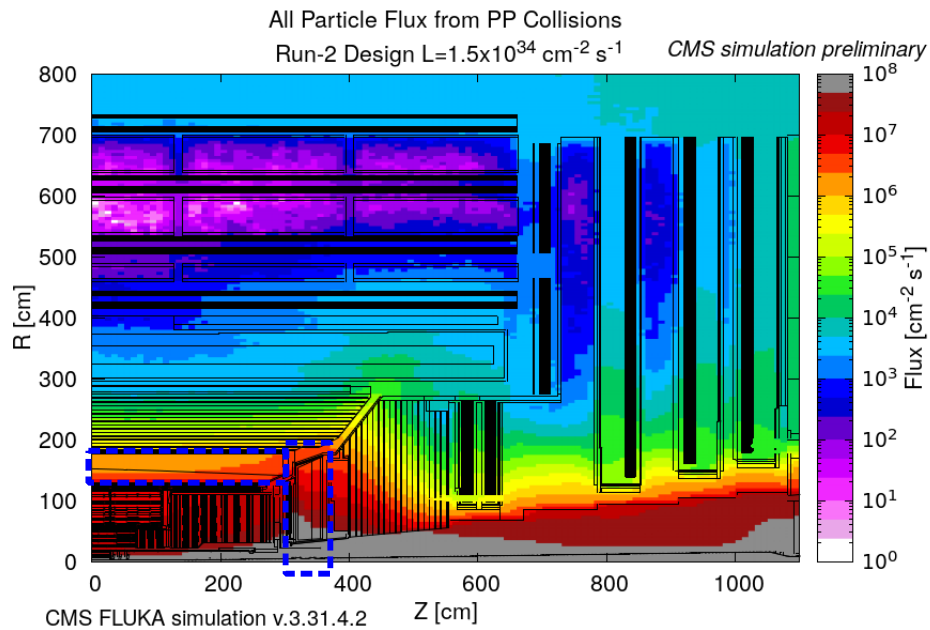


FIGURE 3.9: Estimation of the particle flux in a section of the CMS experiment for 13 TeV pp collisions for a realistic representation of the CMS detector simulated using FLUKA [80]. The problematic endcap region that leads to the L1 trigger preferring is highlighted with a blue rectangle. Figures are taken from the publicly available Reference [81].

The ECAL crystals are prone to a loss of transparency as the radiation dose is accumulated. This produces a shift in their response that translates into the digitized signals being detected as if they had appeared sooner than expected. This effect was corrected for during 2018 data taking, but was not fully accounted for in 2016 and 2017, meaning that the L1 reconstruction would sometimes assign a wrong BX to a reconstructed signal in the ECAL. The L1 is configured not to trigger in the two BX after a triggered one, meaning that if this effect appeared the original true collision would be vetoed by its own signal and the wrong event would be saved, an effect known as L1 prefiring [82]. The probability for such effects to happen was measured using events protected from this effect by the same L1 rule, that contain a L1 trigger 3 BX prior, and parametrized in terms of the kinematics of reconstructed jets, photons and electrons. These effects tend to be greater for depositions at higher values of η , where the higher radiation density produces further detector degradation. These probabilities are included to simulate this effect on all data analysis presented in this thesis.

A secondary effect of the degradation of the endcap ECAL is the presence of high noise at the measurements for later 2017 data taking, producing artificial contributions to p_T^{miss} leading to anomalously high p_T^{miss} values in 2017 data. A partial solution was derived in which objects within the more noisy detector region, at $2.65 < |\eta| < 3.139$ and with low energy $p_T < 50$ GeV are dropped from the p_T^{miss} computation described in Section 3.2.5. This slightly redefinition of the p_T^{miss} quantity is used for the 2017 data used through the analysis presented in this thesis.

Last, during the last half of the 2018 data taking a sector of the HCAL endcap stopped providing measurements and could not be recovered during collision time, making some information needed for proper jet, electron and photon energy calibration to be missed. As a consequence, objects of these kinds reconstructed in the $-1.57 < \phi < -0.87$ and $-3.0 < \eta < -1.3$ region suffer from a resolution loss. The effects of this issue are expected to be dependent on the topologies studied, and so their treatment is discussed into more detail in each of the documented studies.

4

General data analysis techniques and multileptonic physics

In the CMS experiment, electrons and -specially- muons are characteristically well measured in comparison to more complex objects like hadronic jets or photons. Thus, final states with multiple charged leptons tend to lead to relatively clean final states. SM processes that lead to the production of charged leptons in a hadron collider are relatively rare, as the electroweak interaction needs to appear to provide flavour changes from the coloured colliding partons. Explicitly, the LHC produces charged leptons through decay of the W, Z and H bosons, the top quark (which decays to a W and a b), and several unstable hadrons like the B^0 or the K^+ . The τ lepton has a relatively low lifetime of 10^{-13} s, meaning that it usually decays quite close to the interaction vertex and is a source of both electrons and muons through its leptonic decay modes.

The following chapters focuses on the analysis of CMS data in final states containing isolated charged leptons, which are characteristic of processes involving the production of combinations of the W, Z and H bosons, and the top quark that later decay through leptonic channels. As these processes tend to have relatively low cross sections, due to the lower value of the electroweak coupling constants with respect to the strong one, the suppression of QCD based production through the selection of leptonic final states is needed to attain higher purity selections which overall improve the precision of measurements. However, the branching fractions of the W (33%), Z (10%) and H (16%) bosons, and the top quark (33%) to final states with leptons are smaller than those to coloured particles. Thus, the number of leptonic events produced is smaller, reducing the available statistical power for any measurements.

While the different measurements that will be introduced through this thesis present their own peculiarities, the common denominator of containing isolated charged leptons means that several general techniques and descriptions can be successfully applied to all of them. This chapter focuses on the general description of such techniques that will later be expanded in more detail in Chapters 5 and 6. Advanced object reconstruction and identification criteria is presented in Section 4.3. Triggering strategies are described in Section 4.1. MC simulation and corrections are briefly described in Section 2.5. data-driven estimations of typical backgrounds related to multileptonic final decays are reviewed in Section 4.5. Common techniques in statistical inference applied to particle physics are presented in Section 4.6. The discussed techniques are

expanded with concrete examples corresponding to several measurements presented in Sections 4.7 and 4.8.

Both Sections 4.7 and 4.8 describe the analysis of CMS data in multileptonic final states in which I have been personally involved, albeit in a lesser role than the one I had in the ones I describe in Chapters 5 and 6. Section 4.7 describes the study of the production of massive boson pairs (WW, WZ, and ZZ) at the reference dataset taken by the LHC at 5.02 TeV during 2017. These studies provide the first set of measurements of diboson cross sections at a energy scale not explored before by LHC experiments and has been made public as Reference [5]. My involvement in the corresponding analysis group includes the optimization of the lepton identification criteria (related to Section 4.3) the computation of predictions at higher perturbative orders (related to Section 2.5) and overall porting of the analysis techniques detailed in Chapter 5 to this new energy frontier.

Section 4.8 describes an in depth study of the associated production of a top quark pair and a H boson, the $t\bar{t}H$ process. This mode of H boson production is specially relevant as it directly involves the Yukawa coupling of the top quark, the leading contribution to the naturalness problem described in Section 2.4. My involvement in the corresponding research mainly appears at the analysis optimization step, in which I designed the cut based signal extraction method or *control analysis* used in the final publication. The results, released in References [7–9] led to the first observation of the $t\bar{t}H$ production mode.

4.1 Triggering multilepton physics

As discussed in Section 3.2.4, the CMS experiment includes a triggering system to filter the data that is selected and saved during each collision Run of the LHC. Thus, a solid triggering strategy is the first step in studying any desired physical phenomena in the CMS experiment. At the data analysis level the trigger requisites impose restrictions in the available phase space, as regions that have not been triggered can not be explored on data. A high efficiency of the trigger selection is a prerequisite to fully explore a given phase space with no bias introduced by the trigger selection, and usually limits the reach of the CMS experiment into the regions with low momenta objects, where the trigger rates are usually higher.

For trigger selections involving leptons, the different HLT menus used in CMS during pp collisions includes final selections involving one, two or three final state electrons and muons, with quality and p_T requirements introduced to reduce the overall trigger rate. Multileptonic final states greatly benefit from the redundancy of this strategy, as each single lepton trigger can be fired multiple times. For final states with three or more leptons, even the requirements of the double lepton ones might be fulfilled several times on each event. The usual triggering strategy for a multilepton analysis is to select any event that passes any unprescaled HLT selection corresponding to single or double lepton requirements and then apply selection p_T cuts that are tighter than the associated double lepton paths.

Prescaled trigger selections which include looser criteria than unprescaled ones are available at the HLT menus developed by the CMS collaboration. However, they introduce a significant loss of statistical power which makes them unsuitable for most

data analysis. Moreover, combining HLT requirements with different prescaling factors introduce severe problems on determining the effective luminosity available at each region of phase space, which introduces further complexity in comparisons with the MC. Thus, all analysis discussed in the present document use unrescaled HLT selections for most results, except for auxiliary measurements that do not rely as much on the available data statistics.

A summary of the unrescaled single and double lepton trigger selections for each of the data taking years of the Run 2 of the LHC is shown in Table 4.1. The increasingly denser pileup conditions of the 2017 and 2018 years meant that the trigger p_T requirements needed to be tightened in several cases in order to keep the rate under control, so slight differences with respect to 2016 are seen. Of special note is the 5.02 TeV reference run which both has a lower centre of mass energy and average pileup leading to lowered HLT requirements that make the small momenta regions accessible experimentally. However, no trigger requirements involving simultaneously electrons and muons were included in the 5.02 TeV menu.

Selection type	Selection	Data taking period
Single μ	$\mu, p_T > 12$ GeV	5.02 TeV
	Isolated $\mu, p_T > 24$ GeV	2016, 2018
	Isolated $\mu, p_T > 27$ GeV	2017
Single e	Loose $e, p_T > 17$ GeV	5.02 TeV
	Loose $e, p_T > 27$ GeV	2016
	Loose $e, p_T > 32$ GeV	2018
	Loose $e, p_T > 35$ GeV	2017
Double μ	$\mu, p_T > \{10, 10\}$ GeV,	5.02 TeV
	Two isolated $\mu, p_T > \{17, 8\}$ GeV,	2016
	Two isolated $\mu, p_T > \{17, 8\}$ GeV, $m_{\mu\mu} > 3.8$ GeV	2018
	Two isolated $\mu, p_T > \{17, 8\}$ GeV, $m_{\mu\mu} > 8$ GeV	2017
Double e	Two loose $e, p_T > \{23, 12\}$ GeV	2016, 2017, 2018
$e+\mu$	Loose e + Isolated $\mu, p_T^e > 23$ GeV, $p_T^\mu > 8$ GeV	2016, 2017, 2018
	Loose e + Isolated $\mu, p_T^\mu > 23$ GeV, $p_T^e > 8$ GeV	2016
	Loose e + Isolated $\mu, p_T^\mu > 23$ GeV, $p_T^e > 12$ GeV	2017, 2018
Triple e	Three Loose $e, p_T > \{16, 12, 8\}$ GeV	2016, 2017, 2018
$2e+\mu$	Two loose e , one loose $\mu, p_T^e > \{12, 12\}$ GeV, $p_T^\mu > 8$ GeV	2016, 2017, 2018
$1e+2\mu$	One loose e , two loose $\mu, p_T^e > 9$ GeV, $p_T^\mu > \{9, 9\}$ GeV	2016, 2017, 2018
3μ	Three loose $\mu, p_T > \{12, 10, 5\}$ GeV	2016, 2017, 2018

TABLE 4.1: Summary of single and double lepton unrescaled HLT selections applied in the different analysis presented through the thesis. The type of the selection, a brief description of the imposed conditions in terms of lepton identification and p_T requirements, and the associated data taking period is presented. For 13 TeV data, the data taking period corresponds to the year.

4.2 Monte Carlo simulation

So far the discussion has been centred on describing the kind of procedures that can be performed in data in order to reconstruct good quality objects. However, a model of the different physical processes produced in pp collisions corresponding to either SM or BSM physics is needed in order to compare with the data and infer either the properties of the SM or the possible existence of a signal of new physics. As was

briefly introduced in Section 2.5, one of the most common ways of obtaining such models is the Monte Carlo (MC) technique, where full collision events are simulated through the usage of random number generators and our knowledge of the dynamics of the SM (or BSM) couplings. The description of the collision event presented in Section 2.5 including the proton PDFs, a ME generator, and a PS generator leads to final states which can be called generator level, or generator truth. In reality, the whole measurement process is based on the interaction of the final state generated particles with the detector, a process ruled by quantum interactions which also includes a probabilistic description. Thus, MC simulation needs to also include the interaction of the generated particles with the detector, as well as a representation of how these particles are registered in the different subdetector structure presented in Section 3.2. This step is usually known as the simulation part of the MC production. The set of PDFs, ME generator, PS generator, and simulation steps used in the analysis presented in this thesis are discussed below.

The setup used for MC generation has been collectively prepared by the CMS collaboration and, as such, most of the MC samples used are shared between the different analysis. As all of the presented measurements are targeting multileptonic physics, the same kind of processes appear across phase spaces even if their relevance change from measurement to measurement and, for the most part, a consistent description is presented across all different studies. Small differences appear when several alternative samples are used for the most relevant process, such as the case of the precision studies on WZ production presented in Chapter 5, for which a comparison between MC simulations is naturally drawn as part of the presented measurements.

The POWHEG BOX (v2.0) [50–52] ME generator is used to produce MC samples corresponding to $q\bar{q}'$ initiated diboson processes (WW, WZ, and ZZ [83, 84]) as well as $t\bar{t}$ [85] and single-top [86, 87] processes at NLO accuracy in perturbative QCD. The MADGRAPH+aMC@NLO generator [53] is used to generate single boson (Drell–Yan, W + jets), associated production of $t\bar{t}$ with one massive bosons ($t\bar{t}W$, $t\bar{t}Z$, and $t\bar{t}H$), associated production of top quarks or massive bosons with photons ($t\bar{t}\gamma$, $t\gamma$, $W\gamma$, $Z\gamma$, and $WZ\gamma$), triple massive gauge boson (WWW, WWZ, WZZ, and ZZZ), and rare top and Higgs processes (tZq , $t\bar{t}t\bar{t}$, and VH) at NLO accuracy in perturbative QCD. Similarly, the MADGRAPH+aMC@NLO generator is also used to generate relative rare processes involving multiple Higgs bosons, top quarks or massive gauge bosons (tHq , tHW , tFV) at LO accuracy in perturbative QCD. In both cases, version 2.4.2 (2.6.5) of MADGRAPH+aMC@NLO was used for MC samples corresponding to the 2016 (2017, 2018 and 5.02 TeV) data taking periods. For gluon initiated diboson processes (ZZ, and WW) the MCFM generator at LO in perturbative QCD is used [54]. Alternative samples produced with MADGRAPH+aMC@NLO for diboson production at NLO in perturbative QCD are used in the analysis introduced in Section 4.8. Alternative samples for single boson and $t\bar{t}$ production produced at LO in QCD with MADGRAPH+aMC@NLO are abundantly used for cross-checks and object performance studies, as lower order computations are overall cheaper to produce.

The PDF sets used on each ME case vary with the data taking year, as newer results from the PDF collaborations became available during the period of the Run 2. Samples produced for the 2016 data-taking year use the NNPDF30_nlo_as_0118 or NNPDF30_lo_as_0118 PDF sets [88] depending on the order of the computation. For more recent data taking eras the NNPDF31_nnlo_hessian_pdfas [45] set is used independently of the computation order. Events in single boson, double boson and $t\bar{t}$

samples are weighted such that the total cross section prediction matches the cross sections currently known at the higher perturbative order (NNLO in QCD or NNLO in QCD $\times$ NLO EWK), even if the simulation corresponds to a lower one.

All ME computations are interfaced with Pythia v8.212 (2016) or v8.230 (other data taking periods) [55] which performs the PS simulation and the UE description. The Pythia settings include the usage of the NNPDF23_lo_as_0130 PDF set as well as the the CUETP8M1 parameter tune [89] for samples corresponding to the 2016 data taking year. For all other years, including the 5.02 TeV MC, the NNPDF31_nnlo_as_0118 PDF set and the CP5 tune [90], which were developed more recently, are used instead.

The interaction of the produced particles and the detector is simulated with Geant v4 [91] using a realistic description of the whole CMS experiment. Pileup interactions are introduced into the simulation through the premixing technique, where samples of minimum bias events are simulated with Pythia plus Geant and then selected at random to be mixed with the inelastic process of interest. The resulting mix of detector signals are then reconstructed following the same algorithms as data that were described in Section 3.2.5, including a simulation of the triggering system.

4.2.1 Theoretical uncertainties

MC simulations are a useful tool but still suffer from issues originated by the structure of the strong interaction. Several sources of uncertainty arise from such cases, which need to be propagated to the different analysis to account for possible mismodellings that could arise from the limited knowledge of QCD.

As discussed in Section 2.5.1, the DGLAP equations can only predict the PDF behaviour once it has been measured at a given energy scale. As the original measurement has its own experimental uncertainties, such effects need to be propagated to the knowledge of the PDFs. Modern PDF sets achieve this by discretizing the effects in a limited set of PDF replicas, slightly different configurations of the PDFs that correspond to variations according to their uncertainties. Reproducing the MC with the varied PDF replicas the effects of such uncertainties can be propagated to the analysis level. This effect is usually known as PDF uncertainties.

The factorization and renormalization scales introduced in Sections 2.5.1 and 2.5.2 introduce arbitrary cut-offs in the description of QCD. In a computation that could include all orders of QCD, observable physics would be independent of such scales as they would be absorbed in the renormalization procedure. As real computations are cut at fixed orders, residual dependences on the values of μ_R and μ_F appear. Scale uncertainties correspond to an estimation of such uncertainties which is usually attributed to the missing higher perturbative QCD orders and so is expected to decrease as more complete computations are available. A usual convention is to reproduce the MC with varied values of the μ_R and μ_F quantities by factors of two and take the envelope of the effects on the analysis as a final scale systematic uncertainty. Similar uncertainties related to initial state radiation (ISR) or final state radiation (FSR) emission scales can be computed by modifying the associated scales corresponding to this part of the event description only in the PS simulation.

As producing alternative MC samples with enough events is quite costly in computational time, most common MC generators implement a reweighting feature. At LO,

for each generated event and possible alternative configuration of the initial PDF or scale parameters, a weight is computed corresponding to the quotient of the probability of obtaining such event with the new parameters over that of observing it with the nominal ones. Thus, the probability distribution of the whole weighted sample will follow the behaviour of a MC consistent with the altered PDF or scale parameters. At further perturbative orders care must be taken to ensure that the accuracy of the result is preserved, but the final procedure is analogous [92, 93]. MC reweighting is not only limited to modifying the modelling parameters, but can also be used to explore BSM physics by altering parameters of the SM. Such techniques are further used in Chapter 5.

4.2.2 Generator level comparisons

The generation and simulation of MC events is usually quite expensive in terms of computing resources, so sometimes calculations are performed with no detector simulation. While it is faster than the full MC production, this kind of predictions can't be directly compared with data. The usual procedure, instead, is to invert the picture by obtaining detector-free distributions and comparing the resulting quantities at the generator level. A technique to perform such procedures, unfolding, is presented in further detail in Section 5.10.

Care must be taken when defining what exactly a generator level particle is, as it can be discussed at different stages of its evolution during the collision event. A usual distinction is to separate the parton-level particles —those produced as an immediate result of the hard scattering— from the particle-level ones —those that correspond to the true final state after radiation and/or fragmentation. The most clear cut case is the strongly interacting particles, for which a single parton-level object (quark or gluon) will likely originate a myriad of particle-level ones. For the case of leptons, QED radiation usually plays a role, with particle-level leptons corresponding to the final state lepton after any photon radiation. Thus, particle-level quantities are akin to what will be measurable at the detector level, while parton level ones correspond to the high energy interaction process, which encodes the most interesting part of the physics for the analysis presented in this thesis.

Extrapolations from the reconstructed quantities will be done to the particle-level, but several considerations are taken into account to try and recover the original energy scales of the original partonic interaction, defining a new set of particle-level objects. Explicitly, particle-level leptons are dressed, with the momenta of all photons in a $\Delta R < 0.1$ cone of the lepton added to its own momentum following the description of the RIVET dressed lepton object RIVET [94]. The jet clustering algorithms described in Section 4.3 are applied over final state particles to also define particle-level jets. Finally the particle-level missing transverse momentum is the negative vector sum of the transverse momenta of all generated particles, with neutrinos and other undetectable ones excluded.

4.2.3 Fixed order computations

Computations at fixed perturbative orders higher than the NLO approximation are quite complex and resource consuming but have started to become available for several SM processes in the most recent years. Fixed order computations only focus on the hard scattering part of the prediction, ignoring the effects of the PS and the detector simulation. The resulting parton-level objects can also be compared with extrapolated data following extrapolation strategies such as those presented above. In the case of the diboson studies presented in this document, the MATRIX framework is used [56]. The second version of the framework [95] includes predictions accurate up to NNLO in QCD and NLO in EWK using amplitudes provided by OpenLoops [96–98]. In this thesis it is used to provide inclusive and differential cross section predictions at the parton level for the WW [99, 100], WZ [101, 102], and ZZ [103–105] processes. Notice that small differences are to be expected with respect to the particle-level extrapolated quantities, but they are found to be small for fully leptonic final states when dressed leptons are used for the particle-level definition and no hadronic jets are involved.

When computing higher order corrections for both QCD and EWK interactions several possible avenues for combining them appear. Through the presented text, both corrections are applied multiplicatively, meaning that the NNLO QCD and NLO EWK corrections are first estimated on top of the LO cross section and the final correction is the multiplication of both (NNLO in QCD $\times$ NLO EWK). For the specific cases of WW and ZZ production, where gg and $\gamma\gamma$ initial states might appear, a slightly different procedure is followed using the prescription described in Reference [95]. For predictions of WW and ZZ cross sections, the QCD corrections are applied to the $q\bar{q}'$ initiated LO cross section. The $\gamma\gamma$ induced ones are then added up and the whole EWK corrections are applied to the sum. Last, the gg initiated cross section, which can only proceed through double emission or loops and so is technically an NNLO one, is added to the total.

All computations performed with MATRIX in this thesis use fixed renormalization and factorization scales corresponding to the average of the masses of the vector gauge bosons in the hard scattering and make use of the NNPDF31_nnlo_as_0118_luxqed PDF set, which also provides information on the photon PDFs for the computation of the photon initiated contributions to the diboson cross sections.

4.3 Object identification

While the algorithms presented in Section 3.2.5 are quite efficient at reconstructing the different physics objects measured in the CMS experiment, sometimes further requirements need to be imposed in order to filter out contributions from wrongly identified particles or to suppress the presence of object candidates from unwanted sources. A typical case is the separation of final states with isolated leptons, pointing towards the presence of a W, Z or H boson in the collision from those that include non-isolated leptons formed during hadron decays. Applying additional quality criteria on the lepton definition would reduce the presence of the latter, leading to a more pure selection of events which, in turn, tends to provide better measurements.

4.3.1 Jet flavour tagging

While secondary in most analysis, jet identification plays a role in the form of flavour tagging. As discussed in Section 2.3, the short lifetime of the top quarks mean they do not live long enough to hadronize. However, due to the structure of the CKM matrix described in Equation 2.22, a top quark near always produces a b quark on its decay. The b quark does hadronize and, eventually, produce a hadronic shower that can be reconstructed as a jet. If jets that proceed from b quark hadronization (b jets) were to be identifiable, that would prove a valuable handle in tagging events that contain top quarks. Such procedure is known as b tagging. While less interesting for the topic of this thesis, c tagging (for c originated jets), light jet tagging (for jets with any other origin), and quark-gluon tagging (separate gluon initiated from quark initiated jets) exist.

Several b tagging algorithms have been developed by the CMS collaboration. In the studies presented in this document, the DeepCSV [106], and DeepJet [107] algorithms are used. An earlier iteration of the same concept, the CSVv2 algorithm [106], was also used in the earlier results performed during the presented studies, but has been since superseded by the other two. All of the quoted algorithms aim to exploit the characteristic kinematic properties of B mesons, such as their increased lifetime that leads to slightly displaced vertexes, through the usage of machine learning techniques based on neural networks. The main differences between the three are the increased complexity of the input quantities and the increasingly complex neural network architecture. The latest of the three, the DeepJet algorithm, exploits more than 600 features related to reconstructed neutral and charged tracks and secondary vertexes to build a continuous multiclassifier output which provides the probability of each jet being b, c, light quark, or gluon tagged.

A comparison between the DeepCSV and DeepJet algorithm's performance is presented in Figure 4.1. Working points (WPs) of the DeepCSV and DeepJet algorithms are the minimal requirements on the output of each algorithm required to accept a jet as b tagged. They are defined based on fixed values of the light jet misidentification probability to be the tight (0.1% misidentified light quarks), medium (1%) and loose (10%). The different WPs are represented in Figure 4.1, where the better performance in terms of separation of the DeepJet algorithm is also shown.

As low energy jets tend to be measured the worst and the b tagging performance drastically decreases at lower transverse momentums, additional kinematic requirements on jet selection are usually applied. Jets are selected through the different studies if they have a p_T greater than 25 GeV and, sometimes, 30 GeV. Another usual classification is to divide all reconstructed jets between central jets ($|\eta| < 2.5$) and forward jets ($2.5 < |\eta| < 5.0$), as the later fall within the forward part of the detector which has worse resolution and where no flavour tagging procedure can be used. The specific jet selection criteria applied on each of the studies is discussed in its corresponding section or chapter.

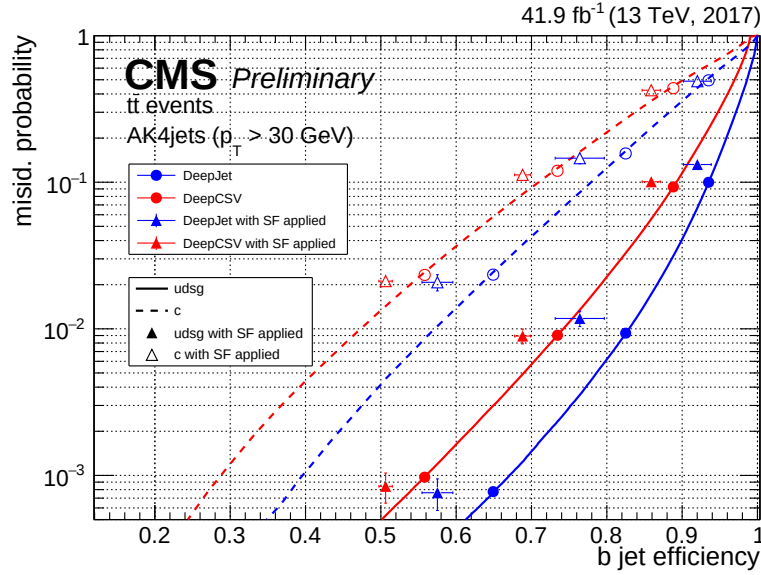


FIGURE 4.1: Performance curves of the DeepCSV (red) and DeepJet (blue) algorithms as binary classifiers to separate b jets from either c jets (dashed lines) or light jets (full lines). Figure was produced by the CMS b tagging working group and is available in Reference [107].

4.3.2 Muon identification

As the name of the collaboration implies, muons are characteristically well reconstructed inside the CMS experiment. However, precision measurements usually require further identification criteria to suppress spurious muon candidates whose origin is not the desired one. In the case of multileptonic physics, the main source of such effects is the already discussed presence of undesired non-isolated muons primarily appearing in B meson decays, but additional noisy contributions might appear due to punch through of hadronic objects or combinatorial effects in high activity events.

First, a preselection of muons for which the measurements in the tracker (inner track), the muon spectrometers alone (standalone track), and their overall reconstruction including both the tracker and the muon spectrometers (global track) are of high quality, restricting PF muons to a subset of them whose quantities are more precisely measured, known as PF-medium muons, elaborating over the techniques introduced in Reference [74]. At least 80% of the hits in the innermost track need to be used in the global reconstruction. Then, criteria based on the presence of non-uniform kinks in the reconstructed track, compatibility between the inner track and the hits in the muon spectrometers, and a low value of the χ^2 corresponding to the reconstructed track parameters and the corresponding input hits are applied.

As discussed in Section 4.3.1, B mesons have a relatively long lifetime. This means that results from their decays will be slightly displaced from the primary interaction vertex, a fact that can be used to reduce the non-isolated muon presence. All muons used in the following sections include requirements in the impact parameters of their tracks with respect to the reconstructed primary vertex. Explicitly, $d_{xy} < 0.05$ cm and $d_z < 0.1$ cm are required for the transversal and longitudinal impact parameters. Furthermore,

the quotient of the 3D impact parameter and the uncertainty on its estimation (SIP_{3D}) is required to fulfil the loose significance criteria $SIP_{3D} < 8$.

The level of isolation of muons with respect to other reconstructed objects can also be quantified, as those produced inside hadronic showers are expected to be close by to other reconstructed candidates. A generic definition of the isolation quantity can be defined as

$$I = \sum_{h^\pm} p_T^{h^\pm} + \max \left(\sum_{\gamma} p_T^{\gamma} + \sum_{h^0} p_T^{h^0} - p_T^{PU}, 0 \right) \quad (4.1)$$

where $h^\pm$, h^0 and γ run over all charged hadrons, neutral hadrons, and photons that are close-by to the muon, and p_T^{PU} corresponds to the contribution to the overall isolation from pileup neutral particles that need to be subtracted from the isolation but can not be directly be assigned to the collision due to their trajectories not being measured in the detector. Depending on how the pileup is treated and how the concept *close by to the muon* is defined, different flavours of lepton isolation exist. In the case of the following studies, an effective-area corrected mini isolation I_{mini} is used. Mini-isolation bases its definition of a *close by object* as one that falls inside a cone of $\Delta R < R_0$ of the muon four-momentum. The definition of R_0 varies in size with the muon p_T as

$$R_0 = \frac{10}{\min(\max(p_T(\mu), 50), 200)} \quad (4.2)$$

the dependence on the p_T is introduced to model the fact that higher momenta non-isolated muons are expected to come from more collimated showers. Effective-area corrections [108] define the pileup subtraction as

$$p_T^{PU} = \rho \mathcal{A} \left(\frac{R_0}{0.3} \right) \quad (4.3)$$

where ρ is the per-event pileup energy density and $\mathcal{A}$ is the effective area of the isolation cone which depends on the η region of the detector. A mild requirement on the relative mini isolation of $I_{mini}(\mu) / p_T(\mu) < 0.4$ is applied to select all muons in the rest of this document.

An additional set of properties that can be used to characterize muons originating from meson decays is to study the properties of close-by jets. In the event that a jet is reconstructed close to the muon, several useful quantities can be estimated. The value of its associated b tagging discriminant value can be used to discriminate against muons from b meson decays. If the relative momentum of the lepton to the jet is specially small, is also likely than the lepton comes from a hadron decay somewhere inside it. Finally, if the lepton and jet are quite collimated, their momenta align, the likelihood of the presence of a non-isolated lepton increases as well. The requirements imposed on these quantities are usually tuned in order to obtain a similar efficiency for misidentified leptons coming from heavy flavoured or light flavoured hadrons, a quantity that is phase space, and so analysis, dependant. The motivations for such tuning are related to the estimation of the non-isolated lepton backgrounds and would be extended further in Section 4.5.

The charge of the muons can be inferred by the sign of the curvature of their associated track. However, for tracks fitted to a relatively small set of hits or for muons of high momentum, in which case their track is near straight, such measurement might fail. In some of the analysis presented phase space requirements are included as part of event selection to focus on specially interesting phase spaces, such as a pair of same-sign muons. For such cases, an additional charge consistency identification criteria is applied. The charge consistency criteria requires that the uncertainty on the measurement of the muon p_T is less than 20% its absolute value.

Observable	Muons		
	Preselected	Loose	Tight
p_T	*	*	*
$ \eta $	< 2.4	< 2.4	< 2.4
$ d_{xy} $	$< 0.05 \text{ cm}$	$< 0.05 \text{ cm}$	$< 0.05 \text{ cm}$
$ d_z $	$< 0.1 \text{ cm}$	$< 0.1 \text{ cm}$	$< 0.1 \text{ cm}$
SIP_{3D}	< 8	< 8	< 8
Relative I_{mini}	< 0.4	< 0.4	< 0.4
PF-medium muon	-	-	✓
b Tag of nearby jet	*	*	*
$p_T(\mu)/p_T(\text{close by jet})$	*	*	*
Muon leptonMVA	-	*	*
Charge consistency	-	*	*

TABLE 4.2: Common identification and isolation criteria applied to select muons in the different analysis presented for the preselected, loose, and tight working points. Requirements marked with a * sign vary from analysis to analysis, depending on the target phase space and are optimized in a case by case basis. Requirements marked with a - sign are not applied at all for the correspondent selection level in any case.

The minimal set of requirements introduced so far for vertexing, isolation and jet related quantities are used to define preselected muons. The muon preselection has near total ($> 99\%$) efficiency for isolated muons and, in fact, it is mostly applied to remove the most blatantly noisy ones. Further discrimination is obtained through the usage of a multivariate algorithm, a Boosted Decision Tree (BDT), which combines this information into a single discriminant known as the leptonMVA. The leptonMVA is trained to separate isolated muons from W, Z and τ decays (prompt muons) from any other sources of reconstructed muon candidates (nonprompt muons) using as inputs the set of variables previously described related to vertexing, isolation and the properties of closeby jets, as well as the muon p_T and η . For the training, signal muons are obtained from a $t\bar{t}H$ MC sample, while background muons are obtained from those in a $t\bar{t}$ MC sample not matched to a generated muon. Different WPs of the leptonMVA discriminant are used through the results presented in this document, with the exact requirements optimized depending on the target phase space. Most of the results presented make use, for various reasons that will be explained into more detail in each case, two different WPs of the identification discriminants, henceforth known as loose and tight muons. A summary of all muon identification criteria for preselected, loose and tight muons is presented in Table 4.2.

A comparison of the performance of the muon leptonMVA discriminant in terms of prompt efficiency with respect to nonprompt rejection is presented in Figure 4.2. In the study depicted in this Figure, events which contain exactly two loose muons with

$p_T > 10$ GeV are selected. The efficiency for prompt muons is measured in a Drell–Yan MC sample in which both muons match a generated one that originates from the Z decay. The efficiency for nonprompt muons is measured in a semileptonic $t\bar{t}$ sample in which at least one of the muons matches a particle in the decay chain of a light or heavy quark. For illustration, the WPs chosen for each of the analysis presented in this thesis are shown, as well as the performance of two additional cases corresponding to alternative muon identification criteria used in other CMS analysis. The later correspond to the requirements imposed in the $t\bar{t}$ differential cross section measurement [109] and W boson helicity studies [110] presented by the CMS collaboration, which both use cut based selection criteria. Notice, however, that the lepton optimization for such analysis targets a completely different phase space, in which lowered effects from muon energy scale uncertainties usually plays a more significant role than the optimization against a relatively minor nonprompt background. The Figure, thus, is only used as illustration of the power of this identification requirements when applied to the specific problem of multileptonic final states, where nonprompt leptons play a prominent background role. It can be seen that around a factor 10 in background rejection can be achieved for similar signal efficiencies through the usage of the leptonMVA discriminant.

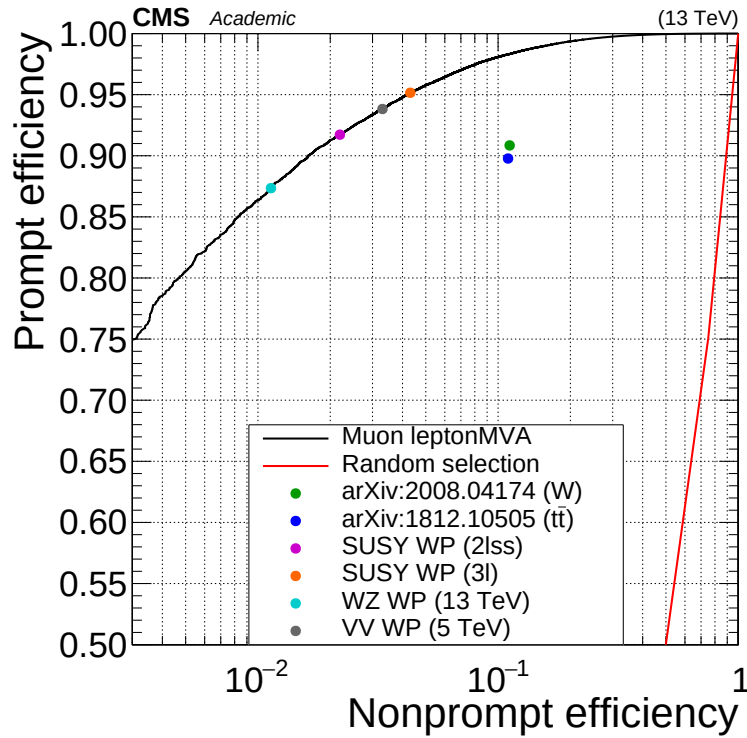


FIGURE 4.2: Efficiency of the leptonMVA identification criteria for prompt muons versus the same quantity for nonprompt muons. The solid black curve corresponds to the continuum set of values corresponding to different requirements on the leptonMVA discriminants, with the different WPs chosen by analysis presented in this thesis included. For comparison, the performance of two cut based algorithms corresponding to $t\bar{t}$ and W targetting analysis published by the CMS collaboration is also shown. Measurements are performed in final states with two muons, using a Drell–Yan sample for the prompt estimation and a $t\bar{t}$ one for the nonprompt one. Preselected muons are used as denominator for the efficiency calculation. A red curve with the results of selecting muons randomly is shown for comparison.

A final note on muon selection has to be made in terms of kinematic requirements. Muon pseudorapidity is strictly limited by the range covered by the muon spectrometers and is usually restricted to $|\eta| < 2.4$, with muons inside the muon barrel system ($|\eta| < 1.24$) usually being slightly better reconstructed. While muon identification efficiency drops towards the region of lower momenta, the main limitations on muon p_T requirements appear due to either the trigger selection level or additional restrictions that could be beneficial for studying high momenta processes.

4.3.3 Electron identification

Electrons provide a challenge that is similar in nature to that of muons, but as their interaction with the detector provides an increased quantity of electromagnetic showering, jets and photons tend to be more easily misidentified as electrons than muons. A very similar strategy to the one described in Section 4.3.2 for muons is followed for identifying electrons. In fact, the criteria applied in vertexing, isolation and jet related quantities is exactly the same and a similar approach based on the leptonMVA discriminant, trained with electrons instead of muons, is equally followed. Additional selection criteria are added to improve the quality of the selected electrons both at the preselection, loose and tight levels.

A comparison of the performance of the electron leptonMVA discriminant in terms of prompt efficiency with respect to nonprompt rejection is presented in Figure 4.3. In the study depicted in this figure, events which contain exactly two loose electrons with $p_T > 10$ GeV are selected. The efficiency for prompt electrons is measured in a Drell–Yan MC sample in which both electrons match a generated one that originates from the Z decay. The efficiency for nonprompt electrons is measured in a semileptonic $t\bar{t}$ sample in which at least one of the electrons matches to the decay chain of a light or heavy quark. For illustration, the WPs chosen for each of the analysis presented in this thesis are shown, as well as the performance of two additional cases corresponding to alternative electron identification criteria. The later correspond to the requirements imposed in the $t\bar{t}$ differential cross section measurement [109] and W boson helicity studies [110] published by the CMS collaboration, which both use cut based selection criteria. Notice, however, that the lepton optimization for such analysis targets a completely different phase space, in which lowered electron energy scales play a more significant role than the optimization against a relatively minor nonprompt background. The figure, thus, is only used as illustration of the power of this identification requirements when applied to the specific problem of multileptonic final states, where nonprompt leptons play a prominent role as background. It can be seen that around a factor of 3 to 5 in background rejection can be achieved for similar signal efficiencies through the usage of the leptonMVA discriminant.

As part of the preselection criteria, an additional BDT discriminant is used. The BDT is trained to separate electron candidates matched to generated electrons from those originating from badly reconstructed jets, all of them obtained from simulated Drell–Yan production samples. The input variables include several quantities describing the shape of the reconstructed energy SC at the ECAL, variables related to the matching of the track and the SC, quantities related to the quality of the electron track and the proportion of energy observed on the HCAL to that of the ECAL for the associated shower. A detailed description of the algorithm and its performance is present in Section 7.3.2 of Reference [111], as the loose WP of the MVA selection technique.

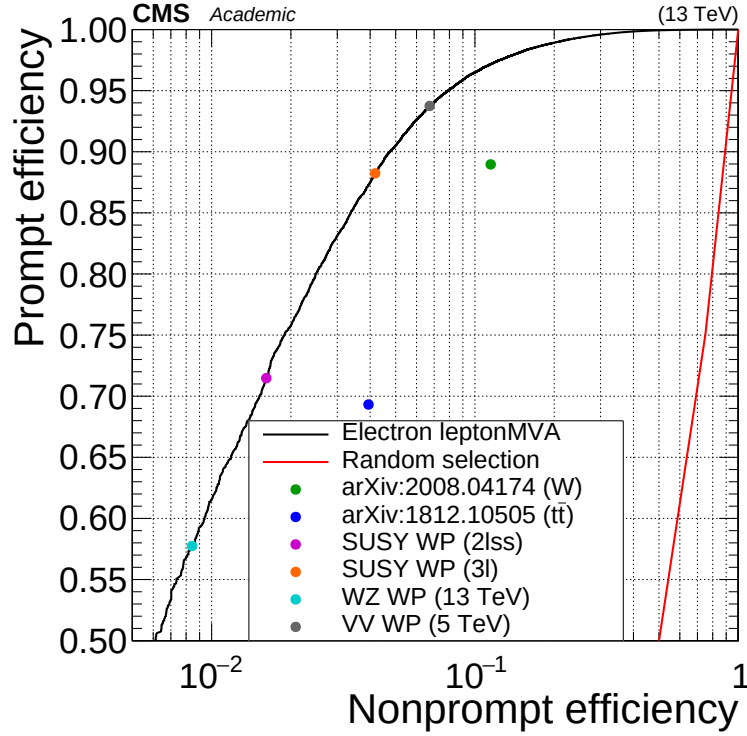


FIGURE 4.3: Efficiency of the leptonMVA identification criteria for prompt electrons versus the same quantity for nonprompt electrons. The solid black curve corresponds to the continuum set of values corresponding to different requirements on the leptonMVA discriminants, with the different WPs chosen by analysis presented in this thesis included. For comparison, the performance of two cut based algorithms corresponding to $t\bar{t}$ and W targetting analysis published by the CMS collaboration is also shown. Measurements are performed in final states with two electrons, using a Drell–Yan sample for the prompt estimation and a $t\bar{t}$ one for the nonprompt one. Preselected electrons are used as denominator for the efficiency calculation. A red curve with the results of selecting muons randomly is shown for comparison.

Additional quantities used in the aforementioned MVA approach can also be used to reduce the rate of non-isolated electrons selected. A requirement on the ratio of energies between the HCAL and the ECAL $H/E < 0.1$ is used to reject objects with too many hadronic energy. The width of the SC built in the ECAL is required to be $\sigma_{i\eta i\eta} < 0.011(0.03)$ for electrons in the barrel (endcap), corresponding to maximal sizes of the electromagnetic shower shape. The difference between the inverses of the estimations of the energy in the ECAL SC and the momenta on the tracker track is requested to be $1/E - 1/p > -0.04$, rejecting events with greater excesses of SC energy not present in the tracker.

High-energy photons that pass through the detector can interact with its material and produce an electron–positron pair. If one of the two charged leptons is absorbed by the detector without a signal such processes are known as asymmetric photon conversions. They are yet another source of misidentified electrons. The presence of asymmetric conversions is reduced by requiring that no layers are lacking a hit in the tracker track from the electron (no missing hits). Furthermore, a pixel conversion veto [112] is applied.

The charge of the electrons is usually measured worse than that of muons when p_T ranges are similar, due to the smaller lever arm in the overall reconstructed track that only extends to the ECAL. Thus, in analysis where the sign of the electron charge is relevant, additional charge consistency criteria are applied. It is based on the equality of three different measurements of the electron charge: based on the GSF track, on the associated KF track from the PF algorithm, and in the difference of positions in η between the innermost and outermost hits in the tracker and the reconstructed SC. After this criteria is applied, the probability of a bad assignment of the charge is kept under the 0.1% (0.001%) for electrons in the endcap (barrel).

As for muons, the requirements on electron p_T vary depending on the process studied. The range in pseudorapidity is restricted to $|\eta| < 2.5$, the physical region of space covered by the ECAL and tracker simultaneously. A summary of all criteria used for the selection of electrons in a generic way is presented in Table 4.3.

Electrons			
Observable	Preselected	Loose	Tight
p_T	*	*	*
$ \eta $	< 2.5	< 2.5	< 2.5
$ d_{xy} $	< 0.05 cm	< 0.05 cm	< 0.05 cm
$ d_z $	< 0.1 cm	< 0.1 cm	< 0.1 cm
SIP_{3D}	< 8	< 8	< 8
Relative I_{mini}	< 0.4	< 0.4	< 0.4
$\sigma_{i\eta i\eta}$	—	$< \{ 0.011 / 0.030 \}^1$	$< \{ 0.011 / 0.030 \}^1$
H/E	—	< 0.10	< 0.10
$1/E - 1/p$	—	> -0.04	> -0.04
MVA-loose electron	✓	✓	✓
Pixel conversion veto	—	✓	✓
Missing hits	≤ 1	$= 0$	$= 0$
b Tag of nearby jet	*	*	*
$p_T(e)/p_T(\text{closeby jet})$	*	*	*
Electron leptonMVA	-	*	*
Charge consistency	-	*	*

TABLE 4.3: Common identification and isolation criteria applied to select electrons in the different analysis presented for the preselection, loose and tight working points. Requirements marked with a * sign vary from analysis to analysis, depending on the target phase space and are optimized in a case by case basis. Requirements marked with a - sign are not applied at all for the correspondent selection level.

A realistic application of the leptonMVA discriminant in multileptonic final states is shown in Figure 4.4. A preselection of three light leptons passing the loose selection criteria and $p_T > 10$ GeV, with two of them forming an opposite-sign same-flavour pair compatible with the Z boson ($60 < M(\ell\ell) < 120$ GeV) and a minimum $p_T^{\text{miss}} > 20$ GeV. In these conditions the main two SM contributions are WZ production (all prompt leptons) and Drell-Yan+Jets production (two prompt leptons and one nonprompt lepton). Due to the relatively low momenta of the jets in Drell-Yan production, which is itself not completely transferred to the non-isolated lepton, the nonprompt leptons tend to be the least energetic ones on each event (l_3), for which the discriminant shows great rejection capability. The optimization of the tight identification criteria that will be introduced in the following chapters relies on studying which

level of requirement in these distributions is to be applied on each selected lepton. In analysis where background reduction is fundamental, a tighter selection is applied, while those that more crucially depend on increasing the available statistical power will use looser ones. Note that in multileptonic final states all effects are magnified, as background contamination and loss of efficiency will be multiplied by the lepton multiplicity.

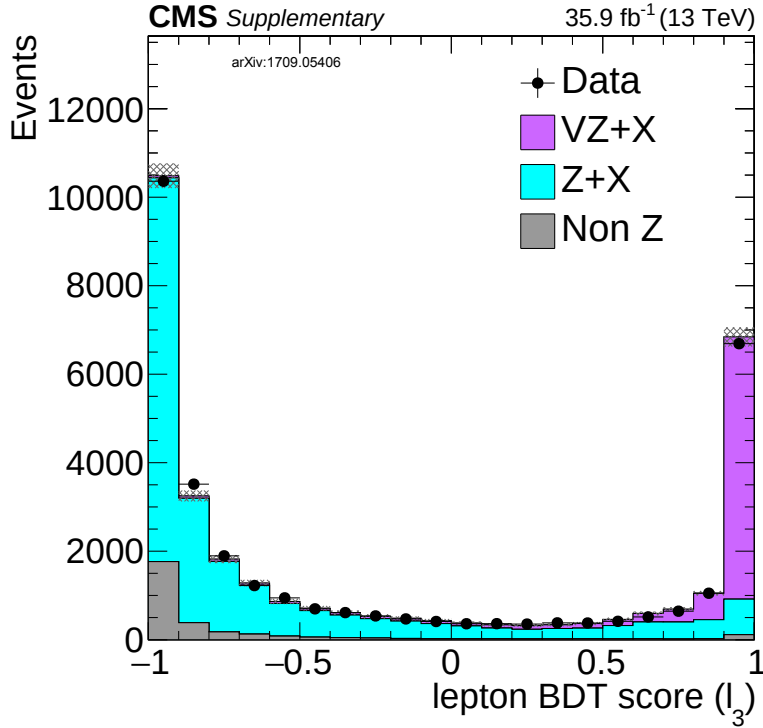


FIGURE 4.4: Distribution of the leptonMVA discriminant for the trailing lepton (less energetic one) in events with three leptons compared for data and MC. Data and simulation corresponding to the 2016 data taking period is used. The figure corresponds to the early 2016 analysis analogous to the one presented in Chapter 6.

4.3.4 Tau identification

The hadron-plus-strips algorithm described in Section 3.2.5.4 is highly efficient in the reconstruction of the τ_h but introduces a sizeable misidentification probability, in which either a quark or gluon originated jet is wrongly identified as a τ_h candidate. A BDT is used to discriminate against misidentified jets [113]. Variables related to the relative isolation of the τ_h candidate, the displacement of its associated vertex and the electron and photon multiplicity inside the τ_h candidate isolation cones are used as an input to the algorithm. The τ_h isolation variables used in the BDT discriminant use a similar formula to Equation 4.1 but with cone size of $\Delta R < 0.3$ rather than the varying size one discussed for the electron and muon mini isolation. The BDT is trained using signal τ_h candidates from Z, W and H boson decays against quark and gluon jets produced in multijet, W and $t\bar{t}$ events. Six different working points of the BDT discriminant are defined corresponding to selection efficiencies ranging from 40% to 90%. A summary of the efficiencies and misidentification rates of the anti jet MVA discriminant is presented in Figure 4.5 (top). A more recent powerful discriminant based

on convolutional neural networks have been developed inside the collaboration, the DeepTau approach [114], but was not used in all the measurements presented due to its availability in during the development of the analysis.

Finally, true electrons and muons can also be misidentified as τ_h candidates. A BDT discriminant is also trained to separate reconstructed τ_h that are matched to a generator level τ from those that do to an electron. The input information for the BDT includes the fractions of energy deposited in the ECAL and HCAL and the amount of produced bremsstrahlung along the leading τ_h candidate track to try to separate the effects from the hadronic and electromagnetic showers in the detector. Five different working points are defined in the τ_h/e discriminant, based on the efficiency of τ_h reconstruction which ranges from 65% to 85%. A summary of the efficiencies and misidentification rates of the anti electron MVA discriminant is presented in Figure 4.5 (bottom).

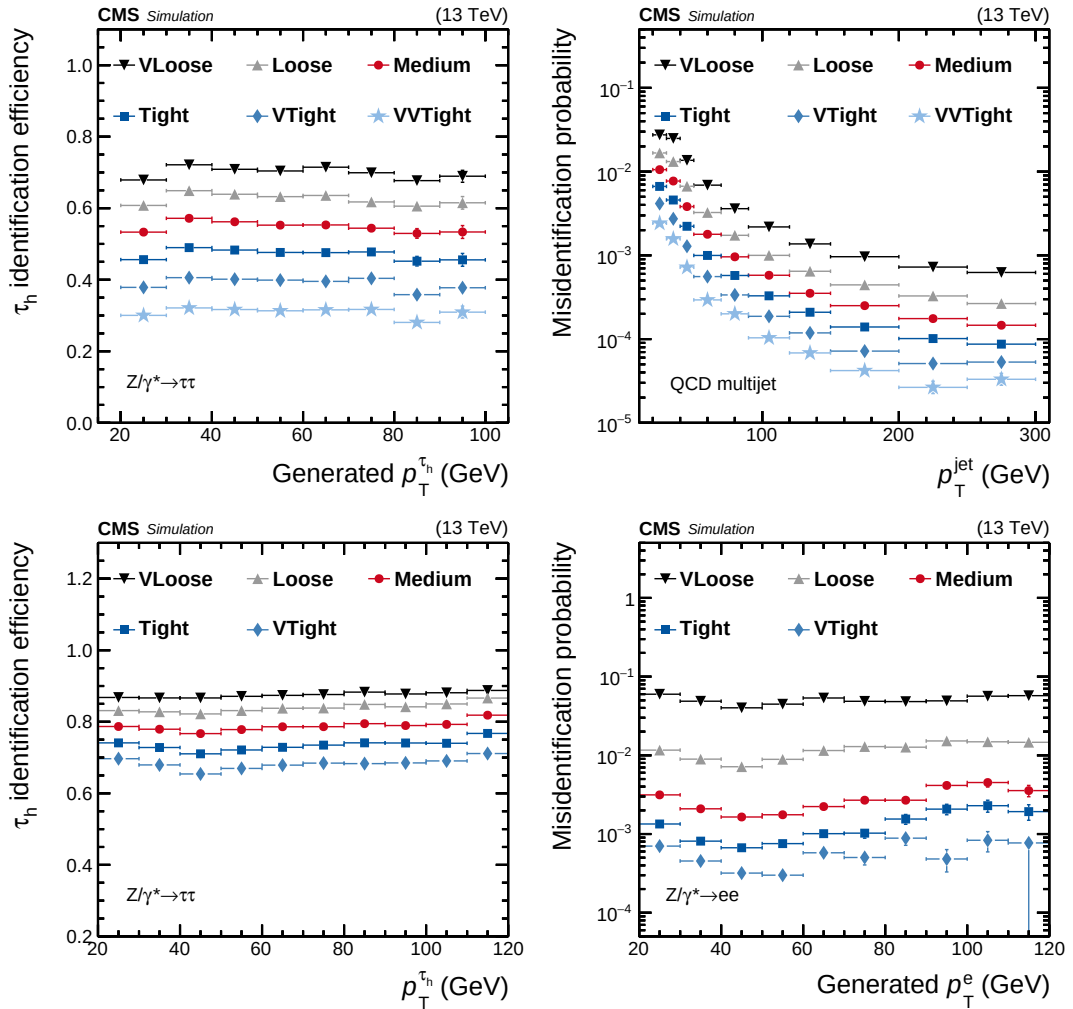


FIGURE 4.5: Efficiency (left) and misidentification probability (right) of the anti-jet (top) and anti-electron (bottom) BDT based identification criteria used to select τ_h candidates. The plots are obtained from Reference [113].

An anti-muon criteria is also used to select τ_h . If less than two reconstructed tracks are found within a cone of size $\Delta R < 0.3$ of the τ_h candidate. The efficiency of this

criteria for τ_h candidates is greater than 99% and reduces the muon misidentification as τ_h rate to less than 0.3%.

As a final comment, fully reconstructing τ_h candidates in the forward regions is extremely challenging due to the unreconstructed electrons and photons outside the ECAL acceptance. Usual kinematic requirements on τ_h of $|\eta| < 2.3$ are thus imposed. Moreover, at the lower p_T values the probability of misidentifying a jet as a τ_h candidate grows quickly, so a minimal requirement of $p_T > 20$ GeV is applied for selecting τ_h candidates. Tightened p_T and η requirements that are seldom used due to the characteristics of the studied processes are discussed in their appropriate sections through this document.

4.4 Corrections to the MC and experimental uncertainties

While MC simulations are able to reproduce the fundamental aspects of physical processes, multiple effects might appear that introduce biases into the simulated samples that make them incompatible with observed data. On top of issues like the non-perturbative nature of QCD described in Section 2.5, the detector response is not always easy to model, involving quite complex interaction processes that behave in quite non linear ways, or data taking conditions, such as detector alignment or magnet field anisotropies, that are as well hard to predict. These possible mismodelling effects can be corrected using part of the data taken by the LHC experiment to perform calibrations of the reconstruction and identification of the different objects that can be used to correct the MC simulations. As any experimental measurement, these corrections have associated uncertainties that needs to be taken into consideration when later data analysis uses such calibrations, becoming sources of systematic uncertainties in most CMS measurements. In the following section an account of all corrections applied in the analysis described through this thesis is presented, as well as their corresponding uncertainties and their method of derivation. Unless otherwise stated, these uncertainties are applied as described through all the results presented in this document.

4.4.1 Electron and muon efficiency corrections

The efficiency of the lepton reconstruction and identification criteria needs to be corrected to account from possible differences between the MC modelling and the true response of the detector in data. While the sources of such issues might be very different for electrons and muons, the procedure for the derivation of the corrections and their associated uncertainties is very similar.

The tool used to measure the lepton efficiencies in data and MC is the tag-and-probe method. Thorough descriptions of its application by the CMS collaboration are presented in References [74] (muons) and [111] (electrons). Events with two same-flavour opposite-sign leptons are selected. One of the leptons is required to pass a strict set of selection criteria and is known as the tag lepton, the other is only required to pass a set of loose criteria and is known as the probe lepton. By counting the number of events in which the probe lepton pass a set of tighter selection criteria the efficiency

of such requirements over the looser selection ones can be computed. Reconstruction efficiencies can equally be estimated by the tag-and-probe method by selecting a reconstructed lepton as a tag plus a loosely selected track as a probe.

In order to estimate the number of passing and failing yields and suppress residual contributions from background leptons –such as non-isolated ones when measuring isolation efficiencies–, an additional selection criteria is applied such that the invariant mass of the two leptons is consistent with a known resonance. For the purposes of the analysis presented in this thesis, the Z resonance is used, as it leads to leptons with p_T on the 10 to 100 GeV range, similar to all physical studies presented later. The invariant mass distribution of the lepton pair is fitted to extract the number of resonant lepton pairs in both the cases in which the probe fails or passes the tight selection. While these numbers do not match all prompt leptons in the selection –for example the non resonant but well isolated lepton pair from $t\bar{t}$ production would be not included in this count–, all resonant pairs are prompt and so the quotient of the yields fitted can be used to estimate the efficiency for signal leptons.

In order to perform the fit, several alternatives exist to define templates for signal and background lepton pairs, like using fully analytical expressions for signal and background contributions [74], or a convolution of the MC prediction with a Gaussian nuisance for the resonant signal plus an analytic background [111]. For the selection criteria that are presented in Sections 4.3.2 and 4.3.3, the second approach was chosen and the computations were repeated independently for each analysis, as different identification criteria are used. For each lepton ID case, the efficiency is computed in MC using events for which leptons are matched to truth generation level just by counting the predicted yields for passing and failing probe leptons. In data, the observed shape of the Drell-Yan MC is convoluted with a Gaussian representing additional resolution effects, while the background contribution is fitted to an analytic function composed of an exponential shape at high energies that turns to an error function at a given cut-off representing the effect of the kinematic cuts on the selected leptons. All parameters of the Gaussian, exponential, error function and the cut-off value are free floating on the tag-and-probe fits.

Efficiencies are computed in data and MC for several bins in p_T and η , representing the different detector response between the barrel and endcap regions, as well as for leptons of different energy ranges. Uncertainties are estimated by recomputing the efficiencies using different tag lepton selections, alternative MC samples and alternative signal and background analytical models. At the analysis level, on each MC event a weight is derived and applied as the product of the efficiency corrections for each lepton. Uncertainties on the efficiency computations are included as systematic uncertainties on the analysis through alternative values of these weights.

4.4.2 Tau efficiency corrections

The selection efficiency for both the isolation, anti electron and anti muon selection criteria discussed in Section 4.3.4 needs to be corrected as well. As the $\tau_h\tau_h$ final state has a sizeable presence of background contributions with jets misidentified as τ_h candidates, the tag-and-probe method is instead performed using a muon as a tag and a reconstructed τ_h as a probe. Both background and signal contribution templates are obtained from MC predictions for the τ_h tag-and-probe fits. The tag-and-probe

measurements are then complemented by similar studies performed in the $t\bar{t}$ and off-shell W +jets final states to provide average estimations of the τ_h efficiency for each discriminant and working point. A detailed description of the techniques developed by the CMS collaboration for τ_h efficiency estimation can be found in Reference [113].

At the analysis level, yet another per event weight is computed as a product of efficiency corrections applied to all reconstructed τ_h depending on their p_T and η . Uncertainties related to the systematic effects presented in the different fits used to extract the efficiency values are equally propagated to these event weights as a systematic uncertainty on all analysis that make use of reconstructed τ_h .

4.4.3 Lepton energy scale corrections

While the simulation of the lepton p_T provided by the standard CMS reconstruction described in Section 3.2.5 tends to be quite accurate, small discrepancies might appear in the lepton energy spectra between data and MC. While these discrepancies might be small, for high precision measurements such effects might be noticeably enough and need to be corrected. Different techniques exist depending on lepton flavour to compute and apply such lepton energy calibrations.

Electron energy resolution corrections are applied for all simulated electrons in bins of η and R_9 , where R_9 is the sum of all energy deposited in a 3×3 crystal array in the ECAL centred around the most energy crystal presented in the electron's associated supercluster. Corrections are derived using the spreading method described in Reference [111] in the $Z \rightarrow ee$ decay mode. Uncertainties on these calibrations are later estimated as systematic effects at the analysis level varying electron energies and all derived quantities, such as p_T^{miss} , by the estimated uncertainty on the electron energy scale.

Muon energy scale corrections based on the Rochester method [115] are also considered. The method provides corrections for muons based on their charge, and η and ϕ coordinates and is based on two sequential steps estimated using the $Z \rightarrow \mu\mu$ final state. The first step derives corrections on each bin that make the mean reconstructed muon p_T in data and realistic MC match that of an ideal MC sample with no alignment effects for each charge- η - ϕ bin. The second step further corrects the result on each η - ϕ bin such that on each one the mean value of the dimuon invariant mass matches the one obtained from the ideal detector. The resulting scale corrections are applied to all muons selected in the analysis and propagated accordingly to derived quantities such as p_T^{miss} .

Corrections to the τ_h energy scale are derived in final states containing a τ_h and an electron or a muon, by studying the distributions of m_{τ_h} and $m_{\ell\tau_h}$ in MC and data separately for τ_h reconstructed on each of its decay modes. An energy scale parameter that modifies the energy of all τ_h in the sample by a fixed fraction is introduced and the quoted distributions are fitted to extract its most likely value, corresponding to the τ_h energy scale correction. The measured quantity is applied to all τ_h selected in MC for analysis that use τ_h energy scale corrections based on their decay mode but independently of their p_T and η . Uncertainties are propagated to the analysis level by reproducing analysis selection varying the τ_h energy according to the uncertainties in the fitted energy scale parameter.

4.4.4 Trigger efficiency corrections

Trigger selection is emulated in the MC simulation, but it still needs to be corrected such that the MC trigger efficiency reflects the one measured in data. For a simple trigger selection, techniques such as the tag-and-probe method have been successfully used by the CMS collaboration [116] to measure trigger efficiencies. However, for analysis that use a complex selection—such as requiring any of the triggers in Table 4.1 to be fired—such strategy is quite unpractical, as efficiencies for each single trigger requirement need to be computed separately and then combined in a non-trivial way depending on the selected final state. Instead, the efficiency of the overall HLT selection is easier to both estimate and translate to the real effect on the analysis level.

The trigger efficiency for fixed HLT and offline selections is defined as the proportion of events that pass both the HLT and offline requirements over those that only pass the offline ones. To measure this quantity in data additional trigger requirements, reference triggers, need to be imposed to select offline events without introducing a bias towards the studied HLT requirements. The analysis presented in this thesis measure the trigger efficiencies of the leptonic trigger strategy described in Section 4.1 using reference triggers based on the presence of moderate p_T^{miss} . The offline requirements are used to build a preselection region (PR) including the same leptons and p_T cuts that are later used to define the analysis' event selection, plus minimal requisites on p_T^{miss} following the reference trigger. The efficiencies are then measured as

$$\epsilon_{\text{trig}} = \frac{\text{\#Yields passing leptonic HLT, } p_T^{\text{miss}} \text{ HLT, and PR selection}}{\text{\#Yields passing } p_T^{\text{miss}} \text{ HLT and PR selection}} \quad (4.4)$$

All MC events are corrected by a global weight corresponding to the quotient of the trigger efficiencies measured in data and MC. Additional systematic uncertainties on the trigger efficiency measurement appear due to the usually limited statistics available in data once the reference trigger criteria is applied and are applied in all analysis considered through this document. An estimation of the bias due to possible correlations between the p_T^{miss} and leptonic triggers can also be evaluated by comparing results obtained with different sets of reference triggers or just as the overall observed data/MC correction. Not all the analysis described later apply such trigger efficiency bias systematic and it will be discussed in an analysis by analysis case.

4.4.5 Jet energy scale and resolutions

The reconstruction of jets in CMS described in Section 3.2.5 does not ensure a perfect estimation of the overall jet energy that could lead to a proper estimation of the original parton energy. Moreover, the complexity of the detector response to composite objects such as jets makes these effects slightly different in data and MC. In order to recover the correlations between measured jet p_T and parton p_T in a consistent way in data and MC, corrections to the jet energy are applied. Those are divided into jet energy scale corrections, which shift the overall p_T estimation in data and MC, and jet energy resolution corrections, which scale the resolution in jet p_T in MC to match that of it observed in data.

Jet energy corrections are divided into several steps that are applied sequentially. First, pileup contributions are subtracted from the overall estimated jet energy in both data and MC. Second, the simulated jet p_T at reconstructed level is compared with the one from its originating parton in simulation. Both data and MC are corrected such that the MC response is uniform with respect to the jets kinematics. Third, residual corrections are applied only to data, corresponding to the observed differences between data and MC responses in several topologies corresponding to dijet or Drell-Yan+jets production. All correction steps are applied for all of the jets reconstructed in an event depending on its p_T , η and covered area and properly propagated to derived quantities such as p_T^{miss} . Several tens of uncertainty contributions related to the jet energy correction derivation are summed up into uncertainties in the final jet p_T estimations and are propagated as systematic effects to analysis presented through this thesis. A thorough description of the set of corrections and the corresponding uncertainties is presented in Reference [117].

4.4.6 B tagging efficiency

The b tagging procedure described in Section 4.3.1 can also be affected by mismodelling effects between data and MC. As for the case of the leptons, it is assumed that possible dependence of the b tagging efficiency mismodelling with the underlying physics can be parametrized in terms of the jet p_T and η , corresponding to a broad range of responses from the detector. A brief description of the underlying methods developed by the CMS collaboration for the estimation of this effect is presented here, while a more detailed one can be found in Section 8 of Reference [106].

The b tagging discriminants discussed in Section 4.3.1 produce a classification of jets into several flavour classes: b , c and light quark/gluon jets. The efficiencies and – correspondingly– misidentification probabilities for each of the classes need to be corrected in MC. In MC events, the access to the generator level information makes a measurement of efficiencies separated by the true nature of the jet trivial, but measurements in data need of more sophisticated techniques.

The identification efficiency of b jets is estimated in data samples enriched in b quark content, either selecting multijet events containing a low p_T non-isolated muon or in the $t\bar{t}$ final state requiring two isolated leptons. In both topologies, several methods are used to exploit kinematic differences between jets and b jets to fit the quantity of them passing or failing the b tagging criteria. Uncertainties related to jet and lepton efficiency and energy scales, gluon splitting and quark fragmentation, and the methods used to separate in data jets and b jets are summarized into an overall b tag efficiency uncertainty. Similarly, the efficiency of c jets is measured in either $W + c$ jet events or in semileptonic $t\bar{t}$ decays. Between both cases, uncertainties related to jet and lepton efficiency and energy scales, quark fragmentation, and the methods used to separate in data jets and b jets are summarized into an overall c tag efficiency uncertainty.

Finally, the misidentification probability corresponding to jets originating in light quarks or gluons is estimated in multijet events. The asymmetry in the impact parameter of light and heavy jets is exploited by building a new tagging discriminant recomputed using only tracks with negative impact parameters, which contain little heavy flavour jets, and measuring its efficiency. This quantity is then corrected to return to the original discriminant using both efficiencies measured in MC events.

Uncertainties in the measurement include dependence on the gluon content, the presence of slightly asymmetric kaons or Λ hadrons, mismeasurements on the tracks and the phase space dependence introduced by the trigger selection.

All analysis presented in this thesis that make use of b tagging techniques include these efficiency corrections. To do so, a weight is defined for each MC event which corresponds to a product of the corrections applied to all the reconstructed jets. For each jet, a weight is computed corresponding to each its true nature, as defined by matching its origin in the generator, and the corresponding efficiencies measured in data and MC for the values of the jet p_T and η . Uncertainties in the efficiencies are propagated by considering alternative weights in which each efficiency is varied according to its uncertainties. As the sources of b and c tagging uncertainty are similar, they are correlated into a single heavy flavour b tagging uncertainty, that is decorrelated from the light mistagging uncertainties.

4.4.7 Pileup profiles

Contrary to the previous effects, which relate to the ability of the MC tuning to faithfully model the detector response observed in data, a last effect of note corresponds to the proper reproduction of the pileup profile observed in data. As data is obtained with a given profile of pileup interactions, it is desirable that the MC reproduces such effects, as they might have consequences in quantities that are sensitive to overall hadronic energy presented in the detector, such as p_T^{miss} . Although those effects are included into the simulation, the exact pileup profile of data is usually unknown at the moment of MC production, as it runs in parallel with the data taking process. Thus, the pileup profile of the MC that is initially designed on data taking expectations need to be corrected later based on the measurements performed in the real data.

The target pileup profile needs to be extracted from data. Explicitly, the mean number of pileup interactions per collision $\langle \text{PU} \rangle$ can be extracted from measurements of the instantaneous luminosity L_{inst} as

$$\langle \text{PU} \rangle \nu_{\text{LHC}} = L_{\text{inst}} \sigma_{pp} \quad (4.5)$$

where ν_{LHC} is the known collision frequency of the LHC, σ_{pp} is the total inelastic proton–proton cross section, and the formula is just the usual relation between the observed events, luminosity and cross section. Instantaneous luminosities are measured in CMS approximately each 23 seconds of data taking (lumisections). The value of the inelastic pp collision cross section has been measured by the CMS collaboration to be $\sigma_{pp} = 69.2 \pm 3.2 \text{ mb}$ [118].

Histograms with the distribution of $\langle \text{PU} \rangle$ are built for MC and data, and the quotient of the two are used as weights to be applied in the MC on a per event basis such that its final pileup distribution matches it of data. If enough events are present in the MC, the main uncertainty on the procedure arises from the limited knowledge on the σ_{pp} quantity. Alternative reweightings of the MC with the σ_{pp} values varied according to its uncertainties are used to estimate the effect of such uncertainty on the different studies presented on this thesis. An example of the input histograms used for this procedure is shown in Figure 4.6.

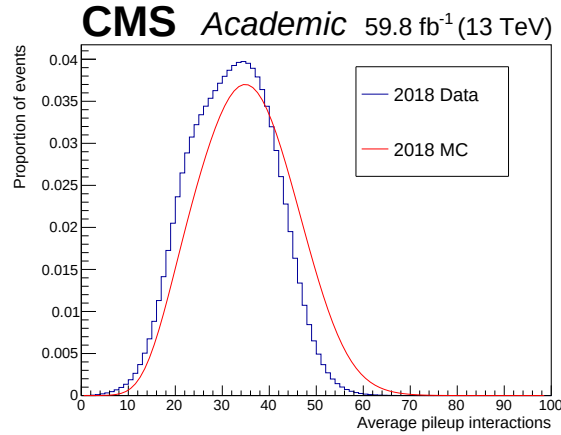


FIGURE 4.6: Profiles of average pileup interactions in data and unweighted MC corresponding to the 2018 data taking year. Only the nominal profile for data, under the $\sigma_{pp} = 69.2 \pm 3.2\text{mb}$ assumption, is shown.

4.5 Data-driven background estimations

Even if all possible SM processes that happen in the LHC collisions can be simulated through MC generators, sometimes it is preferable to use alternative estimation methods that do not depend as heavily in some of the MC simulation steps. Typical cases appear when theoretical computations of higher order corrections are expected to be comparatively relevant and too complex to study, or when some steps of the simulation process are known to be difficult to model in MC simulations. In such cases, estimating the contributions from a background process directly from observed data in a region that is independent from the one where the measurement will be performed might be desirable. If done properly, this is a way to avoid modelling issues, as real data does not include problems of missing higher perturbative orders and directly avoids any modelling issues.

4.5.1 Nonprompt backgrounds

Nonprompt leptons are one of the most problematic sources of background contributions in multileptonic physics. SM processes that lead to relatively low lepton multiplicities can be produced in association with nonprompt leptons, providing final states with greater lepton multiplicities than expected. For example, Drell-Yan or $t\bar{t}$ production will naturally lead to final states with two prompt leptons, but non-isolated leptons or misidentified jets can make a Drell-Yan or $t\bar{t}$ event appear with three reconstructed leptons as an all prompt leptons decay such as WZ production might look like. An schematic diagram comparing such two processes between $t\bar{t}$ and WZ production is presented in Figure 4.7.

Even if the probability of misidentification is low thanks to the object identification techniques introduced in Section 4.3, if the cross section of the original process was high enough the overall nonprompt lepton yields can be significant. Additionally, the modelling of non-isolated leptons is usually specially complex, as they are introduced into the simulation through the PS step, which usually requires very precise tuning to achieve good results.

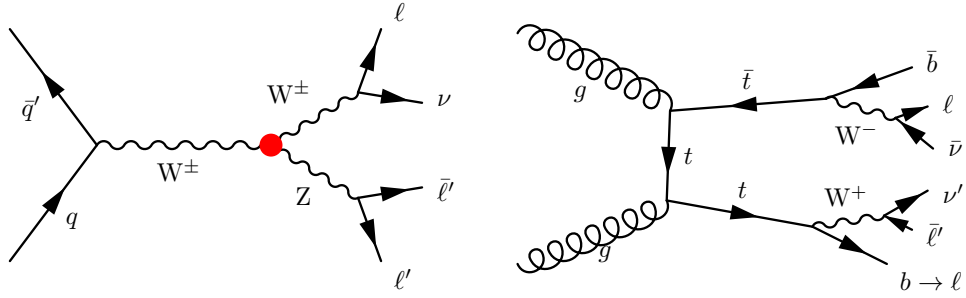


FIGURE 4.7: Schematic diagrams of two SM processes that lead to three final state reconstructed leptons. (Left) WZ production in multileptonic decay, leading to three non-isolated lepton. (Right) $t\bar{t}$ production with dileptonic decay, after hadronization one of the b quarks decays to produce a non-isolated lepton.

The nonprompt background is estimated using the loose-to-tight method [119], sometimes referred in the literature as the tight-to-loose method, fake-factor method, or matrix method. Its objective is to estimate the yields of the nonprompt background in a region of interest, generically called signal region (SR), need to be estimated. The loose-to-tight method starts by defining a sideband selection, the application region (AR), by relaxing the lepton identification criteria requirements to looser ones. To avoid double counting events, at least one lepton of the AR has to fail the tighter selection criteria. The yields on the SR can then be obtained by multiplying the observed events on the AR by a transfer factor based on the probability for a loosely selected lepton to pass the tighter criteria. Such probabilities, or fake-rates, are measured in an orthogonal dataset known as the measurement region (MR). The definition of a loose and tight electron and muon selection identification criteria referred at in Tables 4.2 and 4.3 are motivated by this approach.

Several additional points need to be taken into account when defining the loose and tight lepton criteria. First, the available amount of data in the AR will determine the statistical uncertainties in the final nonprompt yields. If the fake-rate is close to one, the statistical uncertainty of the predicted yields will be that of the AR, which might be problematic if the SR has a sizeable proportion of background events. Second, the method implicitly assumes that the fake-rates obtained in the MR can be extrapolated to the AR which might not be correct. In fact, if the tight over loose efficiency has significantly different values for non-isolated leptons coming from distinct sources, such as b and light quark jets, the assumption would break. Thus, the loose requirements are usually tuned such that the fake-rate probabilities are the same for non-isolated leptons produced in heavy- and light-flavoured hadron decays. As the tight lepton criteria is defined for each analysis the loose criteria needs to be optimized in a case by case basis as well based on this fake-rate universality criteria as well.

4.5.1.1 Fake-rate measurement

For analysis presented in this thesis, the MR is defined to be enriched in QCD events, requesting the presence of a lepton passing the loose selection criteria that is well separated ($\Delta R > 0.7$) from a reconstructed jet. The requirement on the lepton p_T is set to 10 GeV, and data is selected by using trigger paths involving a single low p_T lepton

and a reconstructed jet that have high (> 1000) prescale factors during data taking. The selection is rich in the presence of nonprompt leptons as it tends to include dijet events in which both jets are back-to-back and one of them produces the non-isolated lepton. The fake-rates are then measured as

$$f = \frac{N_T}{N_L} \quad (4.6)$$

where N_T are the number of observed leptons passing the tight criteria in the MR data, N_L are all the leptons in the MR in data, and N_L^P and N_T^P are the estimated quantities of prompt leptons in each case. In order to estimate the contamination from prompt leptons, a fit of the data in the MR is performed for both the loose and tight selection criteria. In both cases, the nonprompt lepton yields are free to float and the overall prompt contributions are modelled from MC templates obtained from W , Z and $t\bar{t}$ production samples. Additional uncertainties corresponding to the statistical and systematic uncertainties on the templates are included into the fit. The fitted distribution corresponds to the M_T^{fix} variable, a slightly redefined transverse mass defined as

$$M_T^{\text{fix}} = \sqrt{p_T^{\text{miss}} p_T^{\text{fix}} (1 - \cos(\phi))} \quad p_T^{\text{fix}} = 35\text{GeV} \quad (4.7)$$

where ϕ is the angle in the transverse plane between the lepton and the p_T^{miss} vector. The M_T^{fix} variable is designed to exploit the behaviour expected from the transverse mass of the lepton- p_T^{miss} system but replacing the p_T of the lepton for a fixed 35 GeV quantity to avoid biases of the fake-rate measurement towards higher lepton momenta. An illustrative example of the resulting M_T^{fix} distributions that are fitted to extract the fake-rate parameters is presented in Figure 4.8 for electrons inside the barrel and moderate values of momentum. Similar ones are used to extract the fake-rates for other electrons and muons.

The fake-rates might vary depending on lepton kinematics. In fact, the different resolution in the measurements of leptons measured inside the barrel or endcap regions of the detector might lead to quite different variations of the fake-rates. As the spectra of the lepton kinematics in the MR and the AR will likely not match, the fake-rates are measured in bins of η , splitting the results between the different detector regions. Moreover, the fake-rate might have some underlying dependence on the energy of the parton leading to a non-isolated lepton, with several of the isolation criteria that enter the leptonMVA discriminant being expected to correlate to this quantity. As the reconstructed lepton p_T ignores all hadronic activity around the lepton it is not a good proxy of such quantity, so a cone-correction is applied to define a cone- p_T for non-isolated leptons that captures the whole parton momentum. The cone- p_T is defined as

$$\text{cone-}p_T(\ell) = \begin{cases} p_T(\ell) & \text{if } \ell \text{ is tight} \\ X p_T(\text{jet}) & \text{if } \ell \text{ is not tight and a close-by jet is found} \\ X p_T(\ell)(1 + I_{\text{mini}}(\ell)) & \text{otherwise} \end{cases} \quad (4.8)$$

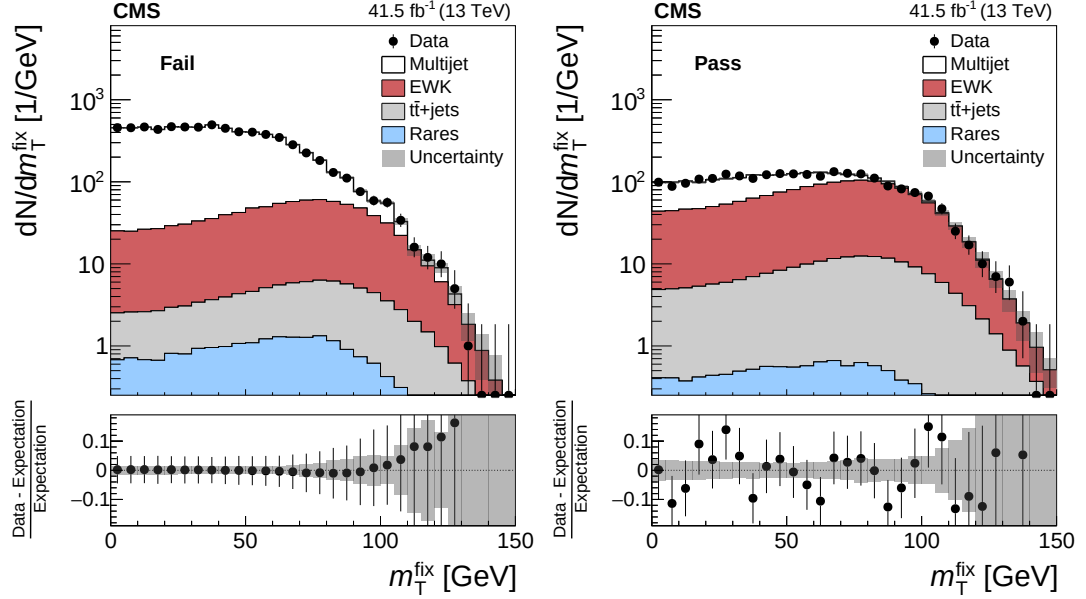


FIGURE 4.8: Distributions of the M_T^{fix} variable in the fake-rate measurement region containing an electron inside the barrel region and with $25 < p_T < 35$ GeV after the fits used to extract the nonprompt yields with the loose identification selection (left) and the tight identification selection (right). The identification criteria used corresponds to the WPs of the $t\bar{t}H$ analysis later presented in Section 4.8. The comparison is performed with data and simulation corresponding to the 2017 data taking year.

the quantity X is a normalization factor that is fixed for each analysis. As the reconstructed p_T is used for prompt leptons, this normalization avoids vast variations of the lepton cone- p_T from appearing around the leptonMVA discriminant cut used for the tight lepton definition and is estimated by requiring that the mean lepton cone- p_T is continuous with respect to the leptonMVA discriminant. As a consequence the estimation of the cone- p_T is similar for similarly identified leptons with no discontinuity introduced by the tight lepton requirements. The cone- p_T is optimized for each tight lepton ID, usually ranging between 0.65 and 0.9. The final fake-rates are thus measured in bins of both lepton η and cone- p_T .

4.5.1.2 Fake-rate application

To obtain the estimation of the nonprompt yields in the SR, the previously derived fake-rates are used to extrapolate the yields from the AR into the SR. The extrapolation, however, is not as direct as a simple multiplication, as there tends to be contamination from prompt processes in the AR. This is corrected by subtracting the estimated prompt yields estimated in the AR following the same techniques that are used in the SR.

Moreover, as the data yields on the SR can not be used to estimate the background contributions on itself, the extrapolation factor is not exactly equal to the measured fake-rate. The exact extrapolation formula can easily be derived by induction. For the case of selections with just 1 loose lepton, if N_T be the yields when the lepton is tight (SR), N_L the yields when it is loose but not tight (AR), and f the fake-rate of the corresponding lepton then (from 4.6):

$$f = \frac{N_T}{N_T + N_L} \rightarrow N_T = \frac{f}{1-f} N_L \quad (4.9)$$

For the general N leptons case, the prediction gets more complex as some of the leptons might be prompt, a point that is a priori unknown in real data. This can be solved by using the different combinations of loose-not-tight final states, relating it to the original configurations of prompt or non-prompt leptons, and solving the resulting systems of equations. Assume that f_i is the fake-rate of lepton number i and all possible configurations of loose-not-tight or tight leptons are codified as the 2^N entries of the $\mathbb{Z}_2^N = \mathbb{Z}_2 \times \dots$ (n times) $\times \mathbb{Z}_2$ set -represented as length- N tuples for which each entry can take either a value 1 (loose not tight) or 0 (tight). Then a general formula for the loose to tight estimation for the all tight (SR) case is

$$N_{T_1, \dots, T_N} = N_{0, \dots, 0} = N_0 = - \sum_{t \in \mathbb{Z}_2^N, t \neq 0} \left[\prod_{i=1}^N \left((-1)^{t[i]} \frac{f_i^{t[i]}}{1 - f_i^{t[i]}} \right) N_t \right] \quad (4.10)$$

$$f_i^{t[i]} = \begin{cases} f^i & \text{if } t[i] = 1 \\ \frac{1}{2} & \text{otherwise} \end{cases}$$

where t runs over all possible configurations $t \in \{(L_1, L_2, \dots, L_N), \dots, (T_1, T_2, \dots, T_N)\}$, and N_t is the number of events that have exactly the same configuration of tight and loose leptons in the exact positions defined by t . Such compact formula is quite useful, as the cases of interest for the multileptonic analysis includes 2, 3, and 4 leptons and the total derivation becomes increasingly more complex, for example for 2 and 3 leptons it can be proven that

$$\begin{aligned} N_{TT} &= \frac{f_1}{1-f_1} N_{LT} + \frac{f_2}{1-f_2} N_{TL} - \frac{f_1 f_2}{(1-f_2)(1-f_1)} N_{LL} \\ N_{TTT} &= \frac{f_1}{1-f_1} N_{LTT} + \frac{f_2}{1-f_2} N_{TLT} + \frac{f_3}{1-f_3} N_{TTL} - \frac{f_1 f_2}{(1-f_2)(1-f_1)} N_{LLT} + \quad (4.11) \\ &\quad - \frac{f_1 f_3}{(1-f_3)(1-f_1)} N_{LTL} - \frac{f_2 f_3}{(1-f_3)(1-f_2)} N_{TLL} + \frac{f_1 f_2 f_3}{(1-f_1)(1-f_2)(1-f_3)} N_{LLL} \end{aligned}$$

Uncertainties in the fake-rates are propagated to the final nonprompt contribution on each analysis by recomputing the predicted yields with the varied fake-rates.

Additionally, a systematic uncertainty is usually included to model the possible dependency of the predicted yields with respect to the flavour of the originating parton for a nonprompt lepton. Several techniques exist to study such possible bias effects, by comparing the nonprompt yield predictions at the final selection obtained with the nominal loose-to-tight prediction and other methods. Comparisons with direct MC estimation, fake-rates derived in $t\bar{t}$ or QCD MC, or fake-rates derived in a $t\bar{t}$ dominated MR have been used in different situations on the past depending on the

application phase space. An upper bound on the observed bias, or non-closure estimation, is usually applied as an additional normalization systematic to the whole nonprompt prediction. These uncertainties are discussed in a case by case basis.

4.5.2 Charge misidentification

In final states where the charge of the leptons is relevant, processes in which such quantity is mismeasured will contribute to the background presence. If the final selection is specially rare in SM processes but the possibly mismeasured final states are not, such background contributions might be relevant for the corresponding studies. Such is the case, for example, of final states involving a pair of leptons with the same charge, which is quite rarely produced in SM processes, while events with an opposite charge lepton pair are abundant in the LHC as a result of Drell–Yan and $t\bar{t}$ production. The tight charge criteria introduced in Section 4.3 greatly renders the probability of a charge mismeasurement for muons negligible, but that of electrons might still be noticeable.

The data-driven procedure for the estimation of the misidentified charge background is similar to that of the nonprompt one and is used primarily through this thesis for final states with exactly a same-sign lepton pair. The probability for the charge of a lepton to be badly estimated (flip-rate) is obtained in a new measurement region. A sideband consisting of events sharing the SR definition and an opposite-sign lepton pair instead of a same-sign one is defined. The yields of the charge misidentified background in the SR are then extrapolated from this sideband using the previously measured flip-rate. While the flip-rate is expected to not be as dependant on the lepton identification criteria as the fake-rates, residual effects might appear due to correlations of such requirements with the lepton kinematics, so the flip-rates are measured separately for each lepton selection case.

4.5.2.1 Flip-rate measurement

The flip-rates are measured selecting events with two final state electrons and an invariant mass close to that of the Z boson $|M(\ell\ell) - m_Z^{\text{PDG}}| < 10 \text{ GeV}$. The lepton p_T is required to be greater than 10 GeV. The flip-rates are estimated counting the proportion of same-sign events with respect to opposite-sign ones in a mixture of MC samples, including either Drell–Yan and $t\bar{t}$. Matching of the reconstructed objects to the generator level truth is used to tag the lepton whose charge is mismeasured in each case. The flip-rates are measured in three bins of η , as the resolution on p_T of the barrel is much better than that of the endcap, and five bins of p_T , as higher momentum leptons propagate in a straighter line and so their curvature is harder to measure properly.

An alternative technique, relying solely in data, is used to estimate the flip rates in the $t\bar{t}H$ analysis presented in Section 4.8. Instead of using MC matched truth, for each possible combinations of bins in η and p_T for each of the two leptons, the following equation is proposed

$$N_{SS}^{ij} = (q_i + q_j - q_i * q_j) N_{OS}^{ij} \quad (4.12)$$

where q_i and q_j are the flip-rates for leptons fulfilling the kinematic requirements of η - p_T bin i and j , respectively. N_{SS}^{ij} and N_{OS}^{ij} are the number of Drell-Yan same-sign and opposite-sign containing leptons fulfilling such kinematic requirements. The cross term $q_i * q_j$ is neglected as the probabilities themselves are expected to be extremely low $< 10^{-3}$. The N_{SS}^{ij} and N_{OS}^{ij} events are estimated from a fit to the $M(\ell\ell)$ distribution in data in which MC templates are used to model the Drell-Yan and residual background contributions. Once the N_{OS}^{ij} and N_{SS}^{ij} quantities are fixed by the fit, the resulting systems of equations in the flip-rate parameters are solved to obtain them. Although this method provides the charge flip measurement directly in data, it has the drawback of introducing additional complexity into the measurement and suffers from the relatively low statistical power of the measurement region, so only two bins in η and three in p_T were used. An example of the $M(\ell\ell)$ distribution in the opposite-sign and same-sign final selections for electrons of moderate p_T is shown in Figure 4.9.

