



SAPIENZA
UNIVERSITÀ DI ROMA

The Light, the Massive and the Unattainable: chasing new Physics in the dimuon channel with ATLAS at LHC

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A thesis submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Physics

31 March 2021

Thesis defended on 2 July 2021
in front of a Board of Examiners composed by:
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dimuon channel with ATLAS at LHC**

Ph.D. thesis. Sapienza – University of Rome

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This thesis has been typeset by $\text{\LaTeX}$ and the Sapthesis class.

Version: June 28, 2021

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*Dedicated to
Zorro I*

Abstract

The studies presented in this thesis are motivated on new physics models which predict the existence of new particles decaying in a dilepton final state. Searches for new resonant phenomena in the mass range 250 GeV to 6 TeV and non resonant phenomena up to an energy scale of 40 TeV are presented. The data were recorded by the ATLAS experiment in proton-proton collisions at a centre-of-mass energy of 13 TeV during Run 2 of the Large Hadron Collider and correspond to an integrated luminosity of 139 fb^{-1} . Fits of the experimental dilepton invariant mass spectra are performed allowing to determine the significance of possible deviations from the estimated backgrounds. No significant deviation is observed. Upper limits are placed on the fiducial cross-section times branching ratio, as well as on the number of signal events. For a set of benchmark models, the limits are converted into lower limits on the resonance mass and on the contact interaction energy scale. A fundamental role is played by the performance of the ATLAS muon spectrometer in the reconstruction of high- p_T muons. This work provides an overview on the muon reconstruction method, defining the requirements for the identification of high- p_T muons, together with several innovations. The high-mass analysis is extended to the lower mass (40-73 GeV) searching for a narrow resonance decaying to a pair of muons. Expected model independent upper limits are set on the fiducial cross-section times branching ratio. A reinterpretation of the limits in the context of dark photon model is also presented. Furthermore, the LHC accelerator will be upgraded with an increase of instantaneous and integrated luminosity. The ATLAS goal is to cope with higher particle rate while preserving the current muon detection efficiency. For this purpose the current innermost stations of the Muon Spectrometer end-caps will be replaced with the New Small Wheel (NSW) detector. The NSW will feature two new detector technologies: resistive Micromegas and sTGC chambers. An overview of the design, construction, assembly procedures and validation test of the Micromegas modules is reported. Results and characterization are also presented.

Acknowledgments

Un grazie speciale a Cesare che un bel po' di anni fa, totalmente ignaro di cio' che lo avrebbe aspettato, mi ha proposto di fare la tesi con lui avviandomi a questo traguardo. Ancora grazie a Cesare e ai miei supervisor, Massimo e Stefano, che durante questi anni mi hanno insegnato davvero tanto, supportatondomi e sopportandomi. Al Boss, a Valerione e a Ambarabauce che mi hanno sempre fatto sentire parte di un unico gruppo. A Sebba, Scurcio e Valery con cui ho condiviso la laurea magistrale e che hanno completamente ribaltato la mia visione della fisica spingendomi a non lasciare questo percorso. Ancora e ancora e ancora grazie Sebba che un giorno, così de botto, hai deciso che avrei dovuto fare il dottorato con te, grazie grazie. A Sebba, Limone, Giustino, Pino e al tacchino colleghi di lavoro, di work trip e di supercazzole continue, avete reso tutto piu' bello e piu' facile. Un grazie a tutta la saletta perche' chiunque ci sia passato ha lasciato un suo ricordo che non dimentichero' mai (non ricordo se il dottor cholo ci sia mai passato...grazie dottore). "Mamma mia sta a veni piu' lungo della tesi". Grazie Maria Francesca, che da una vita ci sei sempre stata e mi hai sempre dato i consgli giusti. A babbo, mamma, Marta e agli amici di sempre che hanno sempre fatto il tifo per me e che continueranno sempre a farlo, vi voglio bene. A strama con cui ho condiviso tanto di questo percorso. Last but not least, A Rappy che da quando e' entrata nella mia vita ha portato una tempesta d'amore e felicità, che si e' sorbita tutte le difficolta' del momento pre consegna sostendomi di continuo e che mi ha anche aggiustato l'inglese della tesi <3. Grazie Pata.

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Chapter 1

Introduction

The Standard Model (SM) of elementary particles and their fundamental interactions provides a very elegant theoretical framework for the description of the constituents of the matter and how they interact.

The search for physics beyond the Standard Model (BSM) is nowadays mainly motivated by the fact that, despite its experimental success, the theory still has some drawbacks and unsolved problems that represent a strong conceptual indication for new physics in the high energy domain.

Furthermore the particle nature of Dark Matter (DM) is amongst the urgent question in fundamental physics.

SM only describes visible matter, but irrefutable astrophysical and cosmological measurements based on gravitational interactions reveal that the universe contains about five times more DM [1], completely different from the ordinary matter.

After completing the Standard Model (SM) theory of particle physics with the discovery of the Higgs boson in 2012, the experiments situated at the Large Hadron Collider [2] (LHC) in Geneva are shifting their interests on both: precision measurements of the SM and signatures of BSM physics. In particular, a focus is on the mystery of DM and search for signals of BSM.

Several extensions of the SM propose a solution to the DM puzzle predicting new particles that could be observed at hadron colliders. The leading class of candidates searched for at the LHC are Weakly Interacting Massive Particles (WIMP), which are predicted to couple to SM particles through a generic weak interaction.

One interesting alternative scenario is the Dark Sector (DS), where DM particles are only a piece of a new extended sector. The new hidden sector with its own complex structure can include new particles and new "dark forces" such as electromagnetic-like forces mediated by new particles named dark photons.

The presence of new forces may have gone easily undetected by all experiments so far due the weakness of the coupling between the DS and the SM. Dark sector searches target the portal mediator rather the DM itself, assuming only the existence of a non-gravitational coupling between the two sectors and without any hypothesis on the DM structure. The new hypothetical interactions are tightly linked to the structure of the SM and can be mediated by vector, Higgs, and neutrino portals. Of specific interest for this thesis is vector portal model, where a massive dark photon kinetically mixes with the SM photon.

One of the most interesting signature is a narrow peak, where neutral particle decays to pairs of light leptons, providing model-independent results that can be interpreted in the context of a dark photon and of an hypothetical Dark Matter mediator.

The LHC collides bunches of protons and delivers data to six experiments, among which there is ATLAS [3]. The data, corresponding to an integrated luminosity of 139 fb^{-1} , were recorded by the ATLAS experiment in proton-proton collisions at a centre-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$ during LHC Run 2 (2015-2018). With the ongoing LHC enhancement of the luminosity, which will allow for the collection of about 300 fb^{-1} by 2023/2024 (LHC Run3), the coming years are scientifically challenging and exciting. More data will allow to widen the scope of LHC Physics studies, and to increase the sensitivity beyond past and present searches.

During the HL-LHC phase, expected to start in 2027 after the so called long shutdown 3, the LHC will operate far beyond its design luminosity values keeping the same bunch spacing, leading to approximately four times higher average number of interactions per bunch crossing, with respect to the 2018 run; thus, ATLAS will have to cope with much harsher experimental conditions. A key development in this context is the New Small Wheel upgrade of the muon system.

This thesis documents ATLAS current and future efforts in the search for new physics phenomena detectable from the production of muon pairs, ranging from a few GeV to several TeV.

The latest ATLAS Run-2 search using 139 fb^{-1} of collected data results are presented and ATLAS New Small Wheel project is discussed.

An overview of the SM theory and its extension to the Dark Matter and Dark Sectors with their phenomenology are discussed in Chapter 2. Chapter 3 summarises the main characteristics of the ATLAS detector and the reconstruction of physics objects. The New Small Wheel upgrade for the ATLAS experiment is described in detail in Chapter 4. The Run-2 searches for new high-mass (greater than 200 GeV) resonant and non resonant phenomena as well as dedicated improvement prospects are discussed in detail in Chapter 5. Finally, Chapter 6 show the extension of high-mass searches to the lower mass range (40-73 GeV), describing the analysis strategy and providing the expected limit for the sensitivity of the search.

Chapter 2

Standard Model and beyond

The Standard Model of particle physics is the theory describing three of the four known fundamental forces (the electromagnetic, weak, and strong interactions) in the universe, as well as classifying all known elementary particles. All the fundamental forces, with the exception of gravity, are described by a quantum field theory. However the gravitational interaction can be considered negligible at the collider energy scale. The model was first introduced in the late 60s and it aimed at the explanation and prediction of an incredible wide array of phenomena of elementary particle physics. Fifty years of experimental evidence have tested the model with great precision but have also shown few hints of a new physics beyond the SM.

This Chapter introduces the basics of SM theory (2.1) and its limitations. An overview of the theoretical models tested by the new physics searches presented in this work(2.2).

2.1 The Standard Model

In the SM formulation each particle is represented as a field and its dynamic is described by a Lagrangian. In its postulation there are symmetries under which the Lagrangian must be invariant. The SM is symmetric under translation, rotation and boost transformations (Lorentz invariance) and it is also gauge invariant under the local $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge symmetry, where $SU(3)_C$, $SU(2)_L$ and $U(1)_Y$ can be each associated with a fundamental interaction: the $SU(3)_C$ non-abelian group is related to the strong force, what the $SU(2)_L \times U(1)_Y$ is related to the electroweak force.

2.1.1 Particles

In the SM framework, all the elementary particles are classified in two groups according to their spin:

- *fermions* are half-integer spin particles which obey Fermi-Dirac statistics
- *bosons* are integer spin particles which follow Bose-Einstein statistics

Fermions can be divided in *leptons* and *quarks*, while bosons are divided in Spin-1 boson (vector) and Spin-0 boson (scalar).

Leptons

Leptons are divided in three families, each one for a different flavour: electron (e) and its neutrino (ν_e), muon (μ) and its neutrino (ν_μ) and tau (τ) and its neutrino (ν_τ). Electron, muon and tau are electric charged particles and interact under the electromagnetic and weak forces, while the neutrinos are neutral particles and interact only via the weak force. The leptons in decreasing order of mass are taus and muons that decay into electrons, the lightest leptons.

Quarks

Quarks, like leptons, are arranged in three families. Each family is composite by a quark pair, one up-type and one down-type. The electric charge is equal to $\frac{2}{3}e$ and to $-\frac{1}{3}e$ for the up-type and down-type, respectively. Each of the six quarks has its own flavour: up (u), down (d), strange (s), charm (c), bottom (b), and top (t), here given in increasing order of mass. Proton and neutron are composed of u and d quarks. Quarks are not only electrically charged but also color charged and interact under the strong, electric and weak forces.

Vector bosons

Vector bosons are responsible of interaction among fermions. In particular the strong force is mediated by eight massless and electrically neutral gluons that are the equivalent of the eight 3×3 *Gell-Man matrices*, one per each generator of the $SU(3)_C$ gauge symmetry. The strong force is responsible for bounding quarks within nucleons and together protons and neutrons in the atomic nucleus.

The electromagnetic force is mediated by the photon (γ), which is massless and electrically neutral and acts as the exchange particle with all electric charged particles. The electro-weak $W^\pm/Z$ bosons are mediators of the weak interaction. The Z boson acts as the exchange particle with all the fermions and its electric charge is 0, while the $W^\pm$ is electrically charged and its action is limited to left-handed fermions (spin and motion direction are opposite) and right-handed (spin and motion direction are the same) anti-fermions. The weak force is responsible for the nuclear β -decays and has a crucial role in the nuclear fusion processes.

Scalar boson

The only spin-0 particle in the SM is the Higgs boson. It gives mass to all elementary particles, with the exception of photons and gluons. Vector bosons gain mass through the process of electro-weak symmetry breaking, while the leptons and quarks via Yukawa coupling. These mechanisms will be outlined later in this chapter.

2.1.2 Elements of quantum field theory

The quantum field theory is used to construct physical model of subatomic particles and their interactions, incorporating quantum mechanics, special relativity and the concept of field.

Quantum electrodynamics

Quantum field theory naturally began with the study of electromagnetic interactions,

since the electromagnetic field was the only known classical field in the 1920s. Quantum electrodynamics [4] (QED) describes the electromagnetic interactions. QED is an abelian gauge theory, with the symmetry group being $U(1)$. Abelian gauge theory is a type of field theory in which the Lagrangian is invariant under local transformations from certain symmetry groups.

In equation 2.1 the Lorentz-invariant Lagrangian is given:

$$\mathcal{L}_{QED} = \bar{\psi}(i\gamma^\mu\partial_\mu - m)\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}, \quad (2.1)$$

where ψ is the Dirac Spinors free fermionic field, when γ_μ are the Dirac matrices in the rest mass frame of the particles[5], $F^{\mu\nu}$ is the kinetic tensor defined as $F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$ and $A_\mu(x)$ is the electromagnetic field. This Lagrangian is required to be invariant under local transformation of the $U(1)$ symmetry group, defined as follows:

$$\psi(x) \rightarrow \psi'(x) = e^{if(x)}\psi(x), \quad (2.2)$$

where x represents the coordinate of the space-time and $f(x)$ defines the transformation for each point. The invariance of the Lagrangian under $U(1)$ symmetry is achieved by introducing the covariant derivative, defined as:

$$D_\mu = \partial_\mu + ieA_\mu, \quad (2.3)$$

in the place of the partial derivative operator ∂_μ and requiring the field A_μ to transform as:

$$A'_\mu \rightarrow A_\mu - \frac{1}{e}\partial_\mu f(x) \quad (2.4)$$

The final QED Lagrangian is therefore under the gauge transformations and give as:

$$\mathcal{L}_{QED} = \bar{\psi}(i\gamma^\mu\partial_\mu - m)\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - e\bar{\psi}\gamma^\mu A_\mu\psi. \quad (2.5)$$

The new interaction term $-e\bar{\psi}\gamma^\mu A_\mu\psi$ describes the coupling between charged fermions and the potential of the electromagnetic field, with e equal to the electron charge.

Quantum chromodynamics

Quantum chromodynamics (QCD) [6] is the quantum field theory for strong interactions between quarks and gluons. It is a non-abelian gauge theory, with symmetry group $SU(3)_C$. Quarks need to transform under the $SU(3)$ symmetry group and are represented as three component spinors ψ . In this $SU(3)$ non-abelian theory, the eight generators are conventionally taken as $T^a = \Lambda^a/2$, where Λ^a are the eight 3×3 Gell-Man matrices.

In order to make the lagrangian invariant under the $SU(3)_C$ symmetry transformation, eight gauge gluon fields, G_μ^a , are introduced and the following covariant derivative is defined:

$$D_\mu = \partial_\mu + i\alpha_s G_{\mu a} T^a, \quad (2.6)$$

where α_s is the QCD coupling constant.

Finally, the QCD Lagrangian is:

$$\mathcal{L}_{QCD} = \bar{\psi}(i\gamma^\mu\partial_\mu - m)\psi + \bar{\psi}(i\alpha_s T^a G_\mu^a - m)\psi - \frac{1}{4}G_{\mu\nu}^a G_a^{\mu\nu}. \quad (2.7)$$

Two important features of QCD are:

- color confinement
- asymptotic freedom

Color confinement means that quarks and gluons cannot be isolated and so it is not possible to observe them directly as free particles. Asymptotic freedom is a property of quarks inside hadrons for which they can be assumed to behave as free particles at high energies typical of HEP collider experiments. Both color confinement and asymptotic freedom are a consequence of α_s behaviour, which becomes larger at higher distance and gets weak at smaller distance.

Electroweak model

The electroweak theory describes the unification of the electromagnetic and weak interactions under the $SU(2)_L \times U(1)_Y$ symmetry group, where L and Y refer to left-handed fields and to hypercharge, respectively. The weak interactions, are mediated by vector gauge bosons and are characterised by a smaller relative intensity than the electromagnetic and strong interactions. Parity violation is a consequence of different left-handed and right-handed components transformation under weak interactions. Three generators of the $SU(2)_L$ group are the weak isospin $\vec{\tau} = \frac{1}{2}\vec{\sigma}$ described by the Pauli matrices, while the generator of the $U(1)_Y$ group is the hypercharge Y . The group's local gauge transformations for left-handed fermions $\psi(x)_L$ and right-handed fermions $\psi(x)_R$ are:

$$\psi(x)_L \rightarrow \chi'(x)_L = e^{i\vec{\alpha}(x)\vec{\tau} + i\beta(x)Y} \psi(x)_L, \quad (2.8)$$

$$\psi(x)_R \rightarrow \psi'(x)_R = e^{i\beta(x)Y} \psi(x)_R. \quad (2.9)$$

$\vec{\alpha}(x)$ and $\beta(x)$ are the phases, χ_L is the weak isospin doublet that describes left-handed fermions.

Introducing the covariant derivative for electroweak interaction as:

$$D_\mu = \partial_\mu + ig' \frac{Y}{2} B_\mu(x) + ig \frac{\tau^a}{2} W_\mu^a(x) \quad (2.10)$$

where g' and g are the coupling constants, $B_\mu(x)$ is the $U(1)$ group field, and $W_\mu^a(x)$ is the $SU(2)$ group field, the electroweak lagrangian is formulated as follows:

$$\mathcal{L}_{EW} = \sum_{j=1}^3 i\bar{\psi}_j(x)\gamma^\mu D_\mu \psi_j(x) - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W_{\mu\nu}^a W_a^{\mu\nu}. \quad (2.11)$$

where the index $j = 1, \dots, 3$ indicates the three generations of fermions.

The observable vector fields are obtained by combining the gauge group fields in the following way:

$$A_\mu = W_\mu^3 \sin\theta_W + B_\mu \cos\theta_W, \quad (2.12)$$

$$Z_\mu = W_\mu^3 \cos\theta_W + B_\mu \sin\theta_W, \quad (2.13)$$

$$W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp W_\mu^2), \quad (2.14)$$

where θ_W is the Weinberg angle. In the next equations, the electric charge e is expressed in terms of the coupling constants and the Weinberg angle as:

$$e = g \sin\theta_W = g' \cos\theta_W. \quad (2.15)$$

This theory appears to be in contrast with experimental results as all SM gauge bosons appear to be massless, any mass term introduced by hand would spoil the theory renormalizability. This discrepancy is resolved by the Higgs mechanism that naturally introduces mass terms in the SM lagrangian.

Higgs mechanism

As anticipated in the previous section, the Higgs mechanism gives a way to solve the gauge bosons mass inconsistency. This mechanism is based on the existence of a scalar boson which, when coupled to field bosons, allows the $W^\pm$ and Z^0 bosons to have a mass different from zero. The model introduces the spontaneous breaking of the $SU(2)_L \times U(1)_Y$ symmetry group into the $U(1)_{EM}$ group. The spontaneous symmetry breaking is obtained by choosing one of the degenerate ground eigenstates of the lagrangian system as the state of minimum energy. This results in the presence of three massless Goldstone bosons, which can be interpreted, applying and $SU(2)$ gauge transformation as the third polarization component of each vector boson. The vector bosons can in this frame acquire mass, while the photon remains massless. The electroweak symmetry breaking requires a new $SU(2)$ isospin doublet complex scalar field:

$$\phi = \begin{pmatrix} \phi_\alpha \\ \phi_\beta \end{pmatrix} = \sqrt{\frac{1}{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \quad (2.16)$$

This new field is invariant under local $SU(2)$ transformation, defining the new covariant derivative:

$$D_\mu = \partial_\mu + ig \frac{\tau_a}{2} W_\mu^a \quad (2.17)$$

where this term $ig \frac{\tau_a}{2} W_\mu^a$ represents the coupling with W_μ^a . As a consequence, the new electroweak lagrangian is:

$$\mathcal{L} = \left(\partial_\mu \phi + ig \frac{\tau}{2} W_\mu \phi \right)^\dagger \left(\partial_\mu \phi + ig \frac{\tau}{2} W^\mu \phi \right) - \frac{1}{4} W_{\mu\nu} W^{\mu\nu} - V(\phi), \quad (2.18)$$

where $V(\phi)$ is the Higgs potential defined as:

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2, \quad (2.19)$$

μ and λ are free parameters.

Theory is stable if $\lambda > 0$ since the potential results inferiorly bounded. Additionally, for values $\mu^2 < 0$ the minimum is degenerate along a circumference, as shown in Figure 2.1.

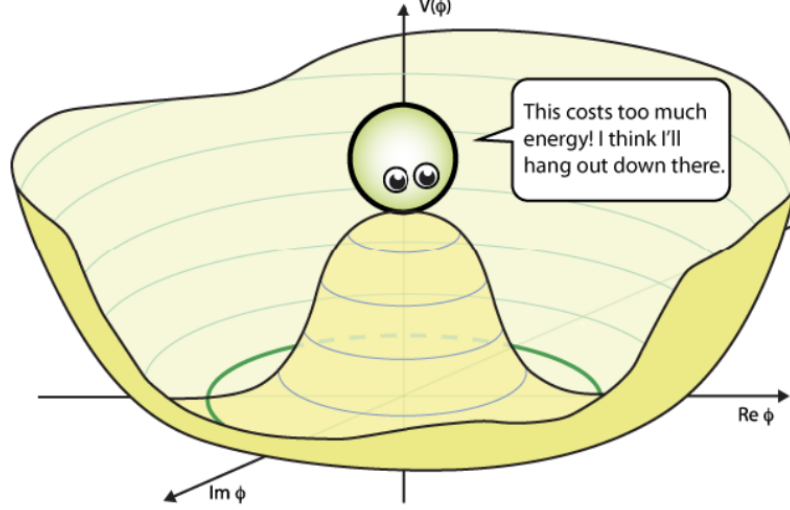


Figure 2.1. An illustration of the Higgs potential. Choosing any of the points at the bottom of the potential (green curve) breaks spontaneously the rotational U(1) symmetry.

The symmetry breaking is obtained by choosing the ground state as $\phi_1 = \phi_2 = \phi_4 = 0$ and $\phi_3 = \sqrt{\frac{-\mu^2}{\lambda}} = v$:

$$\phi(x) = \sqrt{\frac{1}{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}. \quad (2.20)$$

Expanding the ground state $\phi(x)$ using the following parametrization : $\theta_1, \theta_2, \theta_3$, and $h(x)$, allows to compute perturbative calculations as follows:

$$\phi(x) = \sqrt{\frac{1}{2}} \begin{pmatrix} \theta_1 + i\theta_2 \\ v + h - i\theta_3 \end{pmatrix}. \quad (2.21)$$

Where $\theta_1, \theta_2, \theta_3$, are the massless Goldstone bosons scalar fields, which can be removed by a SU(2) gauge transformation. In the following equation the field expressed by the remaining the Higgs scalar field $h(x)$ is given:

$$\phi(x) = \sqrt{\frac{1}{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}. \quad (2.22)$$

The Higgs lagrangian in terms of this field is formulated as:

$$\mathcal{L}_{Higgs} = \frac{1}{2} \partial_\mu h \partial^\mu h + (v + h)^2 \left(\frac{g^2}{4} W_\mu^\dagger W^\mu + \frac{g^2}{8 \cos^2 \theta_W} Z_\mu Z^\mu \right) - \lambda^2 h^2 - \lambda v h^3 - \frac{\lambda}{4} h^4. \quad (2.23)$$

After the spontaneous symmetry breaking the $W^\pm$ and Z vector gauge bosons have gained a mass, while leaving the photon massless, and a new scalar boson h is

included. The model introduces several new parameters to the theory. The vacuum expectation value of the Higgs field v is:

$$v^2 = \frac{1}{\sqrt{2}G_F} \simeq 246 \text{ GeV}^2 \quad (2.24)$$

which is connected to the Fermi constant G_F , while others parameters, such as the Higgs boson mass m_H and λ , remain free.

Last, mass terms for fermions are added in this framework via Yukawa couplings, by adding the following local gauge invariant mass terms to the lagrangian:

$$\mathcal{L}_{Yukawa}^{leptons} = -G_l \left((\bar{\nu}_l, \bar{l})_L \begin{pmatrix} \phi_\alpha \\ \phi_\beta \end{pmatrix} l_R + \bar{l}_R (\bar{\phi}_\alpha, \bar{\phi}_\beta) \begin{pmatrix} \nu_l \\ l \end{pmatrix}_L \right), \quad (2.25)$$

$$\mathcal{L}_{Yukawa}^{quark} = -\lambda_d^{ij} (\bar{u}_i, \bar{d}'_j)_L \begin{pmatrix} \phi_\alpha \\ \phi_\beta \end{pmatrix} d_{jR} - \lambda_u^{ij} (\bar{u}_i, \bar{d}'_j)_L \begin{pmatrix} \bar{\phi}_{alpha} \\ \bar{\phi}_\beta \end{pmatrix} u_{jR} + h.c. \quad (2.26)$$

where $d'_i = V_{CKM} d_i$, are the eigenstates for the d , s , b quarks rotated by the Cabibbo-Kobayashi-Maskawa (CKM) matrix. As a consequence from the spontaneous symmetry breaking the lagrangian is formulated as:

$$\mathcal{L}_{Yukawa}^{leptons} = -\lambda_l \left((\bar{\nu}, \bar{l})_L \begin{pmatrix} \phi_\alpha \\ \phi_\beta \end{pmatrix} l_R + h.c. \right), \quad (2.27)$$

$$\mathcal{L}_{Yukawa}^{quarks} = -m_d^i \bar{d}_i d_i \left(1 + \frac{h}{v} \right) - m_u^i \bar{u}_i u_i \left(1 + \frac{h}{v} \right). \quad (2.28)$$

Fermion masses are proportional to the Higgs coupling to leptons and quarks, and are a free parameter of the theory not predicted by the SM.

2.2 Beyond the standard model

As described in the previous section 2.1, the SM of elementary particles and their fundamental interactions provides a very elegant theoretical framework for the description of the constituents of the matter and how they interact. The search for physics beyond the Standard Model (BSM) is nowadays mainly motivated by the fact that, despite its experimental success, the theory still has some drawbacks and unsolved problems that represent a strong conceptual indication for new physics in the high energy domain as:

- the large number of free parameters: they are the independent parameters of the fermion sector, three coupling constants of the gauge sectors, the two parameters describing the Higgs boson;
- the model does not provide an explanation of matter/antimatter asymmetry and Dark Matter/Energy contributions;
- the unexplained existence of 3 generations of fermions;
- the assumption of zero mass for neutrinos in contrast to experimental evidence;

- the model does not include gravitational interactions;

The following section will provide an overview of the theoretical models underlying the searches presented in this work. An essential description of the model, together with motivation for its validity, are presented.

Weakly Interactive Massive Particles

The SM only describes visible matter, but several independent proofs tell us that the universe contains about five times more "dark matter", completely different from the ordinary matter. Hence, it is clear that the SM gives an incomplete picture of the content of the universe and new physics is needed to solve the problem.

The principal Dark Matter paradigm, commonly assumed in particle physics searches, is that of the Weakly Interactive Massive Particles (WIMP). This paradigm assumes a DM composed of an elementary particle with small couplings to SM, of the same strength of weak interactions. WIMP particle searches are categorised by specific experimental signatures: direct, indirect, and collider searches. Direct detection experiments search for nuclear recoils due to WIMP-nuclei scattering in a large volume of active material. A WIMP flux of about $10^5 \text{cm}^{-2}\text{s}^{-1}$ is expected to flow through the Earth, as a consequence of the Earth movement inside the DM halo that permeates the galaxy, for a reference WIMP candidate with a mass of 100 GeV. The collision rate is thus very small and these processes are extremely rare. Experiments searching for Dark Matter candidates are usually placed in deep underground laboratories to suppress the cosmic-ray background, trying to reach a zero background search. Indirect detection experiments search for WIMP pair annihilations to SM particles, such as neutrinos and positrons, in the sky. In this scenario, gravitational induced accumulation of WIMP particles in heavy objects reach the necessary density for annihilation processes. Instead, collider experiments search for WIMP production in high-energy collisions. All possible dark matter detection channels are schematically shown in Figure 2.2.

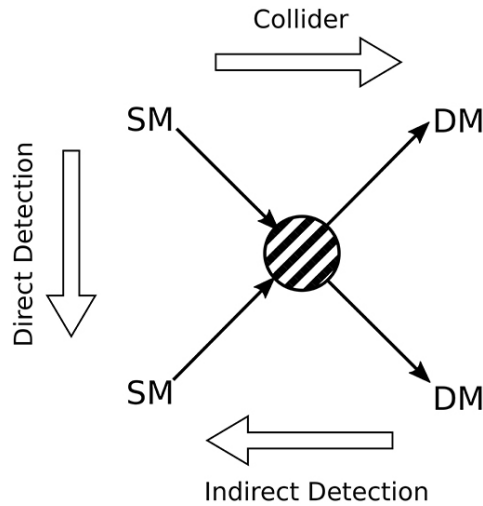


Figure 2.2. Schematic showing the possible dark matter detection channels.

These searches are complementary to one another, each probing different mass ranges and energy scales. The LHC program has put a great effort on WIMP searches, probing a wide spread of WIMP simplified model parameter space ranging from the electroweak scale up to many TeV. Instead, direct and indirect searches explore more minimal models which assume only the DM density and a WIMP-nucleon interaction. A summary of important results of the many direct searches experiment is shown in Figure 2.3, where the WIMP-nucleon cross section is plotted versus the WIMP mass for a spin independent interaction.

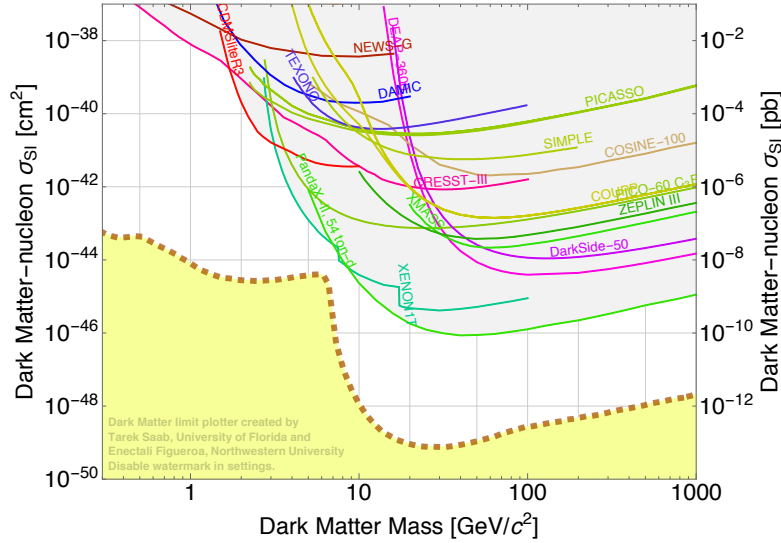


Figure 2.3. Spin-independent WIMP-nucleon scattering results.

The strongest limits on WIMP-nucleon interaction come from PANDAX-II [7] and XENON-1T [8] experiments, based on double-phase technology that allow to exploit both the ionization and scintillation information. These limits are in contradiction with the claimed WIMP observation from DAMA-LIBRA of an observed annual modulation of the event rate at 8.9σ [9]. Although a definitive WIMP discovery has yet to be made, these measurements have motivated an extended search of DM models outside the WIMP paradigm. LHC experimental efforts have been devoted to the energy frontier, exploring new particles masses above the EW scale with significant couplings. The intensity frontier is largely unexplored, where one could search for new particles below the EW scale not yet detected due to their small coupling with the SM particles. In this region, one of the most promising theories are the Dark Sector models, which assume a new hidden structure of forces and particles, of which DM could be composed, and feebly connected to the SM via portals.

In this work, different models which predict the existence of new spin-1 resonances, such as an hypothetical Z'/Z_D Dark Matter mediator, with the subsequent decay into a final state consisting of a pair of leptons ($\mu\mu$, ee) have been tested. These include extensions to the SM as in the E_6 -motivated Z' [10], contact interactions

[11, 12] and in the Dark Sector models [13].

2.2.1 E_6 -motivated Z' models

Additional $U(1)'$ gauge symmetries and associated Z' gauge bosons are one of the best motivated extensions of the SM. One of the benchmark models for Z' bosons is the Sequential Standard Model (SSM), in which the Z' (Z'_{SSM}) has the same couplings to fermions as the SM Z boson. A more theoretically motivated model is a Grand Unification model in which the E_6 gauge group is broken into $SU(5)$ and two additional $U(1)$ groups. The lightest linear combination of the corresponding two new neutral gauge bosons, Z'_ψ and Z'_χ , is considered the Z' candidate: $Z'(\theta_{E6}) = Z'_\psi \cos \theta_{E6} + Z'_\chi \sin \theta_{E6}$, where $-\pi \leq \theta_{E6} < \pi$ is the mixing angle between the two gauge bosons. For the two benchmark models described above the Z' coupling to the SM $W^\pm$ and Z bosons is zero.

This process can be probed in dilepton searches looking for bumps in the $m_{e^+e^-}/m_{\mu^+\mu^-}$ spectra (see Figure 2.4).

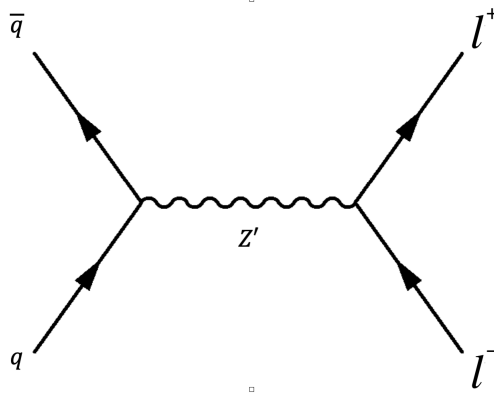


Figure 2.4. Diagrams for Z' production through the Drell-Yan mechanism and decaying in a pair of leptons.

Current bounds

The search for high mass resonant phenomena in dilepton final states is generally sensitive to any model that predicts the presence of narrow dilepton resonances. The generic limit provided with the search should allow for reinterpretations into these models, as the predicted resonance shape is usually similar between different models and the difference in the limits is the result of the different detector acceptance.

Previous direct searches for a Z' have been carried out at the Tevatron experiments [14, 15] and indirect constraints come also from LEP [16–19]. These have resulted in limits on the Z'_{SSM} mass of 1.07 TeV [15] and 1.79 TeV [20], respectively. Searches have also been performed by the ATLAS and CMS Collaborations [21, 22]. The strongest ATLAS exclusion limits for Z'_χ come from the previous search conducted using 36.1 fb^{-1} of proton-proton collision data at $\sqrt{s} = 13 \text{ TeV}$ [23]. That combined analysis of the dielectron and dimuon channels set lower limits at 95% confidence

level (C.L.) on the Z'_χ pole mass of 4.1 TeV (see Figure 2.5). The CMS exclusion limits for this search in 2018 are very similar to ATLAS [24].

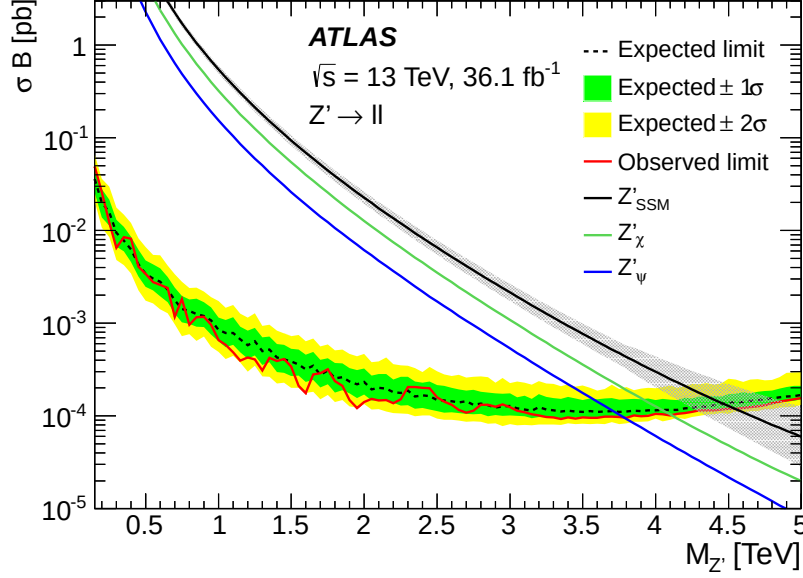


Figure 2.5. Upper 95% CL limits on the Z' production cross-section times branching ratio to two leptons of a single flavour as a function of Z' pole mass ($M_{Z'}$). Results are shown for the combined dilepton channel. The signal theoretical σB are calculated with PYTHIA 8 using the NNPDF23LO PDF set, and corrected to next-to-next-to-leading order in QCD using VRAP and the CT14NNLO PDF set. The signals theoretical uncertainties are shown as a band on the Z' SSM theory line for illustration purposes, but are not included in the σB limit calculation [23].