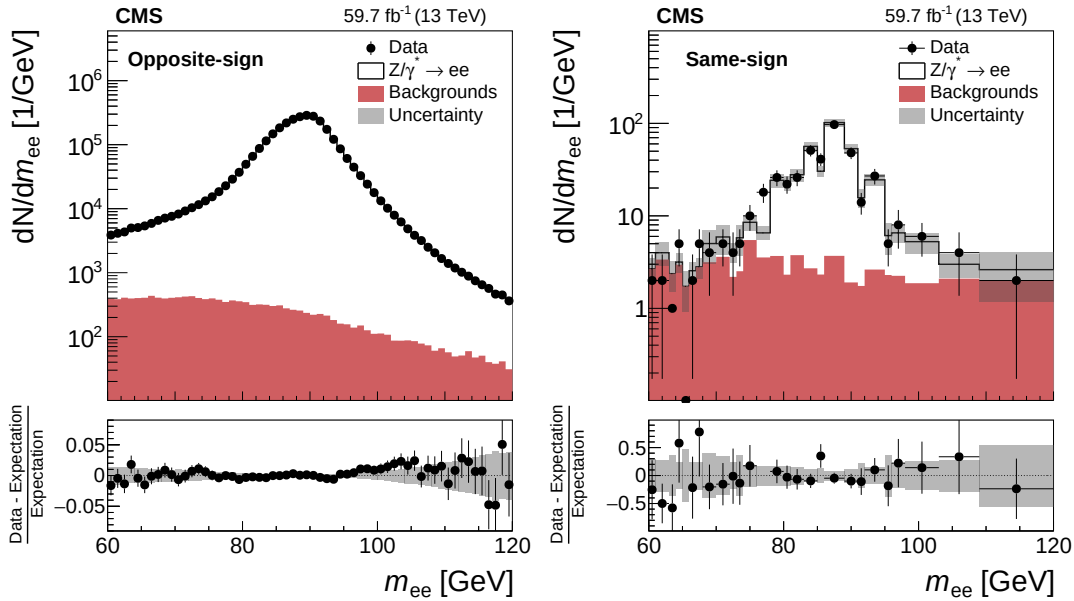


FIGURE 4.9: Distributions of the $M(\ell\ell)$ variable in the flip-rate measurement region containing two electron inside the barrel region and with $25 < p_T < 50$ GeV after the fits used to extract the Drell-Yan yields with the same-sign selection (left) and the opposite-sign selection (right). The identification criteria used corresponds to the WPs of the $t\bar{t}H$ analysis later presented in Section 4.8. The comparison is performed with data and simulation corresponding to the 2018 data taking year.

4.5.2.2 Flip-rate application

As discussed before, the estimation of the mismeasured charged background is performed weighting events from the opposite-sign sideband with the measured flip-rates. Contrary to the fake-rate measurements, the new sideband and SR do match the pass/fail criteria used on the flip-rate measurement and so the extrapolation factor for an event with lepton kinematics in the η - p_T bins i and j is just $Q_{ij} = q_i + q_j$.

An example on the application of the method to predict the background in a same-sign dilepton region is shown in Figure 4.10. It corresponds to the same-sign SR

described in Chapter 6, where two same-sign final state leptons with p_T requirements greater than 25 GeV (20 GeV) and 15 GeV (10 GeV) for electrons (muons) are required. Additional conditions included in the plot are a minimal missing transverse momentum of $p_T^{\text{miss}} > 60$ GeV and the vetoing of events with more than one reconstructed jet. While the presence of the misidentified charge background is minor, around the Z peak it has a sizeable contribution that closely models a similar trend in data. Flip-rates measured using the MC based technique are used, so no double counting of events was done to produce this distribution.

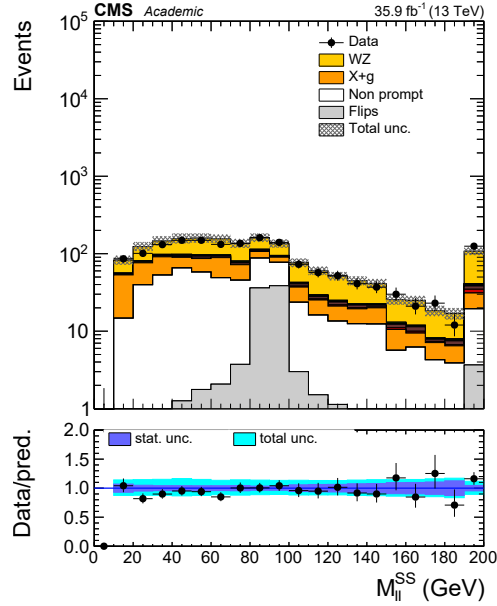


FIGURE 4.10: Distribution of the $M(\ell\ell)$ variable in a same-sign region which includes several kinematic requirements typical of SUSY searches, where the effects of the data-driven charge misidentified background can be seen. The requirements imposed are the presence of two final state light leptons, a minimum of $p_T^{\text{miss}} > 60$ GeV and one or less final state reconstructed jets. Data and simulation corresponding to the 2016 data taking year is used. Flip-rates measured using the MC based technique are used, so no double counting of events was done to produce this distribution.

4.6 Statistical inference techniques and parameter measurements

Once predictions for the behaviour of all physical processes and measurements of that of data are performed, the problem of measuring underlying physical quantities arises. Statistical inference techniques are widely used in the field of High Energy Physics, with parameter estimation being the foundation of most interpretations of data in terms of physical observables such as cross sections, coupling parameters or other relevant magnitudes. A complete description of the fundamentals for most methods used through this thesis can be found in Reference [120].

4.6.1 Maximum likelihood fits and cross section estimations

Counting experiments are one of the most simple inference tests that can be performed in particle physics. A typical case is the observation of d events in a given phase space where s signal and b background events are expected. If the yields in the counting experiment are independent, the likelihood of the observation, i.e. the probability of the observation given the expectations can be modelled through a Poissonian probability mass function (pmf) as

$$L(d) = \frac{e^{-(s+b)}(s+b)^d}{d!} \quad (4.13)$$

In most cases, the behaviour of the signal is relatively unknown. For example, if the overall signal cross section σ_s is not known except for the expected σ_0 value, an additional free parameter $\mu = \sigma_s/\sigma_0$ known as the signal strength is introduced

$$L(d; \mu) = \frac{e^{-(\mu s+b)}(\mu s+b)^d}{d!} \quad (4.14)$$

As discussed through the previous sections, the estimations of background and signal yields are prone to depend on systematic effects related to the different estimation methods with which they are obtained. The uncertainties related to these effects can be introduced into the likelihood function through a set of auxiliary nuisance parameters θ , such that b and s depend on θ as

$$L(d; \mu, \theta) = \frac{e^{-(\mu s(\theta)+b(\theta))}(\mu s(\theta)+b(\theta))^d}{d!} \prod_{\theta} \Theta(\theta) \quad (4.15)$$

where $\Theta(\theta)$ represents the probability density function (pdf) for the auxiliary parameters, corresponding to the expected behaviour of the associated uncertainties or, in the Bayesian interpretation, their prior probabilities. While using Gaussian pdfs was an usual procedure in the past, current studies tend to employ log-Gaussian distributions for nuisances representing overall biases of measurements while gamma pdfs are used for those that are statistical in origin [121]. For each source of uncertainty, the signal and background yields will vary the expected impact of such systematic effect if the associated nuisance parameter θ varies one standard deviation. Such variations are typically encoded to be multiplicative in nature when several ones appear simultaneously.

Finally, in most modern studies experimental measurements are based on several independent observations corresponding to different counting experiments. Such is the case, for example, of studies which look at the binned distributions of a relevant observable in the forms of histograms. An extended likelihood function is then built as a product of the likelihood modelling a counting experiment on each single bin as

$$L(d; \mu, \theta) = \prod_{i=1}^N \frac{e^{-(\mu s_i(\theta)+b_i(\theta))}(\mu s_i(\theta)+b_i(\theta))^{d_i}}{d_i!} \prod_{\theta} \Theta(\theta) \quad (4.16)$$

where s_i , b_i and d_i are the expectations and observations in bin i . Do notice that, while the observations d_i are mutually independent, the expectations might be correlated through nuisance terms (systematic uncertainties) that affect multiple of them simultaneously. As the overall signal strength parameter μ is common to all experiments, information from all of them can be used at the same time to deduce its most likely true value.

The estimation of the parameter μ , which can be physically interpreted as the measurement of the signal cross section, is done through maximum likelihood estimation. The most likely value of μ , $\hat{\mu}$ is the one that maximizes the probability of observing the given data or, correspondingly, the extended likelihood function. The auxiliary parameters θ are maximized as well representing the most likely setup of the effects they represent given the observed data $\hat{\theta}$

$$\hat{\mu}, \hat{\theta} = \underset{\mu, \theta}{\operatorname{argmax}} L(d; \mu, \theta) \quad (4.17)$$

The precision on the measured cross section is usually defined by an estimation of a confidence interval on the parameter μ . To do so, a profiled likelihood ratio is built

$$\lambda(\mu) = \frac{L(d; \mu, \hat{\theta}(\mu))}{L(d; \hat{\mu}, \hat{\theta})} \quad , \quad \hat{\theta}(\mu) = \underset{\theta}{\operatorname{argmax}} L(d; \mu, \theta) \quad (4.18)$$

where the nuisance parameters are *profiled*, maximized for each tested value of μ when evaluating the $\lambda(\mu)$ function. Toy based simulations of the behaviour of $\lambda(\mu)$ can be used to derive its associated pdf numerically for different assumptions on the true value of μ . If the quantity of observed data events in the experiment is big enough, Wald's identity states that

$$q_\mu = -2 \log(\lambda(\mu)) = \frac{(\mu - \hat{\mu})^2}{\sigma^2} \quad (4.19)$$

where the estimator $\hat{\mu}$ follows a Gaussian distribution with standard deviation σ . Inverting this relation, the standard deviation of $\hat{\mu}$ can be computed by scanning the values of q_μ and taking the values μ^+ and μ^- for which $q_\mu = 1$. Those variations are usually interpreted as the estimated uncertainty in the signal strength parameter. Alternatively, a confidence interval in μ can be built using Wilk's theorem, that states that q_μ behaves as a χ^2 distribution with one degree of freedom under the hypothesis that μ is the true value, a confidence interval with 68% coverage can be built that numerically matches the previous equation. These results apply for generic profiled likelihood ratios, independently of the functional form in which the parameter μ modify the yields of s or b .

Generalizations of this procedure can be done to obtain confidence regions of arbitrary multidimensional parameters and for any confidence level (CL), knowing that Wilk's result just changes to a χ^2 with as much degrees of freedom as free parameters the model has. Such procedures are known as likelihood scans and are used abundantly through this thesis to provide confidence levels in one or several dimensions.

4.6.2 Signal significance

When studying new phenomena, the uncertainties affecting the background predictions can produce fluctuations that appear to behave as the searched signal. The consistency of the observed results with the background only hypothesis is quantified in terms of p-values, the probability for the background model to fluctuate up the observed level or more. Significances are transformations of the p-values through the application of the inverse cumulative Gaussian distribution such that the fluctuations can be quoted as what is colloquially described as the *number of typical deviations away from the expectation*. The higher the significance, the more unlikely is that the result corresponds to a fluctuation of the background model.

For simplicity, the case of a single free parameter μ representing a signal strength is considered here. A naïve approach is to consider the profiled likelihood ratio introduced in Equation 4.19 under the null hypothesis of $\mu = 0$ (background only case). Per Wilk's theorem then q_0 follows a χ^2 with one degree of freedom and then compute

$$p_2 = P(\chi_1^2 > q_0^{obs}) \quad \mathcal{Z}_2 = \Phi^{-1}(1 - p_2) \quad (4.20)$$

where the p-value p_2 is obtained from the evaluation of q_0 at the observed data and $\mathcal{Z}_2$ is the significance obtained from such p-value through the Gaussian inverse cumulative distribution function Φ^{-1} . However, it has to be noted that under this approach observations of less events than expected in data are as significant as excesses, as both lead to deviations of the value of q_0 . Physically, most cases of new physics can only lead to excesses of data, a fact that is usually modelled through a modified likelihood ratio defined as:

$$\tilde{q}_0 = \begin{cases} -2 \log(\lambda(0)) & \text{if } \mu \geq 0 \\ 0 & \text{otherwise} \end{cases} \Rightarrow \mathcal{Z} = \sqrt{\tilde{q}_0} \approx \frac{\max(0, \hat{\mu})}{\sigma_0} \quad (4.21)$$

It can be proven that $\tilde{q}_0$ follows a half χ^2 distribution for positive values, with an additional 50% probability to be exactly 0. With this definition, the relation between the significance and the modified likelihood ratio simplifies heavily to the quoted expression $\mathcal{Z}$ as seen in Reference [122] which can be related to the later term using Wald's relation from Equation 4.19. σ_0 is the overall standard deviation in the no signal hypothesis, i.e., including uncertainties corresponding to the data and background processes only. Note that these approximations only hold at the large sample number asymptotic approximation, for cases where the total number of events is small the distribution of the $\hat{q}_0$ test statistic needs to be deduced in other way, usually through numerical techniques like toy pseudo experiments.

It is common consensus to accept that significances greater than $\mathcal{Z} = 5$ are enough to claim the observation of a given phenomena, while values of $\mathcal{Z} = 3$ or greater point towards just evidence of its presence. While the statistical meaning of the number is near equal for significances of 4.99 or 5, in the following results discussion this convention is kept to present different results.

4.6.3 Exclusion upper limits

Finally, if the presence of the signal is not yet fully proven neither a significant signal like presence is observed in data, it is nonetheless interesting to set upper limits on the corresponding model parameters in order to understand the true reach of an study. It is the case, for example, of new physics searches where no signal is found but upper bounds can be set in the cross sections of the models under study to exclude possible realizations of those signal models. Such upper bounds can then be reinterpreted to further constraint the allowed parameter space for complex theoretical models, such as SUSY, which will be discussed in detail in Chapter 6. In all cases used through this thesis the tested case is a simple model with a single signal strength parameter, so the following discussion focuses on such kind of statistical inference.

Practically, an upper limit on the signal strength is a one sided confidence interval at a fixed CL in the parameter μ . For a fixed value of μ the p-values of the observation q_μ^{obs} under the signal plus background (CL_{s+b}) and background only (CL_b) hypothesis can be written as

$$CL_{s+b}(\mu) = P(q_\mu^{obs} | \mu s + b) \quad CL_b(\mu) = P(q_\mu^{obs} | b) \quad (4.22)$$

The usual frequentist recipe for building confidence intervals would be to accept all values of μ such that $CL_{s+b}(\mu) < \alpha$ for an interval at a CL of $1 - \alpha$. This approach, however, becomes problematic in cases where defects are seen in data, as even the background only result could be excluded at a great level for big enough fluctuation. A cure for this effect is the conservative CL_s method, which defines the quantity

$$CL_s(\mu) = \frac{CL_{s+b}(\mu)}{CL_b(\mu)} = \frac{P(q_\mu^{obs} | \mu s + b)}{P(q_\mu^{obs} | b)}, \quad (4.23)$$

with the prescription to accept all μ values such that $CL_s < \alpha$ for exclusion at a confidence level of $1 - \alpha$. By construction, these intervals are more conservative than the CL_{s+b} ones but are robust against the problem of abnormal exclusions for the background only hypothesis.

As in all cases presented before, the CL_s quantity can be estimated by numerical estimations of the distributions of the q_μ statistic, using toy pseudo experiments. However, under the conditions of Wald's and Wilk's theorems, a widely used asymptotic approximation to the CL_s quantity is presented in Equation 36 of Reference [121] as

$$CL_s(\mu) = \frac{1 - \Phi(\sqrt{q_\mu})}{\Phi(\sqrt{q_\mu} - \sqrt{q_A})} \quad (4.24)$$

where q_A is the evaluation of the likelihood ratio in which data has been replaced by the background only Asimov dataset, a set of data equal to the background only model with no fluctuations. The usage of this asymptotic formulae improves computation times significantly and is widely applied through Chapter 6 of this document.

4.7 VV production at 5.02 TeV

As a first application of the techniques introduced in the previous sections, the analysis of diboson production at 5.02 TeV in the CMS experiment [5] is presented. As a probe of the SM at a relatively uncharted energy regime, it proves to be an interesting case study where the generic power of the object identification techniques introduced in this chapter is proven.

Associated production of a pair of on-shell massive electroweak bosons (generically, VV) is a classical probe on the physics of the electroweak sector of the SM. While their total cross sections are not as big as single W or Z production, the involvement of two vector bosons instead of one introduce sensitivity to different types of couplings that are hardly reached by single vector boson processes. First, all massive diboson processes (WW, WZ, and ZZ) can be produced involving triple gauge couplings with amplitudes that are closely related to both the non-Abelian structure of the electroweak interaction through the g coupling described in Equation 2.4. The tightly knit structure of the electroweak sector of the SM as exemplified in Equation 2.13 means that precision measurements of the mass of the W and Z bosons can then be studied in diboson production through the examination of the strength of the triple gauge coupling. Examples of Feynman diagrams at LO that involve diboson production including triple gauge couplings are shown in Figure 4.11.

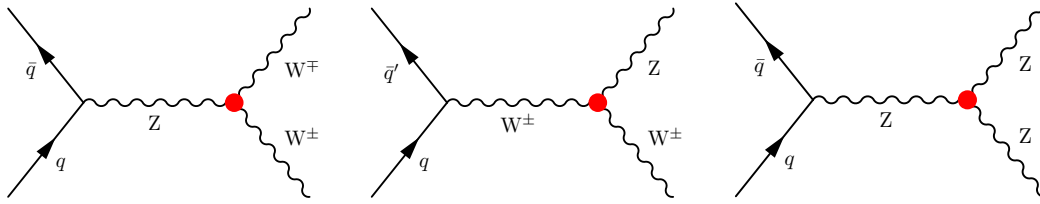


FIGURE 4.11: Feynman diagrams corresponding to the production of boson pairs proceeding through triple gauge couplings at LO in QCD and EWK. In each diagram, the vertex corresponding to the triple gauge couplings is pointed out in red. From left to right: WW, WZ and ZZ production.

As discussed in Section 2.2.1, the Higgs mechanism is responsible for the masses of the W and Z bosons, and strongly couples to both. Although the measured value of the Higgs mass makes decays of the Higgs boson to on-shell WW or ZZ pairs impossible, off-shell decays still provide significant contributions to the Higgs branching fractions. Remnants of the Higgs presence appear as well in the existence of longitudinally polarized W and Z bosons discussed as well in Section 2.2.2.

Experimentally, diboson processes have a clear hierarchy in terms of production cross sections, with the WW one being close to double that of WZ and next to eight times that of ZZ at 13 TeV. As discussed in Section 4.3, charged leptons are the objects that are more precisely measured by the CMS detector and so tend to lead to the final states that are easier to study kinematically. In fact, the higher the lepton multiplicity in the final state, the rarer the SM processes that can produce them are. This establishes an alternative hierarchy related to multileptonic production of diboson processes, with ZZ leading up to the cleanest final states with four charged leptons and WW providing the most challenging final state due to the background contamination from high cross section processes such as $t\bar{t}$ and Drell–Yan production.

The 5.02 TeV dataset taken during the 2017 year specially favours diboson production. On top of the possibility of probing the electroweak sector at an energy regime that has never been studied before, the structure of the electroweak couplings further benefits such a measurement. As there is no direct coupling of the W and Z bosons to the gluon, contributions to the cross section of WW, WZ and ZZ with one or two of the initial partons being gluons are relatively rare, proceeding only through higher perturbative QCD orders or through intermediate quark loops. As a consequence, most of the diboson production cross section comes from $q\bar{q}'$ initiated processes. As evidenced in Figure 2.3, the PDF of the gluon scales way more with the energy than those of the valence quarks, so $q\bar{q}'$ initiated cross sections will vary slower with the energy than gg ones. These two facts coupled, mean that lower energies tend to favour diboson cross sections over other possible background processes such as most processes involving the top quark ($t\bar{t}$, $t\bar{t}Z$, etc.) or the Higgs boson (H, VH, $t\bar{t}H$, etc.).

In comparison with 13 TeV collisions, the 5.02 TeV ones are taken with an order of magnitude less of average pileup interactions, as presented in Figure 3.8 and with a lower overall energy available to the hard scattering process. The consequence is that the p_T thresholds of the leptonic triggers can be lowered while keeping a rate which the detector electronics can work with. Thus, an additional benefit of the 5.02 TeV dataset is the improved range of lepton p_T that can be studied, which directly translates into the possibility of probing vector bosons with lower overall momentum, where soft gluon emissions from the initial state quarks are expected to play more significant roles [123].

4.7.1 Analysis strategy and object selection

Due to the limited luminosity of the 5.02 TeV dataset, restricted to only 300 fb^{-1} , the analysis strategy focuses on preserving as much statistical power as possible by using loose object identification and event selection requirements. Final states with several electrons or muons are chosen as a target phase space as the background presence is too overwhelming in cases where the W or Z bosons decay hadronically. For simplicity, in the rest of the discussion on this analysis we will use the term lepton to refer to electrons and muons unless otherwise stated.

In the case of WW, final states with two leptons already provide significant sensitivity, but the fully leptonic signatures in WZ (three leptons) and ZZ (four leptons) are quite limited in reach due to their lower branching fractions and cross sections. The sensitivity to WZ production is enhanced by including events with a same-sign light lepton pair on the final state, representing a trileptonic final state in which one of the leptons falls out of the detector acceptance. For ZZ, the case in which one of the Z bosons decays to neutrinos is also considered, with leads to around a four times increased total branching ratio with respect to the four charged lepton final states at the sacrifice of additional background contamination.

The electron and muon identification criteria used are based on the leptonMVA discriminant described in Tables 4.2 and 4.3. As a broad range of final states are examined, two different working points of the leptonMVA discriminant are used. The looser one is designed to maximize lepton selection efficiency and matches the pre-selected lepton criteria described in Tables 4.2 and 4.3, with the addition of a tighter cut on the number of lost tracker hits allowed to reduce photon conversion processes.

5.02 TeV lepton ID				
Selection	Loose e (5.02 TeV)	Loose μ (5.02 TeV)	Tight e (5.02 TeV)	Tight μ (5.02 TeV)
Based on	Preselected e	Preselected μ	Tight e	Tight μ
I_{mini}/p_T	< 0.4	< 0.4	< 0.085	< 0.325
Missing hits	$= 0$	-	$= 0$	-
Nearby jet b Tag	-	-	Loose Veto	Loose Veto
LeptonMVA	-	-	> 0.125	> 0.55
Efficiency	80–95%	90–100%	45–90%	60–100%

TABLE 4.4: Common identification and isolation criteria applied to select electrons and muons in the 5.02 TeV diboson analysis for the loose and tight working points. Requirements marked with a - sign are not applied at all for the correspondent selection level. The *based on* row refers to the generic identification criteria presented on Tables 4.2 and 4.3 that the 5.02 TeV requirements are based on. Measured ranges of efficiency, depending on p_T and η , are presented for each working point.

A tighter lepton selection is designed to be applied in final states where non-isolated leptons are expected. It was optimized to enhance the signal significance in the three lepton WZ decay channel by reducing the background contributions from non-isolated leptons. The different variables presented in Sections 4.3.2 and 4.3.3 were tested before setting in the final definition. It is based on the description of the tight lepton criteria introduced in Tables 4.2 and 4.3 with additional restrictions on the lepton isolation and leptonMVA discriminants. A summary of both lepton requirements is presented in Table 4.4, where the range of the lepton selection efficiency computed following the procedures described in Section 4.4.1 is also shown. Besides the lepton selection criteria, neither b tagging nor other object identification requirements are used through the analysis.

All processes are estimated using the MC samples described in Section 4.2, with POWHEG being selected to represent the different diboson signal samples. Signal samples feature a dynamic scale choice, where μ_R and μ_F are set to the overall p_T of the diboson system.

4.7.2 Signal region definitions and background estimation

Several SR are defined at the reconstructed level targetting the different diboson processes and several of their decay modes. A summary of all SR used in the analysis is presented in Table 4.5.

4.7.2.1 WW signal regions

The WW SR requires the presence of a tight electron and a tight muon of opposite charge, an opposite-sign opposite flavour (OSOF) lepton pair. In order to ensure the efficiency of the trigger requirements described in Table 4.1, the leading (subleading) lepton p_T is required to be greater than 20 (10) GeV. To reject the $t\bar{t}$ background, events with at least a reconstructed jet with $p_T > 25$ GeV are vetoed. The transverse momenta of the dilepton system is required to be $p_T^{\ell\ell} > 20$ GeV and the azimuthal separation of both leptons is requested to be small $\Delta\phi_{\ell\ell} < 2.8$. Both requirements avoid the presence of a back-to-back lepton pair that would be expected from Drell-Yan processes. As a

final way of reducing the nonprompt and Drell–Yan contributions, the transverse mass of each lepton and p_T^{miss} is required to be $M_T^\ell > 20$ GeV. The invariant mass of the dilepton system is required to be greater than 12 GeV, to avoid possible contributions from low-mass resonances. The dilepton transverse momentum and invariant mass after all requirements of the WW SR are applied can be observed in Figure 4.12, where the great purity of the final selection can be observed.

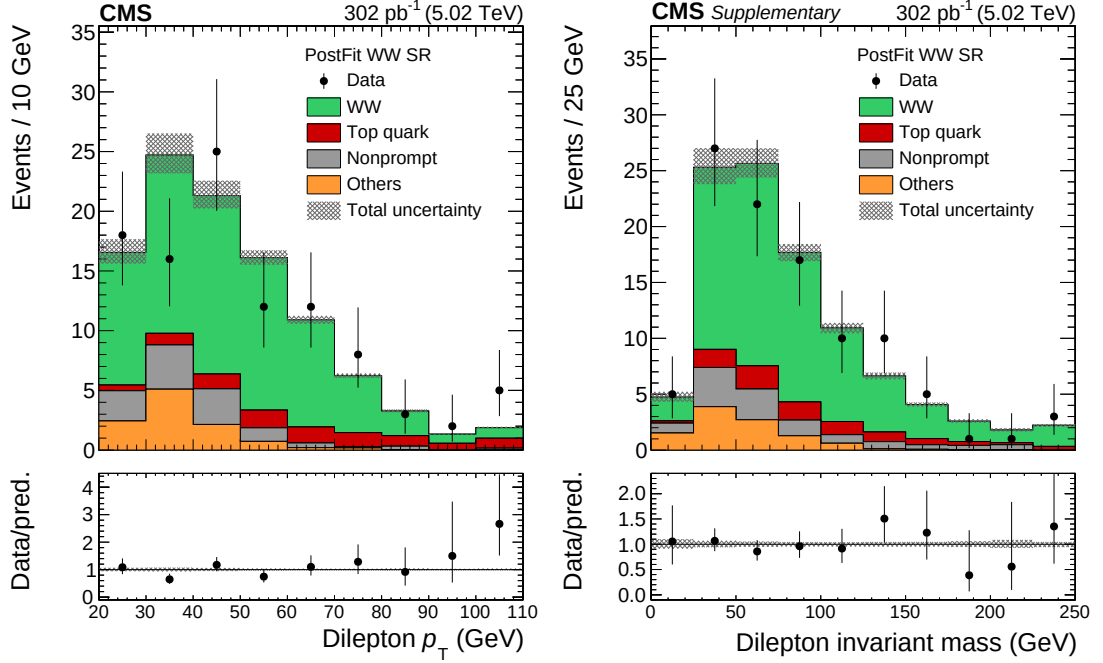


FIGURE 4.12: Expected and observed distributions of two high level variables used for the definition of the WW SR. (Left) reconstructed p_T of the $e\mu$ system. (Right) invariant mass of the $e\mu$ system. All analysis uncertainties are included into the plots at their values after the fit described in Section 4.7.4, meaning that a normalization factor of $k_{\text{WW}} = 1.27$ is applied to the WW signal yields predicted by POWHEG.

The predicted yields at the SR for the signal and all background involving prompt leptons are estimated from MC simulation. The loose-to-tight method described in Section 4.5.1 is used for the prediction, with the slight modification that the MR is defined only in MC due to the limited size of the data sample. A normalization uncertainty of 30% for nonprompt electrons and 15% for nonprompt muons is applied from the level of closure between the loose-to-tight method and the direct MC prediction on the SR.

Separate 10% normalization uncertainties are included for the Drell–Yan and $t\bar{t}$ processes, following estimations in a set of same-flavour and jet enriched control regions (CR). The later closely resembles the recent CMS measurement of $t\bar{t}$ cross section at 5.02 TeV [124] which achieves a similar sensitivity in the measurement of the $t\bar{t}$ production cross section. A 20% normalization uncertainty on residual contributions from non-WW diboson process and a 30% systematic on processes involving asymmetric photon conversions are applied.

4.7.2.2 WZ signal regions

A first WZ SR known as the WZ-3 ℓ SR is defined by requiring the presence of three loose leptons with at least a pair of opposite-sign and same-flavour (OSSF). The W and Z boson decays are reconstructed by assigning each of the decaying leptons to their most likely mother particle. The OSSF lepton pair with a mass closest to the Z boson are known as ℓ_{Z1} and ℓ_{Z2} , ordered by p_T , and are assigned to the Z boson decay. The remaining lepton is known as ℓ_W and is assigned to the W boson decay. As the nonprompt leptons usually appear accompanying $t\bar{t}$ and Drell-Yan production, the single lepton that has opposite charge to the other two is near always prompt. Thus the tight requirements are only applied to the ℓ_W lepton and either the ℓ_{Z1} or ℓ_{Z2} lepton that share its charge sign. Not including the tight requirement for the latest lepton increases the overall efficiency by 10 to 30%, depending on the flavour state, with minimal background presence increase.

Further requirements on the WZ-3 ℓ SR are applied. The minimal p_T of the leptons is required to be of 8 GeV, with a tighter $p_T^{\ell_W} > 20$ GeV criteria further increasing the trigger efficiency and reducing the nonprompt lepton background. To suppress yields from non-resonant processes, the invariant mass of the ℓ_{Z1} and ℓ_{Z2} is required to be consistent with the Z boson mass $|M(\ell_{Z1}\ell_{Z2}) - m_Z^{\text{PDG}}| < 30$ GeV. Finally, the invariant mass of the three leptons has to be off the Z peak mass, $M(\ell_{Z1}\ell_{Z2}\ell_W) > 100$ GeV, to avoid resonant contributions from the $Z \rightarrow \ell\ell\gamma$ process involving an asymmetric photon conversion. Last, to avoid low-mass resonances the invariant mass of any lepton pair is required to be at least 12 GeV. The distribution of the transverse mass of the ℓ_W and p_T^{miss} system and the reconstructed p_T of the Z boson for the WZ-3 ℓ SR is presented in Figure 4.13. While extreme purity is obtained at the tails of the transverse mass distribution, the available statistical power is quite lacking, being the dominant source of any measurement presented at this final state.

Contributions from all SM processes in the WZ-3 ℓ SR are estimated from MC. A 20% normalization uncertainty in the nonprompt yields is estimated in a CR defined by inverting the tight lepton criteria and comparing data and simulation. Small residual contributions from photon conversions include a 30% normalization uncertainty. Other diboson processes include a 20% normalization uncertainty as well based on the expectations on the other measured channels.

In order to improve the sensitivity to the WZ process, a SR with two same-sign tight leptons is also included, the WZ-SS SR, with the idea of recovering events where a lepton falls out of detector acceptance. As selecting electrons introduces sizeable backgrounds from nonprompt and charge misidentified sources, only final states with two muons are used. The tight charge criteria described in Section 4.3.2 is applied to avoid misidentifying the lepton charge. Furthermore, similar criteria to the WW region is followed to avoid the nonprompt background and ensure trigger efficiency. The p_T of the leading (subleading) lepton is required to be over 20 (10) GeV and events with reconstructed jets are vetoed. A minimal $p_T^{\text{miss}} > 25$ GeV requirement further cleans up remaining events from Drell-Yan production plus a nonprompt lepton. As before, the invariant mass of the two leptons is required to be greater than 12 GeV, to avoid the presence of low-mass resonances plus a misidentified lepton charge. The final selection is near background free, but only around 3 signal events survive, with a small nonprompt background which is estimated following the strategy described for the WW SR with a similar normalization uncertainty of 15%.

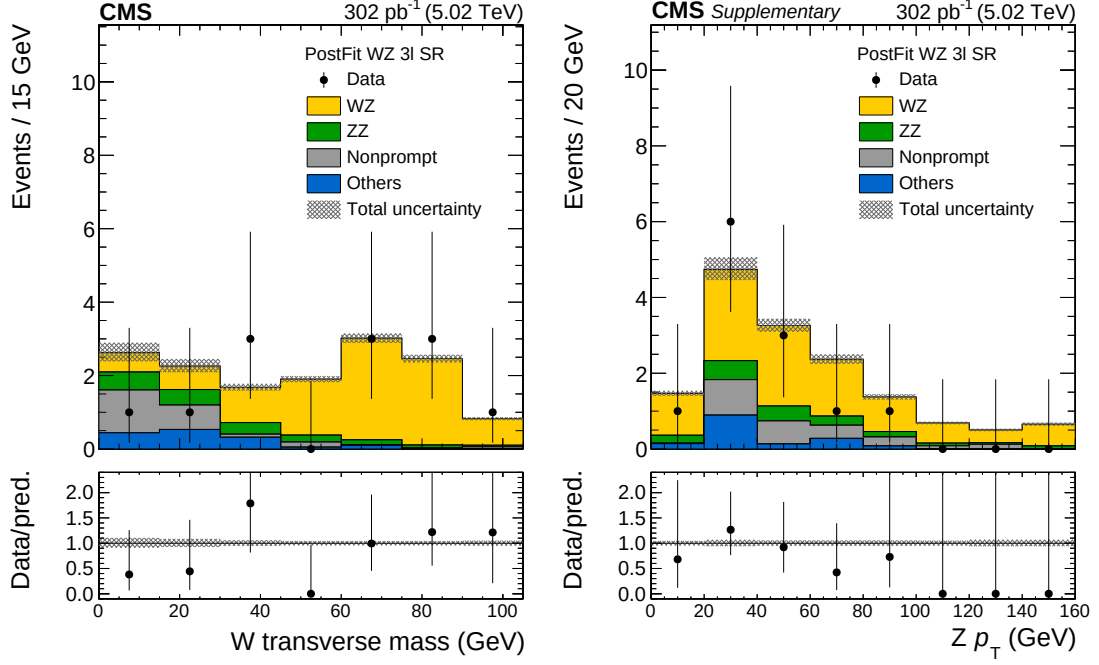


FIGURE 4.13: Expected and observed distributions of two high level variables used for the definition of the WZ-3 ℓ SR. (Left) transverse mass of the system built with the ℓ_W and the p_T^{miss} system. (Right) reconstructed p_T of the Z boson candidate. All analysis uncertainties are included into the plots at their values after the fit described in Section 4.7.4, meaning that a normalization factor of $k_{WZ} = 0.63$ is applied to the WZ signal yields predicted by POWHEG.

4.7.2.3 ZZ signal regions

Last, for ZZ production two different SRs are defined. The ZZ-4 ℓ SR requires the presence of four loose leptons with $p_T > 8$ GeV. The invariant mass of any lepton pair is required to be greater than 12 GeV. While these requirements do not guarantee the presence of a lepton over the minimal trigger threshold for the single lepton triggers, measurements of the trigger efficiency point towards its value being compatible with unity, as double lepton paths are very frequently triggered for events in this selection. With these minimal requirements, the amount of yields present in the ZZ-4 ℓ SR is quite small, as can be seen in Figure 4.14 (left), representing the invariant mass of the four lepton system in this SR. As the resulting region is already quite pure, no further requirements are applied.

To enhance the statistical power of the ZZ-4 ℓ SR, a new region targetting the invisible decay of one of the Z bosons is introduced, the ZZ-2 ℓ 2 ν SR. The branching ratios and combinatorial factors predict around four times more ZZ events in this decay channel, but the much higher background presence requires that additional conditions are applied. Two tight leptons of same-flavour and opposite-sign are requested. As in the other two lepton SRs, the p_T of the leading (subleading) lepton is requested to be greater than 20 (10) GeV to ensure a high trigger efficiency. The invariant mass of the lepton pair is requested to be on the Z peak $|M(\ell\ell) - m_Z^{\text{PDG}}| < 10$ GeV and events with jets are vetoed to reduce contributions from the $t\bar{t}$ background. The presence of the invisible Z can be used to separate the ZZ process from the WW and Drell-Yan contributions. First, a p_T^{miss} compatible with a recoil of similar characteristics as the reconstructed Z is required $|p_T^{\text{miss}} - p_T^{\ell\ell}|/p_T^{\ell\ell} < 0.3$. Second, such quantity is

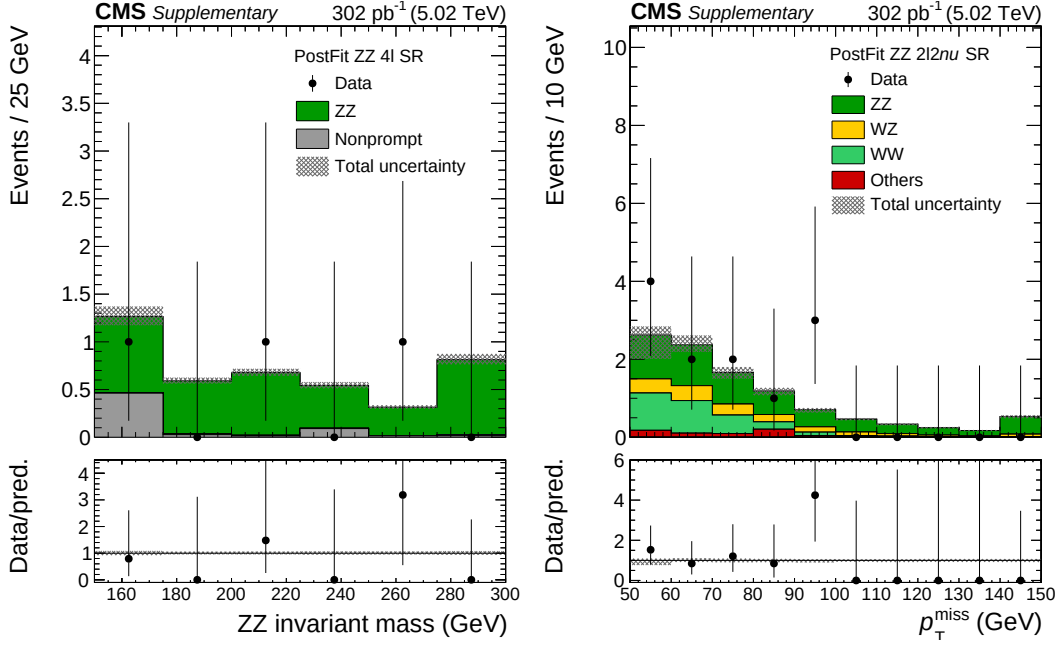


FIGURE 4.14: Expected and observed distributions of two high level variables used for the definition of the two different ZZ SRs. (Left) invariant mass of the four lepton system in the ZZ-4 ℓ SR. (Right) missing transverse momentum in the ZZ-2 ℓ 2 ν SR. All analysis uncertainties are included into the plots at their values after the fit described in Section 4.7.4, meaning that a normalization factor of $k_{\text{ZZ}} = 1.3$ is applied to the ZZ signal yields predicted by POWHEG.

requested to be either significantly big or recoiling with respect to the reconstructed Z by applying $p_{T|\ell\ell}^{\text{miss}} = p_T^{\text{miss}} \cos(\Delta\phi(p_T^{\text{miss}}, p_T^{\ell\ell})) < -50$ GeV. The resulting selection is depicted in Figure 4.14 (right) where it can be seen that the obtained purity is much smaller than in the case of the ZZ-4 ℓ SR but that it still provides a way to recovery significant yields ZZ production. The same background normalization uncertainties as in the WW SR are applied for interpretations of the ZZ-2 ℓ 2 ν SR, with an additional 20% normalization uncertainty on the WW background.

Requirement	WW SR	WZ-SS SR	ZZ-2 ℓ 2 ν SR	WZ-3 ℓ SR	ZZ-4 ℓ SR
N_{ℓ}^{Loose}	2	2	2	3	4
N_{ℓ}^{Tight}	2	2	2	2	0
N_{OSSF}	0	0	1	1	-
N_{OSOF}	1	0	0	-	-
N_{SS}	0	1	0	-	-
$\min(M(\ell\ell')) > 12$ GeV	✓	✓	✓	✓	✓
Lepton p_T (GeV)	$> \{20, 10\}$	$> \{20, 10\}$	$> \{20, 10\}$	$> \{8, 8, 8\}$	$> \{8, 8, 8, 8\}$
Anti- $t\bar{t}$ (1)	$N_{\text{jet}} = 0$	$N_{\text{jet}} = 0$	$N_{\text{jet}} = 0$	$ M(\ell_{Z1}\ell_{Z2}) - m_Z^{\text{PDG}} < 30$ GeV	-
Anti-Drell-Yan (1)	$p_T^{\ell\ell} > 20$ GeV	$p_T^{\text{miss}} > 25$ GeV	$p_{T \ell\ell}^{\text{miss}} < -50$	-	-
Anti-Drell-Yan (2)	$\Delta\phi_{\ell\ell} < 2.8$	Tight charge	$ p_T^{\text{miss}} - p_T^{\ell\ell} /p_T^{\ell\ell} < 0.3$	-	-
Anti-Drell-Yan (3)	$M_{\ell\ell}^2 > 20$ GeV	-	-	-	-
Anti-WW	-	-	$ M(\ell\ell) - m_Z^{\text{PDG}} < 10$ GeV	-	-
Anti-Nonprompt	-	-	-	$p_T(\ell_W) > 20$ GeV	-
Anti-Z γ	-	-	-	$M(\ell_{Z1}\ell_{Z2}\ell_W) > 100$ GeV	-

TABLE 4.5: Summary of all SR definitions used in the 5.02 TeV diboson analysis. The first set of requirements are used to delimit each SR to a specific decay mode of the involved boson pair and apply a minimal selection that has high trigger efficiency. The second set of criteria are applied to increase the purity of each SR designed to reduce specific background processes. A “-” mark means no such criteria of the type are applied.

4.7.3 Additional systematic uncertainties

While all measurements will be limited by the restricted quantity of data taken at 5.02 TeV, and so the statistical uncertainties will be high, several systematic effects are taken into consideration. The ones related to different corrections to simulation presented in Section 4.4, are added to the ones related to the estimation of the main backgrounds that are presented through Section 4.7.2. The following set of uncertainties applies to all predicted MC yields, signal and background, unless otherwise stated

- **Lepton efficiency uncertainties** estimated following the procedure described in Section 4.4.1 for the lepton identification criteria designed for this analysis.
- **Jet energy scale and resolution uncertainties** that are obtained following the description of Section 4.4.5. Only appears for channels with a jet veto (WW SR) or where minimal p_T^{miss} is required (WZ-SS SR and ZZ- $2\ell 2\nu$ SR).
- **Trigger efficiency uncertainties.** As the amount of data makes any trigger efficiency measurement quite challenging, the efficiency is measured in MC following the techniques described in Section 4.4.4 as a function of the trailing lepton p_T . The overall difference between the measured efficiency and unity is applied as a systematic uncertainty.
- **Theoretical uncertainties corresponding to the scale and PDF choice** are included following the prescription of Section 4.2.1 for all signal processes but not for the background ones.
- Uncertainties related to the overall **luminosity** of the 5.02 TeV dataset have been measured by the CMS Collaboration to be at the order of 1.9% [125].
- An additional uncertainty corresponding to the **L1 prefiring issue** is introduced, following the description of Section 3.3.

A summary of all uncertainty sources and their effects on each analysis SR is presented in Table 4.6.

4.7.4 Cross section results

Once all systematic uncertainties are established, the expected and observed yields for each SR and process are presented in Table 4.7.

For each diboson process, a joint likelihood function involving its one or two associated SR is built, following the description presented in Equation 4.16. The different systematic uncertainties are incorporated as nuisances with log-Gaussian prior distributions for all different cases. A maximum likelihood fit is performed for each of the likelihood distributions to extract the best fit values of the signal strength parameters and the different nuisance terms. For the purpose of improving the minimization time and overall fit stability, the Barlow-Beeston approach is used to introduce the terms corresponding to MC statistics, which are joined together into a single nuisance term per bin and minimized analytically in a separate way from the rest of the likelihood

Uncertainty source	WW SR	WZ-SS SR	ZZ-2 ℓ 2 ν SR	WZ-3 ℓ SR	ZZ-4 ℓ SR
Lepton efficiency	2%	2%	2%	3%	2%
Trigger efficiency	3%	3%	1%	0.5%	0.5%
JES	2%	1%	1%	-	-
JES	2%	1%	1%	-	-
Luminosity	2%	2%	2%	2%	2%
L1 Prefiring	1%	1%	1%	1%	1%
Nonprompt e	30%	30%	30%	20%	20%
Nonprompt μ	15%	15%	15%	20%	20%
Misidentified charge	-	20%	-	-	-
Conversions	30%	-	30%	30%	-
$t\bar{t}$	10%	-	10%	-	-
Drell-Yan	10%	-	10%	-	-
Other VV	20%	20%	20%	20%	20%
PDF	1%	1%	2%	1%	2%
μ_R/μ_F	3%	3%	4%	3%	4%

TABLE 4.6: Summary of all uncertainties considered in the 5.02 TeV diboson analysis and their effects on each of the SR considered in the analysis. The effects correspond to the relative variation of the predicted SM yields that are introduced by varying the corresponding uncertainty one standard deviation. Those applied in a single process are only presented as a relative effect in the associated process.

Process	WW SR	WZ-SS SR	ZZ-2 ℓ 2 ν SR	WZ-3 ℓ SR	ZZ-4 ℓ SR
$t\bar{t}$	$9.0 \pm 0.1 \pm 1.1$	-	$0.5 \pm 0.0 \pm 0.1$	-	-
Drell-Yan	$1.8 \pm 0.5 \pm 0.2$	-	$0.2 \pm 0.2 \pm 0.1$	-	-
Other diboson	$5.6 \pm 1.0 \pm 1.1$	$0.1 \pm 0.0 \pm 0.0$	$4.3 \pm 0.1 \pm 0.6$	$1.7 \pm 0.0 \pm 0.1$	-
Conversions	$2.7 \pm 0.7 \pm 0.7$	-	-	$0.9 \pm 0.3 \pm 0.2$	-
Nonprompt e/μ	$11.1 \pm 1.3 \pm 3.4$	$0.5 \pm 0.1 \pm 0.1$	-	$1.2 \pm 0.5 \pm 0.2$	$0.5 \pm 0.2 \pm 0.1$
All backgrounds	$30.4 \pm 1.9 \pm 3.9$	$0.6 \pm 0.1 \pm 0.1$	$4.8 \pm 0.3 \pm 0.7$	$4.0 \pm 0.6 \pm 0.4$	$0.5 \pm 0.2 \pm 0.1$
Signal	$55.2 \pm 0.3 \pm 1.8$	$3.2 \pm 0.8 \pm 0.2$	$4.0 \pm 0.0 \pm 0.2$	$14.8 \pm 0.1 \pm 0.6$	$2.7 \pm 0.0 \pm 0.2$
Data	101	4	12	12	5

TABLE 4.7: Expected and observed yields on each SR of the 5.02 TeV diboson analysis. All uncertainties discussed in Section 4.7.3 are included in the results. The first uncertainty quoted corresponds to contributions from statistical uncertainties, the second corresponds to the sum of all other uncertainty sources. For all signal processes, the normalization corresponds to the one obtained from the POWHEG sample.

[126, 127]. The best fit on the signal yields for the process VV, $N_{\text{SR}}^{\text{VV}}$ and their uncertainties is then obtained from the best fit value of all involved parameters. To obtain the total cross section the well known relationship between the production observed events, cross section ($\sigma(\text{pp} \rightarrow \text{VV})$), and luminosity (L) is inverted to obtain

$$\begin{aligned}
N_{\text{SR}}^{\text{V}_1\text{V}_2} &= \epsilon \text{Br}(\text{V}_1) \text{Br}(\text{V}_2) \sigma(\text{pp} \rightarrow \text{V}_1\text{V}_2) L \Rightarrow \\
&\Rightarrow \sigma(\text{pp} \rightarrow \text{V}_1\text{V}_2) = \frac{N_{\text{SR}}^{\text{V}_1\text{V}_2}}{\epsilon \text{Br}(\text{V}_1) \text{Br}(\text{V}_2) L}
\end{aligned} \tag{4.25}$$

the additional transfer factors $Br(V_1)$, $Br(V_2)$, and ϵ refer to the overall losses of produced events, either through the decay of the vector bosons to non leptonic final states (the branching ratios of the first and second boson, $Br(V_1)$ and $Br(V_2)$) or through the requirements applied in terms of event selection (the efficiency ϵ). The first two are obtained by current world averages [15], but the later need to be measured for each specific diboson process.

To compute the efficiency and the extrapolated cross sections, a concrete definition of what VV production means need to be provided. Due to the mixing of the Z and γ bosons described in Section 2.2.1, all processes involved in Z boson decays will be mixed with non resonant contributions from diagrams with virtual γ^* bosons. The usual agreement to separate the Z from the off-shell γ^* when measuring cross sections is to restrict the total production cross section to a total phase space or total region (TR), where the invariant mass of the Z/ γ^* is close to the peak Z mass m_Z^{PDG} .

For WZ and ZZ, additional requisites are applied in the masses of the generated Z bosons to define the TR. In both cases, final state generated level leptons are dressed with photons in a cone of $\Delta R < 0.1$ following the definition of the RIVET package for dressed leptons [94] which aims to recover the true energy of the particle before FSR radiation. In the WZ case the same lepton tagging algorithm used at the reconstructed level is applied, and a $|M(\ell_{Z1}\ell_{Z2}) - m_Z^{\text{PDG}}| < 30$ GeV requirement is applied on the two leptons matching the Z reconstruction. For the ZZ case, Z boson candidates are formed with all OSSF lepton pairs. The ZZ TR is defined as all events in which two Z candidates fulfilling the $|m_Z^{\text{gen}} - m_Z^{\text{PDG}}| < 30$ GeV condition and built with independent sets of dressed leptons (or generator level neutrinos) appear. The TR for WW production has no requirements imposed.

Once the total regions are defined, efficiencies are measured using the POWHEG MC samples, for each individual channel independently, by dividing the number of events passing the SR criteria over those that pass the TR one. The final values of the total production cross section for WW, WZ and ZZ production at 5.02 TeV are presented in Table 4.8. Results are compared with predictions obtained at fixed order of NNLO in QCD $\times$ NLO in EWK perturbative order following the description of Section 4.2.3 for the treatment of the gluon induced and photon induced contributions.

As expected from the data presented in Table 4.7 small excesses over the predicted cross section are found for WW and ZZ production, while a defect is found for WZ production. Nonetheless, the results are consistent with expectations within one standard deviation for WW and ZZ and within two for WZ production. The high statistical uncertainties presented in the measurement dominate all the different channels and make difficult further optimization which might provide further insight into the apparent effects. A larger dataset taken during the Run 3 of the LHC would help refine these measurements and provide a conclusive answer to these issues.

Figure 4.15 includes a historical comparison of all diboson cross section measurements at the LHC (proton–proton collisions) and TEVATRON (proton–antiproton collisions) experiments with the predictions from MATRIX at NNLO in QCD and NLO in EWK perturbative orders. Measurements presented correspond to the measurements presented by the CDF [128, 129], DO [130–132], ATLAS [133–141] and CMS [3, 142–149] collaborations. The results presented at a centre of mass energy of 5.02 TeV close the gap between the centre of mass energy ranges probed in the past by both experiments.

TABLE 4.8: Observed values of the WW, WZ, and ZZ total production cross sections at a centre of mass energy of 5.02 TeV and the uncertainties in each measurement. The results obtained with fixed order computations from MATRIX at NNLO in QCD and NLO in EWK following the description of Section 4.2.3 for the combination of gluon initiated and photon initiated processes are included. For comparison, the NLO cross sections from POWHEG used to produce the plots in Figures 4.12, 4.13 and 4.14, and yields in Table 4.7 are also shown.

Process		Total cross section
WW	Observed	$37.0^{+5.5}_{-5.2}(\text{stat.})^{+2.7}_{-2.6}(\text{syst.})$ pb
	Expected (MATRIX)	$29.8 \pm 0.7(\text{scale})$ pb
	Expected (POWHEG)	$28.7 \pm 0.3(\text{PDF}) \pm 0.9(\text{scale})$ pb
WZ	Observed	$6.4^{+2.5}_{-2.1}(\text{stat.})^{+0.5}_{-0.3}(\text{syst.})$ pb
	Expected (MATRIX)	$11.3 \pm 0.2(\text{scale})$ pb
	Expected (POWHEG)	$10.1 \pm 0.1(\text{PDF}) \pm 0.3(\text{scale})$ pb
ZZ	Observed	$5.3^{+2.5}_{-2.1}(\text{stat.})^{+0.5}_{-0.4}(\text{syst.})$ pb
	Expected (MATRIX)	$3.5 \pm 0.1(\text{scale})$ pb
	Expected (POWHEG)	$4.1 \pm 0.1(\text{PDF}) \pm 0.2(\text{scale})$ pb

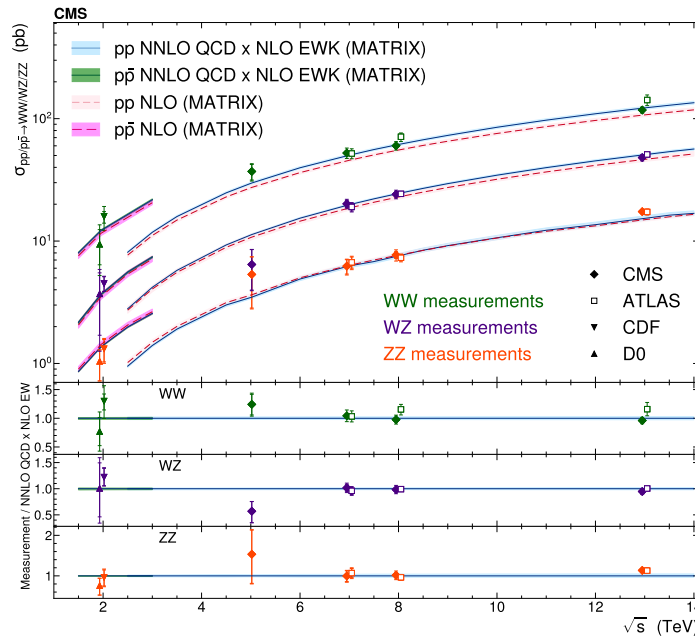


FIGURE 4.15: Expected and observed diboson cross sections obtained with the TEVATRON and LHC colliders at different centre of mass energy values. The expected quantities are obtained with MATRIX and MCFM depending on the process and energy.

4.7.5 Summary

The cross sections of all processes involving a pair of massive electroweak gauge bosons at pp collisions with a centre of mass energy of $\sqrt{s} = 5.02$ TeV are presented for the first time. All decay modes of the bosons that lead to two or more final state

leptons are explored, including some non-standard signatures such as the same-sign and two leptons plus two neutrinos final states that have been used to enhance the sensitivity in the WZ and ZZ cross section measurements.

The resulting measurements close the energy gap in the knowledge of the diboson cross sections between the LHC and TEVATRON measurements, and offer a unique probe for studying diboson production at low momenta at the LHC. The measurements have relative uncertainties of 17% (WW), 40% (WZ) and 50% (ZZ), and correspond to an observation of the WW process at this energy regime. Measurements are dominated by the low statistics corresponding to an overall limited data taking time.

4.8 $t\bar{t}H$ production in multileptonic final states

As a second result that makes use of the techniques discussed for multileptonic analysis, a study of the $t\bar{t}H$ process is presented. As discussed in Section 2.4, the Yukawa coupling of the top quark has an essential role in the hierarchy problem, as the greatest contribution in the big correction terms to the Higgs mass. However, as said mass is smaller than twice the top quark one, no direct $H \rightarrow t\bar{t}$ decay is kinematically allowed for on-shell H bosons in the SM. Thus, direct studies of this quantity must rely on its presence through closed loop contributions or through production modes. In fact, the dominant production mode for the Higgs boson, gg fusion, mainly proceeds through intermediate top quark closed loops, as depicted in Figure 4.16 (left).

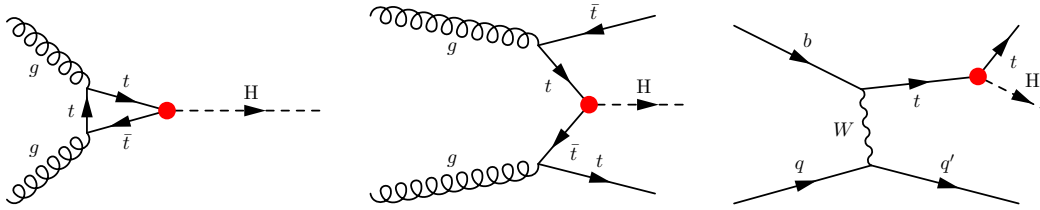


FIGURE 4.16: Example Feynman diagrams for production of the Higgs boson that involve the presence of the top Yukawa coupling at tree level: (left) gg production, (middle) $t\bar{t}H$ production, and (right) tH production. In each diagram, the vertex corresponding to the triple gauge couplings is pointed out in red.

In the case of production modes, the associated production of top quarks with the Higgs boson includes at tree level diagrams that directly involve the top Yukawa coupling, as depicted in Figure 4.16 (middle and right). These final states have quite smaller cross sections than other production modes of the Higgs boson, as depicted in Figure 4.17 (left), but their cross section scales quadratically with the top Yukawa coupling, making them a quite suitable probe to possible anomalies on its value. Additionally, the Higgs boson decays to WW , ZZ and $\tau\tau$ pairs naturally lead to leptonic final states that, when paired with the decays of the top quarks, populates the multileptonic final state topologies. The branching fractions of the H boson to these decay modes are significant, as shown in Figure 4.17 (right), which makes the overall yield contributions in multileptonic final states sizeable enough for these channels to be competitive with the hadronic final states. As the later tend to include near overwhelming contributions from high cross section backgrounds such as $t\bar{t}$, multileptonic $t\bar{t}H$ and tH (including tHq and tHW) production is an attractive mix of production modes and decays to study experimentally.

Historically, results from the CMS collaboration were published with each successive data taking year in multileptonic $t\bar{t}H$ production [6–8] and tH production with the 2016 only and the full Run 2 data [8, 151]. The first observation of $t\bar{t}H$ production in any final state was obtained through the combination of results in different channels in Reference [9]. The ATLAS collaboration provided similar results in References [152] (multilepton 2016), [153] (multilepton 2016 and 2017), and [154] (combination of final states in 2016–2017, observation). The results presented here correspond to the latest result in the multilepton channel by the CMS experiment, Reference [8], and focus on the study of the $t\bar{t}H$ signal only which corresponds to the work I developed inside the corresponding working group. While my focus was on the developing of

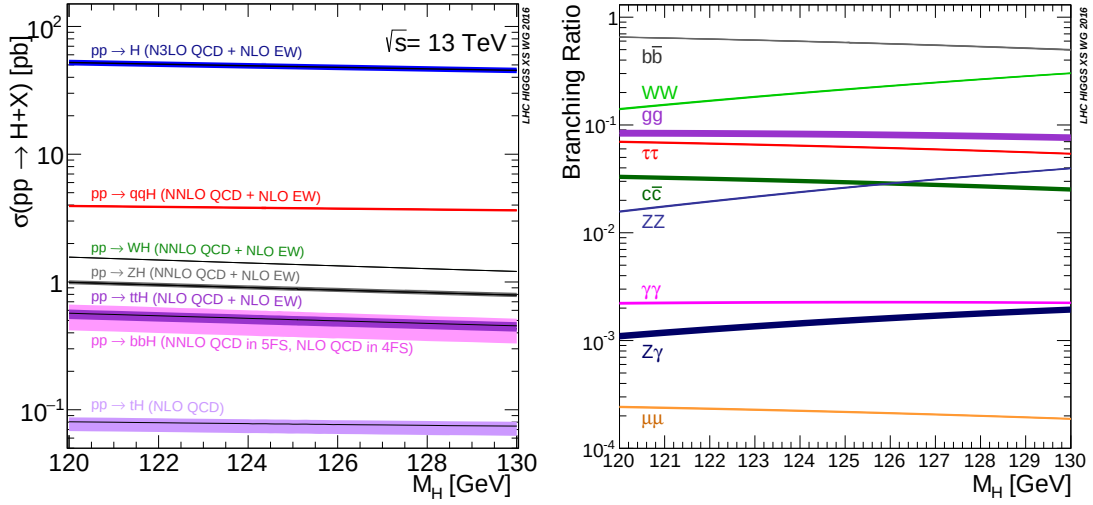


FIGURE 4.17: Production mode cross sections (at 13 TeV in pp collisions, left) and decay mode branching ratios (right) of the Higgs boson as a function of its mass. Figures are available in Reference [150].

the alternative signal extraction strategy, or control analysis, the main details of the background extraction procedure and the nominal signal extraction are included in order to provide a complete picture of the signal extraction and a comparison between the obtained results.

4.8.1 Analysis strategy

In order to retain as much sensibility as possible, the analysis follows a exhaustive strategy in which near all multileptonic signatures involving both light and τ_h leptons are combed. The analysis is divided into ten different channels depending on the multiplicity of τ_h and light leptons, and the charge of the light lepton system. This includes the following categories

- Categories without τ_h : with two light leptons with the same charge ($2\ell_{SS} + 0\tau_h$), three light leptons ($3\ell + 0\tau_h$), or four light leptons ($4\ell + 0\tau_h$).
- Categories with one τ_h : with one light lepton ($1\ell + 1\tau_h$), two light leptons with the same charge ($2\ell_{SS} + 1\tau_h$), two light leptons of opposite charge ($2\ell_{OS} + 1\tau_h$), or three light leptons ($3\ell + 1\tau_h$).
- Categories with two τ_h : with no light leptons ($1\ell + 2\tau_h$), one light lepton ($1\ell + 2\tau_h$), or two light leptons ($2\ell + 2\tau_h$).

As the $t\bar{t}H$ process has a relatively low cross section, in all the quoted categories the presence of $t\bar{t}H$ yields is dominated by higher cross section backgrounds. Once the more trivial selection criteria based on the expected jet multiplicity are applied, those backgrounds correspond to either $t\bar{t}$ production with additional nonprompt leptons, $t\bar{t}W$ and $t\bar{t}Z$ production (all prompt lepton final state), WZ and ZZ production (all prompt final state), or—in the case of categories with only two total leptons— $t\bar{t}$

production. Thus, the analysis strategy is designed with the objective to separate the relatively small contributions from $t\bar{t}H$ from these other background processes. As discussed, the following description will focus on the first item of the list, multileptonic categories, with a thorough description of the treatment for the rest being available in Reference [8].

4.8.1.1 Objects and triggering

On the multileptonic part of the analysis, the background originating from $t\bar{t}$ production plus an additional nonprompt lepton is specially problematic. Thus, the lepton selection strategy presented in Sections 4.3.2 and 4.3.3 proves an invaluable tool to reduce this source of uncertainty. Profiting from the increased total statistics that are available with the Run 2 datasets, a tight lepton identification criteria is employed, as described in Table 4.9. While the criteria is quite stringent, specially for electrons where around half of the prompt ones are lost, the reduction of the nonprompt background yields by two orders of magnitude is needed in order to later provide precise measurements of the $t\bar{t}H$ process.

Selection	t $\bar{t}H$ lepton ID			
	Loose e (t $\bar{t}H$)	Loose μ (t $\bar{t}H$)	Tight e (t $\bar{t}H$)	Tight μ (t $\bar{t}H$)
Based on	Loose e	Loose μ	Loose e	Loose μ
Nearby jet b Tag	<Medium WP	<Interp. WP (<Medium WP)	<Medium WP	<Medium WP
$p_T(\ell)/p_T(\text{close by jet})$	<0.7 (-)	<0.5 (-)	-	-
Charge consistency	In $2\ell SS + 0\tau_h$	In $2\ell SS + 0\tau_h$	In $2\ell SS + 0\tau_h$	In $2\ell SS + 0\tau_h$
LeptonMVA	< 0.80(> 0.80)	< 0.85(> 0.85)	> 0.80	> 0.85
Efficiency	65–75%	95–100%	40–60%	85–95%

TABLE 4.9: Common identification and isolation criteria applied to select electrons and muons in the 13 TeV $t\bar{t}H$ analysis for the loose and tight working points. Requirements marked with a - sign are not applied at all for the correspondent selection level. The based on row refers to the generic identification criteria presented on Tables 4.2 and 4.3 that the 13 TeV requirements are based on. Measured ranges of efficiency, depending on p_T and η , are presented for each working point. For the case of the loose leptons, some requirements are tightened if the lepton does not pass the tight leptonMVA requirement in order to optimize the loose definition for the nonprompt background estimation as introduced in Section 4.5. The b tagging requirements in the closest jet to the lepton use WP criteria as defined in Section 4.3.1, where <Interp. WP refers to a linear interpolation of the b tagging discriminant from the medium WP at a lepton p_T of 20 GeV to the loose WP at a lepton p_T of 45 GeV. The charge consistency requirement is only applied in the $2\ell SS + 0\tau_h$ category, where otherwise sizeable contributions from the charge misidentified background would appear.

Reconstructed jets are required to have $p_T > 25$ GeV and $|\eta| < 5.0$. Those that fall within the problematic HCAL region described in Section 3.3.1, are required to have $p_T > 60$ GeV instead to avoid the effects of the HCAL noise. Only jets with $|\eta| < 2.5$ are considered for b tagging and category classification, with the rest being used only in the training of several MVA discriminants to obtain further sensitivity to $t\bar{t}H$ production. B tagging criteria is used extensively through the analysis, due to the expected presence of at least two b jets from the decays of the top quarks presented in the signal. Two different WPs of the DeepJet algorithm, introduced in Section 4.3.1, corresponding to mistag rates of 11% (loose) and 1.1% (tight) are used. Jets with

$|\eta| > 2.5$ are characteristic of tH production and are collectively labelled as forward jets.

Additional object definition criteria includes the usage of the redefinition for the p_T^{miss} variable in the data and MC corresponding to the 2017 data taking year that was introduced in Section 3.3.1, and the correction of the MC simulation using the per-jet and per-photon weights used to correct for the L1 prefiring issue described in Section 3.3.1. The selection of hadronic taus, a criteria used only to orthogonalize with respect to the other categories, are identified using the DeepTau algorithm discussed in Section 4.3.4. In the following sections the term leptons is used to refer to electrons and muons, as τ_h presence is always vetoed in the different categories discussed.

Events in the multileptonic signal regions are triggered following the strategy stated in Section 4.1, using a common selection of all single and double lepton trigger paths available on each of the data taking years.

4.8.2 Nominal and control analysis

Two complementary strategies are followed for all the separation of the signal processes from each of the three categories with no hadronic taus involved. The first, or nominal analysis (NA), aims to offer the maximum possible discriminant power between the $t\bar{t}H$ and tH signals and the multiple background contributions through the usage of powerful multiclassifiers based on machine learning (ML) algorithms. The second, or control analysis (CA), aims to provide a baseline selection which sacrifices some part of the overall discriminant power in favour of easier reinterpretability of the result. Both approaches are used later to perform the estimation of the $t\bar{t}H$ production rate separately.

4.8.2.1 $2\ell\text{SS} + 0\tau_h$ category

The $2\ell\text{SS} + 0\tau_h$ category is defined by the presence of a pair of light leptons with the same-sign. The p_T of the leptons is required to be above 25 GeV (leading) and 15 GeV (subleading) in order to remain in a region with high trigger efficiency. Additional selection criteria are applied in order to improve the purity of the selection. At least 3 jets are required to appear, according to the minimal jet multiplicity appearing in H production diagrams involving a final state same-sign pair, which also reduces significantly contributions from diboson processes. The invariant mass of the lepton pair is requested to be off the Z peak ($|M(\ell\ell) - m_Z^{\text{PDG}}| > 10$ GeV) to reduce contributions from Drell-Yan production with a mismeasured lepton charge. To mimic the infrared-safeness requirements of the MC and also eliminate residual effects from low-mass resonances, it is also required that $M(\ell\ell) > 12$ GeV. At least one tight b tagged jet or two loosely b tagged ones are required, targetting the b quarks on the decay of the tops for tH and $t\bar{t}H$ production and further reducing the diboson background. Finally, the L_D quantity is defined as

$$L_D = 0.6p_T^{\text{miss}} + 0.4H_T^{\text{miss}} \quad (4.26)$$

where H_T^{miss} is defined as the magnitude of the vector sum of all selected electrons, muons and jets. It has been found that L_D provides a more robust discrimination against background processes in which sizeable contributions to the p_T^{miss} arise from resolution effects than the usual p_T^{miss} definition. Thus, a minimum requirement of $L_D > 30$ GeV is applied. The selected events are then further divided into three different categories depending on the lepton flavour: ee , $e\mu$, and $\mu\mu$.

The nominal analysis uses artificial neural networks (ANN) [155] to build a powerful set of discriminants that separate the $t\bar{t}H$ and tH signals from the different background contributions. A multiclassifier approach is chosen, in which for each event four different scores corresponding to the $t\bar{t}H$, tH , $t\bar{t}W$, and *other* nodes are computed. This approach is chosen in order to separate both the signals from the different background sources and between themselves, in order to improve the resolution to the tH measurement. A separate node for the $t\bar{t}W$ background doubles as an additional control region for the same process, which is difficult to define otherwise due to its quite similar behaviour to the $t\bar{t}H$ process in the $2\ell\text{SS} + 0\tau_h$ final state. The *others* node includes all other minor background contributions. Selected events are assigned to the node with the higher score, forming four additional subcategories of the $2\ell\text{SS} + 0\tau_h$ category. For each event, the node score is distributed in bins of equal background content, and the result is used as a discriminating variable to include in the signal extraction fits. This strategy finally produces twelve different distributions, corresponding to the four output nodes and three flavoured final states. These distributions added up across flavour categories in the signal sensitive $t\bar{t}H$ node are shown in Figure 4.19 (left) for illustration. Other distributions are available in Reference [8].

The ANN are trained with MC samples corresponding to each trained node, with the others one including $t\bar{t}$ (nonprompt), $t\bar{t}Z$, WZ , ZZ and VH contributions. A total of 36 variables corresponding to lepton kinematics and angular distributions, and jet kinematics and b tagging of up to four leading jets (including forward jets), the L_D discriminant and dedicated taggers to identify hadronic top quark and Higgs boson presence are included as training inputs

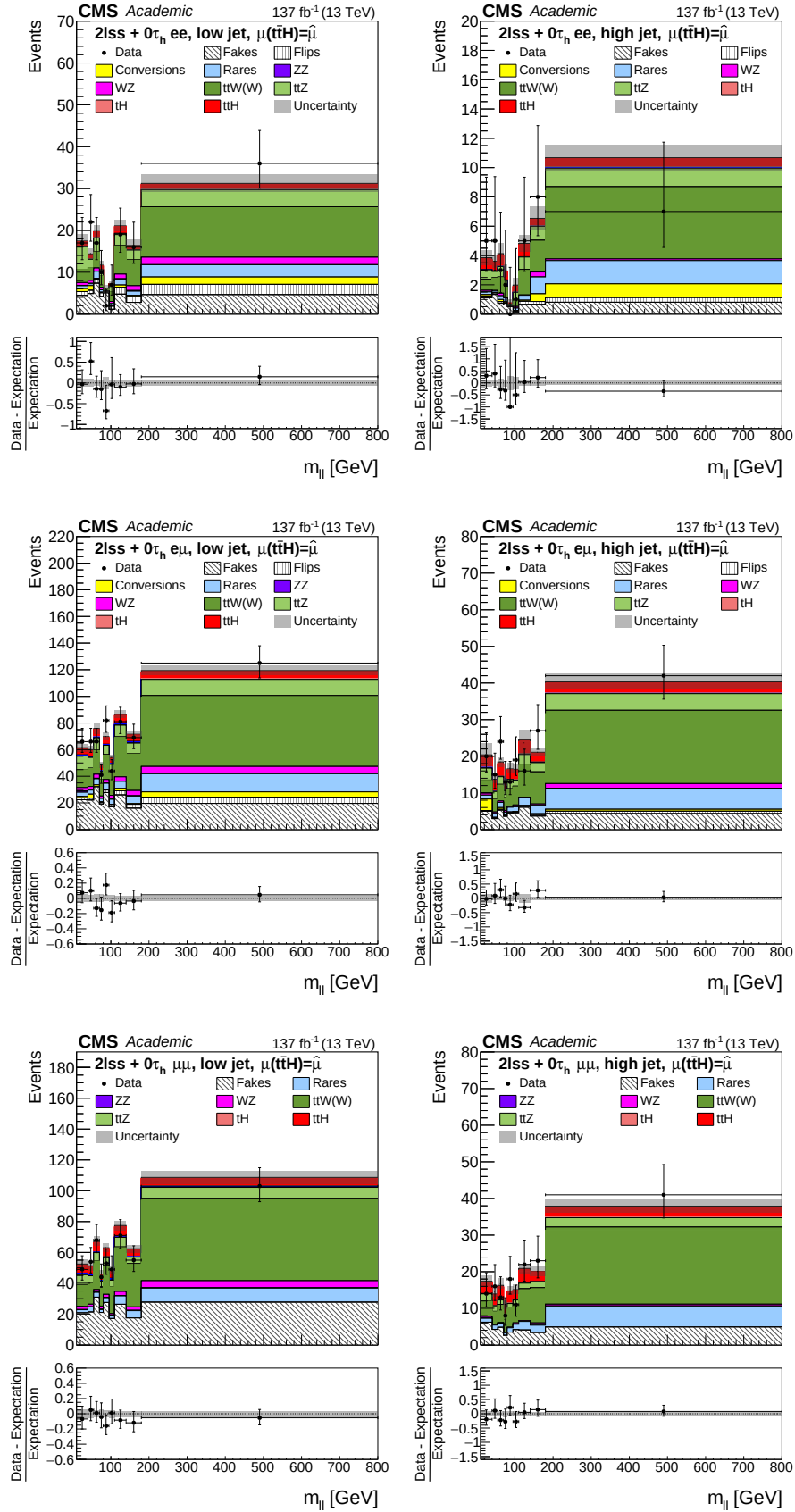


FIGURE 4.18: Observed and expected distributions of the $M(\ell\ell)$ variable in the different categories corresponding to the control $t\bar{t}H$ analysis in the $2\ell\text{SS} + 0\tau_h$ final state. From left to right: low jet and high jet subcategories. From top to bottom: ee , $e\mu$ and $\mu\mu$ final states. All nuisances and free parameters are evaluated at their postfit values after the CA fit described in Section 4.8.4.

The control analysis, in turn, focuses on the usage of a cut-based approach in order to separate the $t\bar{t}H$ signal from the different backgrounds contributions, with no intention to provide significant sensitivity to the challenging tH production mode. The same selection criteria as in the nominal analysis are used, with an exception on the jet multiplicity that is tightened to the presence of at least 4 reconstructed jets as the tH process is no longer a target. The counterpart to the addition of several analysis nodes is the usage of further subcategorization. Each of the flavoured categories is split first according to the final state lepton charge (+2 or -2) to profit from the asymmetry of the $t\bar{t}W$ and WZ backgrounds which are produced in greater quantities with a positive final charge. Then, each subdivision is further split according to the jet multiplicity into the high jet (six or more jets) and low jet (four or five jets) subcategories. The high jet categories serve as a signal-enriched final state akin to the $t\bar{t}H$ selection node, while the low jet categories include further contributions from the $t\bar{t}W$ and nonprompt backgrounds, which tend to produce less jets than $t\bar{t}H$.

On each of the categories, the invariant mass of the dilepton system, the $M(\ell\ell)$ variable, is found to provide decent separation between the $t\bar{t}H$ signal and several of the background processes. By construction, the variable peaks at high values for high activity processes in which leptons are strongly boosted, such as $t\bar{t}t\bar{t}$ and VVV production. In the case of $t\bar{t}H$, one of the leptons tends to appear in the $H \rightarrow WW^* \rightarrow \ell\nu q\bar{q}'$ decay chain, which, if proceeding from the off-shell W tends to be quite soft, the other lepton, from a top quark decay is relatively harder. In contrast, one of the leptons in the $t\bar{t}W$ and $t\bar{t}Z$ appears due to the decay of an on-shell W or Z boson which is accompanied as well by a hard lepton from a top quark decay. As a result, the overall leptonic energy tends to be higher for $t\bar{t}W$ and $t\bar{t}Z$. The invariant mass $M(\ell\ell)$ serves as a reasonable proxy to the energy and so it profits from this behaviour to separate the $t\bar{t}H$ signal from the $t\bar{t}W$ and $t\bar{t}Z$ backgrounds.

A binning strategy of the $M(\ell\ell)$ variable is defined such that the presence of signal on each selected bin is approximately constant, thus ensuring minimal statistics in all of the selected bins. The final distributions used in the control analysis for the $2\ell SS + 0\tau_h$ category are shown in Figure 4.18.

4.8.2.2 $3\ell + 0\tau_h$ category

The $3\ell + 0\tau_h$ category is defined by the presence of exactly three light leptons. To match the trigger requirements, p_T values greater than 25, 15, and 10 GeV are required from the leading, subleading and trailing lepton. Additional requirements are applied as a preselection. As the possible decays of the $t\bar{t}H$ process do not include three leptons of the same charge, the total leptonic charge is restricted to be ± 1 . As for the case of the $2\ell SS + 0\tau_h$ category, at least two jets with one tight b tagged jet or two loosely b tagged jets are required based on the expected object multiplicity of the $t\bar{t}H$ and tHq decays producing three leptons. To reduce the relatively high presence of the $t\bar{t}Z$ and WZ backgrounds, no OSSF lepton pair is allowed to be consistent with the Z peak ($|M(\ell\ell) - m_Z^{\text{PDG}}| > 10$ GeV). The usual infrared-safe requirement of $M(\ell\ell) > 12$ GeV is also applied. A final requirement on the L_D discriminant is applied if the jet multiplicity is 4 or less, in order to reduce the ZZ and residual Drell-Yan+nonprompt lepton contributions. If no OSSF lepton pair is found $L_D > 30$ GeV is applied, if at least an OSSF lepton pair is found, $L_D > 45$ GeV is used instead. The resulting events

are then subcategorized depending on the multiplicity of tight b tagged jets into the b loose (one tight b tagged jet) and b tight (two or more tight b tagged jets) categories.

The nominal analysis once again is based on an ANN multiclassifier to separate the $t\bar{t}H$ and tHq signals from the background. As no significant contribution from the $t\bar{t}W$ background is present in the SR and the other major backgrounds corresponding to WZ and $t\bar{t}Z$ production can be validated easily in sideband control regions, a single background node is included this time. Thus, a $t\bar{t}H$, tHq , and *others* nodes are defined. As the *others* node has significant statistical power, it is further subcategorized according to the lepton flavour final state into the eee , $ee\mu$, $\mu\mu e$, and $\mu\mu\mu$ categories. In total, 11 subcategories are used, as the eee final state proved to have too small statistics for the b tagging splitting criteria in the *other* node. As in the $2\ell SS + 0\tau_h$ case, the value of the ANN in each node is distributed into several bins of equal background content to define discriminant distributions, an example of which for the $t\bar{t}H$ node adding the b tight and b loose categories is shown in Figure 4.19 (right). As for the $2\ell SS + 0\tau_h$ case, samples corresponding to the $t\bar{t}H$ and tHq signals, and a realistic sampling of the backgrounds in the $3\ell + 0\tau_h$ category are used for the training, with a similar set of variables as for the $2\ell SS + 0\tau_h$ case.

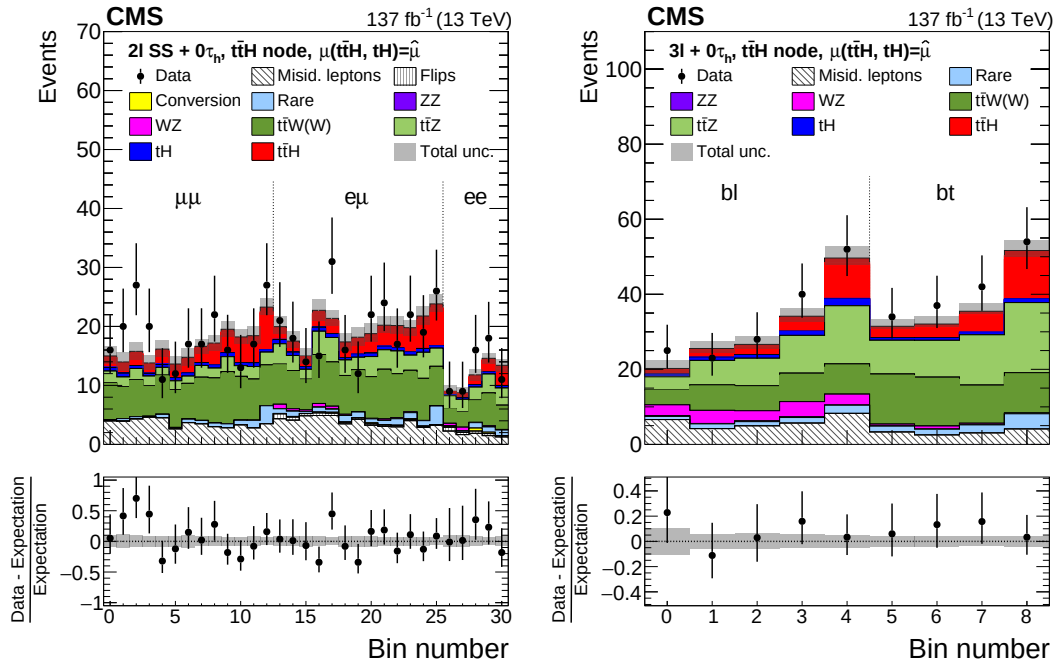


FIGURE 4.19: Observed and expected distributions of the neural network output in the $t\bar{t}H$ node for the nominal $t\bar{t}H$ analysis in the $2\ell SS + 0\tau_h$ and $3\ell + 0\tau_h$ categories. From left to right: $2\ell SS + 0\tau_h$ final state and $3\ell + 0\tau_h$ final state. All nuisances and free parameters are evaluated at their postfit values after the NA fit described in Section 4.8.4.

The control analysis also follows a very similar strategy to the one employed in the $2\ell SS + 0\tau_h$ category, but reduces the final state categorization according to the relatively less available data in the $3\ell + 0\tau_h$ category. The b tagging categories are instead replaced by a new jet multiplicity criteria, to define two new subcategories: high jet (four or more jets), and low jet (two or three jets). The rationale in the classification

is to classify events from the nonprompt lepton background, mostly from $t\bar{t}$ production plus an additional nonprompt lepton, into the low jet category, with the high jet subcategories being dominated by the prompt processes. Then, additional categorization is performed based on the total leptonic charge, as the $t\bar{t}W$ and WZ backgrounds present a notable asymmetry that does not appear in the $t\bar{t}H$ signal. Thus, a total of four final state categories with the combinations of both requirements appear.

The discrimination against the major $t\bar{t}Z$ background, and the minor VVV and $t\bar{t}t\bar{t}$ ones, is obtained using a similar idea to the $M(\ell\ell)$ variable in the $2\ell SS + 0\tau_h$ category. The inclusion of an additional lepton does not break the same reasoning, as in $t\bar{t}H$ production one of the three leptons is likely to appear in an off-shell boson decay still. Thus, the invariant mass of the three lepton system, $M(\ell\ell\ell)$, also provides sensitivity to the $t\bar{t}H$ process which will tend to peak at the lower values. The $M(\ell\ell\ell)$ variable is binned using bins of approximately equal signal presence to define a discriminant distribution on each of the resulting categories. The obtained distributions, aggregated on the final state charge, are shown in Figure 4.20.

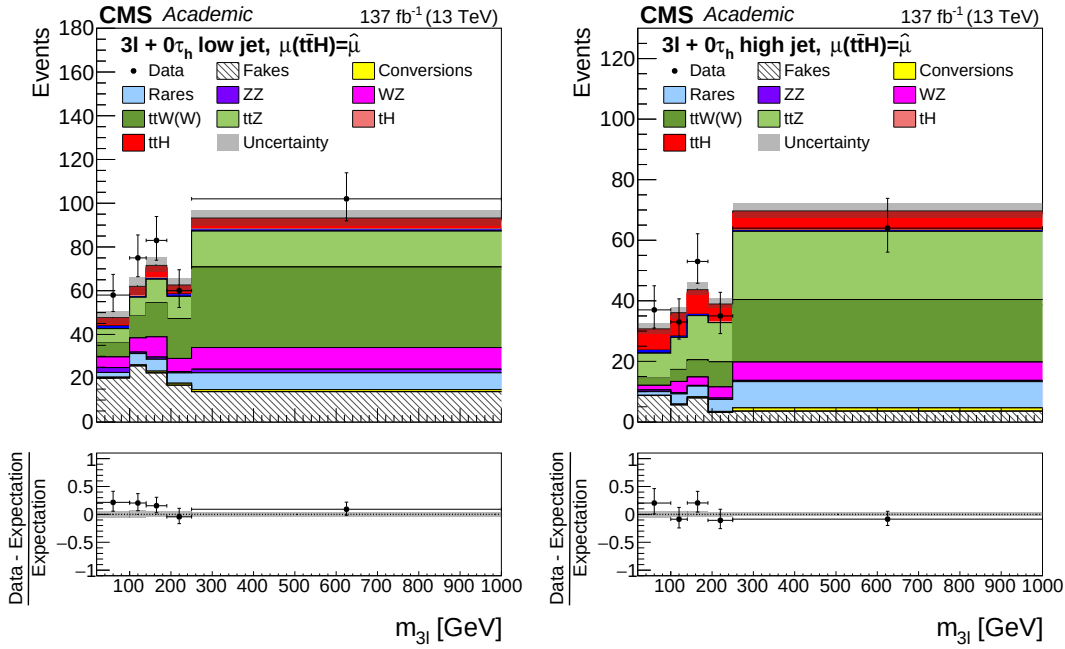


FIGURE 4.20: Observed and expected distributions of the $M(\ell\ell\ell)$ variable in the different categories corresponding to the control $t\bar{t}H$ analysis in the $3\ell + 0\tau_h$ final state. From left to right: low jet and high jet subcategories. All nuisances and free parameters are evaluated at their postfit values after the CA fit described in Section 4.8.4.

4.8.2.3 $4\ell + 0\tau_h$ category

The last of the categories, $4\ell + 0\tau_h$, corresponds to final states with four light leptons. The minimal p_T requirements on the selected leptons are of 25, 15, 15, and 10 GeV from the leading to the trailing lepton. The same jet multiplicity and b tagging requirements as in the three lepton category are applied, based on the $t\bar{t}H$ decay topologies leading to four final state leptons: at least two final state jets, and one tight b tagged jet or two loose b tagged ones. The invariant mass of all OSSF lepton pairs is required to

be off-Z ($|M(\ell\ell) - m_Z^{\text{PDG}}| > 10$ GeV) and a requirement on the invariant mass of the four lepton system $M(\ell\ell\ell\ell) > 140$ GeV is imposed. The perhaps surprising choice for the later, which effectively negates any contribution from the well-known $H \rightarrow 4\ell$ resonance, is motivated by the orthogonalization of the analysis with respect to another one dedicated to the study of such decays [156] with which later combinations in terms of Higgs coupling modifiers are expected. Final selection criteria include the usual infrared-safe requirement of $M(\ell\ell) > 12$ GeV, and a condition on the L_D discriminant following the same criteria as the $3\ell + 0\tau_h$ case.

Both the nominal and control analysis need to deal with the very low expected yields in the $4\ell + 0\tau_h$ category, less than 10 total events, so neither introduces additional subcategorization. The nominal analysis uses a single class BDT discriminant trained in the $t\bar{t}H$ signal against the $t\bar{t}Z$ and ZZ backgrounds. The input variables are the p_T of the four leptons, the L_D discriminant, and the minimum invariant mass of any lepton pair, as well as a boolean tagger on whether the event contains or not an OSSF lepton pair. The resulting discriminant is binned into two bins of equal background content to define the distribution that will enter the signal extraction fit later. This distribution is shown in Figure 4.21 (left).

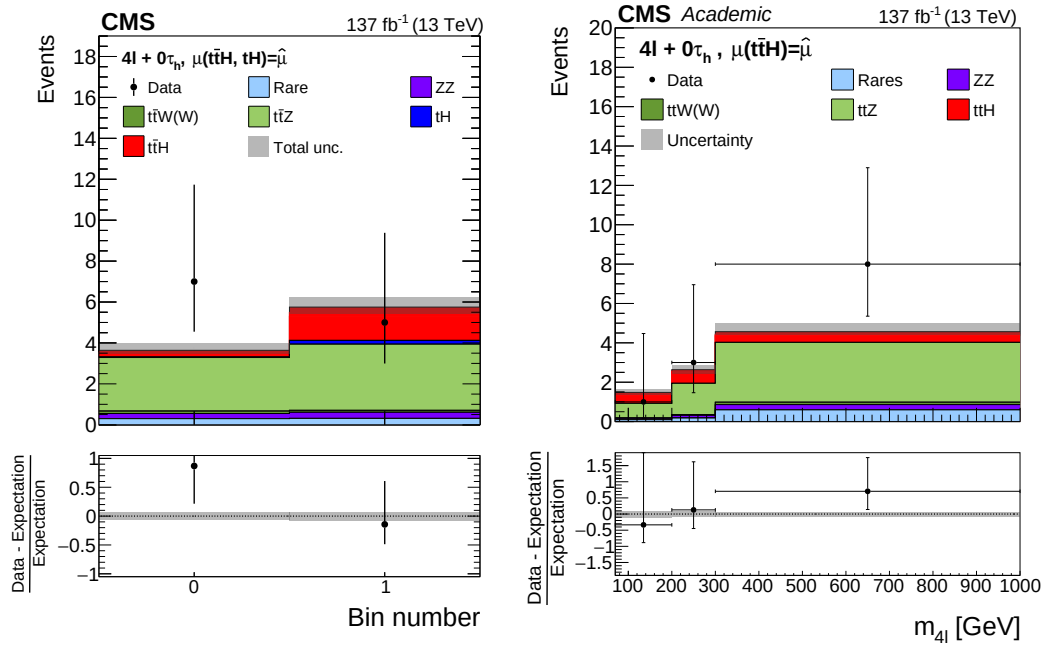


FIGURE 4.21: Observed and expected distributions of the discriminant variables for the different analysis performed in the $4\ell + 0\tau_h$ final state. From left to right: BDT distribution from the NA, and $M(\ell\ell\ell)$ distribution from the CA. All nuisances and free parameters are evaluated at their postfit values after the NA (left) CA (right) fit described in Section 4.8.4.

The control analysis follows a strategy inspired by the approaches presented for the $2\ell\text{SS} + 0\tau_h$ and $3\ell + 0\tau_h$ final states, with the usage of the $M(\ell\ell\ell)$ variable as a discriminant. It is, again, distributed into three bins of equal signal content to define the signal sensitive distribution that will later be supplied to the signal extraction fits. This distribution can be seen in Figure 4.21 (right). A summary of the selection criteria of the nominal and control analysis for all the considered categories is shown in Table 4.10.

Requirement	$2\ell\text{SS} + 0\tau_h$	$3\ell + 0\tau_h$	$4\ell + 0\tau_h$
N_ℓ^{tight}	2	3	4
Lepton p_T	$> \{25, 15\}$ GeV	$> \{25, 15, 10\}$ GeV	$> \{25, 15, 15, 10\}$ GeV
N_j	≥ 3	≥ 2	≥ 2
N_b	1 tight or 2 loose	1 tight or 2 loose	1 tight or 2 loose
$ M(\ell\ell)^{\text{OSSF}} - m_Z^{\text{PDG}} $	> 10 GeV	> 10 GeV	> 10 GeV
$M(\ell\ell)$	> 12 GeV	> 12 GeV	> 12 GeV
L_D	> 30 GeV	Varies	Varies
$\sum_\ell q_\ell$	± 2	± 1	0
$M(\ell\ell\ell)$	-	-	> 140 GeV
NA strategy	ANN	ANN	BDT
NA subcategories	2 signal nodes $\times$ 3 lepton flavour cat. 2 bkg. nodes $\times$ 3 lepton flavour cat.	2 signal nodes $\times$ 2 b tag. cat. 1 bkg. node $\times$ 2 b tag cat. $\times$ 4 lepton flav. cat.	-
NA discriminant bins	116	45	2
CA strategy	$M(\ell\ell)$ bins	$M(\ell\ell)$ bins	$M(\ell\ell\ell)$ bins
Extra CA requirements	$N_j \geq 4$	-	-
CA subcategories	2 charge cat. $\times$ 2 jet multiplicity cat. $\times$ 3 lepton flavour cat.	2 charge cat. $\times$ 2 jet multiplicity cat. 1 bkg. node $\times$ 2 b tagging cat.	-
CA discriminant bins	96	20	3

TABLE 4.10: Summary of the definitions of the $2\ell\text{SS} + 0\tau_h$, $3\ell + 0\tau_h$, and $4\ell + 0\tau_h$ categories used in the $t\bar{t}H$ analysis and the different strategies applied for the signal extraction on each one in the CA and NA signal extraction approaches. A - sign means the associated requirement is not applied in the category.

4.8.2.4 Background estimation

Backgrounds related to nonprompt leptons appear through all three multileptonic categories, but are more prominent on the $3\ell + 0\tau_h$ and, specially, in the $2\ell\text{SS} + 0\tau_h$ one. Their estimation is performed through the usage of the loose-to-tight data-driven whose derivation and application is detailed in Section 4.5.1, including explicit figures corresponding to the fake-rate measurement for $t\bar{t}H$ as shown in Figure 4.8. Alternative fake-rates were also measured in $t\bar{t}$ and multijet simulation for the purpose of performing an additional closure check on the nonprompt background estimation, as they contain a quite different composition of nonprompt lepton sources. A comparison of the direct $t\bar{t}$ MC yields prediction with that obtained applying the loose-to-tight method using the $t\bar{t}$ - and multijet-derived fake-rates is performed differentially in the nonprompt lepton p_T . The underlying idea is that the different flavour composition in the originating quark of $t\bar{t}$ and multijet nonprompt leptons could introduce a bias that would translate into a non-closure represented by different distributions in the test. The results are presented in Figure 4.22.

As observed, the loose-to-tight method closes between the MC and the $t\bar{t}$ fake-rate prediction but deviations are seen with respect to the multijet fake-rate derivation for electrons at low p_T . The ratio between the $t\bar{t}$ fake-rate and multijet fake-rate predictions is fitted to a lineal polynomial and the fake-rates measured in data are corrected by this fitted value depending on lepton p_T and η , thus correcting for the effect of the different flavour composition of the nonprompt leptons in the measurement and application region. The overall correction factor is included as a systematic uncertainty in the predicted nonprompt yields.

The background contributions corresponding to leptons with mismeasured charge is also estimated in a data-driven way following the procedure described in Section 4.5.2. Comparing the direct predictions from MC and the measurements obtained with the data-driven estimation applied on the same MC, differences of up to 30% were observed. As a consequence, a 30% normalization uncertainty is included in this background.

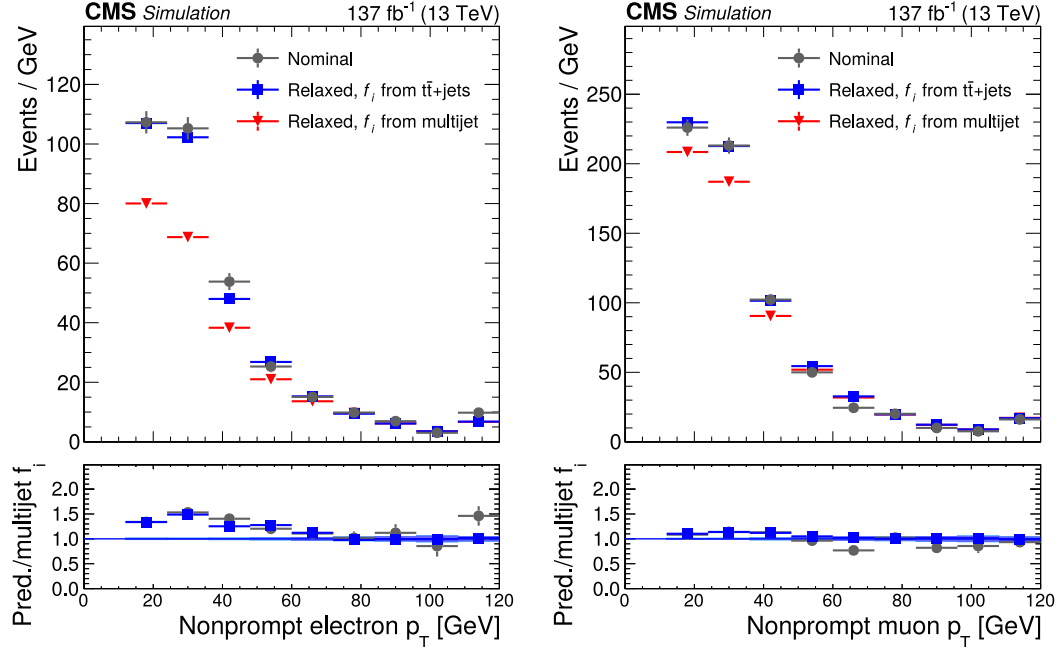


FIGURE 4.22: Closure tests of the loose-to-tight method performed for the nonprompt lepton background estimation in the $t\bar{t}H$ analysis. The direct MC estimation of yields in a $t\bar{t}$ sample is compared with those predicted by the loose-to-tight method using fake-rates derived in $t\bar{t}$ and multijet events. The distributions of the p_T of the nonprompt lepton are shown for final states with: a nonprompt electron (left) and a nonprompt muon (right).

Major background sources corresponding to final states with prompt leptons are estimated using MC simulation. Two different CR are defined in order to study the behaviour of the $t\bar{t}Z$, WZ and ZZ backgrounds.

The 3ℓ -CR is defined with the requirements of the $3\ell + 0\tau_h$ category inverting the Z veto to the request for the presence of a pair of OSSF leptons with an invariant mass compatible with the Z ($|M(\ell\ell) - m_Z^{\text{PDG}}| < 10$ GeV). To enrich the presence of the $t\bar{t}Z$ and WZ backgrounds, only one jet is required to be present and no requisites on its b tagging are applied. Separate sensitivity to both processes is obtained by binning the 3ℓ -CR in jet and tight b tagged jet multiplicity bins. In order to also exploit the CR to study possible differences between lepton flavours, including constraints on lepton efficiency uncertainties, the binned distributions are further separated into the four flavoured states (eee , $ee\mu$, $\mu\mu e$, and $\mu\mu\mu$). The resulting distribution, orthogonal to all signal categories by the Z candidate presence requirement, is included into posterior signal extraction fits in order to constrain uncertainties associated to the $t\bar{t}Z$ and WZ backgrounds. The exact definitions of the binning scheme are detailed in Table 4.11. The distribution of yields across all 3ℓ -CR bins for data and expectations is shown in Figure 4.23 (top left).

The 4ℓ -CR is obtained in a similar way by inverting the Z veto in the $4\ell + 0\tau_h$ category to a Z candidate requirement, the presence of a pair of OSSF leptons compatible with the Z ($|M(\ell\ell) - m_Z^{\text{PDG}}| < 10$ GeV). No a priori requirement on jet or b tagged jet multiplicity is applied to be sensitive to both ZZ and $t\bar{t}Z$ production. To separate both contributions, four different regions are defined. The first bin (bin 0) targets ZZ production and requires the presence of exactly two independent OSSF pairs with

$N_{b,\text{tight}}$	N_{jet}				
	1	2	3	4	≥ 4
0	(0,12,24,36)	(1,13,25,37)	(2,14,26,38)	(3,15,27,39)	
1	(4,16,28,40)		(5,17,29,41)	(6,18,30,42)	(7,19,31,43)
≥ 2	-	(8,20,32,44)	(9,21,33,45)	(10,22,34,46)	(11,23,35,47)

TABLE 4.11: Definition of the binning scheme used in the 3ℓ -CR for the estimation of the WZ and $t\bar{t}Z$ backgrounds in the $t\bar{t}H$ analysis. Each tuple of four numbers relates to the bin number in a corresponding flavoured final state, correspondingly (eee , $ee\mu$, $\mu\mu e$, and $\mu\mu\mu$). The distribution of data and expectation yields corresponding to this binning definition is shown in Figure 4.23 (middle).

$|M(\ell\ell) - m_Z^{\text{PDG}}| < 10$ GeV. The other three bins (bins 1 to 3) require that only one of such a pair appears and include increasingly higher b tagged jet multiplicity from zero to two jets, targetting the transition from the ZZ to the $t\bar{t}Z$ background. The distribution of yields across all 4ℓ -CR bins for data and expectations is shown in Figure 4.23 (right).

On top of the theoretical uncertainties described in Section 4.2.1, additional uncertainties are taken into account for each of the processes. For the case of WZ and ZZ production, its contributions to the SR appear in final states with higher jet multiplicities, where the modelling of the MC highly depends on the PS and might be quite off from the real behaviour of data, so a 30% extrapolation uncertainty for final states with 3 or more jets is included, based on the biggest differences observed between data and prediction in the prefit distributions of the 3ℓ -CR and 4ℓ -CR. Due to the possible existence of unknown contributions to their cross sections from higher order corrections or from BSM processes, the overall WZ, ZZ, and $t\bar{t}Z$ rates are introduced as a free parameters in the signal extraction fits and are determined simultaneously with the $t\bar{t}H$ one.

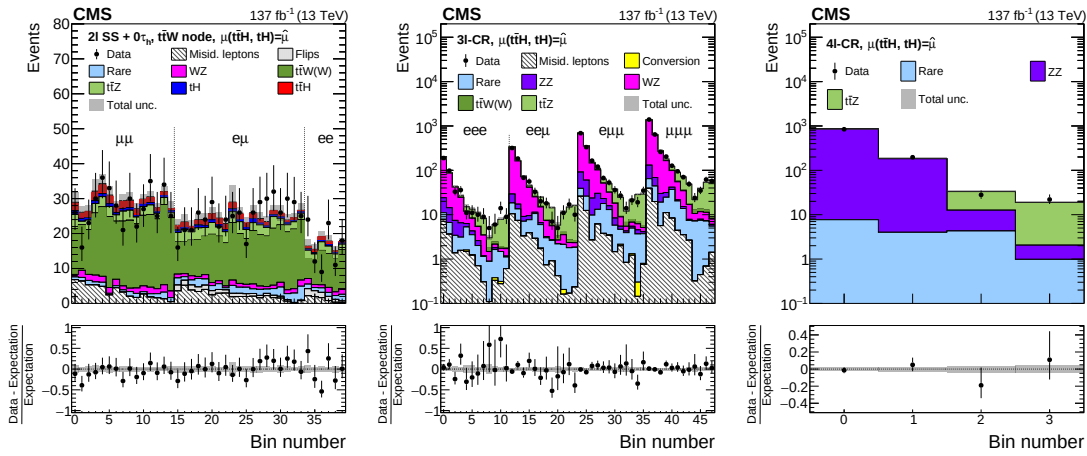


FIGURE 4.23: Expected and observed event yields in the different bins of the $t\bar{t}W$ node of the $2\ell\text{SS} + 0\tau_h$ ANN (left), the 3ℓ -CR (middle) and the 4ℓ -CR (right) used to estimate the behaviour of the $t\bar{t}W$, WZ, ZZ, and $t\bar{t}Z$ background in the $t\bar{t}H$ measurement. All nuisance parameters corresponding to systematic uncertainties and all free floating parameters including into the NA fit described in Section 4.8.4 are included at their postfit values.

The case of the $t\bar{t}W$ background is more complex, as at the phase space presented by this analysis EWK corrections to the cross section are expected to have a non negligible effect. As for many processes with charged final states, the structure of the $t\bar{t}W$ production mode is strongly hierarchical, with $q\bar{q}$ contributions only appearing through additional quark emission, at NLO in perturbative QCD. Thus, the mixed QCD+EWK emission terms might become relatively big, as reported in Reference [157]. On top of the sample produced at NLO perturbative order in QCD described in Section 4.2, additional ones corresponding to the QCD+EW mixed terms are also included to study the shape of higher order corrections, and the overall $t\bar{t}W$ cross section is taken from the NLO+next-to-leading-logarithm (NNLL) resummed result from Reference [158]. Due to this complexity, and the additional possibility of BSM contributions to its presence, the overall rate of the $t\bar{t}W$ process is also included as a free floating parameter to be fitted simultaneously to the overall $t\bar{t}H$ rate. It is expected that the $t\bar{t}W$ node obtained by the ANN corresponding to the $2\ell SS + 0\tau_h$ category will provide further insight into the behaviour of this background. The corresponding ANN output in this node is presented in Figure 4.23 (left).

Other background processes which contribute to the yields in the different categories, such as those including photon conversions, or other low cross section processes are also modelled using MC and conservative 50% uncertainty is assigned on their normalization. For plotting purposes they are grouped into the conversion (processes including an asymmetric photon conversion), other Higgs (VH, ggH, and qqH) and *rare*s (all other processes) categories.

4.8.3 Summary of systematic uncertainties

On top of the background normalization systematic uncertainties discussed on Section 4.8.2.4, other uncertainties are considered related to the different effects introduced in Sections 4.2.1 and 4.4. The following systematic effects are considered:

- **Lepton efficiency uncertainties** were estimated following the procedure described in Section 4.4.1 for the lepton identification criteria designed for this analysis. However, a non negligible effect appears when translating the corrections derived in the jetless Drell–Yan final state into the jet enriched phase space of the signal categories. This effect is estimated by performing an alternative measurement of the corrections in a $t\bar{t}$ dominated opposite–sign dilepton sideband and using the difference between the two correction as additional uncertainties, ranging between 1 to 2 % per lepton.
- **Jet energy scale and resolution uncertainties** that are obtained following the description of Section 4.4.5. As the analysis makes extensive use of reconstructed jets and so might be specially sensitive to the different uncertainties entering the calibration, the overall uncertainties are split into 11 different sources for the jet energy scales and 6 for the jet energy resolutions which are then partially correlated across years.
- **B tagging efficiency uncertainties** are obtained following the description of Section 4.4.6. Instead of just two single systematic uncertainties summarizing the

effects on the tagging and mistagging criteria, additional uncertainties corresponding to the available statistics in the measurement of the corrections for heavy and light flavoured tagging are included as decorrelated across years.

- **Trigger efficiency uncertainties** are measured with the techniques described in Section 4.4.4 using a reference trigger based on p_T^{miss} criteria and separately for the three flavoured final states in the $2\ell\text{SS} + 0\tau_h$ categories, and $3\ell + 0\tau_h$ and $4\ell + 0\tau_h$ categories. They are decorrelated across years due to the main effect being the available statistics in the reference trigger sideband.
- **Pileup modelling uncertainties** are estimated following the description in Section 4.4.7. They are correlated across years.
- **Theoretical uncertainties corresponding to the scale and PDF choice** are included following the description of Section 4.2.1 as separate sources for all involved SM processes. PDF and scales uncertainties are uncorrelated between themselves. Additionally, theoretical uncertainties on the Higgs branching ratios are applied to all processes including H boson production [150].
- Uncertainties related to the overall **luminosity** of the 13 TeV dataset have been measured by the CMS Collaboration for the 2016, 2017 and 2018 datasets separately [159–161]. They are partially correlated across years, leading to a total 1.8% uncertainty in the luminosity of the Run 2 of the LHC.
- **Data quality correction uncertainties** corresponding to the HCAL failure described in Section 3.3.1 are included. They are evaluated as the difference between including or not in the signal extraction jets reconstructed in the affected area for the 2018 data taking year.
- All **background normalization uncertainties** discussed in Section 5.3 are included.
- **Statistical uncertainties** due the limited size of the application region sideband or of the MC samples are included as uncorrelated across bins and years using the Barlow–Beeston method [126, 127].

4.8.4 Results

Both the NA and the CA follow a fitting strategy based on an extended likelihood fit that includes the 3ℓ -CR, the 4ℓ -CR, and the different discriminant distributions from each of the considered categories. Small differences appear between the two depending on the definition of the fitted free parameters that are explained below.

For the NA analysis, the free floating processes are $t\bar{t}H$, tH , $t\bar{t}W$, $t\bar{t}Z$, WW , and ZZ , meaning that several modifications to Equation 4.16 are introduced as follows

$$L(r_{t\bar{t}H}, r_{tH}, r_{WZ}, r_{ZZ}, r_{t\bar{t}Z}, r_{t\bar{t}W}; \theta) = \prod_{i=1}^{\text{Bins}} \mathcal{P}(d_i; y_i(r_{t\bar{t}H}, r_{tH}, r_{WZ}, r_{ZZ}, r_{t\bar{t}Z}, r_{t\bar{t}W}, \theta)) \prod_{\theta} \Theta(\theta)$$

Parameter (category)	Nominal analysis results	Control analysis results
$r_{\text{t}\bar{\text{t}}\text{W}}(\text{all})$	1.43 ± 0.21	1.08 ± 0.20
$r_{\text{t}\bar{\text{t}}\text{Z}}(\text{all})$	1.03 ± 0.14	0.90 ± 0.14
$r_{\text{t}\bar{\text{t}}\text{H}}(2\ell\text{SS} + 0\tau_{\text{h}})$	1.0 ± 0.3	0.5 ± 0.3
$r_{\text{t}\bar{\text{t}}\text{H}}(3\ell + 0\tau_{\text{h}})$	1.5 ± 0.4	1.3 ± 0.5
$r_{\text{t}\bar{\text{t}}\text{H}}(4\ell + 0\tau_{\text{h}})$	1.3 ± 1.6	1.5 ± 1.5
$r_{\text{t}\bar{\text{t}}\text{H}}(\text{all})$	$0.92 \pm 0.19(\text{stat.})^{+0.17}_{-0.13}(\text{syst.})$	$0.91 \pm 0.21(\text{stat.}) \pm 0.18(\text{syst.})$
$r_{\text{tH}}(\text{all})$	$5.7 \pm 2.7(\text{stat.}) \pm 3.0(\text{syst.})$	-

TABLE 4.12: Measured values of the free floating parameters corresponding to the $\text{t}\bar{\text{t}}\text{W}$, $\text{t}\bar{\text{t}}\text{Z}$, and $\text{t}\bar{\text{t}}\text{H}$ normalization in the NA and CA fits from the $\text{t}\bar{\text{t}}\text{H}$ analysis. The *all* category includes a combination of the three categories with light leptons plus all the others detailed in Section 4.8.1 in the NA approach. In the CA approach, the *all* category only includes the addition of the $2\ell\text{SS} + 1\tau_{\text{h}}$ category.

$$\begin{aligned}
y_i(r_{\text{t}\bar{\text{t}}\text{H}}, r_{\text{tH}}, r_{\text{WZ}}, r_{\text{ZZ}}, r_{\text{t}\bar{\text{t}}\text{Z}}, r_{\text{t}\bar{\text{t}}\text{W}}, \theta) = & r_{\text{t}\bar{\text{t}}\text{H}} y_i^{\text{t}\bar{\text{t}}\text{H}}(\theta) + r_{\text{tH}} y_i^{\text{tH}}(\theta) + r_{\text{WZ}} y_i^{\text{WZ}}(\theta) + \\
& + r_{\text{ZZ}} y_i^{\text{ZZ}}(\theta) + r_{\text{t}\bar{\text{t}}\text{Z}} y_i^{\text{t}\bar{\text{t}}\text{Z}}(\theta) + r_{\text{t}\bar{\text{t}}\text{W}} y_i^{\text{t}\bar{\text{t}}\text{W}}(\theta) + \\
& + y_i^{\text{others}}(\theta)
\end{aligned} \tag{4.27}$$

where y_i^{X} corresponds to the expected yields for process X in phase space bin i , and the first product runs over all signal categories and CR bins. A final combination with other discriminant distributions on the categories with $1\tau_{\text{h}}$ and $2\tau_{\text{h}}$ (*all* combination), is presented as the final result of the nominal analysis as well.

For the CA analysis a similar likelihood is built but no sensitivity is expected to the tH process, so the tH term is merged with the *others* background yields. A combination with the most discriminant of the categories with $1\tau_{\text{h}}$ ($2\ell\text{SS} + 1\tau_{\text{h}}$), is presented as an *all* combination for the CA to be compared with the final result from the nominal strategy. More details on the signal extraction for the $2\ell\text{SS} + 1\tau_{\text{h}}$ are presented in Reference [8].

In both cases, the results are obtained by a simultaneous minimization of the likelihood with respect to all parameters. The resulting measured values of each one are presented in Table 4.12 for both the NA and the CA strategies. For the extraction of the uncertainties on each parameter, the rest of the free floating ones in the fit are treated as unconstrained nuisances. The results show consistency between the two approaches, with slightly better performance from the NA, as expected, but overall similar sensitivities from both.

As an additional result, the significance of the presence of the $\text{t}\bar{\text{t}}\text{H}$ process is computed with respect to the background only hypothesis for both the NA and the CA approach, following the formulae described in Section 4.6.2. The former yields an observed (expected) significance of 4.7 (5.2) standard deviations, while for the later the results are 3.8 (4.2) standard deviations.

4.8.5 Summary

A measurement of the signal strength of the $\text{t}\bar{\text{t}}\text{H}$ production mode at a centre of mass energy of 13 TeV is presented. The results correspond to the analysis of data in multi-leptonic final states, with emphasis in the $2\ell\text{SS} + 0\tau_{\text{h}}$, $3\ell + 0\tau_{\text{h}}$, and $4\ell + 0\tau_{\text{h}}$ final

state. Two different approaches are presented, the more powerful nominal analysis based on a ML approach, and the robust control analysis focusing on a cut-based selection. The final results are comparable, offering a measurement of the overall $t\bar{t}H$ signal strength at the level of 25% uncertainty. These correspond to observed signal significances of 4.7 (3.8) standard deviations for the nominal (control) analysis, with expected sensitivities of 5.2 (4.2) standard deviations.

5

Measurement of WZ production at 13 TeV with the CMS experiment

In this chapter, several measurements related to the associated production of a W and a Z bosons (WZ) are presented. The studies are performed with data taken with the CMS detector at $\sqrt{s} = 13$ TeV during the whole Run 2 period, with a total luminosity of 137 fb^{-1} . The aim of these measurements is to profit from this extraordinarily high available luminosity to scrutinize in detail the WZ process and provide a complete picture of its properties under the SM and extensions based on the EFT formalism.

This chapter is organized as follows. First, a brief motivation and a summary of experimental and theoretical developments on the measurement and modelling of WZ production is presented in Section 5.1. A short description of how the more general techniques described in Chapter 4 are applied to the WZ measurements is presented in Section 5.2. A description of the main sources of background and their estimation methods is introduced in Section 5.3. A summary of all sources of uncertainty with an impact on the different measurements is discussed in 5.4. Section 5.5 presents a precision measurement of the inclusive WZ production cross section and an extended discussion on the relevance of different sets of uncertainties. Section 5.6 discusses the measurement of the charge asymmetry in WZ production, its connection to the initial partonic state. Section 5.7 shows how the later can be profited from to extend our knowledge in more general topics like the structure of the proton through the study of parton distribution functions (PDFs). Section 5.8 describes on the measurement of the polarizations of the W and Z bosons and focuses on the presence of longitudinally-polarized gauge bosons through the studies of the W and Z decays. Section 5.9 provides an interpretation of WZ production in terms of searches for BSM physics represented by quite general EFT theories. A cross check of the analysis results which also provides improved reinterpretability is performed in the form of unfolded differential cross section measurements which are discussed in Section 5.10. Finally, Section 5.11 provides an overall summary of the studies.

This chapter corresponds to the results published by the CMS collaboration in References [3] and [4], the second one completes the first as it involves a four times bigger dataset. In both cases I have led the research effort and my contributions include developing the whole analysis workflow, starting from the preparation of the input data formats and the analysis framework setup up to the optimization of the results presented in both papers and more detailed in this chapter. Of note are also

the optimization of all object selection, and the analysis strategies for the different measurements presented except for the differential one, which I only assisted to. The boson polarization estimations, studies of effects on WZ measurements in PDF constraining and the interpretation of EFT effects in terms of CP-odd operators are all novelty measurements in the channel for the CMS collaboration that I introduced during my research work. Also of technical notoriety, but not detailed on this document, is the development of a new procedure to resimulate BSM signals by applying event reweighting to already simulated SM samples which provides a significant save in computational resources and mostly avoids the effects of lacking statistics in signal production for the presented EFT results.

5.1 WZ production as a probe of the electroweak sector

In Section 4.7 a discussion of the power of diboson processes as probes of the electroweak sector of the SM was introduced. While all the description provided there applies for the WZ process, the peculiarities of WZ production make it specially suited to the study of some of the discussed properties.

At the level of the final state signature, WZ production rests in the middle of diboson processes both in terms on overall cross section, of around 50 pb at 13 TeV, and a relatively clean final state that includes three charged leptons. An important advantage over the higher cross section WW is that, even if the neutrino that appears in the final state of WZ can't be measured, its kinematic properties can be deduced from the measurement of the p_T^{miss} quantity, a property that is not available in WW production where two different neutrinos contribute to p_T^{miss} . Thus, while the full reconstruction of the two bosons is not as easily reachable as in the ZZ channel, WZ still provides a way of reconstructing both massive bosons independently. Several more properties characterize WZ as an interesting production mode.

First, WZ production involves interactions from the charged WWZ vertex that do not contribute to ZZ production and, as the Z appears in the final state, do not interfere with the WWH ones as it is the case in WW production. WZ production is, thus, a crucial handle to study the WWZ vertex both from the SM point of view as the BSM one. Using the EFT formalism, high energy theories can be collapsed at the relatively lower energies of the LHC in effective modifications of the WWZ vertex coupling, represented by EFT theories of dimension 6 which can be examined experimentally. In fact, as the WZ system can be fully reconstructed by quantities measured experimentally, the total energy of the system can be accessed in WZ production. This fact is specially useful when trying to setup additional checks in the validity of the EFT approach, as cut-off techniques such as clipping can be applied directly.

Second, measuring boson polarizations is yet again a test of the Higgs mechanism that provides further insight into the inner workings of the electroweak sector of the SM. In WZ the study of the properties of both the W and Z bosons can be done simultaneously, meaning that the polarization of both the W and the Z can be estimated at the same time. In fact, as the kinematics of both vector bosons can be completely reconstructed at the detector level, powerful probes of the polarization effects can be built and directly compared with observed data.

Last, a point has to be made on WZ production which strongly fixes the composition of initial partonic states. The fact that its final state is charged means that the available partonic initial states that can lead to it in proton–proton production is much more limited than other diboson processes. In fact, at LO in the SM, only $q\bar{q}'$ initial partonic states can produce WZ pairs and only quite specific combinations of them can lead to either W^+Z or W^-Z production, with $q\bar{q}$ initial states only appearing at NLO with additional strong radiation as presented in Figure 5.1. Moreover, the loop induced processes through which initial gg states can produce WW and ZZ pairs don't contribute to WZ production, with gg initial states appearing only when two extra partons are produced with the WZ pair as seen in Figure 5.2. This strongly fixed structure makes it a natural probe for the effects of PDF modelling once enough data is collected to counteract its relative low cross section compared to other competitive modes with similar properties, such as W or Z production.

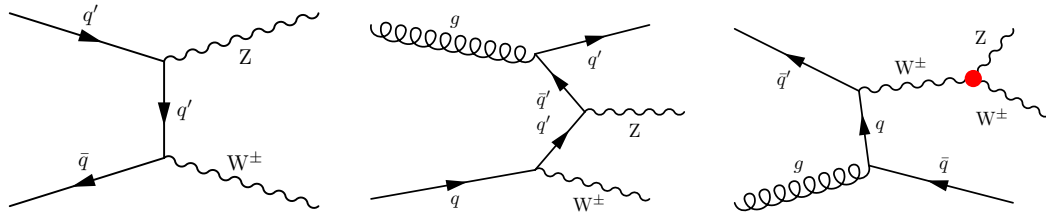


FIGURE 5.1: Feynman diagrams corresponding to WZ production contributing at different orders in QCD. (Left) Example diagram on non-triple gauge coupling production at LO in QCD. (Middle) Example diagram on non-triple gauge coupling production at NLO in QCD with a gluon in the initial state. (Right) Example diagram on triple gauge coupling production at NLO in QCD with a gluon in the initial state.

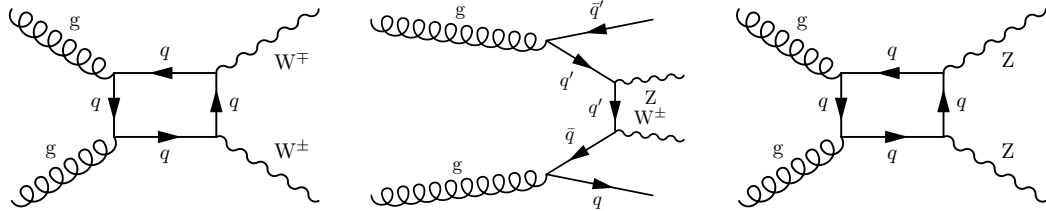


FIGURE 5.2: Feynman diagrams corresponding to the production of boson pairs from initial states with gluon pairs. From left to right: WW, WZ, and ZZ production. Notice that no closed loop-induced diagram is allowed for WZ production, as it would break conservation of the electric charge.

As a brief recall of the history of experimental measurements of the process, WZ was first observed in the multileptonic decay channel in the TEVATRON proton–antiproton collider, with studies performed by the D0 [162] and CDF [163] collaborations at a centre of mass energy of 1.96 TeV. Since then, the LHC experiments have steadily measured its properties as the centre of mass energy of the collider was increased. The ATLAS collaboration has published results at 7 [134, 164], 8 [137], and 13 TeV [140, 165], including both measurements of the inclusive cross sections with relative precisions up to 5%, differential cross sections with respect to several high level observables, EFT interpretations and, more recently, measurements of the polarization fractions of the W and Z bosons. Correspondingly, the CMS collaboration has made similar sets of measurements at each centre of mass energy: 7 and 8 [144], and 13

TeV [3, 4]. The following set of results correspond to the latest two CMS results [3, 4] which can be –except for the increased amount of luminosity included in the later– compared to the latest ATLAS result [140].

From the theory point of view, recent developments in higher order predictions have been made for quite different sets of observables in WZ production. The development of fully differential cross section predictions that combine the effects of the NNLO in QCD and NLO EWK perturbative orders has been achieved by the MATRIX collaboration [95, 102]. Interest on the WZ channel for the estimation of boson polarization fractions crystallized on studies of higher order corrections in polarization observables: NLO in QCD and NLO EWK corrections for single polarized states [166, 167] and NLO QCD corrections for double polarized states [168]. Similarly, effects of NLO QCD corrections in EFT interpretations of WZ production have been recently published [169]. Measurements performed in the WZ channel are, as well, usual participants in EFT global fits [170, 171].

5.2 Analysis strategy

In contrast with the diboson analysis at 5.02 TeV presented in Section 4.7, the measurement performed at 13 TeV profits from a much higher overall luminosity, which leads to the expectation of producing several thousands of WZ events in the multileptonic final state. Thus, while several of the more general methods remain similar, the strategy is much more focused on reducing the different sources of systematic uncertainty rather than increasing as much as possible the efficiency of the signal selection.

This analysis was performed twice during the period of this thesis, the first one an early result using the data from the 2016 data taking year, and the second using the whole statistical power of the Run 2 of the LHC. While the first one was already optimized to provide great sensitivity to the WZ production process, several lessons would be learned that lead to the much more precise second measurement. Thus, while the discussion of this thesis will focus on the results of the second one, comparisons with the first set will provide further insight and reasoning into the strategic choices in terms of object and kinematic selection criteria.

The overall analysis strategy is to define a single SR with high WZ purity and several CR were each of the main background contributions dominates the overall yields. The different signal extraction procedures will focus on different discriminant variables defined in the SR, with the CR included into the signal extraction fits in order to limit the effect of the overall uncertainties assigned to each of the background processes.

5.2.1 Object selection, triggering and data quality checks

As for most measurements in the multileptonic final state, the study of WZ production requires an optimized lepton definition in order to select the high quality isolated leptons that are expected to appear in WZ production. The results from the 2016 analysis, and an earlier 2015 result [172], pointed to the risk of the systematic uncertainties associated to the nonprompt background becoming the dominant source of uncertainty in the analysis. As overall signal efficiency was not as big of a priority

as it was in earlier years, the lepton identification criteria were tightened significantly for the Run 2 results. Based on the lepton selection strategy introduced in Section 4.3, the optimized lepton criteria is presented in Table 5.1. Two sets of criteria are derived, the tight ones will later be used to select leptons through the analysis, while the loose ones are used to define the application region for a data-driven estimation of the non-prompt background as described in Section 4.5.1. A point to be noted is the usage of the charge consistency criteria, which is crucial for later providing a robust estimation of the final state total charge to separately measure the W^+Z and W^-Z cross sections.

13 TeV WZ lepton ID				
Selection	Loose e (WZ)	Loose μ (WZ)	Tight e (WZ)	Tight μ (WZ)
Based on	Loose e	Loose μ	Loose e	Loose μ
Nearby jet b Tag	<Medium WP	<Interp. WP (<Medium WP)	<Medium WP	<Medium WP
$p_T(\ell)/p_T(\text{close by jet})$	<0.7 (-)	<0.5 (-)	-	-
Charge consistency	✓	✓	✓	✓
LeptonMVA	< 0.80(> 0.80)	< 0.85(> 0.85)	> 0.80	> 0.85
Efficiency	65–75%	95–100%	40–60%	85–95%

TABLE 5.1: Common identification and isolation criteria applied to select electrons and muons in the 13 TeV WZ analysis for the loose and tight working points. Requirements marked with a - sign are not applied at all for the correspondent selection level. The based on row refers to the generic identification criteria presented on Tables 4.2 and 4.3 that these requirements are based on. Measured ranges of efficiency, depending on p_T and η , are presented for each working point. For the case of the loose leptons, some requirements are tightened if the lepton does not pass the tight leptonMVA requirement in order to optimize the loose definition for the nonprompt background estimation as introduced in Section 4.5. The b tagging requirements in the closest jet to the lepton use WP criteria as defined in Section 4.3.1, where <Interp. WP refers to a linear interpolation of the b tagging discriminant from the medium WP at a lepton p_T of 20 GeV to the loose WP at a lepton p_T of 45 GeV.

Jets are reconstructed following the anti- k_T algorithm described in Section 3.2.5 and a distance parameter of $\Delta R = 0.4$. All jets are required to have a minimum p_T of 25 GeV and be non-forward jets by applying that $|\eta| < 2.5$. Jets are requested to be separated from any selected tight leptons $\Delta R(\ell, j) > 0.4$. In the 2016 iteration of the analysis the b tagging uncertainties proved to have a major role, due to the relatively high systematic uncertainties in the b tag efficiency estimation for the Medium WP selection. In this new iteration of the analysis, instead, the tight WP of the b tagging discriminant is used, which was found to introduce less uncertainty in b veto regions—expected to contain most of the WZ signal—, with the small drawback of a decrease in the overall vetoing efficiency.

The p_T^{miss} definition follows the overall description presented in Section 3.2.5, with no additional modifications besides the slight redefinition in the 2017 data taking year as explained in Section 3.3.

The triggering strategy follows the description in Section 4.1, events are selected if they pass at least one of the non-5.02 TeV single or double lepton trigger requirements presented in Table 4.1. No significant improvement in performance was observed from the inclusion of the triple lepton triggers over the joint efficiency of the single and double paths.

The approaches presented in Section 3.3.1 to treat data quality issues were applied in the following analysis. The L1 trigger prefiring weights and correction recipe for

p_T^{miss} in the 2017 data taking year are included as described. Dedicated studies using samples that simulated the effects of the malfunctioning HCAL sector probed that the main effect at the analysis level was a small increase in the electron fake-rates that were covered by the existing uncertainties.

5.2.2 Event selection

A first set of requirements are applied to define a preselection region (PR) on which all other selections of the analysis will be based on. The PR requires the presence of exactly three tight light leptons (electrons or muons), with at least an OSSF pair. The same algorithm described in 4.7.2.2 is used to tag the leptons originating from the Z boson decay and the one from the W boson decay. The OSSF lepton pair with the closest mass to the Z boson are named as ℓ_{Z1} and ℓ_{Z2} (ordered by decreasing p_T value). The remaining lepton is named ℓ_W . The transverse momentum of the Z and W boson can then be reconstructed by assuming that the observed p_T^{miss} corresponds to the unseen neutrino from the W boson decay.

Measurements of the trigger efficiency following the strategy presented in Table 4.4.4 show that consistency with a 100% efficiency could be reached by requiring that at least two of the leptons pass the $p_T > 25$ GeV requirement and the last has $p_T > 10$ GeV. By construction, $p_T^{\ell_{Z1}}$ will always need to pass the tighter p_T criteria. It was found that requiring $p_T^{\ell_W} > 25$ GeV provides a significant decrease of the nonprompt background so it was the final criteria used. With these final minimal p_T requirements, the tagging algorithm was found to properly assign the leptons to its parent boson in 95% of the cases, but some mistagging might still occur in the $ee\mu$ and $\mu\mu e$ final states.

The high purity WZ SR (SR-WZ) includes several additional kinematic requirements, quite similar to the ones presented in Section 4.7.2.2, which were originally inspired by these:

- The invariant mass of the ℓ_{Z1} and ℓ_{Z2} lepton pair is required to be on the Z boson peak mass, reducing mostly the presence of non-resonant $t\bar{t}$ production to focus on on-shell Z bosons: $|M(\ell_{Z1}\ell_{Z2}) - m_Z^{\text{PDG}}| < 15$ GeV.
- The invariant mass of the trilepton system is required to be $M(\ell_{Z1}\ell_{Z2}\ell_W) > 100$ GeV, which greatly reduces the presence of $Z \rightarrow \ell\ell\gamma$ production in which the final state photon suffers an asymmetric conversion.
- A minimal requirement on the missing transverse momentum of $p_T^{\text{miss}} > 30$ GeV, representing the missing neutrino of the signal. This criteria reduces the presence of the ZZ and Drell-Yan backgrounds, the later being the main SM processes that composes the nonprompt lepton background. Although no p_T^{miss} is expected from these background processes, a minimal requirement is needed due to the p_T^{miss} resolution effects introduced by the existing pileup in the Run 2 dataset. During the 2016 analysis it was found that p_T^{miss} cut values in the 25 to 35 GeV range were able to provide robust discrimination while simultaneously not being strongly affected by the jet energy scale and pileup uncertainties.
- Events which contain b tagged jets are vetoed, to reduce the prompt backgrounds corresponding to $t\bar{t}Z$ and tZq production. The optimization of the b veto was described in more detail in Section 5.2.1.

- The presence of a fourth loose lepton with p_T of at least 10 GeV is vetoed as well, to reduce the overall presence of the ZZ background.
- To avoid possible contamination of low-mass resonances and simultaneously reproduce the infrared-safe requirement applied in the production of the MC, a minimal requirement in the invariant mass of any OSSF lepton pair of $\min(M(\ell\ell')) > 4$ GeV is applied.

A CR designed to target ZZ production (CR-ZZ) is defined by altering slightly the requirements on the WZ CR. The fourth lepton veto is inverted to the requirement of a fourth tight lepton with $p_T > 10$ GeV instead. For purposes of plotting or computing high level variables, the three leading leptons are used in the CR-ZZ. Additionally, no p_T^{miss} requirements are applied to enhance the efficiency towards selecting the ZZ background.

A top enriched CR (CR-ttZ) is built by inverting the b tag veto to a b tag requirement. All other selection criteria are kept the same as in the SR-WZ.

A final CR dedicated to the photon conversion process (CR-conv) is based on the simultaneous inversion of the p_T^{miss} and $M(\ell_{Z1}\ell_{Z2}\ell_W)$ requirements. The requirement on the invariant mass of the ℓ_{Z1}, ℓ_{Z2} pair is not applied in this CR to enhance the $Z\gamma$ background selection efficiency.

A summary of the SR and CR involved in the analysis is presented in Table 5.2.

Region	N_ℓ	$p_T\{\ell_{Z1}, \ell_{Z2}, \ell_W, \ell_4\}$	N_{OSSF}	$ M(\ell_{Z1}\ell_{Z2}) - m_Z^{\text{PDG}} $	p_T^{miss}	N_b	$\min(M(\ell\ell'))$	$M(\ell_{Z1}\ell_{Z2}\ell_W)$
SR-WZ	=3	$>\{25, 10, 25, -\}$ GeV	≥ 1	< 15 GeV	> 30 GeV	=0	> 4 GeV	> 100 GeV
CR-ZZ	=4	$>\{25, 10, 25, 10\}$ GeV	≥ 1	< 15 GeV	-	=0	> 4 GeV	> 100 GeV
CR-ttZ	=3	$>\{25, 10, 25, -\}$ GeV	≥ 1	< 15 GeV	> 30 GeV	> 0	> 4 GeV	> 100 GeV
CR-conv	=3	$>\{25, 10, 25, -\}$ GeV	≥ 1	-	≤ 30 GeV	=0	> 4 GeV	< 100 GeV

TABLE 5.2: Requirements applied for the definition of the SR-WZ and the three background CR used in the WZ analysis. A - mark means that no requirement in the chosen quantity is applied for the corresponding region.

As the remaining main background process, the nonprompt one, is estimated in a data-driven way no further CR is defined for its validation. Several tests of validity were performed in a low p_T^{miss} CR but, as a result of the tight lepton identification criteria, it was proven to have too many signal contamination to be of any practical use.

5.2.3 Signal modelling

MC estimation is used for the modelling of most SM processes, with the unique exception being that of the nonprompt lepton one. The setup described in Section 4.2 is used for all background processes, but for the signal special care has been taken in order to ensure the independency of the results with respect to the chosen MC simulation used. On top of the usage of the MATRIX framework for comparisons at the generator level, as described in Section 4.2.3, studies presented in this Chapter were performed with two different MC setups.

A POWHEG sample is used as the main MC (nominal sample) for the derivation of all the following results unless otherwise stated in their corresponding sections. It follows

the description presented in 4.2 with the ME computed at NLO in QCD with dynamic factorization and renormalization scales and has been matched to Pythia in order to simulate the showering, hadronization and underlying event.

A MADGRAPH+aMC@NLO sample (alternative sample) is used for cross checks and, when appropriate, derivation of uncertainties through the studies presented. Again, it follows the description in 4.2 for generic MADGRAPH+aMC@NLO samples produced at NLO in QCD and is matched to Pythia in order to simulate the showering, hadronization and underlying event. The full $pp \rightarrow \ell\ell\ell\nu$ process is produced with up to an additional parton at the ME level, for which the FxFx merging scheme [173] needs to be introduced in order to not double count QCD emission events between the ME and PS simulation.

As a final note, the production of WZ pairs plus a jet pair through quartic gauge couplings in vector boson scattering (VBS WZ or EWK WZ) are not included in the signal simulations described but rather treated as a background process. In fact, dedicated simulations performed with MADGRAPH+aMC@NLO are used to estimate their contribution at the SR level. Even if their contributions at the target phase space are small compared with non-VBS WZ, due to the expected precision of the analysis they need to be considered in the background estimations for a consistently precise treatment. Thus, the signal definition involves WZ production plus any additional QCD or EWK radiation except for contributions arising from purely electroweak WZ +jj production.

5.3 Background estimation methods

After the SR-WZ requirements are applied, contributions from several background processes still appear at the selection. Amongst them, the most prominent ones in terms of yield multiplicity correspond to the nonprompt lepton background, and the SM production of ZZ, $t\bar{t}Z$, tZq and $X\gamma$. Additionally, residual contributions from VH, VVV and electroweak WZ production also populate the SR with less than 1% of the overall expected events originating from each one.

5.3.1 Backgrounds with nonprompt leptons

In the specific case of the SR-WZ, events with nonprompt leptons appear mostly due to Drell-Yan + jets events in which at least one additional lepton is produced inside a hadronic jet. A smaller contribution from $t\bar{t}$ production also appears, but is greatly reduced by the b veto requirements applied. The MC simulation of the Drell-Yan and $t\bar{t}$ processes was found to provide a reasonable modelling of the nonprompt background when comparing data and MC in a sideband region defined as the SR-WZ but where at least one of the selected leptons is requested to fail the tight criteria. However, the limited statistical power available on the MC made a data-driven estimation a useful alternative. Thus, the estimation of the nonprompt lepton background is done using the data-driven techniques described in Section 4.5.1. The cone- p_T factors introduced in Section 4.5.1 are estimated to be 0.9 for both electrons and muons.

In addition to the uncertainties related to the fake-rate measurement that were already introduced in Section 4.5.1, additional checks were performed to study possible biases

due to the different proportion of nonprompt leptons coming from different sources in the application and measurement regions. Fake-rates were measured in a multijet and $t\bar{t}$ samples and later applied to $t\bar{t}$ and Drell-Yan events that pass the SR-WZ criteria. The predictions from the data-driven and the multijet MC fake-rate measurements were found to be consistent and lead to slightly lower predicted yields than the ones measured in $t\bar{t}$, hinting towards such a bias. To account for this effect, the data-driven fake-rates were corrected by the difference observed in the fake-rates measured on $t\bar{t}$ and multijet MC. The maximal size of the correction, around a 30%, was taken as an additional normalization uncertainty on the overall nonprompt prediction. The test performed and its results are similar to those described in more detail for the $t\bar{t}H$ analysis in Section 4.8.2.4.

5.3.2 Major backgrounds with only prompt leptons

The background with the highest presence in the SR-WZ is ZZ production, which might populate the three lepton phase space when either one of the Z bosons decay to τ pairs or both decay to light leptons and one of the leptons, usually the less energetic one, fails to enter detector acceptance. The second case also produces additional p_T^{miss} accounting for the missing lepton, which makes it more likely to appear due to the requirements of the SR-WZ. The CR-ZZ described in Table 5.2 is used to estimate the overall normalization of the ZZ process and to cross check the modelling of the different variables involved in interpretations through the results presented in this Chapter. Distributions in the CR-ZZ corresponding to reconstructed quantities used through the analysis are presented in Figure 5.3. Additional distributions related to other interpretations of the results are presented through the following sections as well. For displaying purposes the different contributions to the ZZ cross section ($q\bar{q}'$ and gg induced) are shown separately, but they are included in all SR fits as a single ZZ background contributions.

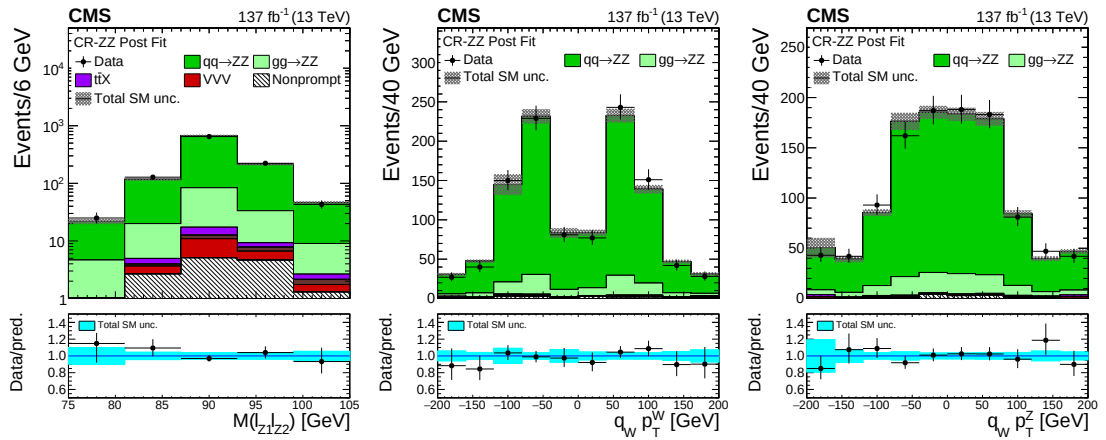


FIGURE 5.3: Several expected and observed distributions at the selection level of the CR-ZZ. From left to right: reconstructed mass of the ℓ_{Z1} and ℓ_{Z2} pair, reconstructed p_T of the Z boson, and reconstructed p_T of the W boson times estimated W boson charge. Only the three leading leptons are used to perform the lepton tagging and reconstruction algorithm for the W and Z bosons. All systematic uncertainties and free floating parameters in the analysis are included in the plot at their post-fit values from the fit described in Section 5.5.

Similarly, the CR- $\bar{t}tZ$ was designed to be enriched in both $\bar{t}tZ$ and tZq production, with the requirement of a b tagged jet greatly reducing any possible contamination. The remaining yields from both processes that enter the SR-WZ correspond to cases in which the b tagging algorithm fails to properly identify the flavour of the jet, and so kinematics are expected to be similar between the CR- $\bar{t}tZ$ and the SR-WZ for both $\bar{t}tZ$ and tZq . Several distributions in the CR- $\bar{t}tZ$ are shown in Figure 5.4, with additional ones presented through the discussion of this chapter as necessary. As the final yields from $\bar{t}tW$ and $\bar{t}tH$ production are extremely depleted in both the SR-WZ and the CR- $\bar{t}tZ$, they are grouped together with the $\bar{t}tZ$ process as a joint $\bar{t}tX$ contribution for both displaying and fitting purposes.

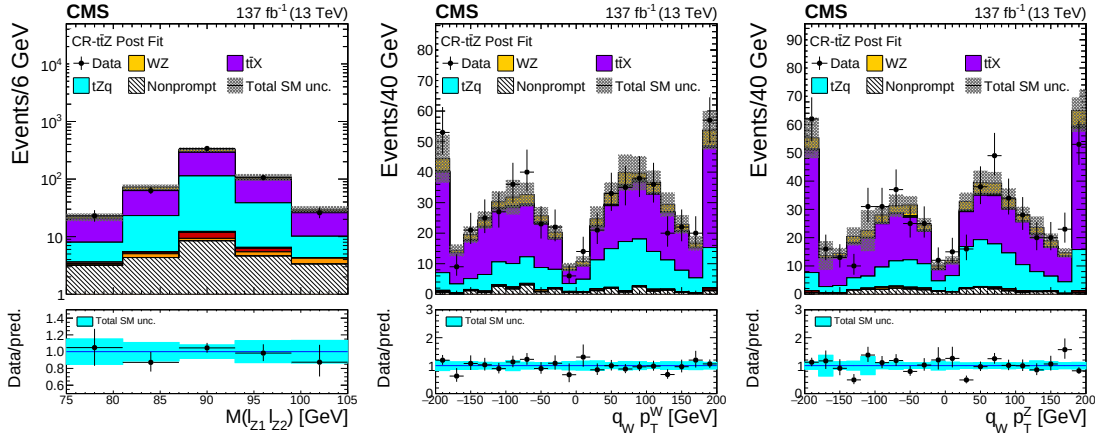


FIGURE 5.4: Several expected and observed distributions at the selection level of the CR- $\bar{t}tZ$. From left to right: reconstructed mass of the ℓ_{Z1} and ℓ_{Z2} pair, reconstructed p_T of the Z boson, and reconstructed p_T of the W boson times estimated W boson charge. All systematic uncertainties and free floating parameters in the analysis are included in the plot at their post-fit values from the fit described in Section 5.5.

Finally, processes involving an asymmetric photon conversion are strongly rejected by the electron identification criteria presented in Section 4.3.3. However, the high cross sections of processes such as $W\gamma$ and $Z\gamma$ means that a non zero contribution remains at the SR-WZ. An estimation of the modelling of the photon conversion phenomena is presented in the $Z\gamma$ enriched sideband known as the CR-conv. Several distributions in such CR are shown in Figure 5.5, with more presented through the following sections. For displaying and fitting purposes, all processes involving asymmetric conversions are grouped together in the $X\gamma$ group, which is nonetheless dominated by a high proportion of $Z\gamma$ yields ($> 99\%$ of all photon conversion yields).

The different CR presented are used to estimate the overall normalization of the corresponding backgrounds which are presented on each one. Explicitly, the normalization of the ZZ , $X\gamma$, $\bar{t}tZ$ and tZq backgrounds will be able to vary according to free floating parameters in the fits, r_{ZZ} , $r_{X\gamma}$, $r_{\bar{t}tZ}$, r_{tZq} , during each of the signal extraction steps that will be discussed into more detail in the following sections. To constrain such normalization parameters, distributions corresponding to key observables in the CR are introduced into the fits as well, meaning that the overall signal and background normalizations will be estimated simultaneously. For the CR- ZZ and CR-conv cases, as a single background process appears, the distribution of the lepton flavour composition of the three leading leptons is used. The expected benefits of such strategy are that by splitting the effects of the lepton efficiency uncertainties into several different input bins it is possible to reach small constrains on their overall impact on the final

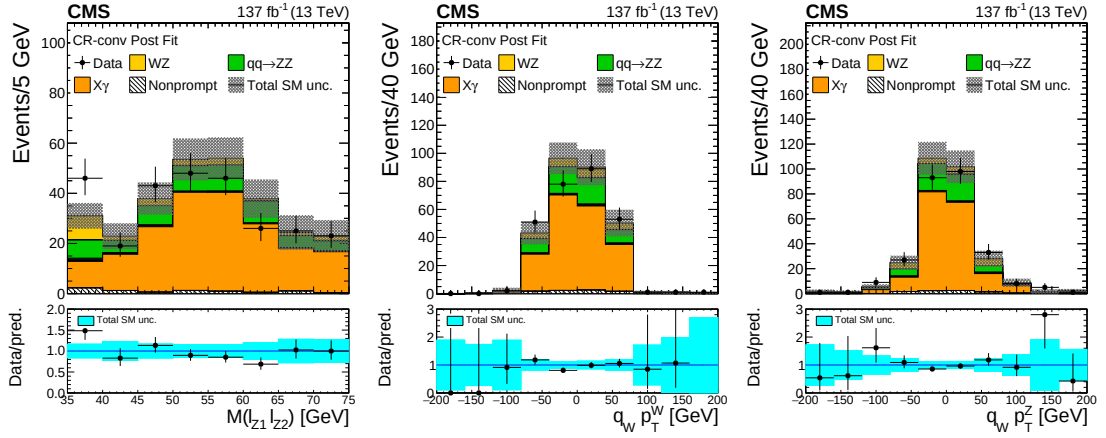


FIGURE 5.5: Several expected and observed distributions at the selection level of the CR-conv. From left to right: reconstructed mass of the ℓ_{Z1} and ℓ_{Z2} pair, reconstructed p_T of the Z boson, and reconstructed p_T of the W boson times estimated W boson charge. All systematic uncertainties and free floating parameters in the analysis are included in the plot at their post-fit values from the fit described in Section 5.5.

measurement. In the CR-tfZ case, two different backgrounds are to be estimated from it, the ttZ and tZq ones, and so the lepton flavour distribution did not prove to be as useful as it offers few discrimination between the two. Instead, the jet multiplicity distribution is used. The three distributions in the CR included into the fits are presented in Figure 5.6.

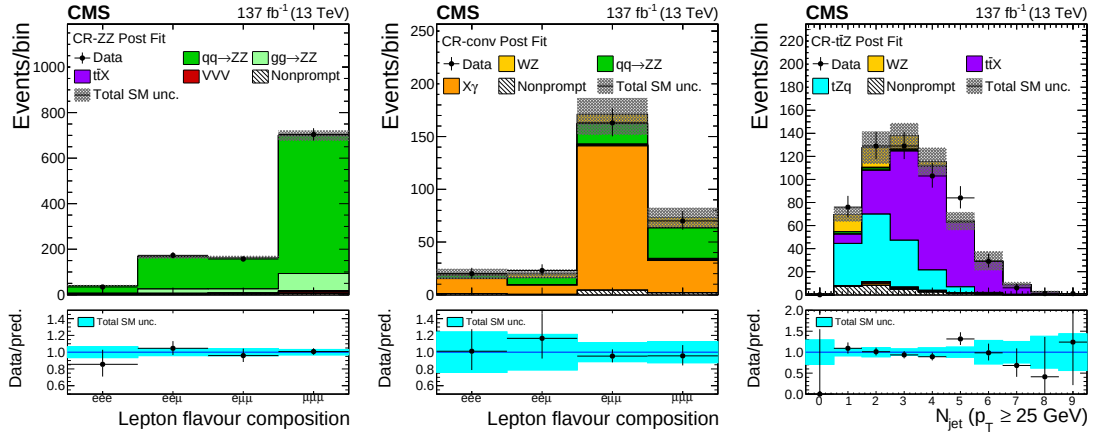


FIGURE 5.6: Expected and observed distributions of the high level observables included into the signal extraction fits for each CR of the analysis. From left to right: lepton flavour composition of the three leading leptons in the CR-ZZ, lepton flavour composition of the three leading leptons in the CR-conv, and jet multiplicity in the CR-tfZ. All systematic uncertainties in the analysis are included in the plot at their post-fit values from the fit described in Section 5.5.

As a cross-check of the simultaneous fit strategy, validation fits on each CR in which only its associated backgrounds are able to float freely are performed. The fitted distributions are the ones depicted in Figure 5.6 and all applicable analysis uncertainties that will be described in detail in Section 5.4 are included into the fit. The resulting values of the normalization parameters and their uncertainties are $r_{ZZ} = 1.06 \pm 0.06$, $r_{t\bar{t}Z} = 1.02 \pm 0.12$, $r_{tZq} = 1.35 \pm 0.30$, and $r_{X\gamma} = 0.95 \pm 0.11$. Notice that the ZZ parameters corresponds to an scaling over the NNLO cross section rather than the NLO

one as described in Section 4.2. The results are consistent with the latest public results for each process by the CMS collaboration for the ZZ [149], $t\bar{t}Z$ [174], and tZq [175] measurements, although with slightly less precision as expected from measurements which are not optimized towards the study of these processes. No result from the CMS collaboration in $Z\gamma$ production that these results be compared to exist at 13 TeV.

5.3.3 Minor backgrounds with only prompt leptons

The remaining set of backgrounds present in the SR-WZ were proven to be more challenging to validate using dedicated CRs as the more natural ones will directly intersect with the SR-WZ. In fact, the latest CMS measurements of electroweak WZ production [176] and VVV production [177] just use subsets of the SR-WZ to perform their cross section estimation. While such subsets could be isolated by themselves, the resulting CR would still be quite contaminated by the WZ signal and might lead to a quite skewed fiducial phase space which would hamper the reinterpretability of the measurements. As such, the three remaining minor backgrounds are estimated from MC and relatively conservative uncertainties of 20% (electroweak WZ), 25% (VH) and 50% (VVV) are applied to their overall normalization, based on the best experimental estimate of their cross sections at the time of the analysis design. While most recent measurements of VVV production point towards better precision in such estimations [177], the final effect of modifying such input parameter was found to be negligible for all measurements presented in this chapter.

5.4 Summary of uncertainty sources

The overall set of uncertainty sources considered in the following results contains the background normalization related ones described in Section 5.3 as well as the different object related ones described generically in Section 4.4. A challenge appears in this analysis related to the data taking period dependency of some uncertainties. The conditions of data-taking, the calibrations of the detector, and even the structure of the very same detector varied between the 2016 and 2018 data taking years, leading to some sources of uncertainty having greater effects in some cases over others. In fact, even if some uncertainties are present in all data taking years, they might even originate from random effects that are independent across the different periods, such as the estimation of a background contribution from a sideband of limited statistical power. Thus, a correlation scheme which details how the effects of the different sources of uncertainty are correlated across years needs to be introduced into the statistical model. Effectively, this will mean that a single source of uncertainty (meaning that the physical source is unique in nature), might lead to a single nuisance parameter (fully correlated), three independent nuisance parameters (fully decorrelated) or four nuisance parameters (one correlated and three decorrelated) instead of the single one introduced in Equation 4.15. As the effects in the results can be sizeable, in the following discussion the used correlation scheme will be detailed for each of the uncertainties involved in the analysis.

The list of all considered uncertainties, the corresponding correlation scheme across years and their expected effects on each year are summarized in Table 5.3. A brief description of the derivation of each uncertainty source is presented as follows:

- **Lepton efficiency uncertainties** are estimated following the procedure described in Section 4.4.1 for the lepton identification criteria designed for this analysis. They are partially correlated across the years, with the small proportion of uncertainty representing the limited statistics of the tag and probe region in data being decorrelated across years and all other sources being correlated.
- **Lepton energy scale uncertainties** are estimated following the procedure described in Section 4.4.3 and applied to both the lepton kinematics and all derived quantities, including p_T^{miss} . They are correlated across years, even if it could be argued that some of the sources are statistical in nature, as the overall impact of the later was found to be quite small.
- **Jet energy scale and resolution uncertainties** are computed following the description of Section 4.4.5. They are partially correlated across years, with all sources of uncertainty corresponding to statistical limitations of measuring sidebands grouped into a set of uncorrelated components and the rest of them grouped as a single correlated term.
- **B tagging efficiency uncertainties** are obtained following the description of Section 4.4.6. Two different sources corresponding to heavy tagging and light flavour mistagging are considered separately. Each one is correlated across years.
- **Trigger efficiency uncertainties** are measured with the techniques described in Section 4.4.4 using a reference trigger based on p_T^{miss} criteria. As discussed in Section 5.2.2, the trigger efficiency is found to be consistent with unity but the measurement still has some inherent uncertainties. Two sets of trigger efficiency uncertainty are considered: the limited statistics of the reference trigger sideband (uncorrelated across years), and an overall estimation of the bias in the measurement taken as the difference of the central measured efficiency and unity (correlated across years).
- **Pileup modelling uncertainties** are estimated following the description in Section 4.4.7 and are correlated across years.
- **Theoretical uncertainties corresponding to the scale and PDF choice** are included following the description of Section 4.2.1 for all signal processes. Additionally, for the WZ signal uncertainties on the ISR emission scale are included as well.
- Uncertainties related to the overall **luminosity** of the 13 TeV dataset have been measured by the CMS Collaboration for the 2016, 2017 and 2018 datasets separately [159–161]. A correlation scheme which splits the overall uncertainty for each year into its contributing sources and then correlates accordingly across years is applied, leading to a set of partially correlated uncertainties which account for roughly a total 1.8% uncertainty in the final total luminosity of the Run 2 of the LHC.
- All **background normalization uncertainties** discussed in Section 5.3 are included.
- **Statistical uncertainties** due the limited size of the application region sideband or of the MC samples are uncorrelated across all analysis selections and years.

Source	2016	2017	2018	Correlation scheme	Processes	Effect measured in
Electron efficiency	0 – -3.3	0 – -3.0	0 – -2.8	Partially correlated	All MC	WZ yields in SR–WZ
Muon efficiency	0 – -2.4	0 – -2.1	0 – -2.0	Partially correlated	All MC	WZ yields in SR–WZ
Electron energy scale	0 – -5	0 – -5	0 – -5	Correlated	All MC	WZ yields in SR–WZ
Muon energy scale	0 – -5	0 – -5	0 – -5	Correlated	All MC	WZ yields in SR–WZ
Trigger efficiency	-1.0/ + 0.6	-0.7/ + 0.6	-0.7/ + 0.6	Partially correlated	All MC	All MC yields
Jet energy scale	0.9	0.7	1.1	Partially correlated	All MC	WZ yields in SR–WZ
b efficiency (heavy)	1.0	0.7	0.9	Correlated	All MC	WZ yields in SR–WZ
b efficiency (light)	0.5	0.4	0.3	Correlated	All MC	WZ yields in SR–WZ
Pileup profile	0.9	0.8	0.8	Correlated	All MC	WZ yields in SR–WZ
ISR	0.2 – -20	0.2 – -20	0.2 – -20	Correlated	WZ	WZ yields in SR–WZ
Nonprompt shape.	5 – -50	5 – -50	5 – -50	Correlated	Nonprompt	Nonprompt yields
Nonprompt norm.	30	30	30	Correlated	Nonprompt	Nonprompt yields
VVV norm.	50	50	50	Correlated	VVV	VVV yields
VH norm.	25	25	25	Correlated	VH	VH yields
WZ EWK norm.	20	20	20	Correlated	WZ EWK	WZ EWK yields
ZZ	Free	Free	Free	Correlated	ZZ	-
t $\bar{t}$ Z norm.	Free	Free	Free	Correlated	t $\bar{t}$ X	-
tZq norm.	Free	Free	Free	Correlated	tZq	-
X γ norm.	Free	Free	Free	Correlated	X γ	-
Integrated luminosity	2.5	2.3	2.5	Partially correlated	All MC	All MC yields
Statistical uncertainties	By bin	By bin	By bin	Uncorrelated	All MC	All yields
Theoretical (PDF + scale)	0.9	0.9	0.9	Correlated	WZ	WZ yields in SR–WZ

TABLE 5.3: Summary of the uncertainties in the analysis, their relative effect for each of the data-taking years (in %), the correlation scheme across data taking eras followed, and which processes are affected by them. Their quoted effects refer to the quantity included in the last column. Systematic uncertainties with an asymmetric effect are marked with a / separating the upwards and downwards variations, while those that vary significantly across analysis bins are marked with a – – denoting the range. Uncertainties marked as free correspond to background normalizations that are free to float in the analysis fit so a relative prefit effect can't be quoted for them.

5.5 Inclusive cross section measurements

The measurement of the inclusive WZ cross section is based in the behaviour of data in the SR–WZ. Several control distributions of expected and observed events in the SR–WZ are presented in Figure 5.7. The top row of the figure represents the transverse momentum of the different leptonic objects involved in the analysis, while the bottom row includes variables more strongly affected by the modelling of the jets. Good overall agreement between observations and expectations are seen in all represented distributions, with some statistical fluctuations in data appearing only at the tails of the distributions with low statistical power.

As it is expected that the lepton efficiency uncertainties will be reasonably different depending on the lepton flavour composition of the final state, four different decay channels corresponding to the eee , $ee\mu$, $\mu\mu e$, and $\mu\mu\mu$ final states, are defined. The cross section measurements will all be performed both separately in each one of them (exclusive final states) as well as combining all of them (inclusive or combined final state). For the exclusive cases, the contributions in the SR–WZ are fitted to a single bin corresponding to the overall yields in the corresponding final state, while for the inclusive case the whole distribution of yields across lepton flavour channels is fitted. This distribution is presented in Figure 5.8.

A joint likelihood distribution following the description presented in Equation 4.16 is build across all bins in the CR distributions presented in Figure 5.6 and the SR distribution presented in 5.8. All uncertainties described in Section 5.4 are included as nuisance terms in the likelihood except for the PDF and scale ones, which will be

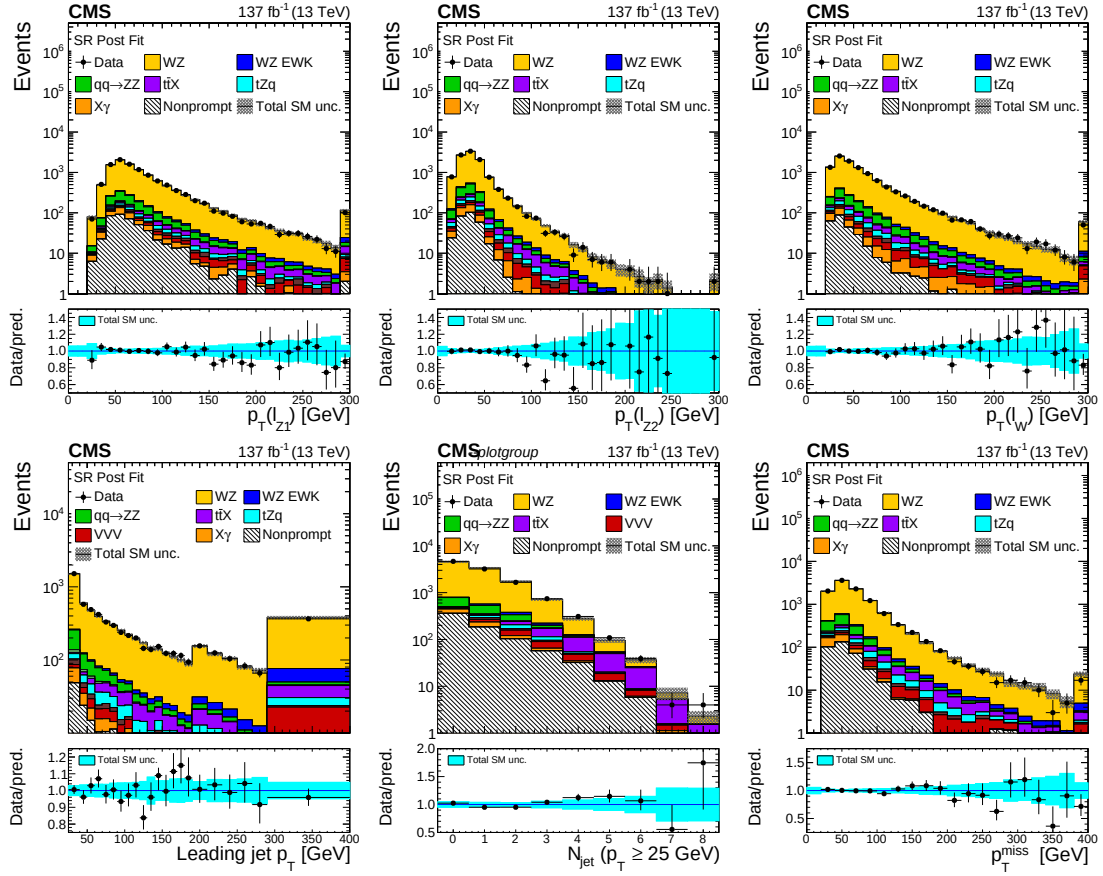


FIGURE 5.7: Several expected and observed distributions at the selection level of the SR-WZ. From left to right (top row): transverse momentum of the ℓ_{Z1} lepton, transverse momentum of the ℓ_{Z2} lepton, and transverse momentum of the ℓ_W lepton. From left to right (bottom row): transverse momentum of the leading reconstructed jet, reconstructed jet multiplicity, and missing transverse momentum. All systematic uncertainties in the analysis are included in the plot at their post-fit values from the fit described in Section 5.5.

discussed into more detail later. A small modification is introduced into the likelihood function in order to account for the free floating parameters corresponding to the background normalization, such that the final likelihood can be expressed as

$$\begin{aligned}
 L(\mu, r_{ZZ}, r_{X\gamma}, r_{t\bar{t}Z}, r_{tZq}; \theta) &= \prod_{i=1}^{\text{Bins}} \mathcal{P}(d_i; \mu s_i(\theta) + b_i(r_{ZZ}, r_{X\gamma}, r_{t\bar{t}Z}, r_{tZq}, \theta)) \prod_{\theta} \Theta(\theta) \\
 b_i(r_{ZZ}, r_{X\gamma}, r_{t\bar{t}Z}, r_{tZq}, \theta) &= r_{ZZ} y_i^{ZZ}(\theta) + r_{t\bar{t}Z} y_i^{t\bar{t}Z}(\theta) + r_{tZq} y_i^{tZq}(\theta) + r_{X\gamma} y_i^{X\gamma}(\theta) \\
 &\quad + y_i^{\text{VBS}}(\theta) + y_i^{\text{VVV}}(\theta) + y_i^{\text{VH}}(\theta)
 \end{aligned} \tag{5.1}$$

where y_i^X represents the yields in bin i of process X , and $\mu, r_{ZZ}, r_{X\gamma}, r_{t\bar{t}Z}, r_{tZq}$ are the set of five unconstrained parameters that will be fitted simultaneously, taking the same role μ took in the derivation presented in Section 4.6 of a free floating independent parameter. In the case of the exclusive channel fits, only the bin corresponding to the measured final state in the WZ-SR is considered into the extended likelihood. Following the prescription described in Section 4.6, an estimation of all free floating

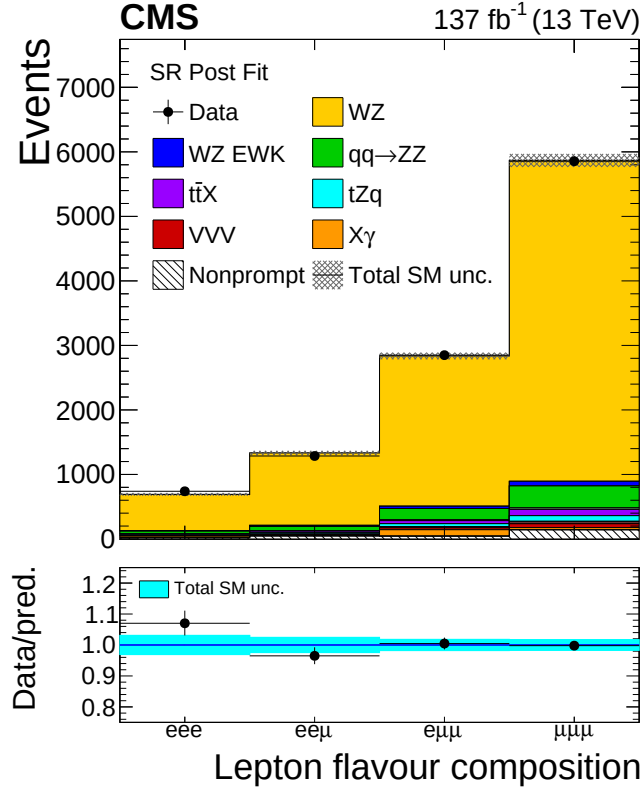


FIGURE 5.8: Distribution of the lepton flavour composition at the selection level of the SR-WZ. All systematic uncertainties in the analysis are included in the plot at their post-fit values from the fit described in Section 5.5.

parameters is found by maximizing the likelihood with respect to all free floating and nuisance parameters. The postfit values of the yields for each SM process and their uncertainties can then be extracted by evaluating each of the $r_X y_i^X$ quantities. The resulting yields in the SR-WZ are presented in Table 5.4 for the fitted values of the nuisances and free parameters obtained with the inclusive fit. The resulting values show good overall agreement for all bins of lepton flavour composition.

A fiducial region (FR) is defined at particle-level in order to extrapolate the results fitted at the reconstructed level to a quantity free of detector effects. The fiducial region is based on the presence of three dressed light leptons, following the description presented in Section 4.2.2. These leptons are required to be either electrons and muons and not to proceed from the decay of a τ lepton. The same tagging algorithm applied at the reconstructed level is used to assign the dressed leptons to the decay of the W or Z bosons to be ℓ_{Z1}^{gen} , ℓ_{Z2}^{gen} , and ℓ_W^{gen} . Once leptons are assigned, several kinematic requirements mimicking those of the SR-WZ are applied to define the fiducial region. First, requirements on the dressed lepton p_T are applied $p_T^{\ell_{Z1}^{\text{gen}}} > 25$ GeV, $p_T^{\ell_{Z2}^{\text{gen}}} > 10$ GeV, and $p_T^{\ell_W^{\text{gen}}} > 25$ GeV, and all three leptons are required to be inside detector acceptance with $|\eta^{\ell_{Z1}^{\text{gen}}}| < 2.5$, $|\eta^{\ell_{Z2}^{\text{gen}}}| < 2.5$, and $|\eta^{\ell_W^{\text{gen}}}| < 2.5$. The invariant mass of the two Z tagged leptons is required to be consistent with the Z one $60 < M(\ell_{Z1}\ell_{Z2})^{\text{gen}} < 120$ GeV, and the invariant mass of the tripleton system is required to be far from a resonant Z decay $M(\ell_{Z1}\ell_{Z2}\ell_W)^{\text{gen}} > 100$ GeV. The minimal requirement on the

Process	eee	$ee\mu$	$\mu\mu e$	$\mu\mu\mu$	Inclusive
Nonprompt	19 ± 8	48 ± 16	45 ± 15	143 ± 39	255 ± 46
ZZ	42.9 ± 1.4	73 ± 7	188 ± 6	363 ± 10	668 ± 15
$X\gamma$	25 ± 3	5.5 ± 0.9	98 ± 10	33 ± 4	161 ± 11
$t\bar{t}X$	12.6 ± 1.3	24 ± 3	47 ± 5	98 ± 11	181 ± 13
VVV	8 ± 3	14 ± 6	30 ± 12	60 ± 24	111 ± 28
VH	3.1 ± 0.6	8.7 ± 1.6	19 ± 4	37 ± 7	68 ± 8
tZq	11.2 ± 1.9	21 ± 4	45 ± 8	88 ± 16	165 ± 19
WZ VBS	8.5 ± 1.3	16 ± 2	35 ± 5	72 ± 11	132 ± 12
Total background	130 ± 10	211 ± 20	507 ± 26	894 ± 54	1741 ± 64
WZ	561 ± 15	1122 ± 24	2328 ± 39	4974 ± 82	8985 ± 95
Total Expected	691 ± 18	1333 ± 28	2835 ± 43	5868 ± 89	10726 ± 95
Data	739 ± 27	1286 ± 36	2849 ± 53	5855 ± 77	10729 ± 104

TABLE 5.4: Expected yields of the signal and background process and observed data events for each flavoured final state and the combination of all of them. Uncertainties and free floating parameters are evaluated at their postfit values after the channel inclusive cross section fit to the SR–WZ and all three CRs of the analysis and propagated to the final yields from each process.

invariant mass of any OSSF lepton pair is applied as well as $\min(M(\ell\ell')^{\text{gen}}) > 4 \text{ GeV}$. The fiducial cross section is then extrapolated using the relation

$$\sigma_{\text{fid}}(\text{pp} \rightarrow \text{WZ}) = \frac{N_{\text{WZ}}^{\text{SR}}}{\epsilon \mathcal{L}} \tau_{\text{corr}} \quad (5.2)$$

where $N_{\text{WZ}}^{\text{SR}}$ are the fitted WZ yields in the SR, $\mathcal{L}$ is the overall integrated luminosity of the Run 2 of the LHC, ϵ is an efficiency factor accounting for the selection efficiency of WZ events from the fiducial to the total region and the last term is a correction factor to account for the presence of leptonic decays coming from τ leptons. The $N_{\text{WZ}}^{\text{SR}}$ quantities are obtained in the flavour exclusive and flavour inclusive channels separately from the fits corresponding to each channel. The efficiencies ϵ are measured with the nominal POWHEG MC sample by counting unweighted MC events that pass the SR and FR selection ($N_{\text{SR}}^{\text{fid}}$) and dividing by the overall events that pass the FR selection ($N_{\text{all}}^{\text{fid}}$):

$$\epsilon = \frac{N_{\text{SR}}^{\text{fid}}}{N_{\text{all}}^{\text{fid}}} \quad (5.3)$$

Efficiencies are measured separately for each of the exclusive and inclusive channels and include the uncertainties related to the PDFs, and the factorization and renormalization scales. A summary of the estimated values of the efficiencies is presented in Table 5.5. Cross checks performed with the alternative MADGRAPH+aMC@NLO WZ sample proved that the efficiency measurements are consistent across the different generators within the statistical uncertainties of the MC samples.

The factor presented at the end of Equation 5.2, τ_{corr} aims to correct for the fact that not all WZ events observed at the SR–WZ level pass the requirements of the FR selection.

Quantity	eee	$ee\mu$	$\mu\mu e$	$\mu\mu\mu$	Inclusive
ϵ	0.0507 ± 0.0006	0.1044 ± 0.0008	0.2166 ± 0.0011	0.4582 ± 0.0013	0.2074 ± 0.0005
$\mathcal{A}$	0.0447 ± 0.0001	0.0448 ± 0.0001	0.0448 ± 0.0001	0.0446 ± 0.0001	0.1789 ± 0.0002
τ_{corr}	0.950 ± 0.002	0.952 ± 0.001	0.946 ± 0.001	0.948 ± 0.001	0.949 ± 0.001

TABLE 5.5: Measured efficiencies, acceptances, and τ corrections for each of the considered flavour exclusive channels and their sum measured using the nominal POWHEG WZ MC. Uncertainties are statistical only.

This is, mostly, due to the presence of τ leptons on WZ decays that themselves decay through leptonic modes and which are excluded from the fiducial region definition. The estimation of such corrections is performed by counting in the nominal POWHEG MC sample the amount of unweighted WZ yields that pass the SR–WZ requirements ($N_{\text{all}}^{\text{SR}}$) and those that pass both the SR–WZ and FR requisites ($N_{\text{fid}}^{\text{SR}}$), following the relation:

$$\tau_{\text{corr}} = \frac{N_{\text{fid}}^{\text{SR}}}{N_{\text{all}}^{\text{SR}}} \quad (5.4)$$

Statistical uncertainties in the τ_{corr} quantity were estimated using the Clopper–Pearson efficiency estimation method and were found to be negligible, given the size of the MC samples, with respect to the overall correction factor. The final values of these corrections for each flavour channel are presented in Table 5.5.

The extrapolated values of the fiducial cross sections for each exclusive flavoured channel and their overall combination are shown in Table 5.6, where their corresponding uncertainties are also shown. The overall uncertainties are split into a statistical component (from data and MC statistics), a theory component (including ISR, PDF and scale uncertainties), a luminosity component, and a systematic component including all the rest of uncertainties described in Section 5.4. The breakdown of effects is obtained by repeating the signal extraction fits while freezing the corresponding set of uncertainties and computing the quadratic difference between this new fit and the nominal one, with the final difference being then assigned to the frozen sources.

The measurements of the fiducial cross section are in good agreement with the predictions obtained with MATRIX that include higher order perturbative corrections, being somehow in between the cases which include or not the relatively small NLO EWK corrections. The measurements point to a relatively big disagreement with respect to the lower accuracy predictions from POWHEG at NLO in QCD, as expected from its own differences with the results that include higher order computations. The overall measurements are clearly more precise in the $\mu\mu\mu$ channel where the lepton selection efficiency is the greatest and measurements are dominated by the systematic uncertainties, the same effect as in the combined measurement. The sacrifice of statistical power in the measurements with electrons lead to an statistically dominated measurement in the eee , and $\mu\mu e$ channels but with uncertainties nonetheless close to the overall systematic value. The overall uncertainty in the inclusive measurement is around the 3.7% level.

The total production cross section is measured in a total region (TR), where the only requirement imposed is that the produced Z boson is to remain on-shell, for the

Channel (Source)	Fiducial cross section
eee (POWHEG)	$62.5^{+2.4}_{-2.0}(\text{scale}) \pm 0.9(\text{PDF}) \text{ fb}$
eee (MATRIX, NNLO QCD)	$76.8^{+1.8}_{-1.6}(\text{scale}) \text{ fb}$
eee (MATRIX, NNLO QCD $\times$ NLO EWK)	$75.3^{+1.7}_{-1.5}(\text{scale}) \text{ fb}$
eee (Measured)	$78.6 \pm 4.1(\text{stat.}) \pm 3.3(\text{syst.}) \pm 1.4(\text{lumi.}) \pm 0.7(\text{theo.}) \text{ fb}$
$ee\mu$ (POWHEG)	$62.5^{+2.4}_{-2.0}(\text{scale}) \pm 0.9(\text{PDF}) \text{ fb}$
$ee\mu$ (MATRIX, NNLO QCD)	$75.3^{+1.8}_{-1.6}(\text{scale}) \text{ fb}$
$ee\mu$ (MATRIX, NNLO QCD $\times$ NLO EWK)	$73.8^{+1.7}_{-1.5}(\text{scale}) \text{ fb}$
$ee\mu$ (Measured)	$71.3 \pm 2.9(\text{stat.}) \pm 2.6(\text{syst.}) \pm 1.3(\text{lumi.}) \pm 0.7(\text{theo.}) \text{ fb}$
$\mu\mu e$ (POWHEG)	$62.5^{+2.4}_{-2.0}(\text{scale}) \pm 0.9(\text{PDF}) \text{ fb}$
$\mu\mu e$ (MATRIX, NNLO QCD)	$75.3^{+1.8}_{-1.6}(\text{scale}) \text{ fb}$
$\mu\mu e$ (MATRIX, NNLO QCD $\times$ NLO EWK)	$73.8^{+1.7}_{-1.5}(\text{scale}) \text{ fb}$
$\mu\mu e$ (Measured)	$74.8 \pm 1.9(\text{stat.}) \pm 2.1(\text{syst.}) \pm 1.4(\text{lumi.}) \pm 0.7(\text{theo.}) \text{ fb}$
$\mu\mu\mu$ (POWHEG)	$62.5^{+2.4}_{-2.0}(\text{scale}) \pm 0.9(\text{PDF}) \text{ fb}$
$\mu\mu\mu$ (MATRIX, NNLO QCD)	$76.8^{+1.8}_{-1.6}(\text{scale}) \text{ fb}$
$\mu\mu\mu$ (MATRIX, NNLO QCD $\times$ NLO EWK)	$75.3^{+1.7}_{-1.5}(\text{scale}) \text{ fb}$
$\mu\mu\mu$ (Measured)	$74.9 \pm 1.4(\text{stat.}) \pm 1.9(\text{syst.}) \pm 1.4(\text{lumi.}) \pm 0.7(\text{theo.}) \text{ fb}$
Inclusive (POWHEG)	$250.0^{+9.7}_{-8.0}(\text{scale}) \pm 3.5(\text{PDF}) \text{ fb}$
Inclusive (MATRIX, NNLO QCD)	$304.2^{+7.3}_{-6.5}(\text{scale}) \text{ fb}$
Inclusive (MATRIX, NNLO QCD $\times$ NLO EWK)	$298.1^{+6.9}_{-6.3}(\text{scale}) \text{ fb}$
Inclusive (Measured)	$298.9 \pm 4.8(\text{stat.}) \pm 7.7(\text{syst.}) \pm 5.4(\text{lumi.}) \pm 2.7(\text{theo.}) \text{ fb}$

TABLE 5.6: Measured fiducial cross sections and their corresponding uncertainties for each of the individual flavour channels, as well as for their combination. The predictions from both MATRIX (at NNLO QCD and NNLO QCD $\times$ NLO EWK) and POWHEG (at NLO QCD) are also included.

reasons already discussed in Section 4.7.4 related to the separation of the Z and the γ^* bosons. Three leptons of any flavour are required with at least an OSSF lepton pair and the only additional requirement is that the reconstructed mass of an OSSF dressed lepton pair has to fulfil $60 < M(\ell_{Z1}\ell_{Z2})^{\text{gen}} < 120 \text{ GeV}$ and the minimal requirement of $\min(M(\ell\ell')^{\text{gen}}) > 4 \text{ GeV}$ on all OSSF lepton pairs. The fiducial cross section result is then extrapolated to the total one using a relation similar to Equation 4.25, namely

$$\sigma_{\text{tot}}(\text{pp} \rightarrow \text{WZ}) = \frac{\sigma_{\text{fid}}(\text{pp} \rightarrow \text{WZ})}{\mathcal{A}Br(\text{W} \rightarrow \ell\nu)Br(\text{Z} \rightarrow \ell\ell)} \quad (5.5)$$

where $\mathcal{A}$ is known as the acceptance, referring to the efficiency of the fiducial selection on top of the total region and representing the overall effect of the detector and trigger coverage. The Br quantities refer to the branching ratios of the W and Z bosons to leptonic final states and are obtained from current world averages. In the case of the flavour split final states, the branching ratios include the fact that only such allowed final states appear, meaning that all total cross sections are computed up to the same final total production cross section. The acceptances are measured in the nominal MC sample in a similar way as the efficiencies by counting the proportion of TR events that pass the FR requirements. A summary of the acceptance values is presented in Table 5.5.