2.2.2 Contact interactions

The presence of a new interaction can be detected at an energy much lower than that required to produce direct evidence of the existence of a new gauge boson. The charged weak interaction responsible for nuclear β decay provides such an example. A non-renormalizable description of this process was successfully formulated by Fermi in the form of a four-fermion contact interaction [25]. A contact interaction can also accommodate deviations from the SM in proton–proton scattering due to quark and lepton compositeness, where a characteristic energy scale Λ corresponds to the binding energy between fermion constituents. A new interaction or compositeness in the process $q\bar{q} \rightarrow \ell^+\ell^-$ can be described by the following four-fermion contact interaction Lagrangian [11, 12]:

$$\mathcal{L} = \frac{g^2}{\Lambda^2} [\eta_{LL} (\bar{q}_L \gamma_\mu q_L) (\bar{\ell}_L \gamma^\mu \ell_L) + \eta_{RR} (\bar{q}_R \gamma_\mu q_R) (\bar{\ell}_R \gamma^\mu \ell_R) + \eta_{LR} (\bar{q}_L \gamma_\mu q_L) (\bar{\ell}_R \gamma^\mu \ell_R) + \eta_{RL} (\bar{q}_R \gamma_\mu q_R) (\bar{\ell}_L \gamma^\mu \ell_L)],$$

where g is a coupling constant chosen by convention to satisfy $g^2/4\pi = 1$, Λ is the contact interaction scale, and $q_{L,R}$ and $\ell_{L,R}$ are left-handed and right-handed quark and lepton fields, respectively. The parameters η_{ij} , where i and j are L or R (left or right), define the chiral structure of the new interaction. Different chiral structures are investigated here, with the left-right model obtained by setting $\eta_{LR} = \pm 1$ and $\eta_{RL} = \eta_{LL} = \eta_{RR} = 0$. Likewise, the left-left, right-left, and right-right models are obtained by setting the corresponding parameters to ± 1 , and the others to zero. The sign of η_{ij} determines whether the interference is constructive ($\eta_{ij} = -1$) or destructive ($\eta_{ij} = +1$). The cross-section for the process $q\bar{q} \rightarrow \ell^+\ell^-$ in the presence of these contact interaction can be written as:

$$\sigma_{\text{tot}}(m_{\ell\ell}) = \sigma_{\text{DY}}(m_{\ell\ell}) - \eta_{ij} \frac{F_I}{\Lambda^2} + \frac{F_C}{\Lambda^4} , \quad (2.29)$$

where the first term accounts for the $q\bar{q} \rightarrow Z/\gamma^* \rightarrow \ell^+\ell^-$ Drell–Yan (DY) process (see Figure 2.6), the second term corresponds to the interference between the DY and Contact Interaction (CI) processes, and the third term describes the pure CI process. These two latter terms include F_I and F_C , respectively, which are functions of $m_{\ell\ell}$ differential cross-section and do not depend on Λ . The relative impact of the interference and pure CI terms depends on both the dilepton mass and Λ .

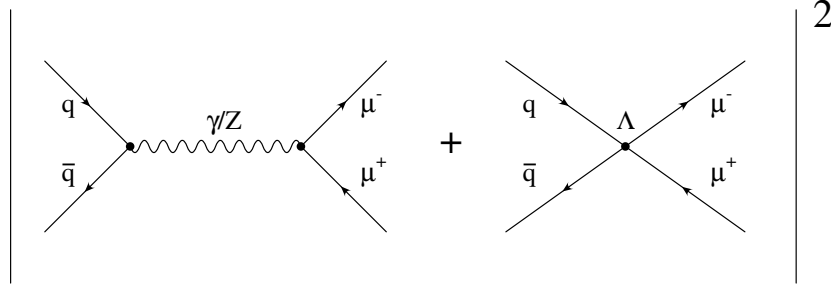


Figure 2.6. Leading-order production mechanism for Drell-Yan with additional contact term with scale Λ in the dimuon final state. Similar diagrams apply to the electron channel.

Current bounds

Previous searches for CI have been carried out in neutrino–nucleus and electron–electron scattering [26], as well as electron–positron [19, 27], electron–proton [28], and proton–antiproton colliders [29, 30]. Searches for CI have also been performed by the ATLAS and CMS Collaborations [22, 31]. The strongest exclusion limits for $\ell\ell q\bar{q}$ CI in which all quark flavours contribute come from the previous ATLAS non-resonant dilepton analysis conducted using 36 fb^{-1} of proton–proton (pp) collision data at $\sqrt{s} = 13 \text{ TeV}$ [23]. That combined analysis of the dielectron and dimuon channels set lower limits at 95% confidence level (C.L.) on the left-left model of $\Lambda = 40.1 \text{ TeV}$ and $\Lambda = 25.4 \text{ TeV}$, for constructive and destructive interference, respectively, given a uniform positive $1/\Lambda^2$, shown in Figure 2.7.

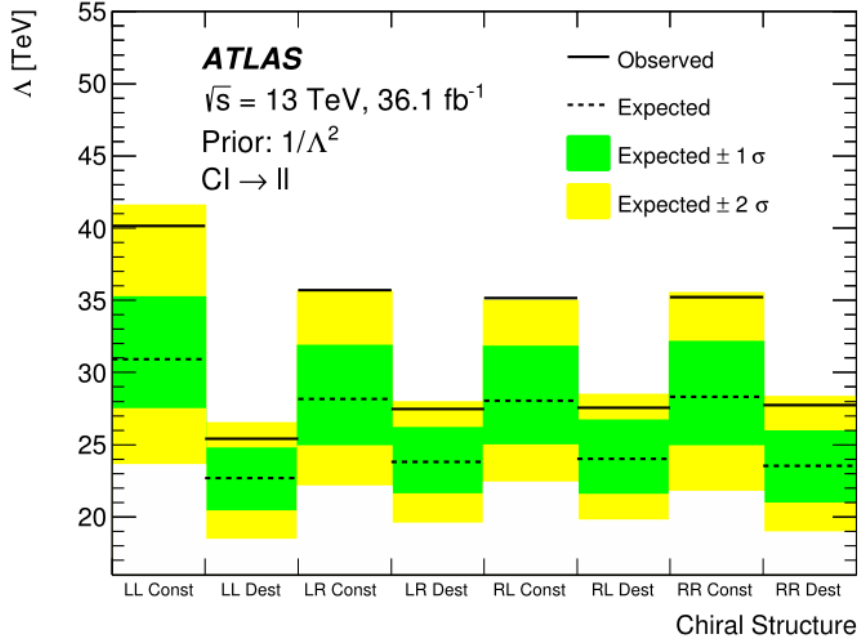


Figure 2.7. Previous ATLAS lower limits on the energy scale Λ at 95% CL. This figure shows results for constructive (const) and destructive (dest) interference, for all considered chiral structures [23].

2.2.3 Dark Sector

A possible Dark Matter candidate is a stable particle of an hidden sector that only couples weakly with SM. A minimal model foresees a dark-sector Fermion χ with a gauge interaction $U_D(1)$, similar to hypercharge $U_Y(1)$ of SM, and an associated gauge boson. The $U_D(1)$ gauge boson mixes with the neutral SM gauge bosons, giving rise to the usual massless photon γ , a massive dark photon Z_D and the usual Z^0 [32, 33].

A kinetically mixed dark U(1)

The dark photon's only renormalizable interaction with the SM is through kinetic mixing with the hypercharge gauge boson. The hidden sector can interact with the SM through the hypercharge portal, via the kinetic mixing coupling (ϵ) In this section a dark photon is assumed by adding the following new gauge terms in the Lagrangian [13]:

$$\mathcal{L} = -\frac{1}{4}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu} - \frac{1}{4}\hat{A}'_{\mu\nu}\hat{A}'^{\mu\nu} + \frac{1}{2}\frac{\epsilon}{\cos\theta_W}\hat{A}'_{\mu\nu}\hat{B}^{\mu\nu} + \frac{1}{2}m_{A',0}^2 A'^\mu \hat{A}'_\mu. \quad (2.30)$$

The new interaction is driven by the parameter ϵ which can assume any value.

Here a calculation of the Z_D cross section normalized to the SM one, with some simplifying assumptions, is reported. A more complete treatment, including the

treatment of the mixing with SM states γ and Z , interference with SM DY and NLO corrections to the decay widths are discussed in [13].

Neglecting for the moment the mixing with the Z boson and the interference terms, the ratio between the cross sections for a process mediated by a dark photon Z_D and a virtual photon γ^* is given by:

$$\frac{d\sigma^{Z_D}}{d\sigma^{\gamma^*}} = \frac{\frac{\epsilon^4}{(m^2 - M^2)^2 + \Gamma^2 m^2}}{\frac{1}{m^4}} \quad (2.31)$$

where M is the mass and Γ is total the width of the Z_D resonance.

If the cross section is integrated around the mass pole over a mass range that is much larger than the width ($\Delta M \gg \Gamma$), the narrow-width approximation can be used:

$$\int_{M-\Delta M/2}^{M+\Delta M/2} \frac{\epsilon^4}{(m^2 - M^2)^2 + \Gamma^2 m^2} dm \simeq \frac{\epsilon^4 \pi}{2M^2 \Gamma^2} \quad (2.32)$$

and

$$\int_{M-\Delta M/2}^{M+\Delta M/2} \frac{1}{m^4} dm \simeq \frac{\Delta M}{M^4}. \quad (2.33)$$

Then the ratio of the two integral gives the ratio of the Z_D cross section to the SM cross section integrated over a mass region around the pole:

$$\frac{N^{Z_D}}{N^{\gamma^*}} \simeq \frac{\pi \epsilon^4 M^2}{2 \Gamma \Delta M}. \quad (2.34)$$

The total width can be expressed as the leptonic width divided by the leptonic branching fraction. Using the LO leptonic width:

$$\Gamma = \frac{\Gamma_{ll}}{B_{ll}} = \epsilon^2 \frac{\alpha_{em} M}{3B_{ll}}, \quad (2.35)$$

the Z_D to SM ratio is given by:

$$\frac{N^{Z_D}}{N^{\gamma^*}} \simeq \frac{3}{2} \pi \frac{1}{\alpha_{em}} \epsilon^2 \frac{M}{\Delta M} B_{ll}. \quad (2.36)$$

It is proportional to ϵ^2 and inversely proportional to ΔM . The latter because the denominator increases with increasing ΔM , as more events from the SM continuum are integrated, while the numerator remains constant, as it includes only the contribution from the resonant peak. For a narrow width resonance, the integration region ΔM is related to the experimental resolution on the mass.

Figure 2.8 shows the dark photon leptonic branching fractions for $\epsilon = 10^{-2}$ (left) and decay length for different value of ϵ .

Assuming only the hypercharge portal, described above, the dominant discovery process would be Drell-Yan production. This channel can be probed in dilepton searches looking for bumps in the $e^+e^-/\mu^+\mu^-$ spectrum, with a very small cross section due to the suppression given by the needed double mixing ϵ^2 , one for production and one for decay (see Figure 2.9).

The Hidden Abelian Higgs Model (HAHM v3) model is used to generate the signal samples. A self-consistent derivation of mixing angles from M_Z , M_{Z_D} mass eigenvalue inputs is implemented. Mixing angles have also been defined in such a way that for small kinetic mixing ($\epsilon \ll 1$), the corresponding mixing angle will also be $\ll 1$ regardless of whether the dark or SM Z is heavier or lighter [35].

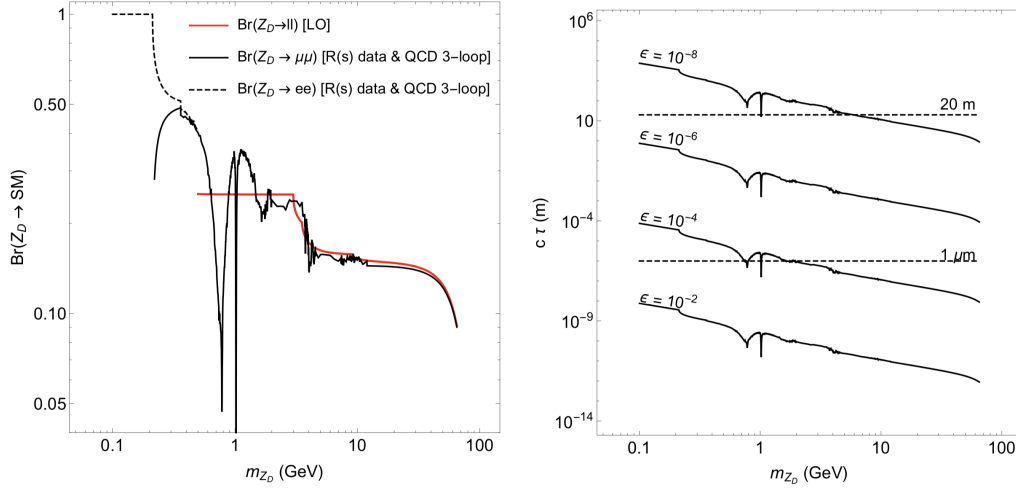


Figure 2.8. Dark photon branching fractions (left) for $A' \rightarrow e^+e^-$ (dashed), $A' \rightarrow \mu^+\mu^-$ (black-solid), $A' \rightarrow \ell^+\ell^-$ (red-solid). The kinetic mixing is fixed at $\epsilon = 10^{-2}$. Dark photon decay length (right) as a function of the dark photon mass for differing value of ϵ [34].

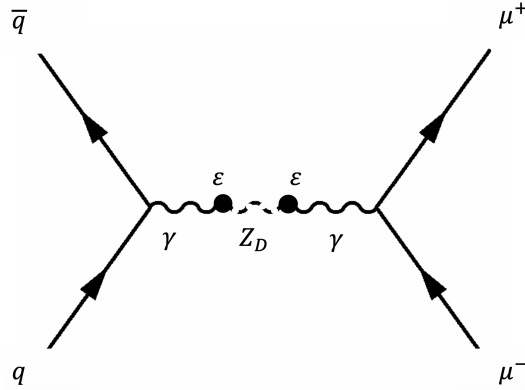


Figure 2.9. Diagrams for dark photon (Z_D) production via hypercharge portal. [13].

Current bounds

Dark photon searches are divided in many different analyses depending on the mass range and lifetime. Dark photon results are usually mapped into a two dimensional plane ϵ versus $m_{A'}$, assuming only a vector portal. Constraints have been set by several experiments covering wide regions of parameter space from the sub-GeV to the multi-TeV mass range. A summary of the most recent constraints [36] on A' searches are shown in Figure 2.10.

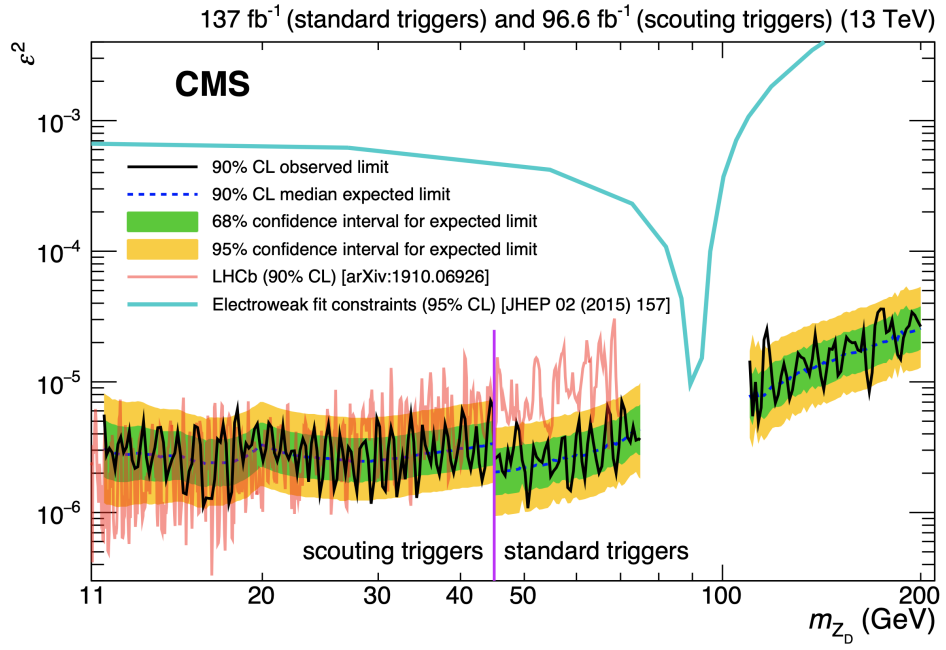


Figure 2.10. Expected and observed 90% CL upper limits on ϵ^2 as a function of the Z_D mass. Results from the dark photon search obtained by the CMS Collaboration, are shown in black [37]. Limits from the dark photon search performed by the LHCb Collaboration [38] are shown in red, and 95% CL constraints from the measurements of the electroweak observables, are shown in light blue [13].

Chapter 3

LHC and the ATLAS detector

In this chapter the Large Hadron Collider (LHC) [2], the world's largest and most powerful particle accelerator, is introduced and the ATLAS detector's structure and functionalities are described with particular emphasis on the muon spectrometer.

3.1 The Large Hadron Collider

The LHC hadron accelerator was built by the Conseil Européen pour la Recherche Nucléaire (CERN) between 1998 and 2008. It replaced the Large Electron-Positron collider (LEP) inside the 27 km long tunnel situated 100 m underground on the border between Switzerland and France close to the Geneva area.

The LHC is a circular proton-proton accelerator able to operate at an unprecedented center-of-mass energy of 14 TeV and an instantaneous luminosity of the order of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. At the time of writing the LHC has been in maintenance shutdown since Nov 2018, after having operated for a three year period at 7 TeV in 2010–2011 and at 8 TeV in 2012, called Run-1, and for a four year period at 13 TeV in 2015–2018, called Run-2.

3.1.1 CERN accelerator complex

The CERN laboratory hosts a complex of several accelerators. The proton beams are created and accelerated by a sequence of sub-accelerators to the final center-of-mass energy and finally collided at different interaction points of the main accelerator, the LHC. A schematic view of the CERN accelerator complex [39] is shown in Figure 3.1. The beam acceleration process is divided in stages, according to the different type of devices that the beam crosses. From the protons source to the last acceleration step we have:

- LINAC2;
- Proton Synchrotron Booster (PSB);
- Proton Synchrotron (PS);
- Super Proton Synchrotron (SPS);

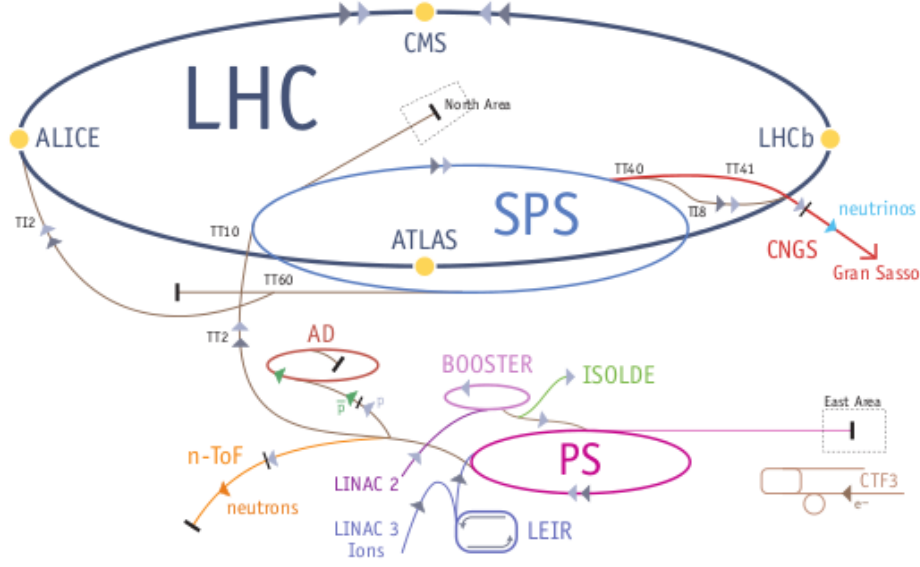


Figure 3.1. Scheme of the CERN accelerator complex, from the first linear accelerator to the LHC and a subset of the many experiments supported by these accelerators [40].

- LHC.

A proton beam is produced from H_2 gas and protons are then accelerated at 300 mA beam current. Protons enter in the PSB with an energy of 50 MeV from the LINAC 2 accelerator, and here they are accelerated up to 1.4 GeV. The PS accelerates protons up to 25 GeV and then the beams are injected in the SPS, where the protons reach an energy of 450 GeV.

As a last step, the two beams enter the LHC where they circulate in opposite directions until they reach the energy required for the collisions. Beams are accelerated thanks to eight resonant cavities, whose electric fields oscillate at 400.8 MHz, in order to kick protons and compensate for losses.

Protons enter the LHC in bunches and, to avoid collisions with gas molecules inside the accelerator, ultra-high vacuum is needed for the pipes in which the particle bunches travel. Each beam is composed by 2808 bunches with a 25ns separation and $\sim 10^{11}$ protons per bunch.

At the LHC *pile-up* plays an important role. When a collision between proton bunches happens, due to the very large value of the pp total interactions and due to the high intensity of the beam, a potential interesting event is covered by other non-interesting events produced in the same collision. Two kinds of pile-up exists: *in-time* pile-up due to additional proton-proton interactions in the same bunch-crossing, and *out-of-time* pile-up due to energy deposits in the calorimeter due to following bunch-crossing.

3.1.2 Run-2 LHC performance

The proton beams enter the LHC divided in bunches at a frequency of 40 MHz, hence separated in time by 25 ns. The bunch fill pattern is designed to maximise the rate of the collisions for a total of 2556 proton filled bunches in Run-2, out of a maximum allowed of 2808. The number of collisions that can be produced in a particle collider per cm^2 and per second depends on a very important machine parameter, the instantaneous luminosity, computed as

$$L = \frac{N_b^2 n_b f_{\text{rev}} \gamma}{4\pi \sigma_x \sigma_y} F. \quad (3.1)$$

The instantaneous luminosity depends only on the machine characteristics and not on specific physics processes. It is proportional to the bunch revolution frequency f_{rev} , the Lorentz boost factor γ and the number of colliding particles contained in each bunch, N_b , times the number of bunches, n_b . It is inversely proportional to the root mean square of the beam width in the x and y directions, σ_x and σ_y . Finally the instantaneous luminosity is corrected by a geometrical factor F which takes into account the crossing angle with which the beams are made to collide. The total luminosity delivered over a time period is called integrated luminosity, and is computed as

$$L_{\text{int}} = \int L dt. \quad (3.2)$$

This is used to quantify the amount of data delivered by the LHC and recorded by the experiment. In Figure 3.2 the integrated luminosity recorded by the ATLAS experiment during Run-2 is shown. In 2015–2018 data taking the LHC delivered 156 fb^{-1} of pp collisions of which ATLAS recorded 147 fb^{-1} .

A high luminosity environment can be extremely challenging for the detector and the trigger systems, having to cope with an extremely high particle multiplicity in the collisions. This is the case for the in-time pile-up effect, when multiple collisions occur during the same bunch crossing, and for the out-of-time pile-up, when the system reads out for a time span longer than the time between two bunch crossings. A parameter used to describe this effect is the average number of interactions per bunch crossings, $\langle \mu \rangle$, computed as follows

$$\langle \mu \rangle = \frac{L \cdot \sigma}{n_b \cdot f_{\text{rev}}} \quad (3.3)$$

where σ is the proton-proton inelastic cross section.

The luminosity-weighted distribution of the mean number of interactions per bunch crossing for the Run-2 data taking is presented in Figure 3.3. The mean $\langle \mu \rangle$ was found to be 33.7 for the full Run-2 data taking.

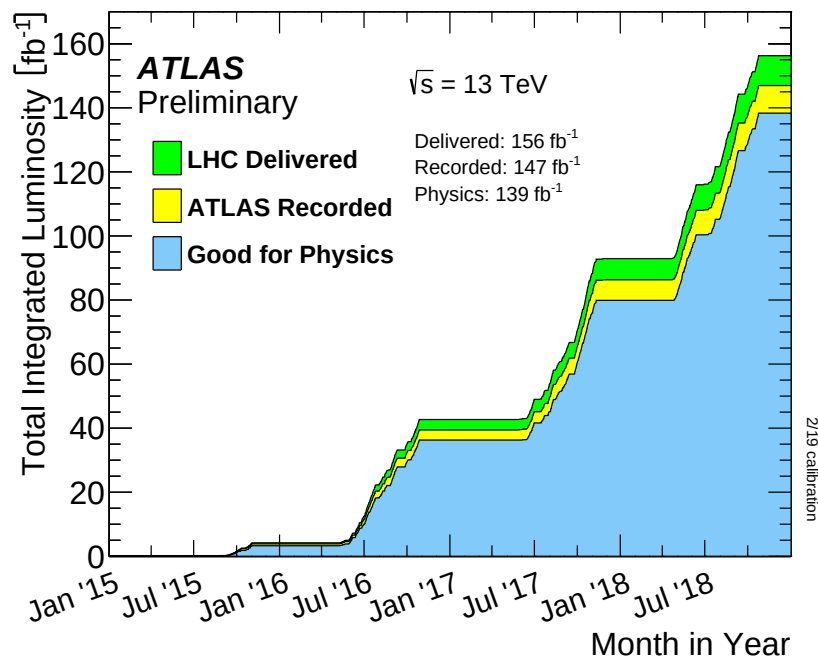


Figure 3.2. Cumulative luminosity versus time delivered to ATLAS (green), recorded by ATLAS (yellow) and certified to be good quality data (blue) during stable beams for pp collisions at 13 TeV centre-of-mass energy in LHC Run 2 [41].

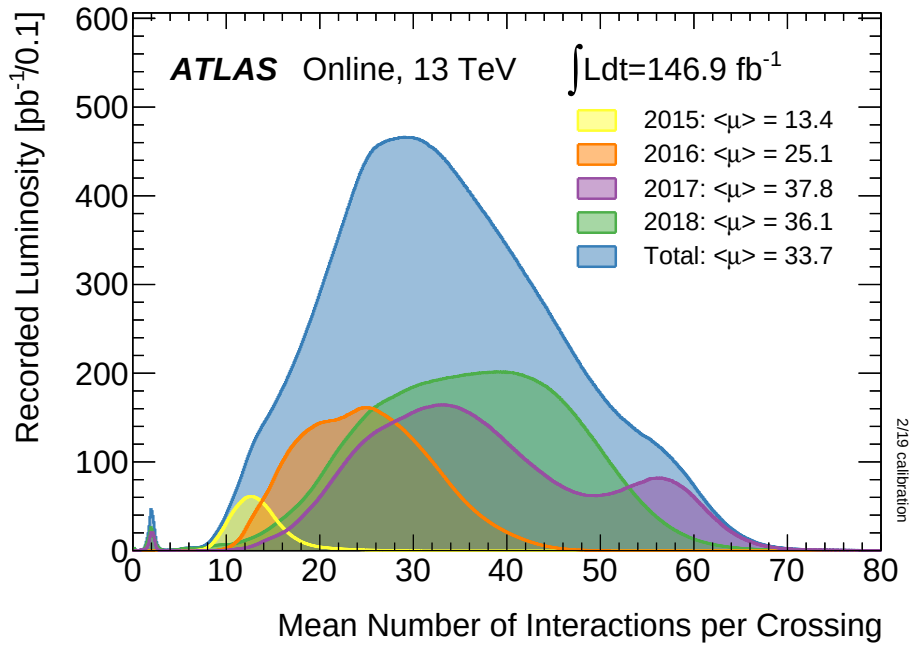


Figure 3.3. Shown is the Luminosity-weighted distribution of the mean number of interactions per crossing for the Run-2 pp collision data at 13 TeV centre-of-mass energy. All data recorded by ATLAS during stable beams is shown, and the integrated luminosity and the $\langle \mu \rangle$ value are given in the figure. The mean number of interactions per crossing corresponds to the mean of the poisson distribution of the number of interactions per crossing calculated for each bunch. [41].

3.2 ATLAS detector

The ATLAS experiment is a general purpose detector designed to study LHC pp interactions at $\sqrt{s} = 14$ TeV. ATLAS is a big collaboration of about 3000 scientific authors from 183 institutions around the world. The experimental apparatus is structured in three concentric cylindrical sub-detectors which surround the pp interaction point. The innermost part is the inner detector (ID) followed by the calorimeters and the Muon Spectrometer (MS). Figure 3.4 shows the full detector: ATLAS is 46 m long, 25 m tall and weights 7000 tons.

In the following section the different detectors that constitute the ATLAS experiment will be described in more detail.

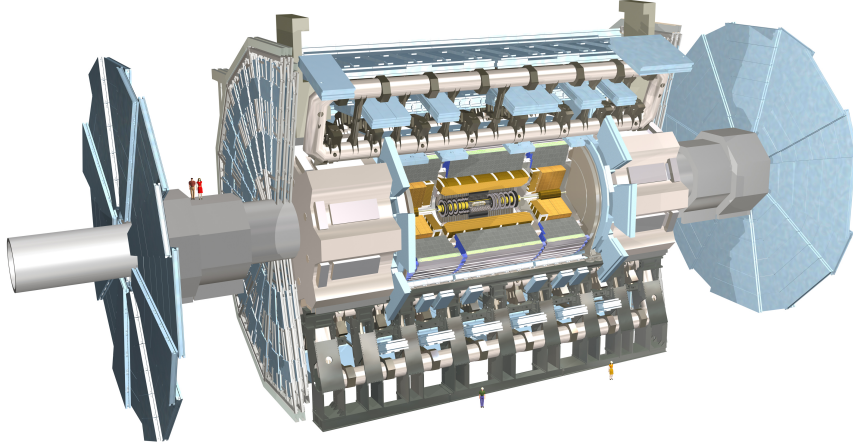


Figure 3.4. The four major components of the ATLAS detector are the Inner Detector, the Calorimeter, the Muon Spectrometer and the Magnet System [3].

3.2.1 Coordinate system

ATLAS experiment uses two coordinate systems: a cartesian right-handed coordinate system and a spherical coordinate system. The cartesian system is used for geometry studies while the spherical one is needed for physics analyses. The nominal beams interaction point is the origin of the coordinate system, with the z axis along the beam direction and the $x - y$ plane that is transverse to the beam direction.

Two regions are defined by the interaction point, *side A* with $z > 0$, *side C* with $z < 0$.

In the spherical coordinate system, the azimuthal angle $\phi \in [-\pi, \pi]$ is measured in the $x - y$ plane and it's defined as:

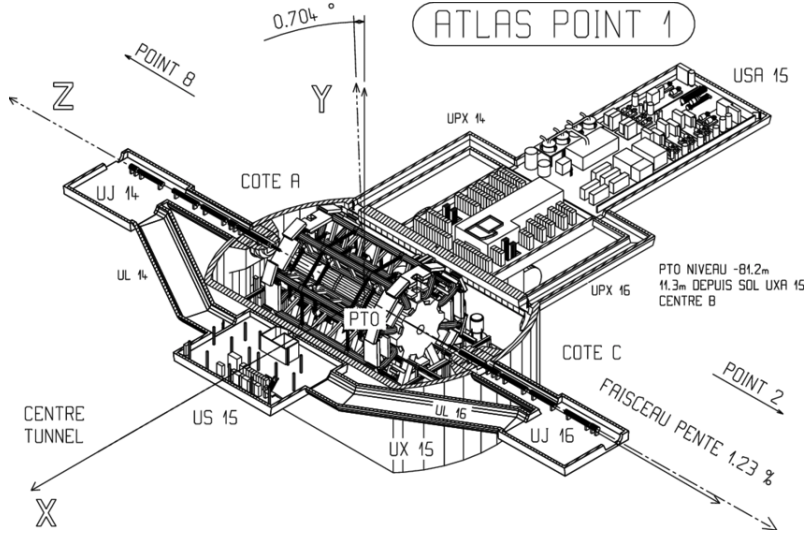


Figure 3.5. ATLAS coordinate system.

$$\phi = \arctan(x/y) \quad (3.4)$$

The azimuthal angle ϕ is equal to zero along the x axis and increases in clockwise direction in positive y direction. The polar angle θ is defined in the $r - z$ plane, where $r = \sqrt{x^2 + y^2}$ and it's equal to zero along the z axis (Figure 3.5).

Since the polar angle is not invariant under Lorentz boost along the z direction, another variable called *pseudorapidity* is used (Figure 3.6):

$$\eta = -\ln \left[\tan\left(\frac{\theta}{2}\right) \right] \quad (3.5)$$

The detector is divided in two regions depending on the η value:

- Barrel region (BR) $|\eta| < 1.05$, that corresponds to the central detector region, so more close to the interaction point;
- Endcap region (ER) $1.05 < |\eta| < 2.7$, that includes the forward apparatus.

The angular separation in the $\eta - \phi$ plane, defined as:

$$\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \quad (3.6)$$

is used to measure the angular distance between two tracks.

Since protons are non-elementary particles, the effective centre of mass interaction energy depends on the momentum fractions carried by the partons that actually participate in the hard scattering process, so it is not exactly known. It is natural to study the kinematics of the interaction in the transverse $x - y$ plane, in which the energy conservation is still valid.

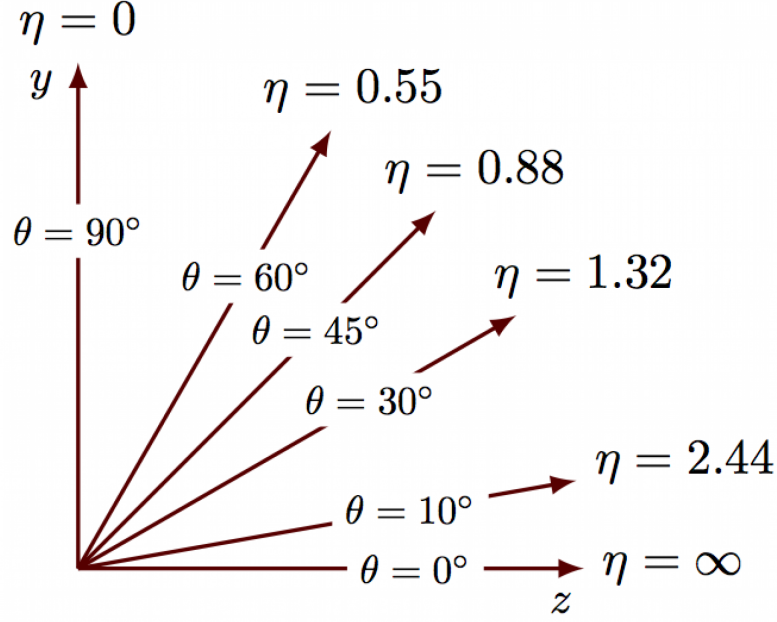


Figure 3.6. Pseudorapidity η for different θ values.