The total cross section measurements and their uncertainties are presented in Table 5.7. Very similar behaviour to the one observed in the fiducial cross section measurements is presented in these results, with most of the overall precision obtained from the $\mu\mu\mu$ channel. A small excess over the expected higher order cross sections from MATRIX is found in the eee channel which nonetheless is consistent with both of them within one

standard deviation. A similar small defect appears in the $ee\mu$ channel with the same level of consistency. A graphic comparing the numerical results of Table 5.7 can be found in Figure 5.9.

Channel or source	Total cross section
POWHEG	$42.5^{+1.6}_{-1.4}(\text{scale}) \pm 0.6(\text{PDF})$ pb
MATRIX, NNLO QCD	$51.2^{+1.2}_{-1.0}(\text{scale})$ pb
MATRIX, NNLO QCD $\times$ NLO EWK	$50.7^{+1.1}_{-1.0}(\text{scale})$ pb
eee (Measured)	$53.2 \pm 2.7(\text{stat.}) \pm 2.3(\text{syst.}) \pm 1.1(\text{lumi.}) \pm 0.5(\text{theo.})$ pb
$ee\mu$ (Measured)	$48.1 \pm 1.7(\text{stat.}) \pm 1.8(\text{syst.}) \pm 1.1(\text{lumi.}) \pm 0.4(\text{theo.})$ pb
$\mu\mu e$ (Measured)	$50.6 \pm 1.3(\text{stat.}) \pm 1.5(\text{syst.}) \pm 1.1(\text{lumi.}) \pm 0.5(\text{theo.})$ pb
$\mu\mu\mu$ (Measured)	$50.8 \pm 1.0(\text{stat.}) \pm 1.5(\text{syst.}) \pm 1.1(\text{lumi.}) \pm 0.5(\text{theo.})$ pb
Combined (Measured)	$50.6 \pm 0.8(\text{stat.}) \pm 1.5(\text{syst.}) \pm 1.1(\text{lumi.}) \pm 0.5(\text{theo.})$ pb

TABLE 5.7: Measured total cross sections and their corresponding uncertainties for each of the individual flavour channels, as well as for their combination. The predictions from both MATRIX (at NNLO QCD and NNLO QCD $\times$ NLO EWK) and POWHEG (at NLO QCD) are also included.

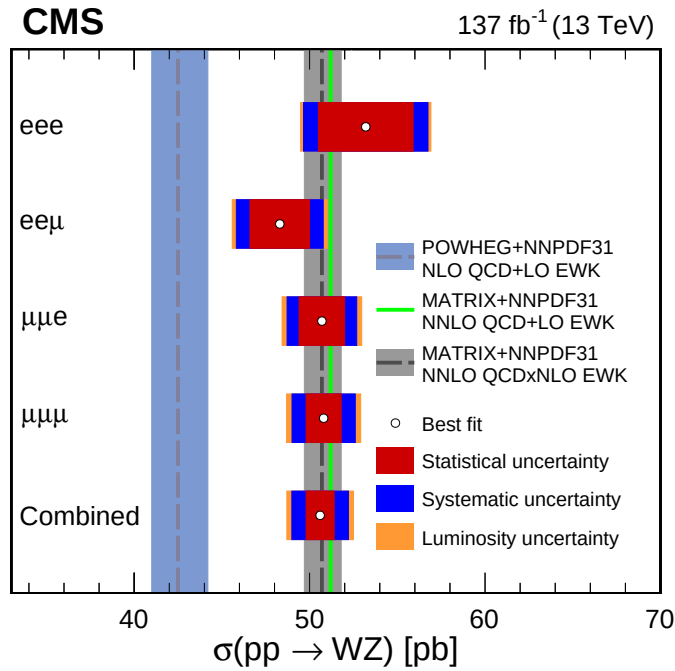


FIGURE 5.9: Observed and expected values of the WZ total production cross section and predictions from POWHEG at NLO in QCD and MATRIX at NNLO in QCD and NNLO in QCD $\times$ NLO in EWK. The predictions from POWHEG include the uncertainty corresponding to PDF and scale uncertainties. The predictions from MATRIX only include scale uncertainties.

The breakdown of the contributions from each source of systematic uncertainty in each of the involved flavoured channels and their combination in terms of the relative uncertainty they contribute towards the overall cross section measurement are

Source	Combined	eee	$ee\mu$	$\mu\mu e$	$\mu\mu\mu$
Electron efficiency	0.6	3.2	1.8	0.9	0
Muon efficiency	1.2	0	0.5	1.0	1.5
Electron energy scale	0.1	0.3	0.1	0.1	0.0
Muon energy scale	0.1	0.0	0.0	0.1	0.1
Trigger efficiency	0.7	0.7	0.8	0.7	0.7
Jet energy scale	0.9	0.8	0.7	1.0	0.9
b tagging	1.6	1.8	1.7	1.8	1.6
Pileup	0.9	1.0	1.2	0.8	0.7
ISR	0.2	0.2	0.2	0.2	0.2
Nonprompt normalization	0.6	0.7	0.8	0.6	0.7
Nonprompt shape	1.0	1.2	1.0	0.9	0.9
VVV normalization	0.5	0.6	0.5	0.5	0.5
VH normalization	0.2	0.1	0.2	0.2	0.2
WZ EWK normalization	0.2	0.2	0.2	0.2	0.2
ZZ normalization	0.3	0.3	0.3	0.3	0.3
$t\bar{t}Z$ normalization	0.3	0.4	0.4	0.4	0.3
tZq normalization	0.4	0.4	0.4	0.4	0.4
$X\gamma$ normalization	0.2	0.5	0.1	0.5	0.1
Total systematic uncertainties	2.8	4.3	3.7	3.0	3.0
Integrated luminosity	2.1	2.2	2.2	2.1	2.1
Statistical uncertainty	1.5	5.0	3.4	2.5	2.0
PDF+scale	0.9	0.9	0.9	0.9	0.9

TABLE 5.8: Breakdown of the relative uncertainty (in percentage) introduced in the measured cross section due to each source of uncertainty described in Section 5.4 for each of the flavour exclusive categories and the combination of the four. In each column, the effects of the uncertainty related to the measurement corresponding to its channel is shown, meaning that different constraining effects in the fit might appear from channel to channel.

presented in Table 5.8. The effect of the uncertainty sources due to the lepton efficiency estimations is relatively big in the flavour channels with higher multiplicities of the corresponding type, but is greatly reduced when combining the information of the four different ones. Uncertainties related to the b tagging uncertainties are the greatest systematic effect related to experimental calibrations, while the nonprompt background still provides the greatest source of uncertainty related to a single background process. The luminosity uncertainties are bigger than any single experimental source but smaller than their overall sum. Statistical uncertainties are relatively small in comparison with the overall systematic ones, except for the eee channel which has the lower lepton selection efficiency of all the flavour exclusive ones.

5.6 Charge asymmetry

As discussed earlier in Section 5.1, the charged nature of the final state in WZ production means that, at tree level, WZ is produced starting from $q\bar{q}'$ partonic initial states, as depicted in Figures 4.11 (middle) and 5.1 (left). Contributions from either $q\bar{g}$ or $g\bar{g}$ initiated process need to include at least one or two extra partons in order

to appear in WZ production as shown in Figures 5.1 and 5.2, and so are expected to be relatively less relevant when computing predictions for inclusive observables. As was discussed briefly in Section 2.5.1, the internal structure of the proton favours the presence of u and d quarks at the high momentum fractions needed to produce on-shell W and Z bosons. Once these two facts are coupled, it can be inferred that W^-Z production will be dominated by initial $d\bar{q}'$ states while W^+Z is by $u\bar{q}'$ ones. From Equation 2.35 and Figure 2.3 it can then be inferred that the W^+Z cross section will be bigger than the W^-Z one.

The differences between W^+Z and W^-Z production are studied based on the charge ratio asymmetry quantity, A_{WZ}^{+-} , defined as the quotient of fiducial cross sections for the two charged final states

$$A_{WZ}^{+-} = \frac{\sigma_{\text{fid}}(\text{pp} \rightarrow W^+Z)}{\sigma_{\text{fid}}(\text{pp} \rightarrow W^-Z)}. \quad (5.6)$$

where the fiducial region is used instead of just the yield at the reconstructed level to improve the reinterpretability of the results. Total production cross section ratios could be considered as well, but the acceptance factors tend to be sensitively different between the two charged final states, due to the different η distribution of the produced vector bosons, and so such extrapolation would introduce yet another degree of dependence on the modelling of the MC that this measurement tries to avoid.

5.6.1 Signal modelling

Instead of repeating the fit described in Section 5.5 separately for the W^+Z and W^-Z contributions, it is specially interesting to perform a simultaneous estimation of the two, as most of the effects of systematic uncertainties would likely be correlated across charged final states. Taking into consideration such correlations, cancellations in the ratio measurement are to be expected which might lead to more precise measurements of the A_{WZ}^{+-} quantity. Thus, instead of separate fits, the modelling of the signal in Equation 5.1 needs to be modified. To do so two different signal modifier parameters need to be added μ (overall WZ normalization) and q (overall excess of W^+Z over W^-Z with respect to expectations). To derive the functional form that needs to be replaced in Equation 5.1 and ensure that both parameters can be interpreted this way the following conditions are applied

$$\mu = \frac{y^+ + y^-}{s^+ + s^-} \quad q = \frac{y^+ / y^-}{s^+ / s^-} \quad (5.7)$$

where y^+ , y^- are the desired functional multipliers for the W^+Z and W^-Z yields, possibly dependent on all other quantities, and s^+ , s^- are just the *bare* predictions for the yields in each final state. Solving for y^+ and y^- , it can be obtained the somewhat counter-intuitive parametrization of

$$y^+ = \mu \frac{q + qA_{WZ,SM}^{+-}}{1 + qA_{WZ,SM}^{+-}} s^+ \quad y^- = \mu \frac{1 + A_{WZ,SM}^{+-}}{1 + qA_{WZ,SM}^{+-}} s^- \quad A_{WZ,SM}^{+-} = \frac{s^+}{s^-} \quad (5.8)$$

applying this per each considered bin of the fit, the total yields are replaced by the bins in the corresponding bins s_i^+ s_i^- , so Equation 5.1 becomes

$$\begin{aligned} & -\mu s_i(\theta) - b_i(r_{ZZ}, r_{X\gamma}, r_{t\bar{t}Z}, r_{tZq}, \theta) \rightarrow \\ & \rightarrow -\mu \frac{1 + A_{WZ,SM}^{+-}}{1 + qA_{WZ,SM}^{+-}} [qs_i^+(\theta) + s_i^-(\theta)] - b_i(r_{ZZ}, r_{X\gamma}, r_{t\bar{t}Z}, r_{tZq}, \theta) \end{aligned} \quad (5.9)$$

where $s_i^+(\theta)$ and $s_i^-(\theta)$ are respectively the yields for the plus and minus final states. The slightly complex definition of the signal modifiers appears such that μ . Using this parametrization, the signal yields at the best fit values of the μ and q quantities can be extracted for the W^+Z and W^-Z , as well as the full correlation matrix of such yields at the best fit value. From the later, the correlation term between the W^+Z and W^-Z yields, V^{+-} , is needed to later properly propagate the overall uncertainties to the A_{WZ}^{+-} quantity. The results on the charge exclusive final state can then be extrapolated to the fiducial phase space following Equation 5.2.

Both the efficiencies and the proportion of non fiducial events in the SR were found to be consistently equal for the W^+Z and W^-Z so the inclusive measurement of both quantities is used to extrapolate the measurements to the fiducial region. The A_{WZ}^{+-} quantity and its uncertainties are then computed as

$$\begin{aligned} A_{WZ}^{+-} &= \frac{\sigma_{\text{fid}}(\text{pp} \rightarrow W^+Z)}{\sigma_{\text{fid}}(\text{pp} \rightarrow W^-Z)} \\ \delta(A_{WZ}^{+-}) &= \sqrt{\left(\frac{1}{\sigma_-}\right)^2 \delta_+^2 + \left(\frac{\sigma_+}{\sigma_-^2}\right)^2 \delta_-^2 - 2V^{+-} \left(\frac{1}{\sigma_-}\right) \left(\frac{\sigma_+}{\sigma_-^2}\right) \delta_+ \delta_-} \end{aligned} \quad (5.10)$$

where $\sigma_+ \pm \delta_+$ and $\sigma_- \pm \delta_-$ are short for the measured fiducial cross sections in each charged final state and their uncertainties. The last term incorporates the correlation between the uncertainties as obtained from the correlation matrix of the fit.

5.6.2 Measured values of the charge asymmetry

The distribution of yields across lepton flavour states used in Section 5.5 has little sensitivity to the charge of the produced W boson. As such, a different variable needs to be included into the fit in the SR that provides a better handle to separate the contributions from W^+Z and W^-Z . The chosen variable is the sum of the charge of all identified leptons in the final state which is expected to be equal to the charge of the W boson in WZ production. No further variable binning is included as expectations are that the measurement of A_{WZ}^{+-} will be strongly dominated by the statistic uncertainty of the observed data. The rest of the likelihood function is built as described for Section 5.5 with the same distributions used to constrain each background process in its dedicated CR.

The estimation of the discriminating variable for the different major backgrounds is validated in each of the background CR and shown in Figure 5.10, where good overall

agreement is seen for all the considered CRs. It has to be pointed out again that these distributions are shown for validation of the variables and that they are not used in the signal extraction fit described in Section 5.6.1.

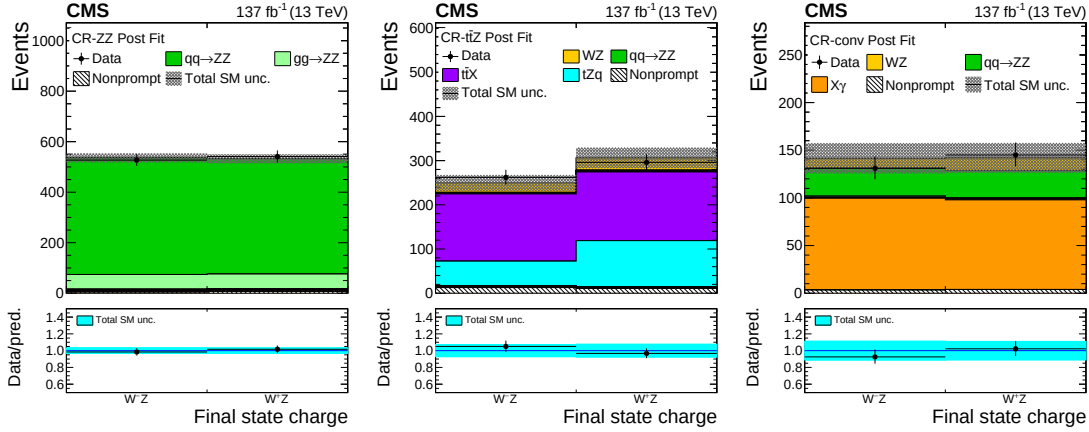


FIGURE 5.10: Expected and observed distributions of the total leptonic charge at reconstructed level using the value of the nuisances after the inclusive cross section fit. From left to right: ZZ CR, $t\bar{t}X$ CR and $X\gamma$ CR. The sum of all uncertainties of the inclusive cross section fit are presented in the shaded bands of the main plot and the light blue band of the ratio plots. In the case of CR-ZZ, only the three leading leptons are used to compute the final state charge, representing the fourth one being missing as in events passing the SR selection.

The distribution of total leptonic charge in the WZ-SR can be observed in Figure 5.11. The clear level of asymmetry between the W^+Z and W^-Z states can be directly observed in both data and expectations. Good agreement, at the 1% level, is found between both of them. The probabilities for the mismeasuring of the charge on the WZ signal due to lepton charge misidentification were found to be overall negligible once the charge consistency criteria is applied in the lepton selection, not even reaching the 0.1% of the overall yields in the most complex eee channel, with similar effects in the W^+Z and W^-Z production that cancel out in the ratio of fiducial cross sections.

The procedure described in the previous section is followed to estimate the charge exclusive fiducial cross section measurements in each of the four final flavoured states introduced for the inclusive cross section measurement in Section 5.5, as well as for the combination of all of them. The results are shown in Table 5.9 (W^+Z production) and 5.10 (W^-Z production). The different measurements show overall preference for the higher order predictions from MATRIX rather than the one from POWHEG, but the sensitivity obtained is not high enough to distinguish between the cases that include or not the NLO EWK corrections which are relatively small for all cases. The greatest fluctuations appear in the eee channel which has the less statistical power, but are still within 1σ of the SM values as predicted by MATRIX. Overall, the results just reproduce the same kind of behaviours that were seen in the charge inclusive cross section measurements, with the $\mu\mu\mu$ channel being the most precise and near as precise as the combined measurement.

The results from the fit to the combination of the four flavour states show, as well, that the non-statistical source of uncertainty in the W^+Z and W^-Z yields is strongly correlated, with a cross-term of the covariance matrix of approximately $V^{+-} \approx 0.75$. This effect is a consequence of the fact that the dominating systematic and luminosity

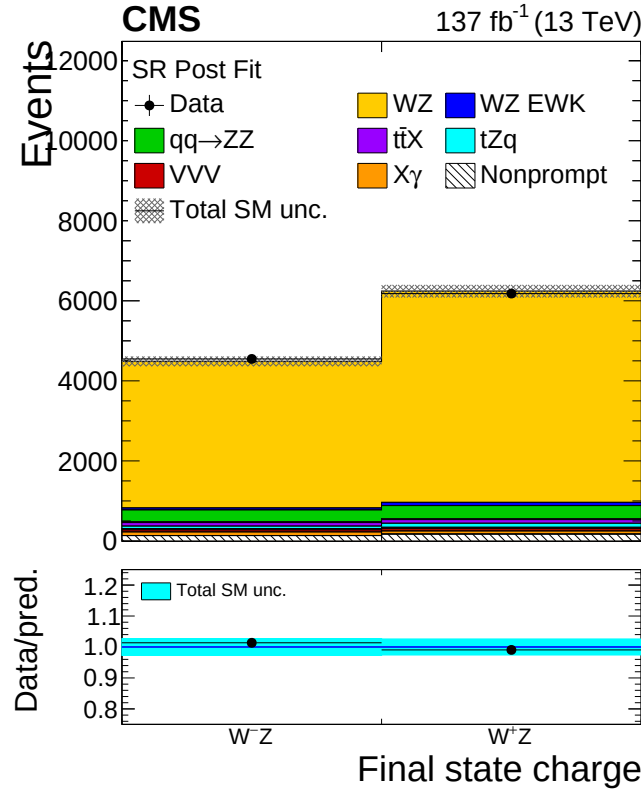


FIGURE 5.11: Expected distribution of the total leptonic charge after the charge asymmetry extraction fit is performed, and corresponding distributions in data. All uncertainties included in the fits are presented in the shaded bands of the main plot and the light blue band of the ratio plots at their postfit values from the charge asymmetry fit.

uncertainties mostly have a similar impact in each of the two charged final states, so the whole set of associated uncertainties are near completely correlated between the two. The remaining 25% of decorrelation is due to the statistical uncertainties that are, of course, decorrelated between the charged final states. The values of A_{WZ}^{+-} computed following Equation 5.10 are presented in Table 5.11 for the flavour exclusive results as well as for their combination.

As expected, the results are strongly dominated by an statistical uncertainty that diminishes as the amount of data present in the measuring channel increases, with the greatest uncertainty of slightly under the 10% corresponding to the eee channel. The final inclusive measurement is the more precise with a total relative uncertainty of under 3%. Another interesting point is how the predictions computed at different orders in perturbative QCD and EWK introduce little changes to the predicted values of the asymmetry measurement. In fact, the predictions do show notable fluctuations only when alternative PDF sets were considered to estimate the charge asymmetry. In a comparison between the NNPDF30_nlo_as_0118_mc, CT14nlo, and MMHT2014nlo68cl PDF sets using the nominal POWHEG sample, the central predictions showed differences of up to 4% between sets. Thus, the quoted uncertainty due to the PDF set used includes the envelope of these effects. The effect of the PDF selection on the overall charge asymmetry prediction derives from the strict fixing of the initial state partons introduced by the charged final state in WZ production, as discussed earlier, and is

TABLE 5.9: Measured fiducial cross sections and their corresponding uncertainties for each of the individual flavour categories, as well as for their combination, for positively charged final states. The predictions from both MATRIX (at NNLO QCD and NNLO QCD $\times$ NLO EWK) and POWHEG (at NLO QCD) are also included.

Channel	Fiducial cross section
eee^+ (POWHEG)	$36.7^{+1.3}_{-0.9}(\text{scale}) \pm 0.7(\text{PDF}) \text{ fb}$
eee^+ (MATRIX, NNLO QCD)	$45.2^{+1.1}_{-0.9}(\text{scale}) \text{ fb}$
eee^+ (MATRIX, NNLO QCD $\times$ NLO EWK)	$44.3^{+1.0}_{-0.9}(\text{scale}) \text{ fb}$
eee^+ (Measured)	$49.3 \pm 3.4(\text{stat.}) \pm 1.9(\text{syst.}) \pm 1.0(\text{lumi.}) \pm 0.5(\text{theo.}) \text{ fb}$
$ee\mu^+$ (POWHEG)	$36.7^{+1.3}_{-0.9}(\text{scale}) \pm 0.7(\text{PDF}) \text{ fb}$
$ee\mu^+$ (MATRIX, NNLO QCD)	$44.3^{+1.0}_{-0.9}(\text{scale}) \text{ fb}$
$ee\mu^+$ (MATRIX, NNLO QCD $\times$ NLO EWK)	$43.3^{+1.0}_{-0.9}(\text{scale}) \text{ fb}$
$ee\mu^+$ (Measured)	$41.5 \pm 1.9(\text{stat.}) \pm 1.6(\text{syst.}) \pm 0.9(\text{lumi.}) \pm 0.4(\text{theo.}) \text{ fb}$
$\mu\mu e^+$ (POWHEG)	$36.7^{+1.3}_{-0.9}(\text{scale}) \pm 0.7(\text{PDF}) \text{ fb}$
$\mu\mu e^+$ (MATRIX, NNLO QCD)	$44.3^{+1.0}_{-0.9}(\text{scale}) \text{ fb}$
$\mu\mu e^+$ (MATRIX, NNLO QCD $\times$ NLO EWK)	$43.3^{+1.0}_{-0.9}(\text{scale}) \text{ fb}$
$\mu\mu e^+$ (Measured)	$43.1 \pm 1.4(\text{stat.}) \pm 1.5(\text{syst.}) \pm 0.9(\text{lumi.}) \pm 0.4(\text{theo.}) \text{ fb}$
$\mu\mu\mu^+$ (POWHEG)	$36.7^{+1.3}_{-0.9}(\text{scale}) \pm 0.7(\text{PDF}) \text{ fb}$
$\mu\mu\mu^+$ (MATRIX, NNLO QCD)	$45.2^{+1.1}_{-0.9}(\text{scale}) \text{ fb}$
$\mu\mu\mu^+$ (MATRIX, NNLO QCD $\times$ NLO EWK)	$44.3^{+1.0}_{-0.9}(\text{scale}) \text{ fb}$
$\mu\mu\mu^+$ (Measured)	$44.3 \pm 1.0(\text{stat.}) \pm 1.5(\text{syst.}) \pm 1.0(\text{lumi.}) \pm 0.4(\text{theo.}) \text{ fb}$
Inclusive (+) (POWHEG)	$146.9^{+5.7}_{-4.7}(\text{scale}) \pm 2.1(\text{PDF}) \text{ fb}$
Inclusive (+) (MATRIX, NNLO QCD)	$179.0^{+4.3}_{-3.8}(\text{scale}) \text{ fb}$
Inclusive (+) (MATRIX, NNLO QCD $\times$ NLO EWK)	$175.3^{+4.1}_{-3.7}(\text{scale}) \text{ fb}$
Inclusive (+) (Measured)	$175.9 \pm 3.0(\text{stat.}) \pm 5.6(\text{syst.}) \pm 3.6(\text{lumi.}) \pm 1.7(\text{theo.}) \text{ fb}$

TABLE 5.10: Measured fiducial cross sections and their corresponding uncertainties for each of the individual flavour categories, as well as for their combination, for negatively charged final states. The predictions from both MATRIX (at NNLO QCD and NNLO QCD $\times$ NLO EWK) and POWHEG (at NLO QCD) are also included.

Channel	Fiducial cross section
eee^- (POWHEG)	$25.8^{+0.9}_{-0.6}(\text{scale}) \pm 0.6(\text{PDF}) \text{ fb}$
eee^- (MATRIX, NNLO QCD)	$31.6^{+0.8}_{-0.7}(\text{scale}) \text{ fb}$
eee^- (MATRIX, NNLO QCD $\times$ NLO EWK)	$31.0^{+0.7}_{-0.6}(\text{scale}) \text{ fb}$
eee^- (Measured)	$36.2 \pm 3.3(\text{stat.}) \pm 1.4(\text{syst.}) \pm 0.7(\text{lumi.}) \pm 0.3(\text{theo.}) \text{ fb}$
$ee\mu^-$ (POWHEG)	$25.8^{+0.9}_{-0.6}(\text{scale}) \pm 0.6(\text{PDF}) \text{ fb}$
$ee\mu^-$ (MATRIX, NNLO QCD)	$31.0^{+0.8}_{-0.7}(\text{scale}) \text{ fb}$
$ee\mu^-$ (MATRIX, NNLO QCD $\times$ NLO EWK)	$30.4^{+0.7}_{-0.6}(\text{scale}) \text{ fb}$
$ee\mu^-$ (Measured)	$29.7 \pm 1.7(\text{stat.}) \pm 1.1(\text{syst.}) \pm 0.6(\text{lumi.}) \pm 0.3(\text{theo.}) \text{ fb}$
$\mu\mu e^-$ (POWHEG)	$25.8^{+0.9}_{-0.6}(\text{scale}) \pm 0.6(\text{PDF}) \text{ fb}$
$\mu\mu e^-$ (MATRIX, NNLO QCD)	$31.0^{+0.8}_{-0.7}(\text{scale}) \text{ fb}$
$\mu\mu e^-$ (MATRIX, NNLO QCD $\times$ NLO EWK)	$30.4^{+0.7}_{-0.6}(\text{scale}) \text{ fb}$
$\mu\mu e^-$ (Measured)	$31.8 \pm 1.4(\text{stat.}) \pm 1.1(\text{syst.}) \pm 0.6(\text{lumi.}) \pm 0.3(\text{theo.}) \text{ fb}$
$\mu\mu\mu^-$ (POWHEG)	$25.8^{+0.9}_{-0.6}(\text{scale}) \pm 0.6(\text{PDF}) \text{ fb}$
$\mu\mu\mu^-$ (MATRIX, NNLO QCD)	$31.6^{+0.8}_{-0.7}(\text{scale}) \text{ fb}$
$\mu\mu\mu^-$ (MATRIX, NNLO QCD $\times$ NLO EWK)	$31.0^{+0.7}_{-0.6}(\text{scale}) \text{ fb}$
$\mu\mu\mu^-$ (Measured)	$30.7 \pm 0.9(\text{stat.}) \pm 1.0(\text{syst.}) \pm 0.7(\text{lumi.}) \pm 0.3(\text{theo.}) \text{ fb}$
Inclusive (-) (POWHEG)	$103.1^{+4.0}_{-3.3}(\text{scale}) \pm 1.4(\text{PDF}) \text{ fb}$
Inclusive (-) (MATRIX, NNLO QCD)	$125.2^{+4.3}_{-3.8}(\text{scale}) \text{ fb}$
Inclusive (-) (MATRIX, NNLO QCD $\times$ NLO EWK)	$122.8^{+4.1}_{-3.7}(\text{scale}) \text{ fb}$
Inclusive (-) (Measured)	$124.8 \pm 2.7(\text{stat.}) \pm 4.0(\text{syst.}) \pm 2.5(\text{lumi.}) \pm 1.1(\text{theo.}) \text{ fb}$

explored into more detail in Section 5.7. A summary plot that shows the content of Table 5.11 can be found in Figure 5.12.

TABLE 5.11: Measured A_{WZ}^{+-} quantities and their corresponding uncertainties for each of the individual flavour categories, as well as for their combination. The predictions from both MATRIX (at NNLO QCD and NNLO QCD $\times$ NLO EWK) and POWHEG (at NLO QCD) are also included. For the case of POWHEG, different PDF sets showed consistently different results so the envelope of uncertainties from the NNPDF, CT14 and MMHT2014 sets were used to estimate the overall uncertainty from the PDF on the measurement. Predictions from MATRIX are included for different elections of the PDF set.

Channel	Asymmetry ratio
POWHEG	$1.42^{+0.06}_{-0.05}(\text{PDF+scale})$
MATRIX (NNLO QCD)	$1.428^{+0.002}_{-0.002}(\text{scale})$
MATRIX (NNLO QCD $\times$ NLO EWK)	$1.427^{+0.002}_{-0.002}(\text{scale})$
eee (Measured)	$1.36 \pm 0.13(\text{stat.}) \pm 0.01(\text{syst.}) \pm 0.01(\text{lumi.})$
$ee\mu$ (Measured)	$1.40 \pm 0.12(\text{stat.}) \pm 0.02(\text{syst.}) \pm 0.01(\text{lumi.})$
$\mu\mu e$ (Measured)	$1.36 \pm 0.08(\text{stat.}) \pm 0.02(\text{syst.}) \pm 0.01(\text{lumi.})$
$\mu\mu\mu$ (Measured)	$1.44 \pm 0.05(\text{stat.}) \pm 0.02(\text{syst.}) \pm 0.01(\text{lumi.})$
Inclusive (Measured)	$1.41 \pm 0.04(\text{stat.}) \pm 0.01(\text{syst.}) \pm 0.01(\text{lumi.})$

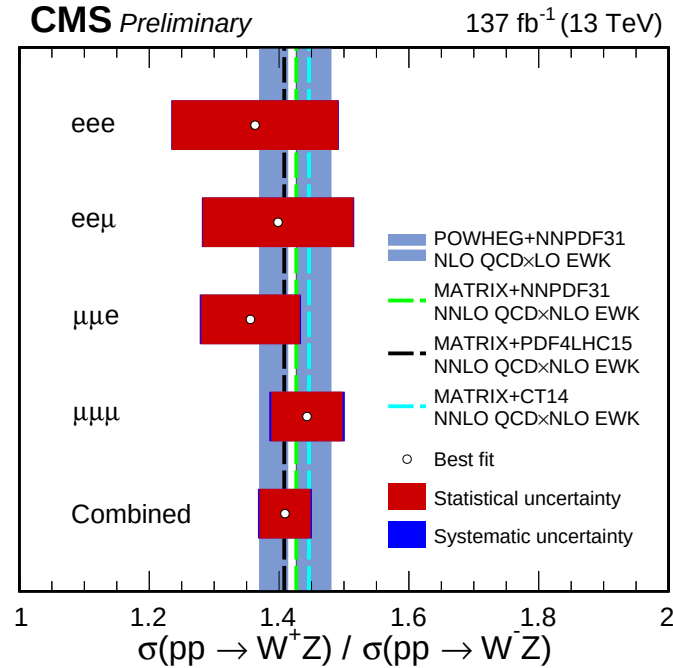


FIGURE 5.12: Observed and expected values of the A_{WZ}^{+-} and predictions from POWHEG at NLO in QCD and MATRIX at NNLO in QCD $\times$ NLO in EWK. The predictions from POWHEG include the uncertainty corresponding to theoretical sources and the overall band includes the envelope of the PDF uncertainties from the NNPDF, CT14nlo, and MMHT2014. The predictions from MATRIX don't include the PDF uncertainties but are shown as separate bands for several NNLO PDF sets.

5.7 WZ production and Parton Distribution Functions

As discussed in Section 5.6, the structure of the proton strongly fixes the hierarchy of production cross sections for W^+Z and W^-Z . Then, it is natural to assume that the ratio of production cross sections of one over the other will be sensitive to variations on the properties of these initial state particles itself, the PDFs of the u and d quarks. The relatively low uncertainty associated to the measurement of this quantity, as described in Section 5.6, points towards the possibility of using this measurement itself to check the validity of current PDF modelling sets. Namely, to check the compatibility of different PDF sets with the presented experimental measurement and the possibility of constraining their associated uncertainties with the new knowledge this measurement provides.

An additional case could be made that the inclusive cross section should also be able to provide a similar sensitivity to the effects of PDF modelling. While the precision achieved in the inclusive cross section measurement is indeed small enough to present such a case, there are several points to take into account against it. First and foremost, the inclusive cross section is much less resilient against higher order theoretical corrections and, as such, to other theoretical uncertainties coming -for example- from the chosen renormalization and factorization scales. As an example, the overall perturbative corrections from the NLO to the NNLO in QCD predictions for the inclusive cross section are greater than 10%, while similar ones for the charge asymmetry are less than 0.1%. Second, in case more data were available, such as after a new data taking period of the LHC, the precision of the statistically dominated charge asymmetry measurement would be improved much quicker than the systematically dominated inclusive cross section, making it a much better probe for future analysis. Last, the overall uncertainty in the charge asymmetry is slightly smaller than that of the inclusive cross section.

5.7.1 Bayesian reweighting applied to PDF consistency checks

In order to estimate the consistency of the charge asymmetry observation with the predictions from a given PDF set, a Bayesian reweighting technique is used [178–180]. The underlying procedure and assumptions are briefly detailed in this section.

The aim of a representation of the PDFs (set) is to provide a full prediction of the PDFs of the proton and the uncertainties on such predictions as extrapolated from several measurements performed on data. As such, they introduce modifications in Equation 2.35 which for a general observable, not necessarily a cross section, $\langle Z \rangle$ that can be computed starting by double-partonic level quantities Z_{ij}

$$\langle Z \rangle = \int d\theta Z(\theta) \Theta(\theta) = \sum_{i,j=0}^{N_f} \int dx_i dx_j d\theta f_i(x_i, \mu_F, \theta) f_j(x_j, \mu_F, \theta) Z_{ij}(x_i x_j) \Theta(\theta) \quad (5.11)$$

where θ represents a set of underlying parameters representing the possible configurations of the PDFs and $\Theta(\theta)$ is the distribution of such underlying parameters. In the case of this studies they are of special interest the so called MC sets, in which

the representation of the PDF set is simplified into a set of N discrete replicas, each one with exactly the same associated probability. The functional form of $\Theta(\theta)$ then becomes

$$\Theta(\theta) = \frac{1}{N} \sum_{r=1}^N \delta(\theta - \theta_r) \quad (5.12)$$

where θ_r are fixed values of the underlying parameters that lead to a fixed setup of the PDFs in replica r . Thus, Equation 5.11 can be expressed as

$$\langle Z \rangle = \frac{1}{N} \sum_{r=1}^N Z_r = \frac{1}{N} \sum_{r=1}^N \sum_{i,j=0}^{N_f} \int dx_i dx_j f_i^r(x_i, \mu_F) f_j^r(x_j, \mu_F) Z_{ij}(x_i x_j s; \mu_R, \mu_F) \quad (5.13)$$

where Z_r are the observable predictions for replica r , and f_j^r and f_i^r are just the PDF prediction for parton flavour j or i , and replica r . Do notice that the dependence of $\langle Z \rangle$ on the different sources of uncertainty is effectively parametrized by the replicas in a discrete probability function in which each of the predictions Z_r has an equal probability associated. All computations can then be done assuming that Z is a discrete random variable in the PDF space that has been sampled N times corresponding to the N PDF replicas. The overall uncertainty on Z can then be obtained through the sample covariance as:

$$\delta^{PDF}(Z) = \sqrt{\frac{1}{N} \sum_{r=1}^N (Z_r - \langle Z \rangle)^2} \quad (5.14)$$

Once the treatment of the PDFs and its uncertainties is well established, the problem of quantifying the compatibility of such predictions with observations and the amount of improvement such observations can provide to increase the precision of the PDF sets arises.

First, assume that a measurement of the Z observable is designed in such a way that the pdf for a measurement result Z and fixed configuration of the PDFs θ is known: $f(Z, \theta)$. Then the consistency of a fixed observed measurement Z_{obs} with the whole PDF representation can be obtained as a p-value just by integrating

$$p(Z_{obs}) = \int_{\Omega_{obs}} dZ \int d\theta f(Z, \theta), \quad \Omega_{obs} = \left\{ Z \left| \int d\theta f(Z, \theta) < \int d\theta f(Z_{obs}, \theta) \right. \right\} \quad (5.15)$$

where Ω_{obs} is just the region where the results are as probable or less than the observed one. Once the MC representation of the PDF set is considered, using Equation 5.12 on Equation 5.15 the p-value relation can be simplified to

$$p(Z_{obs}) = \frac{1}{N} \sum_{r=1}^N \int_{\Omega_{obs}} dZ f(Z, \theta_r) \quad (5.16)$$

where $f(Z, \theta_r)$ is the two dimensional probability function evaluated at the PDF conditions of replica r . The functional form of $f(Z, \theta_r)$ should be fixed depending on the assumptions on the set of experimental uncertainties entering the measurement and their possible correlation to the PDF modelling. Assuming that the uncertainties on the measurement are Gaussian of mean Z and fixed width -representing experimental uncertainty- δ and that the predicted value of the observable obtained from replica r is Z_r , $f(Z, \theta_r)$ just takes the form

$$f(Z, \theta_r) = \frac{e^{-\frac{(Z-Z_r)^2}{2\delta^2}}}{\sqrt{2\pi\delta^2}} \quad (5.17)$$

which is just the likelihood of the expectation Z_r for a measurement and uncertainty of $Z \pm \delta$. Plugging in Equation 5.17 into 5.16 the p value for the consistency of a MC set with a single Gaussian measurement can be obtained as

$$p(Z_{obs}) = \frac{2}{N} \sum_{r=1}^N \int_{Z_{obs}}^{\infty} dZ \frac{e^{-\frac{(Z-Z_r)^2}{2\delta^2}}}{\sqrt{2\pi\delta^2}} \quad (5.18)$$

where a factor 2 arises from considering the two sides of the Gaussian probability tails, as inconsistency with the PDF set might appear from either an excess or a defect of Z over Z_r .

If a PDF set is consistent with the observed measurements, the information from new observables can be incorporated into it in order to improve the its overall predictions in terms of lower uncertainties. The Bayesian reweighting technique used for this procedure is based on the well known Bayes Formula. For a general set of PDF represented by the underlying parameter θ and a new observation Z the posterior probability for the PDF sets can be wrote as

$$f(\theta|Z) = \frac{f(Z|\theta)}{f(Z)} f(\theta) \quad (5.19)$$

the different elements needed for the computation of the posterior $f(\theta|Z)$ have been already developed in the previous pages for the specific case of a MC PDF set as, barring normalization effects, it is defined in Equation 5.17. The prior distribution $f(\theta)$ is just the prior hypothesis $\Theta(\theta)$ described in Equation 5.12. Thus, the conditional probability is, up to normalization factors, equivalent to the result on 5.17. Finally, $f(Z)$ can be, as usual, safely ignored and replaced by the normalization condition of the set of posterior probabilities $\int d\theta f(\theta|Z) = 1$. Applying all pertinent substitutions it can be found that

$$f(\theta|Z) \sim \frac{1}{N} \sum_{r=1}^N \frac{e^{-\frac{(Z-Z_r)^2}{2\delta^2}}}{\sqrt{2\pi\delta^2}} \delta(\theta - \theta_r) \quad (5.20)$$

and, once the normalization condition is applied

$$f(\theta|Z) = \sum_{r=1}^N w_r \delta(\theta - \theta_r), \quad w_r = \frac{e^{-\frac{(Z-Z_r)^2}{2\delta^2}}}{\sum_{s=1}^N \frac{e^{-\frac{(Z-Z_s)^2}{2\delta^2}}}{\sqrt{2\pi\delta^2}}} \quad (5.21)$$

where the w_r quantities, or posterior weights, have been introduced. Notice that these quantities act by assigning a greater posterior probability to specific regions of the PDF phase space that are more compatible with the measurement, effectively weighting the posterior pdf towards the observation. The prediction for any observable and its associated PDF uncertainty with the additional information obtained from the new measurement can just be obtained from updated versions of Equations 5.13 and 5.14 as

$$\langle Z \rangle_{post} = \sum_{r=1}^N w_r Z_r, \quad \delta^{PDF}(Z)_{post} = \sqrt{\sum_{r=1}^N w_r (Z_r - \langle Z \rangle_{post})^2} \quad (5.22)$$

5.7.2 Results on PDF constraining

The procedure discussed in Section 5.7.1 is applied to study the consistency of the charge asymmetry measurements presented in Section 5.6 with the NNPDF30_nlo_as_0118[88] set, with the main motivation behind this choice being that it is the one used for the production of the MC corresponding to the 2016 data taking year, while the nominal sets for 2017 and 2018 do not correspond to MC representations of the PDFs. The whole set of Equations 5.13, 5.14, 5.18, 5.21, and 5.13 apply under the substitution of the generic observable by the charge asymmetry described in Section 5.6, $Z \rightarrow A_{WZ}^{+-}$, and the generic uncertainty by the measured uncertainty of this quantity $\delta \rightarrow \delta(A_{WZ}^{+-})$. The observable predictions from each replica in the PDF set are replaced by the corresponding charge asymmetry predictions $Z_r \rightarrow A_{WZ,r}^{+-}$. Then, the p value for the consistency of the measurements with the NNPDF30_nlo_as_0118set is

$$p(Z_{obs}) = \frac{2}{N} \sum_{r=1}^N \int_{A_{WZ}^{+-}}^{\infty} dZ \frac{e^{-\frac{(A_{WZ}^{+-} - A_{WZ,r}^{+-})^2}{2\delta^2(A_{WZ}^{+-})}}}{\sqrt{2\pi\delta^2(A_{WZ}^{+-})}} = 0.747 \quad (5.23)$$

which points towards a consistent agreement between the PDF set and the measured charge asymmetry. Following the Bayesian Reweighting method, the corresponding posterior weights are computed as

$$w_r = \frac{e^{-\frac{(A_{WZ}^{+-} - A_{WZ,r}^{+-})^2}{2\delta^2(A_{WZ}^{+-})}}}{\sum_{s=1}^N \frac{e^{-\frac{(A_{WZ}^{+-} - A_{WZ,s}^{+-})^2}{2\delta^2(A_{WZ}^{+-})}}}{\sqrt{2\pi\delta^2(A_{WZ}^{+-})}}} \quad (5.24)$$

the resulting set of weights is presented in Figure 5.13 (top) for the $N = 100$ replicas included in the NNPDF30_nlo_as_0118set. As the current measurement still has an

overall sizeable uncertainty due to the limited statistical power of the measurement, the constraints themselves are small except for the most extreme cases in which PDF replicas introduce big variations of the asymmetry ratio, such as for replicas 5 and 63.

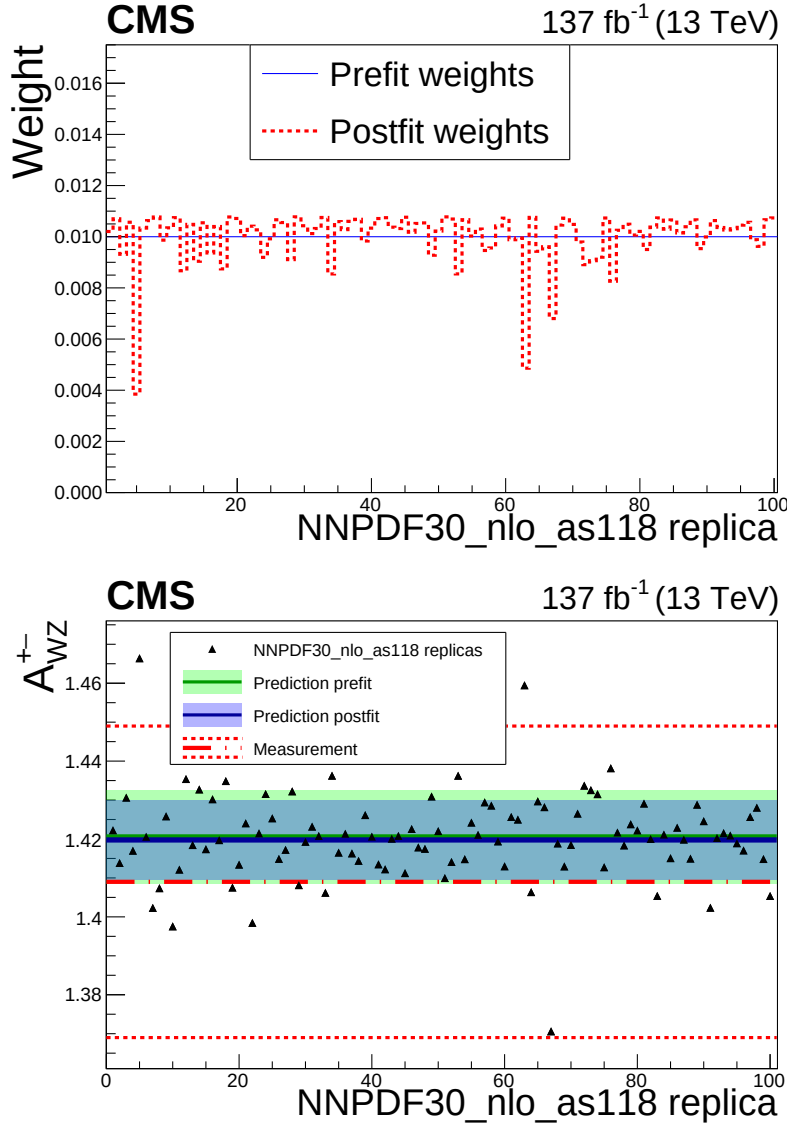


FIGURE 5.13: (Top) Weights associated with each PDF replica in the NNPDF30_nlo_as_0118set before (blue) and after (red) the Bayesian reweighting technique is applied to the measurement of the ratio charge asymmetry. (Bottom) Predictions and observations of the A_{WZ}^{+-} quantity obtained using the simulated POWHEG sample with the NNPDF30_nlo_as_0118PDF set. The central green line and shaded band correspond to the nominal predicted values and the associated PDF uncertainty before Bayesian reweighting is applied. The central blue line and shaded band correspond to the predicted values and the associated PDF uncertainty after Bayesian reweighting is applied. Each of the triangle markers corresponds to the individual $A_{WZ,r}^{+-}$ predictions for each replica. The red lines correspond to the observed value of A_{WZ}^{+-} and the corresponding experimental uncertainties.

Once the postfit weights are obtained, Equation 5.22 can be used to estimate the predictions from the NNPDF30_nlo_as_0118set after the Bayesian reweighting is applied, as well as the updated PDF uncertainty. The results are shown graphically in Figure

5.13 (bottom) in which the good consistency between expectations and observations is seen again. As expected, the clear outlier predictions, represented by the black triangle markers that fall outside the observed bands, correspond to the PDF replicas that are more tightly constrained by the technique. The effect on the PDF uncertainty is, however, relatively small due to the limited quantity of data available, which is itself the limiting factor of the measured values. In fact, the central value of the prediction is only slightly pulled towards the observed A_{WZ}^{+-} value, pointing out towards the fact that the quantity of information in the original PDF set is still quite superior to the one provided by this new measurement. The total uncertainty related to PDF modelling in the prediction of the A_{WZ}^{+-} quantity decreases by around a 10%, which means that the additional information from the WZ charge asymmetry does help to constrain PDF uncertainties and provides additional information to the general knowledge of the proton structure.

5.8 Boson polarization

As discussed in Section 2.2.2, the fact that the W and Z bosons can be longitudinally-polarized is a consequence of their massive nature, itself derived from the spontaneous symmetry breaking mechanism. Measuring the polarization properties of both of them in WZ production is, thus, a probe of the Higgs mechanism of the SM. As small asymmetries are to be expected between W^+Z and W^-Z production on the polarization fractions, due to the different energy spectra of the production modes, the results will be provided both in the charge inclusive and the two possible charge split final states.

5.8.1 Extraction of polarization fractions

The study of the polarization of the W and Z bosons is mostly based on the relations described in Equations 2.18 and 2.19. Those correspond to generic differential cross sections of any processes involving leptonic W (Z) decays with respect to the cosine of the polarization angle $\theta_{gen}^W(\theta_{gen}^Z)$, the angle between the W (Z) vector boson and the charged lepton (negatively charged lepton) on its decay. The formulas are reproduced here for clarity:

$$\frac{d\sigma}{\sigma d\cos(\theta_{gen}^W)} = \frac{3}{8} \left[(1 \mp \cos(\theta_{gen}^W)) f_L^{W,SM} + (1 \pm \cos(\theta_{gen}^W))^2 f_R^{W,SM} + 2 \sin^2(\theta_{gen}^W) f_O^{W,SM} \right] \quad (5.25)$$

$$\frac{d\sigma}{\sigma d\cos(\theta_{gen}^Z)} = \frac{3}{8} \left[(1 + \cos^2(\theta_{gen}^Z) - 2c \cos(\theta_{gen}^Z)) f_L^{Z,SM} + (1 + \cos^2(\theta_{gen}^Z) + 2c \cos(\theta_{gen}^Z)) f_R^{Z,SM} + 2 \sin^2(\theta_{gen}^Z) f_O^{Z,SM} \right] \quad (5.26)$$

where $\{f_L^{W,SM}, f_R^{W,SM}, f_O^{W,SM}\}$ ($\{f_L^{Z,SM}, f_R^{Z,SM}, f_O^{Z,SM}\}$) are called the polarization fractions of the W (Z) bosons and fulfil the additional condition $f_L^{W,SM} + f_R^{W,SM} + f_O^{W,SM} = f_L^{Z,SM} + f_R^{Z,SM} + f_O^{Z,SM} = 1$. In the case of the W, the upper signs on each term correspond to W^+ production and the lower ones to W^- production. The usage of the *gen* subindex and SM superindex differs slightly from the notation in Section 2.2.2 and is introduced to properly separate these expected quantities from the later reconstructed polarization angles and measured values of the polarization fractions.

A first step in the measurement is the extraction of the SM predictions for the polarization fractions. As these fractions are frame dependant quantities, the coordinate frame needs to be fixed first. The Helicity (HE) frame is one of the most common choices in the literature, and in the following sections the definition described in Reference [181] of it is used. To reach the HE frame, the following steps are followed:

1. Start from the laboratory frame, O , corresponding to two incoming protons along the z axis with opposite momentum.
2. The laboratory frame is rotated such that the W (Z) boson is aligned along the new z' axis. This is the O' frame.
3. The O' frame is then boosted along the z' axis until the W (Z) boson is at rest. This is the HE frame.
4. The polarization angle θ_{gen}^W (θ_{gen}^Z) is the angle between the charged lepton (negatively charged lepton) and the z axis of the HE frame computed with the lepton and boson momenta described at the generator level.

As differential cross sections in the HE frame will follow Equations 5.25 and 5.26, the polarization fractions can be extracted from the MC by studying the differential distributions of $\cos(\theta_{gen}^Z)$ and $\cos(\theta_{gen}^W)$ at the generator level. It has to be pointed out that Equations 5.25 and 5.26 only apply if no kinematic requirements are applied to either of the decay products of the massive gauge bosons, so fiducial requirements will directly break the quadratic dependency needed to extract the polarization fractions. Thus, such differential cross sections need to be studied at the total cross section selection level as defined in Section 5.5.

Two complementary approaches are taken for the extraction of the SM predictions. The first one relies on directly fitting the $\cos(\theta_{gen}^W)$ ($\cos(\theta_{gen}^Z)$) distributions to Equation 5.25 (5.26). The second one is to apply that

$$\begin{aligned}
 f_0 + f_L + f_R &= 1 \\
 \int_{-1}^1 \cos(\theta_{gen}^Z) \frac{d\sigma}{\sigma d\cos(\theta_{gen}^Z)} d\cos(\theta) &= c \frac{f_R^{Z,SM} - f_L^{Z,SM}}{2} \\
 \int_{-1}^1 \cos^2 \theta_{gen}^Z \frac{d\sigma}{\sigma d\cos(\theta_{gen}^Z)} d\cos(\theta) &= \frac{f_O^{Z,SM} + 2f_R^{Z,SM} + 2f_L^{Z,SM}}{5}
 \end{aligned} \tag{5.27}$$

which applies for the W boson as well by setting $c = 1$ and inverting the role of the f_R and f_L coefficients for the W^- case. The fitting method is applied using the simulation provided by both POWHEG and MATRIX at the total region level and the results

are cross checked with the ones obtained by the second approach by doing numerical integration over the POWHEG MC. A comparison of the values can be observed in Table 5.12, where good consistency is confirmed between all three different derivations showing agreement between the MATRIX and POWHEG predictions within the statistical uncertainties of the measurements. Around a fourth of the produced W and Z bosons correspond to the specially interesting longitudinally-polarized case.

TABLE 5.12: Predicted SM values for the W and Z polarization parameters for WZ production in the charge inclusive and each of the charge split final state cases. Values are obtained with POWHEG at NLO in QCD and with MATRIX at NNLO in QCD and NLO in EWK. Uncertainties presented correspond to MC statistics for POWHEG and numerical uncertainties in the fitting procedure for MATRIX. Results from both the integral and fit method are presented for POWHEG, only the results from the fitting method are presented for MATRIX.

Boson and charge	Observable	POWHEG expected, integral	POWHEG expected, fit	MATRIX expected, fit
W, inclusive	$f_{O,W,SM}^{W,SM}$	$0.246^{+0.002}_{-0.002}$	$0.247^{+0.001}_{-0.001}$	$0.248^{+0.003}_{-0.003}$
	$f_{L,W,SM}^{W,SM}$	$0.481^{+0.001}_{-0.001}$	$0.481^{+0.002}_{-0.002}$	$0.481^{+0.004}_{-0.004}$
	$f_{R,W,SM}^{W,SM}$	$0.272^{+0.001}_{-0.001}$	$0.272^{+0.002}_{-0.002}$	$0.271^{+0.004}_{-0.004}$
	$f_{O,W,SM}^{W,SM}$	$0.226^{+0.002}_{-0.002}$	$0.229^{+0.002}_{-0.002}$	$0.237^{+0.004}_{-0.004}$
W, plus	$f_{L,W,SM}^{W,SM}$	$0.540^{+0.001}_{-0.001}$	$0.538^{+0.003}_{-0.003}$	$0.528^{+0.005}_{-0.005}$
	$f_{R,W,SM}^{W,SM}$	$0.234^{+0.001}_{-0.001}$	$0.233^{+0.003}_{-0.003}$	$0.235^{+0.005}_{-0.005}$
	$f_{O,W,SM}^{W,SM}$	$0.278^{+0.003}_{-0.003}$	$0.278^{+0.002}_{-0.002}$	$0.268^{+0.005}_{-0.005}$
	$f_{L,W,SM}^{W,SM}$	$0.389^{+0.002}_{-0.002}$	$0.389^{+0.002}_{-0.002}$	$0.404^{+0.005}_{-0.005}$
W, minus	$f_{R,W,SM}^{W,SM}$	$0.333^{+0.002}_{-0.002}$	$0.333^{+0.002}_{-0.002}$	$0.328^{+0.005}_{-0.005}$
	$f_{O,Z,SM}^{Z,SM}$	$0.259^{+0.002}_{-0.002}$	$0.258^{+0.002}_{-0.002}$	$0.253^{+0.003}_{-0.003}$
	$f_{L,Z,SM}^{Z,SM}$	$0.313^{+0.001}_{-0.001}$	$0.313^{+0.002}_{-0.002}$	$0.314^{+0.005}_{-0.005}$
	$f_{R,Z,SM}^{Z,SM}$	$0.429^{+0.001}_{-0.001}$	$0.429^{+0.002}_{-0.002}$	$0.433^{+0.005}_{-0.005}$
Z, plus	$f_{O,Z,SM}^{Z,SM}$	$0.271^{+0.002}_{-0.002}$	$0.271^{+0.002}_{-0.002}$	$0.263^{+0.004}_{-0.004}$
	$f_{L,Z,SM}^{Z,SM}$	$0.326^{+0.001}_{-0.001}$	$0.326^{+0.002}_{-0.002}$	$0.327^{+0.005}_{-0.005}$
	$f_{R,Z,SM}^{Z,SM}$	$0.403^{+0.001}_{-0.001}$	$0.403^{+0.002}_{-0.002}$	$0.410^{+0.005}_{-0.005}$
	$f_{O,Z,SM}^{Z,SM}$	$0.239^{+0.003}_{-0.003}$	$0.239^{+0.002}_{-0.002}$	$0.238^{+0.004}_{-0.004}$
Z, minus	$f_{L,Z,SM}^{Z,SM}$	$0.291^{+0.002}_{-0.002}$	$0.291^{+0.003}_{-0.003}$	$0.292^{+0.005}_{-0.005}$
	$f_{R,Z,SM}^{Z,SM}$	$0.470^{+0.002}_{-0.002}$	$0.470^{+0.003}_{-0.003}$	$0.470^{+0.005}_{-0.005}$

The results from the fitting method obtained with the POWHEG MC sample are shown in Figure 5.14, which includes the distributions of the cosine of the polarization angle at the generator level with and without the fiducial requirements applied. It can be seen that the predicted quadratic behaviour is observed in the first case, and that the application of fiducial requirements breaks this relation. Thus it is impossible to estimate of the polarization fractions at the fiducial level from directly fitting these distributions. Another point of importance is how asymmetries in the polarization fractions arise between the charged final states. The different energy spectra in W^+Z and W^-Z events, with the former tending to be slightly more energetic due to the higher presence of high momentum uquarks than dquarks in the proton, leads to the presence of slightly more longitudinally-polarized bosons for final states with positive charge.

5.8.2 Building the polarized MC

As the differential cross section formulas of Equations 5.25 and 5.26 break down once fiducial requirements are applied, a direct fitting of the $\cos(\theta_{gen}^W)$ and $\cos(\theta_{gen}^Z)$ in data

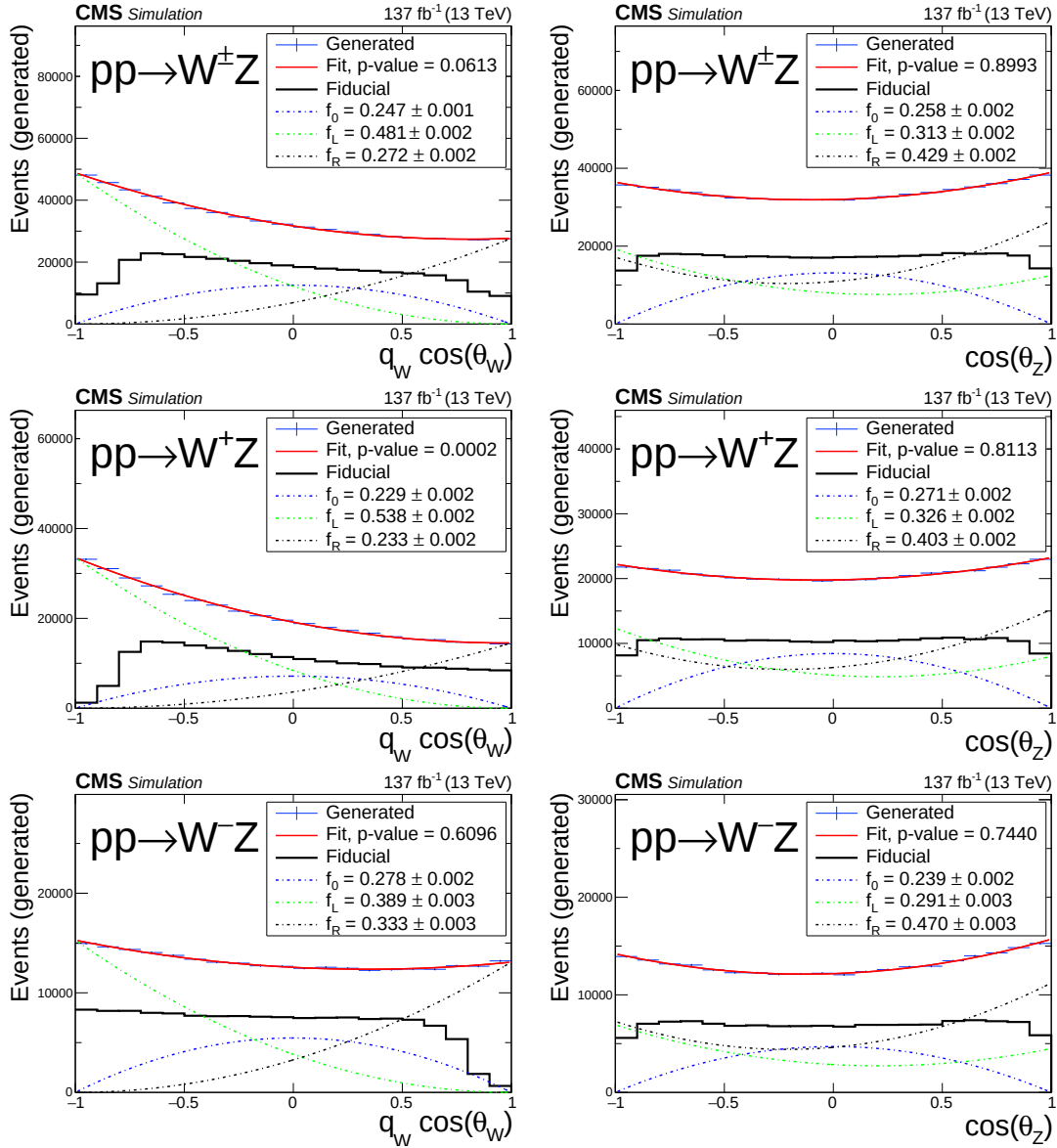


FIGURE 5.14: Distribution of the cosine of the polarization angle in the helicity frame at the generator level for the POWHEG WZ sample and different charged final states. From left to right: W and Z bosons. From top to bottom: total (inclusive) final state, positively charged final state, and negatively charged final state. The blue histogram corresponds to the MC prediction in the total phase space, the solid red line corresponds to the best quadratic fit and the different dashed lines to each of the polarization components obtained in the fit. The thick black line corresponds to the distribution of the same variable restricted to the fiducial phase space. For the W boson, the cosine of the polarization angle is multiplied by the charge of the W boson in the final state.

to a quadratic function is not possible. Even if the four momentum of the W , the Z , the leptons, and the neutrino could be fully reconstructed, just the p_T requirements imposed by the trigger selection would break the dependence in a similar way as shown in Figure 5.14. Thus, an alternative method of extracting these quantities from data has to be developed.

A first possibility would be the extrapolation of the measurements to the generator level quantities as a differential cross section measurement with a target (unfolded) phase space equivalent to the total region. As this target space does not need to be restricted to any given kinematic requirements, the comparison with a quadratic function there would be possible. However, this method requires the somewhat awkward extrapolation of a differential measurement with a target in the total phase space rather than the fiducial. The dependence of the acceptance in the kinematic cuts, summarized in the quotient between the blue histogram and the thick black line in Figure 5.14, would introduce quite skewed response matrices and -likely- the need for strong regularization terms which would likely introduce biases in the measurement. Nonetheless, differential measurements with the target space being the fiducial region are presented for these very same variables in Section 5.10.

The chosen alternative is to extract the values of the polarization fractions at the reconstructed level in a fit similar to that of Section 5.5. To do so, however, predictions from each polarized final state need to be achieved at the reconstructed level, meaning that building polarized MC samples is needed. These kind of samples are obtained from the unpolarized WZ sample used for the rest of the studies presented in this Chapter. They are produced separately for the W and the Z boson polarizations as in no case will both polarizations be measured simultaneously later in the study of observed data. For simplicity, only the method to obtain the samples for the W boson polarization states is discussed, with the Z ones obtained following similar procedures.

First, the nominal MC sample is split into three independent subsamples which will become the left, right and longitudinally-polarized MC samples. To ensure similar statistical errors appear on each one, the relative sizes of the subsamples are made to match those of the expected polarization fractions from Table 5.12. Then, the events on each of these subsamples are reweighted based on the $\cos(\theta_{gen}^W)$ quantity by imposing that the differential distribution of the cross section follows the corresponding term introduced in Equation 5.25. Namely, the weights w_L , w_R and w_O for the left, right and longitudinally-polarized events are

$$\begin{aligned}
 w_L &= \frac{(1 \mp \cos(\theta_{gen}^W))^2}{(1 \mp \cos(\theta_{gen}^W))^2 f_L^{W,SM} + (1 \pm \cos(\theta_{gen}^W))^2 f_R^{W,SM} + 2 \sin^2(\theta_{gen}^W) f_O^{W,SM}} \\
 w_R &= \frac{(1 \pm \cos(\theta_{gen}^W))^2}{(1 \mp \cos(\theta_{gen}^W))^2 f_L^{W,SM} + (1 \pm \cos(\theta_{gen}^W))^2 f_R^{W,SM} + 2 \sin^2(\theta_{gen}^W) f_O^{W,SM}} \\
 w_O &= \frac{2 \sin^2(\theta_{gen}^W)}{(1 \mp \cos(\theta_{gen}^W))^2 f_L^{W,SM} + (1 \pm \cos(\theta_{gen}^W))^2 f_R^{W,SM} + 2 \sin^2(\theta_{gen}^W) f_O^{W,SM}}
 \end{aligned} \tag{5.28}$$

where, as before, the upper sign in $\mp$ and $\pm$ corresponds to W^+Z production and the lower one to W^-Z production. The resulting weighted samples are then scaled to the

expected WZ total production cross section. As a consequence, by construction, the sum of all three of the polarization samples weighted by their corresponding polarization fractions will be equal to the original unpolarized one, except for fluctuations of statistical nature resulting from the split of the original sample into three independent ones.

5.8.3 Statistical model for the extraction of the polarization fractions

Once polarized samples are obtained, a comparison between data and expectations in which the later includes separately the contributions from each of the boson polarization final states is possible. A similar procedure to the one described in Section 5.5 is performed to extract the polarization fractions from this comparisons, with two key differences being the signal modelling and the fitted distribution in the SR. Again, the procedure followed for the W boson polarization will be described in more detail, with the method used to build the statistical model for the Z boson being completely analogous.

For the signal modelling, the contributions of each boson polarization state need to be able to vary independently, so a model with a single normalization parameter that scales all WZ production is not suitable. A priori, it could be considered that there are a total of four independent parameters that regulate the production of polarized WZ production: an overall normalization or cross section parameter μ , an three independent fractions regulating the proportion of each polarization fraction (f_L^W , f_R^W , and f_O^W). A naïve redefinition of the contributions for the Poissonian term in bin i in Equation 5.1 would be

$$\begin{aligned} & -\mu s_i(\theta) - b_i(r_{ZZ}, r_{X\gamma}, r_{\bar{t}tZ}, r_{tZq}, \theta) \rightarrow \\ & \rightarrow -\mu \left[f_L^W l_i(\theta) + f_R^W r_i(\theta) + f_O^W o_i(\theta) \right] - b_i(r_{ZZ}, r_{X\gamma}, r_{\bar{t}tZ}, r_{tZq}, \theta) \end{aligned} \quad (5.29)$$

where l_i , r_i and o_i are the yields corresponding to each WZ state for bin i if such polarized state was the responsible for the whole production cross section. Effectively, the parameters f_L^W , f_R^W and f_O^W represent the fractions corresponding to each polarized state and μ is the overall normalization of the process. However, the normalization constrain $f_L^W + f_R^W + f_O^W = 1$ indicates that only two of the polarization fractions are completely independent. As a consequence only two of them can be varied at once as, if the interpretation of the parameters as a fraction is to be kept, μ needs to be kept as the overall WZ normalization independent parameter. As the longitudinal polarization is the most interesting of the three, f_O^W is kept as the second of the independent fitted parameters. There is some leeway on how to choose the third parameter, but the usual procedure is to use $f_{LR}^W = f_L^W - f_R^W$. The resulting likelihood to fit will be of the form

$$\begin{aligned}
& -\mu s_i(\theta) - b_i(r_{ZZ}, r_{X\gamma}, r_{t\bar{t}Z}, r_{tZq}, \theta) \rightarrow \\
& \rightarrow -\mu \left[\frac{1 + f_{LR}^W - f_O^W}{2} l_i(\theta) + \frac{1 - f_{LR}^W - f_O^W}{2} r_i(\theta) + f_O^W o_i(\theta) \right] - b_i(r_{ZZ}, r_{X\gamma}, r_{t\bar{t}Z}, r_{tZq}, \theta)
\end{aligned} \tag{5.30}$$

a substitution that is applied into Equation 5.1 to build the statistical model to be fitted to extract the free parameters μ , f_O^W and f_{LR}^W .

The second difference of the model with respect to the fit described in Section 5.5 is the distribution fitted in the signal region. Using the distribution of yields across flavoured states would not provide enough information to extract the polarization fractions, as the proportion of each polarized production mode is near identical across all flavoured final states. Thus, a new discriminant variable that provides reasonable separation between the different polarization states needs to be defined.

The chosen discriminant variables are the cosines of the polarization angles built at the reconstructed level: $\cos(\theta^W)$ and $\cos(\theta^Z)$. A sizeable part of the information available at generation is not directly available from measurements, namely the proper assignment of the leptons to the W or Z decay and the four momentum of the neutrino, and the W and Z bosons. The assignment of the three charged leptons to its parent boson is performed using the same lepton tagging algorithm defined in Section 5.2. Then, the four momentum of the Z can be fully reconstructed as the sum of the four momenta of its fully reconstructed decay products. The kinematics of the W boson can not be equally reconstructed, however, as the neutrino is not observed in the detector. Instead, the p_T^{miss} vector is used as a proxy for the neutrino transverse momentum and the longitudinal component of the neutrino momentum is obtained by imposing that the $\nu + \ell_W$ system has invariant mass equal to m_W^{PDG} . The definition of the HE frame presented in Section 5.8.1 is followed to define the $\cos(\theta^W)$ and $\cos(\theta^Z)$ quantities at the reconstructed level.

As an additional check, the same algorithm used to build $\cos(\theta^W)$ and $\cos(\theta^Z)$ in the WZ-SR is performed in the different control regions of the analysis to validate the modelling of these variables for each of the main backgrounds in the analysis. The associated distributions are presented in Figure 5.15 for the ZZ, $t\bar{t}X$ and $X\gamma$ CR. Notice, again, that these distributions are not used in the fitting procedure described on this Section, the standard set of variables pointed out in Section 5.3 and used in the fits described in 5.5 is employed instead.

5.8.4 Measured values of the polarization fractions

The resulting distributions of $\cos(\theta^W)$ and $\cos(\theta^Z)$ at the reconstructed level, with nuisances and free parameters evaluated after the polarization fraction extraction fit are shown in Figure 5.16 for both the W and Z bosons, and the charge inclusive and the two charge split final states. Overall agreement between data and predictions is observed, with some small fluctuations in isolated bins that appear statistical in nature. As expected, the overall shape of the distributions does not follow a quadratic

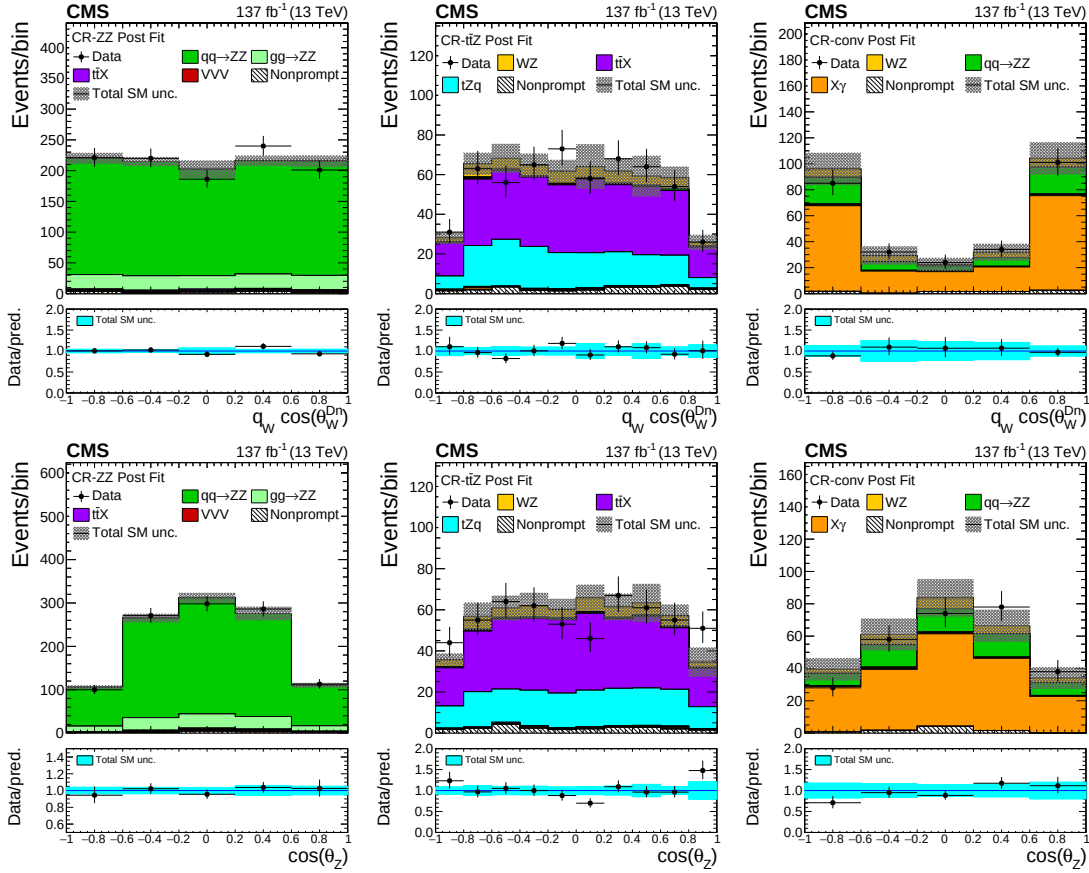


FIGURE 5.15: Expected and observed distribution of the cosines of the W and Z polarization angles at reconstructed level using the value of the nuisances after the inclusive cross section fit. From left to right: ZZ CR, $t\bar{t}X$ CR and $X\gamma$ CR. From top to bottom: W and Z bosons. The sum of all uncertainties of the inclusive cross section fit are presented in the shaded bands of the main plot and the light blue band of the ratio plots. For the W boson, the distributions are multiplied by the charge of the boson.

dependence on the cosine of the polarization angle, but rather reproduce the rather altered behaviour of the fiducial results shown in Figure 5.14.

In the case of the W boson, the clear separation between polarized states found at the generated level is blurred by the resolution with which the $\cos(\theta^W)$ angle is reconstructed, itself dominated by both the several assumptions included in the reconstruction of the W as well as the usually low resolution in the measurement of p_T^{miss} .

For the Z boson, the distribution shown at the reconstructed level follows much more closely the one expected for the fiducial region in Figure 5.14 (bottom), but the mixing of the polarized states -due to the nature of the coupling of the Z to the leptons- appears as in the gen level case to mix the different polarization fraction contributions.

The best fit values of the free parameters of the fit related to the polarization fractions, and the experimental uncertainties on their determination are shown in Table 5.13. The best fit values are computed from the maximum of the log likelihood function with respect to all three fitted parameters simultaneously (μ , f_0 and f_{LR}). Their experimental uncertainties correspond to an 68% CL confidence region corresponding to a

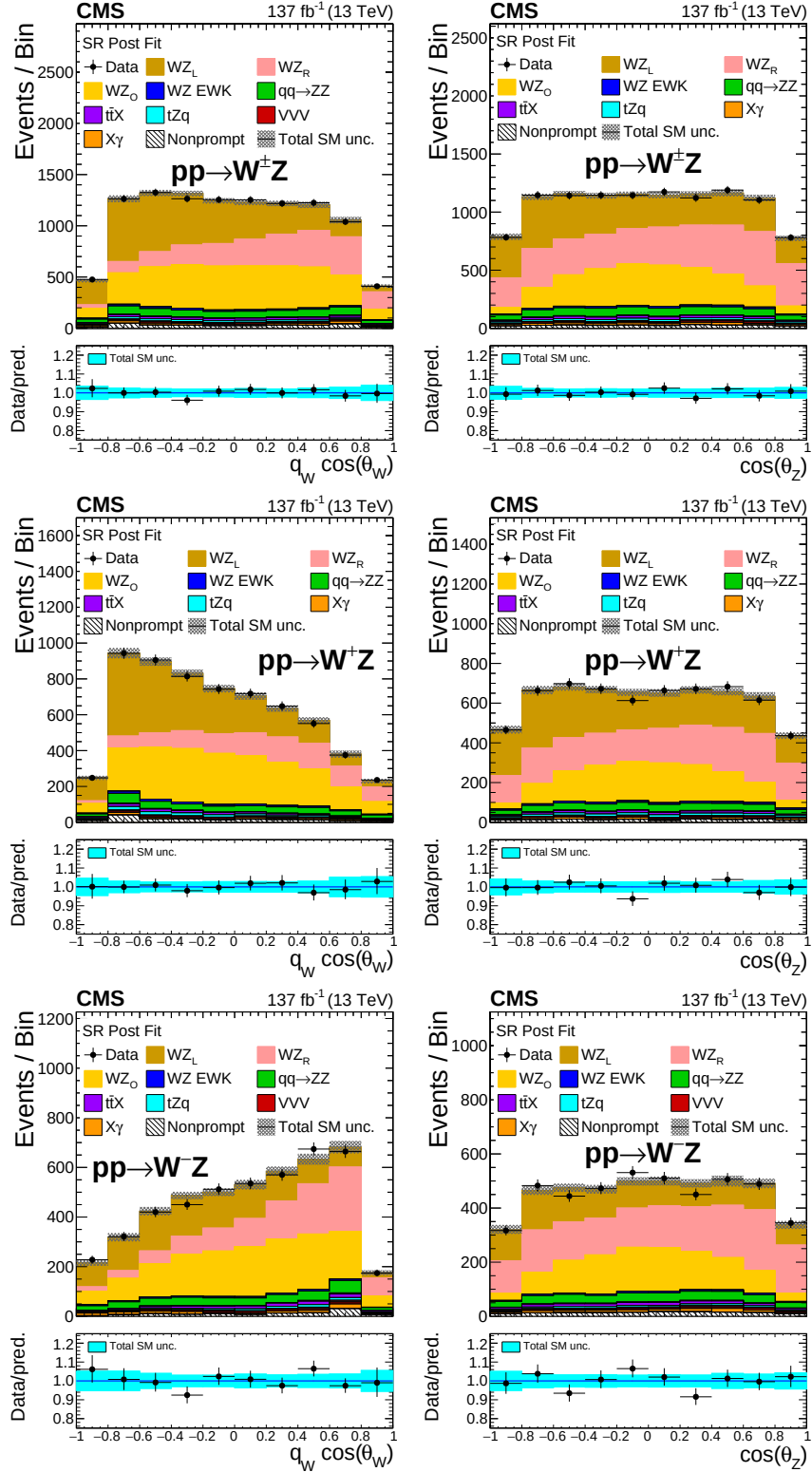


FIGURE 5.16: Expected distribution of the cosines of the W and Z polarization angles at reconstructed level after the polarization fractions extraction fit is performed and corresponding distributions in data. From top to bottom: total (inclusive) final state, positively charged final state, and negatively charged final state. From left to right: W and Z bosons. For each case of boson flavour and final state charge, the postfit value of nuisances corresponding to the fit to its polarization fractions is presented in the plot. All uncertainties included in the fits are presented in the shaded bands of the main plot and the light blue band of the ratio plots. For the W boson, the distributions are multiplied by the charge of the boson.

1D scan of the likelihood to the corresponding parameter in which the other two are profiled as if they were additional nuisance terms.

Table 5.13 also contains as well a comparison with the results predicted by POWHEG at NLO in QCD and MATRIX in NNLO in QCD $\times$ NLO in EWK. While the same uncertainties of numerical origin as in Table 5.12 are presented for MATRIX, in the case of POWHEG the uncertainties included correspond solely to the theoretical ones due to PDF variations which could, in principle, have some relevant effect in the measurement of angular quantities. The derivation of such PDF uncertainties follows the description of Section 5.7.1 -using the prefit set of PDF replicas- and includes the repetition of the quadratic fit for each of the involved replicas in the set. Overall, agreement is found between the measured values and the expected SM ones with the biggest deviations appearing around 1.2σ level for the W^+ longitudinal polarization.

TABLE 5.13: Observed values of the f_O and f_{LR} parameters and their uncertainties as obtained from the fitting procedure described in Section 5.8.3. The expected values as obtained from POWHEG and MATRIX are shown for comparison. The POWHEG predictions include uncertainties derived from PDF modelling only, while the MATRIX ones only include uncertainties due to the limited precision of the fitting procedure.

Boson and charge	Observable	Observed	POWHEG expected	MATRIX expected
W, inclusive	f_O^W	$0.32^{+0.08}_{-0.08}$	$0.2470^{+0.0003}_{-0.0003}$	$0.248^{+0.003}_{-0.003}$
	f_{LR}^W	$0.18^{+0.03}_{-0.03}$	$0.209^{+0.002}_{-0.002}$	$0.210^{+0.006}_{-0.006}$
W, plus	f_O^W	$0.36^{+0.10}_{-0.10}$	$0.2294^{+0.0003}_{-0.0003}$	$0.237^{+0.004}_{-0.004}$
	f_{LR}^W	$0.29^{+0.04}_{-0.04}$	$0.305^{+0.003}_{-0.003}$	$0.293^{+0.007}_{-0.007}$
W, minus	f_O^W	$0.36^{+0.12}_{-0.13}$	$0.2782^{+0.0007}_{-0.0007}$	$0.268^{+0.005}_{-0.005}$
	f_{LR}^W	$0.01^{+0.06}_{-0.05}$	$0.056^{+0.002}_{-0.002}$	$0.076^{+0.007}_{-0.007}$
Z, inclusive	f_O^Z	$0.24^{+0.02}_{-0.02}$	$0.2583^{+0.0003}_{-0.0003}$	$0.253^{+0.003}_{-0.003}$
	f_{LR}^Z	$-0.04^{+0.08}_{-0.08}$	$-0.116^{+0.002}_{-0.002}$	$-0.120^{+0.006}_{-0.006}$
Z, plus	f_O^Z	$0.24^{+0.03}_{-0.03}$	$0.2710^{+0.0003}_{-0.0003}$	$0.263^{+0.004}_{-0.004}$
	f_{LR}^Z	$0.04^{+0.10}_{-0.10}$	$-0.073^{+0.003}_{-0.003}$	$-0.083^{+0.007}_{-0.007}$
Z, minus	f_O^Z	$0.27^{+0.04}_{-0.04}$	$0.2392^{+0.0005}_{-0.0005}$	$0.238^{+0.004}_{-0.004}$
	f_{LR}^Z	$-0.16^{+0.12}_{-0.12}$	$-0.179^{+0.003}_{-0.003}$	$-0.178^{+0.007}_{-0.007}$

Studying the effects of the different sources of uncertainty in the measurements, a curious result can be noted. The main effects that introduce variations in the polarization parameters come from either the other free floating parameters on the fit -the other polarization fraction or the overall cross section normalization- or the statistical uncertainties in data. As near all systematic sources described in Section 5.4 have an effect that is approximately flat for all bins of the $\cos(\theta^W)$ and $\cos(\theta^Z)$ distributions, they tend to be absorbed by the overall normalization parameter μ .

In addition to the presented best fit results, a more complete view of the overall agreement with the SM predictions as well as the level of correlation between the uncertainties affecting each of the measured parameters can be obtained by representing two dimensional confidence regions in the f_{LR} - f_O space. The results for the W and Z bosons in the charge inclusive final state are presented in Figure 5.17. For the results shown in this Figure, the μ parameter is, again, treated as an unconstrained nuisance that is profiled in the multiple fits performed.

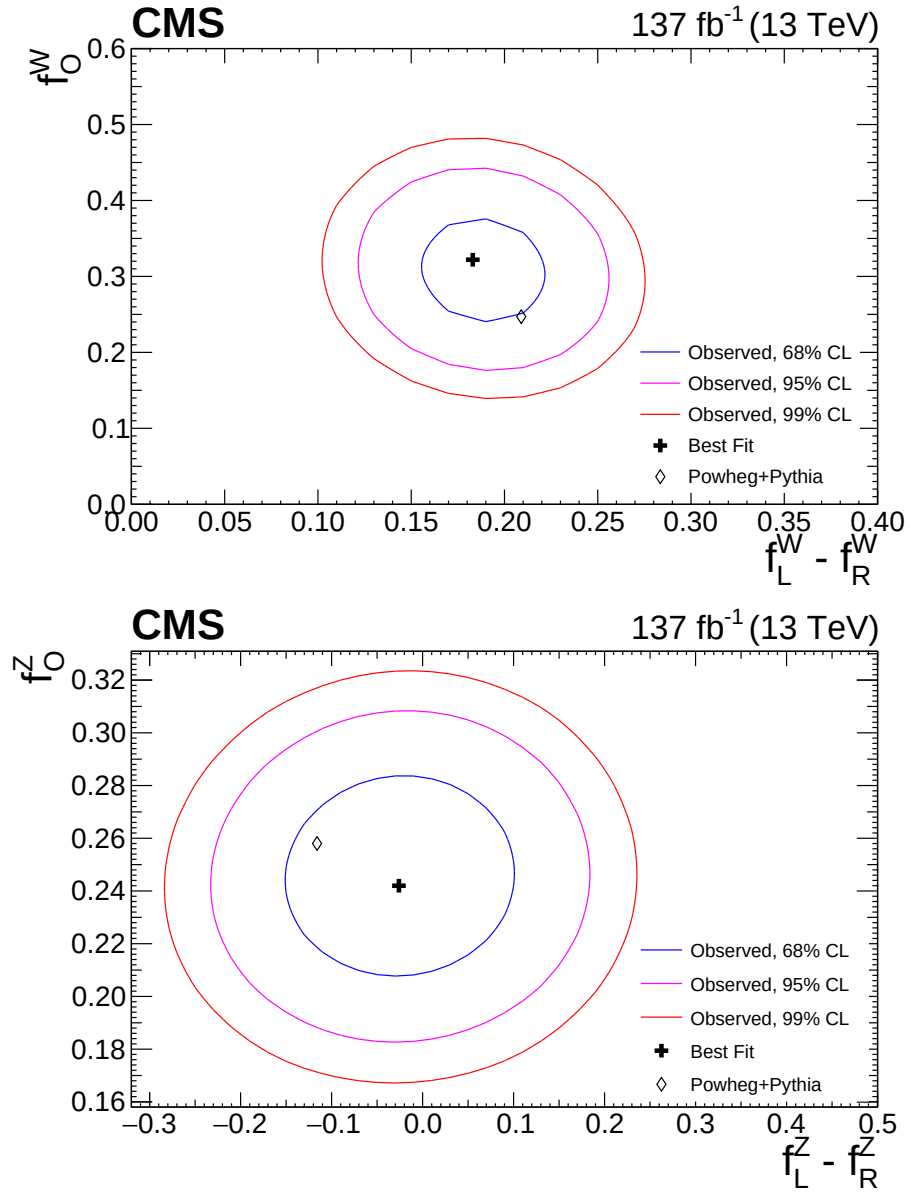


FIGURE 5.17: Observed two dimensional confidence regions for the f_O - f_{LR} polarization parameters for the fits performed to extract the W and Z boson polarization fractions in the charge inclusive final state. The different curves correspond to the 1σ , 2σ and 3σ confidence level. The predictions from POWHEG are included as well, and show overall agreement with observations at the 1σ level.

As a final result, the sensitivity of the analysis to the presence of longitudinally-polarized vector bosons is quantified separately for W and Z production. To do so, a generalization to the formula presented in Equation 4.21 in which the signal contribution is replaced by the statistical model presented in Equation 5.30 is used. The presence of both longitudinally and transversally polarized vector bosons is tested against the hypothesis of only transversal polarization modes appearing in WZ production. The significance achieved is of 5.6σ (4.3σ) observed (expected) standard deviations for the longitudinally-polarized W bosons. For the Z bosons, the asymptotic formulae employed provides results of over 10σ , so a clear observation of longitudinally-polarized Z bosons is achieved.

5.9 EFT interpretations

On top of using the observed results to obtain measurements of the SM properties, an additional interpretation in the framework of EFT, introduced in Section 2.4.2, for the WZ studies is performed. As pointed before, the charged triple gauge coupling has historically been an object of interest in such channels, as it can contain several possible interesting new physics, such as processes involving heavy Higgses that couple to the SM gauge bosons, as represented in Figure 5.18. Do notice that the triple gauge coupling does exist for SM WZ production, but the EFT contraction can heavily modify its structure.

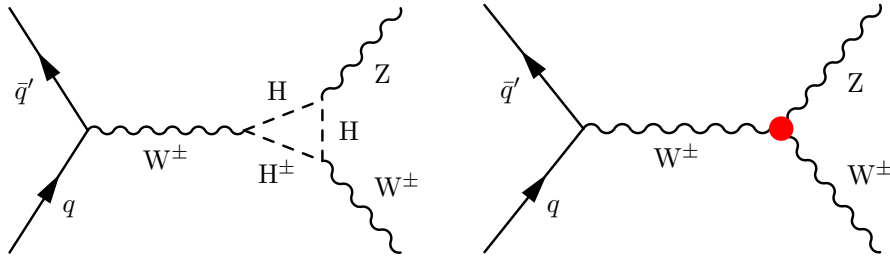


FIGURE 5.18: Feynman diagrams corresponding to BSM WZ production through the presence of a loop containing a BSM Higgs particle ($H^\pm$) (left) and its contraction into an effective vertex (right).

Following the EFT prescription, instead of focusing on a single possible BSM realization, a generic approach is followed in which a general set of five different dimension 6 operators are taken into account. The chosen basis is based on the approach presented in Reference [182], with an effective Lagrangian density of

$$\begin{aligned} \delta\mathcal{L}_{\text{EFT}} = & \frac{c_{\text{www}} \text{Tr}[W_{\mu\nu} W^{\nu\rho} W_\rho^\mu] + c_w (D_\mu H)^\dagger W^{\mu\nu} (D_\nu H) + c_b (D_\mu H)^\dagger B^{\mu\nu} (D_\nu H)}{\Lambda^2} + \\ & + \frac{\tilde{c}_{\text{www}} \text{Tr}[\tilde{W}_{\mu\nu} W^{\nu\rho} W_\rho^\mu] + \tilde{c}_w (D_\mu H)^\dagger \tilde{W}^{\mu\nu} (D_\nu H)}{\Lambda^2} \end{aligned} \quad (5.31)$$

with the definition of the different fields involved that was introduced in Section 2.2.1. The three Wilson coefficients c_{www} , c_{w} , and c_{b} correspond to CP conserving BSM physics, while the remaining two, $\tilde{c}_{\text{www}}$ and $\tilde{c}_{\text{w}}$, break CP symmetry, an interesting possibility given the cosmological observations which were described in Section 2.4. In the past, similar studies were performed in the equivalent anomalous triple gauge couplings (aTGCs) formulation, in which each of the parameters was interpreted as variations of the SM standard triple gauge couplings. As the formulations are equivalent, under the appropriate limit, the later is not presented in this document. The transformation relations that relate the two basis can be found in [182].

5.9.1 EFT signal modelling

The modelling of the signal at the MC level is performed starting from the MADGRAPH+aMC@NLO MC sample, so far introduced to cross check other steps of the analysis. As the objective is to cover a broad range of values of the EFT parameters, potentially a set of five dimensional scans in which all EFT parameters vary simultaneously, generating MC samples with the settings corresponding to each possible configuration of the EFT parameters is prohibitive in terms of computation time. Instead, the event reweighting functionality of MADGRAPH+aMC@NLO is used, specifically the LO-like event reweighting for NLO samples described in Reference [183]. A new technique was developed to reweight already existing MC samples by extracting the Les Houches Event (LHE) parameters from the already produced MC and reprocessing it through MADGRAPH+aMC@NLO that provides the possibility of profiting from the already existing SM MC samples for this procedure. Such technique saves around two to three orders of magnitude in computation time with respect to wholly reproducing event generation and the simulation of the CMS experiment and so allowed for relatively complex scans of the EFT parameter space.

A total of 150 weights are included: 125 weights are disposed in a 3-dimensional 5x5x5 grid for the CP conserving c_{www} , c_{w} , and c_{b} parameters, and the remaining 25 in a 2-dimensional 5x5 grid for the CP breaking terms corresponding to $\tilde{c}_{\text{www}}$ and $\tilde{c}_{\text{w}}$. Applying these per event weights to each MC event passing event selection provides a handle to compare the different EFT configurations to data at the reconstructed level, where statistical inference on the values of the parameters can be done.

A specific statistical model has also been developed to build the signal contributions in the usual joint likelihood function when comparing data and expectations. To extract the best fit values and confidence regions on each of the EFT parameters, a similar procedure to the one described for Section 5.5 is performed, based on an extended likelihood fit which includes both several distributions in the CR designed to constrain the background uncertainties and a distribution in the SR that is sensitive to the different EFT effects. In a similar way to what was done in Section 5.8, the signal yields in Equation 5.30 are modified to now depend on functions of the EFT parameters. The following parametrizations are applied

$$\begin{aligned}
& -\mu s_i(\theta) - b_i(r_{ZZ}, r_{X\gamma}, r_{\tilde{t}\tilde{t}Z}, r_{tZq}, \theta) \\
\rightarrow & -\mu \left[\sum_{j,k,l=0}^{j+k+l=2} \alpha_{jkl}^i \frac{c_w^j c_{www}^k c_b^l}{\Lambda^{2(j+k+l)}} s_i(\theta) \right] - b_i(r_{ZZ}, r_{X\gamma}, r_{\tilde{t}\tilde{t}Z}, r_{tZq}, \theta) \\
& -\mu s_i(\theta) - b_i(r_{ZZ}, r_{X\gamma}, r_{\tilde{t}\tilde{t}Z}, r_{tZq}, \theta) \\
\rightarrow & -\mu \left[\sum_{m,n=0}^{m+n=2} \frac{\beta_{mn}^i \tilde{c}_w^m \tilde{c}_{www}^n}{\Lambda^{2(n+m)}} s_i(\theta) \right] - b_i(r_{ZZ}, r_{X\gamma}, r_{\tilde{t}\tilde{t}Z}, r_{tZq}, \theta)
\end{aligned} \tag{5.32}$$

meaning that in a bin i of the given discriminant of the SR, the expected yields are built as a product of the SM WZ yields, s_i , times an additional function which is quadratic in the EFT parameters. A quadratic form is chosen to represent this effect as it can be easily factorized from the effects of an EFT term in the SM matrix element, as pointed out in Equation 2.33. For each bin in the chosen SR discriminant, the yields corresponding to the 150 different configurations of EFT parameters $y_i(c_w, c_{www}, c_b, \tilde{c}_w, \tilde{c}_{www})$ are divided by the SM prediction, evaluated at the nominal value of the nuisance parameters, to get

$$q_i(c_w, c_{www}, c_b, \tilde{c}_w, \tilde{c}_{www}) = \frac{y_i(c_w, c_{www}, c_b, \tilde{c}_w, \tilde{c}_{www})}{s_i(\theta = 0)} \tag{5.33}$$

The resulting observations of $q_i(c_w, c_{www}, c_b, \tilde{c}_w, \tilde{c}_{www})$ quantities are fitted to quadratic functions described in Equation 5.32 to extract the 10 α_{jkl}^i and 7 β_{mn}^i parameters. Excellent agreement is found for all the chosen variables and fits, with the p-values corresponding to the later being all over the 99% level. The benefit of this approach is that the likelihood can then be built as an analytical function of the EFT parameters as continuous functions, rather than only for the specific points that were included in the simulation, and so general techniques to manipulate the likelihood and do parameter estimation can be easily applied.

From the results of the substitution of Equation 5.32, the new extended likelihood becomes a function of 4 (3) signal modifying parameters for the CP even (CP odd) case: μ , c_{www} , c_w , and c_b (μ , $\tilde{c}_{www}$, and $\tilde{c}_w$). Standard multidimensional, 2D or 1D scans in the parameters of interest can then be done to extract both the best fit values of each parameter and their associated confidence regions following the standard techniques described in Section 4.6.

5.9.2 EFT parameters measurement

The variable that is chosen to extract the value of the EFT parameters is the invariant mass of the WZ system. Instead of fully reconstructing the W boson, as it was described for Section 5.8, the p_T^{miss} quantity is used to build the transversal momentum of the neutrino but no constrain on the W mass is applied. The longitudinal component of the neutrino's four momentum is instead set to 0. It was found that this procedure introduced slightly less uncertainty than the full reconstruction in the overall $M(WZ)$ distribution, as it minimizes the involvement of p_T^{miss} in the computation. The invariant mass of the WZ system defined following this reconstruction algorithm

for the W is named $M(WZ)$. Its distribution for the analysis CRs can be seen in Figure 5.19 where reasonable agreement between data and MC is found. It has to be noted, nonetheless, that such distribution has little contributions at the tails in the $X\gamma$ CR due to the kinematic cuts applied on its definition heavily restricting the range of the $M(WZ)$ variable.

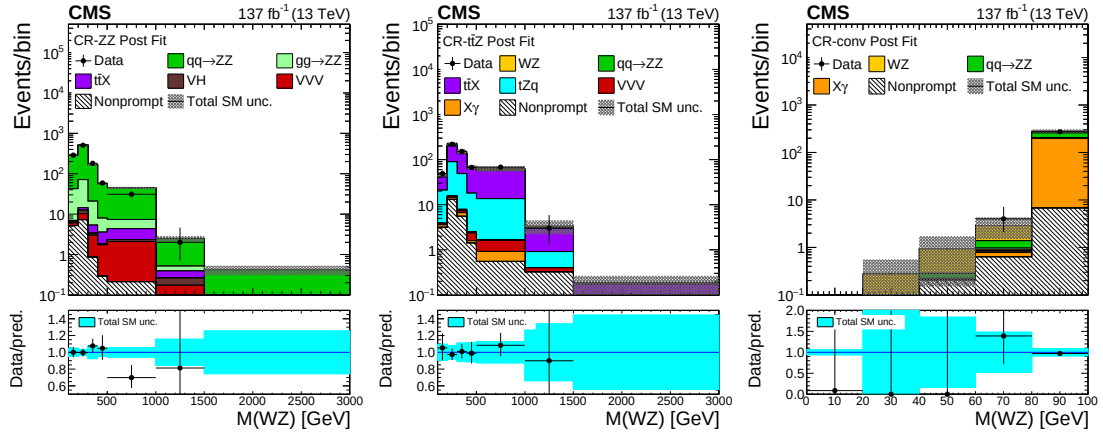


FIGURE 5.19: Expected distribution of the invariant mass of the WZ system at reconstructed level using the value of the nuisances after the inclusive cross section fit. From left to right: ZZ CR, $t\bar{t}X$ CR and $X\gamma$ CR. The sum of all uncertainties of the inclusive cross section fit are presented in the shaded bands of the main plot and the light blue band of the ratio plots.

A similar distribution at the selection level of the WZ -SR is represented in Figure 5.20 (left). An alternative approach was considered in which the reconstructed p_T of the Z boson was used instead of the $M(WZ)$ variable, but the sensitivity at the tails of the distribution was found to be quite smaller than the one of $M(WZ)$, as the variable doesn't capture the whole energy available for the WZ system as well as $M(WZ)$ does. The distribution of such alternative variable is shown in Figure 5.20 (right).

As discussed in Section 5.9.1, the distribution of yields in the $M(WZ)$ variable is combined with the usual set of distributions in the different CR to build a joint likelihood function in which the signal contributions are modelled according to Equation 5.32. Two of such likelihood functions are built, one of them depending on the three CP even EFT parameters and another on the two based on the two CP odd ones. The best fit value for each parameter is computed by finding the minimum of the joint likelihood with respect to the corresponding parameter with all of the rest EFT contributions set to their SM value (0) and the overall normalization μ being free to float and treated as an additional profiled nuisance in all of the fits. 95% CL confidence regions on each EFT parameter are estimated from a scan of the likelihood function with respect to the corresponding EFT parameter in which all other EFT terms are set to 0 except for μ , which is again profiled as an additional nuisance term. Expected values of the confidence intervals are obtained from a similar procedure applied on top of the SM-only Asimov dataset. The results of these one-dimensional fits are shown in Table 5.14.

The results shown in Table 5.14 are overall consistent with the SM expectations of all parameters being equal to 0. Small deviations are found due to data being slightly under predictions for the third and second-to-last-bins in Figure 5.20 (left) and the fact that the c_W and c_b parameters presence can produce destructive interference with the

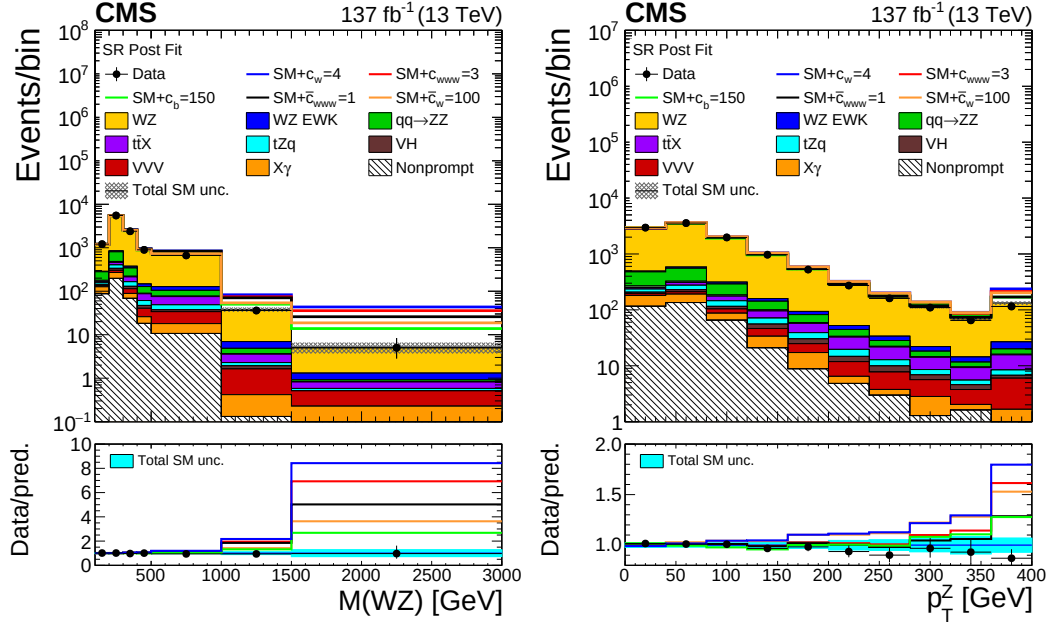


FIGURE 5.20: Expected distribution of several variables at reconstructed level in the SR obtained using the value of the nuisances after the inclusive cross section fit. The variables shown are the invariant mass of the WZ system $M(WZ)$ (left), and the p_T of the Z boson (right). The contributions of the whole set of processes (signal+background) resulting from a given set of EFT parameter values are shown as individual coloured lines superimposed in the plot.

TABLE 5.14: Best fit, expected confidence regions and observed confidence regions at the 95% CL for each of the considered EFT parameters in the interpretation of the $M(WZ)$ distribution. The signal modelling includes both the linear and quadratic term in the EFT parameters. In computing confidence intervals for each parameter the other ones are fixed to their SM values of 0, with the overall WZ normalization entering the fit as an unconstrained nuisance parameter.

Parameter	95% CI, Exp. (TeV^{-2})	95% CI, Obs. (TeV^{-2})	Best fit, Obs. (TeV^{-2})
c_w/Λ^2	$[-2.05, 1.27]$	$[-2.52, 0.33]$	-1.34
c_{www}/Λ^2	$[-1.27, 1.33]$	$[-1.04, 1.19]$	0.15
c_b/Λ^2	$[-86.0, 125.0]$	$[-42.7, 113.0]$	43.6
$\tilde{c}_{www}/\Lambda^2$	$[-0.76, 0.65]$	$[-0.62, 0.53]$	-0.03
$\tilde{c}_w/\Lambda^2$	$[-46.1, 46.1]$	$[-45.9, 45.9]$	0.0

SM which dominates EFT effect for one of their possible values (positive c_b , negative c_w). Nonetheless, the overall results do not point to any clear signal of BSM physics presence.

Two dimensional fits in which several parameters are allowed to vary simultaneously are an interesting way of looking for possible BSM physics that have a simultaneous effect in different dimension 6 couplings, which in some cases might paint a more realistic picture than simply performing one dimensional scans on the different contributions. The procedure to obtain two dimensional confidence regions is quite similar to the one proposed for the 1D scan, with the sole difference that only three of the EFT contributions are fixed to their SM values of 0 for these studies. The resulting 2D

confidence regions are obtained at a 68%, 95% and 99% CL from the 2D scan to the joint likelihood function and can be seen in Figure 5.21.

5.9.3 Additional checks on the validity of the EFT approach

As discussed in Section 2.4.2.2, the EFT approach has several validity limits that need to be tested in order to provide a proper image of the sensitivity of this analysis to different EFT models.

The first of such issues is to study possible dependences of the confidence regions on the energy cut-off scale. Naïvely, one could assume this to be straightforward, as the EFT parameters are always discussed in the form c_i/Λ^2 and so variations in Λ could be propagated to the confidence regions. However, this is far from a consistent approach, as if Λ becomes small enough the EFT approach could start to break at the energy scales already probed in the data. Instead, the procedure that is followed is to redefine the signal contributions that enter Equation 5.33. Once an energy scale $\Lambda = \Lambda_{\text{Cut-off}}$ is fixed, the EFT event weights are fixed for 1 for events such that $M(WZ) > \Lambda_{\text{Cut-off}}$, meaning that no EFT signal is allowed over the cut-off scale. Then the whole signal modelling and parameter extraction procedure is run as previously described in Sections 5.9.1 and 5.9.2 for the resulting modified signal modelling. This procedure is done for a scan of values of the cut-off scale for all involved parameters, and the results can be seen in Figure 5.22.

The results show the expected decrease in sensitivity as the cut-off scale is moved towards the more lower energies regime, but no clear anomaly -bump- in the distributions is found that could be pointing to interesting new physics.

The last test of validity of the EFT approach was discussed in the form of Equation 2.34, where it was shown that the purely BSM term of dimension 6 operators might be competitive, in the Λ power expansion of contributions to a cross section, with the SM+dimension 8 term interference. The approach to test this is to cut off such contributions and only consider the effects that the signal has on the interpretation through the SM–dimension 6 interference contributions to the cross section. This is achieved by slightly modifying the signal modelling from Equation 5.32 to

$$\begin{aligned}
 & -\mu s_i(\theta) - b_i(r_{ZZ}, r_{X\gamma}, r_{t\bar{t}Z}, r_{tZq}, \theta) \\
 \rightarrow & -\mu \left[\sum_{j,k,l=0}^{j+k+l=1} \alpha_{jkl}^i \frac{c_w^j c_{www}^k c_b^l}{\Lambda^{2(j+k+l)}} s_i(\theta) \right] - b_i(r_{ZZ}, r_{X\gamma}, r_{t\bar{t}Z}, r_{tZq}, \theta) \\
 & -\mu s_i(\theta) - b_i(r_{ZZ}, r_{X\gamma}, r_{t\bar{t}Z}, r_{tZq}, \theta) \\
 \rightarrow & -\mu \left[\sum_{m,n=0}^{m+n=1} \frac{\beta_{mn}^i \tilde{c}_w^m \tilde{c}_{www}^n}{\Lambda^{2(n+m)}} s_i(\theta) \right] - b_i(r_{ZZ}, r_{X\gamma}, r_{t\bar{t}Z}, r_{tZq}, \theta)
 \end{aligned} \tag{5.34}$$

and then doing again the whole signal extraction fit described in Sections 5.9.1 and 5.9.2. As no MC was generated with only the interference terms included, the parameters of the linear function are obtained just by restricting the previously quadratic model to just the linear terms, representing the interference at the cross section level.

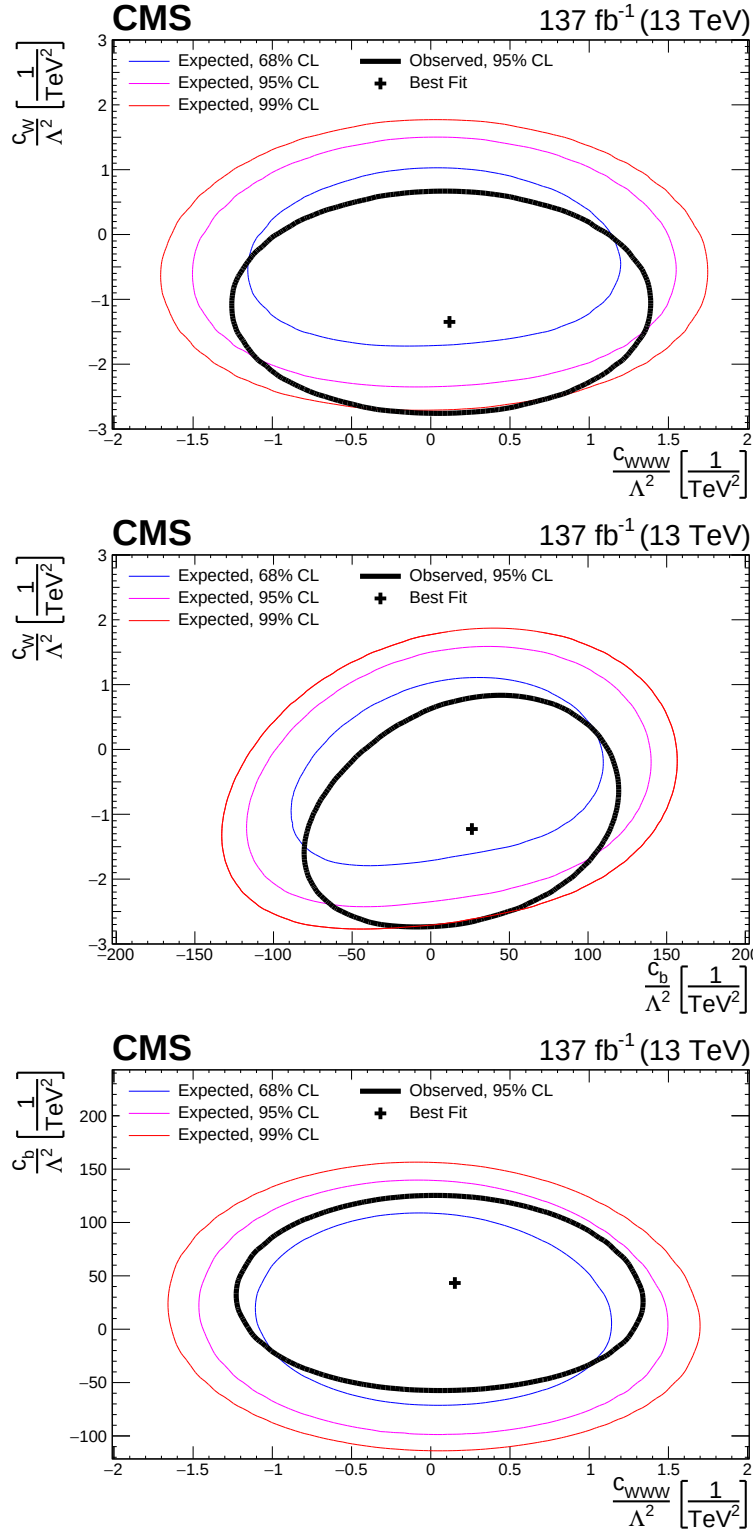


FIGURE 5.21: Best fit, expected 2D confidence regions at the 95% CL, and observed 2D confidence regions at the 68, 95, and 99% CL for several pairs of the considered EFT parameters in the interpretation of the $M(WZ)$ distribution. The signal modelling includes both the linear and quadratic term in the EFT parameters. In computing confidence intervals for each pair of parameters the other three are fixed to their SM values of 0, with the overall WZ normalization entering the fit as an unconstrained nuisance parameter. The parameters considered in each plot are c_W/Λ^2 - c_{www}/Λ^2 (top), c_W/Λ^2 - c_b/Λ^2 (middle), and c_b/Λ^2 - c_{www}/Λ^2 (bottom).

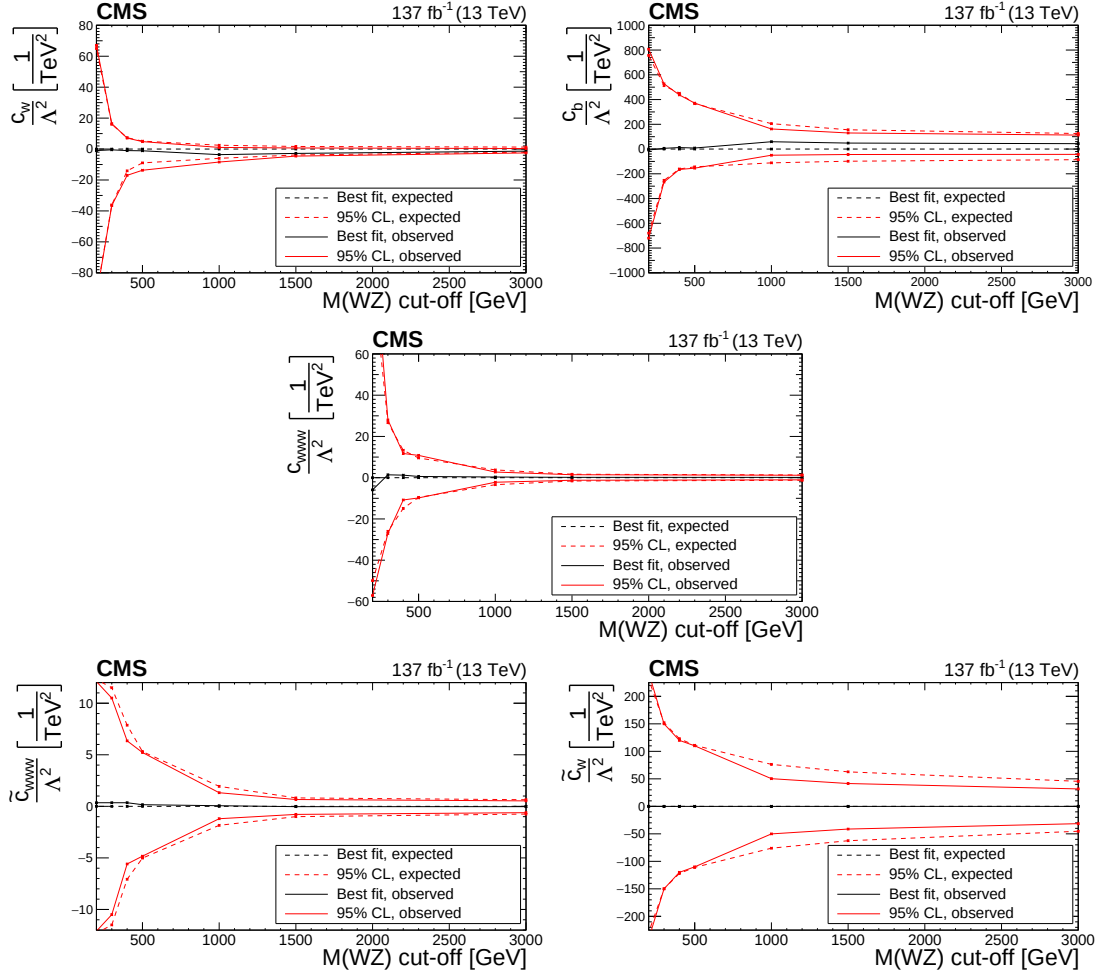


FIGURE 5.22: Evolution of the expected and observed confidence regions at the 95% CL for each of the considered EFT parameters with respect to the energy cut off scale. The signal modelling includes both the linear and quadratic term in the EFT parameters. In computing confidence intervals for each parameter the other ones are fixed to their SM values of 0, with the overall WZ normalization entering the fit as an unconstrained nuisance parameter. The parameter considered in each plot is: c_w/Λ^2 (top left), c_b/Λ^2 (top right), c_{www}/Λ^2 (middle), $\tilde{c}_{www}/\Lambda^2$ (bottom left), and $\tilde{c}_w/\Lambda^2$ (bottom right).

Thus, the values of the α_{jkl}^i and β_{mn}^i parameters are the same ones obtained from the fits to the quadratic functions. The resulting 1D fits are shown in Table 5.15 where, again, consistency with the SM is found for the different EFT parameters. Notice, however, that the sensitivity clearly worsens for this approach, as at the high energies that are probed by the analysis -up to 3TeV- the quadratic terms dominate the cross section contribution.

As a final depiction of the results, the evolution of the likelihood with respect to the different considered EFT parameters in both the linear only and the linear+quadratic approximations is shown in Figure 5.23. Notice that the more precise cases in which the quadratic terms are included lead to sharper likelihood functions around the found minima but there is overall consistency between both approaches at the 95% level marked by the upper red horizontal line.

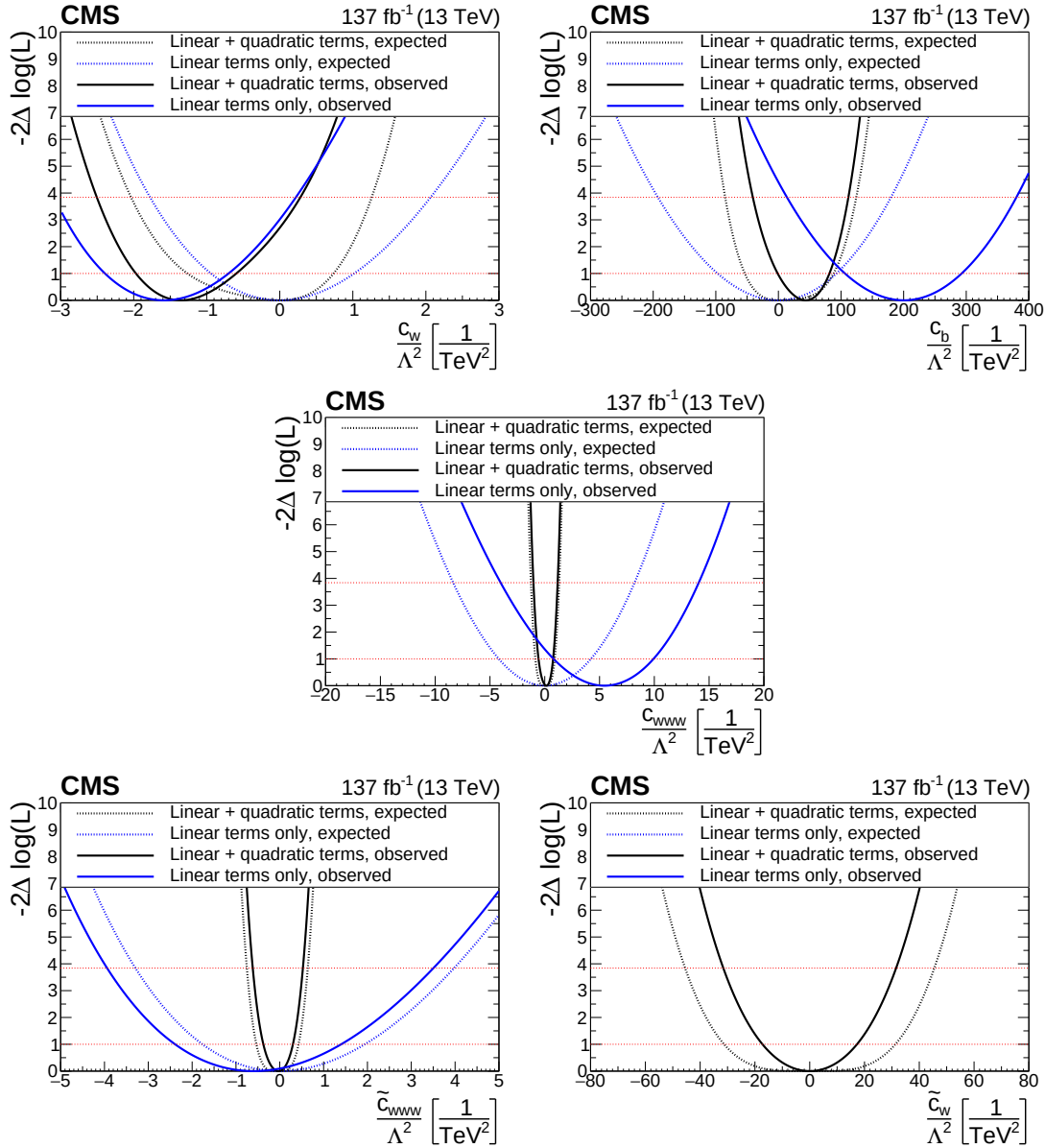


FIGURE 5.23: Expected and observed likelihood scans with respect to each of the considered EFT parameters in the interpretation of the $M(WZ)$ distribution. The effects of the two different considered signal modellings (only linear terms and linear plus quadratic terms) are both shown. In computing confidence intervals for each EFT term the other four are fixed to their SM values of 0, with the overall WZ normalization entering the fit as an unconstrained nuisance parameter. The parameter considered in each plot is: c_w/Λ^2 (top left), c_b/Λ^2 (top right), c_{www}/Λ^2 (middle), $\tilde{c}_{www}/\Lambda^2$ (bottom left), and $\tilde{c}_w/\Lambda^2$ (bottom right). For $\tilde{c}_w$ no sensitivity is found to the linear only terms, so no blue curves are shown.

TABLE 5.15: Best fit, expected confidence regions and observed confidence regions at the 95% CL for each of the considered EFT parameters in the interpretation of the $M(WZ)$ distribution. The signal modelling includes only the linear term in the EFT parameters. In computing confidence intervals for each parameter the other ones are fixed to their SM values of 0, with the overall WZ normalization entering the fit as an unconstrained nuisance parameter. No sensitivity is found to the linear term of the $\tilde{c}_w$ parameter

Parameter	95% CI, Exp. (TeV^{-2})	95% CI, Obs. (TeV^{-2})	Best fit, Obs. (TeV^{-2})
c_w/Λ^2	$[-1.82, 2.12]$	$[-3.11, 0.26]$	-1.59
c_{www}/Λ^2	$[-8.55, 8.46]$	$[-4.20, 14.25]$	5.48
c_b/Λ^2	$[-197, 183]$	$[9, 384]$	201
$\tilde{c}_{www}/\Lambda^2$	$[-3.35, 4.07]$	$[-4.01, 3.61]$	-0.59
$\tilde{c}_w/\Lambda^2$	$[-, -]$	$[-, -]$	-

5.10 Differential cross section measurements

Comparing data and expectations at the reconstructed level is a powerful technique to assess the agreement between the observations and either the SM or different BSM physics. However, it depends on the faithful simulation of the detector effects which can be both relatively costly and difficult to tune outside the LHC collaborations. Results provided at the generator level, such as the fiducial cross sections introduced in Section 5.5, offer a solution that can be compared with alternative models that do not depend on the effects of the CMS detector. Some physics of interest might only have a relevant effect in some phase space regions, such as the EFT contributions being enhanced at high $M(WZ)$ in Section 5.9. The possibility of measuring differential cross sections offers an interesting solution to providing information on those specific phase spaces. The problem can't be easily reduced to the formulae presented in Equation 5.2, as the efficiency might vary between different phase spaces, and migrations might appear between different values of an observable between its generated and reconstructed value. A possible solution is the usage of data unfolding, which is briefly presented in the following section and more detailed in References [120, 184].

5.10.1 Data unfolding

A generic unfolding problem is based on the relation between two different phase spaces. The reconstructed, or folded, space would correspond to the one in which we observe data, and the generated, or unfolded, space is the one in which we want to obtain the final set of measurements.

As a starting point, assume that the behaviour at the reconstructed and generated level are completely known. The set of signal yields measured in M bins in the reconstructed space can be noted as $\{y_j\}_{j=1}^M$. At the generated level these measurements are another set of quantities defined in N bins $\{x_i\}_{i=1}^N$, corresponding to either signal yields or a binned cross section. The effects of the detector are modelled through the definition of the response matrix $\mathcal{R}$ as

$$y_j = \sum_{i=1}^N \mathcal{R}_{ji} x_i \quad (5.35)$$

which encodes both overall efficiency effects, similar to the ones introduced in Equation 5.2, as well as possible migrations between the i generated bin to any of the j reconstructed ones. The simplest way of computing the response matrix is to use MC simulation, for which both x_i and y_j are known, and obtain

$$R_{ij} = \frac{\text{Yields on reconstructed bin } j, \text{ generated bin } i}{\text{Yields on generated bin } i} \quad (5.36)$$

which can be easily computed but, noticeably, introduces a dependence on the MC simulation of the efficiency and migrations. A usual procedure to mitigate this dependence is to use alternative simulation methods and check the stability of the results, even including the differences between the nominal and alternative as additional systematic uncertainties in the procedure.

The usual unfolding problem appears when the target generated level quantities $x = \{x_i\}$ are unknown and need to be extracted from data. A solution to the unfolding problem over a set of observed data $d = \{d_j\}_{j=1}^M$ and background $b = \{b_j\}_{j=1}^M$ events can be represented assuming that the observed signal yields are $y = d - b$. Then, the generator level solution can be obtained from the system of equations given by the matrix product $(d - b) = \mathcal{R}x$. The response matrix $\mathcal{R}$ is not in general invertible—it does not even need to have a quadratic shape—, so the best approximation to the solution of the problem is taken instead, as the one that minimizes the quantity

$$\mathcal{L}_{\mathcal{R}} = ([d - b] - \mathcal{R}x)^T V_y ([d - b] - \mathcal{R}x) \quad (5.37)$$

where V_y represents the covariance matrix of the $[d - b]$ measurements, such that $\mathcal{L}_{\mathcal{R}}$ represents the least squares distance of the obtained results to a perfectly fitting solution taking into account the uncertainties on the final results. This is the unregularized solution to the unfolding problem, also known as the matrix inversion solution.

In reality, when the response matrix is strongly non-diagonal the unregularized solution tends to magnify any fluctuations of the observed data, producing results with very big associated uncertainties. A quantification of these high variances can be made by studying the condition number of the response matrix $A(\mathcal{R})$, defined as

$$A(\mathcal{R}) = \frac{\max_{\delta \in \Delta}(\delta)}{\max(\min_{\delta \in \Delta}(\delta), 0)} \quad (5.38)$$

Where Δ is the set of all singular values of the matrix, the square roots of the eigenvalues of the $\mathcal{R}\mathcal{R}^T$ product. They are generalizations of the own matrix eigenvalues to the generic case in which $\mathcal{R}$ is not necessarily in an square shape. From the physical point of view, they represent whether some regions of the generated phase space have a much stronger effect on the reconstructed one (greater singular value), than others. Higher values of the condition number, conventionally assumed to be greater than

100, tend to introduce significant variations on the measurements at the generator level.

5.10.1.1 Regularized unfolding

In cases where a smart definition of the binning is not enough to suppress the high variance effects from the matrix inversion unfolding, a possible solution to the problem is to slightly alter the definition of the unfolded estimation by introducing artificial biases on the unfolding procedure. First, a direct bias term can be added to Equation 5.37 as

$$\mathcal{L}_{Reg} = \omega^2 (x - x_0)^T \mathcal{T}^T \mathcal{T} (x - x_0) \quad (5.39)$$

which is known as the regularization term. Two different regularization possibilities appear in this equation. The first, is a bias that acts independently on each bin and pulls its result towards a target set of fixed values given by $\{x_{0,i}\}_{i=1}^N$. Usually the expectations for the signal observations at the generated level are used as x_0 , in which case the unfolding procedure will bias the result towards the expectations.

The second contribution, based on the regularization matrix $\mathcal{T}$, introduces a bias that can take into account correlations across bins. Any generic matrix could be used, but the most common ones aim to provide smoother final results by representing derivatives of different order computed numerically with the observed yields. For example, second order Tikhonov's regularization [185] is based on a smoothing of the differential yields x through a numerical estimation of its second derivative, which is expected to reduce peaking fluctuations due to the unfolding procedure. The $\mathcal{T}$ matrix for Tikhonov's regularization is given by

$$\mathcal{T}_{ij}^{\text{Tik}} = 2\delta_{i,j} - \delta_{i-1,j} - \delta_{i+1,j} \quad (5.40)$$

where $\delta_{i,j}$ denotes the Kronecker's δ symbol. The final term in Equation 5.39 is the unfolding strength ω , an additional multiplier that represents the relative strength of the regularization term with respect to the matrix inversion one. To define the value of the ω parameter, the L-curve method [186] is used. The L-curve method is based on reaching an optimal equilibrium between the $\mathcal{L}_{Reg}$ and $\mathcal{L}_{\mathcal{R}}$ terms. A parametric curve in ω is drawn in the $\mathcal{L}_{Reg}$ - $\mathcal{L}_{\mathcal{R}}$ space by evaluating both quantities at the $\{y_j\}$ solutions provided by the unfolding for different test values of ω . The point at which the curvature of this curve is maximal determines the optimal value of ω .

As the unfolding term will bias the result towards a new set of values, the resulting measurements might be also biased in terms of the total predicted cross section, artificially enhancing or depleting its overall value. This last effect can be fixed with yet another addition to Equation 5.37 of an area constraint term defined as

$$\mathcal{L}_{Area} = \lambda \left[\sum_{j=1}^M \left(d_j - b_j - \sum_{i=1}^N \mathcal{R}_{ij} x_i \right) \right] \quad (5.41)$$

which establishes that the total sum of yields has to be equal for the generator space result and the reconstructed space result, once corrected by the detector efficiencies modelled by the response matrix. Here, the λ term represents a Lagrange multiplier regulating the presence or not of this additional term. A complete likelihood for regularized unfolding then reads as

$$\begin{aligned} \mathcal{L}_{\text{Total}}(x; \lambda) = \mathcal{L}_{\mathcal{R}} + \mathcal{L}_{\text{Reg}} + \mathcal{L}_{\text{Area}} = & ([d - b] - \mathcal{R}x)^T V_y ([d - b] - \mathcal{R}x) + \\ & + \omega^2 (x - x_0)^T \mathcal{T}^T \mathcal{T} (x - x_0) + \lambda \left[\sum_{j=1}^M \left(d_j - b_j - \sum_{i=1}^N \mathcal{R}_{ij} x_i \right) \right] \end{aligned} \quad (5.42)$$

As described before, the values of the $\mathcal{T}$ matrix, the x_0 vector, and the ω and λ parameters will define the kind of unfolding that will ultimately be performed. Unregularized, matrix inversion, unfolding is recovered by setting $\omega = \lambda = 0$.

5.10.2 Differential cross section measurements

In order to provide a complete picture of the WZ process, differential cross sections are computed with respect to several variables of interest:

- p_{T}^{Z} : the reconstructed p_{T} of the Z boson, a variable that is sensitive to the presence of BSM physics as shown in Figure 5.20, and also provides a characterization of the process kinematics.
- p_{T}^{W} : the p_{T} of the ℓ_{W} lepton, as a proxy of the W boson energy, to complement the p_{T}^{Z} measurement with the W boson kinematics.
- Leading jet p_{T} : the p_{T} of the highest p_{T} jet, which roughly accounts for the boost of the WZ system in events with hard QCD emissions.
- Jet multiplicity: a distribution of special relevance when WZ acts as a background source in multileptonic physics, such as the one presented in Section 4.8 and the discussion introduced in Chapter 6.
- $\cos(\theta^{\text{W}})$ and $\cos(\theta^{\text{Z}})$: the cosine of the polarization angles for the W and Z bosons as defined in Section 5.8. The measurement serves as a cross-check of the polarization studies.
- $M(\text{WZ})$: the invariant mass of the WZ system as defined in Section 5.9. The measurement serves as a cross-check of the EFT studies.

As an example, the case of p_{T}^{Z} will be considered to discuss the general unfolding procedure. First, the reconstructed phase space is taken as the SR-WZ defined in Section 5.2.2, while the generated one corresponds to the fiducial region defined in Section 5.5. The binning is optimized to try to avoid effects that would require the usage of regularization, by starting with a thin variable binning and then merging adjacent bins that show strong dispersion towards the same regions of the opposite phase space. An

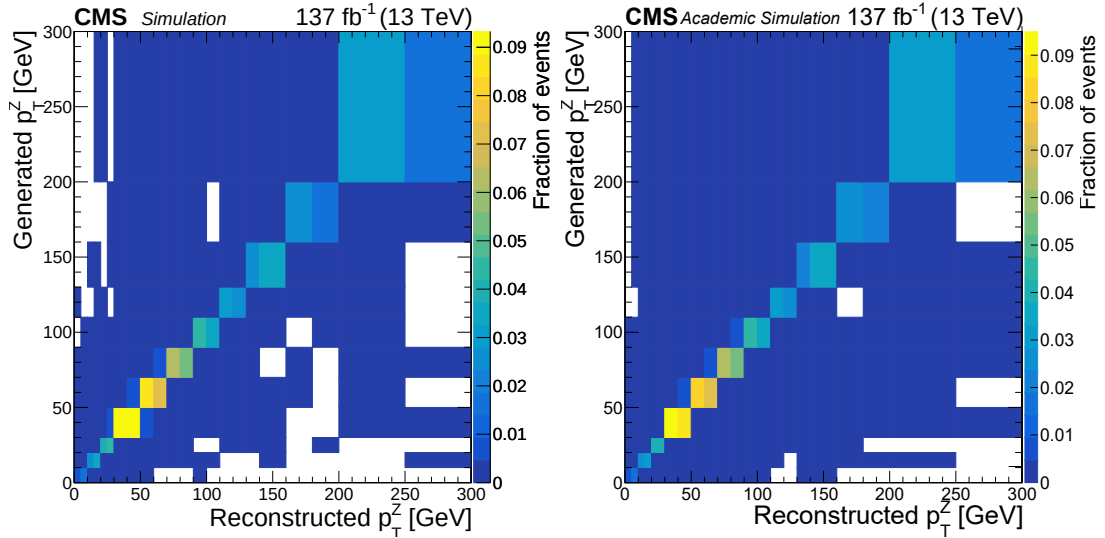


FIGURE 5.24: Response matrices corresponding to the p_T^Z variable in the WZ analysis obtained with the nominal POWHEG sample (left) and the alternative MADGRAPH+aMC@NLO one (right). The condition numbers associated to these matrices are 7.77 (POWHEG) and 8.05 (MADGRAPH+aMC@NLO).

additional condition is applied that at least twice the number of bins is used in the reconstructed space than in the generated one, which is known to improve the stability of the unregularized method [187]. The resulting response matrices for the p_T^Z variable computed with the nominal POWHEG and alternative MADGRAPH+aMC@NLO samples are shown in Figure 5.24. As the condition numbers of both response matrices are low, around 8 in both cases, it is to be expected that no regularization needs to be applied in order to obtain unfolded results.

The unfolding procedure is performed using the TUnfold framework [188]. The process follows the description of Section 5.10.1. First, the observed yields of data and background for each of the bins in the reconstructed phase space, as well as the nominal POWHEG response matrix are fed to the algorithm. As the events containing leptonic τ decays are not included in the fiducial region definition, as described in Section 5.5, they are treated as a background source for the purpose of the unfolding procedure.

Uncertainties affecting the background yields are propagated to the final result through the repetition of the unfolding procedure by varying the input background yields according to the size of the uncertainties. Those affecting the signal process are included through alternative unfolding steps in which the response matrices are varied accordingly. All uncertainties described in Section 5.4 are included into the procedure in this way, and the total variations are added up quadratically on each generator level bin. Although consistency between the two response matrices is found, an additional systematic uncertainty is applied to the signal by adding up the effects introduced by an alternative unfolding performed with the MADGRAPH+aMC@NLO response matrix and the nominal yields for all background processes. In order to test the effects of adding different regularization terms, the procedure is repeated for the following setups:

1. **Without regularization, nor area constraint term** ($\lambda = 0$, $\omega = 0$): corresponding with the pure matrix inversion unfolding described in Section 5.10.1.

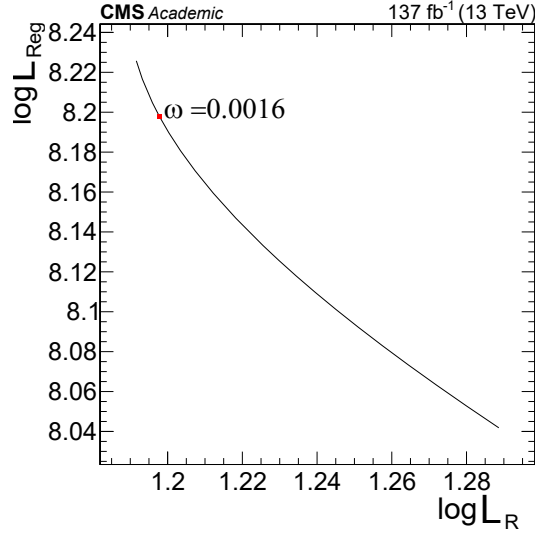


FIGURE 5.25: L-curve used to optimize the regularization strength ω for the unfolding of the p_T^Z variable using Tikhonov regularization. The optimal value of the parameter ω , marked in red, corresponds to the point of maximal curvature (maximal trade-off between regularization and matrix inversion terms) of the L-curve.

2. **With area constraint term but no regularization** ($\lambda \neq 0$, $\omega = 0$): which corresponds to imposing the preservation of the yields from the reconstructed to the generated space. The value of the λ parameter is fitted by the unfolding, as it works as a Lagrange multiplier to ensure that the solution fulfils the area constraint criteria.
3. **With no area constraint and vector bias regularization towards the expected WZ yields** ($\lambda = 0$, $\omega \neq 0$, $\mathcal{T} = \mathbb{I}$, $x_{0,i} = x_i^{\text{WZ}}$): in this case only a bin by bin bias is activated, that skews the reconstructed measurements towards the expected WZ yields. For this purpose, the expected WZ yields are normalized to the NNLO QCDxNLO EWK cross section obtained with MATRIX.
4. **With no area constraint and Tikhonov regularization but no bias vector** ($\lambda = 0$, $\omega \neq 0$, $\mathcal{T} = \mathcal{T}^{\text{Tik}}$, $x_{0,i} = 0$): meaning that the overall curvature of the prediction is smoothed by the regularization procedure but no bias is applied towards the expected yields.
5. **All other 4 possible combinations of cases 2–4.**

The L-curve method, discussed in Section 5.10.1.1, is used to select the value of the ω parameter when needed. A graphical example of the criteria for the unfolding of p_T^Z under method (3) is shown in Figure 5.25. Results for all the involved six unfolding configurations with non-zero regularization led to similar results, with ω having optimal values around 0.001. This means that the optimal setup has very weak regularization terms, results that are consistent with the observed low values of the condition numbers of the response matrices.

Finally, the unfolding is performed using TUnfold and the different setups presented before. The unfolded data is compared with the shape predictions obtained with POWHEG at NLO in QCD, MADGRAPH+amc@NLO at NLO in QCD, and MATRIX at NNLO in QCDxNLO EWK for all of the cases. PDF and scales uncertainties as obtained for the

POWHEG sample are included for comparison, while all uncertainties are propagated to the final unfolded result as detailed before. To avoid the appearance of peaks in the distribution and show the trend of the differential cross section instead, the expected and observed results on each bin are divided by the bin width, meaning that the sum of the bin content equals to 1, rather than its integration. As an example, the results for cases 1–4 are presented in Figure 5.26. It can be observed that differences between the four cases are near negligible, with near no changes except for the first three bins of the distribution. Thus, the unregularized unfolding was chosen as the nominal unfolding procedure. General good agreement between data and MC except for the first of the bins where a small excess of data is observed. A small tendency towards a defect at high values is observed, reproducing the effect of the reconstructed distribution presented in Figure 5.20 (right).

The same strategy and procedure as for the p_T^Z variable is followed to obtain differential cross sections for the rest of quantities of interest. For the leading jet p_T case, an additional requirement is included into the generated phase space selection, in order to mimic the requisite of one reconstructed jet in the fiducial region. Particle-level objects, are clustered with the anti- k_T algorithm and a distance parameter of 0.4 into generator level jets, and at least one of them with $p_T > 25$ GeV and $|\eta| < 2.5$ is required. The response matrices corresponding to the unfolded variables are summarized in Figure 5.27. Condition numbers oscillate between 3 and 64, pointing to the unlikelihood of the need for any kind of regularization.

The same set of checks on alternative unfolding introduced before were performed for each of the variables, with no noticeable differences obtained by the introduction of regularization into the unfolding. Thus, all final differential cross section results are computed using the unregularized unfolding strategy. A noticeable effect is depicted on how the $\cos(\theta^W)$ variable, which heavily involves the presence of p_T^{miss} , suffers from the worse resolution of the whole considered set, which much more intensive migrations across bins than any of the others.

The measured differential cross sections are shown in Figure 5.28. While MATRIX provides distributions of parton-level clustered jets, as it is not matched with a PS it is not expected that it would be able to generate additional emissions that would heavily contribute to the N_{jets} distribution, and so the MATRIX prediction is not included in the comparison of this differential cross section with data.

5.11 Summary

A detailed study of the WZ process at 13 TeV using 137 fb^{-1} of data has been presented. The inclusive WZ total production cross section is measured to be $\sigma(\text{pp} \rightarrow \text{WZ}) = 50.6 \pm 0.8(\text{stat.}) \pm 1.5(\text{syst.}) \pm 1.1(\text{lumi.}) \pm 0.5(\text{theo.}) \text{ pb}$. A relative uncertainty of slightly under the 4%, dominated by around a 3% systematic uncertainty, is achieved. The total cross section results are in better agreement with the fixed order computations obtained with MATRIX at NNLO in QCDxNLO EWK ($50.7 \pm 1.1 \text{ pb}$) than with the predictions from POWHEG at NLO in QCD ($42.5 \pm 1.8 \text{ pb}$). The same quantity is measured separately in four exclusive categories corresponding to the charged lepton flavour composition ($eee, ee\mu, \mu\mu e, \mu\mu\mu$) leading to consistent results.

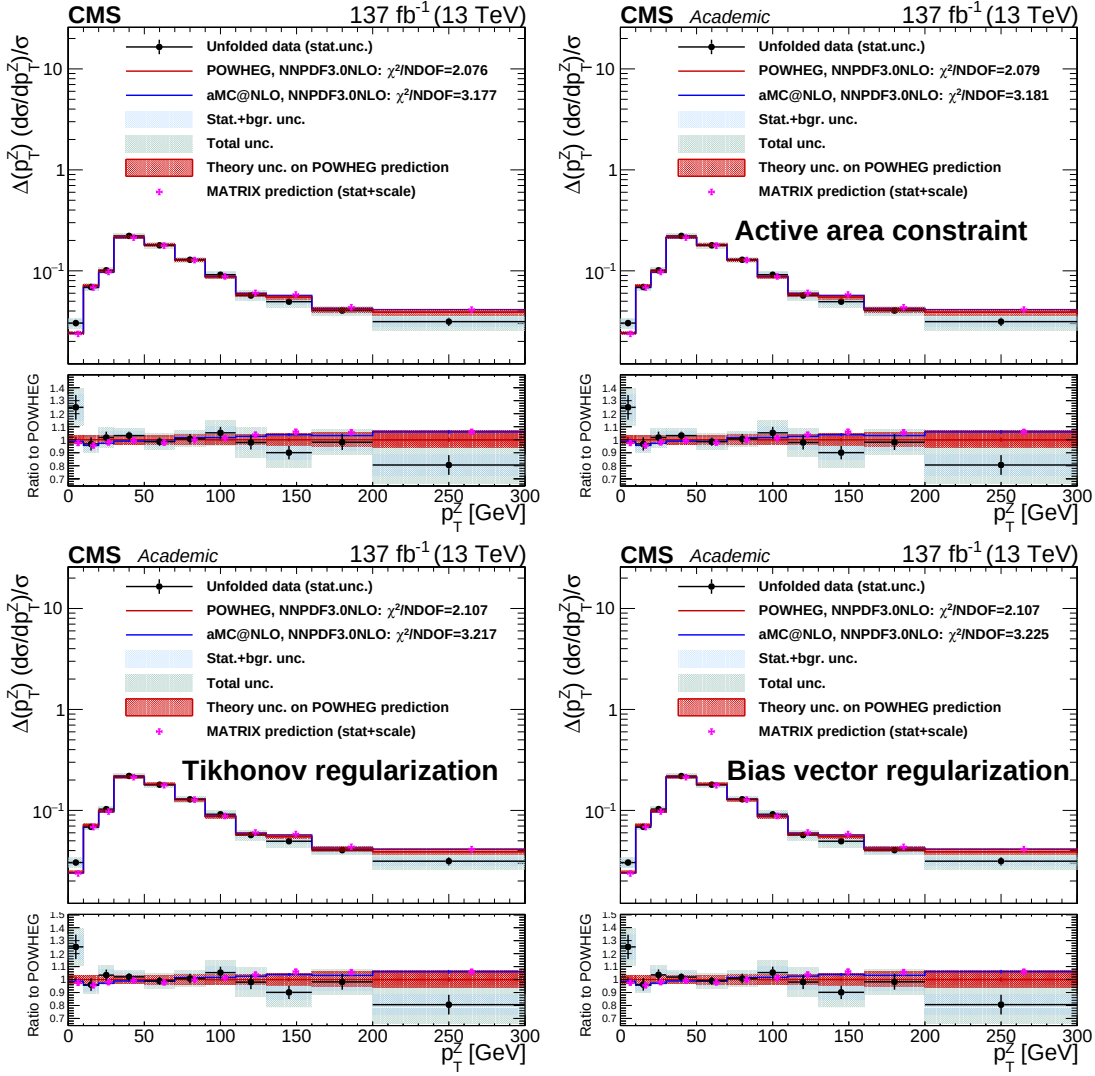


FIGURE 5.26: Differential WZ fiducial cross sections with respect to the p_T^Z quantity for several of the unfolding setups considered: no regularization and no area constraint (unlabelled, top left), no regularization with active area constraint (top right), bias vector regularization with no area constrain (bottom left), and Tikhonov regularization with no area constraint (bottom right). All results are near identical except for small variations in the first three bins. The points corresponding to the MATRIX result are slightly displaced from the bin centres for plotting purposes only, they correspond to the same binning definitions as POWHEG and MADGRAPH+aMC@NLO.

The charge asymmetry in WZ production is also studied, leading to a measurement of $A_{WZ}^{+-} = 1.41 \pm 0.04(\text{stat.}) \pm 0.01(\text{syst.}) \pm 0.01(\text{lumi.})$, compatible with both the POWHEG and MATRIX predictions. The measurement is strongly dominated by the statistical uncertainties, as most systematic effects cancel in the ratio computation. The effect of these measurement are interpreted in terms of impacts on the NNPDF30 set, showing the possibility of obtaining small constrains in the PDF uncertainties from diboson measurements for the first time.

The three polarization fractions of the W and Z bosons are studied independently for the first time in CMS, leading to the determination of confidence levels for the f_0 and f_{LR} quantities. The significance of the presence of longitudinally-polarized massive

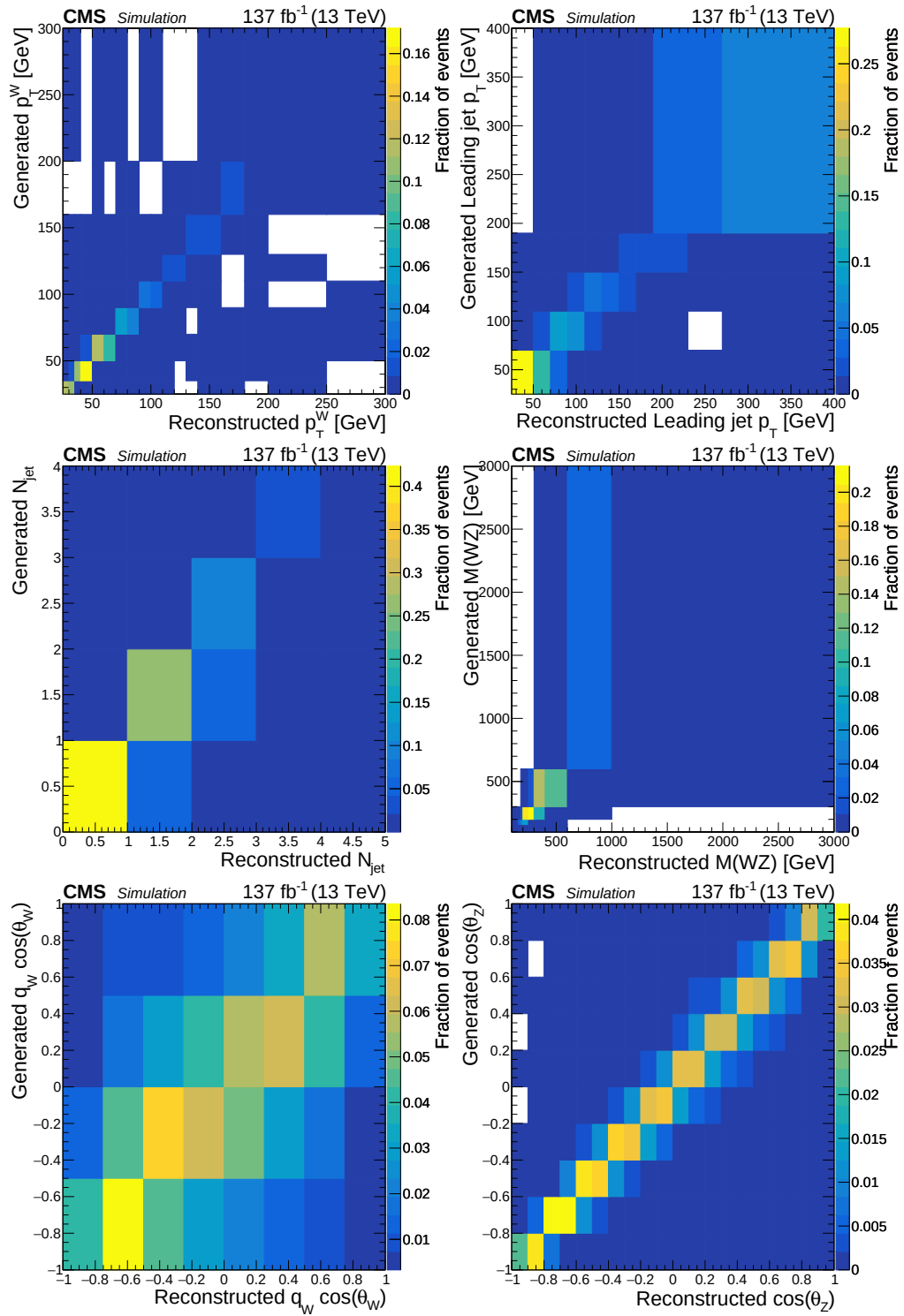


FIGURE 5.27: Response matrices corresponding to the different unfolded variables in the WZ differential cross section measurements. All matrices are obtained with the nominal POWHEG sample. They correspond to the variables: p_T of the ℓ_W lepton (top left, condition number 20.9), p_T of the leading jet (top right, condition number 9.69), jet multiplicity (middle left, condition number 16.9), invariant mass of the WZ system $M(WZ)$ (middle right, condition number 64.0), cosine of the polarization angle θ^W (bottom left, condition number 7.84), and cosine of the polarization angle θ^Z (bottom right, condition number 2.94).

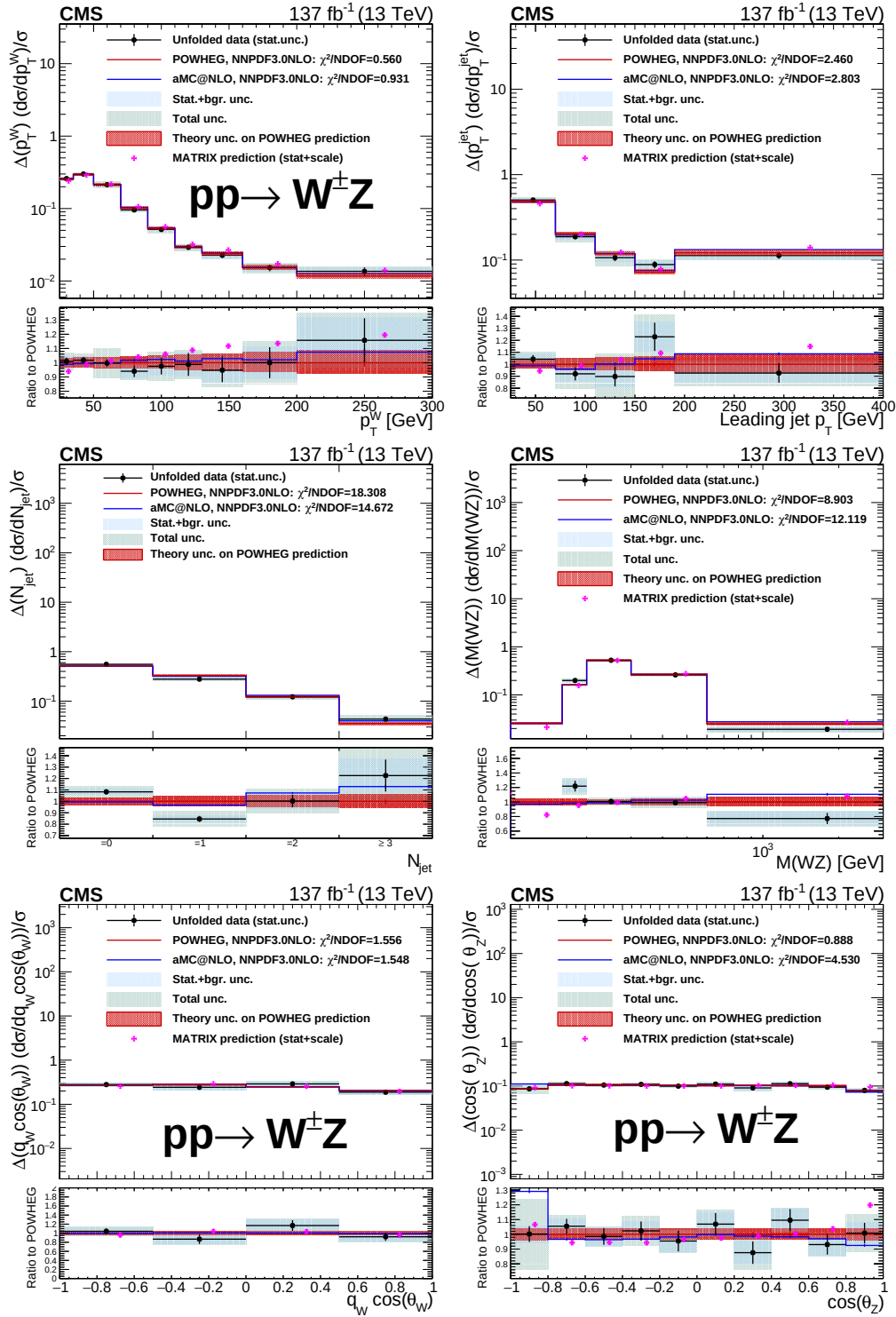


FIGURE 5.28: WZ differential cross sections with respect to several variables of interest in WZ production. The unfolding procedure is performed in all cases without any active regularization terms. The plots correspond to the variables: p_T of the ℓ_W lepton (top left), p_T of the leading jet (top right), jet multiplicity (middle left), invariant mass of the WZ system $M(WZ)$ (middle right), cosine of the polarization angle θ_W (bottom left), and cosine of the polarization angle θ_Z (bottom right). The points corresponding to the MATRIX result are slightly displaced from the bin centres for plotting purposes only, they correspond to the same binning definitions as POWHEG and MADGRAPH+aMC@NLO.

vector bosons is tested against the transversal polarization only and found to be over 5 standard deviations for both the W and Z bosons, leading to the first observation of longitudinally-polarized bosons in diboson production.

The distribution of the invariant mass of the WZ system is studied in order to search for new physics phenomena at the high energy regime. Although no apparent BSM effects are found, the interpretation in terms of EFT theories leads to stronger confidence limits in five different EFT parameters than the ones previously available for the channel. The applicability of the EFT interpretation is tested through several studies on the cut-off energy scale and on the restriction of the cut-off suppressed terms in the total matrix element.

All the results above are cross-checked through the measurements of differential cross sections with respect to several high level observables that characterize either the WZ process as a whole or the different phenomena studied in each of the results above.

6

Search for electroweak SUSY in multileptonic final states

The discovery of new physics, one of the main objectives of the LHC program, is an extremely complex problem due to the completely unknown properties of any BSM reality. Scrutinizing all possible final states for hints of its presence is needed in order to maximize the sensitivity of the experimental searches to new phenomena. The supersymmetric theories introduced in Section 2.4.1 are specially attractive from this point of view, as they offer a strongly motivated underlying model in which physics in a plethora final states can be related through the presence of an extended supersymmetric–extended SM. Thus, different searches can be easily compared and combined. This chapter introduces several searches corresponding to different SUSY models performed with data taken with the CMS detector at $\sqrt{s} = 13$ TeV during the whole Run 2 period.

The chapter is organized as follows. First, Section 6.1 provides a brief motivation and description on the general kind of SUSY models that will be considered, as well as a brief historical summary of the results from past studies performed by both the ATLAS and CMS collaborations on these models. Section 6.2 provides an overall description of the analysis strategy, providing an overview of the final states considered for this search. The generic object identification techniques introduced in Chapter 6 are then applied in order to define optimized selection criteria as described in Section 6.3. Section 6.4 details the different techniques used to estimate the different background contributions to the multileptonic final states. The overall set of uncertainty sources affecting the final measurements are introduced in Section 6.5. The optimized signal extraction criteria and its results in terms of expectations and observations are shown in Section 6.6. Section 6.7 provides the interpretation of these results in terms of excluded regions in the phase space of different SUSY models. Finally, Section 6.8 provides a summary of the presented results.

The results presented in this chapter have been published by the CMS collaboration in References [10] [11], and [12]. The first, Reference [10], corresponds to results obtained with the 2016 dataset only for multileptonic final states, and I was involved on its development through the optimization of the search for final states involving a same-sign lepton pair. The second, Reference [11], corresponds to the combination of the later with results in other final state topologies [189–192]. I was part of its development through the adaptation of the different analysis to conform into a single

statistic model, the revision of such model to ensure its validity, and the developments of tools for the overall combination of final states and their comparisons, as published in the final result. The last paper, Reference [12], corresponds to the extension and improvement of the first using the larger amounts of data and experience accumulated during the Run 2 of the LHC. I was one of the main authors of this analysis for which I optimized the lepton identification criteria, performed the cross-checks and estimations on all the prompt lepton backgrounds –and part of the data-driven ones– and their uncertainties, optimized the cut-based signal region definition, and performed the overall signal extraction and interpretation on terms of the different SUSY models. Additionally, during the studies presented, I developed a new technique to cross-check the robustness of parametric signal extraction approaches with respect to the look-elsewhere effect, details are not given on this report for brevity. The discussion of this Chapter focuses on the results of Reference [12].

6.1 Electroweak SUSY at the LHC

As discussed in Section 2.4.1, SUSY theories offer attractive BSM models which might provide an answer to the hierarchy problem, as well as provide candidates for dark matter candidates and, as an added bonus, provide an unification of the strong and electroweak interactions at a high energy scale. This has motivated the search of supersymmetric partners at the ATLAS and CMS collaborations since the start of the LHC running, with quite an abundant set results published since 2010. Phenomenologically, the main focus of the studies have been on RPC SUSY production, as defined in Section 2.4.1, as it provides natural candidates to dark matter particles.

In RPC SUSY, all SUSY particles are produced in pairs. Depending on the nature of the pair-produced BSM particles, a division is usually done between strong SUSY (where the superpartners have colour charge) and electroweak SUSY (where the superpartners only interact through the electroweak sector of the SM). Heavily simplified descriptions of SUSY already show that the cross sections of strong SUSY are typically higher than those of electroweak SUSY at the LHC, as shown in Figure 6.1. Thus, strong SUSY has been studied in quite some detail by the ATLAS and CMS experiments which, depending on the model assumptions, have been able to exclude the presence of stops, squarks, and gluinos up to the 2 TeV scale [193, 194]. Such stringent constraints pose the question on whether electroweak SUSY might be the only production mode reachable with the current LHC energies and accumulated luminosity.

Electroweak SUSY has the additional benefit of populating the regions of high lepton multiplicity, as neutralinos, charginos and sleptons are all expected to couple to their SM counterparts, the electroweak gauge bosons and the SM leptons. Thus, multileptonic final states appear in even the most simple electroweak SUSY models. This makes electroweak SUSY a more than suitable candidate to be studied with the techniques introduced in Chapter 4. It also strongly correlates these searches to the measurements presented in Section 4.7 and Chapter 5, as diboson production and electroweak SUSY tend to populate very similar final states.

Multiple searches of electroweak SUSY in multileptonic final states have been performed by the CMS [12, 196, 197] and ATLAS collaborations [198–201]. Similar production modes have been studied in other final states by both collaborations, of which

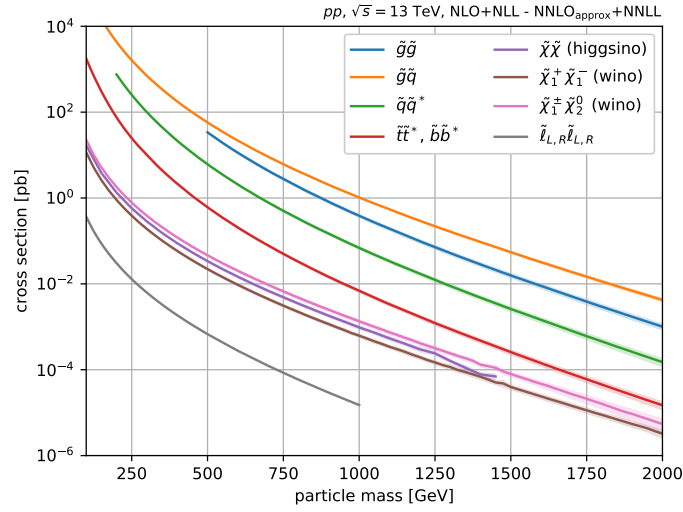


FIGURE 6.1: Cross sections for the pair production of different supersymmetric partners as a function of the sparticle mass at a centre of mass energy of 13 TeV. The top four curves correspond to strongly interacting superpartners, while the bottom four only interact through the electroweak interaction. In the cases considered, all but the involved SUSY partners are assumed to have a high enough mass to be decoupled from the process in question. This figure was taken from the publicly available Reference [195].

the latest focus on: a single lepton plus two b quarks [202, 203], two photons [204, 205], boosted hadronic boson decays [206], and four b quarks [190, 207]. The usage of a consistent description of the SUSY parameter space, agreed on by both collaborations, allows for a direct comparison of the results presented in these studies with those included in the quoted references.

6.1.1 Signal models

At the experimental level, even the most simplest case of a supersymmetric theory described by the MSSM retains quite a lot of complexity in the form of a multidimensional parameter space to be studied. This introduces a technical problem, as probing with MC simulation spaces of such dimensionality has very high requirements in terms of computational power. Moreover, the communication of the obtained results to the broad community of experimentalists and theorists would be hindered, as the whole set of underlying parameters used for the signal extraction would need to be provided.

The consensual solution to both problems is the usage of a common set of models known as simplified models [39, 208] (SMS), as briefly introduced in Section 2.4.1.3. In essence, a simplified model is a projection of the more complex one –in this case, usually MSSM– in which only a handful of particles have low enough masses to be produced at the colliding energies. A typical SMS model includes only two or three SUSY partners in addition to the SM particle content, with their masses and branching fractions being the parameters used to characterize it. The drawback of the simplicity and reinterpretability of the SMS is a somewhat unphysical representation of reality, as a realization of SUSY with such a specific final states is unlikely to be realistic.

Nonetheless, SMS have proven to provide robust templates for the LHC interpretations, and the underlying model can always be recurred to for further investigation in case significant excesses were observed across the different searches. Several sets of SMS are considered in the following discussion, in order to cover a broad range of possible SUSY models.

6.1.1.1 Chargino–neutralino production, light sleptons

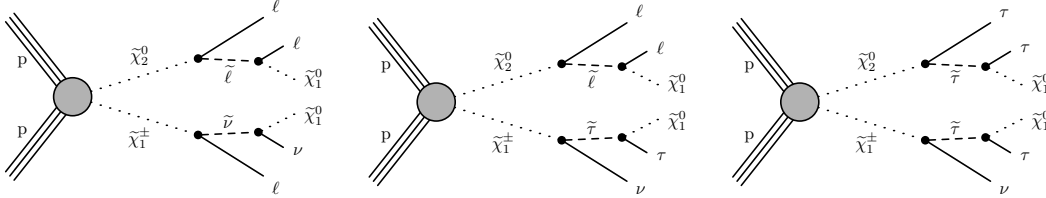


FIGURE 6.2: Production diagrams for simplified SUSY models on which the $\chi_1^\pm$ and χ_2^0 particles decay through intermediate light sleptons. They correspond to: the $T\chi\chi\tilde{\ell}\tilde{\ell}$ model in which the electroweakinos couple equally to all lepton flavours (left), the $T\chi\chi\tilde{\tau}\tilde{\ell}$ model in which the neutralino couples equally to all lepton flavours but the chargino prefers the $\tilde{\tau}$ slepton (middle), and the $T\chi\chi\tilde{\tau}\tilde{\tau}$ in which both pair-produced particles couple preferably to the $\tilde{\tau}$ slepton (right).

A first set of the considered SMS models corresponds to the case in which sleptons are lighter than the lightest chargino and second-to-lightest neutralino. In this case, pair-produced $\chi_1^\pm \chi_2^0$ particles can decay through intermediate states involving sleptons which, in turn, decay to their SM counterparts and the lightest neutralino which is the LSP of these models. Diagrams for the tree-level production modes of these models are shown in Figure 6.2. Further classifications depending on the branching ratios of the $\chi_1^\pm$ and χ_2^0 to the different lepton flavours are introduced, as follows:

- **The flavour-democratic scenario ($T\chi\chi\tilde{\ell}\tilde{\ell}$):** this scenario corresponds to cases in which the lightest slepton states are left-handed, meaning that they couple to the Wino component of the electroweakinos. Under these conditions, the couplings between the sleptons and electroweakinos are similar to that of the electroweak interaction in the SM, so all slepton flavours are produced in the same proportion. A leading order production diagram is shown in Figure 6.2 (left).
- **The tau-enhanced scenario ($T\chi\chi\tilde{\tau}\tilde{\ell}$):** if sleptons of both quiralties appear at low masses, but the chargino is predominantly Higgsino-like. In this case the chargino couplings will be akin to those of the Higgs boson and so the production of $\tilde{\tau}$ leptons will be preferred, ultimately resulting in a enhancement of the $\tilde{\tau}$ content in the final state. A leading order production diagram is shown in Figure 6.2 (middle).
- **The tau-dominated scenario ($T\chi\chi\tilde{\tau}\tilde{\tau}$):** if only right handed sleptons are light enough their couplings to the electroweakinos will be mediated by their higgsino component. Thus, the couplings will be proportional to the Yukawa terms of their SM counterparts and so the $\tilde{\tau}$ lepton will be strongly preferred over other

slepton flavours. A leading order production diagram is shown in Figure 6.2 (right).

Under the assumption that each slepton flavour decays to its SM counterpart, these three models produce multileptonic final states ranging from low to high τ lepton multiplicity, which will later populate different final states consisting on different quantities of reconstructed light leptons and τ_h . The $\chi_1^\pm$ and χ_2^0 are expected to always decay through sleptons in these models. Notice than in all the cases, the decay chain of the χ_2^0 will produce a pair of leptons of same flavour but different charge, but that they are non resonant, an important property that can be exploited experimentally.

In all three cases, the masses of the χ_1^0 , $\chi_1^\pm$, χ_2^0 , and each of the sleptons particles ($\tilde{\ell}$) are free parameters of the models. In order to further simplify the production modes, additional assumptions are made. Namely, all sleptons are assumed to be mass-degenerate ($M_{\tilde{e}} = M_{\tilde{\mu}} = M_{\tilde{\tau}}$), as well as the two non-LSP electroweakinos ($M_{\chi_1^\pm} = M_{\chi_2^0}$). The resulting three parameter space is further simplified through the introduction of the mass parameter x defined such that

$$M_{\tilde{\ell}} = xM_{\chi_1^0} + (1-x)M_{\chi_2^0} \quad (6.1)$$

Values of x close to 0 or 1 will result in more compressed –more similar superpartner masses– scenarios in which quite some imbalance between the p_T of the produced leptons will appear, while values closer to 0.5 are expected to provide sets of leptons at roughly the same energy scale. Thus, three different values of x are considered: 0.05, 0.5, and 0.95. Mixing this parameter with the three branching ratio cases introduced before, a total of 9 different SMS are considered, each of which has as free parameters the masses of the lightest chargino and neutralino ($M_{\chi_1^\pm}$, $M_{\chi_1^0}$).

6.1.1.2 Chargino–neutralino production, heavy sleptons

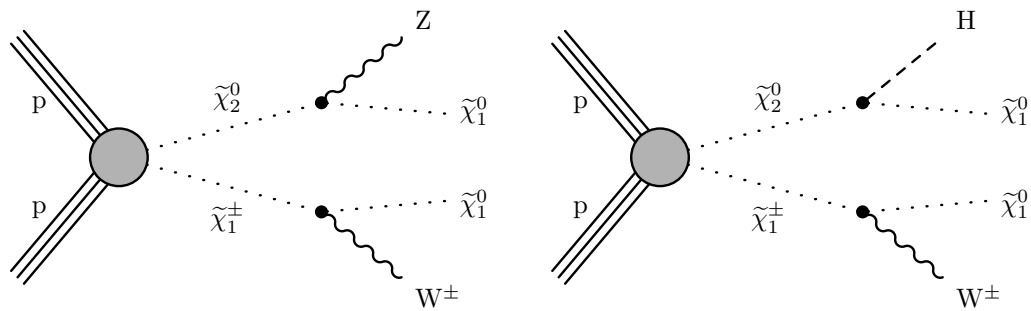


FIGURE 6.3: Production diagrams for simplified SUSY models on which the $\chi_1^\pm$ and χ_2^0 particles decay through the SM gauge bosons. They correspond to: the WZ mediated scenario ($T\chi\chi WZ$, left), and the WH mediated scenario ($T\chi\chi WH$, right).

If the sleptons are heavier than the lightest neutralino and chargino states, both the $\chi_1^\pm$ and χ_2^0 will decay through the SM gauge bosons. The only remaining superpartner is the lightest neutralino, χ_1^0 , which is again the LSP of the model. The somewhat more restrictive nature of this model means that the chargino decay is fixed, as the only

charged boson in the SM is the W . However two possible scenarios are considered based on the branching fractions of the χ_2^0 . They are illustrated in Figure 6.3 and described below.

- **The WZ mediated scenario ($T\chi\chi WZ$):** if the χ_2^0 decays through the SM Z boson, which would lead to final states with roughly the same proportion of all SM lepton flavours. A leading order production diagram is shown in Figure 6.3 (left).
- **The WH mediated scenario ($T\chi\chi WH$):** if the χ_2^0 decays through the SM H boson, which would lead to final states with an increased proportion of τ leptons. A leading order production diagram is shown in Figure 6.3 (right).

For both models, the masses of the NLSP are expected to be equal ($M_{\chi_1^\pm} = M_{\chi_2^0}$), but different from that of the LSP. Thus, both models have as free parameters the masses of the lightest chargino and neutralino ($M_{\chi_1^\pm}, M_{\chi_1^0}$).

6.1.1.3 Neutralino–neutralino production, heavy sleptons

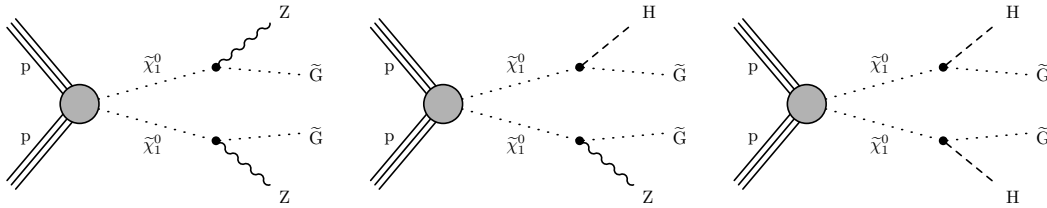


FIGURE 6.4: Production diagrams for simplified SUSY models on the GMSB scenario. They correspond to: the ZZ mediated scenario ($T\chi\chi ZZ$, left), the HZ mediated scenario ($T\chi\chi HZ$, middle), and the HH mediated scenario ($T\chi\chi HH$, right).

Last, the case of neutralino pair production is considered. The cross section for direct neutralino pair production is known to be quite small in the most simplified cases of all other superpartners being decoupled [209–211], so a slightly more complex scenario than the previous two is proposed. Instead, a Gauge–Mediated SUSY Breaking (GMSB) model in which SUSY is coupled to gravity as well is introduced [212]. In this model the $\chi_1^\pm$, χ_2^0 , and χ_1^0 electroweakinos are Higgsino–like and near mass degenerate. Due to this mass degeneration, $\chi_1^\pm$ and χ_2^0 decay to the χ_1^0 final state producing very soft additional activity with remains undetected, and the production mode is effectively a χ_1^0 pair. The χ_1^0 states decay to SM bosons plus the LSP which is a near massless gravitino $\tilde{G}$. Depending on the branching fractions of the χ_1^0 to the SM bosons, three different models are shown in Figure 6.4 and described below

- **The ZZ mediated scenario ($T\chi\chi ZZ$):** if the χ_1^0 decays entirely through the SM Z boson. All lepton flavours are produced equally in this case. A LO diagram of this model is shown in Figure 6.4 (left).
- **The HZ mediated scenario ($T\chi\chi HZ$):** if the χ_1^0 decays equally to the Z and H bosons. A slight preference for τ leptons in the final state appears in this scenario. A LO diagram of this model is shown in Figure 6.4 (middle).

- **The HH mediated scenario** ($T\chi\chi HH$): if the χ_1^0 decays entirely through the SM H boson. The appearance of final state τ leptons are strongly favoured in this case. A LO diagram of this model is shown in Figure 6.4 (right).

In all cases considered, the gravitino is assumed to be near-massless ($M_{\tilde{G}} = 1$ GeV), with the χ_1^0 mass being the only parameter of the model ($M_{\chi_1^0}$).

6.1.2 Signal simulation and modelling

Monte Carlo samples corresponding to the simulation of the signal processes are used in addition to the SM ones described in Section 4.2. Several parameters of the sample production are altered slightly to accommodate the description of BSM process as well as to reduce the resource consumption of the MC production in order to cover a broader range of parameter values in the models considered.

The matrix element generation is done with MADGRAPH+amc@NLO (version 2.4.2) at LO in QCD and includes a description of the SMS up to the pair-produced particles ($\chi_1^\pm \chi_2^0$ or $\chi_1^0 \chi_1^0$ in both cases) with up to two additional extra partons corresponding to real radiation. The MSSM_SLHA Universal Feynman Output model [213, 214] is used to introduce the coupling structure of the MSSM and fix the masses of the pair produced particles. The NNPDF30_lo_as_0130 [88] and NNPDF31_lo_as_0130 PDF sets are used in the simulation corresponding to 2016 (2017 and 2018) collisions. It has to be pointed out that a small difference between the signal and background PDF sets is introduced on the 2017 and 2018 data taking years. The NNPDF31 NNLO PDF sets used in the SM MC production resulted in high proportions of produced events with negative weights in the high p_T^{miss} regions where SUSY is expected to appear, and so they introduced the need for the production of bigger MC samples. As both PDF sets gave consistent descriptions of the signal shapes in the asymptotic regime of infinite statistics, the LO one was chosen for the simulation.

The matrix element result is interfaced with Pythia which, on top of the usual showering and hadronization processes, also simulates the decay chains of the pair-produced sparticles through the scenarios described in the previous sections. Those are restricted through the setting of particle masses, widths, and branching fractions according to the models discussed in the previous sections into Pythia following the SLHA accord [215]. The MLM matching scheme [216] is used to remove the overlap in the real radiation produced with MADGRAPH+amc@NLO and Pythia. The Pythia settings include the usage of the NNPDF23_lo_as_0130 PDF set as well as the the CUETP8M1 parameter tune [89] for samples corresponding to the 2016 data taking year, following the setup used for the SM MC generation. For all other years, the NNPDF31_lo_as_0118 PDF set and the CP2 tune [90] are used, matching the matrix element generator setup but differing slightly from the SM MC production.

All signal processes are normalized to the best current computations of cross sections obtained with the Resummino framework at NLO+next-to-leading-logarithm (NLO+NLL) in perturbative QCD [209–211]. The values used are available in Reference [217] for the chargino–neutralino pair production models, and Reference [218] for the degenerate higgsino GMSB models. The overall effects of the PDF and scale choices in the expected cross section uncertainties are evaluated using the same framework and at the same perturbative orders.

The resource intensive detector simulation is simplified by the usage of the CMS Fast Simulation (FastSim) method [219] which improves computation times by two to three orders of magnitude in comparison with the standard simulation (FullSim). The drawback is the simplification of the detector's material description and of the interaction of the different particles with it. In FastSim, each tracking layer is replaced by a cylinder of sensitive material that records any hits that pass through and reconstruction algorithms are run automatically over the whole track based on all the hits it leaves in the material. Electromagnetic showers in the ECAL are modelled through an analytical parametrization that assumes the ECAL to be completely homogeneous. The energy response of the HCAL with respect to charged and neutral hadrons is smeared through tabulated distributions that are functions of hadron energy and pseudo-rapidity, measured in FullSim, and then distributed across several close-by HCAL regions. Additional noisy hits are added into the ECAL and HCAL following the patterns observed in FullSim. The muon spectrometers are simulated through a similar approach as the tracker material, registering all hits that cross a realistic geometrical representation of each muon chamber.

Although FastSim is tuned to retain a similar performance to that of FullSim, residual effects tend to appear due to additional selection criteria or for the most complex objects definition. Additional corrections on the lepton efficiency, b tagging efficiency, and jet energy corrections described in Section 4.4 are applied on top of the usual ones to correct for the observed differences between FastSim and FullSim. Such corrections are measured by comparing MC samples appropriate to each measurement produced with the same setup in both FastSim and FullSim. Uncertainties corresponding to these corrections are furthermore propagated to the set of analysis uncertainties.

The missing transverse momentum, p_T^{miss} , is one of the most complex objects to model in simulation, and is expected that the ability to provide accurate descriptions of the variable in FastSim is limited. As a conservative approach, the predicted yields from a FastSim MC sample are always obtained twice. First, using the reconstructed p_T^{miss} for the selection, and second using the mean of the reconstructed and generated p_T^{miss} . The difference between the two is included as an additional systematic on the FastSim prediction.