3.2.2 Magnet System

The most peculiar feature of the ATLAS detector is the magnetic system [42]. It's composed by 4 superconducting magnets, it's 26 m long and has a diameter of 20 m. It consists of (fig. 3.7) a central solenoid (CS) and a system of 3 superconducting toroids. The CS is symmetric along the beams direction, it covers the central region of the detector and provides a uniform magnetic field of 2 T along the z axis. The CS is 5.3 m long and has a diameter of 2.4 m. The magnetic field bends tracks of the particles of the Inner Detector in the transverse plane allowing to measure the particle transverse momentum. The system of 3 superconducting toroids (one in the barrel and two in the end-caps) surround the CS and provides a magnetic field, whose peak intensities are 3.9 T and 4.1 T in the central and forward region respectively. This system is one of the peculiarities of the ATLAS detector and its aim is to have a large spatial acceptance for the measurement of muons transverse momentum. Each toroid consists of 8 rectangular coils radially and symmetrically assembled around the beam axis. The end-cap toroid system is rotated by 22.5° with respect to the barrel system in order to have a radial overlap.

The double magnetic system provides two independent measurements of the muon momentum in the inner detector and in the muon spectrometer, and this ensures good muon momentum resolutions from few GeV up to the TeV scale.

3.2.3 Inner Detector

The Inner Detector [43] (ID) is the closest system to the beam pipe and has been designed in order to have a good pattern recognition, an excellent momentum resolution and a good primary and secondary vertex reconstruction for charged

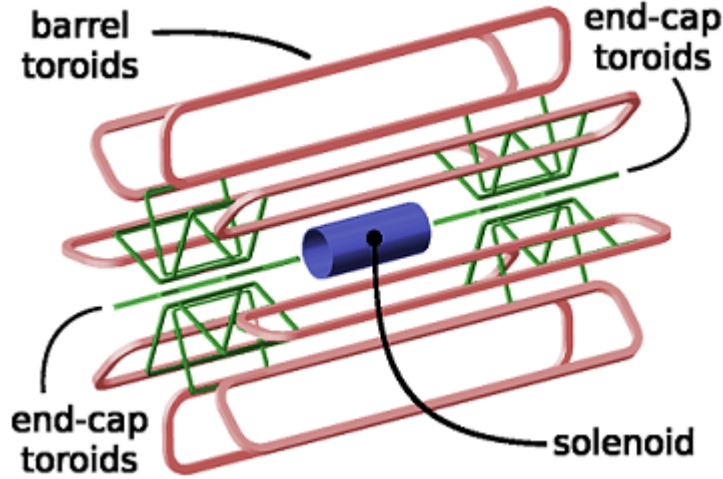


Figure 3.7. ATLAS magnetic system schema.

tracks with transverse momentum of more than 200 MeV. It extends from 33 mm to 1082 mm in radius and covers the pseudorapidity region. The ID is composed by three detectors (fig. 3.8) surrounded by the CS, where magnetic field is parallel to the beam axis: *Pixel Detector*, *Semiconductor Tracker (SCT)* and *Transition Radiation Tracker (TRT)*. In the central part, three layers of high-resolution pixel detectors and eight semiconductor trackers are installed. The combination with the Transition Radiation Tracker, installed in the outer part of the ID, allows to obtain an high resolution in both the z and ϕ directions. The Inner Detector covers the $|\eta| < 2.5$ region.

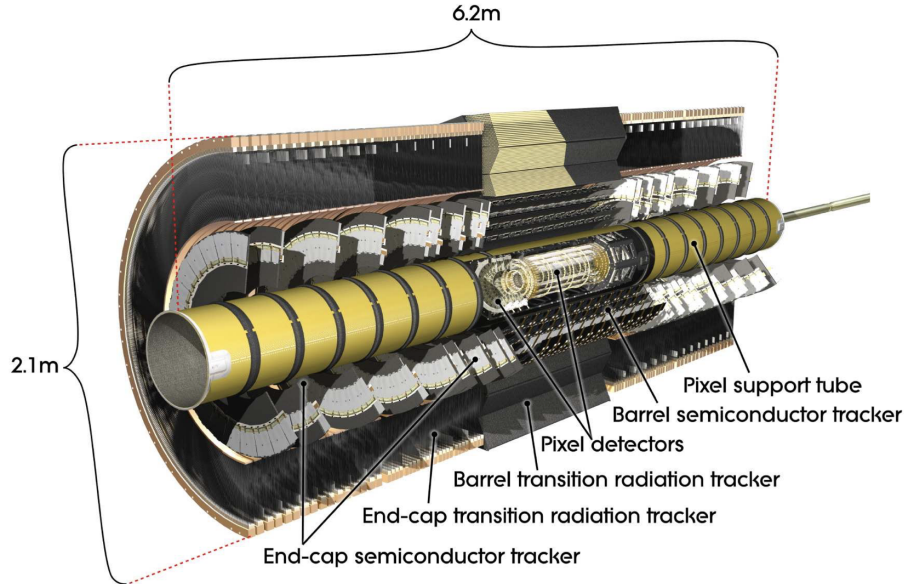


Figure 3.8. The ATLAS Inner Detector.

The external radius of the tracking cavity is 155 cm long and the total length is 7

m. The Inner Detector is the closest part of the ATLAS detector to the interaction point.

Pixel detector

The pixel detector [44] is installed in the innermost area of the ID; it guarantees high-precision measurements, a very good resolution for both determination of the impact parameter and tracks reconstruction for particles with short lifetimes, like τ leptons and b -quarks. The pixel system consists of 3 cylindrical bodies with an average radius of about 4, 11 and 14 cm, and 5 discs per side with a radius between 11 and 20 cm, situated at a radial distance of 50.5, 88.5 and 122.5 mm (Figure 3.9).

During the 2013–2015 shut-down the pixel detector was extended with a fourth layer, the Instertable B-Layer (IBL), installed at a radius of 33.3 mm. The IBL improved significantly the ID performance recorded in Run-1, enhancing the good vertex reconstruction and secondary vertex identification.

A track from the IP is supposed to cross at least 3 pixel layers. The spatial resolutions evaluated on average η are: $\sigma(R - \phi) \simeq 12 \mu\text{m}$ for all pixels; $\sigma(z) \simeq 66 \mu\text{m}$ in the barrel region; $\sigma(R) \simeq 77 \mu\text{m}$ for the discs.

Electronic modules for the detectors readout have big areas, and each pixel module has a single circuit. Moreover, they are equipped with pattern buffers, in order to store the data while waiting for the level-1 trigger decision.

Semiconductor tracking

The Semiconductor Tracker [45] (SCT) is installed in the radial mid-zone (Figure 3.9); it allows for track reconstruction and contributes to the momentum, impact parameter and vertex position measurements, providing at least 4 precision measurements. The sizes of each device are of $6.36 \times 6.40 \text{ cm}^2$ with 768 readout strips in steps of $80 \mu\text{m}$. The spatial resolution is $16 \mu\text{m}$ in $R - \phi$ and $580 \mu\text{m}$ in z .

Transition radiation tracker

The transition radiation tracker (TRT) is the outermost sub-detector of the ID, it provides a large number of additional hits (average number of TRT hits on tracks extracted is 31). The detector is made of straw tubes with 4 mm diameter, able to operate at high particle fluxes thanks to the detecting wires, well isolated within single gas volumes (Figure 3.9). The best electron collection time is $\sim 48 \text{ ns}$, and the spatial resolution coming from the drift time is $\sim 130 \mu\text{m}$.

The overall ID system resolution for charged particles' momentum is

$$\frac{\sigma_{p_T}}{p_T} = 0.05\% p_T [\text{GeV}] \oplus 1\%. \quad (3.7)$$

3.2.4 Calorimeters

The calorimeters (Figure 3.10) are placed between the ID solenoid and the MS. The calorimeters are made of layers of active material and passive (or absorber) material. A particle that crosses the passive layers interacts with the material, and produces a

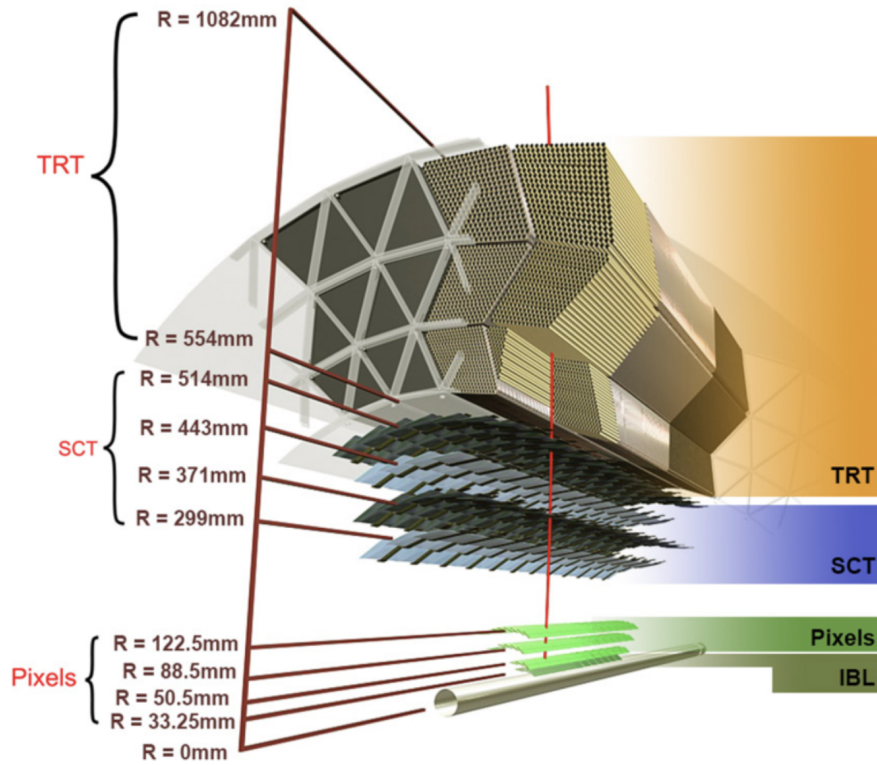


Figure 3.9. The structure of the ATLAS Inner Tracking Detector made of highly granular silicon pixels, silicon strips and straw tubes.

shower of secondary particles that are detected by the active material. The particles of the shower gradually lose their energies crossing the calorimeter, and finally they are completely absorbed.

Two different types of calorimeters are employed, in order to give a good resolution and reconstruction of the electromagnetic showers and to contain the hadronic showers, avoiding their passage into the MS: the Electromagnetic Calorimeter (ECAL) and the Hadronic Calorimeter (HCAL).

The electromagnetic calorimeter is a lead and liquid argon (LAr) detector with an accordion geometry. A pre-sampler detector, that corrects the measurements for the energy lost in the material, is installed just behind the cryostat cold wall.

The active material of the hadronic calorimeter (*Tile Barrel*) is composed of plastic scintillator plates surrounded in an iron absorber. It's divided in 3 sections: a central cylinder and two extended cylinders.

The end-cap calorimeters (HEC) consists of copper (Cu) and liquid argon (LAr), while the two forward calorimeters (FCAL) are made of liquid argon and rod-shaped electrodes in a tungsten matrix.

By detecting and measuring the energy deposited in the material, it's possible to determine the type of the interacting particle and to measure its energy.

Particles that are subject to the strong interaction, impacting on a material, interact

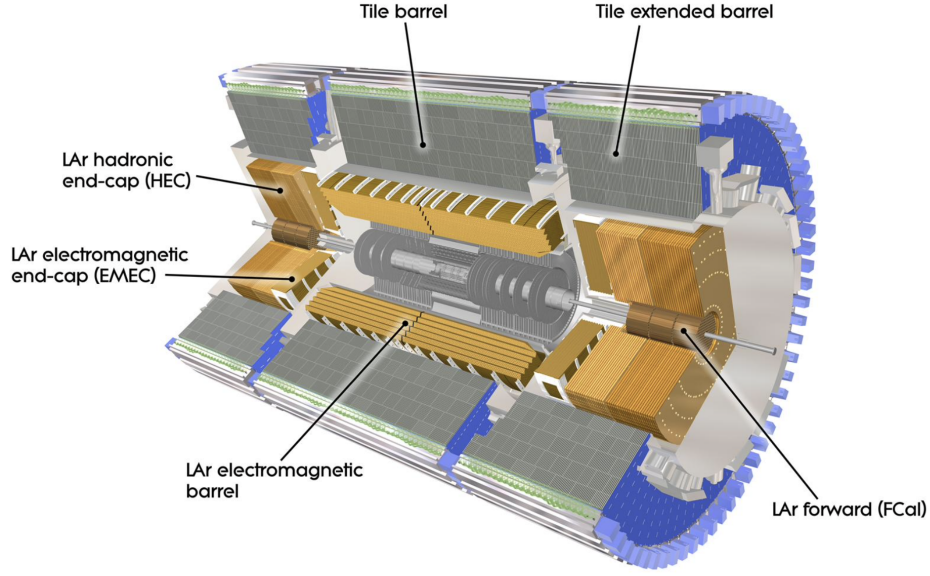


Figure 3.10. ATLAS calorimetric system schema.

with the nuclei of the material and produce a hadronic shower. As in the electromagnetic case, by measuring the energy of the secondary particles it's possible to determine the energy of the starting interacting particle.

The calorimeters are build so that the electrons and the photons are completely absorbed in the electromagnetic calorimeter, while an hadronic particle is absorbed in the hadronic calorimeter.

ECAL

The EM calorimeter [46] consists of 3 different layers in the region $|\eta| < 2.5$. The innermost layer is required to have a very high granularity in η and ϕ ($\Delta\eta \times \Delta\phi = 0.0031 \times 0.098$) to discriminate between γ and π^0 and its thickness is $4.3 X_0$. The middle layer has a thickness of $16 X_0$ and is segmented in cells with dimensions $\Delta\eta \times \Delta\phi = 0.025 \times 0.0245$, to have a good spatial resolution for the reconstructed shower. The outermost layer is $2 X_0$ thick, has a segmentation of $\Delta\eta \times \Delta\phi = 0.05 \times 0.0245$ and it's used for high energy electrons and photons. The total thickness is around $25 X_0$ in the barrel region and around $26 X_0$ in the end-cap regions with 190000 readout channels in total.

The energy resolution of the electromagnetic calorimeter comes from the sum in quadrature of independent terms:

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c \quad (3.8)$$

where a is the sampling factor (that includes also the statistical fluctuations), b is the factor that accounts for the noise coming from the electronic and the signal pile-up, and c is a constant that accounts for mechanical effects, calibrations and

non-uniform sources which arise in systematic errors. The energy resolution of the ATLAS EM calorimeter depends of the values of these parameters and allows very good measurements even for high- E_T electron candidates.

HCAL

ATLAS hadronic calorimeters cover the $|\eta| < 4.9$ region, aim at containing almost completely hadronic showers, at measuring the energy deposits and direction of hadronic showers and at providing measurements of the missing transverse energy with good accuracy. To achieve this goal a number of interaction length, λ_I is needed. λ_I is defined in the hadronic calorimeter in the same way of the radiation length X_0 for the electromagnetic calorimeter. The ATLAS hadronic calorimeter is composed by: **Tile Calorimeter** [47], **Hadronic end-cap calorimeter (HEC)** [48] and **Forward calorimeter (FCAL)**.

Tile Calorimeter is a sampling calorimeter where the iron is used as absorber material and the scintillator as active material. It covers the $|\eta| < 1.7$ region and the thickness is about $10 \lambda_I$ for $|\eta| = 0$ with a granularity of $\Delta\eta \times \Delta\phi \simeq 0.1 \times 0.1$.

Hadronic end-cap calorimeter (HEC) is made of copper plates used to absorb and LAr as active material. It covers the $1.5 < |\eta| < 3.2$ region, with an overlap with the *Tile calorimeter* and the *Forward calorimeter*. The granularity is $\Delta\eta \times \Delta\phi \simeq 0.1 \times 0.1$.

Forward calorimeter (FCAL) is design to work under the high radiation flux that is present in the region where is placed (around 4.7 m from the interaction point). It covers the $3.1 < |\eta| < 4.9$ region and it's able to reduce background particles of the Muon Spectrometer. It is composed by 3 modules for side, all of them with LAr as active material: FCAL1, FCAL2, FCAL3. The first module is optimized for electromagnetic measures, while the other modules measure mainly the energies of the hadronic interactions using tungsten as absorber.

3.2.5 Muon spectrometer

The muon spectrometer [49] (MS) is the outermost ATLAS sub-detector. It is designed to detect charged particles in the pseudorapidity region up to $|\eta| = 2.7$, and to determine the momentum with a relative resolution better than 3% over a wide p_T range and down to 10% at $p_T \approx 1$ TeV. The MS consists of one barrel ($|\eta| < 1.05$) and two end-cap sections. A system of three large superconducting air-core toroidal magnets produces a magnetic field with a bending integral of approximately 2.5 Tm in the barrel and up to 6 Tm in the end-caps. Muons pass through the calorimeter materials losing a small fraction of their energy, typically of the order of few GeV. The MS is composed of trigger detector and high precision tracking chambers immersed in a toroidal magnetic field, which allow a muon transverse momentum measurement independent from the one of the ID. In this section, the following geometrical abbreviations will be used: Barrel (B), Endcap (E), Inner (I), Middle (M), Extended (E), O (Outer), Small (S), Large (L), where I,M,E,O refers to the chamber layer and S,L to the chamber sector. In the case of repeated "E", i.e. "EE", the meaning is Endcap Extended. "A side" refers to positive η regions and "C side" to negative η regions.

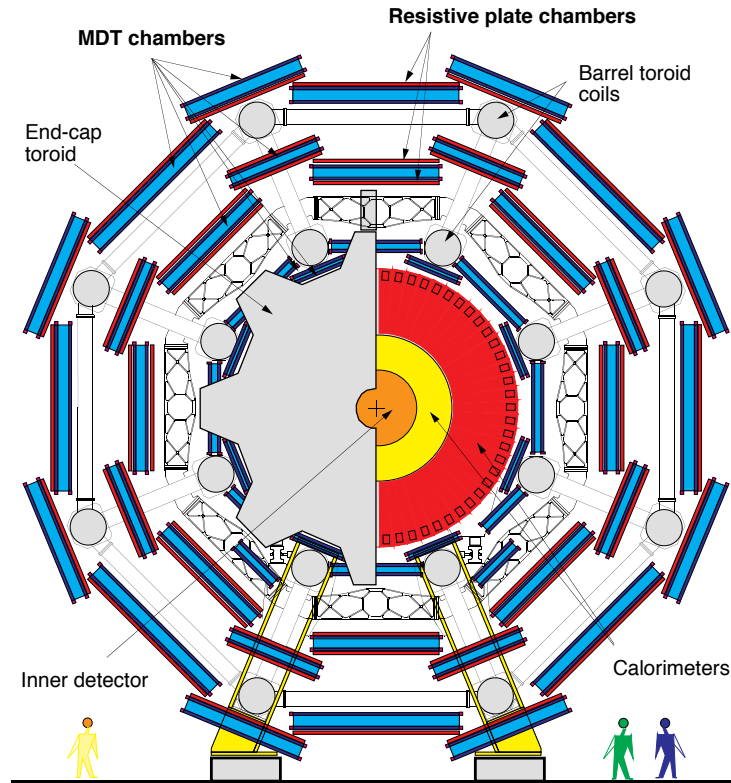


Figure 3.11. Schematic view of the transversal projection of the muon spectrometer [49].

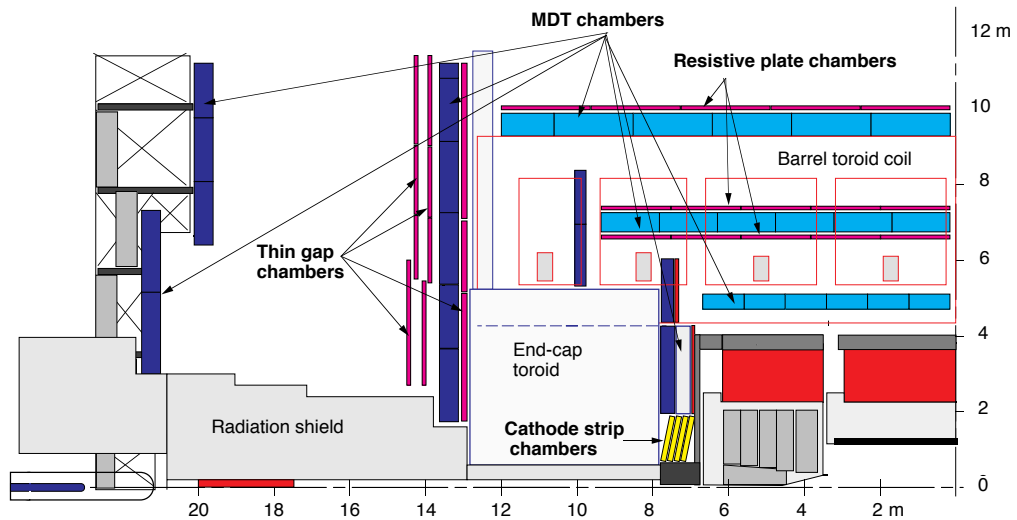


Figure 3.12. Schematic view of the longitudinal projection of the muon spectrometer [49].

MS high precision chambers

Drift Tube chambers (MDT) is composed of two multi-layers of aluminum drift tubes, with diameter of 30 mm and thickness of $400\ \mu\text{m}$, filled with a gas mixture of $93 : 7 - \text{Ar} : \text{CO}_2$ at a pressure of 3 bar. Each chamber typically providing six to eight η measurements along the muon track with a single hit resolution in the precision (rz bending) plane of about $80\ \mu\text{m}$. The total chamber resolution is $35\ \mu\text{m}$. The time measurement of the single hit is known with a resolution dictated by the maximum drift time ($500 \sim \text{ns}$). The precision is improved to few nanoseconds when fitting hits to a track.

In the high occupancy forward region $2 \leq |\eta| \leq 2.7$, where rates greater than $150\ \text{Hz}/\text{cm}^2$ are found, the inner layer is instrumented with a quadruplet of more robust multi-wire strip cathodes chambers (CSC) instead of MDTs. CSC detectors measure positions in the rz plane with a single hit resolution of about $60\ \mu\text{m}$ and provide a time measurement with a resolution of $3.6 \sim \text{ns}$. CSC cathodes are segmented in orthogonal strip wires to allow a measurement in both coordinates with a resolution of $60\ \mu\text{m}$ in R and $5\ \text{mm}$ in the ϕ direction. These chambers present also a good time resolution of about $7\ \text{ns}$.

The layout of the stations and muon chambers are presented in Figures 3.11 and 3.12.

MS trigger chambers

Resistive Plate Chambers (RPC, three doublet layers in the barrel) and Thin Gap Chambers (TGC, one triplet and three doublet in the end-caps) provide triggering capability to the detector for $|\eta| < 1.05$ and $1.0 < |\eta| < 2.4$, respectively, with a time resolution of the order of $\sim 1\ \text{ns}$. Additionally, they give (η, ϕ) position measurements with typical spatial resolution of $5 - 10\ \text{mm}$ up to $|\eta| \approx 2.65$.

The RPC is a gaseous detector consisting of two high-pressure laminate (HPL), obtained by pressing sheets of paper soaked in phenolic/melamine resins at high temperature, separated by a $2\ \text{mm}$ gap filled with a gas mixture of 97% tetrafluoroethane ($\text{C}_2\text{H}_2\text{F}_4$) and 3% isobutane (C_4H_{10}). A high electric field of $4.5\ \text{kV}/\text{mm}$ is maintained between the two plates to amplify the primary ionization of charged particles crossing the detector. The charge induced on metallic strips in the outer sides of the bakelite plates is collected as signal. Two RPC units are placed in each layer orthogonal to one another, providing information on both η and ϕ coordinates. The ϕ coordinate plays an important role for the calibration of the time drift in the MDT detectors. The magnetic field, that depends by the ϕ coordinate, determines the Lorentz angle which influences the MDT space-time relations. Two layers are installed in the middle station, for the low- p_T trigger, and a third layer is installed in the outer station, for the high- p_T trigger.

TGCs are the trigger chambers used in the end-caps. They are designed to have the anode-cathode spacing smaller than the anode-anode spacing for a very short drift time of $20\ \text{ns}$. The chambers are filled with a highly quenching gas mixture of 55% CO_2 and 45% n-pentane ($n - \text{C}_5\text{H}_{12}$) operating in saturation mode.

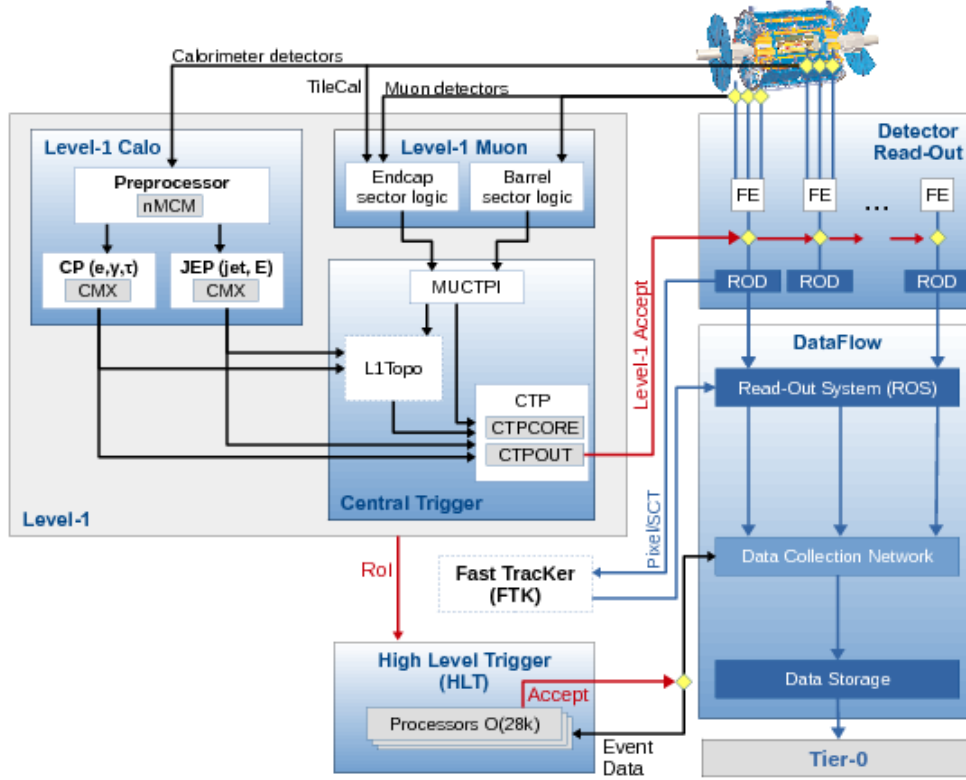


Figure 3.13. Schematic view of ATLAS TDAQ system in Run-2 [51].

3.2.6 Trigger

The trigger and data acquisition (TDAQ) has the crucial task of performing an online event selection to cope with the impressive rate of bunch crossing of the Run-2 LHC system of 40 MHz. Due to limitation in data storage, computing and transfer rates, it is unthinkable to read out and store all LHC events. Moreover, most of the data are not of interest for the ATLAS physics program, as the rate is dominated by low- p_T inelastic and diffractive collisions. A balance between the data acquisition rates and high efficiency for selecting interesting physics data has to be found, keeping in mind that an event not triggered is lost forever. The ATLAS Run-2 TDAQ system [50] is built on two levels of online selection, as shown in Figure 3.13: a first hardware level-1 (L1), that significantly reduces the event rate, and a second software level (HLT), running on the events surviving L1, where the final decision is made.

L1

The hardware L1 exploits quickly accessible coarse data from the calorimeters and MS in dedicated regions of interest (RoI). Calorimeters provide information about clusters of energy deposits, missing transverse energy and raw shape dimensions, while the muon spectrometer provides information from trigger chambers about transverse momentum and track position. At L1 the event rate of 40 MHz is reduced

to 100 kHz with a $2.5 \mu\text{s}$ latency. The latency is defined as the time needed to form the trigger decision and to distribute it to the digitizers.

HLT

The software level integrates the RoI data with the full detector information and runs complex trigger algorithms to select the events. A fast reconstruction step is first used for the trigger selection, followed by a more precise refinement similar to the offline reconstruction. Raw calorimetric informations are reconstructed by fast algorithms into cluster and cell objects, which will later be reconstructed in jet, electron, and photon candidates. Also isolation requirements on the reconstructed candidate could be applied. The final event rate is reduced to 1.5kHz with a latency of $0.2 \mu\text{s}$. In the next section a particular focus will be put on muon trigger, since it plays an important role for all the searches I worked on and presented in this document.

3.2.7 Muon trigger

Many SM processes including Higgs decay together with several hypothetical new physics processes include decay modes into muons, which are a perfect probe for discovering dark sectors. The L1 muon trigger processes information from the MS in a dedicated region of interest (RoI) of dimension 0.4×0.4 in $\Delta\eta \times \Delta\phi$ in the barrel, and 0.2×0.2 in the end-caps, matching coincident hits in space and time. The trigger has to operate in a high rate environment with high efficiency and low transverse momentum threshold. Hits collected from the RPC or TGC trigger chambers are used to build hit patterns. If the pattern is contained inside a fixed window pointing to the IP, whose width defines the p_T threshold, the trigger match is done. A hit pattern of a muon with infinite momentum would result in a straight line, therefore a high- p_T muon would fire also low- p_T triggers, which requires fewer coincidences within a trigger window. Instead, a low- p_T muon would fall outside a high- p_T trigger window. The separation between low- p_T and high- p_T is around 10 GeV. Figure 3.14 shows a schematic picture of the low- p_T and high- p_T triggers. About 20% of Level-1 data are allocated for muon triggers. Here a list of the all unprescaled L1 muon trigger is given:

- 2MU10
- MU20

The HLT is the first step in which ID information is incorporated in the trigger, only track information inside identified RoI at L1 are used due processing time constraint. The muon fast reconstruction integrates each L1 muon candidate with MDT data performing a track fit extrapolated to the ID. The ID fast tracking consists in trigger specific pattern algorithms, designed to identify compatible track segments and hit points.

After describing the ATLAS detectors and the trigger strategy, a description of the reconstruction and identification techniques of objects in ATLAS is presented.

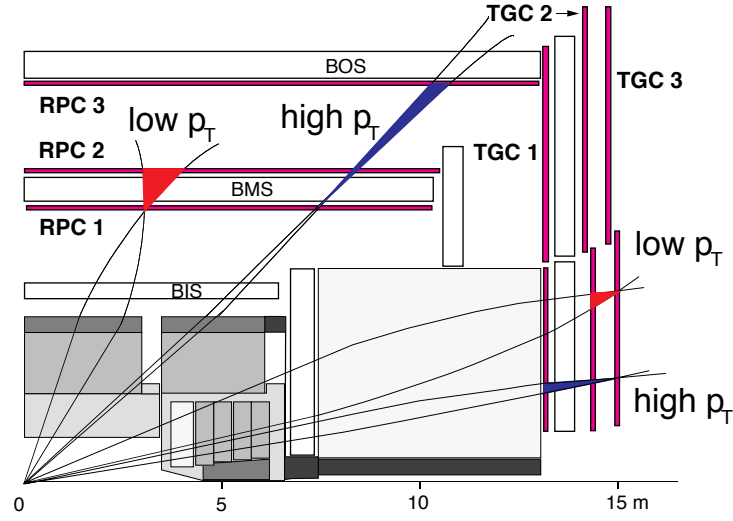


Figure 3.14. L1 muon low- p_T and high- p_T triggers in the Muon Spectrometer barrel and end-cap.

3.3 Reconstruction - Physics objects

This section will describe the reconstruction and identification techniques of the electrons and muons objects in ATLAS, which are among the main components of the high and low mass new physics phenomena. A particular focus will be put on muons, the main topic of my PhD.

Standard object definitions are usually recommended by the ATLAS collaboration, but further optimisation can be done at analysis level to improve the selection and maximise the sensitivity.

3.3.1 Electrons

Electrons are reconstructed with combined information from energy deposits in the ECAL and associated tracks in the ID. The electron candidates are discriminated from background by a likelihood-based identification algorithm, which exploits several properties from track information to calorimeter shower shapes. Correctly identified electrons are then classified into three quality categories: loose, medium, and tight. Electrons selected by a tighter working point are also contained in the looser selections. The electron identification algorithms' performance are presented in Figure 3.15 for electron from $Z \rightarrow ee$ events as a function of the transverse energy and η .

High energy electrons tend to deposit more energy in the last ECAL layers or in the early HCAL layers, presenting narrower cascade shapes. To take into account this effect the loose and medium selections are constructed to be robust against E_T dependence. The tight selection aims at the optimization of the background rejection, additional cuts on electron discriminating variables are included. This selection is very useful for analyses with low energy electrons, where having an high background rejection is fundamental.

Isolation requirements are added to the electron selection to further suppress

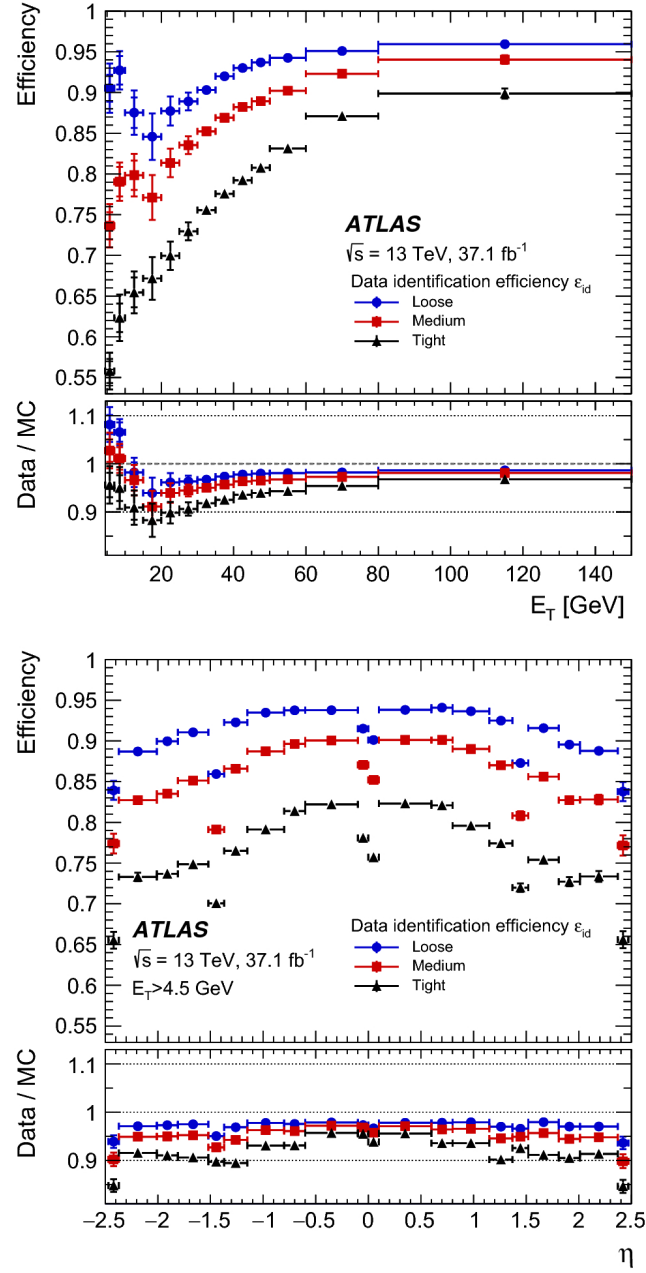


Figure 3.15. Measured electron-identification efficiencies in $Z \rightarrow ee$ events for the Loose (blue circle), Medium (red square), and Tight (black triangle) working points as a function of the transverse energy (top) and $|\eta|$ (bottom). The data efficiencies are obtained by applying data-to-simulation efficiency ratios that are measured in $J/\Psi \rightarrow ee$ and $Z \rightarrow ee$ to the $Z \rightarrow ee$ simulation. For both plots, the bottom panel shows the data-to-simulation ratios.

background from non-prompt electrons, such as electrons originating from converted photons. Analyses using high energy electrons may prefer a loose isolation for a high signal efficiency. The isolation selection evaluates track and energy clusters found within a cone around the electron candidate. In Table 3.1 isolation working points are presented.