Finally, it is known that the modelling of ISR radiation in events interfaced with FastSim tends to be slightly softer than that of FullSim. Corrections are applied as weights which are a function of the overall ISR p_T computed as the sum of the p_T of the pair-produced particles to cure this effect [220]. The corrections were derived comparing data with the prediction from a FastSim Drell-Yan MC sample in a final state with two OSSF leptons compatible with the Z boson. Overall uncertainties in the correction, due to the limited statistics of the region where it is measured, and contributions from different systematic sources in the measurement, are propagated to the analysis as a single systematic uncertainty.

6.2 Analysis strategy

The objective of this search is to provide an exhaustive study of the multileptonic final states that could be sensitive to any production of electroweakinos leading to final states with two to four leptons. Final states with higher lepton multiplicities are

not impossible to appear for some of the models involving the production of at least a Higgs boson, but the low branching fraction of the $H \rightarrow 4\ell$ decay renders the expected events from these decay channels negligible. Several analysis categories are defined based on lepton multiplicity, charge, and flavour composition. Loose electron, muon and τ_h identification criteria are used to classify events to prevent cross contamination from some categories into the sidebands defined in others for the estimation of the nonprompt background.

The categories serve to split the selected events into topologies that are either specially sensitive to different signal scenarios, or have quite different background contributions. In the former case, the splitting allows for the optimization of later steps of the analysis strategy based on the expected signal kinematics, while the later provides the ability to optimize these very same steps against the major SM backgrounds appearing on each category. Each category is binned into several signal regions (SR) designed to provide sensitivity to the different signal models that might appear inside of it. Some categories also include several sidebands orthogonal to the SRs used to estimate the behaviour of the main sources of background as will be discussed in Sections 6.4. The considered categories are:

- **2ℓSS category:** consists of events with a pair of light leptons (electrons or muons) with the same estimated charge. The presence of τ_h candidates is vetoed to orthogonalize this region with respect to the ones with three and four leptons. This final state targets cases of compressed SUSY, such as the $T\chi\chi\tilde{\ell}\tilde{\ell}$ model with $x = 0.95$, in which one of the final state leptons tends to be soft enough to be lost to the detector. The main backgrounds of the category appear when SM WZ production suffers the same lost lepton process, or a single lepton SM process such as W or $t\bar{t}$ production is produced with a nonprompt lepton.
- **3ℓA category:** includes events with three light leptons, at least two of which form a pair of opposite-sign and same flavour (OSSF). This final state might originate from basically all signal scenario models, although it becomes less relevant as the expected τ lepton multiplicity grows. This category is highly similar to the SR defined for the WZ studies presented in Chapter 5, and in consequence includes a significant presence of the WZ background. Due to the complexity this category presents, a parametric machine learning algorithm was introduced to select signal-like events from the category, on top of the standard signal region based strategy.
- **3ℓB category:** includes events with three light leptons and no OSSF pair. This requirement effectively serves as a veto of the Z boson which reduces strongly the presence of the WZ background. The dominant SM contribution comes from processes involving nonprompt light leptons. Unfortunately, the Z veto also makes the region insensitive to the $T\chi\chi WZ$, $T\chi\chi ZZ$, and $T\chi\chi\tilde{\ell}\tilde{\ell}$ models. All other models considered can lead to signatures on this category, specially those involving a H boson such as $T\chi\chi WH$ through the $H \rightarrow WW \rightarrow \ell\ell'\nu\nu$ decay.
- **3ℓC category:** requires an OSSF light lepton pair and a τ_h candidate. As a consequence, it is quite sensitive to the $T\chi\chi\tilde{\tau}\tilde{\ell}$ scenario, and other signal models involving moderate τ presence. However, the background from Drell-Yan production plus a nonprompt τ_h is sizeable due to the relatively high rate of τ_h misidentification.

- 3ℓD category: requires a pair of light leptons with opposite-sign but different flavour (OSOF) and a τ_h candidate. This category complements 3ℓC with a much depleted presence of the Drell–Yan plus nonprompt τ_h background, which is replaced instead by the $t\bar{t}$ plus nonprompt τ_h one.
- 3ℓE category: requires a pair of same-sign leptons plus a τ_h candidate. Targets models in which an OSSF pair of τ leptons is produced where one decays leptonically and the other hadronically. As the rate of such production in signal does not depend on the branching fraction of the Z or H to τ leptons, the presence of signal is enhanced with respect to backgrounds for the $T\chi\chi\tilde{\ell}$ and $T\chi\chi\tilde{\tau}$ scenarios.
- 3ℓF category: includes events with one light lepton and two τ_h candidates. It is designed to catch events with high τ lepton multiplicities from models such as $T\chi\chi\tilde{\tau}\tilde{\tau}$. It suffers from a relatively strong presence of nonprompt leptons, both from misidentified light leptons and τ_h candidates.
- 4ℓG category: has the requirement of four light leptons forming two independent OSSF pairs. As a consequence, it is quite sensitive to $T\chi\chi ZZ$ production but as a drawback contains most of the SM ZZ background, as expected from its usage as a ZZ SR in the 5 TeV analysis discussed in Section 4.7.2.3.
- 4ℓH category: includes all events with four light leptons that do not pass the requirements of 4ℓG. This makes it suitably sensitive to the $T\chi\chi HZ$ scenario in the $H \rightarrow WW \rightarrow \ell\ell'\nu\nu$ decay channel. It has a relatively depleted quantity of SM backgrounds, mostly coming from $t\bar{t}Z$ and residual ZZ production decaying through τ leptons.
- 4ℓI category: consists on events with three light leptons and one τ_h candidate. Exhibits a behaviour very similar to category 4ℓH with an increase in the non-prompt background rate due to the τ_h requirement, but also of the $T\chi\chi HZ$ signal due to the increased sensitivity to the $H \rightarrow \tau\tau$ channel.
- 4ℓJ category: includes events with two light leptons and two τ_h candidates forming two OSSF pairs. Principally targets the presence of the $T\chi\chi HZ$ scenario, but has some sensitivity to $T\chi\chi HH$ as well. The background is completely dominated by the presence of nonprompt τ_h .
- 4ℓK category: includes events with two light leptons and two τ_h candidates that are not selected by category 4ℓJ. Targets the $T\chi\chi HH$ model but, as category 4ℓJ, suffers from a high contribution of the nonprompt τ_h background.

While the search strategy is optimized for each category based on the signal scenarios more likely to appear on it, several of the categories are included to complement the interpretations of other models with significant contributions on them. The objective is to be able to verify signal presence over several channels simultaneously and, if the signal does not appear, provide modest contributions to the overall exclusion of each model. A summary of the categories, their definition and the signal models each one is used to interpret on is shown in Figure 6.5.

As evidenced in the previous list, the main backgrounds for the categories described are very similar to those presented in the WZ analysis discussed in Chapter 5, with the addition of the own WZ process as a SM background and the presence of τ_h which lead

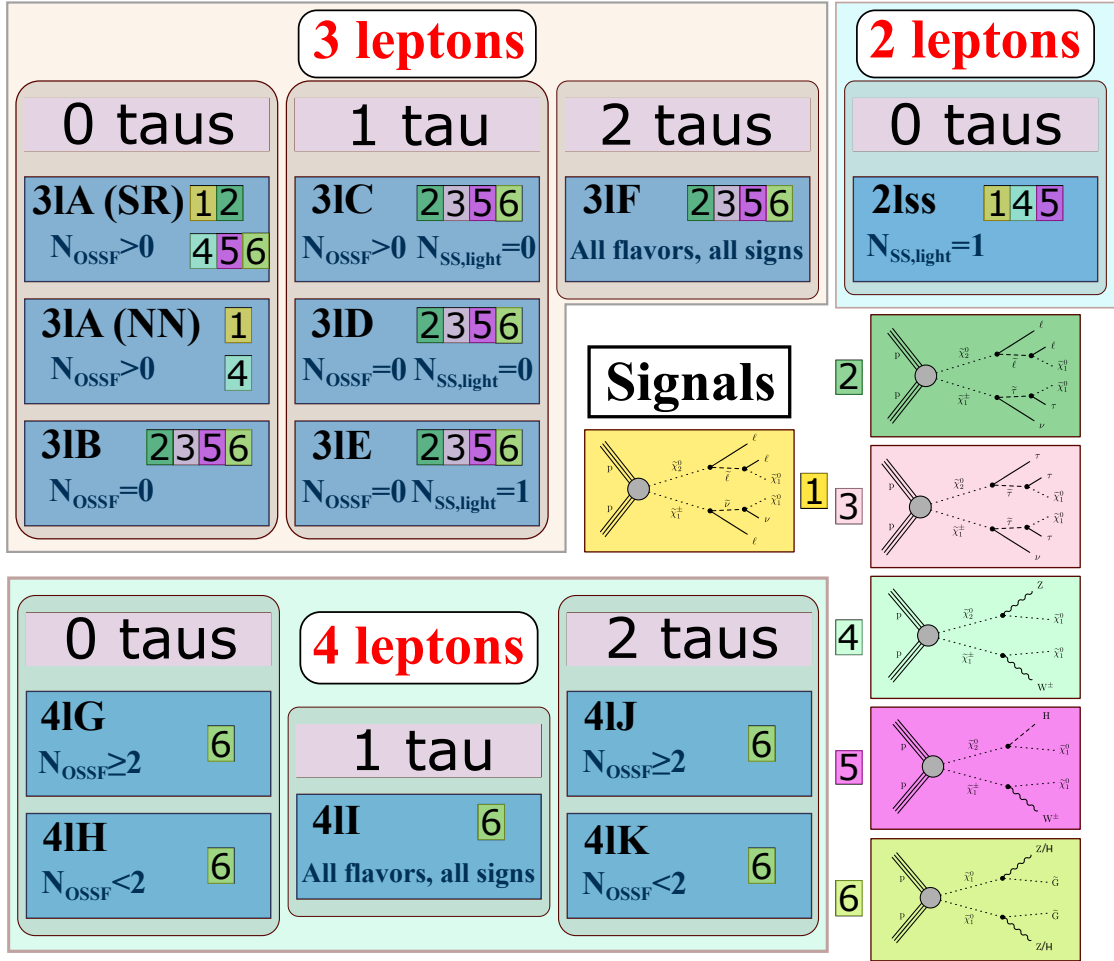


FIGURE 6.5: Summary of all selection categories and the signal models used in this analysis. The small coloured squares containing a number indicating the signal models which are used to interpret the data in the category they are in.

to the nonprompt τ_h presence in categories which require them. The SM backgrounds are then a mixture of diboson processes (WZ , ZZ , $Z\gamma$), and nonprompt backgrounds (Drell–Yan plus nonprompt, $t\bar{t}$ plus nonprompt), plus small contributions from top-enriched processes ($t\bar{t}Z$, tZq). As the signals all involve the presence of prompt leptons, the analysis strategy in terms of object selection and background estimation uses very similar techniques to those previously introduced in Chapters 4 and 5. It also has the important restriction that a lot of regions that could be used to estimate the different SM backgrounds could contain signal presence, a fact that must be operated around with care to avoid biases in the background estimation.

6.3 Object identification, triggering, and data quality checks

As in all the other analysis introduced previously, using optimized criteria for the identification of leptons is a key step in the definition of a robust analysis strategy. Due to the expected sizeable presence of the nonprompt lepton background, the leptonMVA discriminant is expected to provide, again, a powerful selection criteria for

electrons and muons. However, the optimization of the tight criteria is not as straightforward as in the case of the WZ analysis, as several signal models in a broad range of final states need to be considered. In fact, using a very tight selection criteria to avoid high background presence in categories such as $2\ell\text{SS}$ might be quite prejudicial in terms of small signal efficiencies for the $4\ell\text{G}$ category.

To optimize the light lepton selection criteria three different states were considered: same-sign final state (category $2\ell\text{SS}$), three light leptons final state (categories $3\ell\text{A}$ and $3\ell\text{B}$), and four light lepton final state (categories $4\ell\text{G}$ and $4\ell\text{H}$). It was found that in all states involving τ_h candidates the probability for a nonprompt τ_h to appear is always much greater than that of a nonprompt light lepton and so they were excluded from this optimization.

The optimization was performed by studying the trade-off between signal efficiency and background rejection in the 2-D space defined by all possible requirements on the electron and muon MVA discriminants. Upper limits on the cross section of several selected signal models at the exclusion limit of the 2016 analysis were computed using the signal extraction strategy defined in Section 6.7 and a realistic model of the background uncertainties. The results showed that a tighter identification criteria was needed in order to avoid sizeable background presence in the same-sign category, while the optimization for the three and four lepton ones improved towards looser selections with higher signal efficiency. As discussed, categories with τ_h have little background presence originating from nonprompt light leptons in comparison with the nonprompt τ_h one, so the more relaxed of the requirements is expected to be more optimal in this case. As a conclusion, two different tight working points for the light lepton identification criteria were defined, a strict one for the $2\ell\text{SS}$ category, and a more lax one for the rest of the analysis categories. This also provides the option of including the additional charge consistency requirement on the $2\ell\text{SS}$ requisites, which would further reduce the background due to the misidentification of the lepton charge. A summary of the leptonic requisites applied in the analysis is shown in Table 6.1.

As in this case τ_h candidates are a relevant object in the final state, optimization of the τ_h criteria was also performed with a similar method. In this case, categories $3\ell\text{C}$ and $3\ell\text{D}$ were used for which the light lepton requirements were fixed to the nominal ones from Table 6.1 and a simplified signal significance discriminant ($S/\sqrt{S+B}$) was computed for the selection of τ_h candidates with different WPs of the different MVA discriminants, and the anti-muon and anti-electron requirements introduced in Section 4.3.4. An optimal requirement was found in the tight WP selection and the usage of the loose WP of the anti-electron and anti-muon discriminants. The final selection has an efficiency for selecting signal τ_h of around 50% while rejecting around 98% of the nonprompt τ_h wrongly reconstructed by the hadron plus strips algorithm from non τ_h jets. A loose τ_h selection requirement based on the very loose WP of the same algorithm is used to select τ_h for the application of the loose-to-tight method.

Jets are clustered with the anti- k_T criteria and a distance parameter of $\Delta R = 0.4$. Selected jets are required to have a minimum p_T of 25 GeV, and have $|\eta| < 2.5$. Jets are requested to be separated from any selected tight leptons, including τ_h candidates $\Delta R(\ell, j) > 0.4$. The tight WP of the DeepCSV b tagging criteria described in Section 4.3.1 is used to select b tagged jets.

The approaches presented in Section 3.3.1 to treat data quality issues were applied in the following analysis. The L1 trigger prefiring weights and correction recipe for

EWK SUSY lepton ID				
Selection	Loose e (SUSY)	Loose μ (SUSY)	Tight e (SUSY)	Tight μ (SUSY)
Based on	Loose e	Loose μ	Loose e	Loose μ
PF-medium muon	-	✓	-	✓
Nearby jet b Tag	<Tight WP (-)	<Interp. WP (-)	-	-
$p_T(\ell)/p_T(\text{close by jet})$	> 0.6 (-)	> 0.35 (-)	-	-
Charge consistency	-/✓	-/✓	-/✓	-/✓
LeptonMVA	< 0.4/< 0.7(> 0.4/> 0.7)	< 0.4/< 0.7(> 0.4/> 0.7)	> 0.4/> 0.7	> 0.4/> 0.7
Efficiency	90–100%	95–100%	75–85/85–95%	90–95/95–100%

TABLE 6.1: Common identification and isolation criteria applied to select electrons and muons in the multileptonic SUSY analysis for the loose and tight working points. Requirements marked with a - sign are not applied at all for the correspondent selection level. The based on row refers to the generic identification criteria presented on Tables 4.2 and 4.3 that these requirements are based on. Measured ranges of efficiency, depending on p_T and η , are presented for each working point. For the case of the loose leptons, some requirements are tightened if the lepton does not pass the tight leptonMVA requirement in order to optimize the loose definition for the nonprompt background estimation as introduced in Section 4.5. The b tagging requirements in the closest jet to the lepton use WP criteria as defined in Section 4.3.1, where <Interp. WP refers to a linear interpolation of the b tagging discriminant from the medium WP at a lepton p_T of 10 GeV to the loose WP at a lepton p_T of 50 GeV. Two different lepton identification tight WPs were used and their associated requirements are separated by a / sign, corresponding to the criteria applied in categories with three or more leptons, and the 2ℓ SS category.

p_T^{miss} in the 2017 data taking year are included as described. Dedicated studies using samples that simulated the effects of the malfunctioning HCAL sector probed that the main effect at the analysis level was a small increase in the electron fake-rates that were covered by the existing uncertainties.

The triggering strategy follows a very similar procedure to that of the other analysis presented through this document. For all categories except 3ℓ F, events are selected if they pass any of the single or double lepton trigger requirements described in Table 4.1. Category 3ℓ F only includes the presence of a single final state lepton, so single lepton triggers were used for the selection of events in this category. The inclusion of triggers requiring the presence of τ_h candidates at the HLT level were considered but was found to provide little improvement over the light lepton only strategy and so was ultimately discarded.

6.4 Background modelling

The estimation of the major background sources follows a similar strategy to those introduced in Chapter 4. MC simulation is used to provide estimations for all processes involving final states with all prompt, properly measured leptons, while data-driven techniques are used to estimate backgrounds due to the nonprompt lepton or charge misidentification cases. As signals are expected to appear at quite specific regions, corresponding to final states with relatively high energies, several additional estimations are used to validate the background shapes to avoid possible biases that would not be caught by an estimation of a background normalization factor.

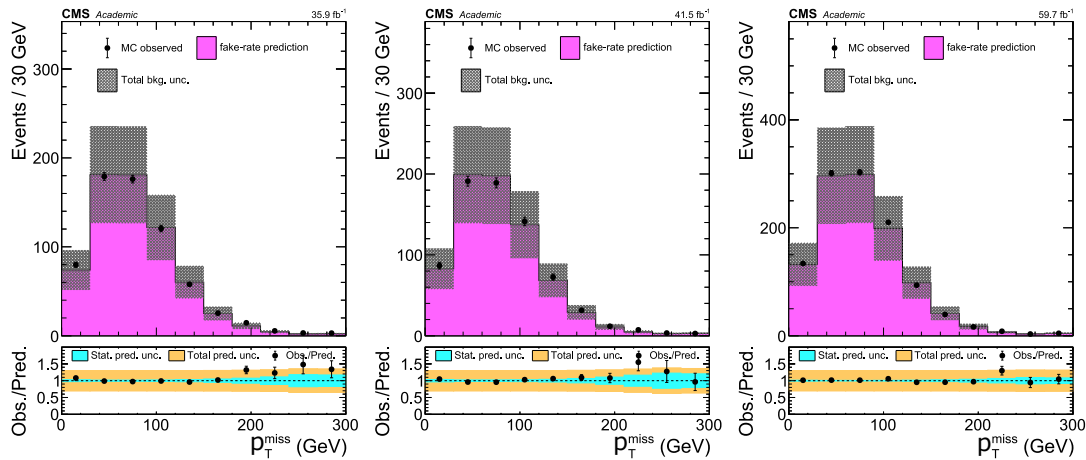


FIGURE 6.6: Closure tests on the nonprompt light lepton background estimation performed on $t\bar{t}$ MC for the multileptonic tight lepton criteria. The tests are performed in the three light lepton final states using the $t\bar{t}$ MC sample described in Section 4.2 and fake-rates estimated in multijet (QCD) simulation. The closure is shown as a function of the p_T^{miss} variable for the 2016 (left), 2017 (middle) and 2018 (right) data taking years.

6.4.1 Nonprompt lepton background

The nonprompt lepton background appears through all the considered categories, including the presence of both nonprompt light leptons and τ_h candidates. Both cases are estimated through the usage of the loose-to-tight method described in Section 4.5.1, but the procedure is slightly different due to the different sources of the nonprompt lepton presence.

Background with nonprompt electrons and muons are estimated following the whole strategy introduced in Section 4.5.1, with the usage of the same multijet enriched definition for the measurement of the fake-rates (measurement region). The loose lepton identification criteria introduced in Table 6.1 are optimized to get similar fake-rates for the light and heavy flavoured nonprompt leptons, to avoid biases in the nonprompt background estimation due to the jet composition of the measurement region. The cone- p_T corrections introduced in Section 4.5.1 are found to be significantly bigger than in the WZ analysis, due to the looser selection requirements, at 0.65 for muons and 0.85 for electrons.

Closure tests on the nonprompt estimation method are performed by deriving fake-rates in simulated multijet events and applying them into Drell-Yan and $t\bar{t}$ simulation for events with three light leptons. The prediction of yields from the loose-to-tight method in these circumstances is compared with that obtained directly with the $t\bar{t}$ and Drell-Yan MC, showing remarkably good agreement after the tuning of the loose lepton criteria. An example of these closure tests can be found in Figure 6.6. Similar sets of closure tests were done for the two considered tight lepton criteria showing consistent results in both cases. A 30% normalization uncertainty, which roughly covers all fluctuations observed in the closure tests was assigned to the nonprompt light lepton background estimation.

Nonprompt τ_h are slightly different in nature as they mostly originate from the misidentification of a hadronic jet, electron or muon as a τ_h candidate. It was found in MC

simulation that, with the application of the anti-muon and anti-electron criteria, the amount of reconstructed candidates matched to muons or electrons was negligible at the level of the final analysis categories, but the probability of misidentifying a jet for a τ_h still remains high. Moreover, it was found that the performance of the isolation MVA algorithm introduced in Section 4.3.4, in terms of nonprompt rejection, was dependent on the phase space topology, with sizeable differences between the fake-rates from light- and heavy-flavoured jets. While it was possible to improve this result by tightening the loose τ_h selection requirement, doing so would deplete the statistical power of the application region sideband and ultimately introduce higher uncertainties in the measurement. Instead, it was decided to measure the fake-rates in two sidebands that are closeby to the analysis selection and defined to target either Drell-Yan or $t\bar{t}$ production to minimize the possible biases from the fake-rate estimation.

The Drell-Yan τ_h fake-rate measurement region is defined from category 3ℓC, with the requirement of $p_T^{\text{miss}} < 50$ GeV and that the two light leptons to be compatible with the Z peak ($75 < M(\ell\ell) < 105$ GeV). Events with one or more b tagged jets are vetoed, and the τ_h candidate has to have at least $p_T > 20$ GeV. The $t\bar{t}$ τ_h fake-rate measurement region is defined based on category 3ℓD, with the additional requirement of at least one b tagged jet in the final selection and the $M(\ell\ell) > 20$ GeV requisite. The standard techniques for the measurement of the fake-rates are then applied on both of these selections to obtain Drell-Yan-like and $t\bar{t}$ -like τ_h fake-rates. The Drell-Yan fake-rates were observed to be around 20–40% bigger than the $t\bar{t}$ ones. The application of this method varies depending on the target category, with categories in which MC simulation show a dominance of $t\bar{t}$ + nonprompt τ_h MC using the $t\bar{t}$ derived fake-rates. Categories 3ℓD and 3ℓE use the $t\bar{t}$ derived fake-rates, while all other categories involving τ_h candidates use the Drell-Yan derived ones.

Closure tests similar to that of the nonprompt light leptons were performed, providing consistent results from the MC and data-driven predictions at the level of the 3ℓC (for Drell-Yan derived fake-rates) and 3ℓD (for $t\bar{t}$ derived fake-rates) categories. An additional check of the validity of the method was performed in data by comparing the overall method prediction with observed data in a new validation region. This Drell-Yan validation region is defined from the selection criteria of 3ℓC category, plus the additional requirements of both light leptons being on the Z peak ($75 < M(\ell\ell) < 105$ GeV), the veto of b tagged jets, and the requirement of $p_T^{\text{miss}} > 50$ GeV. The distribution of p_T^{miss} in this validation region is shown in Figure 6.7.

Signal presence might contaminate the validation region as it extends up to relatively high values of p_T^{miss} . While the amount of expected signal for non-excluded models is relatively small, its possible existence would mean that the nonprompt estimation which apparently fits the data would in reality be slightly overpredicting it. An additional nonprompt normalization term is included to cover this possible effect and other observed non closure effects of 30% for all nonprompt τ_h yields.

6.4.2 Charge misidentified background

The misidentified charge background only has some relevance at the level of the 2ℓSS category, where the charge of a significant proportion of electrons might be mismeasured. The data-driven technique introduced in Section 4.5.2 is used to provide an estimation of this background contribution.

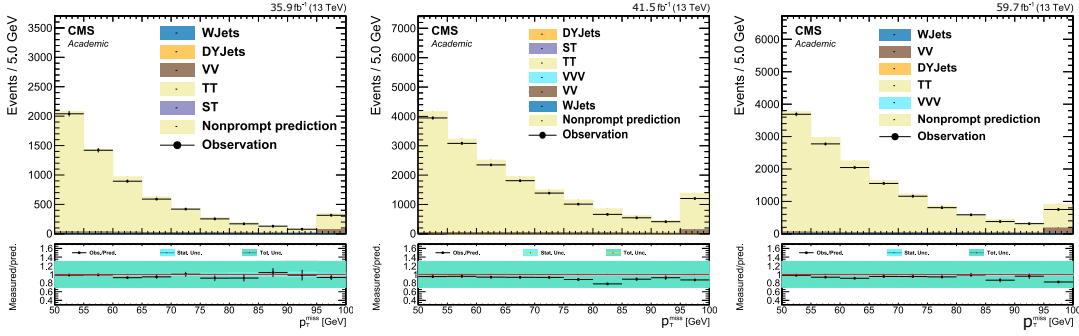


FIGURE 6.7: Validation tests on the nonprompt τ_h background estimation performed on the Drell–Yan validation region inside category $3\ell C$, corresponding to two light leptons compatible with the Z boson (OSSF pair with $75 < M(\ell\ell) < 105$ GeV), high missing transverse momentum ($p_T^{\text{miss}} > 50$ GeV), and a b tagged jet veto. The validation is shown as a function of the p_T^{miss} variable for 2016 (left), 2017 (middle) and 2018 (right) data. All prompt predictions are estimated from MC simulation in which reconstructed leptons are required to match a generator level lepton sharing their flavour. The VV category includes both WZ and ZZ production.

Flip-rates are measured in a soup of MC events including a realistic proportion of Drell–Yan and $t\bar{t}$ events in a two light lepton final state selection. An attempt to estimate muon fake-rates showed that their values were smaller than 10^{-6} after the charge consistency requirement was applied, meaning that their effect at the final analysis selection is negligible. The results were then validated in a low- p_T^{miss} sideband inside the $2\ell SS$ category, containing two electrons with ($75 < M(\ell\ell) < 105$ GeV). Sizeable differences were seen between the 2016, and 2017 and 2018 data taking years, as expected due to the inclusion of the additional pixel layers between the two periods described in Section 3.2.1. As a result, per-year correction factors to the charge misidentified background were derived in this CR, based on normalization differences between data and prediction, and applied to the whole background prediction later down the analysis. The correction factors are 0.89, 1.26, and 1.17 for the 2016, 2017, and 2018 data taking years respectively. After applying these corrections, small fluctuations in the agreement were seen, so an additional 20% normalization uncertainty is included into the mismeasured charge background process.

6.4.3 WZ production

SM WZ production appears in most analysis categories as a dominant prompt background and is estimated using the POWHEG MC sample introduced in Section 4.2. Unfortunately, the dedicated estimation of the process presented in Chapter 5 can not be used directly, as the data used entirely overlaps with regions where supersymmetric processes might appear. Instead, a restricted redefinition of the SR–WZ from Chapter 5 is used to provide an estimation of the overall WZ background normalization. Moreover, SUSY signals are expected to appear at the tails of several the WZ distribution, so the mismodelling of the high energy tails of the WZ background might have a significant effect on the results of the analysis. Thus, additional techniques were developed to study these distributions using sideband regions in data.

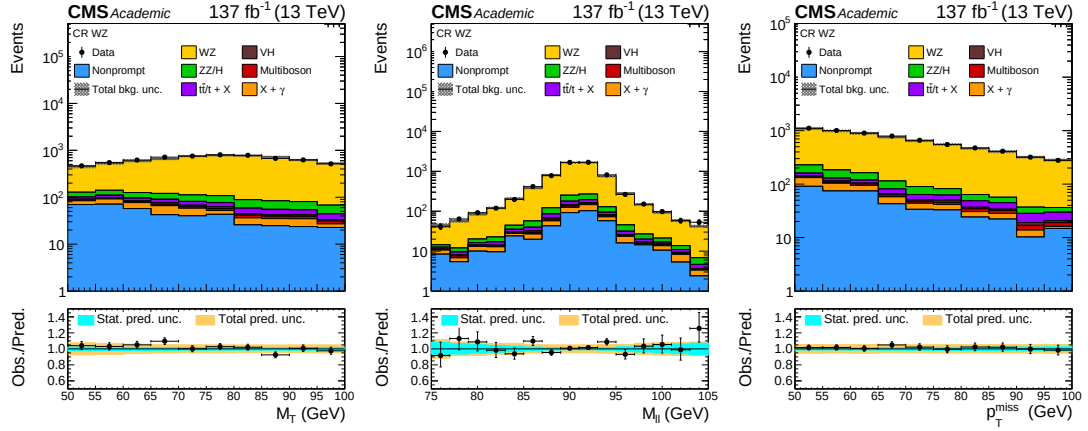


FIGURE 6.8: Expected and observed distributions in the WZ-CR for the whole Run II data. The WZ background is normalized according to the normalization k-factor of 1.17 measured in this CR. The variables shown are: transverse mass of the lepton associated to the W boson and p_T^{miss} (left), invariant mass of the two leptons associated to the Z boson decay (middle), and p_T^{miss} (right).

The normalization of the WZ background is estimated in a WZ-CR inside on the $3\ell A$ category. To ensure the efficiency of the triggering criteria, the lepton p_T are required to be greater than 20 (25), 10 (15), and 10 (10) GeV for the leading, subleading, and trailing leptons if they are muons (electrons). The lepton tagging algorithm defined in Section 4.7.2.2 and used in Section 5.2.2 is also used to assign leptons to the W and Z bosons decays in this CR. Then, the transverse mass of the W boson, M_T^W , is computed as the transverse mass of the p_T^{miss} vector and the momentum of its associated lepton. For SM WZ production, a kinematic endpoint is expected to appear at $M_T^W \approx m_W^{\text{PDG}}$ but signal presence is expected to appear at higher values due to the additional p_T^{miss} presence caused by the invisible LSPs. Similarly, mid values of p_T^{miss} are expected from the WZ background due to the final state neutrino, but higher quantities are expected in signal due to the invisible LSPs. A selection that leads to a small $< 5\%$ signal contamination while ensuring WZ purity is to request that $50 < p_T^{\text{miss}} < 100$ GeV, and $50 < M_T^W < 100$ GeV. A final requirement for the WZ CR is that the two leptons associated to the Z are consistent with a Z decay ($75 < M(\ell\ell) < 105$ GeV). Several distributions in this CR are shown in Figure 6.8. Notice the significant difference with respect to the distributions shown in Figure 5.7, which have a third of the overall nonprompt background contribution as a result of the tighter lepton selection criteria.

An estimation of the overall normalization of the WZ background over the NLO QCD prediction provided by the POWHEG MC sample is computed based on the differences between data and expectations in this CR. This computation is performed by fitting a free floating normalization parameter for the WZ process to the data observed in this CR. It results in a normalization k-factor of $k_{\text{WZ}} = 1.17 \pm 0.05$. This result is consistent with the measurements presented in Section 5.5 of the dedicated WZ analysis and is applied to all WZ predictions through the analysis. To account for roughly up to an additional 5% signal contamination, the upper bound on the yields for non-excluded signal models in this CR, an additional 5% normalization uncertainty is added on top of the fitted one for the WZ process. Thus, an overall 10% normalization uncertainty is assigned to the SM WZ background through the analysis.

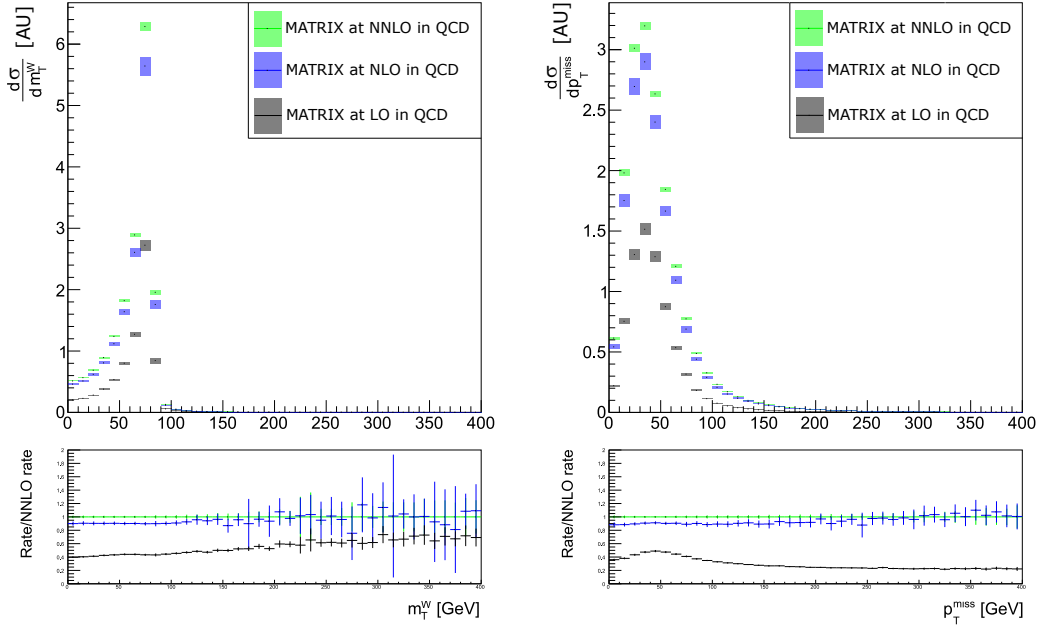


FIGURE 6.9: Distributions –in arbitrary units– of the M_T^W (left) and p_T^{miss} (right) variables at the generator level for the SM WZ process computed with MATRIX at different orders (LO, NLO, NNLO) in perturbative QCD.

Any mismodelling of the SM WZ distributions could contribute to a bias in the background estimation that ultimately would result on the wrong interpretation of data. Thus, several checks were performed to control the behaviour of the most relevant distributions of the SM WZ background.

A first check is performed by comparing the distributions of both p_T^{miss} and M_T^W at the generator level with different approximation orders in perturbative QCD using fixed order computations with the MATRIX framework. The setup of MATRIX is analogous to the one used for the diboson cross section measurements described in Section 4.2.3. The generator level fiducial region is defined by the presence of three parton level light leptons following the p_T requirements of the WZ–CR and with an OSSF pair fulfilling the $75 < M(\ell\ell) < 105$ GeV criteria. A depiction of the results is shown in Figure 6.9. The NNLO corrections over the NLO distributions were found to be relatively flat with respect to the p_T^{miss} and M_T^W variables, with small variations under the 10% effect from the lowest to highest p_T^{miss} and M_T^W values considered. As NLO in QCD accuracy is already achieved by the POWHEG WZ MC sample used in the analysis, it can be argued that any corrections due to higher order effects not present in the MC would be bound by this 10% maximum difference.

Beyond the limitations due to the perturbative order of the MC sample, mismodelling effects might appear on p_T^{miss} that would not only contribute towards additional presence of the WZ background at high p_T^{miss} values, but also at the sensitive regions with high M_T^W values. Near all possible selections applied on the three lepton final state are populated by high contributions from the different signals, so any estimation of the p_T^{miss} resolution effects in three lepton final states is unlikely to be unbiased with respect to signal presence. Instead, the goodness of the p_T^{miss} modelling is studied in

a $W\gamma$ enriched region. The motivation behind this choice is that the WZ and $W\gamma$ production mechanisms are very similar, as depicted in the diagrams in Figure 6.10 which can be compared with those for WZ production introduced in Figures 4.11 and 5.1. The only difference is the presence of greater contributions from diagrams involving a final state radiation (FSR) photon which in the case of WZ production are suppressed by the Z boson mass.

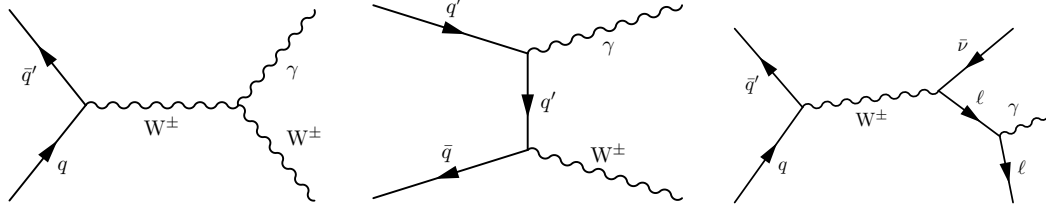


FIGURE 6.10: Feynman diagrams corresponding to $W\gamma$ production at LO in perturbative QCD. The rightmost one, corresponding to the emission of an FSR photon has greatly enhanced contributions with respect to the analogous one in WZ production with is suppressed by the Z boson mass.

A $W\gamma$ -CR is defined by requiring the presence of a tight muon and photon that are requested to be well separated ($\Delta R(\gamma, \mu) > 0.4$) to suppress the effects from the appearance of the photon due to soft radiation by the muon. Events in the $W\gamma$ -CR are selected using the single muon paths detailed in Table 4.1, so the p_T requirement of the muon is set to 25 GeV. To further reduce the presence of FSR photons, the photon is required to have a sizeable p_T of at least 40 GeV. Further requirements are applied to reduce the presence of other processes in the CR such as $Z\gamma$, $t\bar{t}$ and single W production through the requirements of $p_T^{\text{miss}} > 40$ GeV, $M_T^W > 40$ GeV, and the veto of events containing b tagged jets. In this CR, the M_T^W contribution is computed with the only final state muon and the reconstructed p_T^{miss} . The expected and observed yields for the distributions of the p_T^{miss} and M_T^W variables are shown in Figure 6.11 after all selection criteria are applied. SM MC samples are used to provide the estimation of all processes included into this $W\gamma$ -CR rather than any data-driven approach.

The generally good agreement observed in the $W\gamma$ -CR is estimated by making independent fits of the $W\gamma$ production normalization in a 2D-binning based on the p_T^{miss} and M_T^W variables, with the aim of studying possible deviations from unity which would be due to a mismodelling of either of the variables. All results were consistent with unity within their uncertainties, but such uncertainties were relatively big, up to 30%, for the highest $p_T^{\text{miss}}-M_T^W$ bin, corresponding to $M_T^W > 160$ GeV and $p_T^{\text{miss}} > 200$ GeV. The overall uncertainty in these measurements is taken as our overall confidence in the modelling of the p_T^{miss} and M_T^W tails and so a proxy of our confidence in the modelling of the same distributions for the WZ process. Thus, these quantities are included as an additional WZ shape uncertainty with a size that is parametrized on the p_T^{miss} and M_T^W values. As they are bigger than the corrections obtained from higher order computations shown in Figure 6.9, the later are not applied in the analysis as it is assumed that possible effects they model will be covered by the former. As the high uncertainties mostly depend on the limited statistical power of the $W\gamma$ -CR, this uncertainty is uncorrelated across data-taking years.

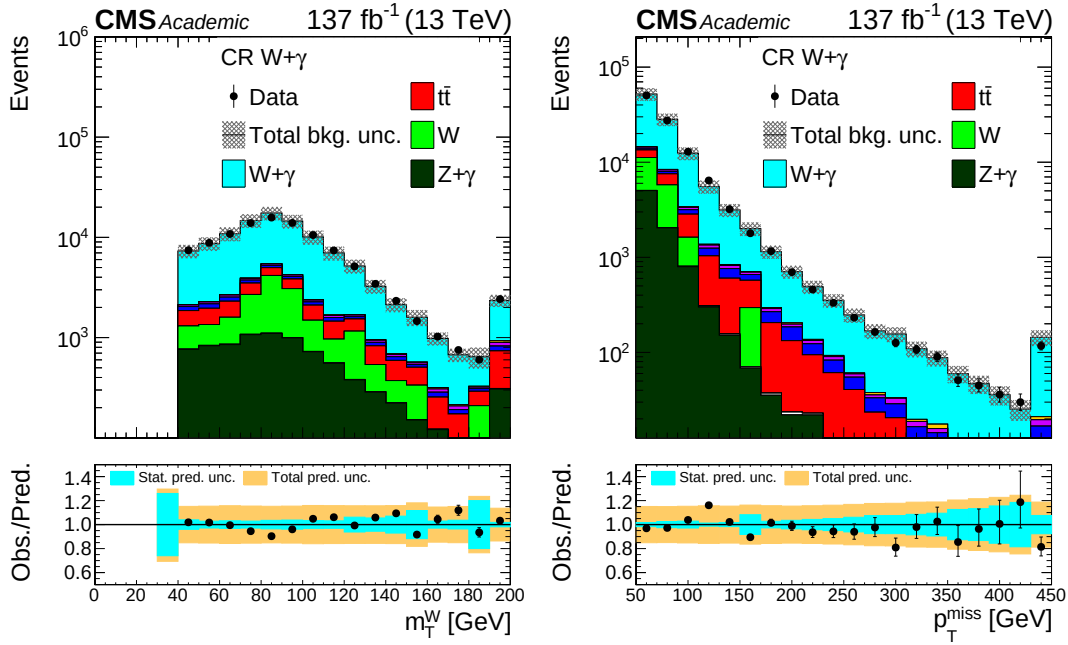


FIGURE 6.11: Expected and observed distributions in the $W\gamma$ -CR for the whole Run II data. All SM processes are estimated using MC simulation and normalized to their SM cross sections. The variables shown are: transverse mass of the final state muon and p_T^{miss} (left), and p_T^{miss} (right).

6.4.4 ZZ production

The ZZ process has a sizeable presence in the regions with four leptons of which at least three or more are light. It is estimated using the different ZZ MC samples introduced in Section 4.2.

A ZZ-CR is defined in a similar way as the one that was introduced for the WZ analysis in Section 5.3. In this case, the selected phase space needs to be restricted in order to reduce as much as possible any kind of signal contamination that could appear at high values of p_T^{miss} . High purity is reached by defining the ZZ-CR as a subset of the $4\ell G$ category. The four leptons are required to have a minimum p_T of 20 (25), 10 (15), 10 (10), and 10 (10) GeV in order of decreasing p_T for muons (electrons), a strategy that ensures near perfect trigger efficiency while retaining high ZZ purity on the final selection. A tagging algorithm to build the kinematics of each Z boson is introduced: the OSSF lepton pair with the mass closest to the peak Z boson mass is used to build the Z_1 boson candidate, while the remaining two leptons are used to build the Z_2 boson candidate. An additional requirement on the ZZ-CR is then imposed by requesting that the reconstructed Z_1 boson is consistent with the Z boson mass ($75 < M_{Z_1} < 105$ GeV). To reduce the possible signal contamination in this CR, a final requirement of $p_T^{\text{miss}} < 50$ GeV is introduced. Several distributions of interest in the ZZ-CR are shown in Figure 6.12.

The level of agreement between data and MC in the ZZ-CR is used to derive a k -factor in a similar way to the WZ one. The resulting measurement shows around $k_{ZZ} = 1.02 \pm 0.10$. The measured k -factor is included to normalize the ZZ contributions through the analysis, with the 10% obtained corresponding to the overall systematic uncertainty on its normalization. For plotting purposes, the contributions

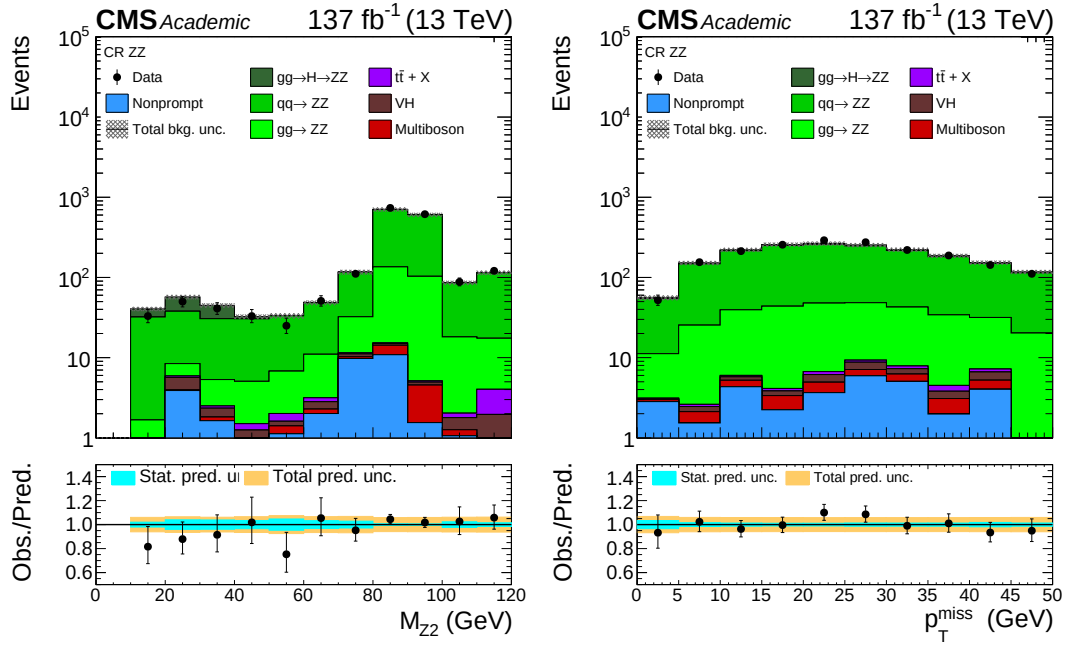


FIGURE 6.12: Expected and observed distributions in the ZZ-CR for the whole Run 2 data. The ZZ background is normalized according to the normalization k -factor of 1.02 measured in this CR. The variables shown are: invariant mass of the second reconstructed Z boson (left), and p_T^{miss} (right).

to the ZZ background will be split into its different components in regions with four or more leptons in order to show the relevance of the $H \rightarrow 4\ell$ resonant decay in the several cases where it appears, but are all otherwise treated as a single entity for fitting purposes.

6.4.5 Minor all-prompt-lepton backgrounds

All other SM backgrounds are estimated through the usage of the MC simulation samples described in Section 4.2. Several control regions were also designed to validate the behaviour of the simulation for the most notable of the remaining backgrounds. These are:

- A photon conversion control region: defined as the WZ CR but with the inversion of several requirements: $p_T^{\text{miss}} < 50$ GeV, and $M(\ell\ell) < 75$ GeV. Additionally, the three lepton invariant mass is required to be consistent with the Z peak to increase the photon conversion purity ($|M(\ell\ell\ell) - m_Z^{\text{PDG}}| < 15$ GeV). Its behaviour is consistent with that observed for the conversion CR of the WZ analysis introduced in Section 5.3, and results in an estimated 10% normalization uncertainty for the photon conversion background ($X\gamma$), which includes both $W\gamma$, $Z\gamma$, and $WZ\gamma$ production.
- A top-enriched control region: defined with similar criteria as the WZ CR, but with no p_T^{miss} or M_T^W requirements, and requesting the presence of at least one b tagged jet. Its behaviour is consistent with the similarly defined $t\bar{t}Z$ -CR shown for the WZ analysis in Section 5.3, and it is used in a similar way to validate

the top-enriched prompt lepton background sources ($t\bar{t}X$, and tZq) which are grouped into a single background contribution through the analysis. An overall 15% normalization uncertainty is derived in this CR for the top-enriched processes.

Remaining contributions from either VH or triple boson production is estimated directly from MC. No suitable control region was found for these background contributions and so a 50% conservative uncertainty on their normalization is applied through the analysis.

6.5 Summary of uncertainty sources

The background related uncertainties that were introduced so far in Section 6.4 are added on top to those related to corrections introduced to the MC to amend the modelling of the object selection criteria or energy scale estimation, as well as additional uncertainties related to the pileup modelling and the overall measured luminosity uncertainty. The complete set of uncertainties considered is summarized in Table 6.2 and detailed as follows:

- **Electron and muon efficiency uncertainties** are estimated following the procedure described in Section 4.4.1 for the lepton identification criteria designed for this analysis. An additional term is included to account for possible extrapolation effects to the high momenta range where some signals might appear by performing the measurements of the corrections as a function of the p_T of the reconstructed Z. The mean of the obtained correction is applied as the final lepton efficiency correction, and the envelope of the effects is added as an additional source of systematic uncertainty in quadrature to the set of uncertainties described in Section 4.4.1. As most of the final effect corresponds to this extrapolation uncertainty, which is similar across years, the overall lepton efficiency uncertainties are correlated across years. They are, nonetheless, split into the e and μ uncertainty sources.
- **Tau efficiency uncertainties** are estimated following the modified tag-and-probe method introduced in Section 4.4.2 that uses a μ - τ_h pair for the estimation of the prompt τ_h efficiencies. Their effects are correlated across data-taking years.
- **Jet energy scale and resolution uncertainties** that are obtained following the description of Section 4.4.5. They are partially correlated across years, with all sources of uncertainty corresponding to statistical limitations of measuring sidebands grouped into uncorrelated components and the rest of them appearing as correlated ones. Additional corrections are applied for the FastSim signals, to account for the differences in jet modelling found between FastSim and FullSim. Both the FastSim-only and the overall corrections are introduced as separate uncertainties, with the former being partially correlated across years as described in Section 4.4.5. The effects of the FullSim to FastSim correction were found to be relatively consistent across years so the corresponding FastSim uncertainties were kept correlated.

- **B tagging efficiency uncertainties** are obtained following the description of Section 4.4.6. Two different sources corresponding to heavy tagging and light flavour mistagging are considered separately. Each one is correlated across years. As for the case of the jet energy corrections, additional b tagging uncertainties corresponding to the extra set of corrections to the b tagging in FastSim are included as additional systematic uncertainty effects on the signals.
- **Trigger efficiency uncertainties** are measured with the techniques described in Section 4.4.4 using a reference trigger based on p_T^{miss} criteria. The trigger efficiencies are measured separately in bins of light lepton multiplicity corresponding to: one light lepton final states (category 3 ℓ F), two light lepton final states (categories 2 ℓ SS, 3 ℓ C, 3 ℓ D, 3 ℓ E, 4 ℓ J, and 4 ℓ K), and three light lepton final states or more (categories 3 ℓ A, 3 ℓ B, 4 ℓ G, 4 ℓ H, and 4 ℓ I). The differences between the central measured value of the trigger efficiency and unity are taken as a conservative estimate of the trigger efficiency measurement bias, ranging from 0.5% in the 3 ℓ selection to the 5% in the single lepton one. This bias is introduced as a systematic uncertainty correlated across years. The statistical uncertainty in the data sideband corresponding to the reference trigger selection is propagated as an additional analysis uncertainty ranging from
- **Pileup modelling uncertainties** are estimated following the description in Section 4.4.7 and are correlated across years.
- **Theoretical uncertainties corresponding to the scale and PDF choice** are included following the description of Section 4.2.1 for all signal processes.
- **Signal modelling uncertainties** corresponding to the p_T^{miss} and ISR p_T modelling are included as two separate sources correlated across years through the corrections described in Section 6.1.2.
- Uncertainties related to the overall **luminosity** of the 13 TeV dataset have been measured by the CMS Collaboration for the 2016, 2017 and 2018 datasets separately [159–161]. A correlation scheme which splits the overall uncertainty for each into its contributing sources and then correlates accordingly across years is applied, leading to a set of partially correlated uncertainties which account for roughly a total 1.8% uncertainty in the final total luminosity of the Run 2 of the LHC.
- All **background normalization uncertainties** discussed in Section 6.4 are included through the different methods outlined in their corresponding sections.
- **Statistical uncertainties** appear due the limited size of the application region sideband, in the two data-driven backgrounds, or of the MC samples are uncorrelated across bins and years, They are introduced through the Barlow–Beeston method in all signal extraction fits [126].

Source	Typical uncertainty (%)	Correlation across data-taking years
e/μ efficiency	1–2 per lepton	Correlated
τ_h efficiency	1–3 per lepton	Correlated
Pileup	1–2	Correlated
Integrated luminosity	1.8	Partially correlated
Trigger efficiency	1.4–5	Partially correlated
Jet energy corrections	1	Partially correlated
Jet energy corrections (fast simulation)	1	Correlated
b tagging efficiency	1–3	Correlated
b tagging efficiency (fast simulation)	1–3	Correlated
PDF	1–10	Correlated
Renormalization and factorization scales	1–10	Correlated
Signal ISR	1–5	Correlated
Signal p_T^{miss}	1–2	Correlated
WZ shape	5–30	Uncorrelated
WZ normalization	10	Correlated
ZZ normalization	10	Correlated
Conversion normalization	10	Correlated
Nonprompt normalization ($e/\mu/\tau_h$)	30	Correlated
Charge misidentification normalization	20	Correlated
Top enriched normalization	15	Correlated
Multiboson normalization	50	Correlated
Luminosity	2.3–2.5	Partially correlated

TABLE 6.2: Summary of the uncertainties in the analysis, the usual size of their relative effects, and the correlation scheme across data taking eras followed. Their quoted effects refer to their effect on percentage of estimated background yields across all SR bins of the analysis. Only SR in which the total statistical uncertainty of the background estimation is smaller than the effects of the studied source are considered to avoid mixing the effect of several uncertainties with that of the MC statistics in this table. Systematic uncertainties with a broad range of variations across SR are indicated through a — separating their minimum and maximum effect. The size of systematic uncertainties with effect on the signal processes only are estimated through variations in the yields of any of the considered signal model, following the same procedure as the rest. As the uncertainties in the lepton efficiency vary according to the selected lepton multiplicity which changes from category to category, they are quoted in a per lepton basis instead of an overall effect.

6.6 Signal extraction strategy

The kinematics of the different signal scenarios vary quite significantly depending not only on the SMS coupling assumptions, but also on the masses of the involved superpartners. Larger masses of the LSP particles will usually be correlated with sizeable presence of p_T^{miss} in the detector, as the invisible LSP will remain undetected by CMS. In a more subtle way, the difference in mass between the pair produced particle and the LSP, δM , characterizes the signal kinematics, as it represents the energy that could be transmitted to the SM particles produced during the decay of the pair-produced particles. Higher values of δM lead to more boosted SM particles in the final state and overall higher energy final states in which is known as uncompressed signals, or uncompressed signal models. Lower values of δM , corresponding to compressed signal models, offer very little additional energy to the SM particles appearing from the decay of the superpartners and tend to lead to softer final states. As the δM quantity is continuous, multiple possibilities between these two extreme behaviours will appear for all the different signal scenarios.

As a consequence of the wide range of possible signal kinematics, the strategy to extract the signal presence needs to have an equally wide sensitivity to ensure an efficient scan of the SMS parameter space. To do so, for each of the analysis categories introduced in Section 6.2 several search regions (SR) optimized to reduce the SM background presence while enhancing that of different signal models are defined. As the background and signal kinematics vary from category to category, these SR are optimized independently for each of them. Some additional regions with less sensitivity to the different signals but high background presence are also defined as a way to provide some residual sensitivity to high cross section signals or to validate the background estimations on the absence of signal presence. Sections 6.6.1 to 6.6.4 describe the signal region optimization for all the categories used in the analysis.

The high complexity of this search is the ideal environment in which machine learning (ML) algorithms can provide further insight on top of the strategies based on the more usual SR approach. However, most standard ML methods aim to separate data into several independent classes, either one signal and one background component, or multiple signal and background classes. This classical usage of ML for classification is impractical in this case, as the kinematic peculiarities of the different signal models makes the usage of a single signal class of little use, and the usage of a multiclassifier introducing each variation of the signal model parameters as an independent class is inoperative computationally. Instead, a parametric ML approach is followed, in which a single family of discriminants depending on several parameters characterizing the signals are trained simultaneously. This approach is used to define an alternative signal extraction definition to the most complex of the analysis categories, $3\ell A$. A description of the parametric ML strategy is introduced in Section 6.6.5.

6.6.1 Final states with exactly two leptons

The $2\ell SS$ category basic selection requires the presence of exactly two tight light leptons (electrons or muons) with the same charge. The presence of loosely selected τ_h candidates or light leptons is vetoed so this category is orthogonal to other categories in the analysis and their application regions sidebands used to estimate the nonprompt

lepton background. The selection and classification of events in the $2\ell\text{SS}$ category is designed to target the $T\chi\chi WZ$ and $T\chi\chi\bar{\ell}\ell$ scenarios in final states with three leptons where one of them is undetected, either for being too soft or falling out of detector acceptance. Thus, the category is expected to provide the most sensitivity to the more compressed SUSY scenarios, with lower values of δM , where soft leptons are likelier to appear. Minimal preselection criteria are applied in all the SR of the $2\ell\text{SS}$ category. They are summarized in the following points:

- The leading lepton p_T is required to be greater than 20 GeV in $\mu\mu$ events and 25 GeV in ee and $e\mu$ events. The subleading lepton p_T is required to be at least 15 (10) GeV if it is an electron (muon). These requirements are applied in order to ensure the efficiency of the trigger selection.
- The semileptonic $t\bar{t}$ contribution, significant part of the nonprompt lepton background, is reduced by the application of a veto of events containing at least one b tagged jet. Further discrimination is obtained by vetoing events with two or more reconstructed jets with $p_T > 40$ GeV, which still allows for the presence of signal with sizeable ISR contribution.
- A minimum of $p_T^{\text{miss}} > 60$ GeV is required, which drastically reduces the background contributions from Drell–Yan events in which the charge of one of the leptons is wrongly identified.
- Contributions from Drell–Yan plus one nonprompt lepton in which one of the prompt leptons is undetected are further reduced through the recovery of low quality leptons. If any reconstructed leptons failing both the loose and tight identification criteria form an OSSF pair with one of the selected leptons, and their invariant mass is within 15 GeV of the Z peak mass, the corresponding event is vetoed.

Selected events are then categorized onto SR based on several high-level variables:

- **The p_T^{miss} :** generically sensitive to all signal models, as signal presence will be enhanced at high p_T^{miss} values due to the invisible χ_1^0 particles on the final states. Background processes have either none (Drell–Yan) or only moderate (WZ , $t\bar{t}$) expected amounts of p_T^{miss} .
- **The transverse momentum of the dilepton system ($p_T^{\ell\ell}$):** characterizes the overall softness of the two reconstructed leptons, and so can be used to separate the most compressed signal scenarios (low δM) which will typically correspond to relatively low $p_T^{\ell\ell}$ values, from the most uncompressed ones (high δM) which appear at high $p_T^{\ell\ell}$ values.
- **The total leptonic charge** is used to profit from the charge asymmetry in WZ production, largely discussed in Section 5.6 which is expected to have different sizes in the various signal production modes.
- **The stransverse mass of the two leptons and p_T^{miss} ($M_{T2}(\ell\ell)$):** the stransverse mass variable of two bodies X and Y is an extension of the standard transverse mass of an object X defined as [221]:

$$M_{T2}(X, Y) = \min_q \left[\max \left(M_T(p_x, q), M_T(p_y, p_T^{\text{miss}} - q) \right) \right] \quad (6.2)$$

where the auxiliary momentum q can take any possible value. In the case of the production of a pair of identical particles of type A decaying to a pair of visible–invisible final states X and Y , $M_{T2}(X, Y)$ is kinematically bound by the mass of the original particle m_A . In the case of WW production, for example, $M_{T2}(\ell\ell)$ can be built with the two final state leptons. At least one partition of p_T^{miss} selects the q and $p_T^{\text{miss}} - q$ momentum values corresponding to the true transverse momentum of the neutrinos. For that specific partition, both $M_T(p_\ell, q) < m_W^{\text{PDG}}$ and $M_T(p_{\ell'}, p_T^{\text{miss}} - q) < m_W^{\text{PDG}}$ from the properties of the transverse mass. As a consequence, the final bound of $M_{T2}(\ell\ell) < m_W^{\text{PDG}}$ is fulfilled as a whole. The same principle can be used to reason that for the $t\bar{t}$ process $M_{T2}(\ell\ell) < m_W^{\text{PDG}}$. Contributions to higher $M_{T2}(\ell\ell)$ values might appear if more than two invisible particles are produced (as in the case of all signal scenarios), or detector resolutions skew the estimation of p_T^{miss} or the lepton kinematics. Around a fourth of the events have $M_{T2}(\ell\ell) = 0$ –whenever p_T^{miss} falls between the p_T of the two leptons– which slightly limits its usefulness.

The four discriminant variables are combined to obtain several SR. The SR definition was obtained by optimizing the sensitivity of the final selection to several signal models corresponding to $T\chi\chi\tilde{\ell}\ell$ production with $x = 0.05$ and $x = 0.95$ within the compressed SUSY scenarios. Sensitivity to the uncompressed scenarios is obtained in high $M_{T2}(\ell\ell)$, high $p_T^{\ell\ell}$ scenarios, where the SM background is strongly depleted and significant boosts to the signal leptons from the high $\chi_1^\pm$ mass enhance the presence of signal. High $M_{T2}(\ell\ell)$, low $p_T^{\ell\ell}$ selections tend to be more sensitive to the compressed SUSY signals due to the inverse effect. The definition of the SR, and the expected background and observed yields on each one are detailed in Table 6.3. A detail of the expected and observed distributions across the $2\ell\text{SS}$ signal regions is shown in Figure 6.13, which also includes a subset of signals used for the optimization of the SR strategy. Overall good agreement is found between data and expectations, with small fluctuations in several of the SR that are nonetheless consistent with the SM expectations within one standard deviation.

$M_{T2}(\ell\ell)$ (GeV)	$p_T^{\ell\ell}$ (GeV)	$60 < p_T^{\text{miss}} < 100$ GeV (exp.) (obs.)		$100 \leq p_T^{\text{miss}} < 200$ GeV (exp.) (obs.) (charge)			$p_T^{\text{miss}} \geq 200$ GeV (exp.) (obs.) (charge)		
0	< 70	683 ± 80 (exp.)					731 (obs.)		
	≥ 70	364 ± 64	410	22 ± 4	28	(++)	5 ± 2	10	(++)
				12 ± 4	20	(--)	1 ± 1	2	(--)
0–80	< 30	662 ± 82 (exp.)		721 (obs.)		(++)	1 ± 1	2	
		557 ± 74 (exp.)		611 (obs.)		(--)			
	≥ 30	4241 ± 394 (exp.)					4316 (obs.)		
> 80	< 200	98 ± 10	99	76 ± 8	96	(++)	2 ± 1	3	(++)
				48 ± 6	65	(--)	1 ± 1	3	(--)
	≥ 200	12 ± 3	11	3 ± 2	10	(++)	3 ± 1	6	(++)
				4 ± 1	6	(--)	3 ± 1	6	(--)

TABLE 6.3: Expected and observed yields on each of the search regions for category $2\ell\text{SS}$, events with two leptons with the same charge. For each search region, the number of expected background events and its total uncertainty is shown in the left part of the cell, and the number of observed events on the right part of the cell. The parenthetical symbols indicates the lepton charge selection criteria in case there is one. Uncertainties include the whole set of sources described in Section 6.5.

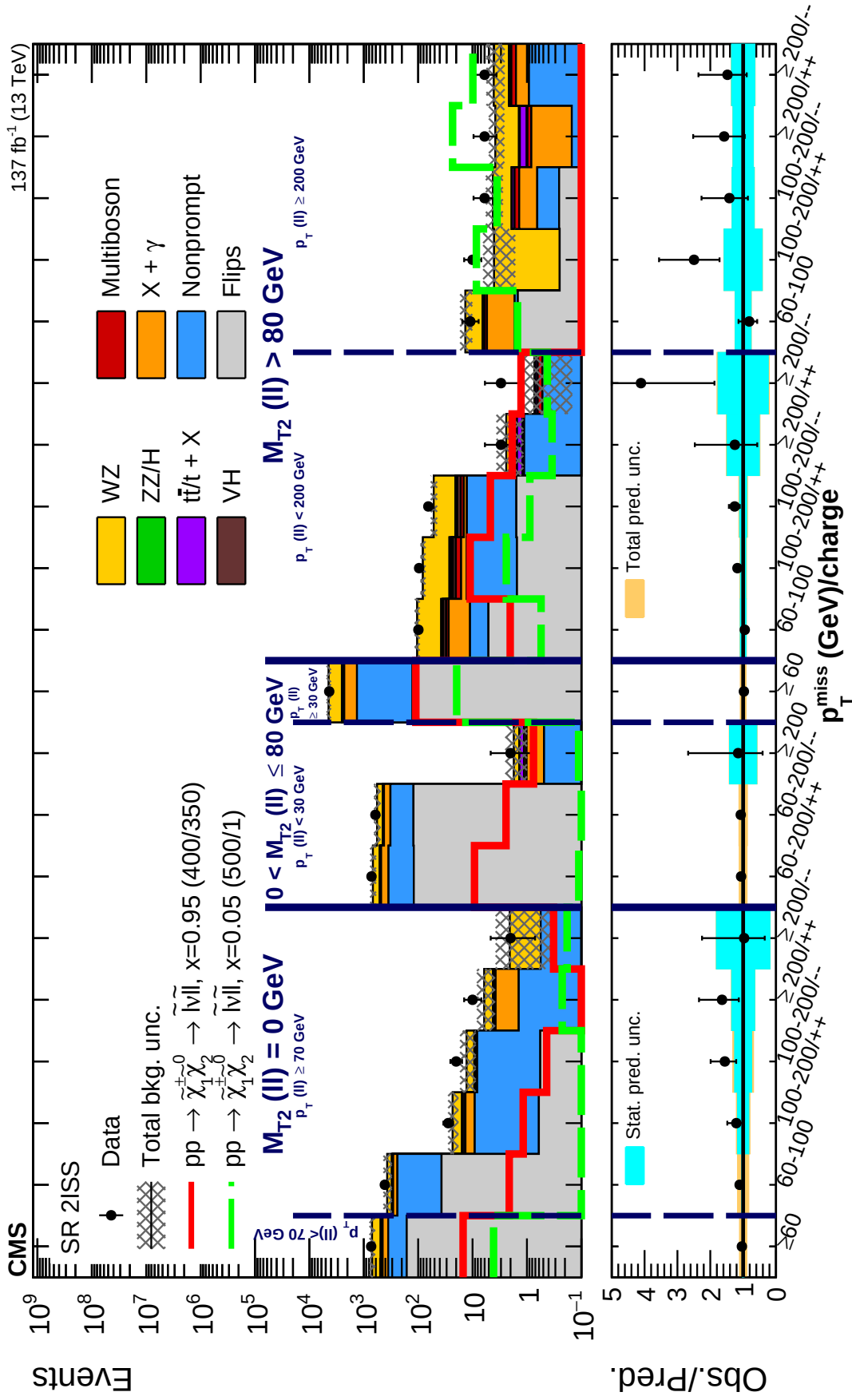


FIGURE 6.13: Expected and observed distribution of yields in the search regions of category 2/SS, events with a pair of same-sign leptons. The uncertainties shown include all sources described in Section 6.5.

6.6.2 Final states with exactly three leptons and no τ_h candidates

Final states with three light leptons include categories $3\ell A$ and $3\ell B$, and several common preselection criteria are applied to both of them. The p_T of the leading, subleading, and trailing leptons are required to be greater than 20 (25), 15 (10), and 10 (10) GeV if they are muons (electrons). These requirements have been found to provide a selection where the trigger strategy is near fully efficient. An additional requirement is imposed such that $p_T^{\text{miss}} > 50$ GeV, to reduce the presence of the nonprompt lepton background due to Drell–Yan production and orthogonalize the selection from the photon conversion CR described in Section 6.4.5. Contributions from top–enriched backgrounds are reduced with the application of a b tagged jet veto, which orthogonalizes all SR from the top enriched CR introduced in Section 6.4.5. Finally, the invariant mass of any OSSF lepton pair is required to be greater than 12 GeV, mimicking the infrared safe criteria already discussed in Section 4.7.2.2.

Category $3\ell A$ is sensitive to all signal models described in Section 6.1.1, so a high quantity of SR are defined in order to be able to cover the wide range of kinematics signals might be presented in. The same lepton tagging algorithm used for the definition of the WZ–SR in Sections 4.7.2.2 and 5.2.2, as well as for the WZ–CR in Section 6.4 is used to assign leptons to the W and Z boson decays. Depending on the invariant mass of the lepton pair closest to the Z, $M(\ell\ell)$, two different subcategories are considered:

- **On-shell $3\ell A$ subcategory:** consisting on events that pass the $75 < M(\ell\ell) < 105$ GeV requirement and targetting signal scenarios that involve the resonant production of a SM Z boson, such as the $T\chi\chi WZ$, $T\chi\chi ZZ$ and $T\chi\chi HZ$ models
- **Off-shell $3\ell A$ subcategory:** consisting on events that do not pass the $75 < M(\ell\ell) < 105$ GeV requirement and targetting topologies that involve the non-resonant production of the OSSF lepton pair, such as the $T\chi\chi\tilde{\ell}\tilde{\ell}$ and $T\chi\chi WH$ models.

In the on-shell $3\ell A$ subcategory, the following variables are considered to define the SR binning

- **The transverse mass of the reconstructed W boson (M_T^W):** built with the lepton tagged as coming from the W boson decay and p_T^{miss} . It is expected to have a kinematic endpoint at m_W^{PDG} for the dominant WZ background although, as discussed in Section 6.4, resolution effects might produce some background contributions at higher values. For the case of signals it extends to roughly $M_{\chi_1^\pm}$ in the case of $T\chi\chi WZ$ production, so additional binning at high M_T^W values is introduced to be sensitive to a broad range of $M_{\chi_1^\pm}$ values.
- **The overall hadronic energy of the event (H_T):** defined as the scalar sum of the p_T of all selected jets in the event. It offers significant different behaviour between different signal scenarios. In the most compressed cases significant hadronic recoil with respect to the superpartners is needed to produce energetic enough leptons, which leads to significant H_T . The most uncompressed signals, with high δM , tend to have a more strong presence at low H_T values as no

M_T (GeV)	p_T^{miss} (GeV)	$H_T < 100$ GeV (exp.) (obs.)		$100 \leq H_T < 200$ GeV (exp.) (obs.)		$H_T \geq 200$ GeV (exp.) (obs.)	
0–100	50–100	7118 $\pm$ 818	7368	1135 $\pm$ 135	1169	1213 $\pm$ 160	1260
	100–150	1070 $\pm$ 139	1050	341 $\pm$ 42	362		
	150–200	219 $\pm$ 27	211	96 $\pm$ 12	109		
	200–250	61 $\pm$ 9	62	30 $\pm$ 4	30	300 $\pm$ 43	294
	250–350	44 $\pm$ 6	36	19 $\pm$ 3	15	90 $\pm$ 14	79
	≥ 350					46 $\pm$ 7	36
100–160	50–100	1202 $\pm$ 180	1268	214 $\pm$ 33	232	172 $\pm$ 28	199
	100–150	228 $\pm$ 49	268	54 $\pm$ 12	70	60 $\pm$ 10	65
	150–200	23 $\pm$ 5	25	11 $\pm$ 2	12	20 $\pm$ 4	26
	200–250	5 $\pm$ 1	6	2 $\pm$ 1	4	8 $\pm$ 2	12
	250–300					3 $\pm$ 1	1
	≥ 300					3 $\pm$ 1	3
≥ 160	50–100	80 $\pm$ 14	113	30 $\pm$ 5	36	43 $\pm$ 8	53
	100–150	52 $\pm$ 8	49	11 $\pm$ 4	9	19 $\pm$ 4	20
	150–200	17 $\pm$ 3	18	5 $\pm$ 1	4	7 $\pm$ 1	7
	200–250	10 $\pm$ 2	15	3 $\pm$ 1	10	5 $\pm$ 1	2
	250–300					2 $\pm$ 1	2
	≥ 300					4 $\pm$ 1	3

TABLE 6.4: Expected and observed yields on each of the on-shell search regions for category $3\ell A$, events with three light leptons including at least an OSSF light lepton pair. For each search region, the number of expected background events and its total uncertainty is shown in the left part of the cell, and the number of observed events on the right part of the cell. Uncertainties include the whole set of sources described in Section 6.5. A requirement of $75 < M(\ell\ell) < 105$ GeV is applied in all SR presented in this table. The three SR marked in red on the second row partially overlap with the WZ–CR introduced in Section 6.4 and so are removed from the signal extraction fits in the interpretation of the analysis results.

additional hadronic recoil is needed to produce leptons that are energetic enough to be detected.

- **The p_T^{miss} :** which is also expected to appear for all signal processes in an at least moderate quantity, and so can be used to discriminate against most SM backgrounds where all the p_T^{miss} appears due to relatively low energy neutrinos produced in the W boson decays.

The complete set of on-shell SR are optimized based on the sensitivity to three different $T\chi\chi WZ$ signal models corresponding to the uncompressed ($\delta M = 500$ GeV), compressed ($\delta M = 50$ GeV), and mildly compressed ($\delta M = 90$ GeV) scenarios. The last one is of special interests as it separates the regime in which the produced SM Z boson is on- and off-shell. Reaching sensitivity to $T\chi\chi WZ$ production is specially challenging for the $\delta M = 90$ GeV case, as it has a behaviour that is near identical to that of the SM WZ background. This point justifies the inclusion of these kind of signal models in the SR optimization for the on-shell $3\ell A$ SR. The final set of on-shell SR, as well as the expected and observed yields on each one are shown in Table 6.4. The three SR marked in red overlap with the WZ–CR defined in Section 6.4.3 and so are not used for further reinterpretation of the results in Section 6.7.

For the off-shell $3\ell A$ subcategory, SR are defined based on the following observables:

- **The invariant mass of the OSSF lepton pair closest to the Z peak ($M(\ell\ell)$):** this variable is bound upwards by the δM value, a fact that is significant for the most compressed SUSY scenarios in all considered models which will populate the low $M(\ell\ell)$ regions. Non resonant models such as $T\chi\chi\tilde{\ell}\tilde{\ell}$ can also produce events at very high $M(\ell\ell)$ values as then the variable is not constricted by the Z boson resonance. In these cases $M(\ell\ell)$ partially reconstructs the overall mass of the produced χ_2^0 .
- **The reconstructed transverse mass of the W boson (M_T^W):** built with the lepton tagged as coming from the W decay and p_T^{miss} . It has the same properties for the off-shell subcategory that those introduced for the on-shell one.
- **The transverse mass of the whole leptonic system ($M_T^{3\ell}$):** which is built as a standard transverse mass with the vectorial p_T sum over the three reconstructed leptons used as the visible object, and p_T^{miss} as the invisible one as usual. As a measurement of the overall energy of the leptonic system it acts as a proxy of the overall energy of the pair-produced sparticles which is expected to be at the order of the $\chi_1^\pm$ mass. Thus, models with high $M_{\chi_1^\pm}$ values are expected to populate the high $M_T^{3\ell}$ regions.

Requirements on all the three variables are used to define the SR strategy which are optimized using several $T\chi\chi\tilde{\ell}\tilde{\ell}$ models corresponding to the uncompressed (high δM) and compressed (low δM) scenarios for all possible values of the x parameter. The resulting set of off-shell $3\ell A$ SR and the expected and observed yields on each one are shown in Table 6.5.

M_T (GeV)	$M_T^{3\ell}$ (GeV)	$M(\ell\ell) < 50$ GeV		$50 \leq M(\ell\ell) < 75$ GeV		$105 \leq M(\ell\ell) < 250$ GeV		$M(\ell\ell) \geq 250$ GeV	
		(exp.)	(obs.)	(exp.)	(obs.)	(exp.)	(obs.)	(exp.)	(obs.)
0–100	0–50	245 ± 54	247	899 ± 153	952	565 ± 63	625	47 ± 11	61
	50–100	231 ± 34	254						
	100–400	261 ± 33	288	370 ± 45	393				
	≥ 400			5 ± 1	7	9 ± 1	9	2 ± 1	3
100–200	0–200	191 ± 31	216	208 ± 31	206	144 ± 21	158	15 ± 3	27
	≥ 200			21 ± 4	27	24 ± 4	27		
≥ 200	0–400	28 ± 3	36	27 ± 5	37	32 ± 5	29	5 ± 1	9
	≥ 400			3 ± 1	1	4 ± 1	1		

TABLE 6.5: Expected and observed yields on each of the off-shell search regions for category $3\ell A$, events with three light leptons including at least an OSSF light lepton pair. For each search region, the number of expected background events and its total uncertainty is shown in the left part of the cell, and the number of observed events on the right part of the cell. Uncertainties include the whole set of sources described in Section 6.5.

The expected background and observed distributions of events across all SR in category $3\ell A$ is shown in Figure 6.14. Several of the signal models used in the SR optimization studies are also shown in the plot as individual lines. Overall good agreement is found between data and expectations, with small fluctuations in data that are compatible with the SM predictions within the statistical uncertainties. Thus, no significant presence of a SUSY signal is observed in category $3\ell A$.

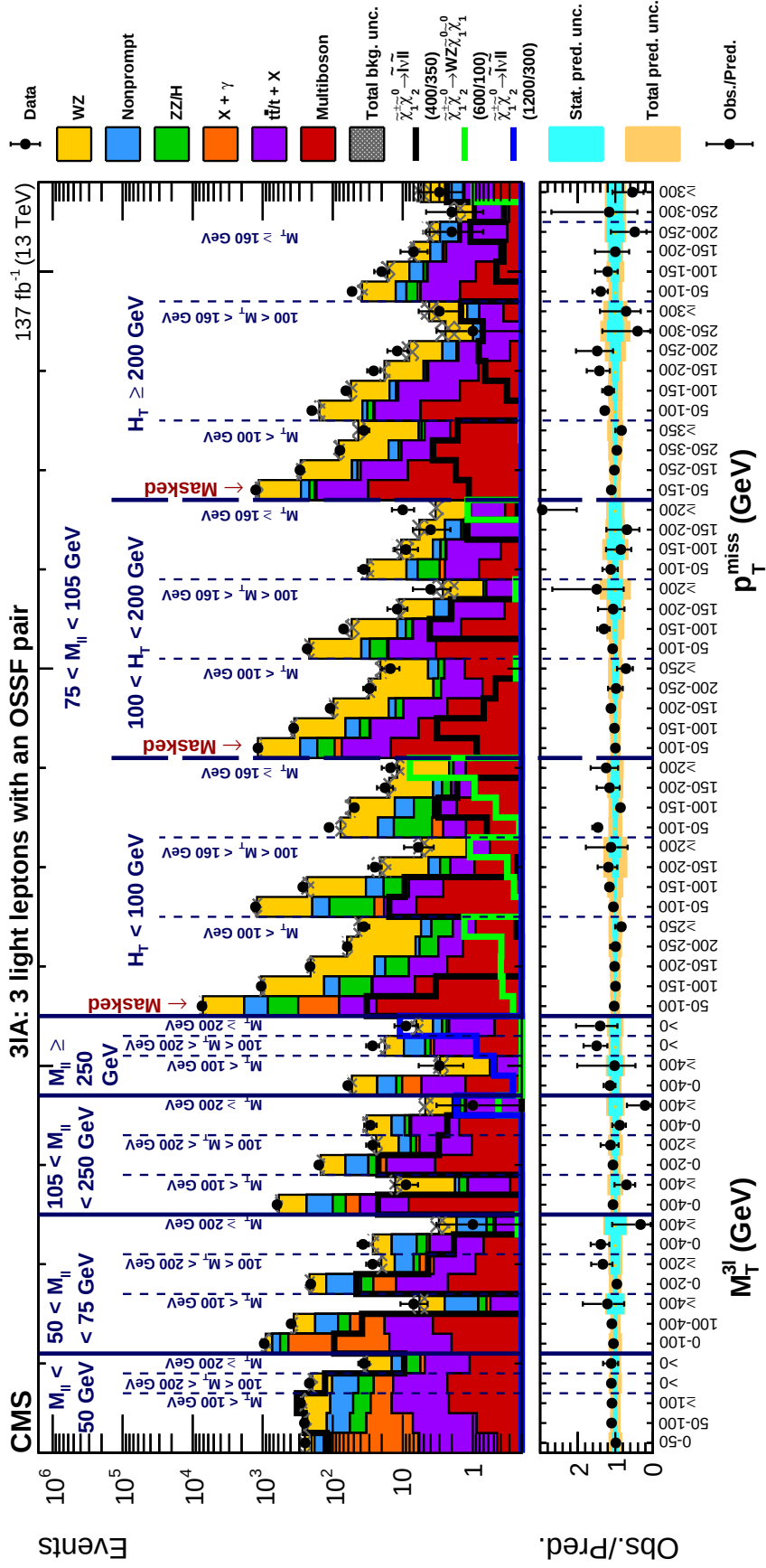


FIGURE 6.14: Expected and observed distribution of yields in the search regions of category 3lA, events with three light leptons containing at least one OSSF lepton pair. The distribution includes both the off-shell regions (leftmost part of the plot) and the on-shell ones (rightmost part). The uncertainties shown include all sources described in Section 6.5.

$\min(\Delta R(\ell, \ell')) < 0.4$ (exp.)	$\min(\Delta R(\ell, \ell')) < 0.4$ (obs.)	$0.4 \leq \min(\Delta R(\ell, \ell')) < 1$ (exp.)	$0.4 \leq \min(\Delta R(\ell, \ell')) < 1$ (obs.)	$\min(\Delta R(\ell, \ell')) \geq 1$ (exp.)	$\min(\Delta R(\ell, \ell')) \geq 1$ (obs.)
8 ± 1	14	112 ± 23	111	323 ± 82	330

TABLE 6.6: Expected and observed yields on each of the search regions for category $3\ell B$, events with three light leptons containing no OSSF lepton pair. For each search region, the number of expected background events and its total uncertainty is shown in the left part of the cell, and the number of observed events on the right part of the cell. Uncertainties include the whole set of sources described in Section 6.5.

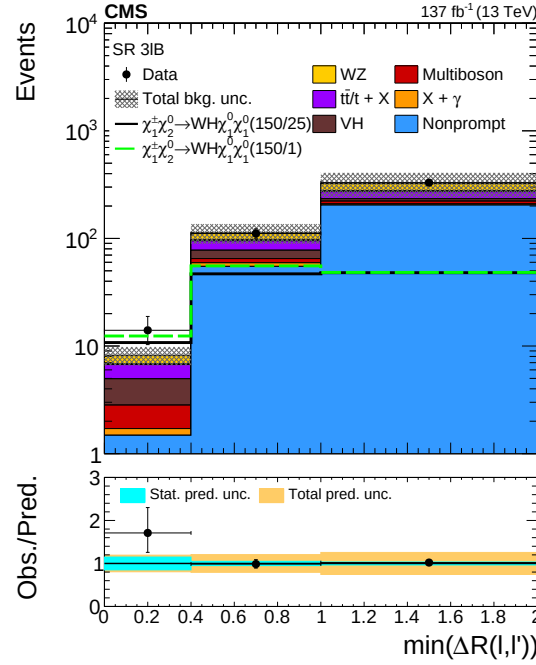


FIGURE 6.15: Expected and observed distribution of yields in the search regions of category $3\ell B$, events with three light leptons containing no OSSF lepton pair. The uncertainties shown include all sources described in Section 6.5.

Category $3\ell B$ has a much more limited set of models it is sensitive too. Most of the signal models described in Section 6.1.1 are not expected to provide sizeable contributions into this category, as that would require the production of an OSSF τ pair, with each of the τ leptons decaying each to a different flavoured light lepton, a relatively rare process. Conversely, the quantity of SM background yields are reduced as well, being dominated by processes that do not include resonant lepton pairs: the nonprompt lepton background, $t\bar{t}W$, and VH production.

SR in the $3\ell B$ category are optimized to obtain sensitivity to the $T\chi\chi WH$ final state, to which it offers unique sensitivity through the $H \rightarrow WW \rightarrow \ell\ell'\nu\nu$ and $W \rightarrow \ell\nu$ decay channels. In this decay mode of the Higgs boson, the leptons produced tend to appear in a slightly collimated way, closely than in most other SM processes. As which lepton pair corresponds to the H decay can not be easily discerned, the minimal angular distance between any lepton pair is taken as a proxy quantity $\min(\Delta R(\ell, \ell'))$. The SR bins defined using this quantity are represented in Table 6.6, with the corresponding distribution of yields shown in Figure 6.15. A small excess is seen in data at the very low ΔR SR, which is nonetheless consistent with the SM expectations within one standard deviation.

6.6.3 Final states with three leptons including τ_h candidates

Final states with three leptons including one or more τ_h candidates correspond to categories $3\ell C$, $3\ell D$, $3\ell E$ and $3\ell F$. As before, several common preselection criteria are applied to both of them. The p_T of the leading, subleading, and trailing leptons are required to be greater than 20 (25), 15 (10), and 10 (10) GeV if they are muons (electrons). Any selected τ_h candidate is required to have a p_T of at least 20 GeV. The invariant mass of any OSSF lepton pair is required to be greater than 12 GeV, mimicking the infrared safe criteria already discussed in Section 4.7.2.2. Finally, a minimum missing transverse momentum of $p_T^{\text{miss}} > 50$ GeV is required in all categories. Events with a b tagged jet are vetoed across all categories.

Events selected in category $3\ell C$ include the final state with an OSSF lepton pair and a τ_h candidate. The SR need to be orthogonalized from the measurement and validation regions of the nonprompt τ_h background described in Section 6.4.1 to avoid double counting of events in the signal extraction and background estimation. This is achieved by applying an additional requirement on the mass of the OSSF lepton pair by vetoing the region defined by $(75 < M(\ell\ell) < 105 \text{ GeV})$. Further classification of events is done through the usage of the following variables:

- **The transverse missing momentum** (p_T^{miss}): signal processes tend to appear at higher values of p_T^{miss} due to the presence of the invisible LSPs in the final state. Moreover, the bulk of the background presence appears due to Drell–Yan production in association with a nonprompt τ_h , where the measured p_T^{miss} is purely instrumental and so expected to be small.
- **The transverse mass of the two light leptons** ($M_{T2}(\ell\ell)$): defined in the same way as in the $2\ell SS$ category. For WW and $t\bar{t}$ production, which contribute to the nonprompt lepton background, a kinematic endpoint appears at m_W^{PDG} as before, so it can be used to discriminate against these SM backgrounds.
- **The transverse mass of the two light lepton system** ($M_T(\ell\ell)$): defined as the transverse mass of the whole light lepton system. For models such as $T\chi\chi\tilde{\tau}\tilde{\ell}$ this quantity roughly corresponds to the transverse mass of the original χ_2^0 particle. Thus, signal events for the highest sparticle mass scenarios are expected to produce events at high $M_T(\ell\ell)$.

The SR definition is optimized using signal models corresponding to the $T\chi\chi\tilde{\tau}\tilde{\ell}$ scenario with $x = 0.5$, where the power from category $3\ell C$ is expected to be the most relevant across all categories. Signal models at the uncompressed ($\delta M = 900$ GeV) and moderately compressed ($\delta M = 300$ GeV) regions are used for the optimization. The resulting definitions of the SR, and the expected background and observed yields on each one are shown in Table 6.7.

The distribution of observed and expected yields across the SR in category $3\ell C$ is shown in Figure 6.16. Several of the signal models used for the optimization of the SR strategy are included for reference. It can be seen how, even after the optimization of the requirements in terms of object and event selection that targets the reduction of the nonprompt background, sizeable presence of nonprompt leptons still appears at several of the SR. Overall, quite decent agreement between observations and expectations is seen, with no distinguishable features in the distribution of yields.

p_T^{miss} (GeV)	$M_T(\ell\ell)$ (GeV)	$M_{T2}(\ell\ell) < 80$ GeV		$80 \leq M_{T2}(\ell\ell) < 120$ GeV		$M_{T2}(\ell\ell) \geq 120$ GeV	
		(exp.)	(obs.)	(exp.)	(obs.)	(exp.)	(obs.)
50–200	≥ 0	4157 ± 1586	3927	191 ± 65	167	22 ± 5	20
200–300	≥ 0	34 ± 11	42	4 ± 1	3	5 ± 1	5
≥ 300	0–250	9 ± 3 (exp.)				7 (obs.)	
	250–500	2 ± 1 (exp.)				1 (obs.)	
	≥ 500	3 ± 1 (exp.)				4 (obs.)	

TABLE 6.7: Expected and observed yields on each of the search regions for category 3 ℓ C, events with two light leptons forming OSSF lepton pair and a τ_h candidate. For each search region, the number of expected background events and its total uncertainty is shown in the left part of the cell, and the number of observed events on the right part of the cell. Uncertainties include the whole set of sources described in Section 6.5.

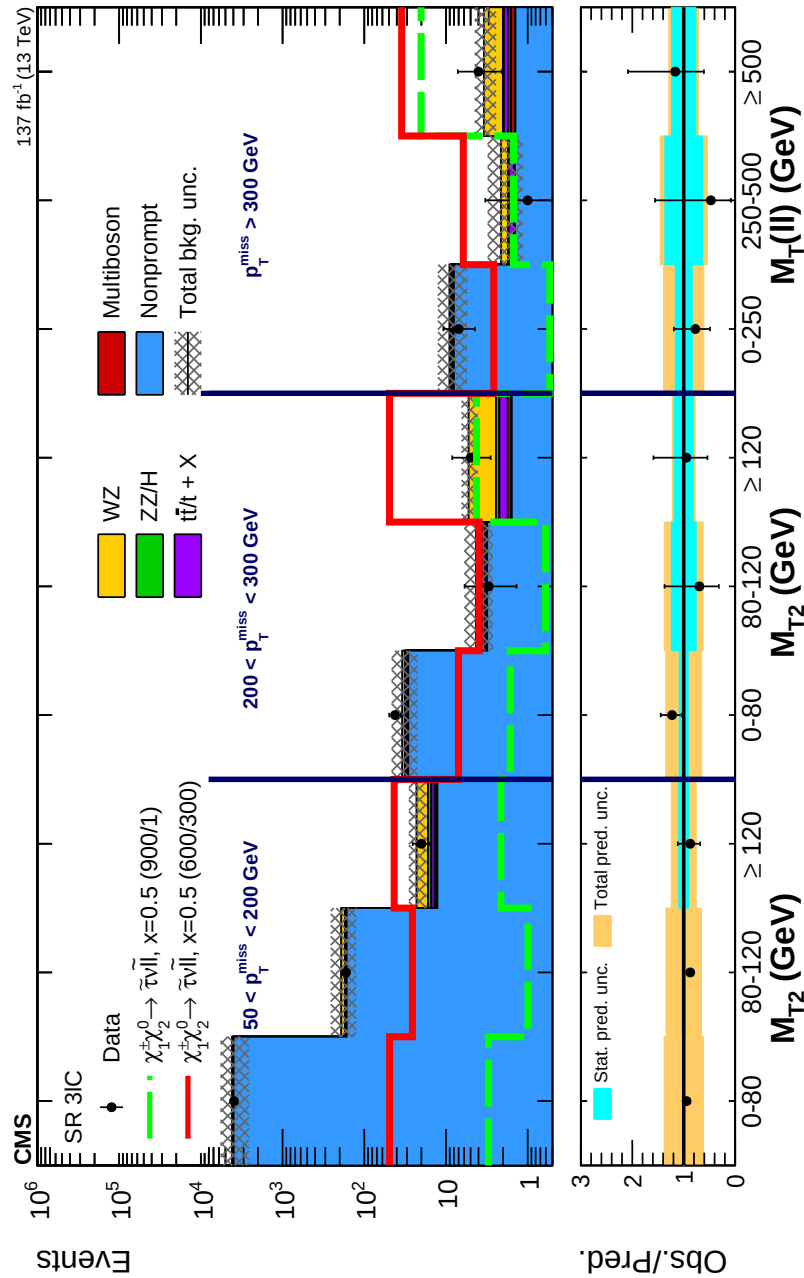


FIGURE 6.16: Expected and observed distribution of yields in the search regions of category 3 ℓ C, events with two light leptons forming OSSF lepton pair and a τ_h candidate. The uncertainties shown include all sources described in Section 6.5.

$M_{T2}(\ell\ell)$ (GeV)	p_T^{miss} (GeV)	$M(\ell\ell) < 60$ GeV		$60 \leq M(\ell\ell) < 100$ GeV		$M(\ell\ell) \geq 100$ GeV	
		(exp.)	(obs.)	(exp.)	(obs.)	(exp.)	(obs.)
0–100	50–100	675 ± 243	705	584 ± 212	615	190 ± 68	209
	100–150	235 ± 87	284	210 ± 77	231	70 ± 26	64
	150–200	49 ± 18	72	55 ± 20	48	24 ± 9	21
	200–250	16 ± 6	13	13 ± 4	8	12 ± 4	7
	≥ 250	13 ± 4	11	6 ± 2	6		
≥ 100	50–200	17 ± 5 (exp.)				20 (obs.)	
	≥ 200	1 ± 1 (exp.)				1 (obs.)	

TABLE 6.8: Expected and observed yields on each of the search regions for category 3 ℓ D, events with two light leptons forming OSOF lepton pair and a τ_h candidate. For each search region, the number of expected background events and its total uncertainty is shown in the left part of the cell, and the number of observed events on the right part of the cell. Uncertainties include the whole set of sources described in Section 6.5.

Category 3 ℓ D corresponds to events with two light leptons forming an OSOF pair and a τ_h candidate. It offers complementarity to category 3 ℓ C with a relatively similar final state that is dominated by the $t\bar{t}$ plus nonprompt τ_h background rather than the Drell–Yan plus nonprompt τ_h one. No additional selection criteria is applied to events in category 3 ℓ D. The variables used for the definition of the SR are:

- **The p_T^{miss} :** for similar reasons as in category 3 ℓ C.
- **The $M_{T2}(\ell\ell)$:** for similar reasons as in category 3 ℓ C.
- **The invariant mass of the two light leptons system ($M(\ell\ell)$):** serves as an additional requirement to separate the residual contributions from the Drell–Yan plus nonprompt τ_h background. Such process can appear in the 3 ℓ D category when the produced Z boson decays to a τ lepton pair and each of the resulting τ leptons decays to a different flavour of light lepton. Such process tends to peak around 60 GeV for resonant Drell–Yan production but is unbounded for non resonant signals models such as $T\chi\chi\tilde{\tau}\tilde{\ell}$.

The SR definition and the expected background and observed yields on each one for category 3 ℓ D are described in Table 6.8. The whole distribution of yields is shown graphically in Figure 6.17. Several distributions corresponding to the configurations of the $T\chi\chi\tilde{\tau}\tilde{\ell}$ model that were used for the optimization of the SR strategy are shown in the figure. It can also be seen how the overall background is completely dominated by the the nonprompt τ_h presence, with very little effects from any of the prompt lepton SM processes. The relatively big uncertainties associated to the nonprompt background introduce some loss of discriminating power for the different signal models with respect to other categories. While some upwards and downwards fluctuations appear in data, no clear presence of any kind of BSM signal is seen.

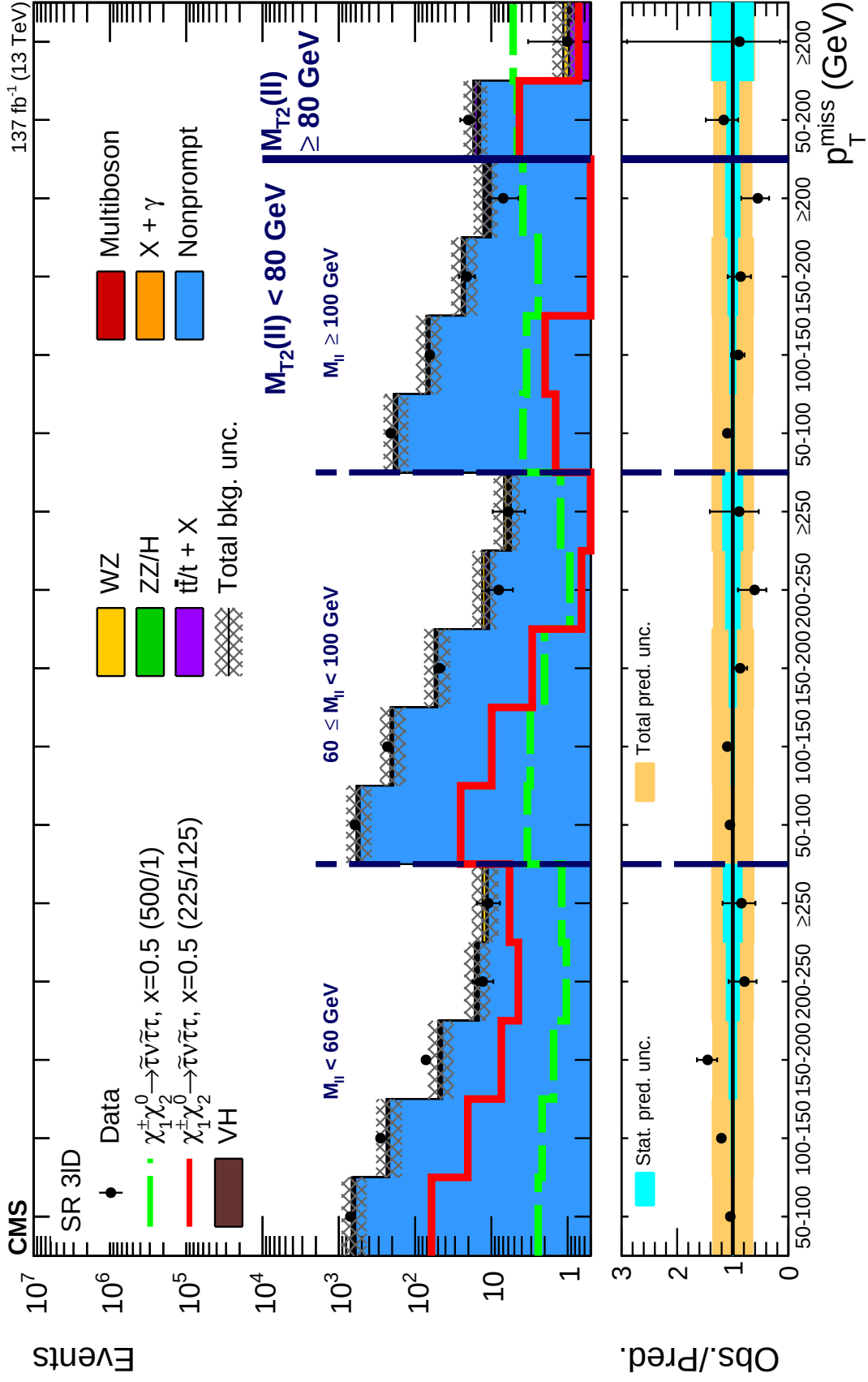


FIGURE 6.17: Expected and observed distribution of yields in the search regions of category 3ℓD, events with two light leptons forming OSOF lepton pair and a τ_h candidate. The uncertainties shown include all sources described in Section 6.5.

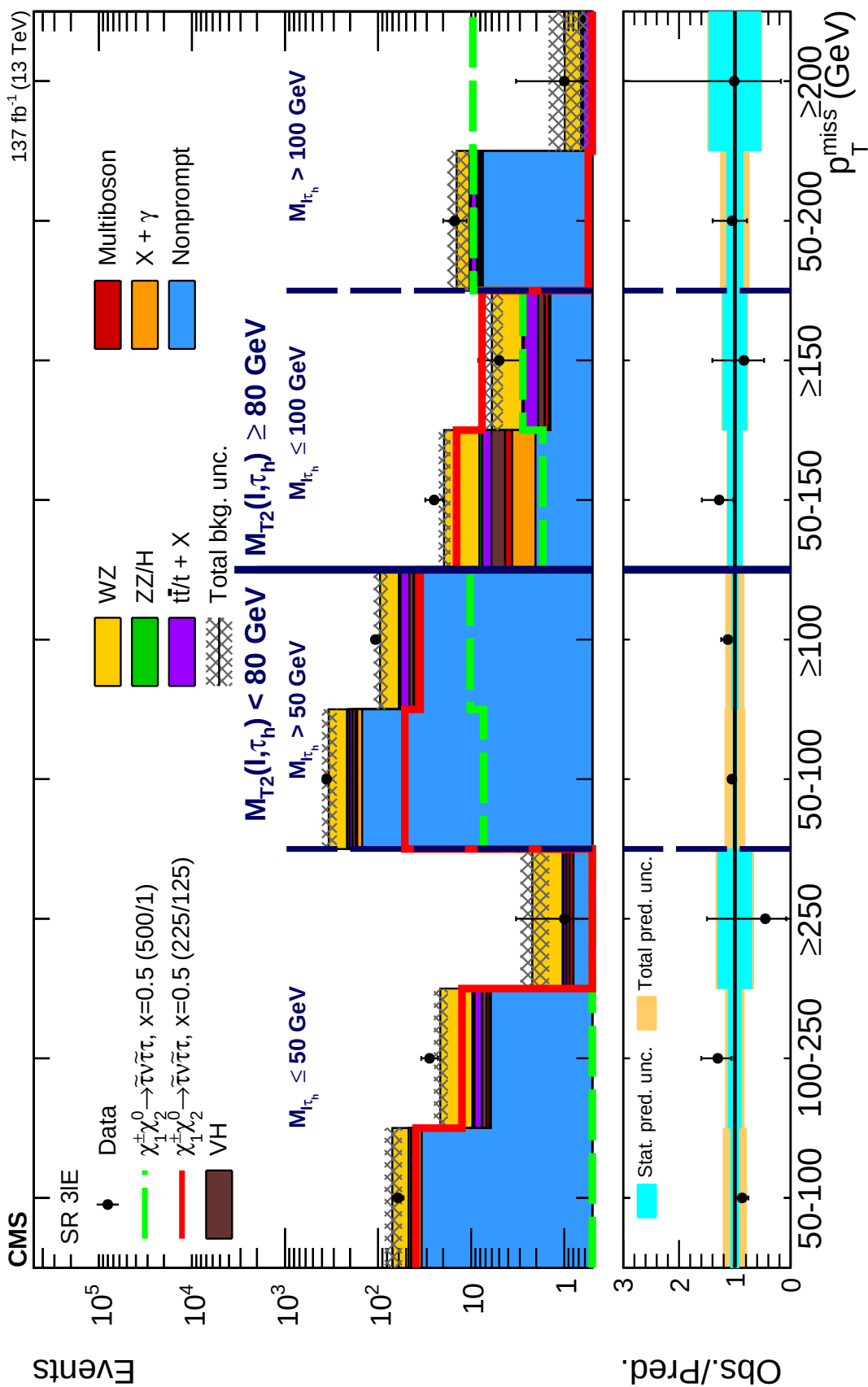
$M_{T2}(\ell, \tau_h)(\text{GeV})$	$p_T^{\text{miss}}(\text{GeV})$	$M(\tau_h \ell) \leq 50 \text{ GeV}$		$50 < M(\tau_h \ell) \leq 100 \text{ GeV}$		$M(\tau_h \ell) > 100 \text{ GeV}$	
		(exp.)	(obs.)	(exp.)	(obs.)	(exp.)	(obs.)
0–80	50–100	70 ± 14	61	339 ± 60 (exp.)		357 (obs.)	
	100–250	21 ± 3	28	95 ± 15 (exp.)		107 (obs.)	
	≥ 250	2 ± 1	1				
≥ 80	50–150	19 ± 2 (exp.)		25 (obs.)		14 ± 3	15
	150–200	5 ± 1 (exp.)		5 (obs.)		1 ± 1	
	≥ 200						

TABLE 6.9: Expected and observed yields on each of the search regions for category $3\ell E$, events with two light leptons with the same charge and a τ_h candidate. For each search region, the number of expected background events and its total uncertainty is shown in the left part of the cell, and the number of observed events on the right part of the cell. Uncertainties include the whole set of sources described in Section 6.5.

Category $3\ell E$ contains events with a same-sign lepton pair and a τ_h candidate. The region contains a genuine presence of prompt lepton background coming from processes that lead to three lepton final states, such as WZ and $t\bar{t}Z$ production and later decay through τ leptons. However, the fake-rate of the τ_h candidates is still big enough for the nonprompt τ_h background to be quite relevant across the whole category. No additional preselection criteria are applied for events in category $3\ell E$. The set of variables used for the SR definition are:

- **The p_T^{miss} :** which, as in all previous cases, tends to provide sensitivity towards the presence of most signal models.
- **The invariant mass of the best reconstructed Z candidate ($M(\tau_h \ell)$):** if the reconstructed τ_h candidate has opposite charge to both light leptons, it is possible that a $Z \rightarrow \tau\tau$ decay appeared with each τ lepton decaying through different channels. The OS lepton pair with the mass closest to 60 GeV is chosen as the best Z candidate, while the peak mass is reduced from m_Z^{PDG} to account for the energy loss due to the neutrinos in the τ decay. If the τ_h has the same sign as all light leptons this quantity is set to zero. For processes with genuine Z bosons, such as WZ and $t\bar{t}Z$, events are expected to have relatively low values of $M(\tau_h \ell)$, while signal models such as $T\chi\chi\tilde{\tau}\tilde{\ell}$ have no upper bound on its possible values.
- **The transverse mass of the leading lepton and the τ_h candidate ($M_{T2}(\ell, \tau_h)$):** under the assumption that the softest of the light leptons corresponds to a non-prompt one, this quantity tries to provide similar discrimination against the $t\bar{t}$ and WW backgrounds as the corresponding transverse mass in category $3\ell C$. As the assumption on the lepton origin is not always fulfilled the results are not as powerful as in category $3\ell C$ but they nonetheless show some separation between the different signal and background processes.

The final set of SR in category $3\ell E$ is optimized based on the performance for the exclusion of several signal models corresponding to the $T\chi\chi\tilde{\tau}\tilde{\ell}$ scenario at different mass splitting ranges of $\delta M = 500 \text{ GeV}$ and $\delta M = 100 \text{ GeV}$. The optimized SR definitions, and the expected background and observed yields on each of the SR are presented in Table 6.9. The distributions are also shown graphically in Figure 6.18, where several of the signal models used for the SR optimization are included as well. As in previous categories, no sign of a signal like is seen in any of the considered SR.



$M_{T2}(\ell, \tau_h)$ (GeV)	p_T^{miss} (GeV)	$M(\tau_h \ell) < 100$ GeV		$M(\tau_h \ell) \geq 100$ GeV	
		(exp.)	(obs.)	(exp.)	(obs.)
0–100	50–100	1159 ± 432	1085	584 ± 202	593
	100–150	186 ± 67	178	124 ± 41	122
	150–200	35 ± 12	40	36 ± 11	33
	200–250	9 ± 3	9	17 ± 5 (exp.)	19 (obs.)
	250–300	1 ± 1	3		
	≥ 300	2 ± 1	4		
≥ 100	50–200	22 ± 7 (exp.)		18 (obs.)	
	≥ 200	3 ± 1 (exp.)		2 (obs.)	

TABLE 6.10: Expected and observed yields on each of the search regions for category $3\ell F$, events with two τ_h candidates and one light lepton. For each search region, the number of expected background events and its total uncertainty is shown in the left part of the cell, and the number of observed events on the right part of the cell.

Uncertainties include the whole set of sources described in Section 6.5.

The final of the three lepton categories, $3\ell F$, is the only one requiring the presence of two τ_h candidates. To increase the efficiency of the triggering in this category, the light lepton p_T is tightened to 25 GeV for all lepton flavours. No other additional requirements are applied in this category. The variables used for the classification of events inside the $3\ell F$ category follow a very similar approach to that of the $3\ell E$ category. They are:

- **The p_T^{miss} :** which, as in all previous cases, tends to provide sensitivity towards the presence of most signal models.
- **The $M(\tau_h \ell)$:** a similar idea to that of the $3\ell E$ category to provide separation between the Drell–Yan background and the different signals. The pair of the light lepton and the leading τ_h candidate is used to reconstruct this Z candidate, as the softest tau tends to be a nonprompt one in Drell–Yan production.
- **The $M_{T2}(\ell, \tau_h)$:** under the assumption that the softest of the τ_h candidates corresponds to a nonprompt one, this quantity tries to provide similar discrimination against the $t\bar{t}$ and WW backgrounds as the corresponding transverse mass in category $3\ell C$.

The resulting definitions of the SR, and the distribution of expected background and observed yields across them are shown in Table 6.10. The optimization of the SR strategy was performed following the same strategy as in previous cases, focusing on several cases of the $T\chi\chi\tilde{\tau}\tilde{\tau}$ model with $\delta M = 500$ GeV and $\delta M = 100$ GeV. The results are also shown in Figure 6.19 where the distribution of several of the signal models involved in the optimization are also shown. No significant excesses that could appear due to a BSM signal are found in any of the SR of category $3\ell F$.

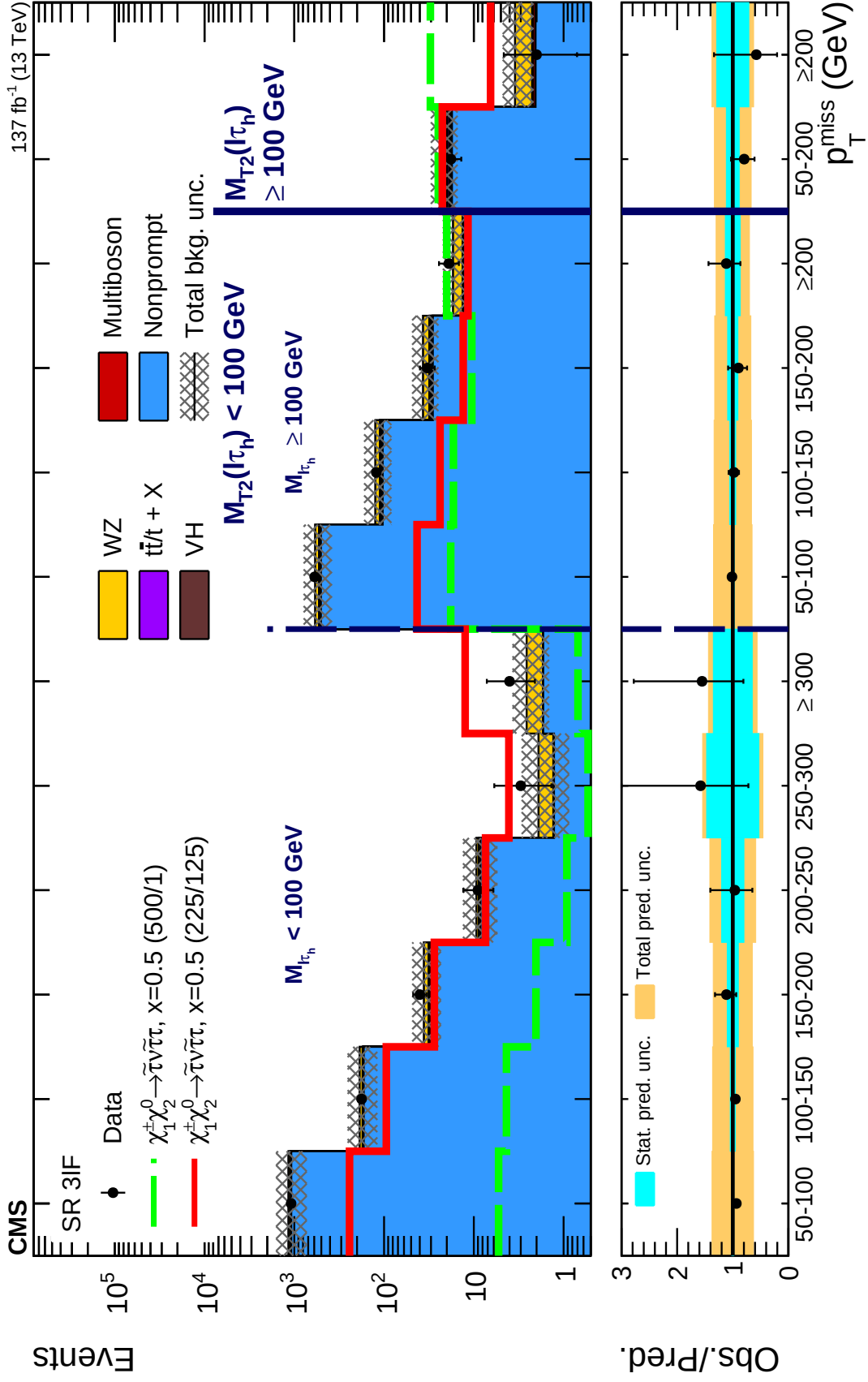


FIGURE 6.19: Expected and observed distribution of yields in the search regions of category 3/F, events with two τ_h candidates and one light lepton. The uncertainties shown include all sources described in Section 6.5.

6.6.4 Final states with four leptons

Final states with four leptons are classified into the $4\ell G$, $4\ell H$, $4\ell I$, $4\ell J$ and $4\ell K$ categories. All of these categories are expected to provide sensitivity to the different GMSB signal models introduced in Section 6.1.1. Several common selection requirements are applied to all events selected in the four lepton categories. First, to ensure high trigger efficiency the leptons are required to have a p_T greater than 20 (25), 15 (10), 10 (10) and 10 (10) GeV if they are muons (electrons). All reconstructed τ_h candidates are required to have $p_T > 20$ GeV. A minimum quantity of missing transverse momentum $p_T^{\text{miss}} > 50$ GeV is included to avoid double counting between the events passing the SR criteria and those in the ZZ -CR described in Section 6.4.4. Events with b tagged jets are vetoed to reduce the presence of top enriched backgrounds such as $t\bar{t}H$ and $t\bar{t}Z$. Finally, the invariant mass of any OSSF lepton pair is required to be greater than 12 GeV, mimicking the infrared safe criteria already discussed in Section 4.7.2.2.

Category $4\ell G$ corresponds to final states with two different pairs of OSSF leptons. The SR definition is based around the assumption that two Z candidates can be reconstructed from the final state leptons. The OSSF lepton pair with the mass closest to the Z boson is used to build the first Z candidate (Z_1). The remaining leptons are used to build the second Z boson candidate (Z_2). Then, the following variables are considered:

- **The reconstructed mass of the second Z candidate (M_{Z_2}):** which is just the invariant mass of the OSSF pair forming the Z_2 boson candidate. While most signal processes that are expected to populate this region include the presence of at least one Z boson, not all of them will produce a second Z resonance. The M_{Z_2} variable can then be used to distinguish between events compatible with ZZ on-shell production (for values of M_{Z_2} close to m_Z^{PDG}), and those in which the second lepton pair is unlikely to originate from a Z boson, as the ones that would be produced in the $T\chi\chi HZ$ model (M_{Z_2} values lower than M_{Z_2}).
- **The stransverse mass built with the two Z candidates ($M_{T_2}(ZZ)$):** an evolved version of the stransverse mass introduced in Section 6.6.1 which substitutes each of the leptons in the computation by one of the reconstructed Z candidates. An analogy can be drawn between the computation of this quantity for WW production with leptons, and for $T\chi\chi ZZ$ production with the Z candidates. The roles of the W bosons are replaced here for the χ_1^0 partners, with the Z bosons being the analogous of the charged leptons (visible particles in the decay), and the $\tilde{G}$ taking the role of the neutrinos (invisible particles in the decay). As a result, this variable will have a kinematic endpoint for signal at around $M_{\chi_1^0}$ for the $T\chi\chi ZZ$ model. For ZZ production, where p_T^{miss} is entirely instrumental in origin, it is expected that the variable will peak at very low values, close to the Z boson mass.

The SR of the analysis are optimized based on the behaviour of the $T\chi\chi ZZ$ model for the signal scenario with $\delta M = 300$ GeV and $\delta M = 500$ GeV scenarios, and the $T\chi\chi HZ$ model in the $\delta M = 150$ GeV scenario. The optimized SR strategy corresponds to the distribution of the $M_{T_2}(ZZ)$ variable, with the partition of several of the bins using M_{Z_2} to slightly increase the sensitivity towards $T\chi\chi HZ$ production. A summary of

$M_{T2}(ZZ)$ (GeV)	$M_{ZZ} \geq 60$ GeV		$M_{ZZ} < 60$ GeV	
	(exp.)	(obs.)	(exp.)	(obs.)
0–150	370 ± 20 (exp.)		380 (obs.)	
150–250	18 ± 1	15	6 ± 1	6
250–400	1 ± 1 (exp.)		0 (obs.)	
≥ 400	0 ± 1 (exp.)		0 (obs.)	

TABLE 6.11: Expected and observed yields on each of the search regions for category $4\ell G$, events with four light leptons forming two different OSSF pairs. For each search region, the number of expected background events and its total uncertainty is shown in the left part of the cell, and the number of observed events on the right part of the cell. Uncertainties include the whole set of sources described in Section 6.5.

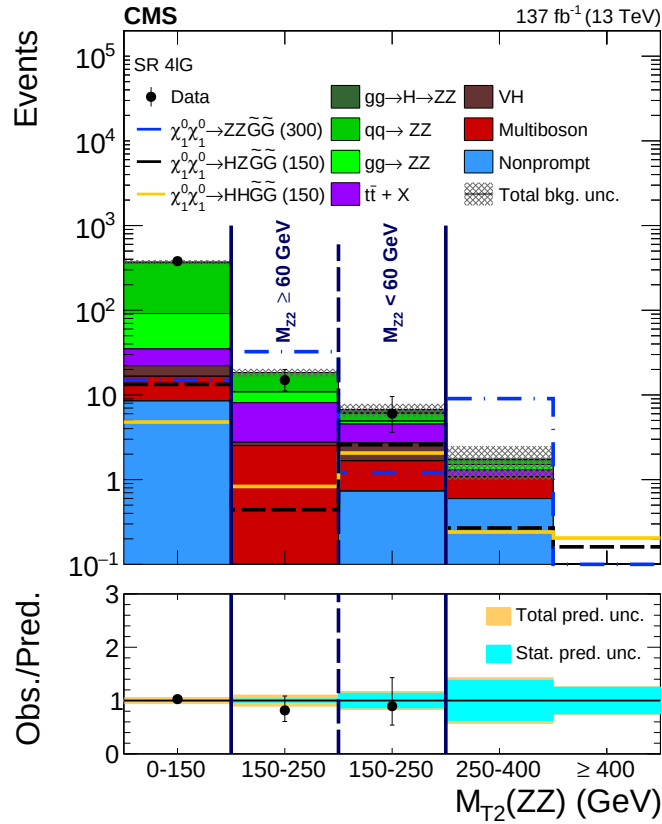


FIGURE 6.20: Expected and observed distribution of yields in the search regions of category $4\ell G$, events with four light leptons forming two different OSSF pairs. The uncertainties shown include all sources described in Section 6.5.

the resulting SR definitions, and the expected background and observed yields across each one are shown in Table 6.11. The corresponding distributions across SR are also shown graphically in Figure 6.20, including several of the signal models used for the optimization and one from the additional GMSB model ($T\chi\chi HH$) which was not included for such procedure due to its overall low yields in the $4\ell G$ category. The only significant effect observed in the distribution is the absence of observed events in the fourth SR, where around one SM background event is expected. Nonetheless, the results shows consistency between data and expectations within the statistical uncertainties of the measurement.

Categories 4ℓH, 4ℓI, 4ℓJ, and 4ℓK show sensitivity to the same set of signal models: $T\chi\chi HH$ and $T\chi\chi HZ$ production. The main differences between them are the different background contributions, with prompt non-ZZ backgrounds such as $t\bar{t}Z$ production being dominant at 4ℓH and slowly receding in importance as the τ_h multiplicity increases with respect to the nonprompt τ_h background which dominates the 4ℓK region. Nonetheless, the sensitivity to the same set of signal models can be used to define a common set of SR definitions based on the reconstruction of hypothetical Z and H candidates.

The leading Z candidate, or Z_1 , is built with the OSSF lepton pair from each event which has a mass closest to m_Z^{PDG} . If no OSSF lepton pairs are in the event, OSOF pairs are considered, to account for possible decays through leptonically decaying τ leptons. The reconstructed mass of this candidate (M_{Z1}) is used to separate processes which include a resonant $Z \rightarrow \ell\ell$ decay (such as the $t\bar{t}Z$ background and the $T\chi\chi HZ$ signal) from those do not (such as the $T\chi\chi HH$ signal). In the very unlikely case that all the final state leptons have the same charge, the M_{Z1} variable is set to zero so the corresponding event falls in the SR designed to target processes unlikely to contain a true Z boson and the two leading light leptons are used to build the Z_1 candidate.

The two leptons that are not used to build Z_1 are used to reconstruct the $\tilde{c}$ candidate of the event, independently of their charge or flavour. The distance in the $\eta - \phi$ plane between those two leptons (ΔR^H) is used as a second signal extraction discriminant, targetting the $H \rightarrow WW \rightarrow \ell\ell'\nu\nu$ decay as discussed for category 3ℓB in Section 6.6.2.

Three SR are defined on each category. An HZ-like SR is defined by selecting events inclusively in M_{Z1} but requiring that $\Delta R^H < 0.8$ so the two leptons associated to the H candidate are more likely to originate from a true H boson. From the remaining events, those that have $M_{Z1} < 60\text{GeV}$ are included into an HH-like region, targetting processes which contain no on-shell Z production. The remaining events are included into a final SR to catch possible residual signal contributions into each category. These selection requirements were optimized with the study of the distributions for the $T\chi\chi HH$ and $T\chi\chi HZ$ models with $M_{\chi_1^0} = 150\text{ GeV}$.

The results of this SR approach for categories 4ℓH and 4ℓI are shown numerically in Tables 6.12 and 6.13, and graphically in Figure 6.21 including the distributions of the signal models used for the SR optimization. The main background sources in both cases correspond to prompt lepton sources so the main underlying uncertainties on the expected background predictions are statistical in nature. Nonetheless, good agreement is found across the different SR except for small excesses at the one standard deviation level in the HH-like SR for both categories.

The corresponding results of this approach for categories 4ℓJ and 4ℓK are also shown in Tables 6.14 and 6.15, and Figure 6.22. In these cases, the nonprompt τ_h background has a much more sizeable presence leading to final states in which the background normalization uncertainties play a much more important role. No significant features are observed in the comparison of data and expectations in these categories.

M_{Z1} (GeV)	$\Delta R^H < 0.8$		$\Delta R^H \geq 0.8$	
	(exp.)	(obs.)	(exp.)	(obs.)
0–60	4 ± 1	3	3 ± 1	4
> 60			41 ± 5	49

TABLE 6.12: Expected and observed yields on each of the search regions for category 4 ℓ H, events with four light leptons forming less than two different OSSF pairs. For each search region, the number of expected background events and its total uncertainty is shown in the left part of the cell, and the number of observed events on the right part of the cell. Uncertainties include the whole set of sources described in Section 6.5.

M_{Z1} (GeV)	$\Delta R^H < 0.8$		$\Delta R^H \geq 0.8$	
	(exp.)	(obs.)	(exp.)	(obs.)
0–60	9 ± 1	7	10 ± 2	14
> 60			95 ± 16	92

TABLE 6.13: Expected and observed yields on each of the search regions for category 4 ℓ I, events with three light leptons and a τ_h . For each search region, the number of expected background events and its total uncertainty is shown in the left part of the cell, and the number of observed events on the right part of the cell. Uncertainties include the whole set of sources described in Section 6.5.

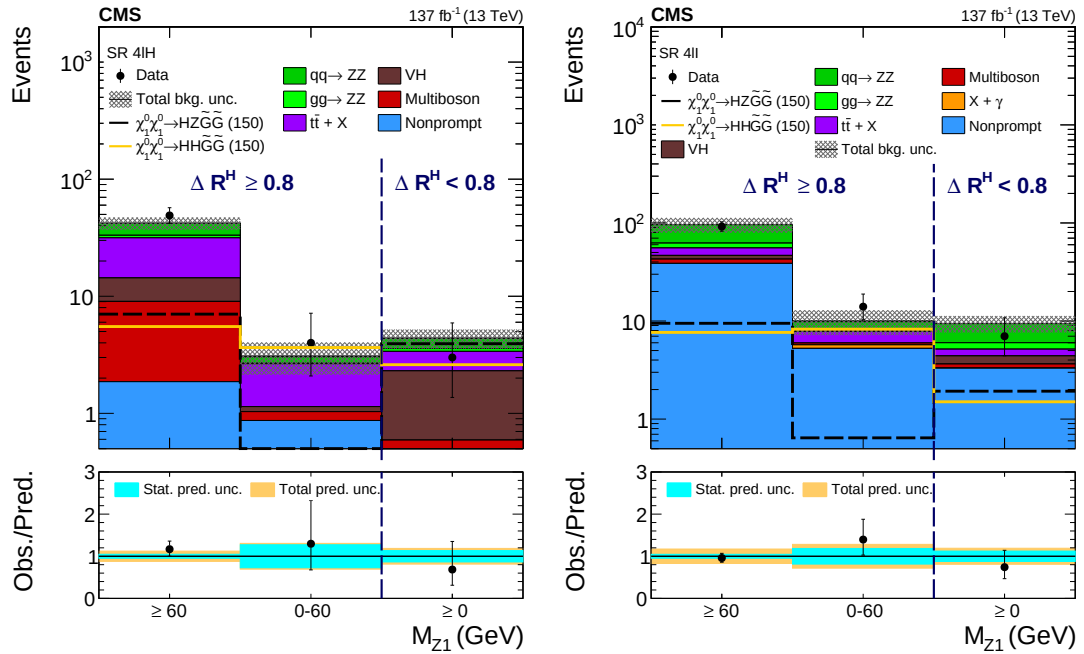


FIGURE 6.21: Expected and observed distribution of yields in the search regions of category 4 ℓ H, events with four light leptons forming less than different OSSF pairs, and category 4 ℓ I, three light leptons and a τ_h . The uncertainties shown include all sources described in Section 6.5.

M_{Z1} (GeV)	$\Delta R^H < 0.8$		$\Delta R^H \geq 0.8$	
	(exp.)	(obs.)	(exp.)	(obs.)
0–60	4 ± 1	4	10 ± 4	6
> 60			35 ± 8	34

TABLE 6.14: Expected and observed yields on each of the search regions for category 4ℓJ, events with two light leptons and two τ_h forming both an OSSF pair. For each search region, the number of expected background events and its total uncertainty is shown in the left part of the cell, and the number of observed events on the right part of the cell. Uncertainties include the whole set of sources described in Section 6.5.

M_{Z1} (GeV)	$\Delta R^H < 0.8$		$\Delta R^H \geq 0.8$	
	(exp.)	(obs.)	(exp.)	(obs.)
0–60	1 ± 1	1	5 ± 2	5
> 60			15 ± 6	8

TABLE 6.15: Expected and observed yields on each of the search regions for category 4ℓK, events with two light leptons and two τ_h forming less than two OSSF pairs. For each search region, the number of expected background events and its total uncertainty is shown in the left part of the cell, and the number of observed events on the right part of the cell. Uncertainties include the whole set of sources described in Section 6.5.

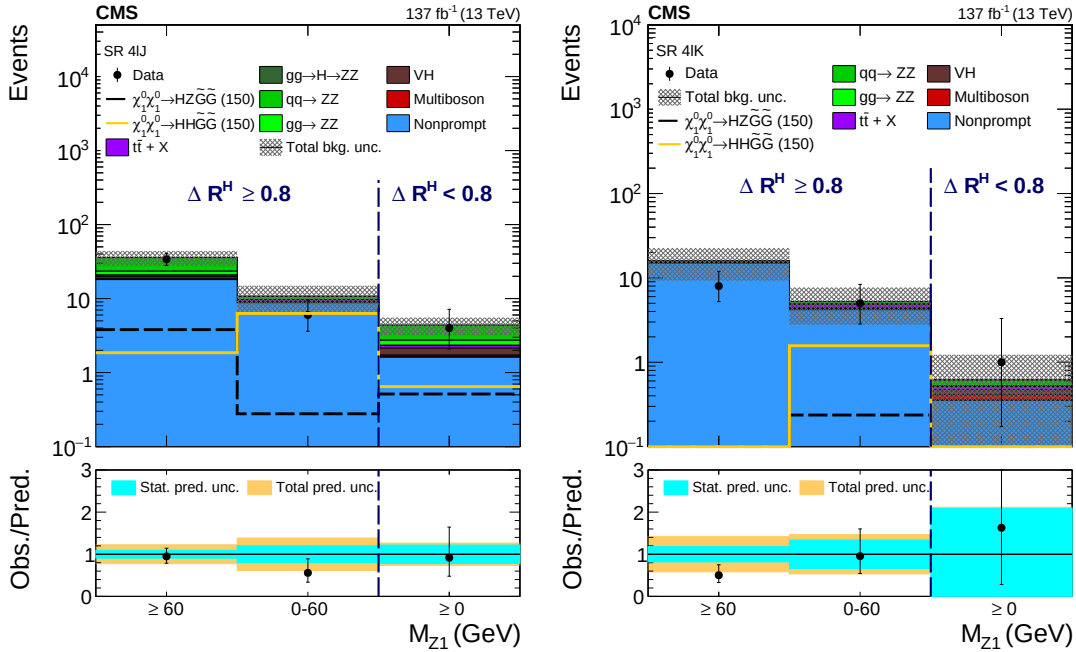


FIGURE 6.22: Expected and observed distribution of yields in the search regions of category 4ℓJ, events with two light leptons and two τ_h including two OSSF lepton pairs, and category 4ℓK, all other final states with two light leptons and two τ_h . The uncertainties shown include all sources described in Section 6.5.

6.6.5 Signal extraction with parametric neural networks

The complexity of the SR approach for category $3\ell A$ is evident from the sheer amount of SR presented in Tables 6.4 and 6.5. A machine learning (ML) approach for the signal extraction procedure is developed as an alternative method to the SR one introduced through Section 6.6.2. As the kinematics of the signal processes vary significantly between the different regions of each SMS parameter space, a simple approach based on discriminants dedicated to event classification between the SM background and the whole set of all analysis signals proves to be lacking in sensitivity when compared with the more dedicated SR approach. At the other hand of the spectra, introducing a single discriminant for each signal process proves a challenge both computationally (as more than three thousand different signal models are considered) and in terms of the limited sizes of the MC samples used to represent each signal model. The chosen approach takes the best of both worlds with the usage of a parametric discriminant, a parametric neural network (PNN) [222].

6.6.5.1 Parametric multivariate analysis

A generic multivariate approach (MVA), such as the ones usually considered through artificial neural networks (NNs) [223] is fundamentally a single application f that translates a set of measurements $x_1, \dots, x_n$ into a final summary value d

$$\begin{aligned} f: \quad \mathcal{I} &\rightarrow \mathbb{R} \\ x = (x_1, \dots, x_n) &\rightarrow f(x_1, \dots, x_n) \end{aligned} \quad (6.3)$$

where $\mathcal{I}$ is the set of all possible measurements of the $x_1, \dots, x_n$ properties. The function f is defined to fulfil some optimality criteria relating to its ability to predict some unknown quantity of each event. In the problem of classification, such quantity is the membership of the tested properties to an object of one or other class of events, and optimality of the f application is usually measured through the accuracy in which such predictions match the real class of the object. The supervised machine learning approach is based on the existence of previously classified events, or training dataset, in which such accuracy can be quantified through the usage of a loss function such as cross-entropy [223]. The process of optimization that leads to an optimal classifier f that minimizes the chosen loss function is known as training of the discriminant. The output of the MVA algorithm is then a real number that, upon further normalization, can be interpreted as the predicted probability for a given set of measurements to come from a given class. In the case of the data classification problem presented in this document, classes correspond to signal and background events, and the properties $x_1, \dots, x_n$ to measurable physical properties. The training sets are built with the well identified MC simulations from the background and signal processes.

The modification of the MVA algorithm to make it parametric is rather direct. The set of all possible measurements $\mathcal{I}$ is extended through an additional set $\mathcal{M}$ containing all possible values of a given parameter M that characterizes different realizations of any of the involved classes. Then, the parametric MVA algorithm is defined as

$$\begin{aligned} \hat{f}: \quad \mathcal{I} \times \mathcal{M} &\rightarrow \mathbb{R} \\ \hat{x} = (x_1, \dots, x_n, M) &\rightarrow \hat{f}(x_1, \dots, x_n, M) \end{aligned} \quad (6.4)$$

In case both classes have some dependence on the parameter M , the training process in supervised learning can proceed as usual, using the input quantities obtained from each labelled set. It is of more physical interest, however, the case in which one of the classes depends on the parameter and the other does not. This is the case, for example, of the SMS signals that depend on the SUSY particles masses, while the SM background does not. In this case, the value of the parameter M is randomized for the class where it doesn't have an effect, while its real value is used in the one where it does. If the randomization is done such a way that the distributions of the M parameter across observations from both classes are equal, no direct discrimination appears from this variable, but rather only from its correlation with the rest of the input quantities.

The big difference between the parametric and non-parametric approaches appear at the prediction level. As the underlying parameter is usually unknown, it is in fact of interest to predict it, the prescription is to evaluate the $\hat{f}(x_1, \dots, x_n, M)$ discriminant for all possible values of the parameter M . The restriction of $\hat{f}$ to a fixed value of M acts then as a non-parametric MVA approach. As $\hat{f}$ has at least as most information from each object as a non-parametric approach, the projections of the parametric approach to each value of M are at least as powerful as non parametric discriminants defined for that same fixed value. In reality, where the optimal $\hat{f}$ is obtained through ML techniques, this condition is not necessarily fulfilled due to the finiteness of the training samples and of the inherent limits in convergence of the finiteness of the ML model (such as the limited number of neurons or layers). Thus, those conditions need to be checked carefully to ensure the optimality of the parametric approach.

In ideal conditions, the parametric approach in ML provides the option of simultaneously learn generic features that are common to all signal models, as well as peculiarities typical of specific values of the involved parameters while still profiting from the increased statistical power of the whole signal training dataset.

6.6.5.2 Parametric approach in EWK SUSY

For the case presented in this document, parametric ML is used to separate signal events corresponding to several SMS from the SM background in category $3\ell A$. The signal models considered where the ones whose sensitivity is expected to be dominated by the $3\ell A$ category: $T\chi\chi WZ$ and $T\chi\chi\tilde{\ell}\tilde{\ell}$. As kinematics vary from SMS to SMS, different parametric discriminants are trained for the $T\chi\chi WZ$ scenario and each of the $T\chi\chi\tilde{\ell}\tilde{\ell}$ ones corresponding to the three values of the mass parameter x . While the signal models are parametrized in the values of $M_{\chi_1^\pm}$ and $M_{\chi_1^0}$, it was found that the difference between the two masses $\delta M = M_{\chi_1^\pm} - M_{\chi_1^0}$ encoded the most part of the signal kinematic properties and so could be used as a single input parameter of the trainings. The other input variables correspond to known signal sensitive ones used already in the $3\ell A$ category:

- The p_T^{miss} as used in the SR strategy definition.

- **The $M(\ell\ell)$** as used in the SR strategy definition.
- **The M_T^W** as used in the SR strategy definition.
- **The $M_T^{3\ell}$** as used in the SR strategy definition.
- **The H_T** as used in the SR strategy definition.
- **The total leptonic energy (L_T)**: is defined as the scalar sum of the p_T of the final state leptons. It is expected to provide sensitivity to very uncompressed signal scenarios where the boost introduced into the leptonic system due to the $\chi_1^\pm$ mass produces high values of L_T on signal events.
- **The invariant mass of the three lepton system ($M(\ell\ell\ell)$)**: which is a further probe of the overall energy of the system, again sensitive to the presence of highly boosted leptons in the uncompressed signal scenarios.

Alternative trainings performed with low level information corresponding to the full lepton and jet four-momenta provided little to no improvement in the final discriminator performances and so was discarded for the final result in favour of this simplified approach.

The training was performed for each of the four SMS models separately using the TENSORFLOW framework [224] through the KERAS interface [225]. Parametric neural networks are used with four to six hidden layers containing between 128 and 512 nodes per layer depending on the model. To reduce the presence of overtraining problems in the network training, the dropout technique [226] is used, with 30% of the nodes of each neural network layer dropped randomly in each step of the minimization algorithm. The minimization itself is done using stochastic minimization through the usage of the Adam optimizer [227].

The optimality of the resulting parametric neural network discriminants is checked in two different ways. First, alternative non-parametric trainings are performed for each value of the parameter are performed and compared with the results obtained from the parametric approach for the same signals in order to assess possible losses of performance due to the parametric training. The training samples have a limited granularity in δM so it is also checked that the parametric approach has enough information to extrapolate the information from nearby regions included in the training sample to possible signal configurations unseen by the training. This second check is performed by training alternative PNNs in which signals with a chosen value of δM are excluded from the training sample and comparing the resulting performance of these PNNs the non-parametric ones at the same values of the parameter.

The results of the validity checks are shown in Figure 6.23 for the $T_{\chi\chi WZ}$ and $T_{\chi\chi\tilde{\ell}\tilde{\ell}}$ ($x = 0.5$) models. For both comparisons, several repetitions of the trainings are performed varying the network structure and minimization parameters in order to assess the possible effects of non-optimality arising from an incorrect setup of the NN training configuration. The comparisons are done in terms of the area under curve (AUC) quantity computed over all signal events at the given δM value and the background contributions in the $3\ell A$ category. The nominal PNN approach is found to perform equal to or better than the non parametric one, ensuring its apparent optimality. At the same time, the dedicated non parametric training perform similarly than the one

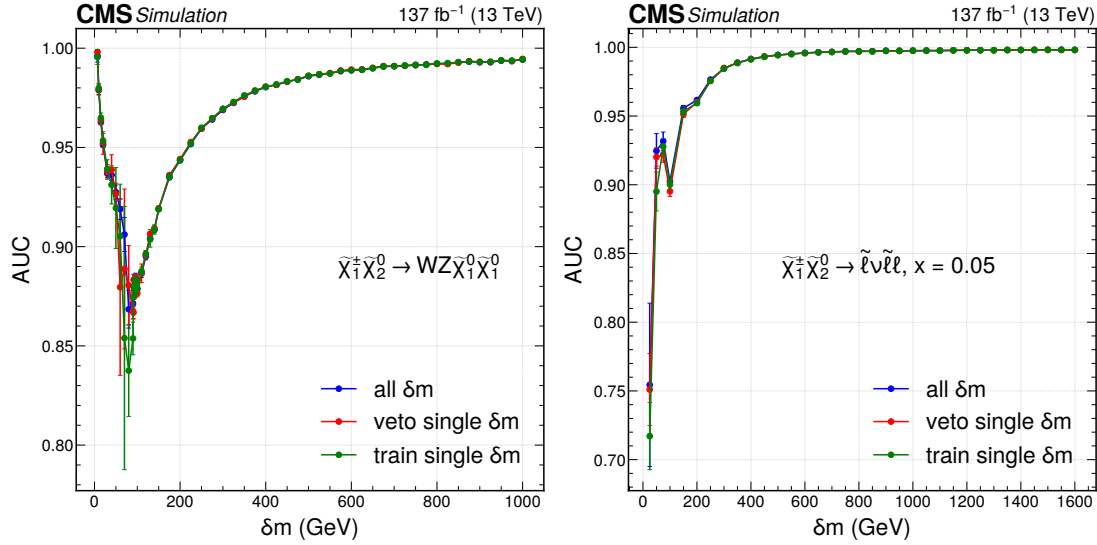


FIGURE 6.23: Checks on the validity of the neural network approach as a function of the δM parameter for the $T\chi\chi WZ$ and $T\chi\chi\ell\ell$ ($x = 0.05$) signal models. The AUC is compared for each δM value between the nominal PNN training (blue), a non parametric NN trained with signals at the given value of δM (green), and a PNN approach excluding the signals with the given δM value from its training (red).

that veto specific values of δM in the training, ensuring the capability of the parametric training to extrapolate the results towards regions of the signal parameter space unseen by the training.

6.6.5.3 Results of the parametric strategy

As discussed in Section 6.6.5.1, the parametric approach produces a different discriminant for each value of the parameter. As four different PNNs are trained and each of the signal models has around 60 different possible values of the δM parameter. This means that more than 200 different distributions are produced by the PNN for the signal extraction procedure. For each of the signal models, the distribution corresponding to its production scenario and δM value is used to perform the signal extraction procedure described in Section 6.7.

The output discriminants are binned in an objective way by requesting that the last of the PNN discriminant bins contains exactly 1 background event in the 2016 data taking year, with each of the previous bins having twice the expected background yields. This way, a distribution of naturally growing signal presence is built which still ensures a minimal statistical power in the latest discriminant bins while the first set of bins of the discriminant are signal-depleted enough to constrain the biggest of the background related uncertainties in the signal extraction fits. For brevity, only several of the most representative PNN distributions are shown in Figure 6.24.

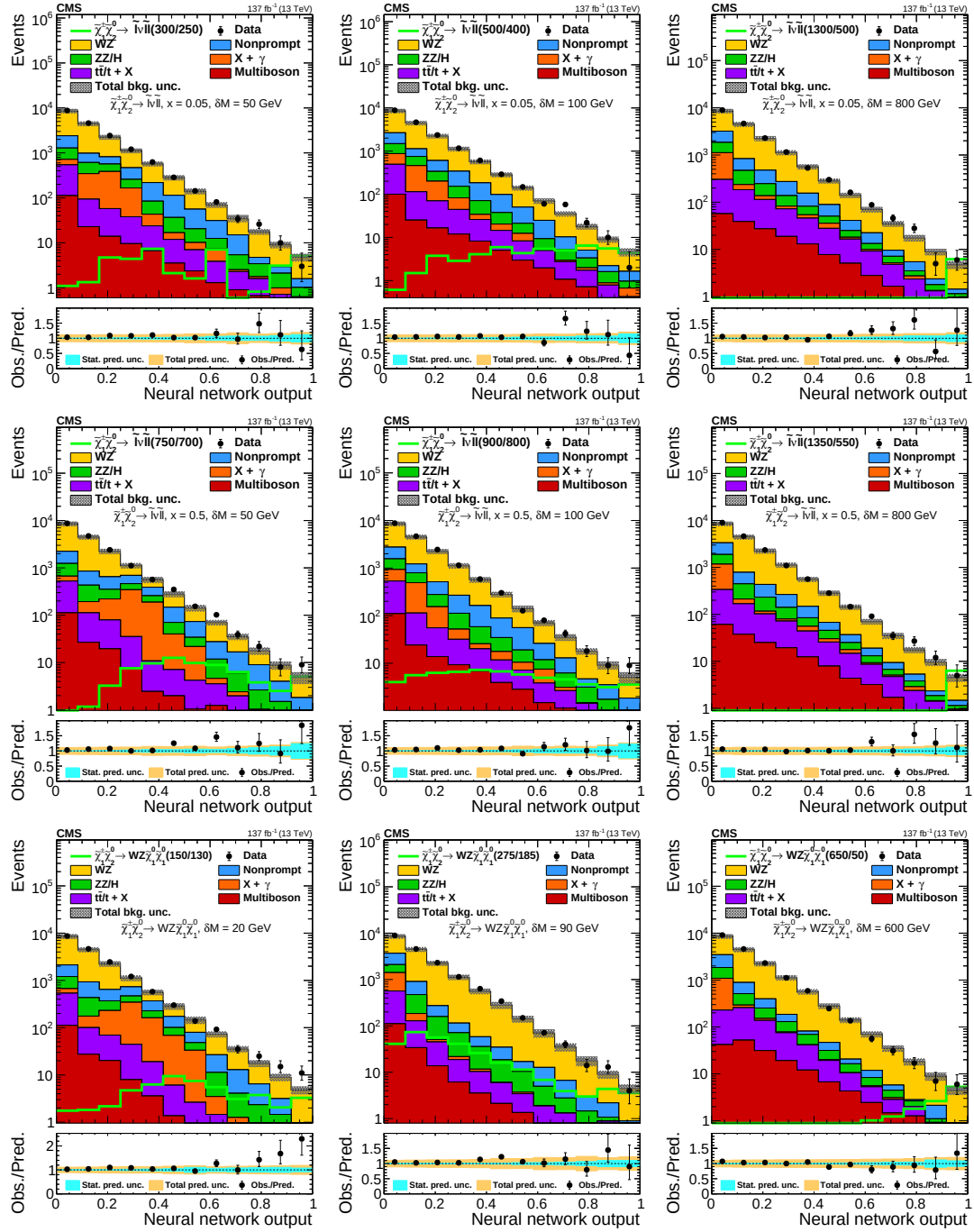


FIGURE 6.24: Expected and observed distribution of events for the PNN discriminants evaluated for several significant values of δM in the $T\chi\chi\ell\ell$ and $T\chi\chi\ell\bar{\ell}$ scenarios. From top to bottom and left to right: $T\chi\chi\ell\bar{\ell}$ with $x = 0.05$ and $\delta M = 50$ GeV (top left), $T\chi\chi\ell\bar{\ell}$ with $x = 0.05$ and $\delta M = 100$ GeV (top middle), $T\chi\chi\ell\bar{\ell}$ with $x = 0.05$ and $\delta M = 800$ GeV (top right), $T\chi\chi\ell\bar{\ell}$ with $x = 0.5$ and $\delta M = 50$ GeV (middle left), $T\chi\chi\ell\bar{\ell}$ with $x = 0.5$ and $\delta M = 100$ GeV (middle middle), $T\chi\chi\ell\bar{\ell}$ with $x = 0.5$ and $\delta M = 800$ GeV (middle right), $T\chi\chi WZ$ with $\delta M = 20$ GeV (bottom left), $T\chi\chi WZ$ with $\delta M = 90$ GeV (bottom middle), and $T\chi\chi WZ$ with $\delta M = 600$ GeV (bottom right).

6.7 Interpretations in terms of simplified models

As no significant deviation is found in the signal sensitive distributions shown through Section 6.6, the observed data is interpreted to set exclusion upper limits on the SMS introduced in Section 6.1.1 following the description of the method discussed in Section 4.6.3. As discussed in Section 6.2, not all categories are sensitive to all possible signal scenarios, so which data is used on each interpretation is restricted to the cases where non negligible sensitivity is expected. On each analysis category and for each signal model at a fixed value of its parameters, a likelihood function is built across all SR bins in the category, following the description of Equation 4.16. Different categories are combined by multiplying their associated likelihoods.

The overall strategy for the upper limit setting, indicating which categories are used for which model, is summarized in Table 6.16. In cases where both the SR and NN signal extraction approaches were available in the $3\ell A$ category, both were combined separately with the cut-based signal region approach performed in the rest of the $2\ell SS$ region to provide the final interpretation. In all the cases, exclusion upper limits at the 95% CL, using the CL_s criteria, are set for various values of the parameters in each of the signal scenarios. The asymptotic approximation for the exclusion upper limit presented in Equation 4.24 is used to improve the speed of the computation. It was cross-checked for two to three parameter values on each SMS that the result is consistent with the one provided by a full computation of the distribution of the q_μ statistic through the usage of toy pseudodata.

6.7.1 Chargino–neutralino production with decays to light sleptons

The first set of models correspond to those including $\chi_1^\pm \chi_2^0$ production and decay through the presence of light sleptons.

The results from the $T\chi\chi\tilde{\ell}\tilde{\ell}$ scenario are shown in Figure 6.25, including a comparison of the results obtained with both the SR (blue) and the NN (red) approaches to the signal extraction. The region excluded in the 2016 analysis is included in all figures in green in order to provide a baseline comparison to estimate the improvements introduced by the studies presented in this document. In the purely SR based approach, which was followed by both the 2016–only and full Run 2 results, improvements of around 200 GeV $M_{\chi_1^\pm}$ and 300 GeV in $M_{\chi_1^0}$ appear. The effects correspond to signal cross sections up to 3.3 times smaller being excluded by the analysis, significantly over the factor 2 that would be obtained with a direct recast of the original analysis just by using the increased quantity of data. The improvements originate from the optimization of the SR strategy as well as an overall reduction in most background related uncertainties, most notably that of the WZ background estimation which has a sizeable effect on both the $2\ell SS$ and $3\ell A$ regions.

The inclusion of the NN discriminant further improves the results provided by the SR approach by 50 GeV to 150 GeV in $M_{\chi_1^\pm}$ and 100 GeV in $M_{\chi_1^0}$, corresponding to cross sections between 2 and 5 times smaller being excluded. The effects is more strongly seen in the uncompressed regions of high δM value, where the $3\ell A$ category dominates the sensitivity, as in the compressed regions of low δM the results are driven by the $2\ell SS$ category. In the $x = 0.5$ case, as the $2\ell SS$ category loses sensitivity

Model	Categories used	Figure	Feynman diagram
$T_{\chi\chi\tilde{\ell}\tilde{\ell}}$	$2\ell\text{SS}, 3\ell\text{A}$ (search regions and neural network fit separately)	6.25	
$T_{\chi\chi\tilde{\tau}\tilde{\ell}}$	$3\ell\text{A}-3\ell\text{F}$	6.26	
$T_{\chi\chi\tilde{\tau}\tilde{\tau}}$	$3\ell\text{B}-3\ell\text{F}$	6.27	
$T_{\chi\chi\text{WH}}$	$2\ell\text{SS}, 3\ell\text{A}-3\ell\text{F}$	6.28	
$T_{\chi\chi\text{WZ}}$	$2\ell\text{SS}, 3\ell\text{A}$ (search regions and neural network fit separately)	6.29	
$T_{\chi\chi\text{ZZ}}$	$2\ell\text{SS}, 3\ell\text{A}-3\ell\text{F}, 4\ell\text{G}-4\ell\text{K}$	6.30	
$T_{\chi\chi\text{HZ}}$	$2\ell\text{SS}, 3\ell\text{A}-3\ell\text{F}, 4\ell\text{G}-4\ell\text{K}$	6.30	
$T_{\chi\chi\text{HH}}$	$2\ell\text{SS}, 3\ell\text{A}-3\ell\text{F}, 4\ell\text{G}-4\ell\text{K}$	6.30	

TABLE 6.16: Summary of the event categories used for the interpretation of the results in terms of different models, leading-order Feynman diagrams of the associated models, and references to the figure summarizing the expected and observed 95% CL upper limits.

slightly due to the relative less presence of low p_T missing leptons, the NN approach provides improvements up to much lower values of the δM parameter. The most strict exclusion corresponds to the signals with $M_{\chi_1^\pm} = 1500$ GeV in the $x = 0.95$ scenario, with a cross section of 0.08 fb.

Results obtained in the $T\chi\chi\tilde{\tau}\tilde{\ell}$ scenario are shown in Figure 6.26 for all three possible values of the mass splitting parameter x . The redefinition of the signal extraction strategy on the $3\ell A-3\ell E$ categories provided significant gains in the most uncompressed regions of the models with $x = 0.05$ and $x = 0.95$. In the case of $x = 0.5$, the results provide the exclusion of cross sections up to 2 times smaller than the results obtained in 2016, a direct scaling with the available luminosity. For the cases of $x = 0.05$ and $x = 0.95$ the gain is much clear, up to a factor 3 increase in the cross sections of the excluded models thanks to the redefinition of several signal regions to target more compressed scenarios in detriment of the most uncompressed ones. This same phenomena is seen at the shapes of the exclusion curve, where greater improvements are seen at the regions of lower δM values (more compressed scenarios) in detriment of those with high δM , corresponding to the uncompressed ones. The excluded regions are expanded up to 100 GeV in $M_{\chi_1^\pm}$ and up to 150 GeV in $M_{\chi_1^0}$.

Finally, the interpretations in terms of the $T\chi\chi\tilde{\tau}\tilde{\tau}$ models are included in Figure 6.27 for all three values of the mass splitting parameter x . The sensitivity to the scenarios with $x = 0.05$ and $x = 0.95$ where deemed to be too small to provide an exclusion result in the 2016 result, due to the limited range of final states with τ_h in the most compressed scenarios as low p_T τ_h candidates are difficult to reconstruct efficiently. Thus, the following results correspond to the first time these models are tested by the CMS collaboration at the 13 TeV energy regime.

Significant improvements are shown for the $x = 0.5$ model which was included in the original 2016 interpretation, up to a factor 6 lower cross sections are excluded in comparison with the 2016 results. The improvements are strongly driven by the $3\ell D-3\ell F$ reoptimized categories and the more precise estimation of the nonprompt τ_h background. The results improve the overall reach in 350 GeV for $M_{\chi_1^\pm}$ and 150 GeV for $M_{\chi_1^0}$ for $x = 0.5$, and set the first exclusion limits for $x = 0.05$ and $x = 0.95$ at values of around 800 GeV for $M_{\chi_1^\pm}$ and 200 GeV for $M_{\chi_1^0}$.

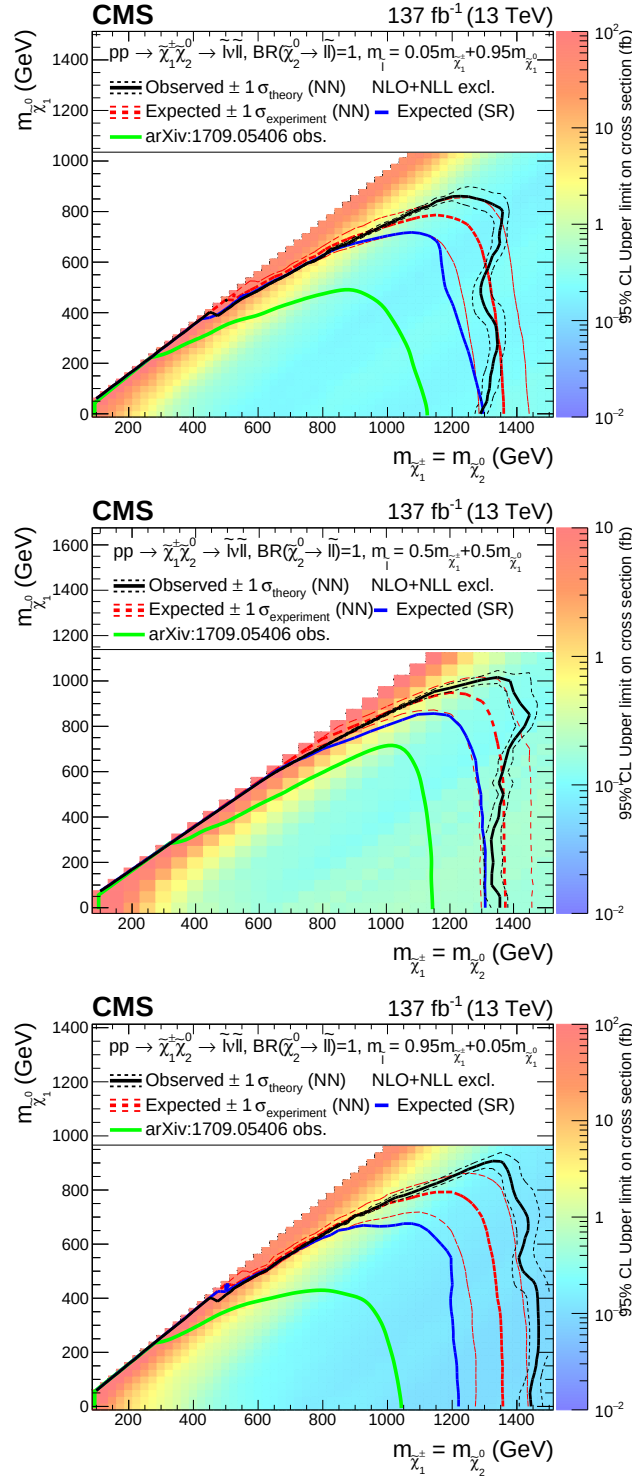


FIGURE 6.25: Interpretations of the results obtained in categories $2\ell SS$ and $3\ell A$ in terms of upper bounds in the cross section of the $T\chi\chi\tilde{\ell}\tilde{\ell}$ simplified model as a function of $M_{\chi_2^0}$ and $M_{\chi_1^\pm}$. The observed (expected) excluded region at a 95% CL is delimited by a full black (red) line for the analysis using the parametric NN with the whole Run 2 data. The green line corresponds to the same interpretation performed with the 2016 only result. The expected results of the analysis using the SR approach are shown in the blue curve. The coloured background contains the upper limit at a 95% CL on the cross section for each individual configuration of the mass parameters. Several mass splitting parameters are considered: $x = 0.05$ (top), $x = 0.5$ (middle), and $x = 0.95$ (bottom).

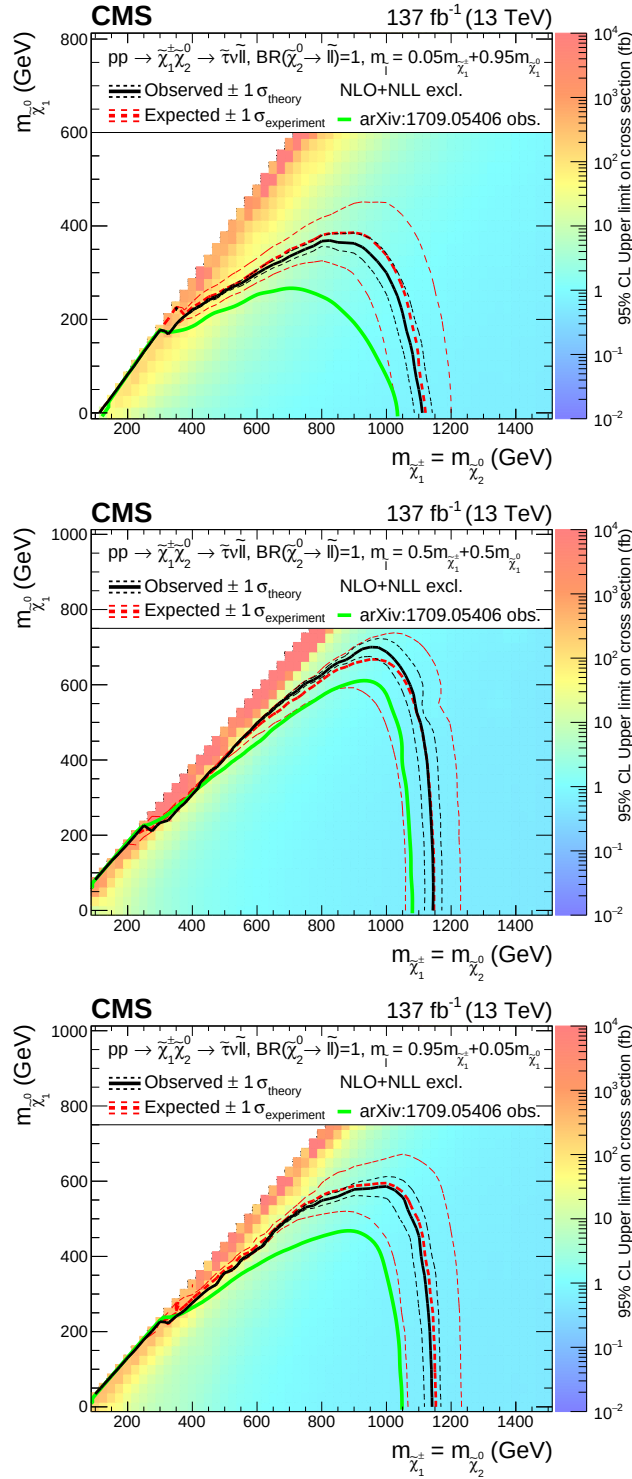


FIGURE 6.26: Interpretations of the results obtained in categories 3lA–3lF in terms of upper bounds in the cross section of the $T\chi\chi\tilde{\tau}\bar{\ell}$ simplified model. The contents of the figure are analogous to those described for Figure 6.25.

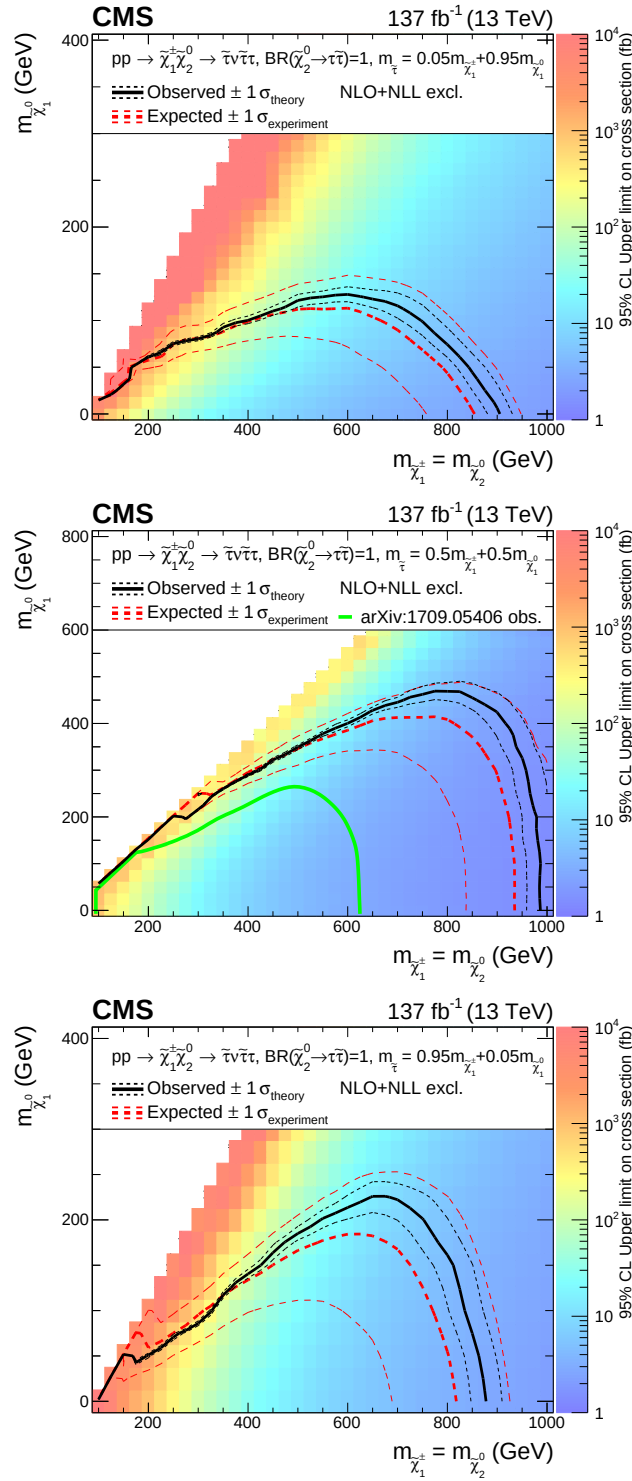


FIGURE 6.27: Interpretations of the results obtained in categories 3ℓB–3ℓF in terms of upper bounds in the cross section of the $T\chi\chi\tilde{\tau}\tilde{\tau}$ simplified model as a function of $M_{\tilde{\chi}_2^0}$ and $M_{\tilde{\chi}_1^\pm}$. The observed (expected) excluded region at a 95% CL is delimited by a full black (red) line with the whole Run 2 data. The green line corresponds to the same interpretation performed with the 2016 only result which only included the $x = 0.5$ mass splitting case. The coloured background contains the upper limit at a 95% CL on the cross section for each individual configuration of the mass parameters. Several mass splitting parameters are considered: $x = 0.05$ (top), $x = 0.5$ (middle), and $x = 0.95$ (bottom).

6.7.2 Chargino–neutralino production with decays to SM bosons

Interpretations in terms of the $T\chi\chi WH$ model are shown in Figure 6.28. The measurements are strongly limited by the low branching fraction of the H boson to multileptonic final state, but nonetheless improve significantly what was obtained in the 2016 analysis. The improvements can be quantified as a 125 GeV increase in the $M_{\chi_1^\pm}$ and 50 GeV increase in the $M_{\chi_1^0}$ exclusions. While it might seem small in comparison with those introduced before, the expected cross sections vary quite quickly at these mass scales, with the overall improvement in terms of excluded cross sections being around a factor 8.

The exclusion itself is strongly driven by the $3\ell B$ category which was repurposed in this analysis to specifically target final states similar to those produced in this signal model. The small excess of data seen in the first SR of $3\ell B$ is responsible for the slightly lower observed exclusion with respect to the expected one, but the overall results show reasonable agreement within one standard deviation.

The interpretation of the $T\chi\chi WZ$ models is one of the most notable results of the analysis and is shown in Figure 6.29. As in the case of the $T\chi\chi\tilde{\ell}\tilde{\ell}$ model, both the SR and NN approach are shown in the same figure to compare the performance of both. In both cases, the dedicated study of the WZ background uncertainties and the overall optimization of the signal strategies have resulted in a very clear improvement in the challenging region corresponding to $\delta M = 90$ GeV, which presented a big gap in the excluded region in the 2016 analysis. While the gap is not completely closed, the results of both approaches point towards the absence of BSM physics in this region, covering one of the main remaining gaps in the overall exclusion provided by the CMS collaboration.

In terms of exclusion performance, the improvements are very clear in the more uncompressed region, where the reoptimization of the SR approach and the reduced set of uncertainties related to the WZ background provide an improvement of roughly 200 GeV in the $M_{\chi_1^\pm}$ exclusion. Similarly, the more compressed regions show improvements of around 150 GeV in the excluded $M_{\chi_1^0}$ values. The overall improvement in the size of excluded cross sections is of around a factor 5.

The addition of the NN strategy on top of the previous improvements proves to be more noticeable in the more uncompressed scenarios and close to the $\delta M = 90$ GeV gap region, where between 50 GeV worth of exclusion are introduced over the SR approach. This corresponds to cross sections roughly 1.8 times smaller being excluded by the NN strategy. Again, at the most compressed regions of $\delta M < 50$ GeV, the differences between the NN and SR approach are negligible as the exclusion is completely driven by the results from the $2\ell SS$ category.

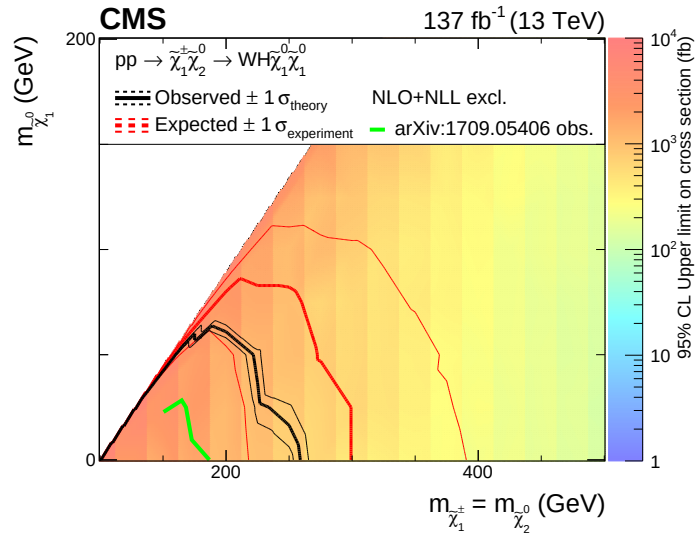


FIGURE 6.28: Interpretations of the results obtained in categories 2 ℓ SS and 3 ℓ A–3 ℓ F in terms of upper bounds in the cross section of the $T\chi\chi WH$ simplified model as a function of $M_{\tilde{\chi}_2^0}$ and $M_{\tilde{\chi}_1^\pm}$. The observed (expected) excluded region at a 95% CL is delimited by a full black (red) line for the analysis with the whole Run 2 data. The green line corresponds to the same interpretation performed with the 2016 only result. The coloured background contains the upper limit at a 95% CL on the cross section for each individual configuration of the mass parameters.

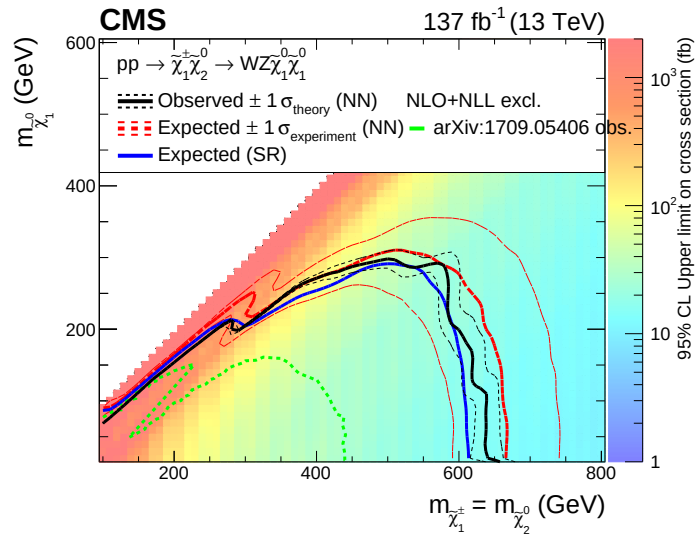


FIGURE 6.29: Interpretations of the results obtained in categories 2 ℓ SS and 3 ℓ A in terms of upper bounds in the cross section of the $T\chi\chi WZ$ simplified model as a function of $M_{\tilde{\chi}_2^0}$ and $M_{\tilde{\chi}_1^\pm}$. The observed (expected) excluded region at a 95% CL is delimited by a full black (red) line for the analysis using the parametric NN with the whole Run 2 data. The green line corresponds to the same interpretation performed with the 2016 only result. The expected results of the analysis using the SR approach are shown in the blue curve. The coloured background contains the upper limit at a 95% CL on the cross section for each individual configuration of the mass parameters.

6.7.3 Neutralino–neutralino production in GMSB models

The last set of signal models considered corresponds to the GMSB higgsino–like neutralino–neutralino pair production. The interpretation of the different results on these set of models is the most complex of the analysis, as they use results of all the categories considered. The results obtained for all three models, depending on the branching ratio $Br(\chi_1^0 \rightarrow Z\tilde{G})$ are shown in Figure 6.30. The whole reoptimization of the signal extraction strategy in categories 4ℓG–4ℓK provides sizeable improvements with respect to the 2016 strategy followed for these cases.

Exclusion limits in the $T\chi\chi HH$ model are driven by categories 4ℓH–4ℓK and improve on the results obtained in 2016 by around 75 GeV in $M_{\chi_1^0}$, corresponding to cross sections roughly a factor 5 smaller than the 2016 analysis expected to be excluded. At low masses a small overall excess is seen, driven by the excesses seen in the first two SR of categories 3ℓB, 4ℓH and 4ℓI, which drives the excluded cross section slightly upward but remains consistent with the expectations at the two standard deviation level.

In the case of the $T\chi\chi HZ$ model, the improvements shown account for roughly 125 GeV more of $M_{\chi_1^0}$ excluded, corresponding to an increase in the reach in cross section around a factor 5 with respect to the 2016 result. Again, the improvement is mostly lead by the new optimized search strategy introduced in categories 4ℓH–4ℓK. The results show a consistent defect at low $M_{\chi_1^0}$ values resulting from the defect observed across categories 4ℓH–4ℓJ in the signal region corresponding to low ΔR values. The observed results, nonetheless, are still consistent with expectations at the two standard deviations level.

The exclusions for the last model, $T\chi\chi ZZ$, are strongly driven by the 4ℓG category, with the apparent defect on its last SR bins being translated on greater observed upper limits than the expected ones. The results are still within one standard deviation from the expectations. An improvement of roughly 150 GeV in the excluded values of $M_{\chi_1^0}$ is shown with respect to the 2016 analysis, around a factor 4 lower cross sections are excluded.

6.7.4 Comparison with other experimental bounds

The main advantage in the usage of the agreed upon simplified models is the possibility of obtaining easy comparisons with searches performed in other final states or experiments that target similar underlying physics. A brief description of the state of the art measurements in electroweakino pair production provides key context for the meaningfulness of the results presented in this document in the broad world of BSM physics searches. Unfortunately, neither the ATLAS, nor the CMS collaborations have published results recently in the light sleptons scenarios, so comparisons with those ones can not be directly made.

The most recent results from the CMS and ATLAS collaborations in the $T\chi\chi WH$ models are presented in Figure 6.31. At first glance, it is clear that both collaborations have significantly similar reach in for the model presented, and that the multileptonic final state is not the one offering the greatest sensitivity, in comparison to others such as $1\ell+2b$ jets, due to the low branching fraction of the Higgs boson to multileptonic

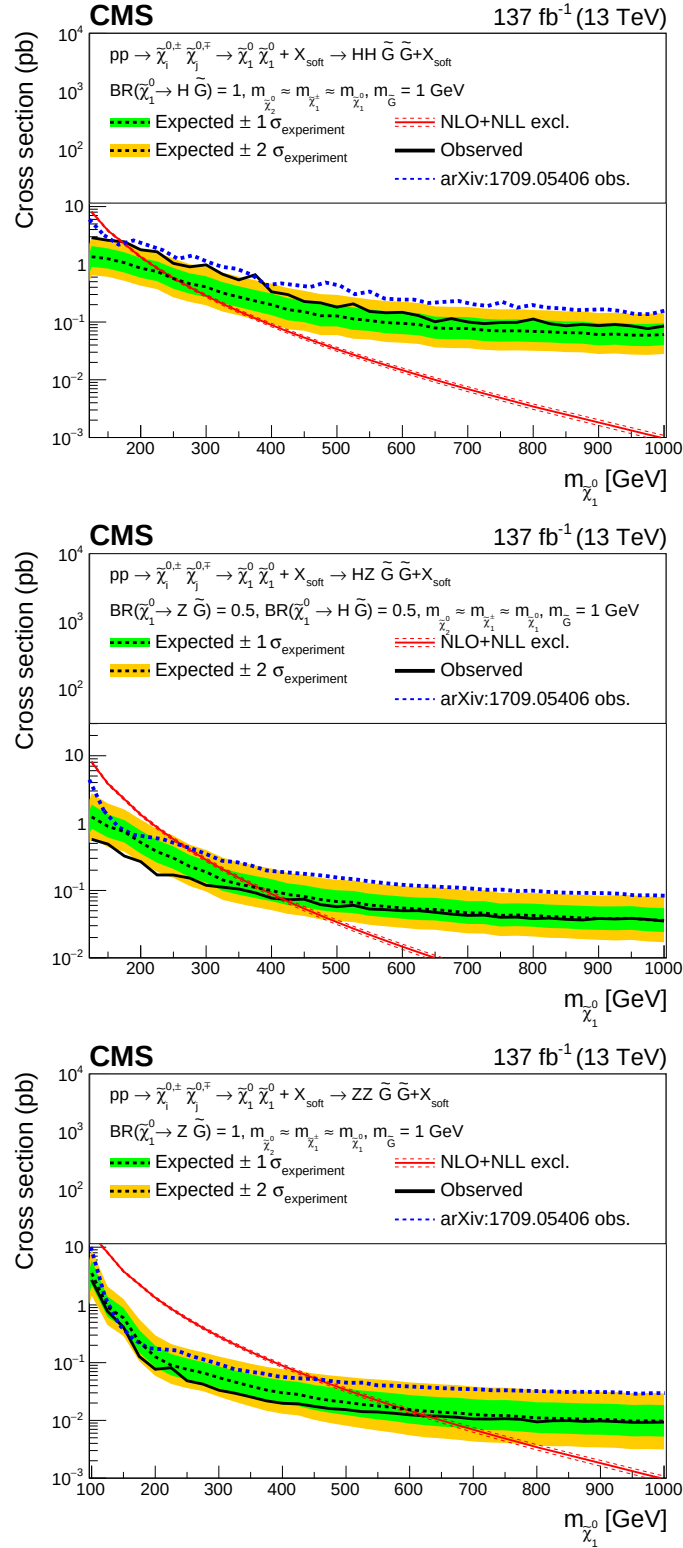


FIGURE 6.30: Interpretations of the results obtained in categories 2 ℓ SS, 3 ℓ A–3 ℓ F, and 4 ℓ G–4 ℓ K in terms of upper bounds in the cross section of several GMSB simplified models as a function of $M_{\chi_1^0}$. Observed (expected) upper limits are shown in a full (dotted) black line for the analysis with the whole Run 2 data. The dotted blue line corresponds to the same interpretation performed with the 2016 only result. The current best predictions for the cross sections of these simplified models are shown in the red curve. The green (yellow) bands correspond to the expected ± 1 standard deviation (± 2) quantiles. From top to bottom: $T_{\chi\chi HH}$ (top), $T_{\chi\chi HZ}$ (middle), and $T_{\chi\chi ZZ}$ (bottom) simplified models.

final states. A comparison could be drawn between the two multileptonic results, the one described in this region and that introduced by the ATLAS collaboration in [228], but the results are not completely fair as the later does not include final states with reconstructed τ_h , thus reducing its reach by about 50-75 GeV (around a factor 2 in cross section). The combination of the multileptonic result with other CMS measurements could still provide some complementary sensitivity at the most compressed scenarios, improving slightly the overall results there.

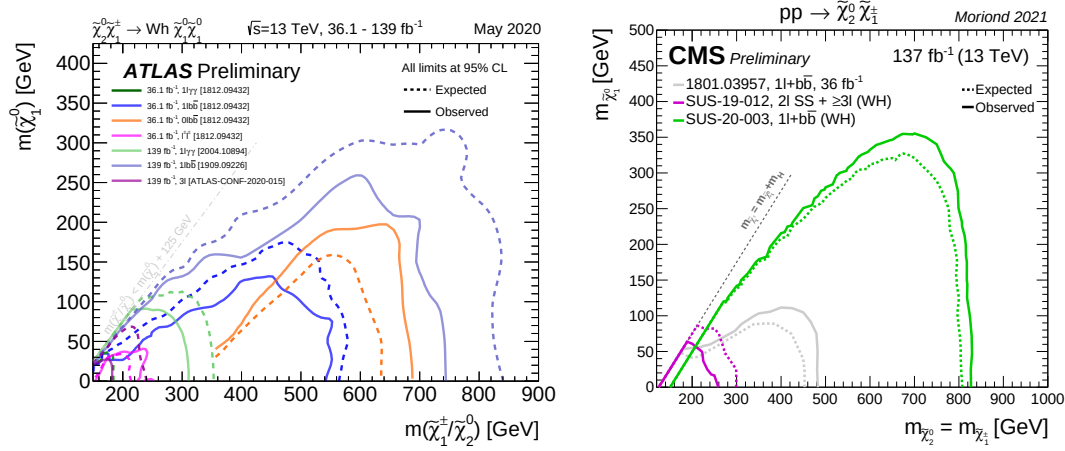


FIGURE 6.31: Summary of the exclusion limits in the $T\chi\chi WH$ models obtained from both the ATLAS (left) and CMS (right) collaborations. The ATLAS collaboration summary plots are taken from Reference [193], while the CMS collaboration summary plots are taken from Reference [194]. The analysis presented in this document is shown in purple on the right plot, while the recent analogous result from the ATLAS collaboration, [228], is shown in dark purple in the left one.

The most recent results from the CMS and ATLAS collaborations in the $T\chi\chi WZ$ models are presented in Figure 6.32. Comparing across final states, clear complementarity can be shown between the multilepton analysis described in this document (red curve), the two OSSF lepton pair analysis (blue curve, [197]) dominant at the most uncompressed scenarios, and the one targetting soft leptons (black curve, [201]) which prevails at lower mass splittings. The combination of results from the three analysis is expected to bring further sensitivity across the board and close the small gaps found between the different final states.

The ATLAS collaboration results in yellow correspond to an envelope of the results with two soft light leptons [201] and three light leptons [228], so a comparison can be drawn with the envelope of CMS results shown in the right plot in red (multileptons, discussed in this document) and black (soft leptons, [196]). The reach is actually pretty similar, although the ATLAS results still present a significant gap in the exclusion region between $\delta M = m_Z^{PDG}$ and $\delta M = m_H^{PDG}$ which has been mostly closed by the CMS results. Otherwise, the transition region around $\delta M = 50$ GeV between the soft leptons and multileptonic analysis seems to be better covered by the ATLAS experiment, which would justify the combination of results across the different final states by the CMS collaboration as well.