Operating point	efficiency		
	calorimeter isolation	track isolation	total efficiency
LooseTrackOnly	-	99 %	99 %
Loose	99 %	99 %	~98 %
Tight	96 %	99 %	~95 %
Gradient	$0.1143 \% \times E_T + 92.14 \%$	$0.1143 \% \times E_T + 92.14 \%$	90/99 % at 25/60 GeV
GradientLoose	$0.057 \% \times E_T + 95.57 \%$	$0.057 \% \times E_T + 95.57 \%$	95/99 % at 25/60 GeV

Table 3.1. Electron isolation working points efficiencies information.

In the following, the electron information is used to obtain the high mass new phenomena results with the full Run-2 data.

3.3.2 Muons

The muon system is designed to reconstruct muons, providing an independent measurement of momentum from their curvature in the toroidal field [52].

The five muon types

ATLAS uses five complementary algorithms to reconstruct muons: *Extrapolated muons*, *Combined muons*, *MuGirl muons*, *Segment-Tagged muons* and *Calorimeter-Tagged muons*.

The first algorithm uses exclusively information from the MS and yields the backward extrapolated towards the IP muons (based on the MS-only extrapolated tracks). The other four algorithms combine the information from the MS, ID, and calorimeter detectors to fully reconstruct muons. These algorithms yield four different muon types; Combined muons, MuGirl muons, Segment-Tagged muons, and Calo-Tagged muons. These four algorithms are complementary. The Combined muons rely on a well reconstructed muon track that is then extrapolated backward to the ID to make a complete track. The MuGirl algorithm takes the opposite approach starting from tracks reconstructed in the inner detector and extrapolating them to the MS. Segment-Tagged muons do not require a fully reconstructed muon track, but only muon segments associated to an ID track, which one would expect for lower p_T muons that do not have enough energy to fully cross the entire MS. Finally, Calo-Tagged muons are identified selecting ID tracks with a calorimeter energy deposition compatible with a minimum ionizing particle. They are completely independent from the muon system and can be used as unbiased probed to measure the efficiency of muon spectrometer reconstruction.

Extrapolated muons (ME muons)

These muons are reconstructed exclusively from hits in the muon spectrometer and a loose requirement on compatibility with originating from the IP. ME muons

are mainly used to extend the acceptance for muon reconstruction into the region $2.5 < |\eta| < 2.7$, which is not covered by the ID.

Combined muons (CB muons)

The *combined algorithm* uses the inner detector (ID) and MS-only extrapolated tracks as input. It looks for inner detector tracks in a cone around the extrapolated MS track. This strategy follows an *outside-in* approach where the information from the MS detector is used to trigger the muon reconstruction, looking for confirmation in the ID. The main advantage is the smaller combinatorics in the MS while the main disadvantage is due to the limited coverage of the muon system in some regions (e.g. $|\eta| < 0.1$). For each pair of tracks it calculates a matching χ^2 using the track parameters of the tracks defined at the interaction point and at the MS-entrance. Based on the probabilities of the two χ^2 values and after a preselection, the pairs are ranked. The first pair is selected and a combined fit using the hits of the inner detector track, the energy loss in the calorimeter, and the hits of the track in the muon system is performed. Tracks that satisfy the final selection criteria for combined tracks are kept. The algorithm then proceeds with the next pair in the list, for all pairs with matching χ^2 probability above a minimum threshold (10^{-5}). If the matching probability is under the threshold the combined fit is done only if there was no successful fit from a pair with matching probability above the threshold. After each successful fit, the resulting combined track is compared to the previous best combined track and the better of the two is chosen based on the matching χ^2 , ID-MS momentum compatibility, and on the spectrometer field integral value. Before producing the final combined tracks, the hits in the muon system are re-calibrated using the phi coordinates obtained with the tridimensional combined fit, and the expected errors of the hits are updated to obtain the best possible momentum resolution. To ensure consistency between the combined and the extrapolated track, the extrapolated track is recreated by refitting the muon system hits and the calorimeter energy loss of the combined track, leading to the muon spectrometer extrapolated (ME) track.

MuGirl muons

The search for MuGirl muons starts from inner detectors track and hits in the muon system. This strategy follows an *inside-out* approach where the information from the ID detector is used to trigger the muon reconstruction, looking for confirmation in the MS detector. The main advantage is the uniform coverage of the inner tracker in $|\eta| < 2.5$ while the main disadvantage is due to the much higher combinatorics.

The inner detector tracks with p_T above 2 GeV are extrapolated outwards and hits of all technologies in the muon system found along the extrapolated trajectory are associated. A segment search is performed using the hits in the individual station layers as input. The reconstructed segments are selected using the same procedure as for the segment-tagged muons described in the following paragraph. If at least one segment is selected, a combined fit using the inner detector track and the selected segments is performed. The same fit, refinement, and selection procedure used for the muon combined reconstruction are also used by MuGirl.

Segment-Tagged muons (ST muons)

The search for Segment-Tagged (ST) muons starts from inner detector tracks and reconstructed muon segments. The inner detector tracks with p_T above 2 GeV are extrapolated outwards to the precision plane of the muon segments. There a matching is performed using position and angle in the precision rz plane and the position in the xy -plane. All muon stations are searched for. Since for low p_T muons is difficult to cross all the muon stations due to the magnetic field, if the ID track is successfully matched to at least one MS segment, it is identified as a muon. In the endcap region there is also no requirement of a segment in the CSC detectors.

If muon segments are matched to more than one inner detector track, the ambiguities are resolved and the best match is chosen. Finally, additional cuts on the quality of the segments are applied to reduce the contribution of fake muons.

Calorimeter-Tagged muons (CT muons)

Calorimeter-Tagged (CT) muons are identified starting from inner detector tracks with p_T above 5 GeV, to reduce the higher background contamination expected from the calorimeter tagging technique. By extrapolating the track through the calorimeter, the measured energy deposits in the electro-magnetic and hadronic calorimeters are collected. Non-isolated muons are removed by applying a cut that the total momentum of the tracks found in a cone $\Delta R < 0.4$ around the muon be less than five times the muon momentum. A CT muon is then defined as a minimum-ionizing particle that deposits less than a certain amount of energy in the different calorimeter layers.

Determination of energy loss in calorimeters

For all muon types, the energy loss in the calorimeters is determined and included in the refit. Depending on the situation, the energy loss used on the refit is either measured or estimated from a parameterization based on MC. The measured energy loss is determined using the energy deposits in the calorimeter around the muon trajectory and correcting for the dead material. The estimated energy loss is obtained using a precise momentum dependent parameterization of the energy loss expected from ionization and radiation (including pair production) based on tracking geometry. The maximum allowed value for the expected energy loss due to radiation is set to 100 GeV to avoid problems with almost-straight tracks with very large estimated momentum.

In Table 3.2 the information contributing to the different muon types is summarized.

Muon selection working point

Five muon selection levels are currently provided for use in physics analyses: *Loose*, *Medium*, *Tight*, *Low- p_T* , and *High- p_T* . They are designed to address the specific needs of different physics groups. For the first three, these are high efficiency, small systematic uncertainties, and good purity respectively. The High- p_T working point is designed to provide a momentum measurement as robust as possible for the p_T range of hundreds of GeV up to several TeV, ensuring the best possible resolution

	CB	MuGirl	ST	CT	ME
ID track	yes	yes	primary	primary	no
MS segments	yes	yes	yes	no	yes
MS track	yes	no	no	no	yes
ME track	yes	yes	no	no	primary
CB track	primary	primary	no	no	no

Table 3.2. Summary of the information contributing to the different muon types. “Primary” indicates the track that is used to define the parameters of the muon.

and outlier rejection for searches in the tails of e.g. transverse mass or invariant mass distributions. In the opposite corner of phase space, the Low- p_T working point is designed to maximize the efficiency for muons down to $p_T = 3$ GeV while maintaining a reasonable fake rate.

Muon candidates originating from in-flight decays (background) of charged hadrons are often characterized by the presence of a distinctive “kink” topology in the reconstructed track. The direct consequence is a poor compatibility within the uncertainties between the measured momentum in the ID and the MS, and a poor χ^2 quality of the ID-MS combined track fit. Several variables exploiting such unique features and offering good discrimination between genuine muons and background muon candidates were studied in simulated $t\bar{t}$ events. The rich decay pattern available in $t\bar{t}$ event simulation is suitable for the tuning of the working points as it offers, in a wide transverse momentum range, both prompt and non-prompt muons, and plenty of charged hadrons from jets which can be used for fake rate studies. The MC-truth information is used to categorize muons from W decays as “prompt”, muons from semi-leptonic b - and c -quark decays as “non-isolated”, and muon candidates from hadron decays as “backgrounds”. Among the variables studied, the so-called “ q/p significance”, ρ' , and the normalized χ^2 of the combined track fit (χ^2/N_{DoF}) are chosen to define the selection working points. These variables are briefly described below.

The “ q/p significance” is defined as the absolute difference between the ID and the MS q/p measurements ($(q/p)_{\text{ID}}$ and $(q/p)_{\text{ME}}$), divided by the sum in quadrature of the corresponding uncertainties (σ_{ID} and σ_{ME}):

$$\frac{|(q/p)_{\text{ID}} - (q/p)_{\text{ME}}|}{\sqrt{\sigma_{\text{ID}}^2 + \sigma_{\text{ME}}^2}}. \quad (3.9)$$

It provides good separation between prompt and background muon candidates, accompanied by a stable selection efficiency across the detector geometric acceptance and within a wide momentum range.

The ρ' variable is defined as the absolute difference between transverse momentum measurements in the ID and MS divided by the combined track measurement:

$$\rho' = \frac{|p_T^{\text{ID}} - p_T^{\text{ME}}|}{p_T^{\text{CB}}}. \quad (3.10)$$

The ρ' variable offers a good separation between prompt and background muons, but is only used for the *Tight* working point providing a higher purity at the price

of some efficiency loss. Momentum calibrations are applied to the ID, ME and CB muon momentum measurements when calculating the “ q/p significance” and ρ' variables.

The normalized χ^2 of the combined track fit also offers good separation between prompt and background muons. Due to the complexity of the track fit across the entire detector, however, this variable is sensitive to several effects that might not be accurately reproduced in simulation. As a consequence, only a very loose requirement is employed to reject pathological tracks, and only for the *Tight* working point.

To guarantee a robust momentum measurement and depending on the muon type, specific requirements on the number of hits in the MS are used. One precision layer (also called “station”) is assigned to an MS track when it has at least three hits in one station of MDT or CSC. If not, and if three or more hits are missing in a layer of MDT or CSC traversed by the track, a precision hole layer is counted.

The distribution of the q/p significance, χ^2/N_{DoF} , and ρ' variables coming from $t\bar{t}$ simulation are shown in Figure 3.16 and 3.17.

For combined muons, a combined track fit is in general performed, taking into account the hit information from both the ID and MS. Such a fit is sensitive to relative misalignments between the two detector systems, and if these are underestimated or not properly accounted for in the fit, pathological features of the combined track may arise. To avoid such features to propagate to physics results, it is recommended to reject muons that satisfy

$$\frac{[\sigma(q/p)/(q/p)]_{\text{ID}}}{[\sigma(q/p)/(q/p)]_{\text{CB}}} < 0.8 \quad \text{or} \quad \frac{[\sigma(q/p)/(q/p)]_{\text{MS}}}{[\sigma(q/p)/(q/p)]_{\text{CB}}} < 0.8, \quad (3.11)$$

i.e. essentially muons for which the relative combined track fit error is larger than the individual relative error from any of the two detector systems (by some margin). This requirement has been shown to efficiently reject muons affected by ID/MS misalignments.

The exception is for the high- p_T working point, where a dedicated cut based on the relative combined track fit error alone is used to efficiently reject muons with a suboptimal p_T measurement.

The *Loose* working point

The *Loose* identification criteria are designed to maximize the reconstruction efficiency while providing good quality muon tracks. They are specifically optimized for reconstructing Higgs boson candidates in the four-lepton final state [53, 54]. All muon types are used. Calo-tagged (CT) and Segment-tagged (ST) muons are restricted to the $|\eta| < 0.1$ region, where the ATLAS muon spectrometer is only partially instrumented to allow for cabling and services to the calorimeters and inner detector, leading to a loss of efficiency for CB and MuGirl tracks. Muon-spectrometer-only Extrapolated (ME) muons are deployed between $2.5 < |\eta| < 2.7$, to extend the acceptance outside the ID geometrical coverage. Finally, CB and MuGirl muons satisfying the *Medium* requirements are also part of the *Loose* working point. We expect CB and ME muons to contribute 97.5% of this category, with approximately 1.5% of muon candidates recovered by the CT reconstruction algorithm and the remaining 1% reconstructed with the MuGirl algorithm or as ST muons.

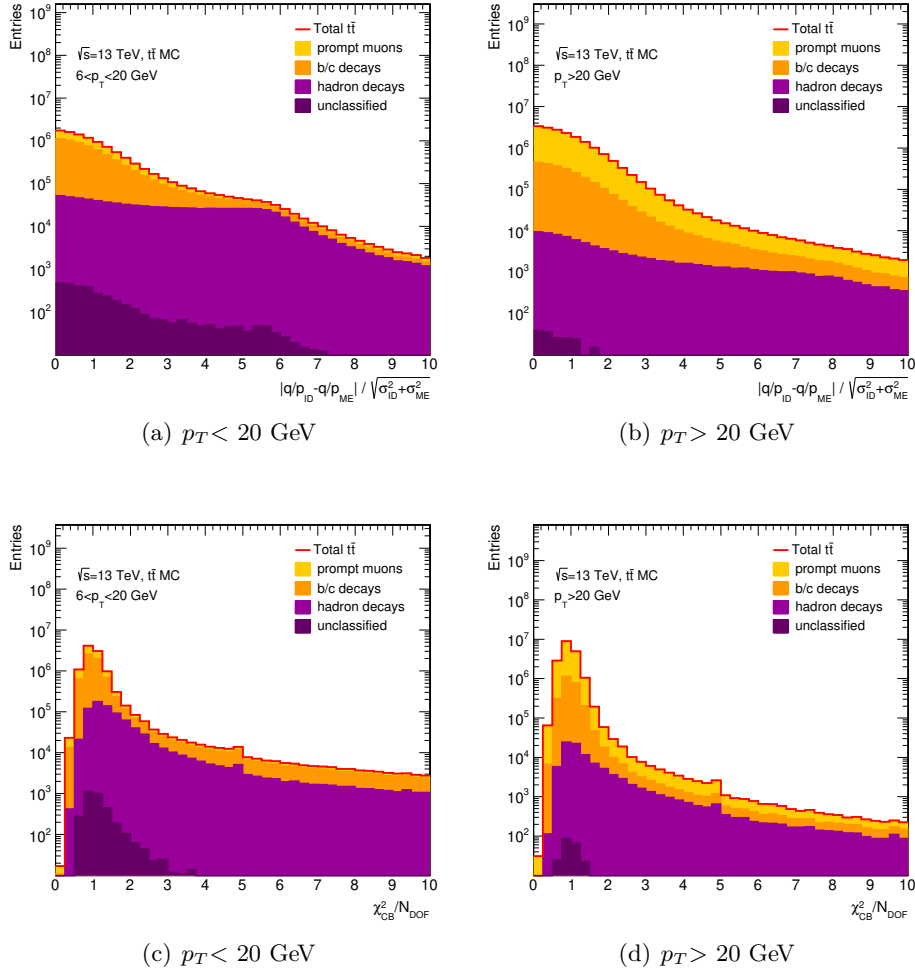


Figure 3.16. Distributions of the “ q/p significance” variable (top) and the normalized χ^2 of the combined track fit (bottom) in simulated $t\bar{t}$ events for muons with $6 < p_T < 20$ GeV (left) and with $p_T > 20$ GeV (right). Each plot shows the breakdown in different real/fake muon categories as obtained from the MC-truth information, following the convention outlined at the beginning of this chapter. Muons that cannot be assigned unambiguously to a category are also shown. A $|\Delta z_{0,PV} \cdot \sin(\theta)| < 0.5$ mm requirement is applied, to remove unclassified muon candidates coming from pileup interactions.

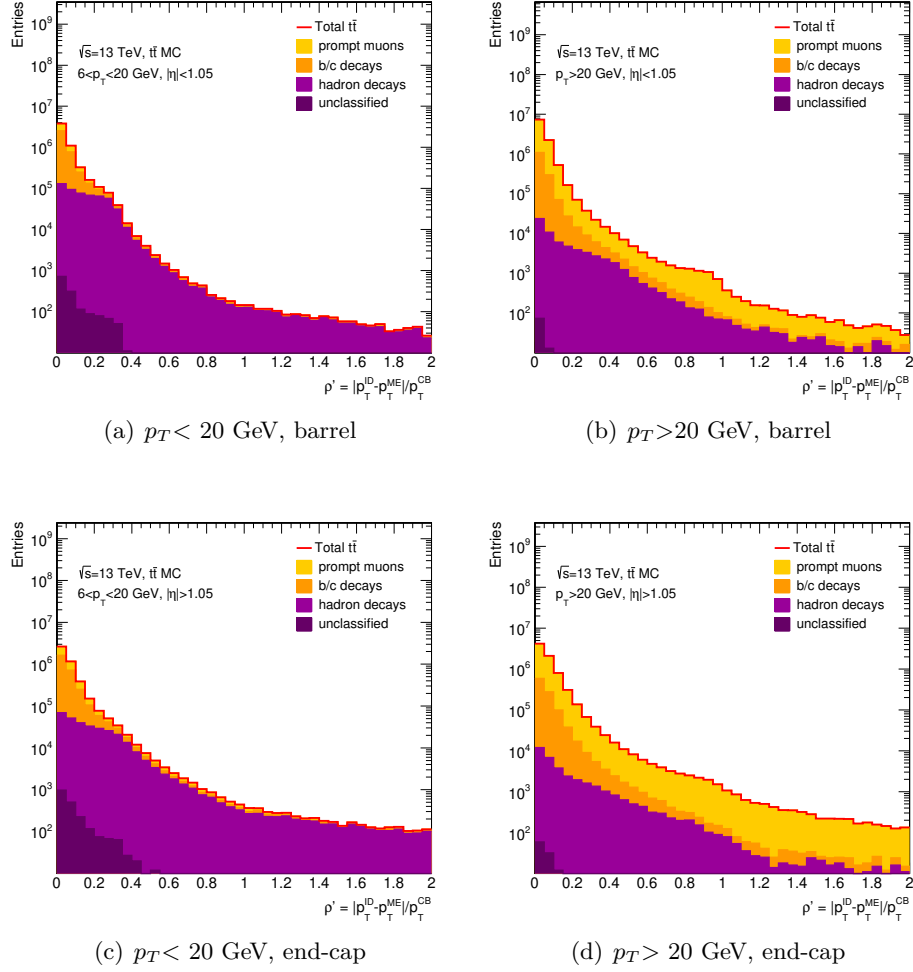


Figure 3.17. Distributions of the ρ' variable (top) in simulated $t\bar{t}$ events for muons in the barrel ($|\eta| < 1.05$) and the end-cap ($1.25 < |\eta| < 2.5$). Each plot shows the breakdown in different real/fake muon categories as obtained from the MC-truth information. Muons that cannot be assigned unambiguously to a category are also shown. A $|\Delta z_{0,PV} \cdot \sin(\theta)| < 0.5$ mm requirement is applied, to remove unclassified muon candidates coming from pileup interactions.

The *Medium* working point

The *Medium* identification criteria provide the default selection for muons in ATLAS. They minimize the systematic uncertainties associated with muon reconstruction and calibration. Only ME, MuGirl and CB tracks are used in this selection. The former two are required to have at least three precision layers, and are employed only in the $2.5 < |\eta| < 2.7$ region. The latter are required to have at least 3 hits on at least two station of MDT, except for the $|\eta| < 0.1$ region where tracks with at least one precision layer but no more than one precision hole layer are allowed. Moreover, a loose selection on the compatibility between ID and MS momentum measurements is applied to suppress the contamination due to hadrons mis-identified as muons. Specifically, the “ q/p significance” variable is required to be less than 7. We expect this category to be 99.5% combined muons, with a few muon candidates recovered by the MuGirl reconstruction algorithm. In figure 3.18 the muon efficiency reconstruction for the standard ATLAS muon working point is shown as a function of p_T and η . Due to some detectors inefficiency, a discrepancy at the level of 0.5% between data/MC efficiency is observed. From these measurements, the scale factor ($\varepsilon_{Data}/\varepsilon_{MC}$ - bottom panel), is calculated and it is applied in all the muon ATLAS analyses to correct the observed discrepancy.

The *Tight* working point

Tight muons are selected to maximize the purity of muons at the cost of some efficiency losses and potentially larger systematic uncertainties. Only CB muons with at least 2 stations and satisfying the *Medium* selection criteria are considered. ME muons are not considered for the *Tight* working point. A cut on the normalized χ^2 of the combined track fit ($\chi^2/N_{\text{DoF}} < 8$) is deployed to remove pathological tracks. At this point in the selection, an optimization was performed in the two-dimensional plane spanned by ρ' and “ q/p significance” and further divided into discrete p_T bins. The dominant background contributions after the above selection typically occur with low transverse momentum ($p_T \lesssim 20$ GeV); therefore a gradient approach was taken wherein larger efficiency losses were allowed in the lower p_T bins to more effectively reduce the backgrounds. An efficiency curve in the region of $4 < p_T < 20$ GeV for prompt + non-isolated muons was derived by fitting the background muons in a $t\bar{t}$ sample with a falling exponential. Any muon with $p_T > 20$ GeV was required to have an efficiency of at least 96% to provide a smooth transition between these two p_T regimes. In the optimization, cuts on ρ' and the “ q/p significance” were chosen such that the efficiency for selecting a prompt or non-isolated muon was above 95% for $p_T > 8$ GeV, while simultaneously choosing the cut which maximized the rejection of background muons. A factor of two improvement in the rejection of background muons above the *Medium* working point was achieved.

The *Low- p_T* working point

The Low- p_T identification working-point was designed with the goal of obtaining optimal muon identification down to a p_T of 3 GeV. The selection switches to the *Medium* working point requirements above $p_T = 18$ GeV. For the *Low- p_T* WP, only CB and MuGirl tracks are used. For $|\eta| < 1.3$, at least one MS station is required,

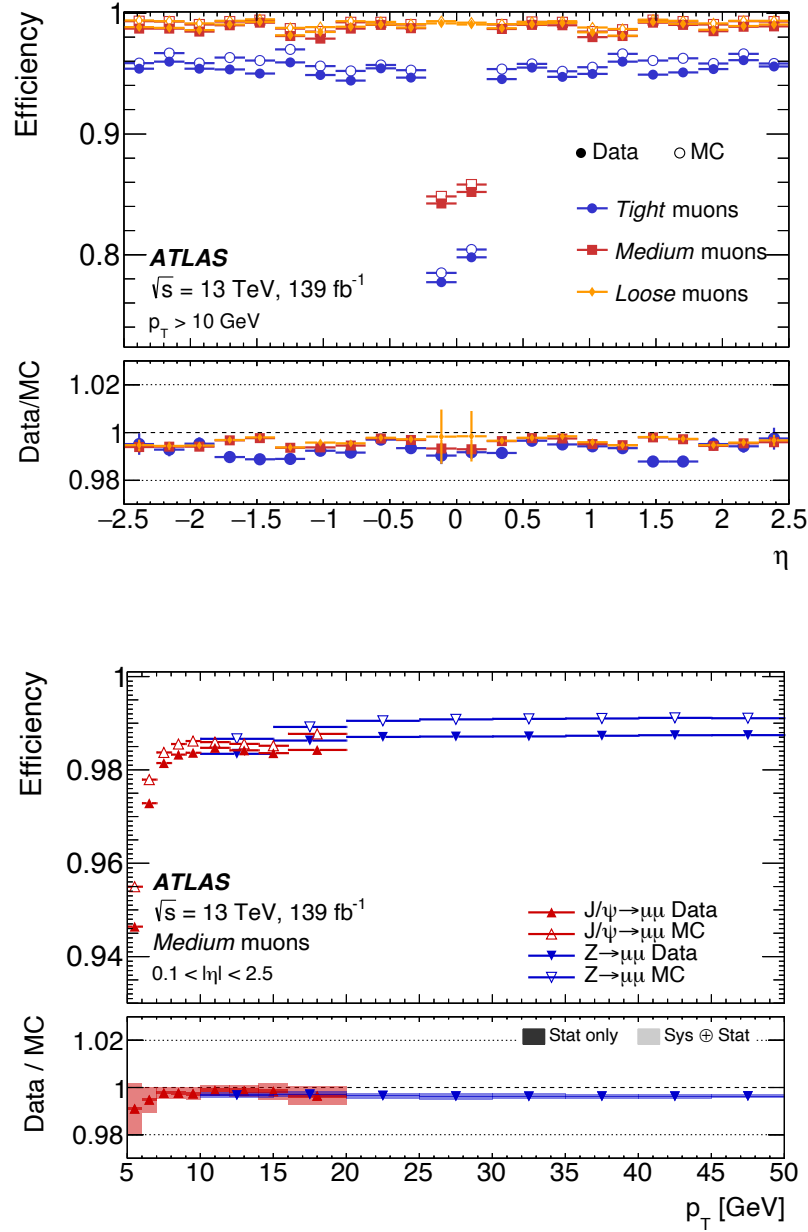


Figure 3.18. Muon reconstruction efficiency in $Z \rightarrow \mu\mu$ events as a function of η for the loose, medium and tight working point (top) and as a function of p_T in the region $0.1 < |\eta| < 2.5$ for the medium working point (bottom). The predicted efficiencies are depicted as open markers, while filled markers illustrate the result of the measurement in collision data. The panels at the bottom shows the ratio of the measured to predicted efficiencies, with statistical and systematic uncertainties. The results are based on the full pp collision data collected in 2015-2018 at 13 TeV.

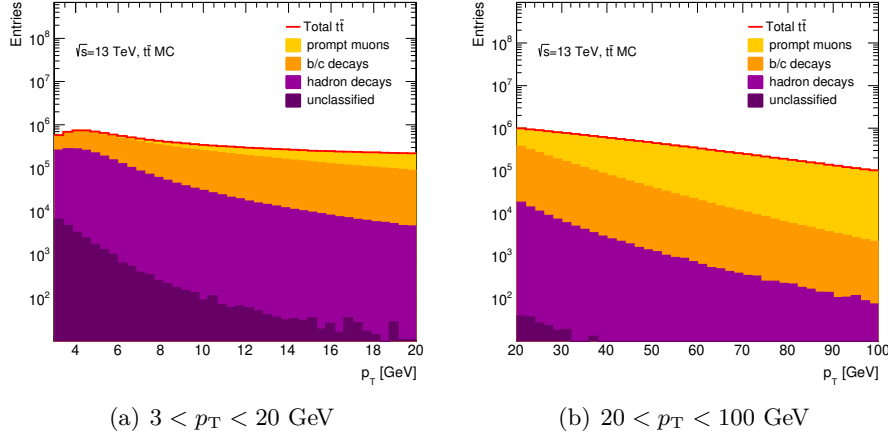


Figure 3.19. Composition of muons in $t\bar{t}$ simulation as coming from truth classification, divided into two transverse momentum regimes: $3 < p_T < 20$ GeV (left) and $20 < p_T < 100$ GeV (right). A $|\Delta z_{0,PV} \cdot \sin(\theta)| < 0.5$ mm requirement is applied, to remove unclassified muon candidates coming from pileup interactions.

for $1.3 < |\eta| < 1.55$, at least two MS stations are required, for $|\eta| > 1.55$, the *Medium* WP requirements are applied. Moreover, a very loose selection on following variables is used to suppress fakes:

- the momentum balance significance (MBS) is defined as momentum difference between the ID and MS standalone measurements with respect to the uncertainty sigma on energy lost in the calorimeter system
- the scattering neighbor significance (SNS) is a variable estimating the significance of a change in trajectory (kink) along the track, expected in the presence of a hadron decaying to a muon. It is computed considering pairs of adjacent hits along the track, and evaluating the significance of the angular distance in the bending plane between the two half tracks ending/starting at each of them. The SNS is the largest value of such significances over the whole track
- the scattering curvature significance (SCS) is computed as the normalized integral of the scattering angle significances, corrected for single kinks along the trajectory that diminish the absolute value of the integral significance

where $|\text{MBS}|$, $|\text{SNS}|$ and $|\text{SCS}|$ are all required to be smaller than 3.

The *High- p_T* working point

During my Ph.D. I was the responsible for the ATLAS *High- p_T* working point. My work aimed at the improvement of both *High- p_T* efficiency selection and systematic uncertainties associated. A very detailed description on the *High- p_T* working point will be presented in section 5, focusing on all my original studies. The impact of my work on the search for new highmass phenomena decaying in a pair of muons will be also discussed.

3.3.3 The Run-3 and the High Luminosity LHC upgrades.

From December 2018 the Run-2 data taking is officially finished. Proton-proton collisions will restart in 2021, with the operations that will be conducted up to the 2023. This period is called Run-3; collisions at center of mass energy of 14 TeV will be performed and the luminosity will reach the value of 2.5 times the nominal one ($10^{34} \text{ cm}^{-2}\text{s}^{-1}$) with expected 300 fb^{-1} data collected.

The long shut-down before the start of the Run-3 is called LS2, and in this period new electronics, trigger and detector components are under installation as a first step to prepare the ATLAS detector to the High Luminosity LHC (HL-LHC) that will take place in 2026 (new systems will be also installed during the next long shut-down LS3 in 2024).

The High Luminosity LHC (HL-LHC) is a new phase of the LHC. With upgrades on the accelerator, instantaneous luminosities of a factor 5 larger than the LHC nominal value will be achieved, so that experiments will enlarge their data sample by one order of magnitude compared with the LHC baseline programme. At the HL-LHC beams will collide with about 200 simultaneous collisions per beam crossing; this will increase the ATLAS sensitivity on new or rare physics events, but requires the installation of new performing detectors, able to work in these conditions (hard-radiation, needed of finer granularity and faster readout).

For the Run-3 will be available improvements for the muon spectrometer: *New Small Wheels* (NSW) that can handle the higher flux of neutrons and photons expected in the future LHC interactions, 16 new chambers of *Small Monitored Drift Tubes* (*sMDT*) and *Resistive Plate Chambers* (*RPCs*) to be installed in the barrel region in order to improve the overall trigger coverage.

There will be improvements also for the Liquid Argon (LAr) calorimeter: new front-end electronics and optical-fibre cabling will be installed, greatly improving the resolution of the detector at trigger level, providing 4 times higher granularity that allow to better differentiate jets of particles from electrons and photons.

In this context, I gave a leading contribution to the NSW project that will be presented in next chapter.

Chapter 4

The Micromegas detector for the ATLAS upgrade

In the next years, the LHC accelerator will be upgraded with an increase of instantaneous and integrated luminosity, so that the particle rate will drastically increase. The ATLAS goal is to cope with this large particle rate and at the same time trying to conserve the high muon detection efficiency keeping a good momentum resolution up to $\sim \text{TeV}$. For this purpose the current innermost stations of the Muon Spectrometer end-caps, the Small Wheels, will be replaced in the years 2019-2021 shutdown with the New Small Wheel detector for high luminosity LHC runs. An overview of the design, construction and assembly procedures of the Micromegas modules will be reported with particular reference to the drift panels for the SM1 chambers built by the Rome1 INFN section. Efficiency results and characterizations for the Micromegas detector, finalized at CERN (double wedge), will also be presented.

4.1 New Small Wheel

The New Small Wheel [55] (NSW) will feature two new detector technologies: resistive Micromegas (MM) and small strip Thin Gap Chambers (sTGC).

It is designed to detect muons in the pseudorapidity region $1.3 < |\eta| < 2.7$ and face particle rates up to 15 kHz/cm^2 . In Figure 4.1 the NSW layout is illustrated: there will be two wheels, one for each ATLAS side, each of which is made of sixteen sectors (eight large and eight small); each sector consists of six sTGC and four MM quadruplets.

Both MM and sTGC detectors, given their excellent spatial ($\simeq 100 \mu\text{m}$) and time ($\simeq 10 \text{ ns}$) resolutions, will be used for precision tracking and will provide the trigger system, resulting into a fully redundant NSW measurement.

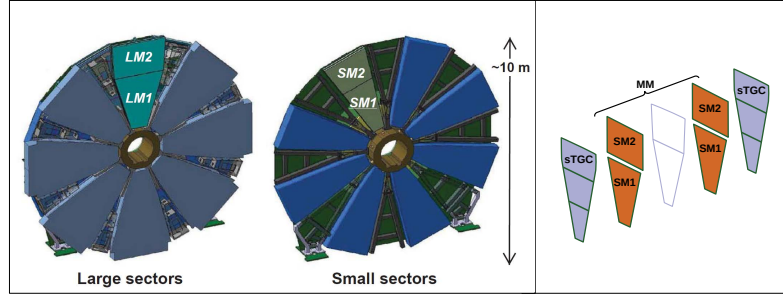


Figure 4.1. Overview of the ATLAS New Small Wheel system. Left: detail of large and small sectors, each of which is segmented in two parts of different size, respectively LM1, LM2 and SM1, SM2. Right: small sector layout; four MM (orange) and six sTGC (grey) quadruplets are shown.

4.2 sTGC detector

The sTGC detector [56] is mainly selected for performing the trigger function, so a good timing resolution to identify the bunch crossing is required. The aim of the trigger is to identify tracks pointing to the Interaction Point with 1 mrad angular resolution at the final level trigger. This requirement translates into a space resolution of $\sim 100 \mu\text{m}$ per layer.

The sTGC layout is shown in Figure ?? . It is made of a grid of tungsten wires plated in gold, with $50 \mu\text{m}$ thickness at a distance of about 1.8 mm. The cathodic planes consist of a compound of graphite and resin. On one cathode there are the read-out strips perpendicular to the wires while on the other there are pads each covering a large rectangular surface. The strips have a 3.2 mm pitch, much smaller than the current ATLAS TGC, here the name "small strip" TGCs. The chamber is filled with a gas mixture of 55% CO_2 and 45% n-pentane, which has an electron drift velocity of about $3 \text{ cm}/\mu\text{s}$ under an electric field of $2.9 \text{ kV}/\text{cm}$.

The project for NSW has two quadruplets separated by 35 cm in z . Each quadruplet consists of four sTGC(s), each with pads, wires and read-out strips. Pads are used to produce a coincidence of three to four to identify tracks of muons pointing roughly toward the point of interaction at the first level. They are also used to define which region of read-out strips should be read to obtain a precise measurement in the bending coordinate for the online selection of muons. The azimuthal coordinate, for which a precision of about 10 mm is required, is obtained from the read-out of the wires. Charge of all strips, pads, and wires is read for offline reconstruction.