Finally, the results from the ATLAS collaboration in the GMSB signal models are shown in Figure 6.33, which includes a full scan of the branching fraction $Br(\chi_1^0 \rightarrow$

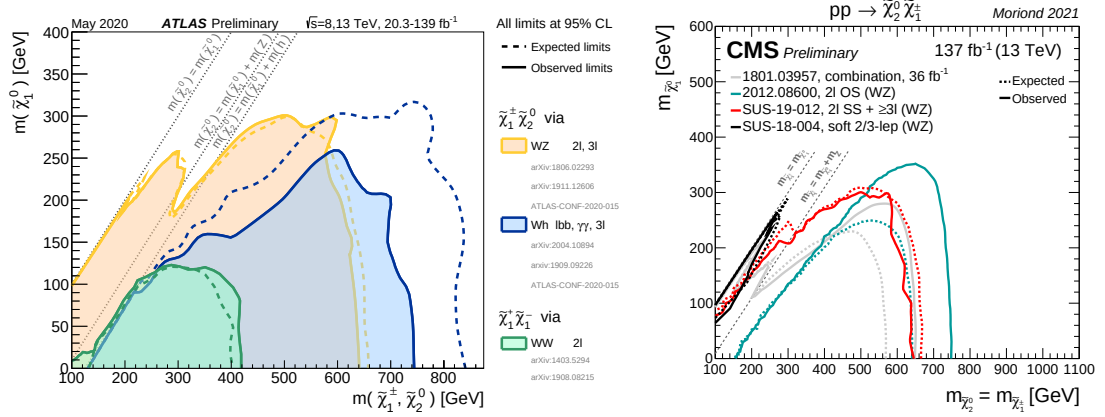


FIGURE 6.32: Summary of the exclusion limits in the $T\chi\chi WZ$ models obtained from both the ATLAS (left) and CMS (right) collaborations. The ATLAS collaboration summary plots are taken from Reference [193], while the CMS collaboration summary plots are taken from Reference [194]. The analysis presented in this document is shown in red on the right plot. Results in green and blue from the ATLAS collaboration correspond to different simplified models.

$Z\tilde{G}$) rather than the three projections at 0, 0.5 and 1 presented in Figure 6.30. Nonetheless, a somehow direct comparison between the analysis shown in orange, [199], involving final states with four leptons including τ_h candidates, and the results presented here can be drawn. The results of the ATLAS collaboration lack the usage of final states with three or less leptons and tend to be slightly worse than those provided in this document by a range of around 50 GeV in excluded mass. It is clear, nonetheless, that neither multileptonic analysis will have the reach attained by channels targeting the channels with higher branching fractions of the Higgs boson, such as the $4b$ final state presented in blue, but combination of final states might still provide some opportunities at regions close to the $T\chi\chi HZ$ scenario introduced in this document.

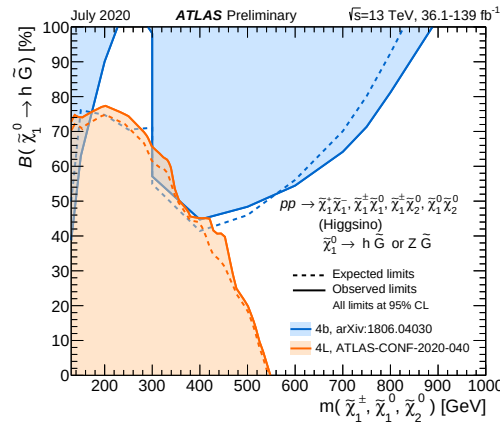


FIGURE 6.33: Summary of the exclusion limits in the GMSB signal models obtained from both the ATLAS collaborations. The plot is taken from Reference [193]. The results presented in Figure 6.30 correspond to slices of the plot at branching ratios of 0, 0.5 and 1. The ATLAS result analogous to the ones presented in this document is shown in orange [199].

6.8 Summary

A detailed search for electroweak SUSY production in multileptonic final states at a centre of mass energy of 13 TeV has been performed using 137 fb^{-1} of data obtained with the CMS detector. Final states that include between two and four leptons, including different combinations of reconstructed electrons, muons, and hadronically decaying τ leptons, were scrutinized. Several sensitive SR were defined inspired by the expected behaviour of several SMS models for electroweak SUSY production in each of the considered final states. For the final state with three light leptons including a pair of opposite sign and same flavour, an additional discriminant based on parametric neural networks was used in order to maximize the sensitivity of the analysis to the presence of a broad range of new physics. No significant excess of data that could be attributed to the presence of a SUSY signal was found in any of the explored SR or the different bins of the PNN distributions.

The obtained distributions were interpreted to set exclusion upper limits in different signal production scenarios corresponding to various values of the masses of electroweakinos and sleptons, as well as different assumptions on the decays of the electroweakinos. The results were further compared with those obtained in the 2016 analysis with 36 fb^{-1} of data to provide an idea of the increase in the analysis reach due to both the greater statistical power of the Run 2 dataset and the effect of the improvements introduced to the analysis since the publication of that result.

In simplified models for which the sleptons have smaller masses than the electroweakinos, and so the later can decay through the former, interpretations are performed in several scenarios depending on the chirality of the low mass sleptons and its couplings to the electroweakinos. Limits on the $\chi_1^\pm$ and χ_2^0 masses of up to 1400 GeV, the most stringent limits on the $M_{\chi_1^\pm}$ and $M_{\chi_2^0}$ parameters to date, are set.

For cases in which the sleptons are too heavy and the $\chi_1^\pm$ and χ_2^0 decay to SM bosons, interpretations are provided for the $T\chi\chi WZ$ and $T\chi\chi WH$ models. The results on the $T\chi\chi WZ$ provide a noticeable improvement of the ones of the previous iterations and are able to cover the challenging region with $\delta M = 90 \text{ GeV}$, for which all previous results from the CMS and ATLAS collaborations showed a gap in the exclusion region due to the complication of separating the corresponding SUSY signals from the SM WZ background.

A final set of interpretations are performed in models of Higgsino pair production and decay in gauge mediated SUSY breaking. The excluded cross section values improve up to a factor of 5 with respect to the previous iterations of these searches.

Muon reconstruction at the L1 trigger during the Phase II of the LHC

In previous chapters, data from the Run 2 of the LHC has proven to be extremely useful in deepening our understanding of the properties of the SM, as well as in the search for new physics. Still, this data has limitations on its reach towards some challenging scenarios consisting on exceedingly rare processes, with very low cross sections, or those with complex non standard signatures that the usual reconstruction algorithms tend to be inefficient for. Future data taking by the LHC experiments and the improvement of the capabilities of the different detectors are crucial to improve the precision of the SM measurements and reach new highs of discovery potential in the CMS experiment.

The current plan for the LHC schedule includes the production of pp collisions during the next three years (2022–2024) in an slightly more intense setup than the conditions at the end of the Run 2 in terms of instantaneous luminosity and average pileup. A total of 300 fb^{-1} of data are expected to be available by the end of this Run 3 of the LHC. After three additional years of no collision data taking (long shutdown 3, LS3), at the end of 2027 the Phase II of the LHC is expected to start and last until the mid-late 2030s. The Phase II of the LHC is expected to be characterized by a significant increase in the instantaneous luminosity provided by the collider, around a factor of 5 more than that of the Run 2. As a result, a high total luminosity of more than 3000 fb^{-1} is expected to be available at the end of this period, more than 20 times what was available for this thesis, motivating the sobriquet of High-Luminosity LHC (HL-LHC) for this running period. Additionally, the proton beam energy is expected to be upgraded to 7 TeV per beam, for a centre of mass energy of $\sqrt{s} = 14 \text{ TeV}$, a crucial point in pushing the sensitivity to BSM physics scenarios in this data. A depiction of the LHC plans in the following years is presented in Figure 7.1.

With the HL-LHC runs having 140 average pileup interactions as the new norm, detector hardware will need to be upgraded in order to cope with both the higher irradiation environment and to be able to efficiently process the increased amount of interactions without a loss in overall efficiency. In hand with the detector upgrade, the reconstruction software will need to be updated as well at both the triggering and offline reconstruction levels. In the case of the former, new algorithms will need to

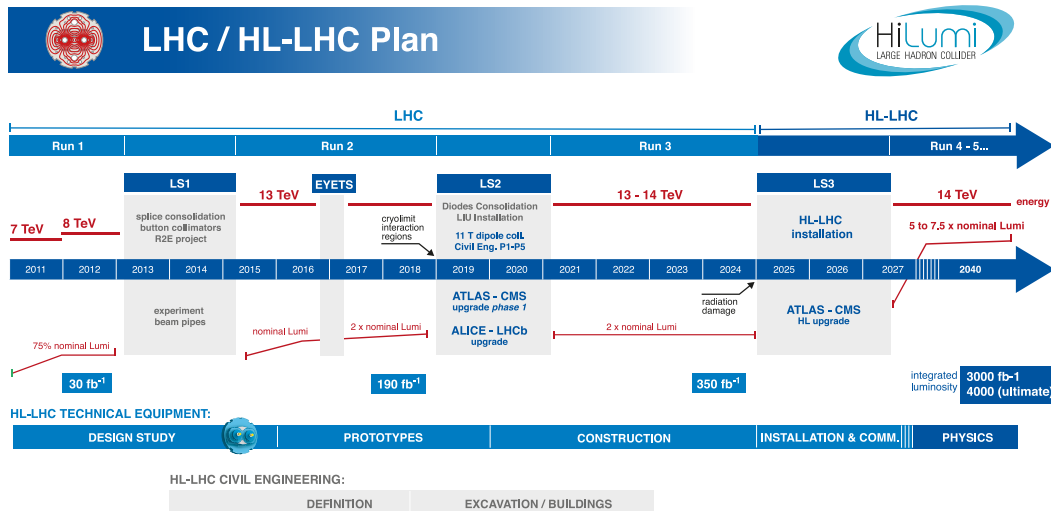


FIGURE 7.1: Originally planned schedule for the LHC operations in the following twenty years. The start of the Run 3 operations was, unfortunately, delayed due to the covid-19 pandemic since the creation of this depiction to the start of 2022.

be developed in order to at least maintain the Run 2 performance metrics without losing the current physics coverage of the CMS experiment. Of course, this upgrading period is also an excellent opportunity for improving this performance and even introducing new capabilities to the trigger system that further expands such physics coverage. These upgrades are expected to be effectively implemented in the CMS experiment during the LS3 non-collision period, but the developing and testing process have already been started way in advance.

This chapter describes the improvements introduced in the L1 trigger system in preparation for the Phase II of the LHC in which I've been involved during the last years. They are dedicated to the triggering of muons, arguably the most relevant reconstructed particle in all the physic studies discussed through this thesis in Chapters 4, 5, and 6, the key component in most traditional multileptonic studies, and a possible probe for some new physics topologies that are relatively unexplored yet by the CMS experiment. Section 7.1 briefly introduces the overall challenges introduced by the HL-LHC and the planned upgrades of the muon spectrometers designed to counteract them. Section 7.3 is dedicated to the algorithms used to reconstruct muons in the L1 trigger at the level of a single DT station, or L1 barrel trigger primitives. Section 7.2 introduces muon track finding algorithms (MTF), the procedure to obtain L1 objects reconstructed across all the muon spectrometers. Section 7.4 briefly summarizes the topics presented.

The results presented have been part of the common effort of the CMS collaboration presented in Reference [13] and further elaborations on top of them that have been made since. Several points related to Reference [229], on which I was not involved, are also included due to their relevance to this work. My contributions to L1 trigger primitives world include the development of a new pattern recognition method for the grouping of hit candidates that are likely to come from a single original muon and the first implementation of a C++ based emulator of the algorithm that fully couples

to the latest steps in trigger primitive reconstruction. In the MTF work I was part of the working group dedicated to the overlap region, covering the transition region between the barrel and the endcap, I worked in the extension of the Run 2 algorithm to the Phase II of the LHC, with the estimates of its capabilities under high pile-up conditions, and of the effects that detector degradation might have on its overall performance. I've also worked on the development of alternative triggering methods in the overlap region targetting the production of long lived particles decaying into muons.

7.1 Challenges of the Phase II of the LHC and the muon detectors upgrade

With the increase of the instantaneous luminosity from the Phase II of the LHC several phenomena will appear with a direct effect on data taking and will need to be addressed:

1. The most direct consequence is the effective increase in the rate of collisions. If the instantaneous luminosity is multiplied by five, so are the rate at which muons will be produced, **increasing the overall occupancy of all the muon chambers**. As a consequence, the experiment will need to be able to keep up with this increased rate of signals both in the detecting material and in the read-out electronics, which will face an influx of information several times higher than before. The problem is more severe at the trigger level, where it has a twofold effect. First, the rate at which interesting collisions are produced will be increased, meaning that an hypothetical recast of the overall trigger strategy used during the Run 2 would be producing triggering rates several times higher than usual, going beyond the current limits of the whole trigger system. Second, the inputs to the L1 trigger (and down the line the HLT) will increase in size proportionally with the instantaneous luminosity, meaning that the L1 reconstruction will have to deal with a much more complex final state. The L1 latency, the time the L1 algorithms take to analyse and select or discard a bunch crossing, can not be guaranteed to stay at the current levels for most L1 reconstruction algorithms. Keeping the same efficiency and resolution while under these harsher conditions is key to, at least, maintain the physics program of the Run 2 of the LHC.
2. A second significant effect is **detector degradation and failures**. As the Phase II is expected to last for ten or more years, the continuous operation of the different detectors might start to have an effect on their overall performance, with failures of either the detecting mechanism or the readout electronics being more possible as the data taking goes by. Moreover, a increase in the instantaneous luminosity produces an equal increase on the overall radiation received through all of the detector. Subdetectors that do not enjoy from a radiation hard enough build might start to feel the effects of degradation, or ageing, with an increasingly bigger effect as the collision program progresses. A design of the muon systems that is robust against degradation effects is needed to prevent a loss of sensitivity towards the end of the Phase II of the LHC.
3. Last, while not a direct consequence of the new running conditions of the HL-LHC, the upgrade of the detector offers a unique opportunity to prepare it for

new physical signatures, extending the current reach of the CMS detector. With the current searches for BSM physics having yet to produce a hint of new physics, additional modifications of the capabilities of CMS might be favourable to more exotic signatures. For example, the sensitivity to several kind of non-standard signals have been strongly limited by the current triggering capabilities. Possible avenues for new physics, such as displaced muons originating for long-lived signatures that decay far from the beam crossing point [230], or the possibility of detecting minimally interacting heavy stable charged particles (HSCP), which behave like muons but propagate way slower through the detector, would all benefit from dedicated reconstruction algorithms to fully record data corresponding to these possible processes.

Updates to the existing subdetectors, including the readout systems and the electronic components in charge of the L1 reconstruction, are planned in order to address these issues, with slightly different changes introduced in each of the subsystems. One of the most significant upgrades for the purpose of muon triggering is the inclusion of measurements from the tracking system into the L1 inputs, which will allow to mimic the offline reconstruction techniques of global muons, as described in Section 3.2.5.1. As a consequence of the increased amount of information expected from each collision, the L1 budget latency will be increased to roughly $12.5 \mu\text{s}$. While this fact benefits L1 reconstruction through what effectively allowing for more complex algorithms to be run at the L1 trigger, the trade off is the need to keep an already increased quantity of detector information that might overload the capabilities of some or all of the detector electronics.

Of special interest for the discussion of this chapter are the changes that will be introduced inside the DT system. A brief description of the DT subdetector and its distribution into wheels, sectors, and stations was introduced in Section 3.2.3. In the barrel, specifically, the DT cells themselves are expected to keep up with the increased detection rate but the readout and trigger electronics currently situated inside the detector itself (MiniCrates) will be unable to keep with the processing rate and latency of the HL-LHC. Moreover, the MiniCrates have also been found to be susceptible to failures after long times of radiation exposure. The Phase II setup features several radiation hard field programmable gate arrays (FPGA [231]) that will register the timing of a hit inside a DT cell and transmit them to out-of-detector electronics for further processing. In contrast to the Phase I setup, where the building of segments across muon stations was done on-detector, the full reconstruction of L1 candidates will be performed in FPGA cards outside of it. This procedure allows for an easier combination of the inputs from a whole DT station and even from the RPC detectors. The DT cells themselves have been found to be relatively unaffected by ageing processes except on the regions where radiation is harder (see Figure 3.9), at the highest $|\eta|$ wheels ($\text{Wh}\pm 2$) and innermost stations (MB1) due to the proximity to most of the radiation from the beam line. Direct measurements in the GIF++ irradiation facilities show a decreased of the hit detection efficiency down to $\sim 71\%$ in these region of the detector, while they are well above 85% for the rest at the end of the Phase II data taking [232]. This numbers include a safety factor of 2 in the overall taken luminosity, so real figures at the end of data taking might be even more optimistic, but care must be taken so that this effect does not produce a decrease in data quality.

While less relevant for the discussion at hand, the CSC and RPC subsystems will also include upgrade of the detector electronics, with much of the sensitive chambers

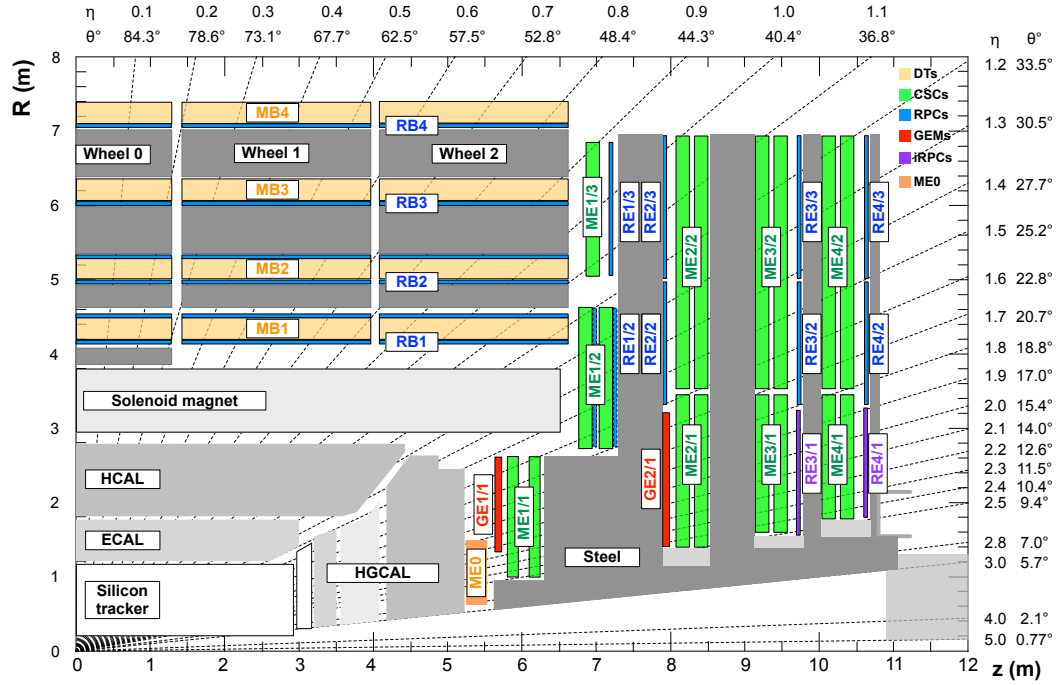


FIGURE 7.2: Schematic view of the CMS experiment with a detailed description of the expected different muon spectrometers and their disposition through the detector after the Phase II upgrade. A cross section of a quarter of the detector in the $R - z$ plane is shown. Non detecting material is shown in dark grey, DT stations are depicted in yellow, CSC rings are shown in green, and the Run 2 RPC layers are presented in blue. The new stations included during the Phase II are the GEM shown in red, and the innermost RPC station (ME0, shown in orange) and outermost RPC stations (RE3/1, RE4/1) shown in purple.

themselves kept as they were being used for the Phase I. Similar irradiation studies performed on the CSCs show that the efficiency loss during the Phase II of the LHC due to ageing is negligible. While the RPC system will suffer no gradual degradation from detector ageing, estimates show that electronic failures might eventually produce the turn off of several of the chambers during data taking. Additional changes in the muon detectors will be the inclusion of new detector layers up to $|\eta| < 2.8$, further extending the physics coverage for muons, with the addition of additional RPC stations and new gas electron multiplier (GEM) detectors. A complete picture of the expected setup of the muon chambers during the Phase II is shown in Figure 7.2 which can be compared with the Run 2 setup of Figure 3.6.

The process of the muon reconstruction at the L1 trigger level for the Phase II of the LHC roughly reproduces the different reconstruction algorithms used already in offline muon reconstruction. A schematic view of the process is shown in Figure 7.3 and can be summarized as follows:

1. Signals from each detector subsystem (DT, RPC, CSC, GEM) are produced. In the DT and CSC subsystem, local segments corresponding to a single station/ring known as Trigger Primitives (TP) are built, optionally including the RPC information for the DT TP building. The information from all subdetectors is standardized into a common data type (stubs) containing quality, timing, and

position (and/or bending) information. The results of this step are akin to the muon segments in the offline reconstruction.

2. The trigger stubs are fed to track reconstruction algorithms known as track finders (TF) which build objects across the whole muon spectrometers combining their information. Three different track finders are considered to account for the peculiarities of the different regions of the detector: the barrel muon track finder (BMTF, $|\eta| < 0.9$), overlap muon track finder (OMTF, $0.8 < |\eta| < 1.2$) and endcap muon track finder (EMTF, $|\eta| > 1.1$). The results from the TFs are akin to standalone muons in the offline reconstruction.
3. The output from the TF and all the stubs are combined with the L1 tracks obtained from the tracking system into the global muon trigger (GMT) algorithm. Two correlators combine the information from the L1 tracks and the muon spectrometers to produce Track+Stub candidates (similar to the offline tracker muons), or Track+TF candidates (similar to the offline global muons). The joint set of TF, Track+Stub, and Track+TF candidates are sent to the global trigger which makes the ultimate selection decision.

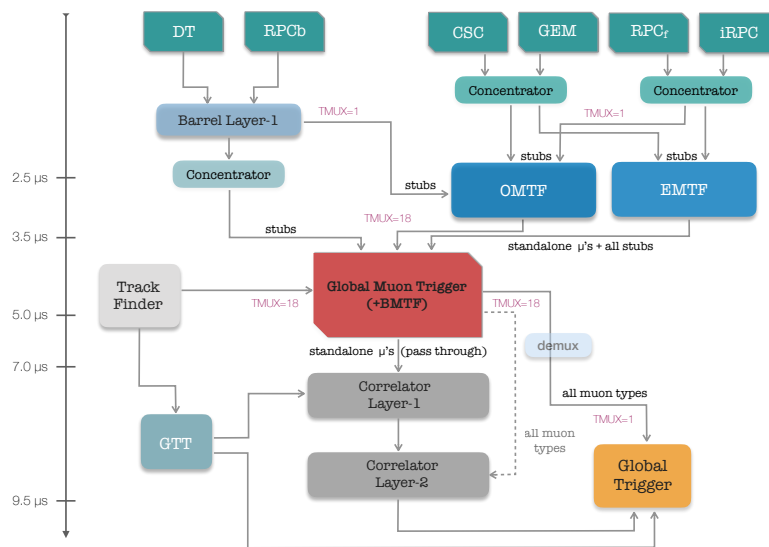


FIGURE 7.3: Schematic view of the muon trigger for the Phase II of the LHC, the expected accumulated latency after each step of the process is shown in the Y axis.

7.2 L1 track finders at the overlap muon region in the CMS experiment

The OMTF, introduced in Section 7.1, is the track finding algorithm that performs the correlation of muon stubs into what amounts to standalone muon tracks inside the muon systems. It is restricted to the overlap region of the detector, formally defined as $0.82 < |\eta| < 1.24$, which includes the transition between the barrel and endcap regions. As such, one of the main challenges for the OMTF algorithm is to fully profit from the highly redundant but inhomogeneous input from the DT, CSC and RPC

systems to provide an overall estimation of the muon track, including a measurement of the muon transverse momentum. The current implementation of the OMTF for the Phase II of the LHC is based on the algorithm used during Run 2 [233] and so it has been proven performant at real data taking situations. The Phase II implementation is optimized for running on the FPGA processors which will be used during the Phase II data taking.

7.2.1 The naïve Bayes classifier in the OMTF

The OMTF reconstruction is based on the usage of a naïve Bayes classifier [234] for the reconstruction of muons at the L1 Trigger. The core concept of a naïve Bayes classifier is quite similar to most machine learning premises. The objective is to classify data in several independent classes $\{P_1, \dots, P_m\}$ based on a set of different observations $l_1, \dots, l_n$. According to Bayes' theorem, there is a relation between the conditional probabilities relating the classes and measurements given by

$$p(P_i|l_1, \dots, l_n) = \frac{p(P_i)p(l_1, \dots, l_n|P_i)}{\sum_{j=1}^m p(l_1, \dots, l_n|P_j)} \rightarrow p(P_i|l_1, \dots, l_n) \propto p(P_i)p(l_1, \dots, l_n|P_i) \quad (7.1)$$

where the denominator can be safely ignored as a global normalization condition for the purposes of the algorithm. The naïve condition is the assumption that all l_j measurements are independent between themselves, in which case the right-hand side conditional probability factorizes:

$$p(l_1, \dots, l_n|P_i) = \prod_{j=1}^n p(l_j|P_i) \quad (7.2)$$

Plugging Equation 7.2 into Equation 7.1, a formula for the probability of class P_i given measurements $l_1, \dots, l_n$ is obtained as

$$p(P_i|l_1, \dots, l_n) \propto p(P_i) \prod_{j=1}^n p(l_j|P_i) \quad (7.3)$$

If suitable priors $p(P_i)$ are chosen, and the conditional probabilities $p(l_j|P_i)$ are known, the posterior probabilities can be compared. The biggest one will correspond to the most likely class given the observed data.

In the OMTF, the input measurements $l_1, \dots, l_n$ are related to the measured ϕ positions of the different input stubs $\phi_1, \dots, \phi_n$. Muons can be produced in any direction and so their initial ϕ is unknown a priori to the algorithm. Thus, the rotational invariance has to be broken by fixing one of the measured hits as the reference hit ϕ_0 , and choosing all the differences of other measurements $\delta(\phi)_l = \phi_l - \phi_0$ as the input quantities $l_1, \dots, l_n$. For the case of the DT TP, for which both estimations of ϕ and $\tan(\phi)$ are provided separately, both quantities are treated as separate measurements, with ϕ_0 not being subtracted from $\tan(\phi)$. Thus, a total of 18 measurements are considered for the algorithm: 3×2 in the three innermost DT stations, the 5 RPC stations surrounding the DTs, 4 CSC rings, and the 3 RPC chambers surrounding the CSCs.

On the OMTF the classes P_i correspond to different ranges in muon p_T , with a thinner binning at the low p_T regime where most differences are seen between the muon tracks for small variations in momenta. As the final ingredient in the Bayes classifier, the probabilities $p(l_j|P_i)$ are encoded into golden patterns. Each golden pattern is represented as a set of 18 discrete histograms (PDFs) containing the proportion of muons in the associated p_T range that are expected to have the associated values of $\delta(\phi)_l$ or $\tan(\phi)$. The histograms are filled in a process that very much resembles supervised machine learning using muons from a muon gun simulation which includes muons with p_T ranging from 2 to 100 GeV. A final modification to reduce the memory consumption of these patterns is applied on the input data by subtracting an additional quantity $\Delta(\phi)_i^{\text{mean}}$ corresponding to the mean value of each of the aforementioned histograms, such that they can be saved with mean 0 and smaller overall numbers to reduce memory consumption. The input measurements in detector layer l for momentum hypothesis i are then $\phi_{dist,l}^i = \phi_l - \phi_0 - \Delta(\phi)_i^{\text{mean}}$. A depiction of all distances involved is shown in Figure 7.4. The prior probabilities $p(P_i)$ are all assumed to be equal.

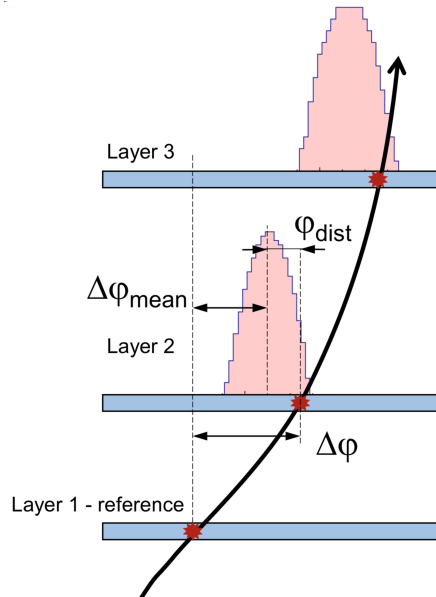


FIGURE 7.4: Schematic view of the input preparation to the OMTF algorithm. The observed hit in the lower layer acts as a reference hit, with the ϕ_{dist} measurement corresponding to the final input to the OMTF algorithm. In red, the expected distributions of hits given the reference (a PDF inside a golden pattern) are shown.

At the evaluation level, the observed set of stubs is first classified, and reference hits are chosen amongst the three DT stations, the two innermost CSC rings and the two RPC stations surrounding the DT MB1. The probabilities for all p_T hypothesis and the four most likely reference hits –in a priority order that favours DT and CSC reference hits over RPC ones– are computed, with stubs that lead to a very low probability in a given case being ignored. The results are then classified for each reference hit based on candidate quality (number of total measurements included in the reconstructed L1 muon), and then the value of the resulting probability $p(P_i|l_1, \dots, l_n)$. A minimal of three measurements in different detector layers are requested to produce an OMTF L1 candidate. The results across different reference hits are compared and, if the estimated ϕ of the muon is found to be compatible the one with higher quality or, if tied, equal probability criteria is chosen as the final L1 muon candidate.

7.2.2 OMTF performance in the Phase II of the LHC

The main objective of the track finding algorithm is the efficient reconstruction of all muons produced inside their associated $|\eta|$ range. However, the HLT of CMS has limited acceptance so the output rate of the track finders need to be carefully controlled as well. Such control is obtained through minimal quality or p_T requirements on the produced L1 candidates. As most of the L1 rate is caused by low momenta muons originating from pileup, moderate requirements in p_T tend to reduce the overall L1 rate dramatically. The trade off is that these requirements introduce already limitations on the physics of the triggering strategy, with collision events with low p_T muons possibly being lost already at the L1 trigger step. Thus, a precise estimation of the p_T is needed in order to reduce as much as possible the L1 p_T requirement without a significant increase of the overall rate.

The performance of the OMTF algorithm has been studied using MC simulation that reproduces the geometry and conditions of the Phase II of the LHC, including the injection of realistic pileup profiles with between 0 and 300 mean pileup collisions. It was observed that the results are overall stable for different pileup conditions so only results with 200 average pileup interactions are shown.

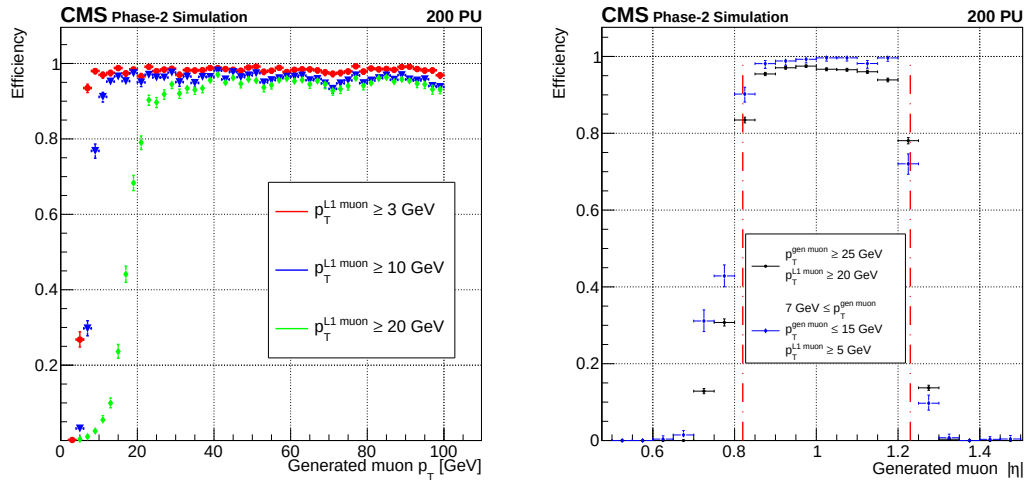


FIGURE 7.5: Efficiency of the OMTF algorithm with respect to the kinematics of the L1 muon candidate. (Left) with respect to the generator level muon p_T ; the figure includes a requirement on the generated muon of $0.82 < |\eta| < 1.24$. (Right) with respect to the generator level muon η ; the figure includes two different set of generator and L1 predicted muon p_T .

Efficiencies are measured in inclusive muon gun MC samples that are generated for flat muon p_T between 2 and 100 GeV and η between -2.8 and 2.8 . The efficiencies of the OMTF with respect to the generator level muon kinematics are shown in Figure 7.5. Efficiencies are computed with all generator level muons as denominator and L1 OMTF candidates matched geometrically ($\Delta R < 0.4$) to a generator level muon as numerator. As shown in the Figure, the overall efficiency of the algorithm is close to 100% if no p_T requirements are applied, but once requisites typical of a single (20 GeV) or double (10 GeV) lepton trigger are applied around 3–4% of efficiency is lost. The turn on of the 20 GeV curve, a typical p_T requirement at the L1 trigger, shows a momentum resolution of around 5 GeV next to the L1 p_T cut. The efficiency is

relatively flat on η , with the algorithm being even slightly efficient out of its natural bounds corresponding to the geometrical region of the overlap region of the detector which is marked in red.

As the OMTF algorithm incorporates information from the muon station that is expected to be more affected by the ageing effects, the innermost station of the outermost DT wheel, it is important to check that the performance of the algorithm is resilient against possible losses in the local segment reconstruction due to detector degradation. It is known that these stations most affected by ageing are the ones more usually selected as the best reference hit, as they tend to be the innermost detector layer hit and so offer the best overall lever arm for the muon momentum estimation, so the effect of the ageing might be relevant. The effect of DT degradation is introduced into the simulated samples by randomly dropping local hits on each of the DT layers according to the hit efficiency probability provided by station and sector in Reference [232]. The DT TPs are then recomputed and the OMTF rerun with the new set of TPs. The electronic failures of the RPCs are represented through the turn-off of a realistic set of 30–40 RPC stations through the detector. Two different ageing scenarios corresponding to 1000 fb^{-1} and 3000 fb^{-1} of accumulated luminosity are considered. The effects of detector degradation can be seen in Figure 7.6. They are relatively mild, with appreciable losses appearing only in the 3000 fb^{-1} scenario where around 2–3 % efficiency is lost with a small degradation on the turn-on curve. The effect is, as expected, a bit more pronounced in the low $|\eta|$ region where the most affected DT station is.

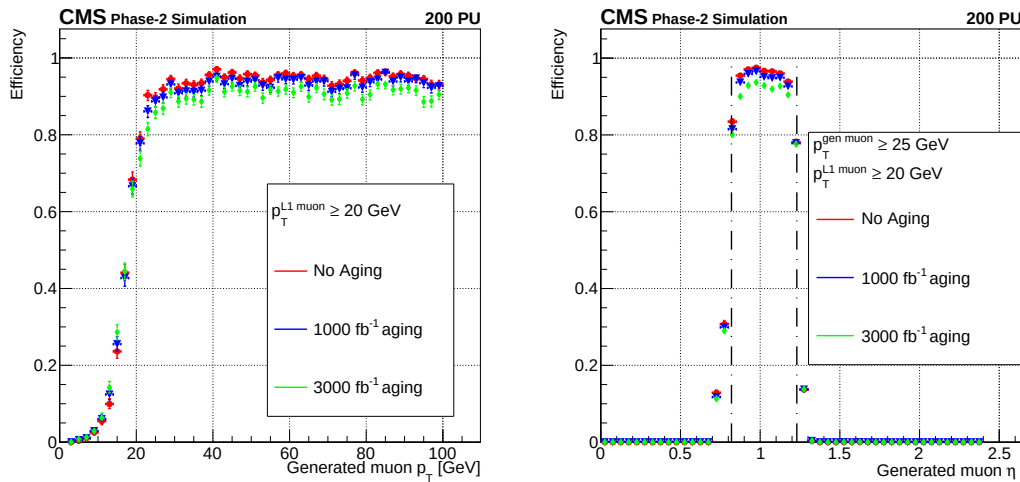


FIGURE 7.6: Efficiency of the OMTF algorithm with respect to the kinematics of the L1 muon candidate under detector ageing conditions. (Left) with respect to the generator level muon p_T ; the figure includes a requirement on the generated muon of $0.82 < |\eta| < 1.24$. (Right) with respect to the generator level muon η ; the figure includes the requirement of a high p_T muon selection at the L1 reconstruction (20 GeV) and generator (25 GeV) levels.

The rate of the OMTF algorithm is also studied in detail. A neutrino gun sample is used for the simulation of purely pileup data, representing the behaviour of the triggering system when no bias is applied through the trigger selection. The rate is estimated as a function of the L1 p_T requirement in Figure 7.7 (left). The rate for a p_T cut of 20 GeV is around 14 kHz at a mean pileup of 200 interactions, corresponding to a quantity affordable as an input of the HLT given the expectations of the Phase

II electronics. A degradation of the L1 rate of around 2 kHz more under the most extreme ageing conditions is observed, which is still within the acceptable HLT range.

A final study is performed to verify the stability of the OMTF algorithm as the average number of pileup interactions increases, an effect that might be seen during the HL-LHC operations if the conditions are favourable. The rate was computed with a L1 p_T cut of 25 GeV for several pile-up hypothesis in simulation, and also compared with the performance of the previous iteration of the algorithm in Run 2 data. A linear fit to the simulated points shows that the effect is consistent with a safe linear dependence of the L1 rate with respect to the average pileup interactions as shown in Figure 7.7 (right).

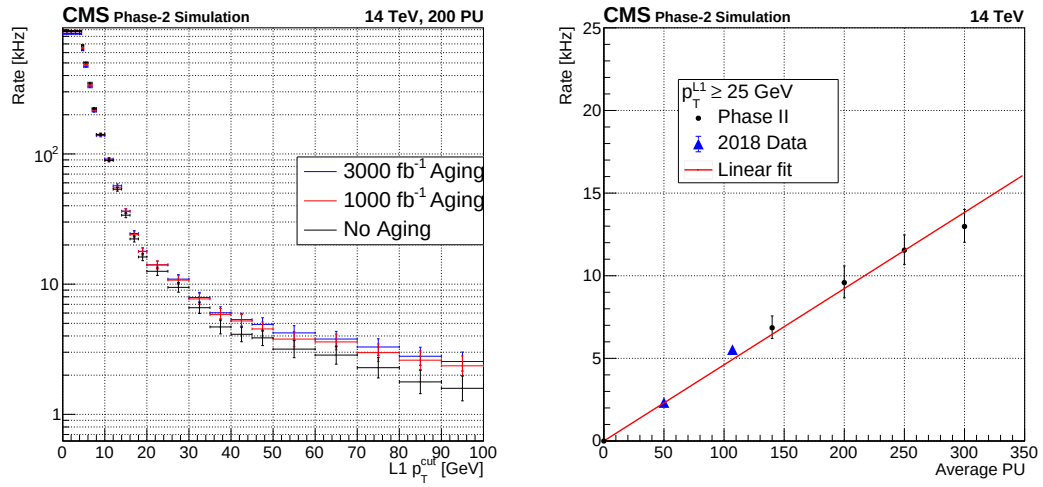


FIGURE 7.7: (Left) rate of the OMTF algorithm with respect to the L1 p_T requirement with and without detector ageing conditions. (Right) stability of the L1 OMTF for a L1 p_T cut of 25 GeV with respect to different simulated (black) or measured in Run 2 data (blue) conditions.

7.2.3 Prospects and methods for measuring long lived signatures in the OMTF

Long-lived BSM particles are one of the non-standard signatures that could be detected inside the muon spectrometers. Several BSM models propose the existence of BSM particles with lifetimes at the order of nanoseconds that later decay to muons and rarely interact with the detector before [230]. Experimentally, these particles will travel a significant distance from the beam axis before decaying to several SM components which can be detected as usual in the detector. These SM products will appear to be displaced, meaning that their tracks will converge into the vertex where the long-lived particle decayed instead of towards the beam crossing one. Depending on how far the secondary vertex is from the beam crossing, the standard track reconstruction algorithms will fail to properly recognise the product of displaced particles, as they usually assume all tracks to point towards the beam line.

Displaced muons are also problematic to reconstruct at the L1 trigger as well. As their tracks do not necessarily point towards the centre of the detector, algorithms like the OMTF will have trouble on properly reconstructing their behaviour. In fact,

the main issue of displaced muon reconstruction is that, at the level of the muon spectrometers, the tracks of high p_T displaced muons are much more similar to those of low p_T non-displaced (prompt) ones than those of high p_T . This effect originates due to the non-pointing nature of a displaced muon being easily mimicked through the bending in the muon track introduced by a low p_T muon. A depiction comparing these three types of muons is shown in Figure 7.8 where the behaviour along the ϕ axis for different kinds of muons are shown. As a consequence of their similarity with low p_T prompt muons, displaced muons will be reconstructed by the nominal OMTF algorithm as prompt low p_T muons and so will be taken out of the final L1 acceptance once a minimal L1 p_T requirement is applied to reduce the rate.

Several solutions have been explored in order to extend the capabilities of the current OMTF algorithm (prompt-OMTF) to include displaced signatures. One of such proposals is the expansion of the OMTF algorithm through the usage of dedicated golden patterns trained in displaced muon gun samples (displaced-OMTF). Instead of multiple p_T classes, the displaced-OMTF is parametrized in terms of the transverse displacement of the muon with respect to the beam crossing, d_{xy} , which can be computed at the generator level in order to fill the golden pattern histograms. As it uses the same pattern recognition strategy as the prompt-OMTF, an efficiency similar to the prompt-OMTF could be reached for the presence of displaced muons. An additional strong point of this strategy is that it can be included into the existing hardware as a natural extension of the prompt-OMTF algorithm, as the reference hit selection and the pattern recognition step logic of the algorithm is identical between the prompt- and displaced-OMTF algorithms.

The main challenge in the design of a displaced-OMTF, however, is the fact that low p_T muons are usually misidentified as displaced high p_T muons. The issue, thus, is not only to design an optimal efficiency-wise procedure but also be able to reject the majority of the low p_T prompt muons that would represent the bulk of the displaced-OMTF rate. The main strategy that has been developed is the combination of both algorithms into a single one, the prompt+displaced-OMTF or combined-OMTF.

The combined-OMTF acts as a natural extension of the prompt-OMTF in order to, again, profit from the existing implementation of the algorithm. In the combined-OMTF algorithm, both the prompt and displaced algorithms are run in parallel, until a set of prompt and displaced candidates are obtained. Then, the same ϕ -matching algorithm used to reject repeated prompt candidates is used to select pairs of prompt-displaced candidates that are assumed to correspond to the same reconstructed object. The final candidate for the muon is then selected based on the quality and overall posterior probability criteria. The underlying idea of the procedure is that the high efficiency of the prompt-OMTF algorithm can be used to select the true low p_T prompt muons and then subtract them from the set of displaced-OMTF candidates. The resulting set of L1 muons is either a prompt candidate with an estimation of its p_T , or a displaced candidate with an estimation of its d_{xy} . Further requirements on p_T and d_{xy} can then be optimized to design the L1 muon trigger requirements.

Additional tweaks to the classification algorithm have also been developed to further reduce the rate. The quality criteria, usually equal to the number of detector layers with measurements, can be tweaked to forbid displaced muon reconstruction from appearing due to very noisy layer hit configurations, such as muons only leaving signals on the innermost DT and CSC stations which tend to correspond to low p_T

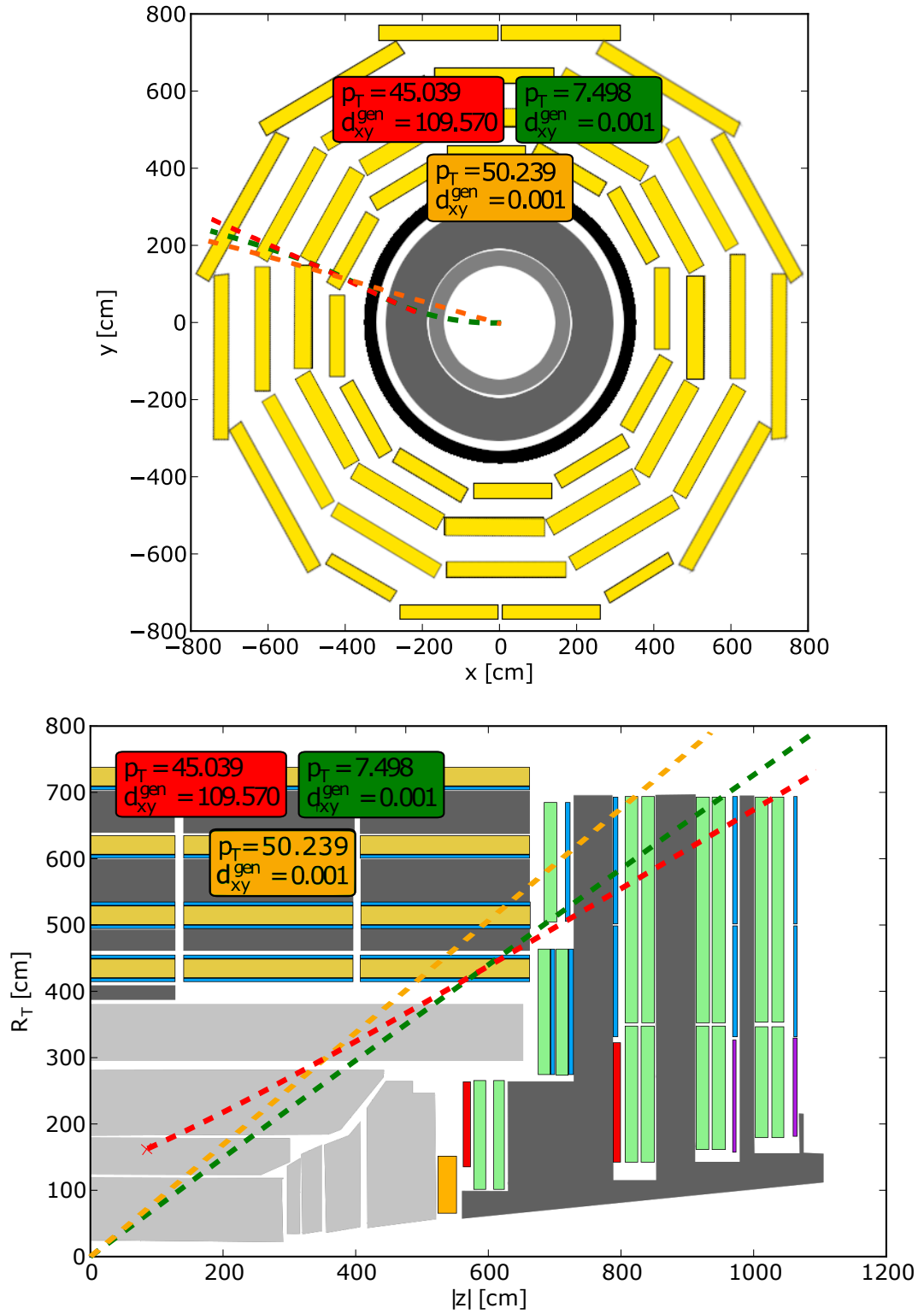


FIGURE 7.8: Comparison of the trajectories from a high momentum displaced muon (red) and a high (orange) and low (green) momentum prompt muons under the CMS magnetic field. In the transverse plane (top), and in the R - z plane (bottom). In the legends, the p_T of the generated muons is measured in GeV, and the displacement in cm.

punch-throughs. The PDF criteria is also modified by redefining the prior quantities introduced in Equation 7.3 such that the prompt muon priors are much higher than the displaced muon ones. In this sense, the high efficiency of the prompt-OMTF to true low p_T prompt muons reduces the overall L1 rate much more significantly. With the application of these tweaks, reasonable performances can be achieved, with overall rates of the displaced trigger at the 10–20 kHz level (for a 200 average pileup scenario consistent with Figure 7.7), and recover roughly 30–60% of the displaced muons depending on the level of displacement.

7.3 Local L1 trigger primitives at the CMS muon barrel systems

One of the inputs for the OMTF, the DT trigger primitives (DTTPs), are the key building block for triggering muons at the barrel region of the CMS experiment. As introduced in Section 7.1, they correspond to the reconstruction of segments of the muon track inside a single DT station. A muon station is composed of two or three superlayers (SL) each one composed of four staggered stacked layers (L) which are planes containing a varying number of parallelly placed DT cells (C). Two of the SLs are segmented along the ϕ direction (ϕ -SL), and the other –when present– is segmented along the θ direction (θ -SL). Non detecting material (the honeycomb spacer) separates one of the ϕ -SL from the other two. A depiction of a DT station is shown in Figure 7.9.

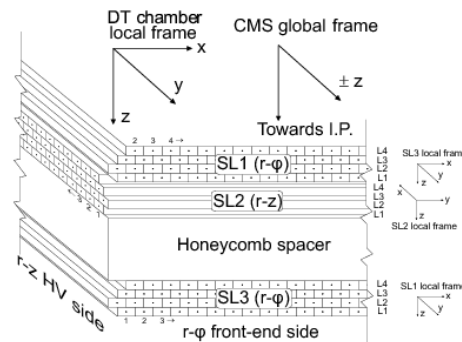


FIGURE 7.9: Schematic view of a DT station including its three different superlayers. The image is available in Reference [235].

7.3.1 DT trigger primitives reconstructed with an analytical method

New DTTP reconstruction algorithms have been developed for the Phase II of the LHC that profit from the full capabilities of the new triggering electronics and the possibility of combining results from the different station SLs and, potentially, the RPC system as well. While it is not my central point of work, a brief introduction to the analytical method of DTTP reconstruction is shown here for completeness.

The analytical method (AM) is one of the proposed reconstruction algorithms to tackle the task of DTTP reconstruction. It uses inputs corresponding to the measurements obtained directly from the detector: the set of registered hits in a station, their layer

and cell position, and the timing estimation for each of the corresponding hits. The algorithm then proceeds in three steps:

- **Grouping:** in each SL, groups of 3 or 4 hits that are geometrically consistent are selected. This is achieved by scanning through the whole SL in groups of 10 cells forming a cone, opening from one cell in the lowermost layer to four cells in the uppermost ones. Inside the 10 cells, the possible patterns corresponding to a muon track –a straight line passing through the SL– are examined. Hits that follow any of the expected patterns are grouped into candidates of up to four hits. For hit i , the centre of the cell position x_i , layer position y_i , and measured time t_i are registered. In case the reconstructed 10-cell pattern allows to fix a hit laterality, the side of the wire where the muon–gas interaction was produced, it is saved as well as a binary variable (H_i which is -1 for left side, $+1$ for the right side).
- **Fitting:** the fundamental parameters of each set of at least three hits are determined through the usage of analytical relations. The analytic formulae used are the result of a chi-square relation obtained by fitting the positions of the detected hits, modified by their drift times, to a straight line passing through the SL. The position of each hit is parametrized as:

$$\phi_i = x_i + H_i v_{\text{drift}}(t_i - t_0 - dt_i) \quad R_i = y_i \quad (7.4)$$

where v_{drift} is the drift speed of electrons inside the DT gas, the propagation speed of the detected signal through the DT cell. dt_i accounts for effects such as the propagation of the signal through the electronics, and the time of flight of the muon from the collision to the station, and can be calibrated generically for each layer before data taking. The fitted function has a linear shape described as

$$\phi = \phi_0 + (R - R_0) \tan \phi \quad (7.5)$$

The fitted quantities correspond to the time at what the muon was produced in the collision (t_0), the angular position at a radial distance R_0 (ϕ_0), and the slope of the track with respect to an axis perpendicular to the station ($\tan(\phi)$). The resulting TP candidate is assigned a bunch-crossing based on its measured t_0 . The results of these fits are known as uncorrelated TPs. If the grouping step provides more than one candidate, for example if the laterality of all hits could not be univocally defined, the one with the smallest χ^2 of the resulting linear fits is used to select the best final uncorrelated TP. Uncorrelated TPs are assigned quality criteria based on the number of reconstructed hits inside of them.

- **Correlation:** for fits involving the ϕ -SLs, a last step is included. It is attempted to correlate uncorrelated TP candidates from different ϕ -SLs between them. If an uncorrelated TP is found in both ϕ SLs with a measured t_0 smaller than one bunch-crossing spacing (25 ns), a new candidate containing all hits in both segments is formed. The properties of this new candidate are estimated as the arithmetic mean of its uncorrelated TP components (for t_0 and ϕ), or as the slope of the straight line from the innermost to outermost TP positions (for $\tan(\phi)$). If the χ^2 corresponding to the fit of all the hits in the correlated group to the resulting line is small enough, the obtained measurement is kept as a correlated TP. The number of hits in each ϕ -SL is used to describe the correlated TP, such

as $3 + 3$, $3 + 4$, $4 + 4$, etc. By analogy, uncorrelated TPs will usually be designed as $3 + 0$, $4 + 0$, etc.

- **DT+RPC superprimitive building:** as an optional final step, if a geometrical match is later found between a DT TP and an RPC cluster, a joint DT+RPC superprimitive is built and passed-through to the later steps of the L1 trigger.

The final output of the AM algorithm is a set of lower quality uncorrelated TPs plus higher quality correlated TPs. For each one, measurements of its position and slope inside the DT station are provided. After the rest of the algorithm is finished, uncorrelated TPs that match geometrically to non-grouped hits in the opposite SL are known as confirmed uncorrelated TP and are considered of intermediate quality between the uncorrelated and correlated cases. The whole set of TPs are what is later feed to the track finders as DT stubs, such as for the OMTF described in Section 7.2.

The main strength of the AM algorithm is the exhaustiveness with which it probes all possible configurations of hits in its search for L1 TP candidates. Its performance has been evaluated in simulation corresponding to Phase II conditions, with and without the simulation of DT ageing and RPC failures included. The effects of ageing are included in the same way as in the results presented in Section 7.2.2. The results are shown in Figure 7.10. It can be seen that very high efficiencies are reached through all stations and wheels, with more than 98% efficiency under standard non-aged conditions. The effect of detector degradation is only significant for the first and last stations (MB1 and MB4) where radiation is expected to be harsher leading to overall less hit efficiency and more difficult reconstructions. With the inclusion of the RPC system to build superprimitives, the effect of ageing in the efficiency is minimized to roughly a 5% loss in the most complex cases, corresponding to the innermost DT station on the most external wheels.

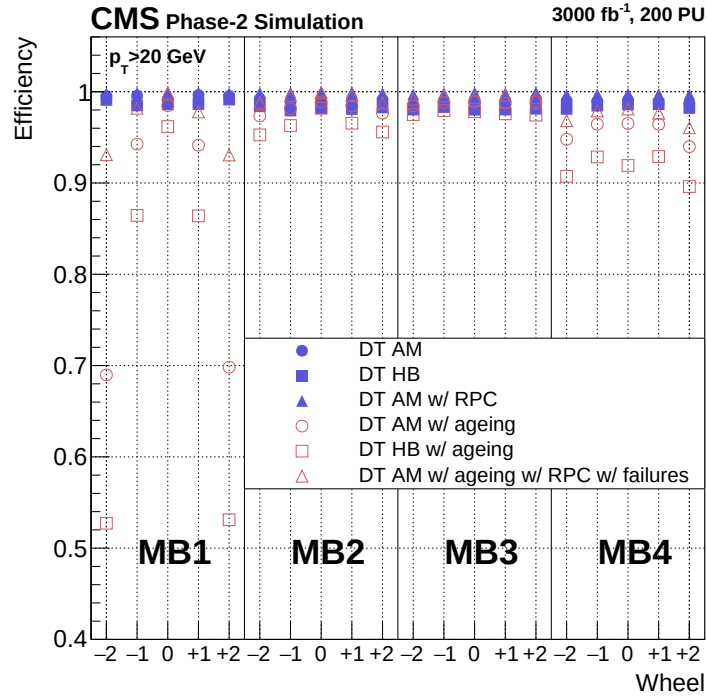


FIGURE 7.10: Efficiency of the AM method for L1 DT trigger primitive reconstruction. The denominator in the efficiency computation corresponds to segments reconstructed using the offline reconstruction algorithms matched to generator level muons with $p_T > 20$ GeV. The numerator includes the same requirements but also matched to a reconstructed L1 candidate. The AM algorithm with and without the additional matching to RPC clusters, and with and without the effects of ageing is shown. Another L1 DTTP reconstruction algorithm, the histogram based (HB) is also shown, its description can be found in [13].

7.3.2 A Bayesian alternative for grouping and correlation

The AM has been proven to provide a robust reconstruction of muon segments at the DT stations, but several points could be changed in order to try to improve its already good performance. One of such options is to develop a method to perform the grouping and correlation step simultaneously and previous to any fitting procedure for the ϕ -SLs. The merits of a successful implementation of such an algorithm are varied. First, it could allow to recover a small fraction of TPs for cases in which a muon produces few hits in the detector. For those cases, it provides the possibility of building $2 + 2$ or even $2 + 1$ correlated TPs without the need for the minimal three hits –a requisite of the fitting step– being in the same SL. This effect is specially important for the most extreme ageing cases where the greatest losses of registered hits are expected and such extreme situations might start to happen. A second advantage is the possibility of reducing the overall computational time of the algorithm by avoiding to perform the uncorrelated TP fits if a good correlated candidate is found. A grouping plus correlation algorithm, known as the Pseudo-Bayes classifier, has been developed inspired on the OMTF strategy introduced in Section 7.2.1.

The Pseudo-Bayes classifier is based on a set of precomputed *golden patterns* representing possible muons with different values of $\tan(\phi)$. Two muons with the same

slope would correspond to the same golden pattern representation, independently of their position in the station, to profit from the translational symmetry of each station. Each pattern is seeded by exactly two reference hits inside an station. Explicitly, three numbers are needed to encode $\tan(\phi)$ as a function of the measurable two hit coordinates: the lowest layer of the two hits (L_{Down}), the highest layer number of the two hits (L_{Up}), and the difference in cell counts between the two hits ($\delta C = C_{\text{Up}} - C_{\text{Down}}$).

For all possible values of the seeds (L_{Down} , L_{Up} , δC) and the four combination of lateralities in the up and down reference layers, a pattern is generated. For the purposes of this step C_{Down} is set to the leftmost (rightmost) cell in the station so δC is scanned by looking at all possible values of C_{Up} for positive (negative) slope patterns. The pattern generation step starts by tracing a straight line (reference line) passing through the centre of the two semicells corresponding to the chosen lateralities of the reference hits. The DT cells that are crossed by these straight lines are known as the *expected hits* inside the golden pattern, relating to the positions where the hypothetical muon represented by the pattern would leave energy depositions. The expected hits are then parametrized to profit from the translational invariance of the station as ($L_i, C_i - C_{\text{Down}}, H_i$) for the hits in layer L_i and cell C_i with laterality H_i . An example of a golden pattern, with its seed definition and expected hits is shown in Figure 7.11.

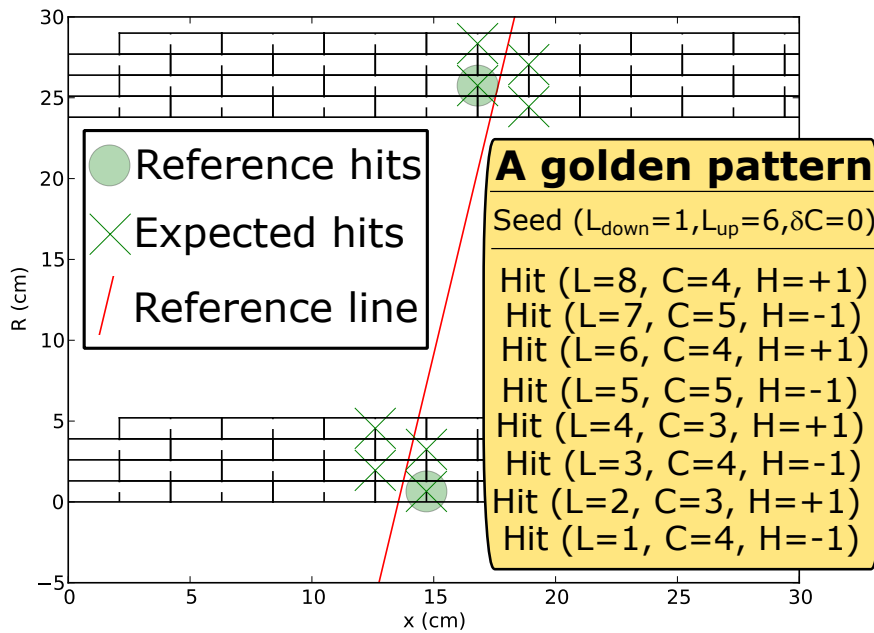


FIGURE 7.11: Example golden pattern of the Pseudo-Bayes algorithm represented over a zoomed in depiction of a DT station projected into the y - x plane (in the figure R - x). Reference and expected hits are marked in green, with their corresponding coordinates shown in the legend.

The Pseudo-Bayes equivalent to the grouping and correlation steps of the analytical method is a pattern recognition step that has as an input all hits in the station, with the information of their observed layers ($\hat{L}_i$) and cells ($\hat{C}_i$). It proceeds as follows:

1. First, a pair of hits from different layers are chosen to serve as test reference hits $(\hat{L}_{\text{Down}}, \hat{C}_{\text{Down}})$ and $(\hat{L}_{\text{Up}}, \hat{C}_{\text{Up}})$. All patterns whose seeds match the measured properties of these reference hits $(\hat{L}_{\text{Down}}, \hat{L}_{\text{Up}}, \hat{C}_{\text{Up}} - \hat{C}_{\text{Down}})$ are preselected.
2. All hits registered in the station are expressed in cell coordinates relative to the lowest reference hit building the observed hits $(\hat{L}_i, \hat{C}_i - \hat{C}_{\text{Down}})$.
3. If the coordinates of an observed hit are in the list of expected hits coordinates for a pattern it is considered as selected for the associated pattern. Its laterality is fixed to the one predicted by the pattern.
4. Steps 1–3 are repeated for all possible pairs of seeding hits.
5. The resulting grouped candidates are reduced to a small set by a ghostbusting procedure. The highest quality pattern is selected and its associated hits are selected as a grouped set and deleted from all other patterns. The procedure is repeated until all remaining patterns have three or less associated hits. The quality of the pattern is determined by the total number of associated hits and the balancing between the different SL (meaning that groups with hits in both ϕ -SLs are preferred). If two different candidates are of equal quality in any ghostbusting step, both are selected as groups.

The final set of hit groups are then sent to the fitting step procedure to obtain an estimation of the segment properties and a final TP candidate. An example of the application of the Pseudo-Bayes algorithm to group the hits corresponding to the passing of a single muon through a DT station is shown in Figure 7.13, where it can be seen that the algorithm properly reconstructs the original muon and it is able to assign the lateralities of the hits properly. The muon segment was generated as a straight line inside the station, and its crossings through the detecting material are the hits shown.

An analogy to the algorithm introduced in Section 7.2.1, which inspired this one, serves to prove that the Pseudo-Bayes algorithm is in fact a naïve Bayes classifier. The following correspondences can be noted:

- **Predicted classes** (P_i): they correspond to a set of discretized values of $\tan(\phi)$ inside the station. Each pair of reference hits with their laterality assumptions uniquely defines a class of lines with fixed $\tan(\phi)$ inside the station.
- **Measurements** (l_j): correspond to the positions of the measured hits relative to the one in the seed of the lowest layer, measured as a $(C_i - C_L, L_i)$ tuple.
- **Conditional probabilities** ($p(l_j|P_i)$): correspond to the discrete probability distributions represented by the patterns. The pdfs of these distributions are equal to 1 if l_j is in the pattern of class P_i , and 0 otherwise.

The Pseudo-Bayes algorithm has been proven to be resilient to the presence of both random noise hits inside the DT stations, as well as to be able to properly separate signals from different simultaneous muons arriving at the same station in small time intervals. Both phenomena are expected to happen with relative frequency in the

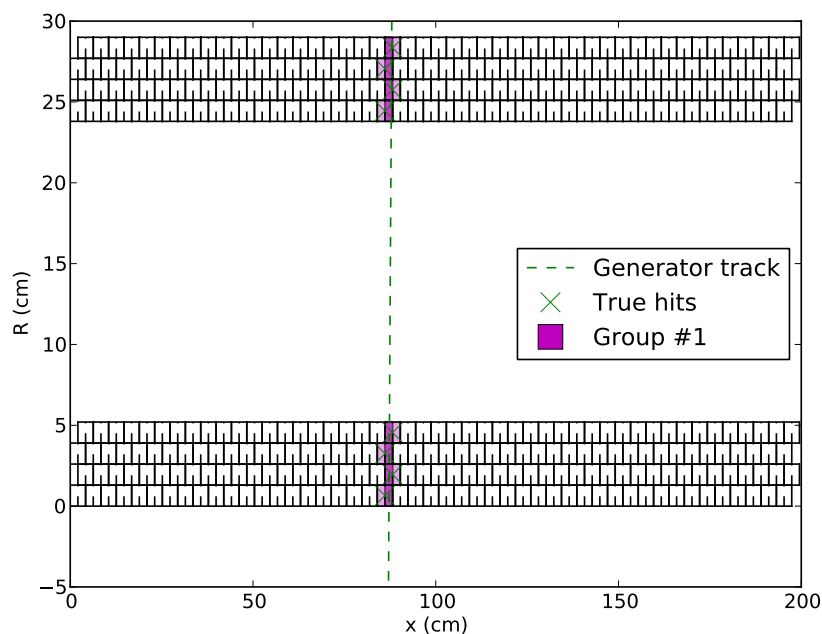


FIGURE 7.12: Reconstruction of a L1 group candidate using the Bayesian grouping algorithm over a set of registered hits across two ϕ -SL in the y - x plane (in the figure R - x). The green dashed line corresponds to the track of the generator level muon, the green crosses are the *true hits* corresponding to the energy depositions of the muon inside the station. The coloured cells correspond to the final group candidate, with the darker sides marking the predicted lateralities for each registered hit.

Phase II of the LHC due to the increased detector occupancy. The first effect was simulated by adding randomly generated noise hits to the ones appearing by the passing of a true muon through the DT station and running the Pseudo-Bayes algorithm to analyse the result. One of such cases is presented in Figure 7.13 (top). The second possibility was studied by mixing the hits from several generated muons into a single set of inputs and running the Pseudo-Bayes algorithm into the resulting set of hits and the results are shown in Figure 7.13 (bottom). In both cases the Pseudo-Bayes algorithm provides reasonable grouping estimations of the true muons depositions. The algorithm is currently into study for its implementation as an alternative grouping scheme for the AM TP production method.

7.4 Summary

The high luminosity LHC (HL-LHC) will provide great quantities of new data which could then be used to improve our understanding of both SM and BSM physics to yet unseen precision levels. The Phase II upgrade of the CMS detector has been designed in order to cope with the harsher data taking conditions these new data taking runs will bring, including both improvements in the detector hardware and the different reconstruction and selection algorithms. Triggering will be specially delicate during the HL-LHC as the increase in the instantaneous luminosity delivered by the LHC will introduce a proportional increase in the overall trigger rate if no changes to the

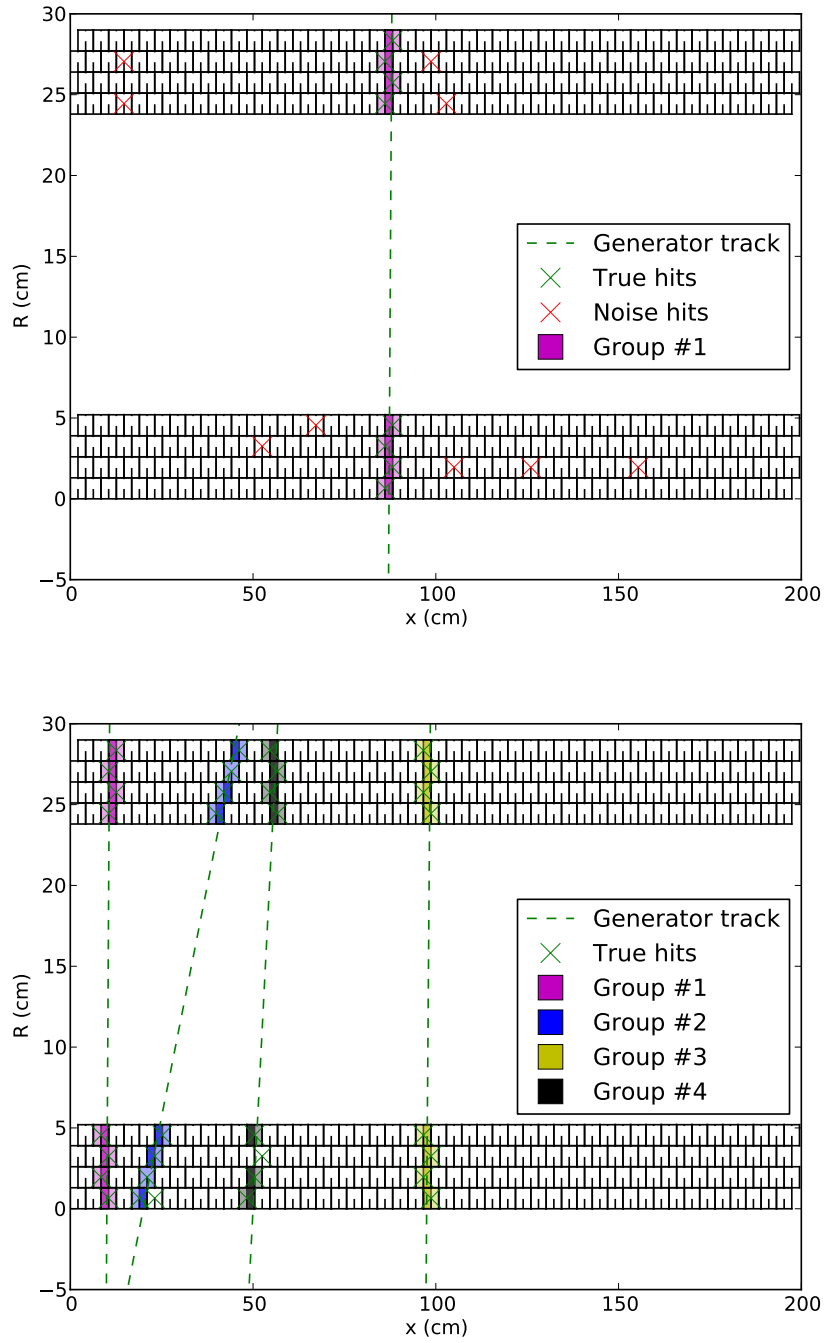


FIGURE 7.13: Reconstruction of L1 group candidates with the Bayesian grouping algorithm under random noise (top) and higher muon multiplicity (bottom) conditions. The green dashed line corresponds to the track of the generator level muon, the green crosses are the *true hits* corresponding to the energy depositions of the muon inside the station. The red crosses correspond to *noise hits* added randomly to the input. The coloured cells correspond to the final group candidate, with the darker sides marking the predicted lateralities for each registered hit. The figures represent a DT station in the y - x plane (in the figure R - x).

Run 2 setup are introduced. The development of several algorithms for different steps in the L1 muon trigger have been presented in this chapter.

The overlap muon track finder (OMTF) algorithm uses a naïve Bayes classifier to combine the inputs from the DT, CSC, and RPC subsystems into a single muon track build only with the muon spectrometers in the region of $0.82 < |\eta| < 1.24$. The performance of the prompt-OMTF, designed to provide an accurate estimation of the p_T of prompt muons, has been studied in a realistic simulation of the conditions of the HL-LHC, showing an overall muon reconstruction efficiency over 95% once a minimal p_T cut is applied to reduce the L1 muon rate. An alternative strategy to trigger on muons resulting from long-lived particles, the displaced-OMTF, and its combination with the previous algorithm, the combined-OMTF, are also introduced.

The DT trigger primitives (DTTP) are one of the building blocks used by algorithms such as the OMTF to build the L1 muon candidates inside the barrel region ($|\eta| < 1.2$). The analytical method (AM) algorithm used to build DTTP at the station level is briefly introduced, and its performance in the HL-LHC conditions is shown to have an efficiency of over 98% under perfect detector conditions. A possible avenue for improvement by merging together two of the steps of the AM DTTP computations is also discussed, in the form of the pattern recognition method known as the Pseudo-Bayes algorithm.

Summary and conclusions

This thesis presents results that profit from pp collisions recorded by the CMS detector during the Run 2 of the LHC in order to provide precision measurements of the Standard Model (SM), and search for the presence of new physics beyond its range of applicability. All the studies described through this text correspond to final states involving two or more leptons, multileptonic, a signature characteristic of the presence of the electroweak sector of the SM.

The first set of measurements of diboson (WW, WZ, and ZZ) production cross sections at a centre of mass energy of $\sqrt{s} = 5.02$ TeV have been presented. The results, part of the recent [5] publication, are limited by the luminosity delivered by the LHC at this energy regime, of around 300 pb^{-1} , and so are dominated by statistical uncertainties. The measured values of each cross section are:

$$\begin{aligned}\sigma_{5\text{TeV}}(\text{pp} \rightarrow \text{WW}) &= 37.0^{+5.5}_{-5.2}(\text{stat.})^{+2.7}_{-2.6}(\text{syst.}) \text{ pb} \\ \sigma_{5\text{TeV}}(\text{pp} \rightarrow \text{WZ}) &= 6.4^{+2.5}_{-2.1}(\text{stat.})^{+0.5}_{-0.3}(\text{syst.}) \text{ pb} \\ \sigma_{5\text{TeV}}(\text{pp} \rightarrow \text{ZZ}) &= 5.3^{+2.5}_{-2.1}(\text{stat.})^{+0.5}_{-0.4}(\text{syst.}) \text{ pb}\end{aligned}$$

These results include the first observation of the WW process at a centre of mass energy of $\sqrt{s} = 5.02$ TeV at an statistical significance of more than 5 standard deviations.

The properties of the Yukawa coupling of the top quark are probed indirectly through the study of the $t\bar{t}H$ production mode in multileptonic final states at a centre of mass energy of $\sqrt{s} = 13$ TeV, measurements that correspond to publications [7–9]. The optimization of the signal extraction approach based on simple selection requirements, leads to an overall significance of 4 standard deviations, with a total uncertainty on the $t\bar{t}H$ cross section of 28% composed by similar contributions from systematic and statistical uncertainties.

An in depth study of the properties of the WZ process at a centre of mass energy of $\sqrt{s} = 13$ TeV in multileptonic final states is described. The results correspond to the publications [3, 4] and offer the most precise estimations of the properties of this diboson production mode from any experiment to date. The total production cross section is measured to be

$$\sigma_{13\text{TeV}}(\text{pp} \rightarrow \text{WZ}) = 50.6 \pm 0.8(\text{stat.}) \pm 1.5(\text{syst.}) \pm 1.1(\text{lumi.}) \pm 0.5(\text{theo.}) \text{ pb}$$

which is the most precise measurement of any diboson cross section at the LHC, with a relative uncertainty slightly smaller than 4%. The result is consistent with the current best theoretical estimations of the cross section at NNLO in QCDxNLO in EWK perturbative orders [95]. The final result is dominated by systematic uncertainties corresponding to object selection efficiencies, but the overall effect of the uncertainties in the luminosity has a non negligible contribution as the single biggest source of uncertainty.

The charge asymmetry in WZ production, a consequence of the inner structure of the proton, is measured to be of $A_{WZ}^{+-} = 1.41 \pm 0.04$, in good agreement with the SM expectations. The high precision of the result makes it suitable for its interpretation in terms of possible constraints of the parton distribution functions (PDF). Such interpretation leads to a reduction of around 10% in uncertainties associated to our limited knowledge of the PDFs.

The polarization states of the W and Z bosons are studied by building reconstructed-level angular distributions sensitive to the different polarization states of each of the massive bosons. These studies lead to the observation of longitudinally polarized W and Z bosons in WZ production, the first observation of longitudinally polarized W bosons in diboson production. The results obtained are in agreement with SM predictions, an important check of the electroweak symmetry breaking mechanism of the SM.

The overall mass of the WZ system is used to search for the presence of new physics represented by a set of five different effective field theory (EFT) terms. While no significant excess that could be due to new physics is seen at high $M(WZ)$ values, confidence regions at the 95% CL are obtained for each of the involved parameters. Additional checks are performed to test the validity of the EFT approach in this final state, leading to several sets of alternative constraints in the EFT parameters arising from different underlying assumptions on the EFT models.

Differential cross sections of the WZ process are measured with respect to several high level variables that characterize the WZ model, including those used to perform the various measurements detailed above. An unregularized unfolding procedure is performed to obtain detector-free cross section results that can be freely compared to different particle level predictions from the broad high energy physics community.

A search for electroweak supersymmetry (SUSY) using data corresponding to the Run 2 of the LHC at a centre of mass energy of $\sqrt{s} = 13$ TeV is also presented. It corresponds to several results published through the development of this thesis [10–12]. Multileptonic final states involving all combinations of lepton flavours and multiplicities ranging from two to four reconstructed charged leptons are studied. An exhaustive approach is followed to probe for all possible final state configurations in which the decays of charginos or neutralinos could provide a multileptonic final state. A total of twelve different final state categories are separately optimized to reach a final selection of around two hundred signal regions (SR) corresponding to final states where different realizations of SUSY might appear. The SR approach is complemented by the training of a parametric neural network (PNN) discriminant constructed to improve the sensitivity towards signals present in final states with three light leptons compatible with WZ production, the most complex of the final states probed.

Neither the SR nor the PNN approach shows a significant excess in data that could be attributed to the presence of a new physics signal due to the existence of SUSY. The results are interpreted in terms of fourteen different simplified models (SMS) corresponding to various hypothesis on the decay modes of chargino–neutralino ($\chi_1^\pm \chi_2^0$) and neutralino–neutralino ($\chi_1^0 \chi_1^0$) pairs and the relations of the neutralino, chargino, and slepton masses.

The results of the interpretation in terms of slepton mediated chargino and neutralino decays lead to the exclusion of models with production cross sections down to 0.1 fb, corresponding to the exclusion of superpartner masses up to $M_{\chi_1^\pm} = M_{\chi_2^0} = 1400$ GeV, and $M_{\chi_1^0} = 900$ GeV. These are the most stringent upper limits on chargino and neutralino masses from collider experiments to date.

The studies presented in the $T\chi\chi WZ$ model are able to close the previously unexcluded gap for models with mass splittings of $M_{\chi_2^0} - M_{\chi_1^0} = 90$ GeV, a challenging region that remained vastly unexplored by either the ATLAS or CMS collaborations. This successful exclusion is obtained thanks to the improvements developed for the signal extraction procedure, the optimization of the SR strategy and the introduction of the new PNN discriminants to the studies.

Finally, the focus is turned towards the future of multileptonic physics in the shape of the high luminosity LHC (HL–LHC) and the associated upgrade of the CMS detector. Multileptonic physics at the HL–LHC will strongly depend on the presence of a robust trigger strategy both for standard SM processes and for possible new BSM signatures. Several of the developments in the L1 trigger for the Phase II upgrade of the CMS detector are presented, corresponding to the improvement in muon triggering, one of the building blocks of multileptonic physics.

As an overall conclusion, in this thesis I make extensive use of the possibilities offered by the data taken with the CMS experiment to study multileptonic final states. The results I provide correspond to precise measurements of the properties of the electroweak sector, including the best measurements of WZ production and some of the most stringent constraints in electroweak SUSY production up to date.

Resumen y conclusiones

En esta tesis se presentan medidas de precisión del Modelo Estándar (ME), y de búsqueda de procesos de nueva física más allá del rango de aplicación del mismo. Las medidas se han obtenido sobre datos registrados con el detector CMS en colisiones protón-protón producidas durante el *Run 2* del LHC. Los estudios descritos en capítulos previos se corresponden con estados finales con dos o más leptones cargados, multileptónicos, los cuales son un indicio de la aparición de la interacción electrodébil del ME.

Se ha presentado la primera medida de secciones eficaces de producción de pares bosónicos (WW , WZ , ZZ) con datos tomados a una energía en el sistema de centro de masas de $\sqrt{s} = 5.02$ TeV. La precisión de estos resultados, publicados en la Referencia [5], está limitada por la relativamente pequeña luminosidad proporcionada por el LHC en este régimen de energías, alrededor de 300 pb^{-1} , por lo que la incertidumbre en las medidas mayoritariamente de carácter estadístico. Los valores medidos para cada sección eficaz son:

$$\begin{aligned}\sigma_{5\text{TeV}}(\text{pp} \rightarrow WW) &= 37.0^{+5.5}_{-5.2}(\text{estad.})^{+2.7}_{-2.6}(\text{sist.}) \text{ pb} \\ \sigma_{5\text{TeV}}(\text{pp} \rightarrow WZ) &= 6.4^{+2.5}_{-2.1}(\text{estad.})^{+0.5}_{-0.3}(\text{sist.}) \text{ pb} \\ \sigma_{5\text{TeV}}(\text{pp} \rightarrow ZZ) &= 5.3^{+2.5}_{-2.1}(\text{estad.})^{+0.5}_{-0.4}(\text{sist.}) \text{ pb}\end{aligned}$$

Estos resultados se corresponden con la primera observación del proceso WW a una energía en el centro de masas de $\sqrt{s} = 5.02$ TeV, con una significancia estadística de más de 5 desviaciones típicas.

Las propiedades del acoplamiento de Yukawa del quark top han sido estudiadas de forma indirecta a través del proceso $t\bar{t}H$ en estados finales multileptónicos y a una energía en el centro de masas de $\sqrt{s} = 13$ TeV, medidas que han sido publicadas en las Referencias [7–9]. Un modelo basado en criterios de selección simples sobre variables individuales ha sido optimizado para aumentar la sensibilidad del análisis a la presencia de la señal $t\bar{t}H$. El resultado final es de una significancia de 4 desviaciones típicas para la presencia de la misma, con una incertidumbre total del 28% en su sección eficaz total. Esta incertidumbre incluye contribuciones de igual tamaño por parte de fuentes estadísticas y sistemáticas.

Se presenta también un estudio en profundidad de las propiedades del proceso WZ a una energía en el centro de masas de $\sqrt{s} = 13$ TeV y en estados finales multileptónicos. Los resultados, publicados en las Referencias [3, 4], se corresponden con las medidas más precisas de las propiedades de este proceso de producción dibosónica por parte de cualquier experimento hasta la fecha. La medida de la sección eficaz total de producción resultan en un valor de:

$$\sigma_{13\text{TeV}}(\text{pp} \rightarrow \text{WZ}) = 50.6 \pm 0.8(\text{estad.}) \pm 1.5(\text{sist.}) \pm 1.1(\text{lumi.}) \pm 0.5(\text{teo.}) \text{ pb}$$

Esta es la medida más precisa de la sección eficaz de cualquier proceso dibosónico realizada en un experimento del LHC hasta la fecha, con una incertidumbre relativa inferior al 4%. Las más precisas predicciones de esta cantidad, correspondientes a cálculos perturbativos hasta un orden NNLO en QCDxNLO en EWK son consistentes con la sección eficaz observada [95]. La incertidumbre total de esta medida está dominada por efectos sistemáticos en la reconstrucción de objetos, pero la fuente con una mayor contribución individual a la misma es la incertidumbre en la medida de la luminosidad.

La estructura interna del protón da lugar a una asimetría de carga en la producción de WZ. Se ha medido un valor de $A_{\text{WZ}}^{+-} = 1.41 \pm 0.04$ para esta asimetría, que está en acuerdo con los valores predichos por el ME. La alta precisión de este resultado indica que pueda ser aprovechado para intentar aumentar nuestro conocimiento de las funciones de distribución partónicas (PDF, por sus siglas en inglés). Las restricciones obtenidas por esta interpretación conducen a una reducción en las incertidumbres asociadas a las PDFs de un 10% para medidas relacionadas con el proceso WZ.

Se han estudiado las polarizaciones de los bosones W y Z a través de distribuciones angulares definidas sobre objetos reconstruidos que son sensibles a los diferentes estados polarizados de ambas partículas. Como resultado de estos estudios se han observado los estados polarizados longitudinalmente tanto para el bosón W como para el Z. Esta es la primera observación de bosones W polarizados longitudinalmente en un estado final dibosónico, lo que supone una confirmación directa del mecanismo de ruptura espontánea de la simetría electrodébil incluido en el ME.

La existencia de procesos de nueva física modelizados a través de teorías de campo efectivas (TCE) que puedan afectar al proceso WZ es estudiada utilizando la masa total del sistema WZ. Ningún exceso significativo es observado en los datos que pudiera corresponderse con alguno de los cinco términos TCE estudiados. En consecuencia, los resultados son interpretados estadísticamente para dar lugar a regiones de confianza al 95% para cada uno de los parámetros TCE asociados. La validez de la aproximación TCE es estudiada con varios estudios adicionales referidos a las distintas aproximaciones inherentes a la misma, dando lugar a intervalos de confianza alternativos en cada uno de estos parámetros.

Las secciones eficaces diferenciales de el proceso WZ con respecto a varias variables de alto nivel han sido medidas. Las variables seleccionadas para ello se corresponden con las utilizadas en las medidas discutidas en los párrafos anteriores así como varias cantidades adicionales que caracterizan la cinemática del proceso WZ. Los resultados son proporcionados a nivel de partícula, para lo que se ha usado *unfolding* sin términos de regularización adicionales de cara a deshacer posibles efectos debidos a la presencia del detector.

Se presentan también los resultados correspondientes a la búsqueda de supersimetría (SUSY) electrodébil a una energía en el centro de masas de $\sqrt{s} = 13$ TeV. Estos resultados han sido publicados durante el desarrollo de esta tesis en las Referencias [10–12]. Los estudios correspondientes a la búsqueda de SUSY involucran estados finales multileptónicos incluyendo de dos a cuatro leptones de todos los sabores. Esta búsqueda se plantea desde la perspectiva de un estudio exhaustivo con optimizaciones específicas dedicadas a cada uno de los posibles estados finales que puedan aparecer en la desintegración de charginos o neutralinos. Un total de doce categorías distintas, basadas en la carga, sabor y multiplicidad de los leptones involucrados, son subdivididas para dar lugar a cerca de doscientas regiones de señal (RS) correspondientes a regiones del espacio de fases dónde diferentes configuraciones de SUSY podrían aparecer. Para complementar la estrategia basada en RS se han entrenado varias redes neuronales paramétricas (RNP) en estados finales con tres leptones compatibles con la producción de un par dibosónico WZ, el estado final que da lugar a una mayor complejidad dentro de los estudiados.

No se ha observado ningún exceso reseñable en nuestros datos que pueda atribuirse a algún tipo de proceso supersimétrico ni en la estrategia RS ni en la RNP. Los resultados de ambas son interpretados de cara a obtener límites en los parámetros de catorce modelos simplificados de SUSY (MSS) correspondientes a distintos modos de desintegración de pares chargino–neutralino ($\chi_1^\pm \chi_2^0$) y neutralino–neutralino ($\chi_1^0 \chi_1^0$).

Bajo la hipótesis de que los sleptones sean más ligeros que el par $\chi_1^\pm \chi_2^0$, los modelos SUSY son excluidos para secciones eficaces de hasta 0.1 fb, lo que equivale a límites superiores en las masas de los compañeros supersimétricos de $M_{\chi_1^\pm} = M_{\chi_2^0} = 1400$ GeV y $M_{\chi_1^0} = 900$ GeV. Estos límites superiores se corresponden con los mayores números obtenidos hasta la fecha para las masas del chargino y el neutralino.

Los resultados correspondientes al modelo $T\chi\chi WZ$ merecen mención especial, ya que son capaces de excluir la mayor parte de la elusiva región del espacio de parámetros correspondiente a $M_{\chi_2^0} - M_{\chi_1^0} = 90$ GeV, región que hasta la fecha había eludido los esfuerzos de las colaboraciones ATLAS y CMS. La optimización de ambas estrategias (RS y RNP) ha sido crucial para aprovechar al máximo los datos del *Run 2* del LHC de cara a obtener este resultado.

Como punto final, se han introducido desarrollos más allá del estudio de las colisiones ya registradas por el detector CMS. El futuro de la física multileptónica en el LHC de alta luminosidad depende de una exitosa mejora del detector CMS previa al inicio de la toma de datos en este. Disponer de una estrategia de *trigger* robusta que sea capaz de proporcionar una alta eficiencia de selección tanto para procesos del ME como para posibles nuevas señales de nueva física es crucial para el futuro de la física multileptónica. Se han presentado varios estudios correspondientes al desarrollo de nuevos algoritmos en el *L1 trigger* de CMS para la mejora de la Fase II del LHC de cara a asegurar un funcionamiento óptimo del *trigger* de muones, uno de los pilares de la física multileptónica.

Como conclusión final, en esta tesis he utilizado los datos obtenidos por el experimento CMS de cara a realizar estudios exhaustivos de estados finales multileptónicos. Los resultados que presento en este documento se corresponden con medidas de precisión de la interacción electrodébil, tanto del ME como de procesos de nueva física, incluyendo las mejores medidas hasta la fecha del proceso de producción WZ y varios

de los resultados más restrictivos en términos de producción electrodébil de procesos supersimétricos.

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