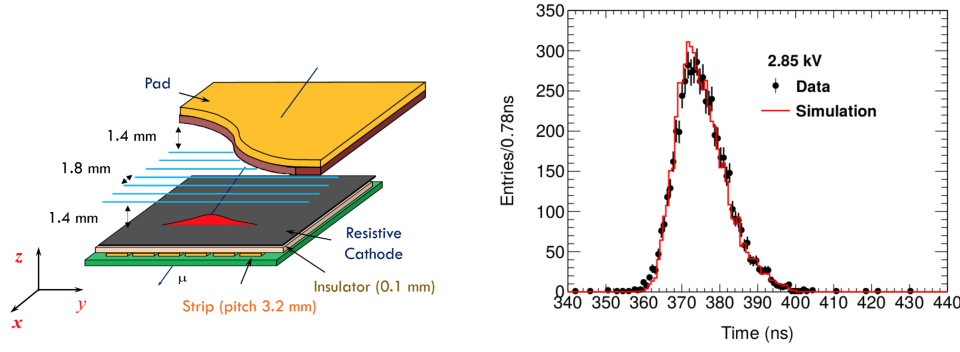


Figure 4.2. Basic structure of a sTGC (left). Full width at half maximum of Drift times measurement distribution is less than 25 ns proving the bunch crossing identification capability of the sTGC detector (right)

4.3 Micromegas detector

A Micromegas chamber [57] is a gaseous detector which consists of two parallel electrodes mounted on a drift (cathode) and a read-out (anode) panel. The two panels are kept at a constant distance of about 5 mm. A metallic mesh connected to ground is tensioned between the two electrodes and kept parallel to the panels. The 5 mm region between the cathode and the mesh is the conversion and drift gap with a low electric field ($\simeq 600$ V/cm), the $128 \mu\text{m}$ region between the mesh and the anode is the amplification gap with an higher electric field ($\simeq 50$ kV/cm). The spacing between the mesh and the anode is actually determined by some insulating pillars of $128 \mu\text{m}$ fixed height supporting the mesh over the read-out panel. Resistive and read-out strips are mounted on the read-out panel with a pitch of $\simeq 400 \mu\text{m}$, designed to reduce the probability of discharge and to read the capacitively-induced electric signal. Micromegas are suitably operated with a two component non-flammable gas mixture: $93 : 7 - \text{Ar} : \text{CO}_2$. A different gas composition, consisting of $93 : 5 : 2 - \text{Ar} : \text{CO}_2 : \text{C}_4\text{H}_{10}$, allowing a better HV stability is under investigation. This gas mixture should provide an higher efficiency detection applying a lower tension in the amplification gap.

A charged particle crossing the conversion and the drift gap ionizes the atoms. The electrons liberated by this ionization process drift towards the mesh. The values of the field reached in the amplification gap is 50-100 times stronger than the drifting field. The electron avalanche takes place in the thin amplification region, immediately above the read-out electrode as shown in Figure 4.2. The amplification process takes a fraction of a nanosecond, resulting in a fast pulse on the read-out strip.

4.4 The ATLAS Micromegas quadruplets structure

Each ATLAS Micromegas module [58] (quadruplet) is made of three drift panels (panels 1, 3 and 5 in Figure 4.3), which include cathode (copper film illustrated with a red line Figure 4.3) and mesh, and of two read-out panels (panels 2 and 4 in Figure 4.3), which include pillars and four (two per readout panel) strips layers

(Figure 4.4).

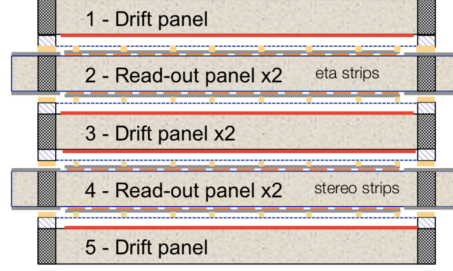


Figure 4.3. A schematic view of the five panels (1-3-5 are drift panels and 2-4 are readout panels) of a MM quadruplet.

The first and second layer of the readout panel have strips in the η direction and are called η layers (Figure 4.4), while in the third and fourth layer of the second readout panel strips are inclined of an angle $\theta = \pm 1.5^\circ$ with respect to the η direction and are called stereo layers (Figure 4.4). The stereo layers are divided into U layer (third layer) and V layer (fourth layer) depending on the strips inclination. The η coordinate is obtained by using the first two layers, while from the third and fourth ones it is possible to measure η and ϕ exploiting the following relations [59]:

$$\eta = \frac{x_{layer3} + x_{layer4}}{2 \cdot \cos \theta} \quad \phi = \frac{x_{layer3} - x_{layer4}}{2 \cdot \sin \theta} \quad (4.1)$$

where x_{layer3} and x_{layer4} are respectively the local positions on layer3 and on layer4 and θ is the strips inclination angle (Figure 4.4). Equations 4.1 are valid under the assumption of small distance (thickness of readout panel) between layer3 and layer4 along the Z direction.

The panels have a trapezoidal shape and the size is $\simeq 2 \text{ m}^2$ for the small sector and $\simeq 3 \text{ m}^2$ for the large one. In order to guarantee the uniformity of the electric field and a good quality in the precision measurements, panel surfaces are required to be planar ($\text{RMS} \leq 37 \text{ } \mu\text{m}$ or equivalently $\pm 110 \text{ } \mu\text{m}$ mechanical tolerance) and strips should be aligned between layers to better than $60 \text{ } \mu\text{m}$.

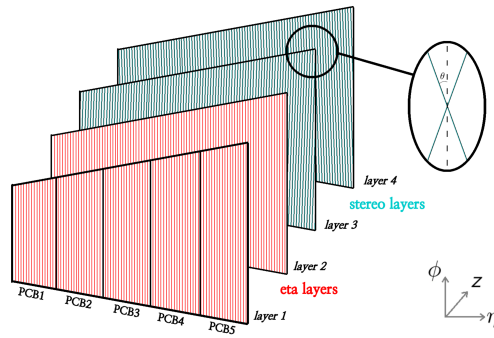


Figure 4.4. A layout of the readout panels strips layers (eta layers - panel number 2 ; stereo layers - panel number 4 Figure 4.3). A cartesian plane to indicate the strips position with respect to the ATLAS coordinates.

4.5 SM1 Construction

During my PhD activity, I had a leading role in the micromegas project for the ATLAS NSW upgrade. In this section a very detailed focus will be put on the construction and validation of the drift panels for the SM1 micromegas quadruplets, which I was one of the responsible for.

Rome1, Rome3, Pavia, Frascati, Cosenza, Lecce and Napoli INFN teams are the ones involved in the SM1 construction. Before assembling the quadruplet in Frascati site, the components are separately built and validated in other sites. Rome1 takes care of drift panels construction that is finalized by Cosenza, Rome3 deals with the mesh stretching and finally the read-out panels are built in Pavia (Figure 4.5). After the construction, planarity and high voltage tests are performed to validate both drift and read-out panels.

INFN is committed to build 1/4 of the chambers. The other construction sites are in Germany (SM2), in Saclay (LM1) and in Dubna-Thessaloniki (LM2). All construction sites use very similar construction and assembly procedures.

The total number of drift panels needed for the SM1 MM project is 96 (3 per quadruplet, 2 quadruplets per double wedge, 8 small double wedge per wheel, 2 wheel per ATLAS). Rome1 built 105 drift panels, nine more of the needed number (spares), to ensure the highest possible quality for the final MM quadruplet assembly.



Figure 4.5. Top left: drift panel construction in Rome1. Top right: mesh stretching in Roma3. Bottom left: read-out panel construction in Pavia. Bottom right: final assembly of the module in Frascati.

4.5.1 Drift panel components

Drift panels are categorized into two types according to their position in the quadruplet of a MM chamber:

- outer: panels 1 and 5 in Figure 4.3, make up the outside part of the chambers and have only one face with copper (red line) ;

- central: panel 3 in Figure 4.3, that is located at the center of the quadruplet and has two faces with the copper deposited above because it is used for two different MM gaps within a quadruplet.

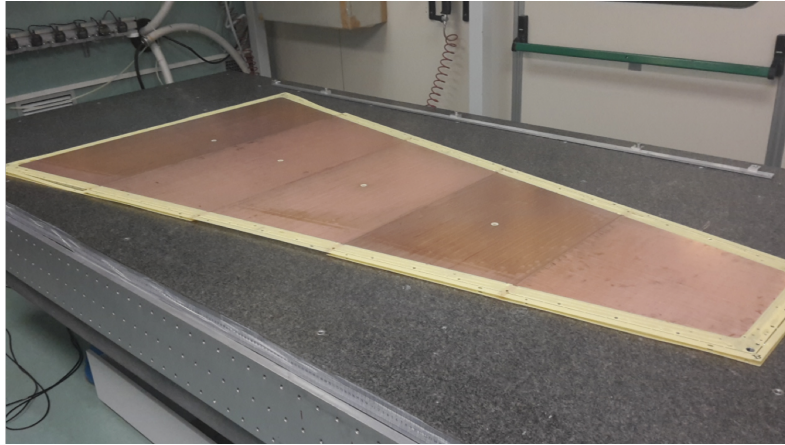


Figure 4.6. Central panels assembled in Rome1.

Figure 4.6 shows a drift panel built in Rome1 site.

A single panel is made by glueing two skins on a stiff plane and consists of several elements needed to make it work, make it durable and lightweight and attach it to others to create the complete MM module. Here a description of all the components used for the drift panel realization is given:

- first Printed Circuit Boards (PCBs or fibreglass skin)
- aluminium honeycomb surrounded with an aluminium frame
- interconnections, HV connectors and gas pipe
- second PCB

In Figure 4.7 a schematic view of the micromegas drift panel structure is shown.

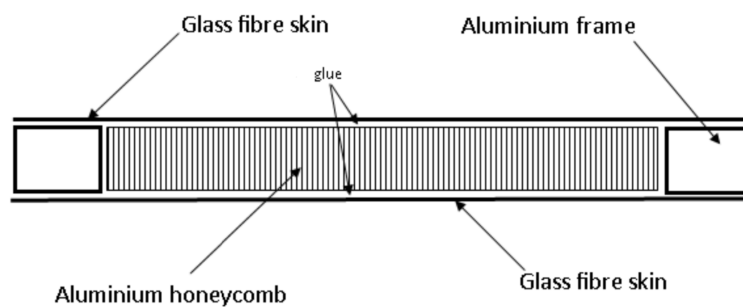


Figure 4.1. Schematic view of the MicroMegas drift panel section structure.

Figure 4.7. Schematic view of the MicroMegas drift panel section structure.

PCB

PCBs have a trapezoidal shape and are $500\ \mu\text{m}$ thick fiberglass of various size, on which, with a lithographic techniques, a film of copper of about $17\ \mu\text{m}$ is deposited (Figure 4.8). Each single panel is composed by 10 PCBs (5 for each side, in increasing order of size: PCB1, PCB2, PCB3, PCB4 and PCB5).

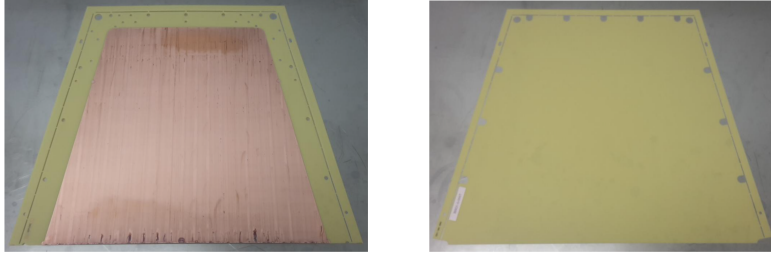


Figure 4.8. The two-sides PCB1, with (left) and without (right) the copper film, used for building SM1 drift panels.

The PCB thickness has been measured in Rome1 INFN section with the Limbo. Limbo is a system composed by 10 comparators that measure the difference between the plane and the surface where the sensors are laying (Figure 4.10) with a resolution of μm . To ensure that there is no offset in the measurements, a recalibration of the Limbo is made using calibrated bars of $0.060\ \text{mm}$, $1.000\ \text{mm}$, $2.000\ \text{mm}$, $3.000\ \text{mm}$, $5.000\ \text{mm}$ and $6.000\ \text{mm}$. Ten measurements for each bar (using all comparators) are done and the results are shown in Figure 4.9. No significant offset in the previous measurements is observed. Only the PCBs within the requirement (thickness $\sim 535 \pm 25\ \mu\text{m}$ or $520 \pm 25\ \mu\text{m}$ for the PCB with and without the copper film), have been used for the drift panel construction.

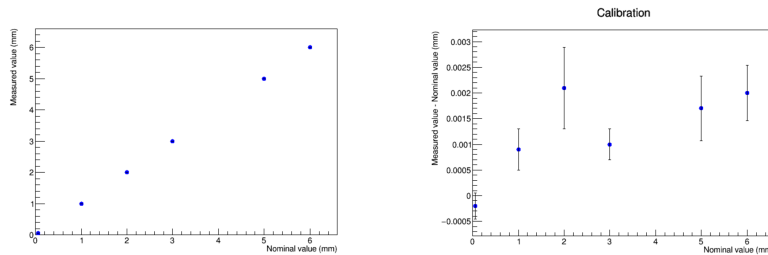


Figure 4.9. Left: Measured value as a function of the Nominal values of the calibrated bars. Each measurement is done by using all calipers of the Limbo; the associated error are smallest than the blue point. Right: Differences between the measured value and the nominal value for each type of calibrated bars. The error bars are the RMS of the measurements done.

The distribution of the PCBs thickness, with (left) and without (right) copper, as measured by the Rome1 group is shown in Figure 4.11, respectively. The difference between the mean of the two distribution results to be $\sim 16\ \mu\text{m}$, in agreement with the nominal thickness of copper.

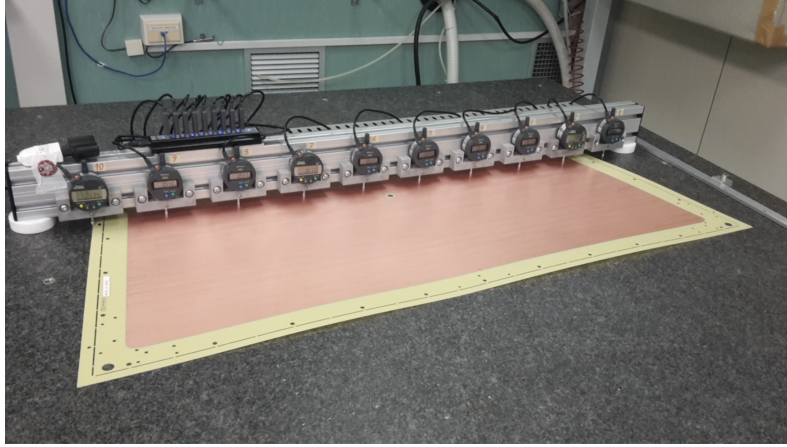


Figure 4.10. Limbo system during a PCB thickness measurement.

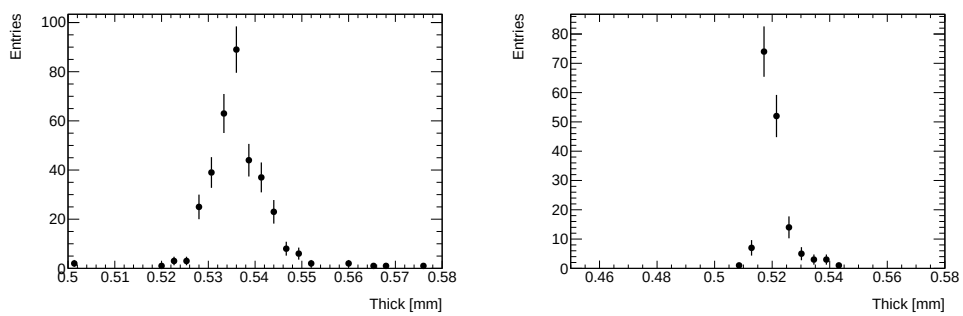


Figure 4.11. Thickness distribution of PCBs with (left) and without (right) the copper film.

Honeycomb and Frames

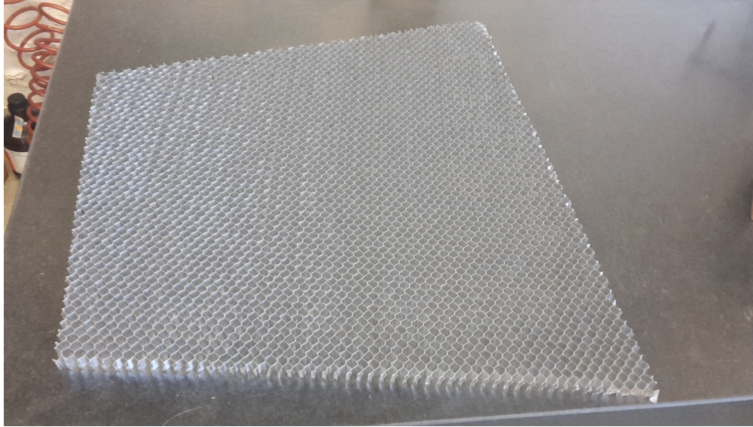


Figure 4.12. Cut aluminium honeycomb sheet.

Honeycomb and frames constitute the body of the drift panel and are used to make a stiff structure. Each panel is composed by 5 honeycomb sheets and 10 frames. Honeycomb sheets are 10.1 *mm* (nominal value) thick, shaped according to the PCB shape, as shown in Figure 4.12. The honeycomb is in average 100 thicker than the frames, in order to compensate for the glue thickness on top of the frames.

The honeycomb thickness was measured in Rome1 INFN section with the Mitutoyo Linear Height 600 [60]. Mitutoyo Linear Height is composed by one comparator to measure the difference between the plane and the surface where the sensor is laying (Figure 4.13). Only honeycomb within the requirement (thickness $\sim 10.100 \pm 0.070$ *mm*), have been used for the drift panel construction.

Frames are 10 *mm* thick and are placed along the perimeter of the drift panel (six) and transversal (four) with respect to the longest side of the trapezoidal, as illustrated in Figure 4.14. Only frames within the requirement (thickness $\sim 10.000 \pm 0.070$ *mm*), have been used for the drift panel construction.

The thickness of the frame bars was first measured in Pavia. An ulterior validation check of the frame thickness is performed by the Rome1 group with the Limbo system.

In Figure 4.15 the thickness distribution of the honeycomb sheets (left) and frames (right), measured by the Rome1 groups, is shown. Only honeycombs and frames resulted to be in agreement with the nominal value within the bounds of tolerance have been used for the drift panel construction.

The PCBs, honeycomb and frames distribution present an asymmetric tail (Figures 4.11,4.15) that is thought to be due to small imprecision in the production site. The spread observed in all these distributions is a convolution of Limbo/Mitutoyo and construction site resolution.

Interconnections, HV connectors and Gas pipe



Figure 4.13. Mitutoyo Linear Height 600 during a honeycomb thickness measurement. Over the honeycomb cut sheet have been placed some weights (lead) to prevent the bending of the sheet.

Each panel will compose the micromegas quadruplet module with the 4 gas gaps (section 4.4). Interconnections are used to connect the drift and read-out panel and to keep the distance between them once an over pressure is created in the gaps after flushing the gas. Interconnections are integrated into each panel and are centred on all PCBs except for the smallest one. In Figure 4.16 (leftmost), a photo of one of the interconnections needed for the drift panel construction is shown.

High-Voltage (HV) (Figure 4.16 middle-left) and gas pipes (Figure 4.16 middle-right) are important components of each panel. HV connectors are mounted laterally on each panel to connect the 300 V to the whole coppered area of the panel to make sure that it works correctly as a cathode. The gas pipes are placed in both bases of the trapezoid to enter the gas mixture inside each gap and to provide the exit.

4.5.2 Drift panel construction

The drift panels of the SM1 modules are assembled using the vacuum bag method, described below. The construction procedure of the drift panels is studied to build a drift panel in one (outer panel) or two (central panel) days.

Araldite 2011 is the glue used to assemble the drift panel. Glue begins to dry after 80/90 minutes in contact with air and takes few hours to complete its action. All the procedures are done in 1-2 hours and then 24 hours are left to complete glue curing.

The drift panel construction takes place in a clean room to ensure that there are no impurities that can enter in the panel and damage its operation and is performed on the top of a granite table (planarity $< 10 \mu m$).

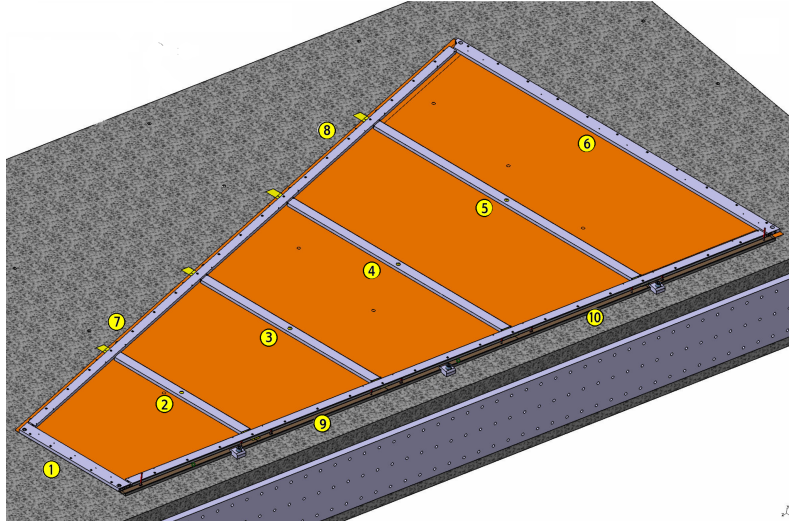


Figure 4.14. Scheme of the position of the frames in each SM1 drift panel.

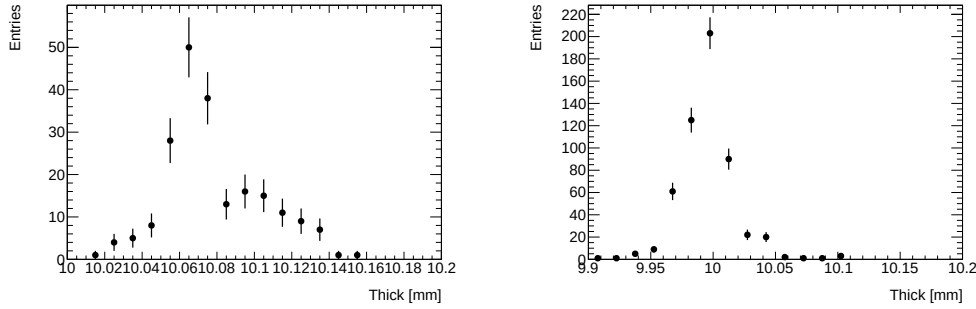


Figure 4.15. Thickness distribution of the honeycomb (left) and frames (right).

To assure everything is ready for the construction, all machining are done prior to panel assembly without glueing the components (dry-run). An aluminium bar, with several removable precision pins, is mounted on the granite table and will be used as a guide for the PCBs placement and it is also necessary to ensure that the PCBs are aligned.

First of all the glue is deposited on the top side of PCBs by using a special gluing machine equipped with a mechanical arm (Figure 4.17 - left). After depositing the glue on the PCBs are moved on the granite table with the no glued side in contact with it (Figure 4.17 - right).

PCBs are aligned with respect to the aluminium bar holes and are fixed using two precision pins. A strip of kapton is fixed at the ends of two nearby PCBs in order to set better the distance between the PCBs avoiding their overlapping and gas leaking in the junction regions.

Honeycomb, frame bars, interconnections, HV connectors and gas pipes are placed on the glued PCBs (Figure 4.18). Honeycomb sheets are electrically connected to the frames for subsequently grounding them.

At this point the construction procedures for the outer and central panel follow a different schedule.



Figure 4.16. From left to right: the interconnections, HV connector, gas pipe used for the drift panel construction; the PCB1 during the construction phase, the position inside the panel of the honeycomb cutted sheet, the HV connectors and the gas pipes is shown.

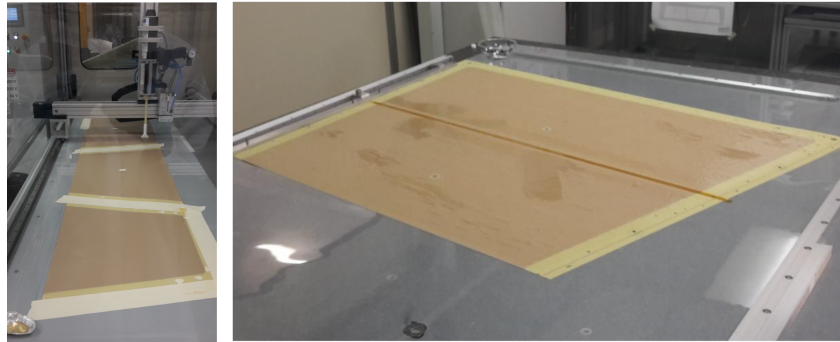


Figure 4.17. The gluing machine during the type 1, 2 and 3 PCB bonding step. Tape on PCBs borders ensures the glue not to be deposited in the PCB holes (left). Type 5 and 4 PCBs placed on the granite plane fixed to the aluminium bar with the precision pins (right).

Outer Drift Panel

The glue is deposited on the second set of PCBs using the same procedure described above. The second layer of PCBs is then glued on top of the honeycomb and bar frames to close the panel. The mask (Figure 4.19 - left) and the vacuum bag is put on the upper PCB's layer to finalize the construction (Figure 4.19 - right). The air is pumped out, pressing the components against the granite table (overpressure of ~ 100 mbar). The vacuum bag is kept on top of the panel for ~ 24 hours to ensure the glue hardens.

Central Drift Panel

The second layer of PCBs is placed on top of the honeycomb and bar frames to close the panel without depositing the glue on it. The vacuum bag is then put on the upper PCB's layer and is kept for ~ 24 hours to finalize the first part of the central panel construction (Figure 4.19). The second part of the construction starts removing the vacuum bag and the second set of PCBs. The body of the panel, built the day before, is then moved on an adjacent table. After freeing the granite table, the glue is deposited on the second set of PCBs with the dedicated machine (Figure 4.17 - left). Once the PCBs are placed and aligned on the granite table, the

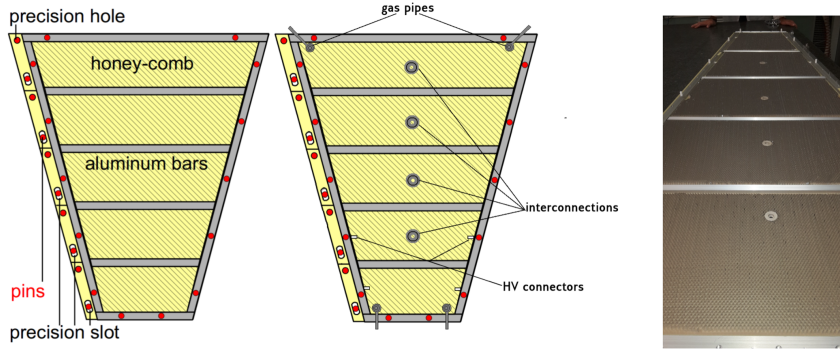


Figure 4.18. Scheme of the PCBs, honeycomb, frame bars, interconnections, HV connectors and gas pipes position during a panel assembling.

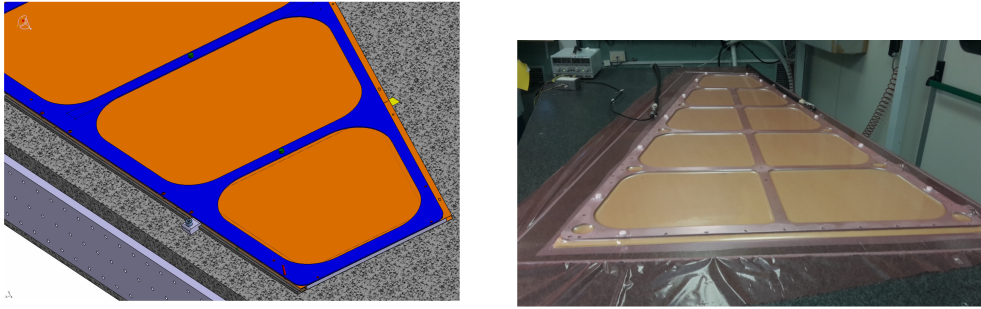


Figure 4.19. Left: Schematization of the position of the mask on the upper PCBs for pressing the panel. Right: drift panel while applying the mask and the vacuum bag on top of the panel.

body of the panel is rotated and put on the top of the PBCs using a stiff bar. As for the outer panel the last step consists of putting the mask and the vacuum bag on the top of the panel, pressing the components against the granite table and waiting for ~ 24 hours to ensure the glue hardens.

4.5.3 Drift panels QA/QC

Only optimal drift panels, within the ATLAS requirements, can be used to assemble the SM1 micromegas quadruplets. Drift panel control measurements are fundamental to ensure the quality of the panel. These measurements are based on the control of the planarity of the panel and its dark current (HV test).

Planarity measurements

The ATLAS requests for the drift panel planarity are an $\text{RMS} < 37 \mu\text{m}$ and a difference between the maximum and the minimum value not larger than $220 \mu\text{m}$. The thickness measurements have been obtained by using the Limbo system of the Rome1 INFN section (Figure 4.20). The planarity measurements are performed on the x-y plane (which corresponds to the granite plane on which the panel is located). For each panel 20 measurements (10 per side) have been executed, starting from the

smallest PCB (PCB1) moving the Limbo (~ 10 cm per step) in the PCB5 direction.

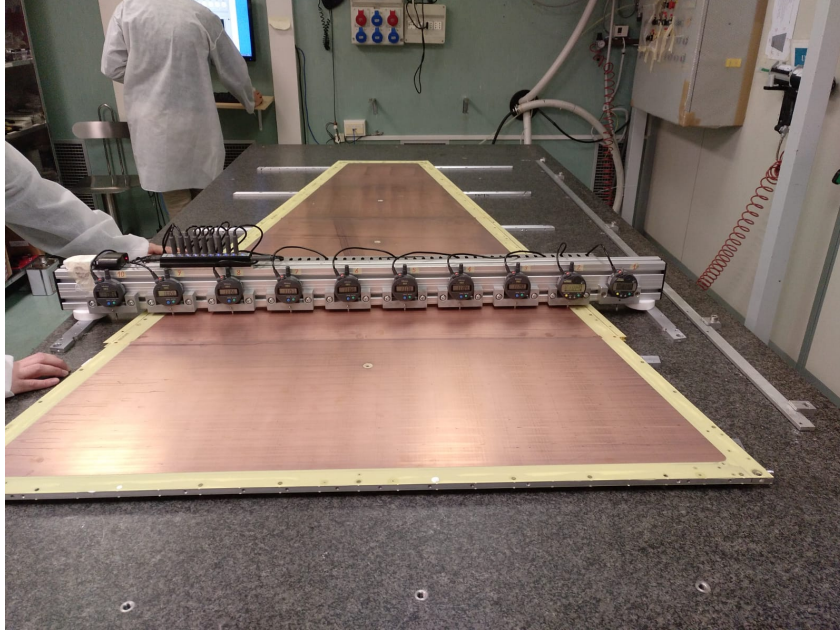


Figure 4.20. Drift panel while applying the mask and the vacuum bag on top of the panel.

After acquiring the thickness measurements from the Limbo comparators, the distributions of residuals is evaluated as the difference of the raw data and fitted best-plane. The fitted thickness is given by the parameter c , obtained by fitting the raw measurements with the following function:

$$f(x, y) = a \cdot x + b \cdot y + c \quad (4.2)$$

while a and b correspond to the inclination of the panel. In figures 4.21- 4.22 an example of the planarity measurements results for both outer and central tested panels is presented. In particular, the raw thickness and the residual distribution on the x - y plane for the two sides of the panels is shown, while the RMS, max-min average, raw and residual thickness are given in Table 4.1.

Side	Outer		Central	
	A	B	A	B
raw thickness	11.23 mm	11.18 mm	11.23 mm	11.21 mm
raw RMS	36 μm	32 μm	27 μm	46 μm
max-min raw	199 μm	159 μm	114 μm	221 μm
fitted thickness	11.23 mm	11.18 mm	11.23 mm	11.21 mm
fitted RMS	34 μm	31 μm	26 μm	43 μm
max-min after fit	250 μm	160 μm	114 μm	220 μm

Table 4.1. Raw and fitted results for one of the outer and central tested panels.

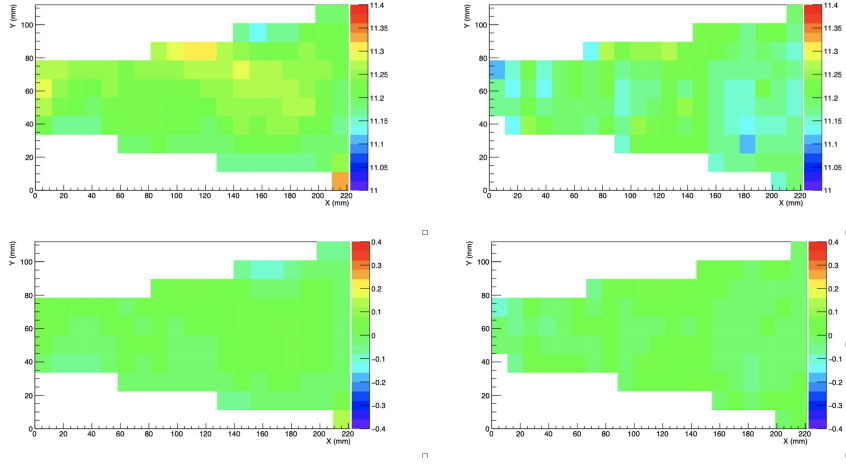


Figure 4.21. Left: Coppered side - Right: fibreglass skin side. Up: Bi-dimensional plot of the outer panel ; coloured is represented the thickness (in mm) of the measured point. Down: Bi-dimensional plot of the outer panel; coloured is represented the residual value (in mm) of the measured point.

HV test

HV test is another fundamental test needed to validate the drift panels before using them for the micromegas quadruplet assemble. ATLAS requests for the dark current to be smaller than few nA. These measurements are done by connecting the coppered side of each PCB to each others and then connecting them to a generator of tension set to 1000 V as shown in Figure 4.23. The ground is connected to the honeycomb through one of the frame bar holes.

All the drift panel built by the Rome1 group satisfied the ATLAS requirements.

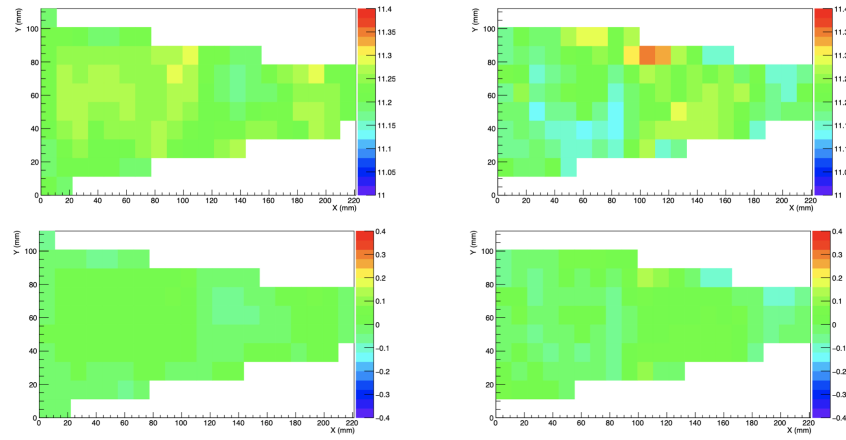


Figure 4.22. Left: side A - Right: side B. Up: Bi-dimensional plot of the central panel ; coloured is represented the thickness (in mm) of the measured point. Down: Bi-dimensional plot of the central panel; coloured is represented the residual value (in mm) of the measured point.

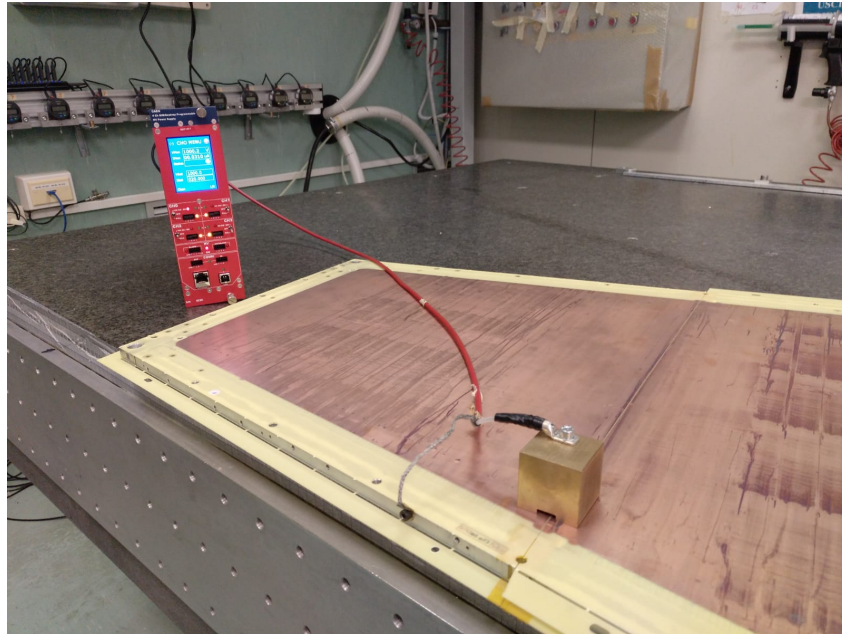


Figure 4.23. Finalized drift panel during the HV test.

4.6 Micromegas efficiency performance

Once the SM1, SM2, LM1 and LM2 micromegas quadruplets are assembled and validated in the respective construction sites, they are shipped to BB5 building at CERN. There, after an additional validation check, the micromegas quadruplets are assembled in their final setup: the "double wedge" (DW). DW are divided in small and large. Each DW is composed by 2 SM1 and SM2 (small DW) or 2 LM1 and LM2 (large DW) quadruplets. Each layer of the SM1 and LM1 quadruplets consists of 10 sections, while SM2 and LM2 layers are composed by 6 sections.

HV test at BB5

During my time at CERN, my work at BB5 aimed at the HV double wedge validation and at the optimization of its HV mapping configuration.

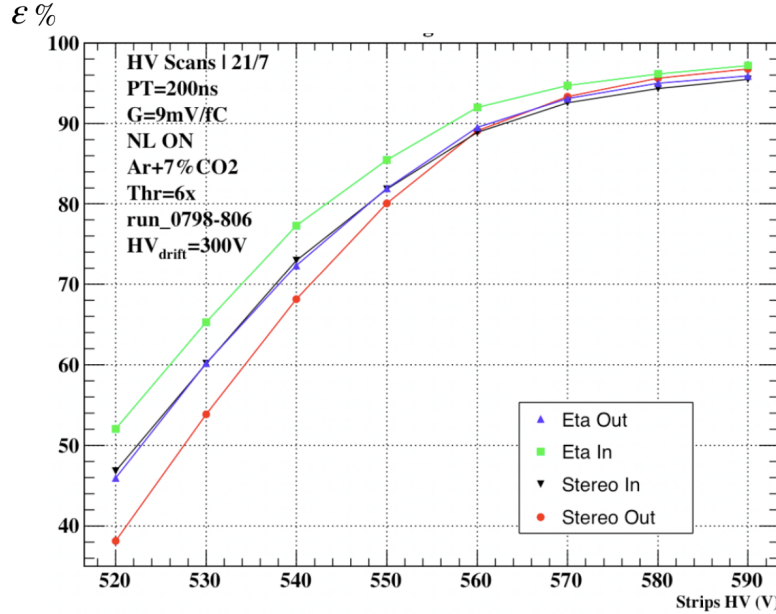


Figure 4.24. Micromegas reconstruction efficiency as a function of the HV applied on the amplification gap for the eta and stereo layer.

In Figure 4.24 the detections efficiency of the micromegas layers as a function of the HV in the amplification gap is shown. The micromegas HV working point has been set around 570 V, since it resulted to be the optimal compromise between high efficiency detection and good HV stability.

One of the most challenging side of this project is related to the HV stability. Several tests aiming at the understanding of the micromegas HV behaviour were performed. Figure 4.25 shows the maximum HV reached in stable conditions by a HV section versus the minimum resistance (R_{min}) value measured on the corresponding PCB. A correlation between the problematic HV sections, which cannot be operated at the default voltage $HV = 570$ V, and low values of the resistance is observed. A

thin layer ($\sim 50 \mu m$) of glue was deposited on the low-resistance regions of the active area to passivate them at the price of reducing the acceptance of the detector of 1-2%. The crucial point of my study is about the HV granularity that is per layer and not per section, so the presence of one bad section (high current, not stable voltage) is enough to make the entire layer inefficient. To overcome this limitation a splitter box has been built. The splitter box is used to apply the HV on each section of the layer independently, such that if a bad section is found it is possible to switch it off. To avoid detection holes in case of non optimal sections in the quadruplet, the splitter box allows to apply a lower HV to these sections putting them in the "hospital line" without worsening the high efficiency of the optimal sections. A dedicated study on detailed knowledge of the various sections performance is necessary, since 4 hospital line per each DW (one per quadruplet) are available on the splitter box. After acquiring the performance information needed, for each DW, a final HV detector mapping aiming at the optimization of the efficiency detection has been undertaken.

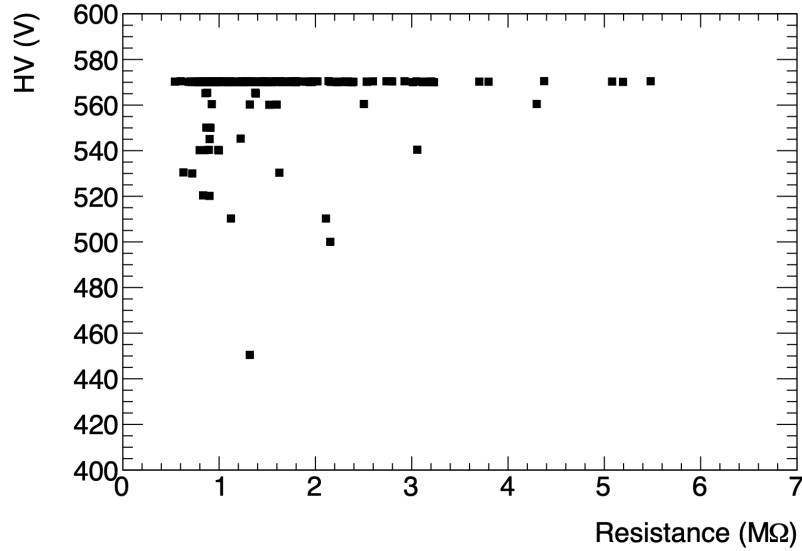


Figure 4.25. Distribution of the maximum stable HV value reached by PCBs versus R_{min} .

Double wedge efficiency

In particular I was the responsible of the HV validation and optimization of first 8 small DW that will be installed in the new small wheel A. The nomenclature used to name the DW is the following:

- letter A-B refers to the wheel where the DW will be mounted on (NSW A, NSW B)
- number 1-16 corresponds to the i th DW on a single wheel, odd for large and even for the small sectors

A dedicated Cosmic Ray Stand (CRS) is installed in the building BB5 at CERN. It is composed by two sets of scintillators (of different dimensions) used for triggering

the good events. The trigger logic is the OR of the AND between the two up+down scintillator reaching the expected rate of 105 Hz (Figure 4.26). The muon tracks have been reconstructed with all eight layers. An example of such a muon track (from event display) from the first double wedge on the cosmic stand of BB5 is shown in Figure 4.27.

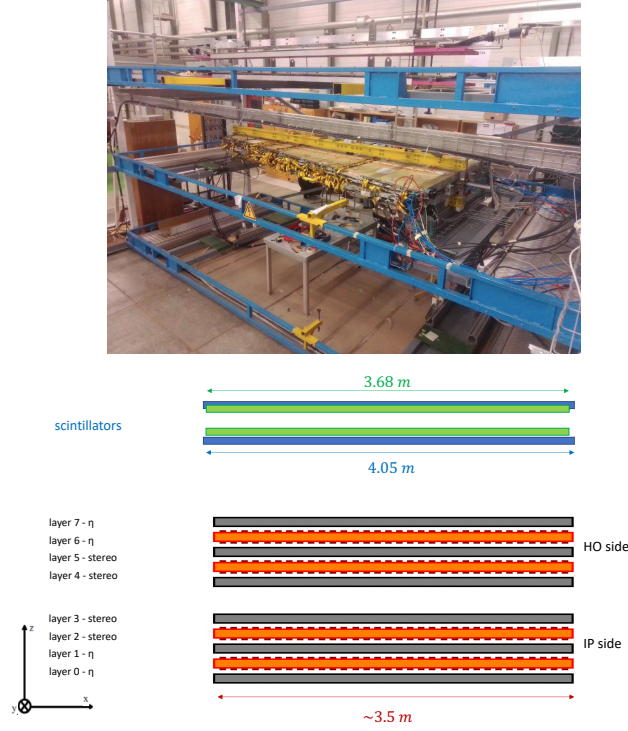


Figure 4.26. Photo (top) and layout (bottom) of the Cosmic Ray Stand at BB5.

As final QA/QC step, the DW chambers were installed in the CRS, for a complete qualification in terms of detector efficiency.

The efficiency was first evaluated per each layer of the DW as follows: the layer of interest is hidden, the track is reconstructed by using the other 7 DW layers and then a coincidence in the layer of interest, within $\pm 5 \sigma_{residual}$ ($\sim 1 \text{ cm}$) from the reconstructed track, is searched. The DW efficiency is therefore obtained by combining efficiencies of the different layers. In Figure 4.28 the efficiencies of the 8 small (left) and 3 large (right) DW are shown. Each color represents the detection efficiency corresponding to the different requests on the number of coincidences in the 8 DW gaps.

In Figure 4.29 the efficiency of each section, for the standard 6/8 coincidences request (yellow), of the 8 tested, optimized and validated small DW is shown.

The target efficiency of 95 %, averaged on the sections, has been achieved for all the small DW that are installed on the NSW A.

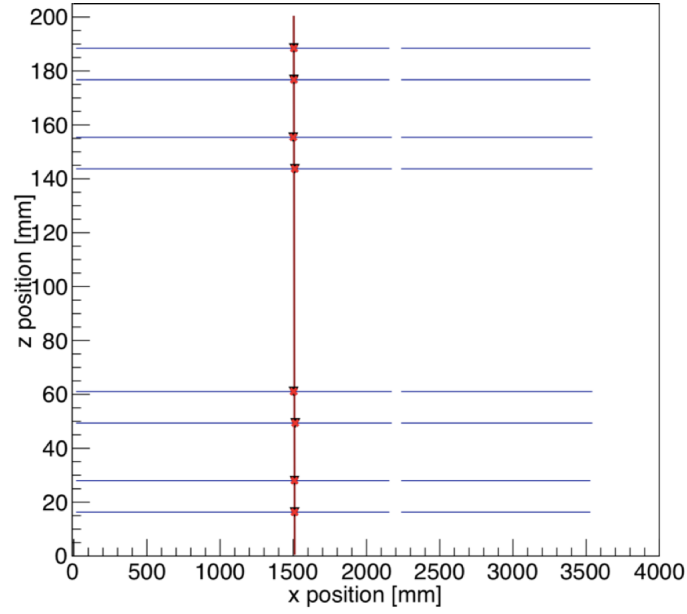


Figure 4.27. Example of a fully reconstructed cosmic muon event. The hits are reconstructed on all the eight layers of the first Micromegas DW.

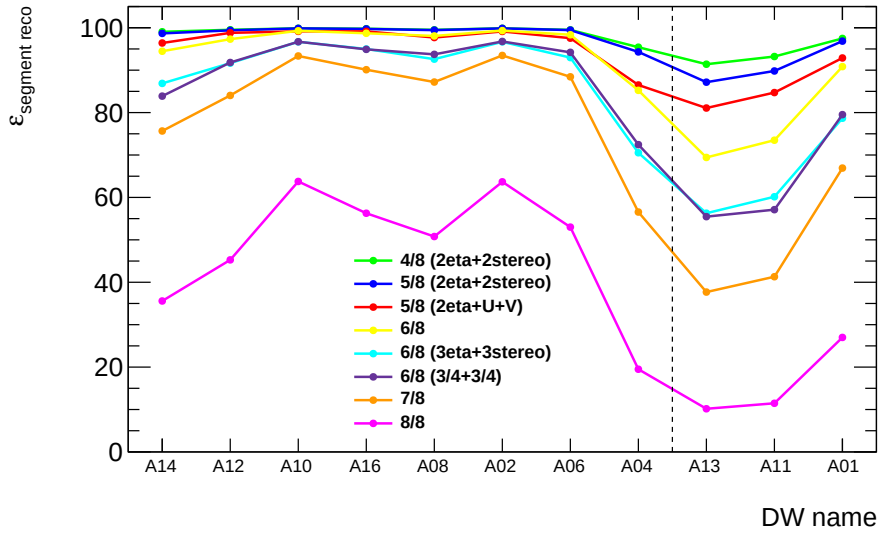


Figure 4.28. Efficiency detection of the 8 small and 3 large DW for different coincidences request on the detector gaps. The inserts within the brackets refer to the minimum number of strip layers (section 4.4) where the coincidences have to be found .

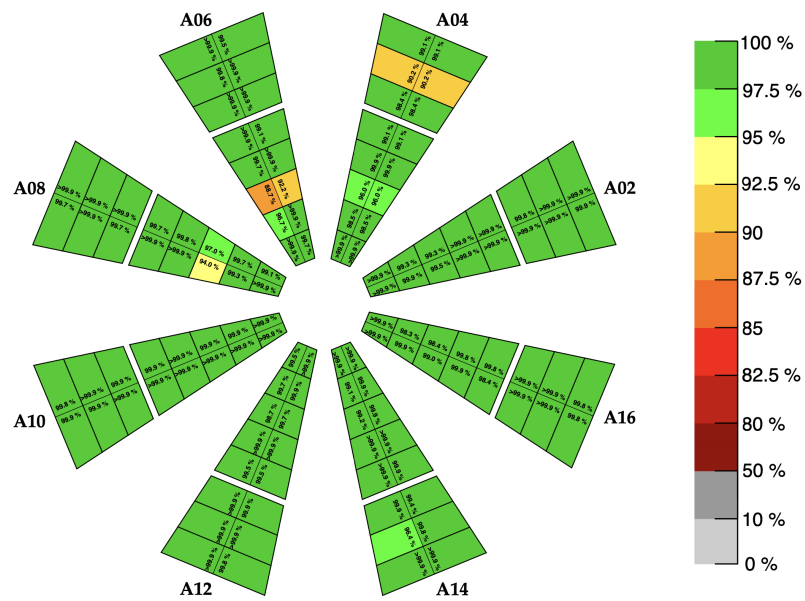


Figure 4.29. Efficiency detection for each section of the 8 small DW. Scale goes from 0 (grey) up to 100 (green). A02, A04, A06, A08, A10, A12, A14, A16 is the nomenclature used to identify each small DW and refers to its position in the new small wheel.

Chapter 5

Search for new high-mass phenomena in the dilepton final state

Searches in the dilepton (dielectron and dimuon) final state, produced by both e^+e^- and pp collisions, have a long history with the discovery of the J/Ψ meson in 1974 [61, 62] an Υ meson in 1977 [63] as well as the Z boson in 1983 [64, 65]. As these were key steps which led to the establishment of the Standard Model (SM) of particle physics, the study of the same final state could help to pave the way to a better understanding of the physics processes beyond it.

An analysis of high-mass dileptons final states to test models that predict new resonances is presented in this section. It covers an invariant dilepton mass spectrum that goes from 200 GeV up to 4 TeV. In the first part (section 5.1), a new physics signal is sought as a narrow dilepton invariant mass peak on top of a smoothly-falling background continuum.

The search for non-resonant dilepton phenomena, such that may be produce by a resonance above the scale of direct detection at the LHC, is also presented. The new physics signature investigated is a broad, non-resonant excess of events over a smoothly falling dilepton invariant-mass spectrum (see section 5.2).

My work is mainly focused on the dimuon decay channel, where a fundamental role is played by the performance of the ATLAS muon spectrometer (MS) in the reconstruction of high-momentum muons. An accurate knowledge of the global alignment of the ID-MS detectors and in particular of the misalignment between the precision chambers of MS, as well as an high muon identification efficiency at high p_T , are indeed crucial to achieve the good momentum resolution needed to maximise the signal-to-background discrimination power.

In all the reported studies, a model independent search strategy is adopted, focusing only on the experimental topology of the final state. The results can then be interpreted in specific models with different parameter assumptions.

The searches for high-mass resonant and non resonant phenomena presented in this chapter employ the full dataset collected by ATLAS during 2015–2018 data taking at $\sqrt{s} = 13$ TeV.

The data and simulation samples used in these searches are detailed in Sections

5.1.1 and 5.2.1.

The event selection is motivated and described in Sections 5.1.2 and 5.2.2.

In section 5.1.3 a description of the detector resolution for both the electron and muon channel is given.

Sections 5.1.4, 5.1.5, 5.1.6, 5.2.3 and 5.2.4, define the signal modelling, background estimation and systematic uncertainties for the resonant and non resonant analysis, respectively.

A description of the statistical analysis is given in sections 5.1.7 and 5.2.5.

The search results and interpretation of the two analyses are presented in Section 5.1.8 and in Section 5.2.6.

Finally a description of a new study developed to increase the sensitivity of these searches is reported in Section 5.3

5.1 Search for resonant phenomena in dilepton mass spectra

5.1.1 Data and simulation

The dataset used in this analysis was collected during 2015–2018 in pp collisions at a center-of-mass energy of 13 TeV. Only runs with stable beam conditions and with all detector systems normally operating are selected. Recorded events in the dielectron and in the dimuon channel were selected using a set of dedicated triggers described in Section 5.1.2. The total integrated luminosity of the dataset is determined to be $139.0 \pm 2.4 \text{ fb}^{-1}$ (Figure 3.2). The peak instantaneous luminosity delivered to ATLAS during stable beams for pp collisions at 13 TeV centre-of-mass energy is $21 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$.

When doing a MC-based analysis, as a rule of thumb, the size of the MC sample should be such that the statistical error of the MC is smaller than 20% of the statistical uncertainty on the data. Otherwise, the data is too-close to the MC in terms of "precision". Due to the limited statistics in the MC samples compared to the data, this analysis is carried out entirely in a data-driven way, simulated event samples for the signal and background processes are used only to determine appropriate functions to fit the data, to check the agreement between data and all the background sources and to evaluate the signal efficiency.

The main backgrounds in decreasing order of importance are Drell-Yan (DY), top-quark pair ($t\bar{t}$), single-top-quark and diboson production. Multi-jet and W+jets processes have been considered only in the dielectron channel, the same processes in the dimuon channel, as well as processes with τ -leptons in both channels, have a negligible impact and are not included. The full information on the Monte Carlo samples used for this analysis is summarized in Table 5.1, where event generators and software packages used to produce the background and signal simulated samples are reported.

5.1.2 Event selection

Dilepton candidates are selected in the data and simulated events by requiring at least one pair of reconstructed same-flavour lepton candidates. Events are required

Table 5.1. The event generators used for simulation of the signal and background processes. The acronyms ME and PS stand for matrix element and parton shower. The top-quark mass is set to 172.5 GeV.

Background Process	ME Generator and ME PDFs	PS and non-perturbative effect with PDFs
Z/γ^*	POWHEG-Box, CT10, PHOTOS	PYTHIA v8.186, CTEQ6L1, EVTGEN1.2.0
$t\bar{t}$	POWHEG-Box, NNPDF3.0NLO	PYTHIA v8.230, EVTGEN1.6.0
Single top s-channel, Wt	POWHEG-Box, NNPDF3.0NLO	PYTHIA v8.230, NNPDF3.0NLO, EVTGEN1.6.0
Single top t-channel	POWHEG-Box, NNPDF3.04fNLO, MADSPIN	PYTHIA v8.230, NNPDF3.0NLO, EVTGEN1.6.0
Diboson (WW , WZ and ZZ)	SHERPA 2.1.1, CT10	SHERPA 2.1.1
Signal Process		
LO Drell-Yan	PYTHIA v8.186, NNPDF3.0NLO	PYTHIA v8.186, NNPDF3.0NLO, EVTGEN1.2.0
Randall-Sundrum $G^* \rightarrow ll$	PYTHIA v8.210, NNPDF3.0NLO	PYTHIA v8.210, NNPDF3.0NLO, EVTGEN1.2.0
MSSM $gg \rightarrow H \rightarrow ll$	POWHEG-Box, CT10	PYTHIA v8.212, CTEQ6L1, EVTGEN1.2.0

to have a primary vertex with at least two associated tracks. The primary vertex is selected as the one with the largest $\sum p_T^2$, where the sum is over all tracks with transverse momentum $p_T > 0.5$ GeV that are associated with the vertex.

The selected pair needs to be oppositely charged in the dimuon channel, the opposite charge requirement in the dimuon channel helps to ensure a proper p_T reconstruction, as muons with a misidentified charge will have strongly distorted p_T measurements. In the dielectron channel the two candidates in the pair are not required to be of opposite charge. Indeed the efficiency loss due to an opposite sign requirement in the dielectron channel grows from 1.6% at $m_{ee} = 150$ GeV to 5.6% at $m_{ee} = 1$ TeV. A linear increase of the efficiency loss by about 5% per 1 TeV is then observed towards higher m_{ee} , resulting in an efficiency loss of 23.8% at $m_{ee} = 5$ TeV. As the dominant DY background creates same-sign pairs too, a higher reduction fraction is only possible for subdominant backgrounds and thus no gain in sensitivity is expected. If more than two leptons are present in the event, the two leptons with the largest E_T (p_T) in the electron (muon) channel are selected to form the dilepton pair. In events with a dielectron pair and a dimuon pair, the dielectron pair is selected because of the better resolution for m_{ll} values greater than 1 TeV. A cut on the dilepton invariant mass of $m_{ll} > 225$ GeV, in both the dielectron and dimuon channel, is also applied to avoid the Z boson peak region, which cannot be described by the same parameterisation as the high-mass part of the dilepton distributions.

Lepton candidate tracks are requested to be consistent with the primary vertex both along the beamline, where the longitudinal impact parameter z_0 must be $|\Delta_{z_0}^{BL} \sin \theta| < 0.5$ mm, and in the transverse plane, where the significance of the transverse impact parameter $|\frac{d_0^{BL}}{\sigma_{d_0}}|$ have to be less than 5 and 3 for the electrons and muons, respectively. Here, d_0 is defined as the shortest distance between a track and the BL in the transverse plane, while z_0 is defined as the distance in z between the primary vertex and the point on the track used to evaluate d_0 . To reduce background from misidentified tracks, lepton candidates are required to be isolated. Electrons must pass the "gradient" isolation working point which targets an E_T -dependent value of the isolation efficiency, uniform in η , using a combination of track and calorimeter isolation requirement [66]. For muons, the summed scalar p_T of good-quality tracks > 1 GeV originating from the primary vertex within a cone of a p_T dependent size¹ ΔR around the muon, but not including the muon-candidate

¹ ΔR has a maximum value of 0.3 and decreases as a function of p_T as $10 \text{ GeV}/p_T[\text{GeV}]$.

track itself, is required to be less than 6% of the p_T of the muon candidate. The efficiency of this selection is above 99% for both electrons and muons with $p_T > 60$ GeV.

Events in the dielectron channel were recorded using a dielectron trigger based on the loose identification criteria with E_T thresholds between 12 and 24 GeV for both electrons, depending on the data-taking period. A track in the ID is identified as an electron if it can be matched to an energy deposit in the calorimeter compatible with that of an electromagnetic shower. Reconstructed electrons are identified in the central region of the ATLAS detector ($|\eta| < 2.47$ and be outside the range $1.37 < |\eta| < 1.52$ corresponding to the transition region between the barrel and endcap EM calorimeters). Electron candidates are also required to have $E_T > 30$ GeV. The medium electron working point used for the final selection has, in the plateau region, an identification and reconstruction efficiency for prompt electrons above 94% (see Figure 3.15).

A summary of the electron selection criteria can be found in table 5.2.

Electron selection	
Pseudorapidity range	$(\eta < 1.37) \quad \quad (1.52 < \eta < 2.47)$
Transverse energy	$E_T > 30$ GeV
Track to vertex association	$ d_0^{BL}(\sigma) < 5$
	$ \Delta z_0^{BL} \sin \theta < 0.5$ mm
Identification	Medium
Isolation	Gradient

Table 5.2. Chosen selection for electrons.

Events in the dimuon channel are required to pass at least one of two single-muon triggers: the first requires a p_T of at least 50 GeV, while the second has a threshold lowered to 26 GeV but requires the muon candidate to be isolated. A good muon momentum resolution in the region from hundreds of GeV to several TeV is crucial for searches for new high-mass phenomena. It is therefore important to reject poorly measured muons, where the reconstructed p_T is much higher than the true value, to avoid the contamination of the high-mass region with events migrating from lower masses. In this analysis only muons with a p_T greater than 30 GeV and able to satisfy the high- p_T working point requirements, described below, are considered.

The High- p_T working point

The high- p_T selection [52] aims at the optimization of the momentum resolution for tracks with transverse momentum above 100 GeV. Only CB and MuGirl muons are used in the High- p_T working point. The selection requires at least three hits in each of three layers of precision tracking chambers in the MS. Only particular categories of 2-station muons missing precision hits in the MS layer can be used in analyses using this selection, more detail are given in section 5.3. Specific regions of the MS where the alignment is suboptimal are vetoed as a caution:

- the barrel-end-cap overlap region $1.01 < |\eta| < 1.1$ and the BIS7/8 chambers (due to relative alignment uncertainties),

Process	$m_{\mu\mu}$ [GeV]	σBr [pb]
$Z \rightarrow \mu\mu$	120 – 180	$1.748 \times 10^{+01}$
$Z \rightarrow \mu\mu$	180 – 250	$2.921 \times 10^{+00}$
$Z \rightarrow \mu\mu$	250 – 400	$1.082 \times 10^{+00}$
$Z \rightarrow \mu\mu$	400 – 600	1.955×10^{-01}
$Z \rightarrow \mu\mu$	600 – 800	3.740×10^{-02}
$Z \rightarrow \mu\mu$	800 – 1000	1.061×10^{-02}
$Z \rightarrow \mu\mu$	1000 – 1250	4.258×10^{-03}
$Z \rightarrow \mu\mu$	1250 – 1500	1.422×10^{-03}
$Z \rightarrow \mu\mu$	1500 – 1750	5.452×10^{-04}
$Z \rightarrow \mu\mu$	1750 – 2000	2.299×10^{-04}
$Z \rightarrow \mu\mu$	2000 – 2250	1.039×10^{-04}
$Z \rightarrow \mu\mu$	2250 – 2500	4.940×10^{-05}
$Z \rightarrow \mu\mu$	2500 – 2750	2.445×10^{-05}
$Z \rightarrow \mu\mu$	2750 – 3000	1.249×10^{-05}
$Z \rightarrow \mu\mu$	3000 – 3500	1.003×10^{-05}
$Z \rightarrow \mu\mu$	3500 – 4000	2.934×10^{-06}
$Z \rightarrow \mu\mu$	4000 – 4500	8.976×10^{-07}
$Z \rightarrow \mu\mu$	4500 – 5000	2.807×10^{-07}
$Z \rightarrow \mu\mu$	5000 – ∞	1.265×10^{-07}

Table 5.3. List of MC next to leading order Drell Yan samples used to evaluate the efficiency gain as a function of the transverse momentum.

- the BMG chambers (for 2017 and 2018 data, corresponding to the data taking periods when these chambers were installed and active).

The muon high- p_T selection has an η -averaged efficiency² of 78% at 200 GeV (see Figure 5.1) which decreases to 64% at 2.5 TeV due to increased probability of occasional "catastrophic" energy loss at high- p_T . Additionally, a set of selection criteria based on the relative uncertainty on the charge-to-momentum ratio (q/p) of reconstructed muon tracks, described in the following paragraph, is used to identify events containing high- p_T muons with optimal momentum resolution. The high- p_T muons reconstruction efficiency as a function of the truth muons transverse momentum is evaluated using the NLO Drell Yan MC samples listed in Tables 5.3 and does not include the trigger efficiency.

q/p criterion

The q/p criterion aims to reject muons in the tails of the σ_{p_T}/p_T distributions. The cut is based on the relative uncertainty of the q/p measurement. As the resolution worsens at high- p_T , the efficiency would also decrease at high- p_T . The expected relative resolution of the momentum ($\frac{\sigma(q/p)^{exp}}{(q/p)}$) measurement is parametrised as a

²For samples with a flat η distribution and $|\eta| < 2.5$.

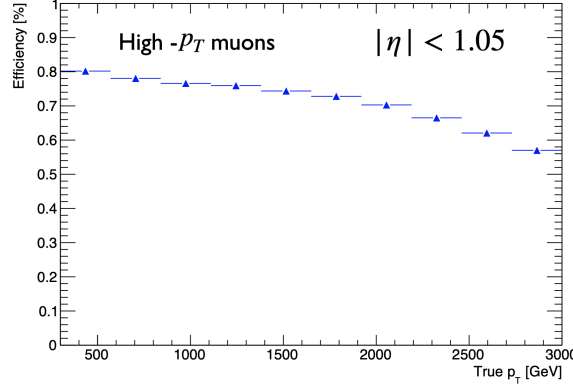


Figure 5.1. Expected reconstruction efficiency for muons passing the high- p_T selection criteria in the barrel. The plots show the measurement carried out as a function of p_T obtained by using the NLO DY MC samples.

Muon selection	
Transverse momentum	$p_T > 30 \text{ GeV}$
Pseudorapidity range	$ \eta < 2.5$
Track to vertex association	$ d_0^{BL}(\sigma) < 3$
	$ \Delta z_0^{BL} \sin \theta < 0.5 \text{ mm}$
Identification	High-pT
Isolation	FCTightTrackOnly

Table 5.4. Chosen selection for muons.

function of p_T in five different η regions, following the usual parametrisation:

$$\frac{\sigma(q/p)^{exp}}{(q/p)} = \sqrt{(p_0/p_T)^2 + p_1^2 + (p_2 \cdot p_T)^2}, \quad (5.1)$$

where p_0 , p_1 and p_2 are coefficients related to the energy loss in the calorimeter material, multiple scattering and error on hit measurements (e.g uncertainty on sagitta), respectively. The η regions are chosen to coincide with specific regions of the ATLAS detector having different p_T resolution, and are defined as follows: $|\eta| \leq 1.05$, $1.05 < |\eta| \leq 1.3$, $1.3 < |\eta| \leq 1.7$, $1.7 < |\eta| \leq 2.0$, and $|\eta| > 2.0$.

A cut on the relative uncertainty of the q/p measurement of the muon ($\frac{\sigma(q/p)}{(q/p)}$) is applied as:

$$\frac{\sigma(q/p)}{(q/p)} < C(p_T) \cdot \frac{\sigma(q/p)^{exp}}{(q/p)} \quad (5.2)$$

where $\sigma(q/p)$ is the uncertainty on the track q/p as estimated by the combined track fit, while $C(p_T)$ is a p_T -dependent coefficient, which is constant for $p_T < 1 \text{ TeV}$ and decreases linearly if $p_T > 1 \text{ TeV}$ as:

$$C(p_T) = C_0 - \frac{p_T[\text{GeV}]}{a}. \quad (5.3)$$

where C_0 is the initial value and a is a normalization factor chosen to reach a value of the coefficient equal 1 at 5 TeV. In the original formulation of the cut, used until

2018, the initial value of $C(p_T)$ was equal to 1.8. A q/p criterion optimization study was undertaken in order to improve the efficiency of this criterion. Increasing the initial value of $C(p_T)$ up to 2.5, the cut efficiency improves while still effectively removing the tails of the resolution distributions. An efficiency gain of up to 5% with respect to the previous definition of the q/p criterion, has been observed. This new q/p criterion formulation has been already used in this search and will be used in all the future ATLAS analyses. This criterion is fully efficient below 1 TeV, and introduces an additional inefficiency of 7% at 2.5 TeV to the high- p_T selection.

A summary of the muon selection criteria is given in table 5.4.

Figure 5.2 shows the dielectron (left) and dimuon (right) reconstructed invariant mass distributions for data and the SM background estimates, after applying all the event selection cuts described above.

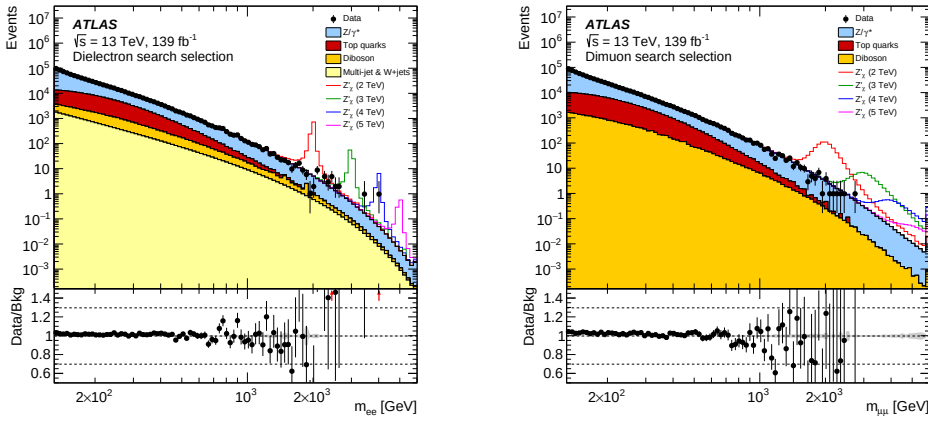


Figure 5.2. Distributions of dielectron (left) and dimuon (right) reconstructed invariant mass after selection, for data and the SM background estimates as well as their ratio (for illustration only). The data points are shown together with their statistical uncertainty. Selected Z' signals with a pole mass of 2, 3, 4 and 5 TeV are overlaid. In the lower panel, the shaded band corresponds to the MC statistical uncertainty, dashed lines correspond to $\pm 30\%$ and red arrows indicate data points that are outside the displayed range.

5.1.3 Reconstructed dilepton mass modelling

The generic signal shapes are constructed from non-relativistic Breit-Wigner functions of various widths convolved with the detector resolution. The relative dilepton mass resolution is defined as $R = (m_{ll} - m_{ll}^{true})/m_{ll}^{true}$, where m_{ll}^{true} is the generated dilepton mass at Born level before Final State Radiation (FSR).

Several function choices have been tested to obtain a good description of the detector resolution throughout the full m_{ll} spectrum and finally the sum of a Gaussian and a Crystal-Ball is used. The function is thus given as shown in equation 5.4 and has in total 7 parameters.

$$P(\mathcal{R}) = \kappa \cdot \text{CB}(\mathcal{R}|\mu_{\text{CB}}, \sigma_{\text{CB}}, \alpha_{\text{CB}}, n_{\text{CB}}) + (1 - \kappa) \cdot \text{Gauss}(\mathcal{R}|\mu_{\text{G}}, \sigma_{\text{G}}) \quad (5.4)$$

The Gaussian part of the function describes the main peak of the response distribution. The Crystal-Ball (CB) component has longer tails on one side of the distribution and thus describes asymmetric the tails of the response. For the dielectron channel the tail is mainly due to QED radiation (e.g. Bremsstrahlung). In the dimuon channel, the tails mainly emerge from badly reconstructed muons. The parameters inside equation 5.4 have the following properties:

- μ_{CB} and μ_{G} describe the mean value of the CB and Gaussian components, respectively. As $\mathcal{R}$ is given by $(m_{ll} - m_{ll}^{\text{true}})/m_{ll}^{\text{true}}$, and typically $m_{ll} \approx m_{ll}^{\text{true}}$, the typical values of μ_i should be close to 0. Due to the dimensionless definition of $\mathcal{R}$, the μ_i parameters are dimensionless, too.
- σ_{CB} and σ_{G} are the width parameters of the CB and Gaussian components, respectively. Their value corresponds to the relative uncertainty of the response, such that they are dimensionless in this parametrisation. A decreasing behaviour, as a function of m_{ll} , is expected for the ee channel, limited by the constant term of the calorimeter resolution. The $\mu\mu$ channel is expected to have an increasing resolution, as for high- p_{T} the track curvature is low and thus the relative error on the Sagitta high (see paragraph 5.1.2).
- α_{CB} defines the cut-off in the Crystal-Ball function after which the Gaussian behaviour is replaced by a power-law. α_{CB} is given in units of σ_{CB} . No strong m_{ll} -dependence is expected.
- n_{CB} is the exponent in the power-law region of the Crystal-Ball function. No strong m_{ll} -dependence is expected.
- κ defines the fraction of the Crystal-Ball function in the total pdf. The m_{ll} -dependence of this parameter should reflect the relative importance of the tails.

Each of the parameters needs a dedicated description, the parameterisation of the relative dilepton mass resolution as a function of m_{ll}^{true} is determined by fitting to ll NLO DY MC events with the function described above. The MC sample is separated in 200 m_{ll}^{true} bins of equal size on a logarithmic scale from 130 GeV to 6 TeV.

Examples of the response description after the simultaneous fit can be found in figure 5.3 for the ee and $\mu\mu$ in the low, medium and high truth mass regions. The χ^2/ndf distributions for all m_{ll} bins of the simultaneous fit are given in figure 5.4.

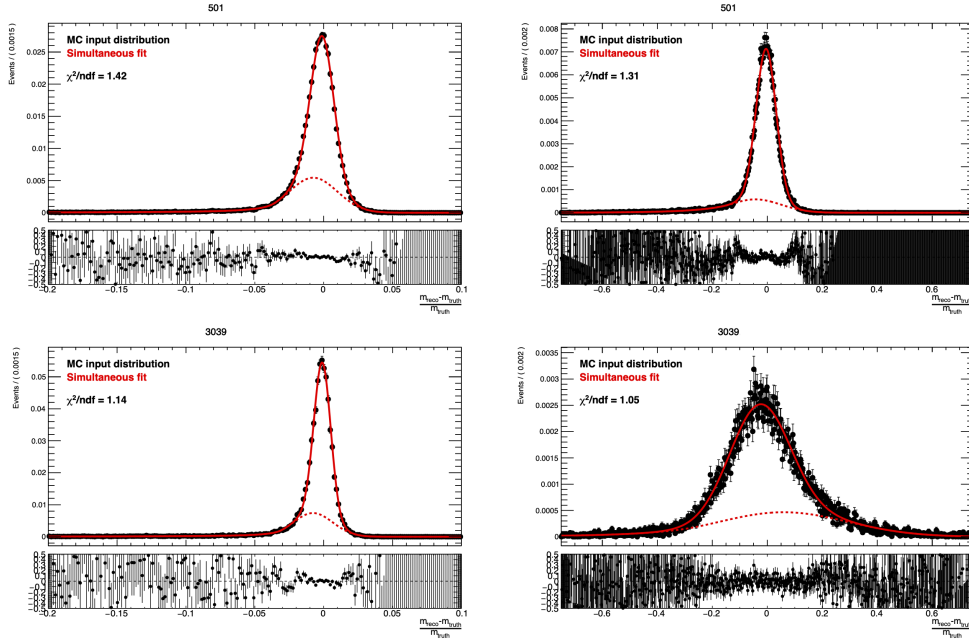


Figure 5.3. Examples of the response description after the simultaneous fit for the ee (left) and $\mu\mu$ (right) channels. Two different truth mass bins are shown and the mean truth mass given in the title of the figures. The red line corresponds to the functional description by the sum of a Crystal-Ball (red dashed line) and a Gaussian. The lower panels give the relative difference between the functional description and the distribution for all figures.

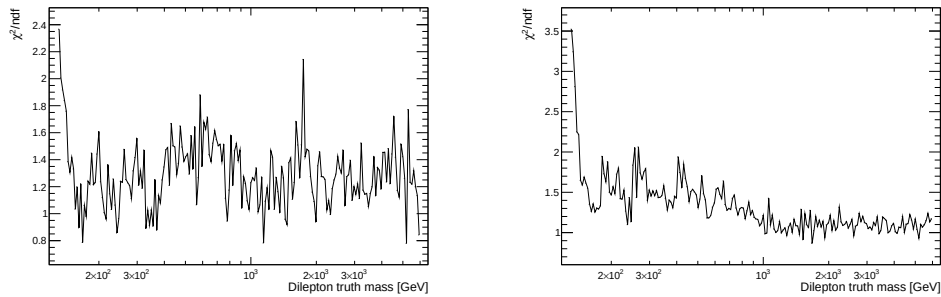


Figure 5.4. χ^2/ndf distributions of the response description after the simultaneous fit for the ee (left) and $\mu\mu$ (right) channels. Only the region with $M_{\text{truth}} \geq 250 \text{ GeV}$ is later used for the signal modelling.

Parameter m_{ll} -dependence	Fit result
$\mu_{CB}(m_{ll}) = p_{\mu_{CB},1} + p_{\mu_{CB},2}/\ln(m_{ll}) + p_{\mu_{CB},3} \cdot \ln(m_{ll}) + p_{\mu_{CB},4} \cdot \ln(m_{ll})^4$	$p_{\mu_{CB},1} = 0.13287$ $p_{\mu_{CB},2} = -0.410663$ $p_{\mu_{CB},3} = -0.0126743$ $p_{\mu_{CB},4} = 2.9547 \cdot 10^{-6}$
$\sigma_{CB}(m_{ll}) = \sqrt{p_{\sigma_{CB},1}^2 + (p_{\sigma_{CB},2}/\sqrt{m_{ll}})^2 + (p_{\sigma_{CB},3}/m_{ll})^2}$	$p_{\sigma_{CB},1} = 0.0136624$ $p_{\sigma_{CB},2} = 0.230678$ $p_{\sigma_{CB},3} = 1.73254$
$\alpha_{CB}(m_{ll}) = p_{\alpha_{CB},1}$	$p_{\alpha_{CB},1} = 1.59112$
$n_{CB}(m_{ll}) = p_{n_{CB},1} + p_{n_{CB},2} \cdot \exp(-p_{n_{CB},3} \cdot m_{ll})$	$p_{n_{CB},1} = 1.13055$ $p_{n_{CB},2} = 0.76705$ $p_{n_{CB},3} = 0.00298312$
$\mu_G(m_{ll}) = p_{\mu_G,1} + p_{\mu_G,2}/m_{ll} + p_{\mu_G,3} \cdot m_{ll} + p_{\mu_G,4} \cdot \ln(m_{ll})^3 + p_{\mu_G,5}/m_{ll}^2 + p_{\mu_G,6} \cdot m_{ll}^2$	$p_{\mu_G,1} = -0.00402708$ $p_{\mu_G,2} = 0.814172$ $p_{\mu_G,3} = -3.94281 \cdot 10^{-7}$ $p_{\mu_G,4} = 7.97076 \cdot 10^{-6}$ $p_{\mu_G,5} = -87.6397$ $p_{\mu_G,6} = -1.64806 \cdot 10^{-11}$
$\sigma_G(m_{ll}) = \sqrt{p_{\sigma_G,1}^2 + (p_{\sigma_G,2}/\sqrt{m_{ll}})^2 + (p_{\sigma_G,3}/m_{ll})^2}$	$p_{\sigma_G,1} = 0.00553858$ $p_{\sigma_G,2} = 0.140909$ $p_{\sigma_G,3} = 0.644418$
$\kappa(m_{ll}) = p_{\kappa,1} + p_{\kappa,2} \cdot \exp(-p_{\kappa,3} \cdot m_{ll}) + p_{\kappa,4} \cdot m_{ll} + p_{\kappa,5} \cdot m_{ll}^3$	$p_{\kappa,1} = 0.347003$ $p_{\kappa,2} = 0.135768$ $p_{\kappa,3} = 0.00372497$ $p_{\kappa,4} = -2.2822 \cdot 10^{-5}$ $p_{\kappa,5} = 5.06351 \cdot 10^{-13}$

Table 5.5. Description of the m_{ll} -dependence for the 7 transfer function parameters in the dielectron channel.

Parameter m_{ll} -dependence	Fit result
$\mu_{CB}(m_{ll}) = p_{\mu_{CB},1} + p_{\mu_{CB},2}/m_{ll} + p_{\mu_{CB},3}/m_{ll}^2 + p_{\mu_{CB},4}/m_{ll}^3 + p_{\mu_{CB},5} \cdot m_{ll} + p_{\mu_{CB},6} \cdot m_{ll}^2 + p_{\mu_{CB},7} \cdot m_{ll}^3$	$p_{\mu_{CB},1} = -0.0891397$ $p_{\mu_{CB},2} = 10.6169$ $p_{\mu_{CB},3} = -951.712$ $p_{\mu_{CB},4} = 74775.3$ $p_{\mu_{CB},5} = 5.60192 \cdot 10^{-5}$ $p_{\mu_{CB},6} = -1.58827 \cdot 10^{-9}$ $p_{\mu_{CB},7} = -3.81706 \cdot 10^{-13}$
$\sigma_{CB}(m_{ll}) = p_{\sigma_{CB},1} + p_{\sigma_{CB},2}/m_{ll} + p_{\sigma_{CB},3}/m_{ll}^2 + p_{\sigma_{CB},4} \cdot m_{ll} + p_{\sigma_{CB},5} \cdot m_{ll}^2$	$p_{\sigma_{CB},1} = 0.0836349$ $p_{\sigma_{CB},2} = -8.98476$ $p_{\sigma_{CB},3} = 491.19$ $p_{\sigma_{CB},4} = 5.18068 \cdot 10^{-5}$ $p_{\sigma_{CB},5} = -3.45042 \cdot 10^{-10}$
$\alpha_{CB}(m_{ll}) = p_{\alpha_{CB},1} + p_{\alpha_{CB},2}/m_{ll} + p_{\alpha_{CB},3}/m_{ll}^2 + p_{\alpha_{CB},4}/m_{ll}^3 + p_{\alpha_{CB},5} \cdot m_{ll}$	$p_{\alpha_{CB},1} = 0.512577$ $p_{\alpha_{CB},2} = 252.922$ $p_{\alpha_{CB},3} = -79337.4$ $p_{\alpha_{CB},4} = 7.31863 \cdot 10^6$ $p_{\alpha_{CB},5} = 0.000237883$
$n_{CB}(m_{ll}) = p_{n_{CB},1}$	$p_{n_{CB},1} = 6.08818$
$\mu_G(m_{ll}) = p_{\mu_G,1} + p_{\mu_G,2} \cdot m_{ll} + p_{\mu_G,3} \cdot m_{ll}^2 + p_{\mu_G,4} \cdot m_{ll}^3 + p_{\mu_G,5} \cdot m_{ll}^4$	$p_{\mu_G,1} = -0.00410659$ $p_{\mu_G,2} = 2.82352 \cdot 10^{-6}$ $p_{\mu_G,3} = -6.264 \cdot 10^{-9}$ $p_{\mu_G,4} = 1.25547 \cdot 10^{-12}$ $p_{\mu_G,5} = -9.94431 \cdot 10^{-17}$
$\sigma_G(m_{ll}) = p_{\sigma_G,1} + p_{\sigma_G,2}/m_{ll} + p_{\sigma_G,3}/m_{ll}^2 + p_{\sigma_G,4} \cdot m_{ll} + p_{\sigma_G,5} \cdot m_{ll}^2$	$p_{\sigma_G,1} = 0.0214264$ $p_{\sigma_G,2} = -0.795058$ $p_{\sigma_G,3} = 15.4726$ $p_{\sigma_G,4} = 3.38205 \cdot 10^{-5}$ $p_{\sigma_G,5} = -1.64984 \cdot 10^{-9}$
$\kappa(m_{ll}) = p_{\kappa,1} + p_{\kappa,2}/m_{ll} + p_{\kappa,3}/m_{ll}^2 + p_{\kappa,4} \cdot m_{ll} + p_{\kappa,5} \cdot m_{ll}^2$	$p_{\kappa,1} = 0.235477$ $p_{\kappa,2} = -31.2227$ $p_{\kappa,3} = 3447.34$ $p_{\kappa,4} = 4.54408 \cdot 10^{-5}$ $p_{\kappa,5} = -3.25374 \cdot 10^{-9}$

Table 5.6. Description of the m_{ll} -dependence for the 7 transfer function parameters in the dimuon channel.

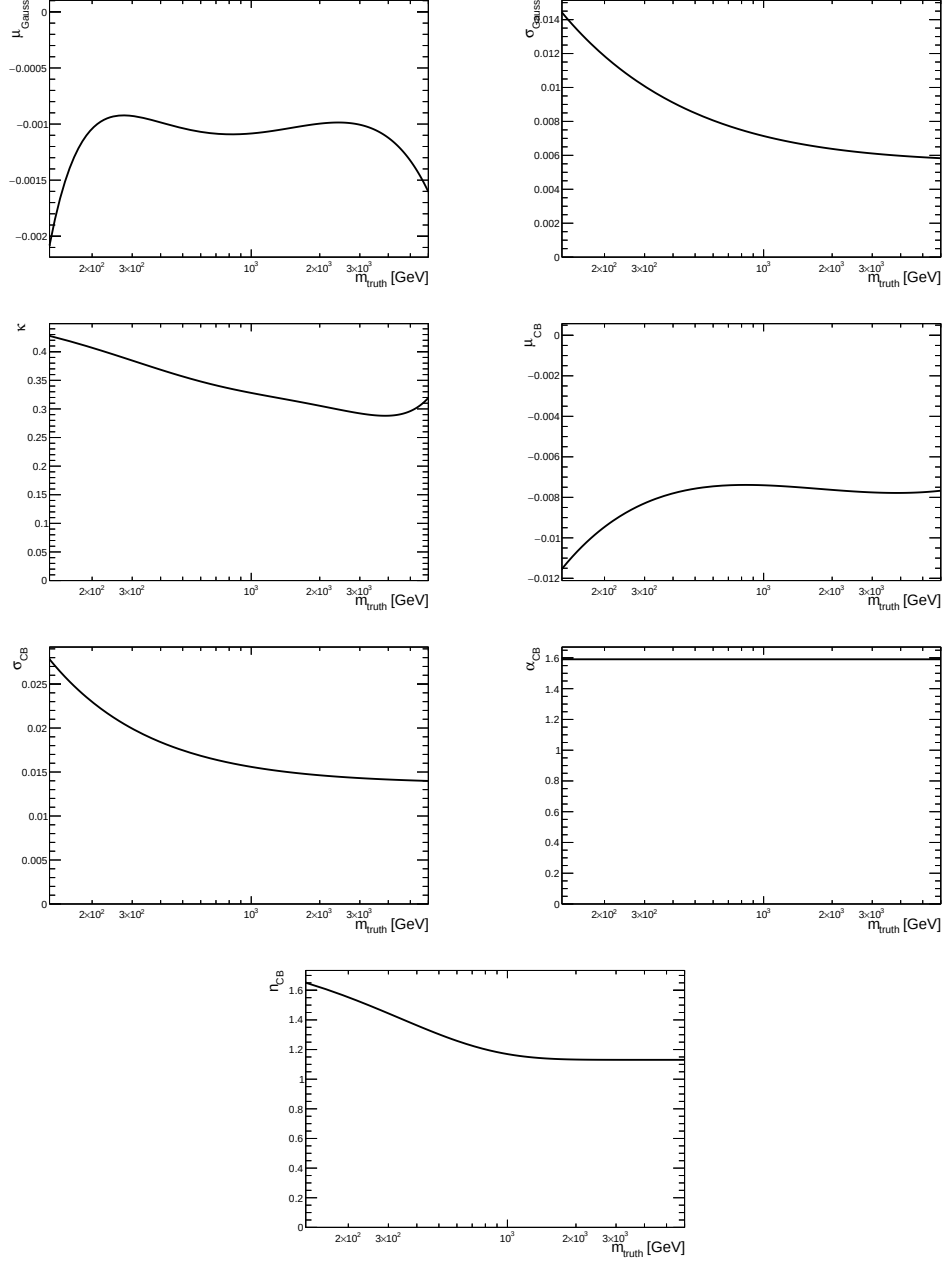


Figure 5.5. m_{ll} -dependence of the transfer function parameters after the simultaneous fit in the ee channel. The shown variables are, from top left to bottom right, μ_G , σ_G , κ , μ_{CB} , σ_{CB} , α_{CB} and n_{CB} .

The parameter dependencies with m_{ll} are shown in figures 5.5 and 5.6 for the ee and $\mu\mu$ channels, respectively. The behaviour of κ reflects the relative importance of the tails inside the parametrisation, as κ gives the fraction of the Crystal-Ball component inside the total pdf. In the electron channel, at low M_{truth} FSR effects are expected to have a higher relative importance, as more FSR photons might not be reconstructed as part of the electrons. In the muon channel, at low M_{truth}

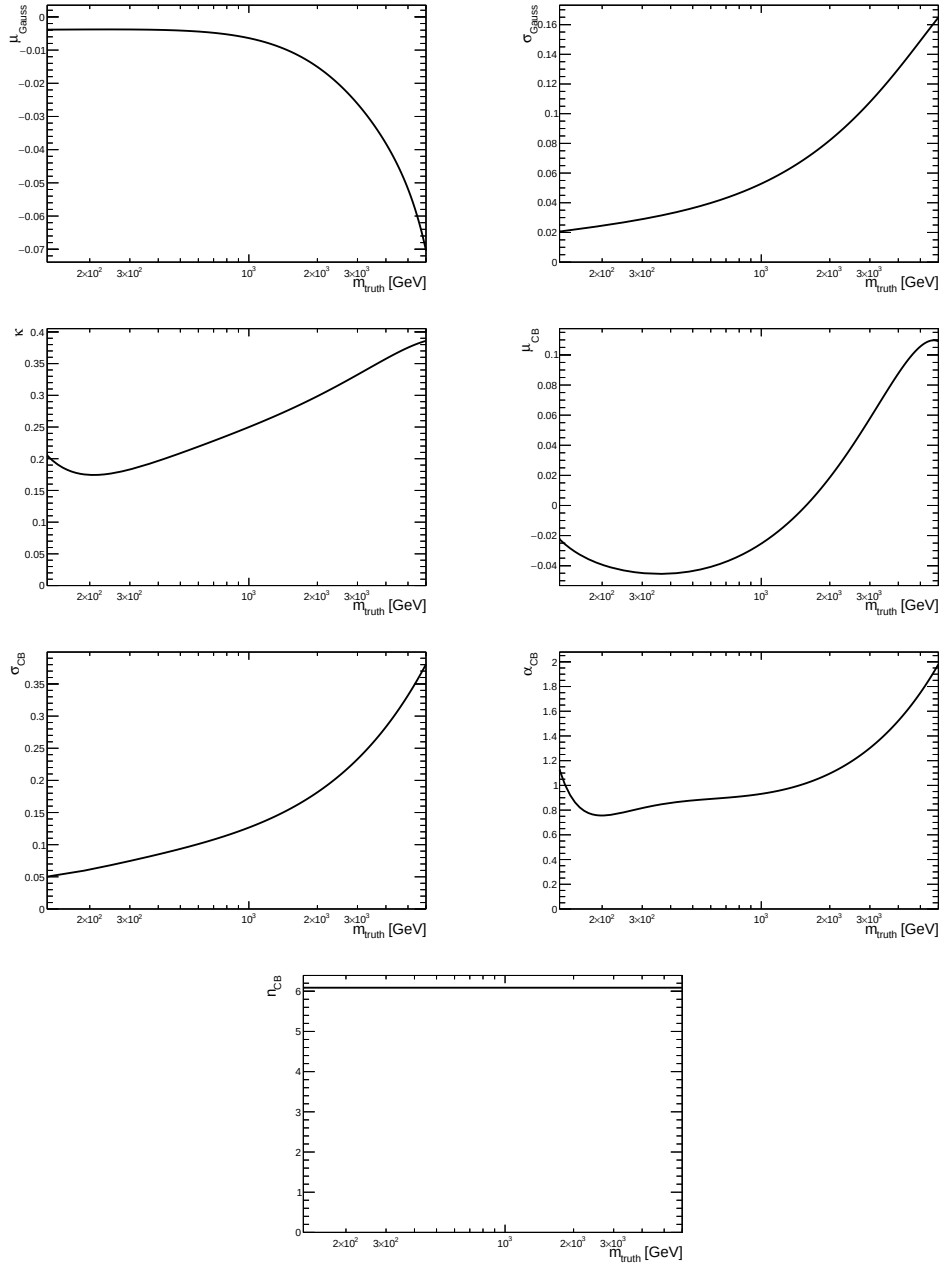


Figure 5.6. m_{II} -dependence of the transfer function parameters after the simultaneous fit in the $\mu\mu$ channel. The shown variables are, from top left to bottom right, μ_G , σ_G , κ , μ_{CB} , σ_{CB} , α_{CB} and n_{CB} .

the response tails are more pronounced in the negative region (potentially due to energy losses before the MS), at high M_{inv} stronger tails are visible for positive response values (potentially due to the approximately Gaussian behaviour in the q/p measurements, which creates longer tails towards high p_T values). The functional form of these parametrisations is given in tables 5.5 and 5.6 for the ee and $\mu\mu$ channels, respectively.

The relative mass resolution is extracted by combining the width parameters according to their relative weight according to equation 5.5.

$$\sigma_{\text{combined}}(m_{ll}) = \sqrt{\kappa(m_{ll}) \cdot \sigma_{\text{CB}}^2(m_{ll}) + (1 - \kappa(m_{ll})) \cdot \sigma_{\text{G}}^2(m_{ll})} \quad (5.5)$$

5.1.4 Signal modelling

A new physics resonant signal is sought as a narrow dilepton invariant mass peak on top of a smoothly-falling background continuum, by fitting the data dilepton mass distribution. The fit function consists of a smooth functional form for the background, and a generic signal shape. The generic signal shapes are constructed from non-relativistic Breit-Wigner functions of various widths convolved with the detector resolution, obtained as described in the previous section 5.1.3. The shape of the dilepton invariant mass distribution for a signal resonance with intrinsic width that is negligible compared with the detector resolution (zero-width signal) is obtained from the mass resolution only.

In order to interpret the results and compare them to any model, the fiducial volume for the signal model and the cross-section calculation is defined by applying the following acceptance cuts:

- $p_{\text{T,lep,truth}} > 30 \text{ GeV}$, applied to the leading and subleading lepton on truth-level.
- $|\eta_{\text{lep,truth}}| < 2.5$, applied to the leading and subleading lepton on truth-level.
- $M_{\text{truth}} - M_{\text{Pole}} > -2\Gamma_{\text{Pole}}$ with M_{Pole} as the pole mass of the resonance and Γ_{Pole} as the resonance width.

These acceptance cuts are also added in order to reduce the model dependence from off-shell effects. The cut on the mass is needed due to the model-dependence of the tails in the M_{truth} spectrum of potential new resonances, which might dominate the total cross-section while not having a significant impact on the statistical analysis. The nominal combined reconstruction and identification acceptance and efficiency in the fiducial region are extracted from the DY sample and thus assumes the kinematics of a spin-1 boson. The definition of the fiducial volume allows to obtain separate acceptance and efficiency curves for 0-width resonances. The definition of both quantities is given in equations 5.6 and 5.7:

$$A(m_{ll}) = \left. \frac{\text{events passing acceptance cuts}}{\text{events in MC sample}} \right|_{m_{ll} \text{ within bin}} \quad (5.6)$$

$$\varepsilon(m_{ll}) = \left. \frac{\text{events passing selection cuts}}{\text{events passing acceptance cuts}} \right|_{m_{ll} \text{ within bin}} \quad (5.7)$$

where events passing acceptance cuts and events passing selection cuts refer to the fiducial volume definition described above, and to the event selection described in Section 5.1.2, respectively. The results are given in Figures 5.7 and 5.8 for the acceptance and efficiency, respectively. The acceptance in both channels agrees well and increases for high M_{truth} due to the more central event topologies. The efficiency

differs for the ee and $\mu\mu$ channels. While in the ee channel, an increasing efficiency can be observed towards higher masses (64% at 225 GeV up to 74% at 6 TeV), the dimuon channel efficiency decreases (54% at 225 GeV to 38% at 6 TeV) due to the more stringent muon ID requirements (see section 5.1.2).

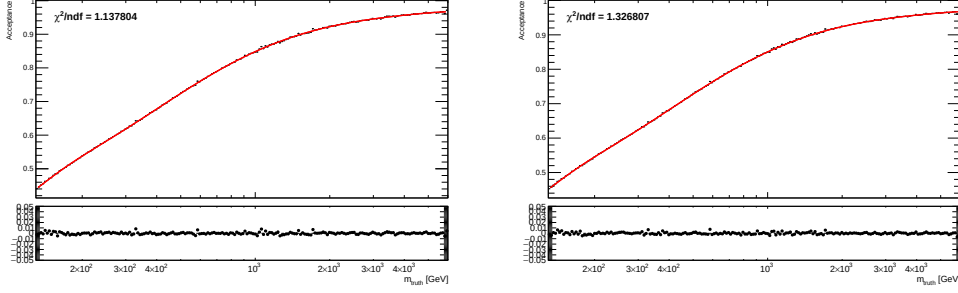


Figure 5.7. Acceptance for the ee (left) and $\mu\mu$ (right) channels. A polynomial fit (red line) is performed to the values obtained from fullsim MC (black points). The error bands are due to MC statistics and have a non-linear behaviour due to the mass-sliced DY samples. The lower panels give the relative difference between the fit and the distribution for the two figures.

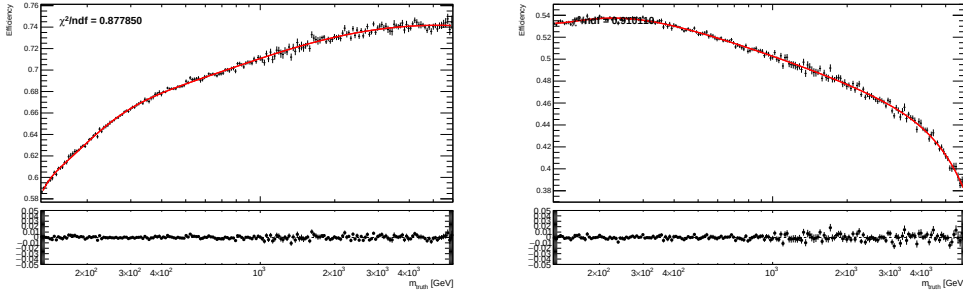


Figure 5.8. Efficiency distribution for the ee (left) and $\mu\mu$ (right) channels. A polynomial fit (red line) is performed to the values obtained from fullsim MC (black points). The error bands are due to MC statistics and have a non-linear behaviour due to the mass-sliced DY samples. The lower panels give the relative difference between the distributions for the two figures.

5.1.5 Background modelling

The "data-driven" background estimation is pursued with a global fit approach. The term "data-driven" refers to the background estimate, which is obtained by fitting a functional form to the data distribution. The global fit approach uses a single functional form to model the background shape for the full available mass spectrum at the same time.

The smooth functional form for the background is based on fit performance studies on a MC background template. The following definitions for the templates is used:

- the templates are scaled to the luminosity of 139 fb^{-1} and given for the ee and $\mu\mu$ channels
- the templates cover M_{inv} [150 GeV, 6000 GeV], even if search does not use the full coverage necessarily
- the following background components have been summed to compose the final MC background template:
 - smooth DY background templates
 - smooth $t\bar{t}$ background templates
 - single-top background templates
 - diboson background templates
 - fake electron background component in the ee channel to model W+jets and multi-jet contributions

A dedicated technique, called "transfer function", is used in this analysis for smoothing the DY and $t\bar{t}$ background templates to overcome limitations due to low MC statistics and so to reduce statistical fluctuations. The procedure to combine truth-only MC samples and the transfer functions is defined as follows: the transition between a known truth spectrum, $S_t(M_t)$, and an unknown reconstructed spectrum, $S_r(M_r)$, can be parametrised by a transfer function, $P(M_r|M_t)$. It describes the probability to reconstruct an event at the invariant mass of M_r for events with a truth mass of M_t that pass the selection. The reconstruction level spectrum can then be obtained by using the following convolution:

$$S_r(M_r) = P(M_r|M_t) \otimes (S_t(M_t)A\varepsilon(M_t)) \quad (5.8)$$

The acceptance $\times$ efficiency, $A\varepsilon(M_t)$, describes the probability that an event with a truth invariant mass of M_t passes the selection (see equations 5.6 and 5.7). It is defined by the fraction of accepted events (independent of their M_r) inside a M_t -bin. The parametrisation of the transfer function is defined as a generic signal model, as $P(M_r|M_t)$ describes the detector mass resolution for a given M_t value.

A fit to the dilepton mass background template is performed, under the signal plus background hypothesis. The function choice for the global fit is based on the so-called "spurious signal test": the obtained number of signal events in these fits, spurious signal (N_{Spur}), is a measure of the mismodelling of the function with respect to the best available knowledge of the background shape. The test is then given by the ratio of N_{Spur} to the uncertainty on the number of background events, σ_S , which gives a measure of the functional mismodelling in comparison to the expected statistical background fluctuations. If this ratio is much smaller than 1, no impact on the statistical analysis is expected and the background modelling is thus "good enough". The function choice is finally performed on the following criteria, which are determined as a function of m_{ll} :

- the number of spurious signal events, N_{Spur} , needs to be considerably smaller than its uncertainty, σ_S . Typical values to reject a function based on this criterion are $N_{Spur}/\sigma_S > 50\%$ which correspond to an increasing of the statistical uncertainty smaller than 12%, while for precision measurements in the Higgs sector a value of 20% has been used at lower integrated luminosities.
- if several function options have spurious signal contributions that are small enough, the option with the least parameters is chosen. This check is performed by looking into the expected sensitivity of the search at different pole masses and signal width assumptions.

The chosen functional form is:

$$f_{ll}(m_{ll}) = f_{BW,Z}(m_{ll}) \cdot (1 - x^c)^b \cdot x^{\sum_{i=0}^3 p_i \cdot \log(x)^i} \quad (5.9)$$

where $x = m_{ll}/\sqrt{s}$ and parameters b and p_i with $i = 0, \dots, 3$ are left free in the fit to data and independent for dielectron and dimuon channels. The second term, $(1 - x^c)^b$, ensures that the background shape evaluates to zero at $x \rightarrow 1$. For a pure empiric reason the parameter c is 1 for the dielectron and 1/3 for the dimuon channel. The function $f_{BW,Z}(m_{ll})$ is a non-relativistic Breit-Wigner function with $m_Z = 91.1876$ GeV and $\Gamma_Z = 2.4952$ GeV, that models the shape of the peak from Z boson production. A background-only fit example is shown in Figure 5.9 for the MC background template. While no large deviations from peaking signal-like contributions or an overall mismodelling of the chosen functions are visible by eye, the remaining differences between the chosen function and the template need to be parametrised in terms of spurious signal values.

The spurious signal values for the Zero-Width resonance case are given in figures 5.10, 5.11 and use a fit range of reconstructed $M_{Inv} \in [225 \text{ GeV}, 6 \text{ TeV}]$. For the ee channel a maximal value of $N_{Spur}/\sigma_S \simeq 30\%$ is obtained, which is most likely an effect of statistical fluctuations in the background template. In the $\mu\mu$ channel a maximal value of $N_{Spur}/\sigma_S \simeq 30\%$ obtained too, which is again most likely an effect of statistical fluctuations. Compared to the ee channel, slightly higher spurious signal values are present in the high M_{Pole} region, but are still well below the typical requirement of $N_{Spur}/\sigma_S \leq 50\%$. The spurious signal is thus at a reasonable level in both channels and low enough for the further statistical analysis.

The spurious signal values that are given in figures 5.10 and 5.11 show the obtained values for the nominal background templates as well as the envelope from systematic variations of the parton distribution functions and other background uncertainties (see section 5.1.6 for a full description). While a small increase of the spurious signal due to the background variations can be observed in both channels, the chosen function captures the variations well and the final estimate is well below typical requirements on N_{Spur}/σ_S . For the following parametrisation of the spurious signal, the envelope of the obtained spurious signal values from all background variations is used to obtain a conservative estimate.

5.1.6 Uncertainties

Due to the data-driven background estimation, uncertainties related to the background modelling are propagated into the determination of the spurious signal. The

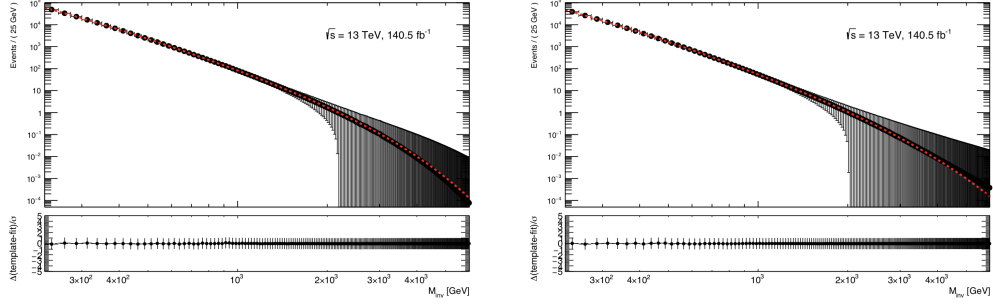


Figure 5.9. Background-only fit results in the ee (left) and $\mu\mu$ (right) channels from the global fit option, using the functions given in equation 5.9. The shown template corresponds to an integrated luminosity of 140.5 fb^{-1} and is used in the optimisation procedure. No large deviations from peaking signal-like contributions or an overall mismodelling of the chosen functions are visible by eye.

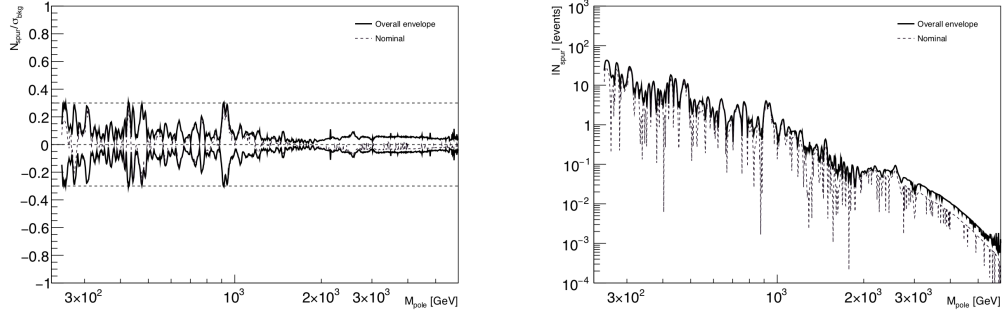


Figure 5.10. Spurious signal estimation at $\Gamma/M = 0\%$ in the ee channel with the nominal function choice (see equations 5.9). The left plot shows N_{spur}/σ_S for a range of $M_{\text{pole}} \in [225 \text{ GeV}, 6000 \text{ GeV}]$, while the plot on the right shows $|N_{\text{spur}}|$. The dashed line corresponds to the nominal background template, while the thick solid line corresponds to the envelope of the determined spurious signal values from PDF variations.

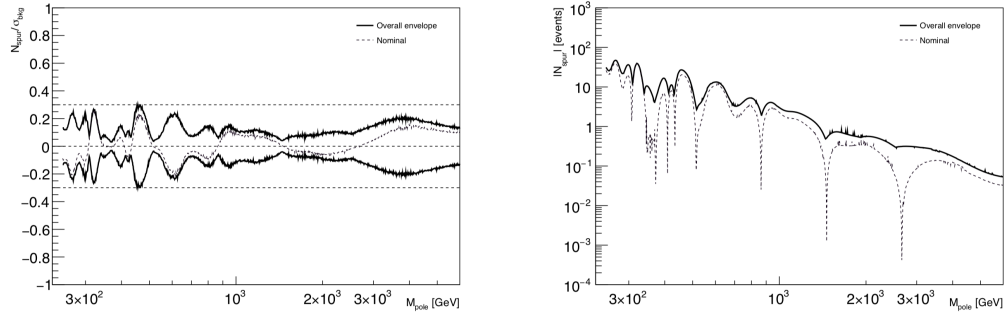


Figure 5.11. Spurious signal estimation at $\Gamma/M = 0\%$ in the $\mu\mu$ channel with the nominal function choice (see equations 5.9). The left plot shows N_{spur}/σ_S for a range of $M_{\text{pole}} \in [225 \text{ GeV}, 6000 \text{ GeV}]$, while the plot on the right shows $|N_{\text{spur}}|$. The dashed line corresponds to the nominal background template, while the thick solid line corresponds to the envelope of the determined spurious signal values from PDF variations.

functional form used for the data-driven fits needs to be able to accommodate for these shape changes, such that spurious signal estimates are performed for each vari-

ation. The main uncertainty that changes the shape of the background distribution in the high-mass tail are PDF and other modelling uncertainties. The uncertainties considered include variations due to PDFs and normalisation of the $t\bar{t}$ background component [67]. Uncertainties on the multi-jet and W+jet background contributions [68] are also considered in the dielectron channel. For the chosen function, the largest spurious signal (accounting for all systematic variations) must be less than 30% of the statistical uncertainty in the fitted signal yield (from the background distribution) for the zero-width signal. The largest systematic uncertainty at low mass in both channels originates from the spurious signals. The parametrisation of $|N_{Spur}|$ is performed by selecting the main maxima of the spurious signal distribution and fitting a functional description to it. The fit results are shown in figures 5.12. The spurious signal parametrisation is repeated for all width assumptions from $\Gamma/M = 0\%$ to 10% .

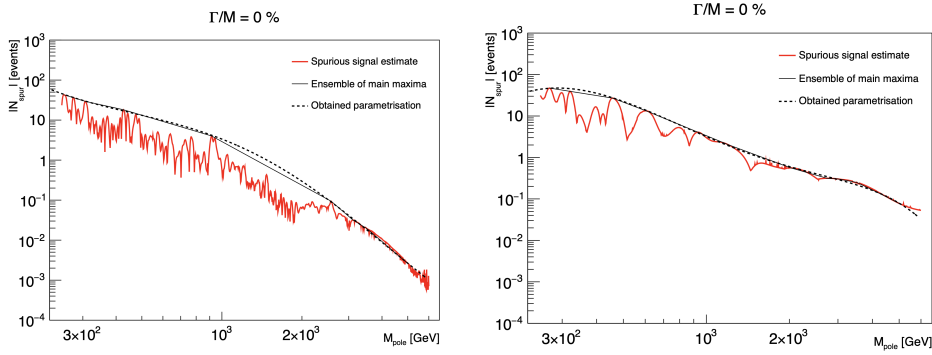


Figure 5.12. Spurious signal parametrisation for the $\Gamma/M = 0\%$ case in the ee channel (left) and $\mu^+\mu^-$ channel (right). The spurious signal values are given by the red line and correspond to the envelope of $|N_{Spur}|$ given in figures 5.10- 5.11, while the black solid lines gives the connection of the main maxima. The functional fit is depicted by the black dotted line.

The uncertainty of the detector response fits (Figure 5.3) is determined using a bootstrapping technique for the available NLO DY MC samples. The extraction of the uncertainties from a single fit to the nominal templates is difficult due to the large number of parameters, which in addition are partially correlated. In order to obtain statistically different samples, each of the MC events is weighted according to a Poisson distribution with mean = 1. Ten thousand of such toy MC samples are generated with different seeds and the detector response fits are performed on each of them. Based on this fit ensemble, it is possible to extract the distribution of each parameter, the correlation between the parameters as well as the uncertainty on the final detector response variables. It was observed that the variations are very small in the peak region and only have a significant size in the tails of the distribution. Due to the very low number of events in this region, the uncertainty on the detector response shape is neglected in the statistical analysis, as the uncertainty is considerably smaller than the experimental uncertainties described below.

The largest systematic uncertainties in the dielectron channel at high mass that change the detector response significantly are the energy/momentum scale and resolution uncertainties. Scale uncertainties mainly affect the mean value of the

response distribution (i.e. for a given M_{true} the M_{reco} scale is shifted), which is parametrised by the μ_i ($i \in CB, G$) parameters. Resolution uncertainties mainly affect the width of the response distribution (i.e. for a given M_{true} the M_{reco} spread is increased), which is parametrised by the σ_i parameters. For each of the $p_{\mu_{CB_i}}, p_{\mu_{G_i}}, (p_{\sigma_{CB_i}}, p_{\sigma_{G_i}})$ parameters (Table 5.5- 5.6) a nominal value and values a -1σ and $+1 \sigma$ are thus obtained for scale (resolution) uncertainties. For each of the considered uncertainties a comparison of the response distributions and their respective functional description for the variations is given in Figure 5.13. Figure 5.14 shows the obtained behaviour for the energy/momentum scale and resolution systematic uncertainties.

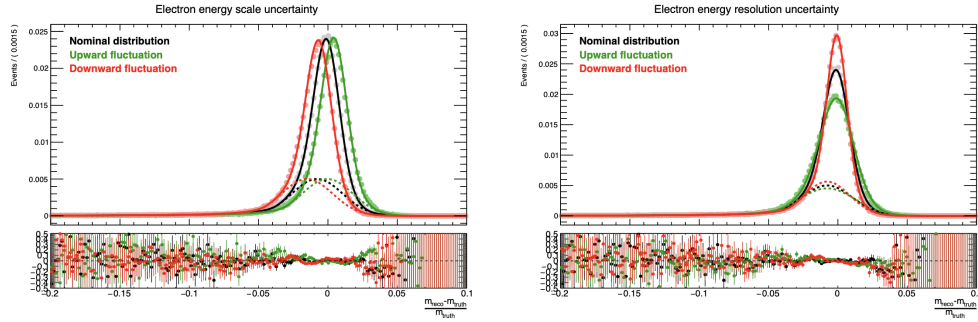


Figure 5.13. Visualisation of the effect of systematic uncertainties on the response distribution (points) and the detector response parametrisation (smooth line) for the ee channel. The lower panels give the relative difference between the MC distribution and the respective fit for the two figures.

While in the dimuon channel the dominant uncertainty is associated with the q/p criterion. This uncertainty is estimated with a conservative approach in a dataset collected in 2015-2016, corresponding to 36 fb^{-1} (see paragraph 5.2.4), by comparing efficiencies obtained in data and in simulation.

The impact of systematic uncertainties on the signal yield is shown in Table 5.7. Only systematic uncertainties which change the fitted signal yield by more than 0.5% at any point in the mass spectrum are considered.

5.1.7 Statistical analysis

The numbers of signal and background events, as a function of the signal mass and width hypothesis, are estimated from simultaneous maximum-likelihood fits of the signal-plus-background models to the data m_{ll} distribution. Frameworks based on RooFit [69] and RooStats [70] were chosen as the analysis strategy was based on a data-driven background estimation. RooStats is based on the Frequentist approach. The full likelihood function is a product of Poisson probabilities in each bin comparing the expected (from the fit) and observed (from the data) yields. Systematic uncertainties are included in the fits via nuisance parameters constrained by penalty terms which are either Gaussian (e.g. energy and momentum scale uncertainties) or log-normal (efficiency and resolution uncertainties). In the equation

Table 5.7. The relative impact of 1σ variation of systematic uncertainties on the signal yield in percent for zero relative width signals at the pole masses of 300 GeV, 2 and 5 TeV for dielectron and dimuon channels. Sources of uncertainties leading to an impact smaller than 0.5% on the signal yield at any point of the mass mass spectrum are not shown. A signal is injected at the cross-section limit.

Uncertainty source	Dielectron			Dimuon		
for m_X [GeV]	300	2000	5000	300	2000	5000
Spurious signal	± 12.5	± 4.6	± 0.1	± 11.7	± 3.8	± 2.1
Lepton identification	± 1.6	± 5.6	± 5.6	± 1.8	$+12$ -10	$+25$ -20
Isolation	± 0.3	± 1.1	± 1.1	± 0.4	± 0.4	± 0.4
Luminosity	± 1.7	± 1.7	± 1.7	± 1.7	± 1.7	± 1.7
Electron energy scale	-1.7 -4.0	-1.9 -6.0	$+0.1$ -0.4	-	-	-
Electron energy resolution	$+7.9$ -8.3	$+9.0$ -11.8	$+0.4$ -0.9	-	-	-
Muon ID resolution	-	-	-	$+0.8$ -2.3	$+0.9$ -1.3	$+0.6$ -0.4
Muon MS resolution	-	-	-	$+2.8$ -3.8	$+3.2$ -3.0	± 2.4
q/p criterion	-	-	-	± 0.6	$+9.0$ -8.2	$+55$ -35

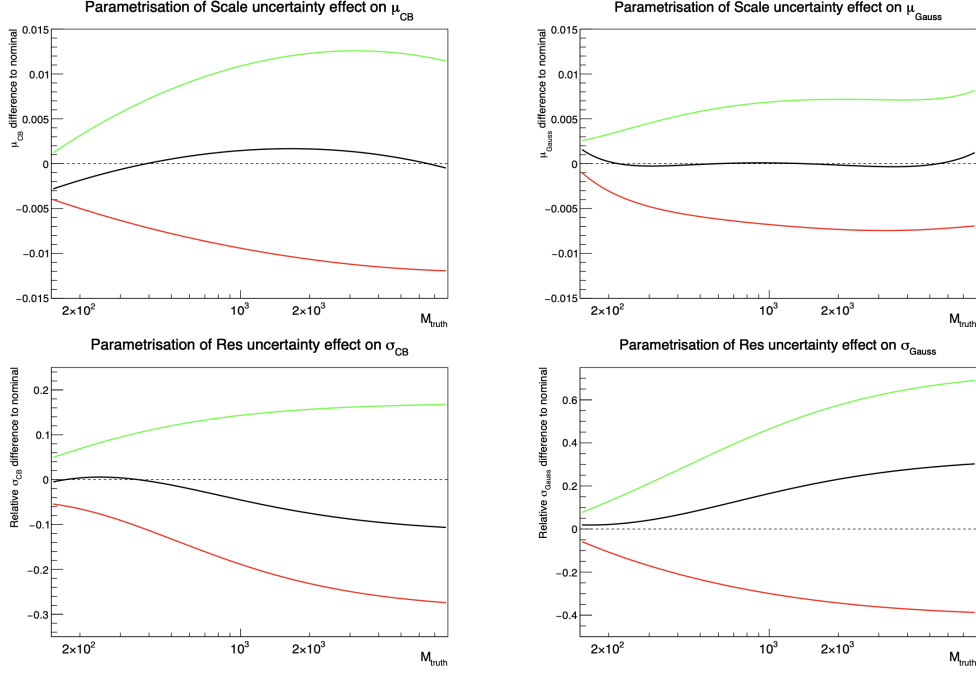


Figure 5.14. Effect of the systematic uncertainty on the electron energy scale (upper plots) and resolution (lower plots) in terms of the variation of the μ_{CB}/σ_{CB} (left) and μ_G/σ_G (right) detector response parameters. The green line corresponds to the upward-fluctuation, the red line to the downward-fluctuation and the black line is the difference (i.e. the asymmetry) between the two.

5.10 the likelihood expression is given:

$$\begin{aligned}
 L(m_X, \Gamma_X \mid \mu, \vec{p}, \vec{\theta}) = & \prod_{i \in \text{bins}} \text{Prob} \left(N_{obs}^i, f_{bkg}^i(\vec{p}) + \left(\mu A_\epsilon(m_X, \Gamma_X, \vec{\theta}) \mathcal{L}(\theta_\mathcal{L}) \right. \right. \\
 & \left. \left. + \theta_{SS} \mid N_{SS}(m_X, \Gamma_X) \mid \right) f_{sig}^i(m_X, \Gamma_X, \vec{\theta}) \right) \times \prod_{a \in \text{syst.}} \text{Gaus}(\theta_a, 0, 1)
 \end{aligned} \tag{5.10}$$

where the parameter of interest, μ , is directly the signal cross section of the mediator X , since in this definition it is separated out from the acceptance times efficiency, $A_\epsilon(m_X, \Gamma_X, \vec{\theta})$, and the integrated luminosity $\mathcal{L}(\theta_\mathcal{L})$. Γ_X and m_X represent the width and the mass of the mediator, respectively. The f_{bkg} and f_{sig} are the background and signal pdf functions evaluated for each bin, while $\vec{p}$ and $\vec{\theta}$ refer to the background function parameters and to the nuisance parameters. N_{obs} is the number of observed events in data, and N_{SS} is an extra term in the signal yield normalization factor for the spurious signal nuisance parameter θ_{SS} . Dielectron and dimuon channels are considered both as independent channels and in a combined approach, under a lepton-flavour universality assumption [71]. Combining a second channel is just like multiplying another whole likelihood function which is composed of its own factors for each of the bins in the new region of the electron and muon channel likelihoods. The nuisance parameters are either shared or independent. The luminosity uncertainty is constrained simultaneously by both channels in the same

factor, also most importantly, the generic signal cross section μ is shared by both channels. Channel-specific sources of uncertainty such as electron energy- muon momentum resolution enter through separate nuisance parameters. The significance of an excess is quantified based on the probability that the background fluctuates creating a signal-like excess equal or larger than what is observed. This probability (p-value) is denoted as p_0 .

p_0 is computed using a test statistic defined as follows:

$$q_0 = \begin{cases} 0 & \text{for } \hat{\mu} < 0, \\ -2\ln \frac{L(data|0, \hat{\theta}_0)}{L(data|\hat{\mu}, \hat{\theta})} & \text{for } \hat{\mu} \geq 0, \end{cases} \quad (5.11)$$

where the hat over θ_0, θ and μ refers to the set of parameters that maximise the likelihood function, while the subscript 0 discriminate the only-background from the signal plus background hypothesis. The more important is an excess, the larger is the difference between the two likelihoods considered in this equation and the larger is the corresponding q_0 value. (For a given dataset, $L(data|\hat{\mu}, \hat{\theta})$ is always larger or equal than $L(data|0, \hat{\theta}_0)$.)

The different treatment for the cases with $\hat{\mu} < 0$ is associated with the physical fact that the number of signal events can only be positive. In this case, it produces a peak in the distribution of q_0 , at $q_0 = 0$; it represents the 50% of the times that background-only datasets have downward fluctuations.

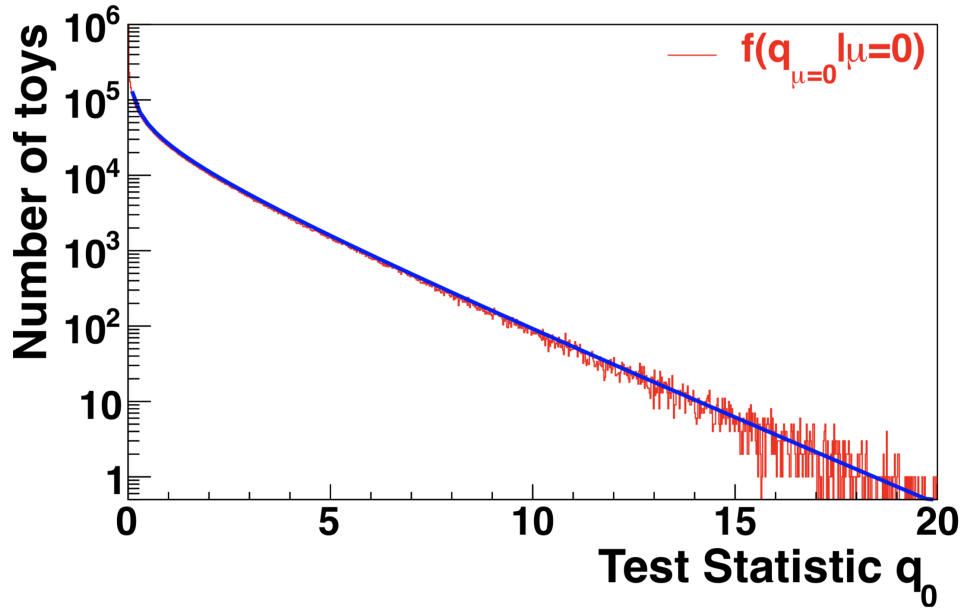


Figure 5.15. Distribution of the q_0 test statistic for background-only toys. The solid line corresponds to the χ^2 distribution for one degree of freedom.

Background-only toys are generated following the frequentist conventions, using the nuisance parameter values $\hat{\theta}_0^{obs}$ (i.e. the parameter vector extracted by the fit which maximise the likelihood function) and event counts following Poisson probabilities. From this toys distribution a probability density function $f(q_0|0, \hat{\theta}_0^{obs})$ is built. Figure 5.15 shows an example of the q_0 distribution for background-only

toys. The probability p_0 corresponding to a given experimental observation q_0^{obs} is evaluated as follows:

$$p_0 = P(q_0 \geq q_0^{obs} | \text{background-only}) = \int_{q_0^{obs}}^{\infty} f(q_0 | 0, \hat{\theta}_0^{obs}) dq_0 \quad (5.12)$$

The p_0 values are translated to a scale of significance (Z), or number of standard deviations. It is done by using the inverse of the cumulative function for the normal Gaussian Φ ,

$$Z = \Phi^{-1}(1 - p_0) \quad (5.13)$$

Upper limits at the 95% confidence level (CL) are set on the fiducial cross-section times branching ratio into the corresponding dilepton final state, given the integrated luminosity of the data and the signal efficiency. The limits are evaluated with the modified frequentist CLS method [72] using the asymptotic approximation to the test-statistic distribution [73].

Asymptotic approximation

In the asymptotic limit, the distribution of q_0 for background-only datasets follows a χ^2 distribution for one degree of freedom, for Wilks' theorem [74]. It is illustrated in Figure 5.15, where the solid line corresponds to the χ^2 distribution for one degree of freedom. Then, the probability p_0 can be directly calculated from q_0 as

$$p_0 = 1 - \Phi(\sqrt{q_0}) \quad (5.14)$$

as well as the significance

$$Z = \sqrt{q_0}. \quad (5.15)$$

Which largely reduces the computing time and resources required.

5.1.8 Results

The present section contains results of the resonant search obtained with the global fit background estimation. The dilepton invariant-mass distributions for the events that pass the full analysis selection are shown in Figure 5.16.

In both channels, a global fit to data is performed, using the equation described in 5.9. The probability that the data are compatible with the background-only hypothesis is shown in Figure 5.17 as a function of pole mass for zero-width signal, the significance values are calculated with a spacing of 1 GeV in the pole masses, which is lower than the experimental resolution for the ee and $\mu\mu$ channels in the complete mass range. The largest deviation from the background-only hypothesis is in the dielectron channel with a local p_0 of 2.9 σ at 774 GeV. Limit curves for the ee , $\mu\mu$ and ll channels are presented.

Figures 5.18 and 5.19 show the upper limits on the fiducial cross-section times branching ratio to two electrons or two muons or two leptons of a single flavour for generic resonances of various relative widths as a function of their mass. The limit values are obtained with a spacing of 1 GeV for the observed limits in the low mass region, while the expected limits are obtained each 10 GeV. The granularity is

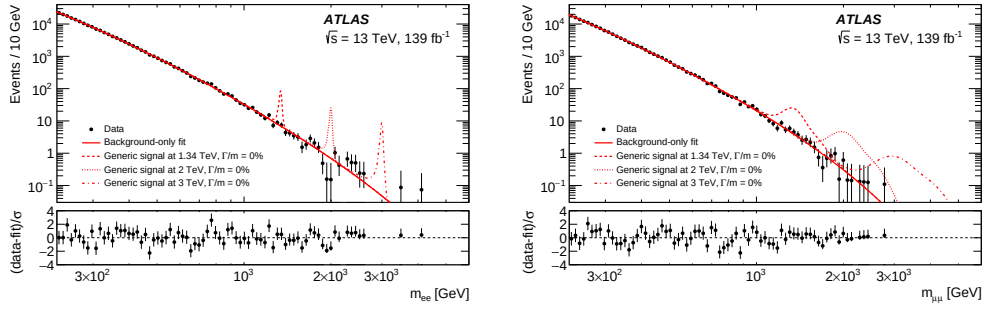


Figure 5.16. Distribution of the dielectron (left) and dimuon (right) invariant mass for events passing the full selection. Generic zero-width signal shapes, scaled to 20 times the value of the corresponding expected upper limit at 95% CL on the fiducial cross-section times branching ratio, with pole masses of $m_X = 1.34, 2$ and 3 TeV as well as background-only fits are superimposed. The data points are plotted at the centre of each bin. The error bars indicate statistical uncertainties only. The differences between the data and the fit results in units of standard deviations of the statistical uncertainty are shown in the bottom panels.

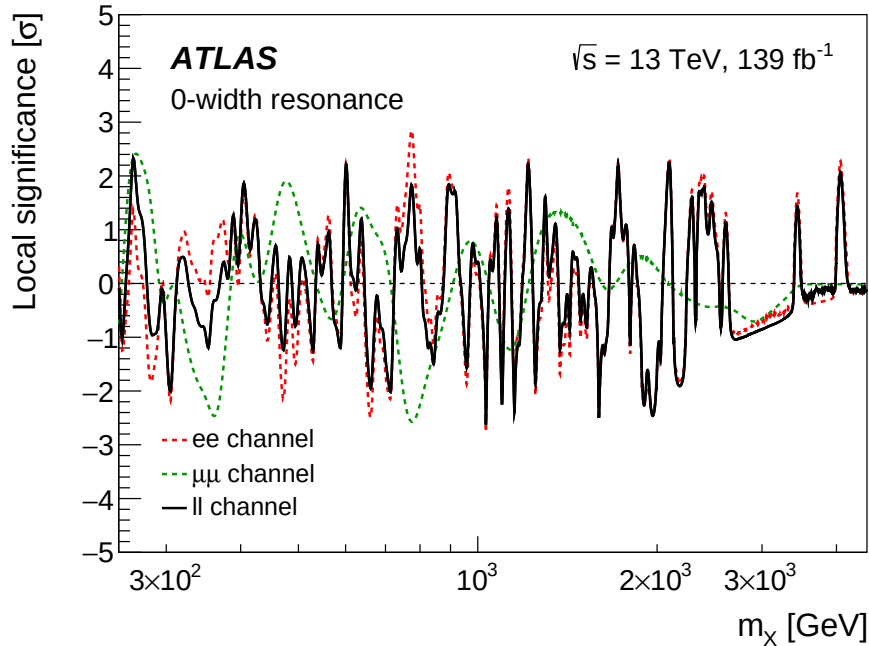


Figure 5.17. Probability that the observed spectrum is compatible with the background-only hypothesis as a function of the pole mass m_X , for a signal width assumption of $\Gamma/M = 0\%$ on truth-level for the full Run 2 dataset in the dielectron (ee), dimuon ($\mu\mu$) and combined (ll) channels. All experimental uncertainties as well as the spurious signal uncertainty are taken into account.

reduced towards the high mass region, but chosen to stay below the experimental resolution of the ee channel in case of the observed limits. The lowest limits are given in the combined ll channel, while the ee channel typically contributes stronger limits than the $\mu\mu$ channel. The generic cross-section limit is compared to the model

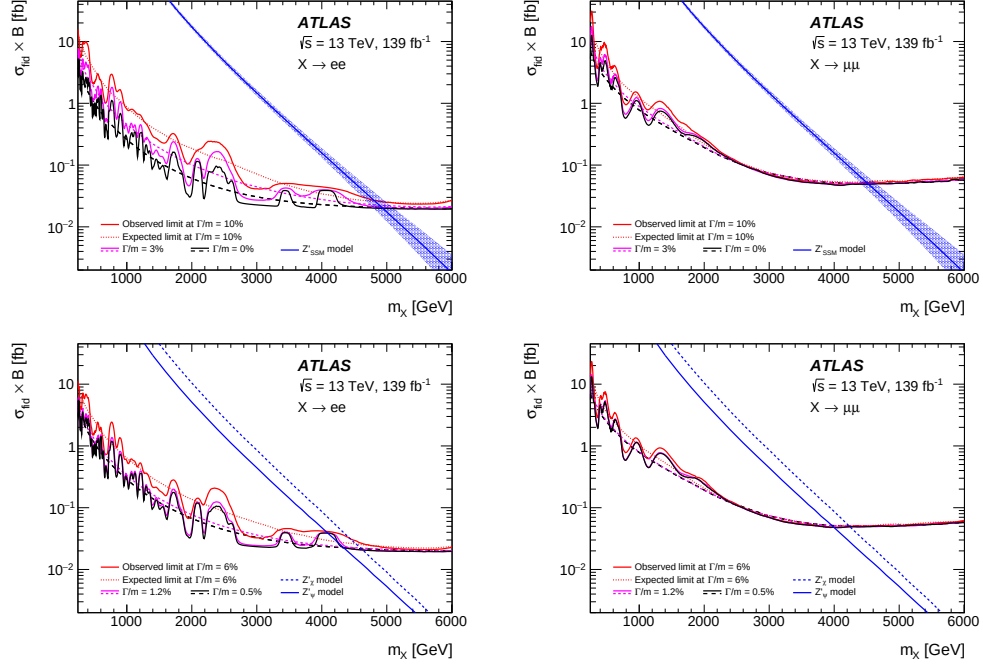


Figure 5.18. Upper limits at 95% CL on the fiducial cross-section times branching ratio as a function of pole mass for different relative width signals for the ee channel (left) and for the $\mu\mu$ channel (right). Observed limits are shown as a solid line and expected limits as a dotted/dashed line. The theoretical cross-section for Z'_χ , Z'_ψ and Z'_{SSM} are also shown in the fiducial region [75]. All experimental uncertainties as well as the spurious signal uncertainty are taken into account. The signal theoretical uncertainties are shown as a band on the Z'_{SSM} theory line, just for illustration purposes and they are not included in the limits calculation.

prediction of Z'_χ , Z'_ψ and Z'_{SSM} to reinterpret it and obtain mass limit. The cross-section value for the model prediction is obtained in the fiducial volume, in order to stay consistent with the definition of the generic signal model. The mass limits are obtained by calculating the intersection between the expected and observed limits with the model prediction. Table 5.8 lists the mass limits for the tested model in all three channels [75]. These exceed previously reported results by 500-800 GeV [23].

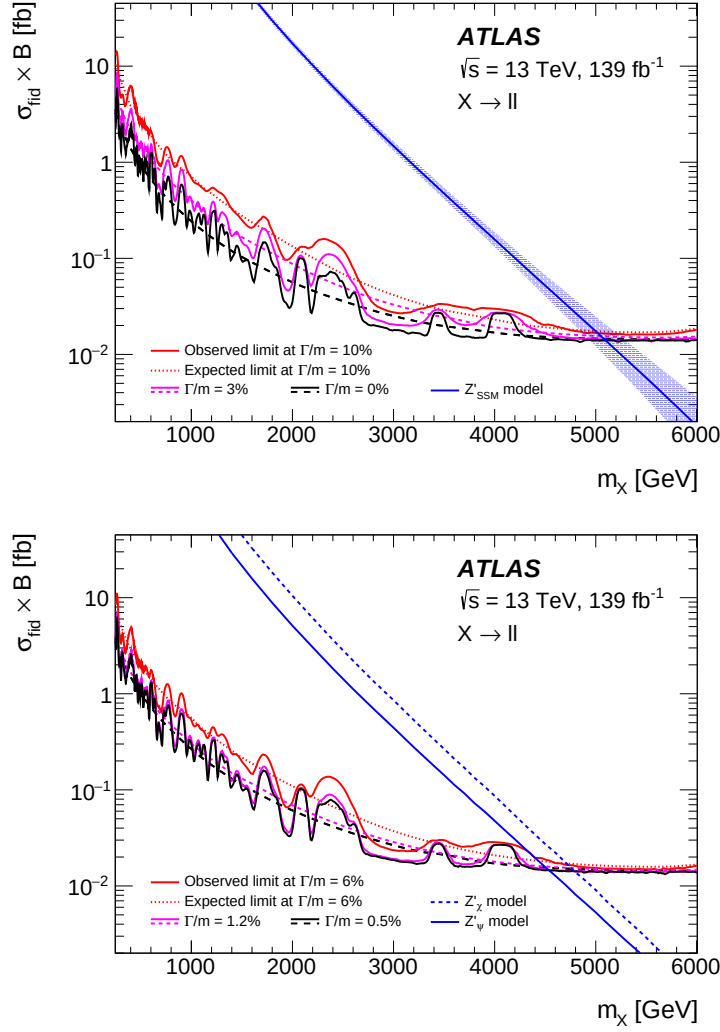


Figure 5.19. Upper limits at 95% CL on the fiducial cross-section times branching ratio as a function of pole mass for different relative width signals for the combined dilepton channel. Observed limits are shown as a solid line and expected limits as a dotted/dashed line. The theoretical cross-section for Z'_{SSM} (top) Z'_χ , Z'_ψ (bottom) are also shown in the fiducial region [75]. All experimental uncertainties as well as the spurious signal uncertainty are taken into account. The signal theoretical uncertainties are shown as a band on the Z'_{SSM} theory line, just for illustration purposes and they are not included in the limits calculation.

Model	Lower limits on $m_{Z'}$ [TeV]					
	ee		$\mu\mu$		$\ell\ell$	
	obs	exp	obs	exp	obs	exp
Z'_ψ	4.1	4.3	4.0	4.0	4.5	4.5
Z'_χ	4.6	4.6	4.2	4.2	4.8	4.8
Z'_{SSM}	4.9	4.9	4.5	4.5	5.1	5.1

Table 5.8. Observed and expected 95% CL lower mass limits for Z'_χ , Z'_ψ and Z'_{SSM} gauge boson model, quoted to the nearest 100 GeV, in the ee and $\mu\mu$ channels as well as their combination (ll) [75]. Region with m_X below 250 GeV is not excluded.

5.2 Search for non-resonant high-mass phenomena in dilepton mass spectra

5.2.1 Data and simulation

The data and simulated event samples used in this analysis are the same as those used in the search described in section 5.1. The integrated luminosity of the dataset is determined to be $139.0 \pm 2.4 \text{ fb}^{-1}$ (Figure 3.2).

The previous ATLAS search for non-resonant features in the dilepton mass spectra was published in late 2017 with 36.1 fb^{-1} of data. In that study, the background contributions to the spectra were modeled using MC. The majority of the background comes from DY production (Z/γ^*). Unfortunately, large theoretical uncertainties including the choice of the parton distribution function (PDF) used to generate the MC, variations in the PDF, the strong coupling (α_s), and others parameters, collectively referred to as "PDF uncertainties", all result in large uncertainties in the MC background shape and normalization. The impact of these uncertainties was to lower the sensitivity of the limits by a large factor. With the increase in integrated luminosity, the negative impact of these uncertainties is exacerbated: statistical uncertainty has decreased while the PDF uncertainty has remained the same.

To avoid the effect of the PDF uncertainties, this analysis adopts a "data-driven" background modeling strategy. Instead of the MC background estimate, a functional form is fitted to the data in a control region. In doing this, the theoretical uncertainties from the MC are replaced by the statistical uncertainties nuisance parameters of the background model.

Signal and background simulated samples are used to select the fit functions, study background compositions, estimate part of the uncertainties and evaluate the signal efficiencies, similarly to the resonant search. The main simulated backgrounds are the same already described in section 5.1.1. The MC event generators are listed in Table 5.9.

Table 5.9. The programs and PDFs used to generate the hard-scatter matrix element (ME) and to simulate parton showering (PS) in the signal and background processes. The top-quark mass is set to 172.5 GeV.

Background Process	ME Generator and ME PDFs	PS and non-perturbative effect with PDFs
NLO Drell-Yan	POWHEG-Box, CT10, PHOTOS	PYTHIA v8.186, CTEQ6L1, EVTGEN1.2.0
$t\bar{t}$	POWHEG-Box, NNPDF3.0NLO	PYTHIA v8.230, EVTGEN1.6.0
Single top s-channel, Wt	POWHEG-Box, NNPDF3.0NLO	PYTHIA v8.230, NNPDF3.0NLO, EVTGEN1.6.0
Single top t-channel	POWHEG-Box, NNPDF3.04NLO, MADSPIN	PYTHIA v8.230, NNPDF3.0NLO, EVTGEN1.6.0
Diboson (WW , WZ and ZZ)	SHERPA 2.1.1, CT10	SHERPA 2.1.1
Signal Process		
LO Drell-Yan	PYTHIA v8.186, NNPDF23LO	PYTHIA v8.186, NNPDF23LO, EVTGEN1.2.0
LO CI	PYTHIA v8.186, NNPDF23LO	PYTHIA v8.186, NNPDF23LO, EVTGEN1.2.0

5.2.2 Event selection

As far as the object definition and event selection concern, the criteria are the same used in the resonant analysis and presented in section 5.1.2 that are summarized here. The dataset was collected during LHC Run 2 (2015-2018) in stable beam conditions, with all detector systems operating normally and while fulfilling all quality requirements. Events in the dielectron channel were recorded using a

dielectron trigger, while events in the dimuon channel were required to pass at least one of two single-muon triggers. At least one pp interaction vertex must be reconstructed in the event. Furthermore, at least two same-flavour charged leptons consistent with the primary vertex per event, have to be reconstructed. A selected muon pair must contain oppositely charged muons. For an electron pair, the opposite-charge requirement is not applied because of the higher probability of charge misidentification for high-energy electrons. The reconstructed mass of the dilepton system after the full analysis selection, m_{ll} , is required to be above 130 GeV to avoid the Z boson peak and tail region, which cannot be described by the same parameterisation as the high-mass part of the dilepton distributions.

5.2.3 Background modelling

Fit in the control region

The dilepton invariant mass distribution in data is fitted by a parametric background-model function in a low-mass control region (CR) as shown in Figure 5.20. The resulting background model is then extrapolated from the CR to higher-mass single-bin signal region (SR). The normalization of the background model is set such that its integral in the CR matches the number of observed events in the CR.

In order to improve the sensitivity of the analysis two optimisations are performed in two steps. The first step consists in the choice of the fit function. After fixing the fit function, the CR and SR choice is optimised using the chosen function. The extrapolation function will be used to estimate the background in the signal region.

Background function choice

A key component of this estimate depends on the optimization and choice of the fitting function. For this reason, it is important to choose a function with desirable behaviour:

- good modeling of the fit in the control region
- good agreement of the extrapolation with the MC in the signal region

each function was tested in a number of different scenarios that correspond to the expected use in the analysis.

- different mass ranges for the fit
- different injected MC contact interactions signals

In order to find a function or several functions that fulfill these requirements, a number of functional forms were considered. These functions are required to go to zero when $x = m_{ll}$ approaches the center of mass energy, $\sqrt{s} = 13$ TeV.

Each function is fitted to the dilepton mass MC background template, consisting of the sum of all the simulated background contributions, in a variety of CRs and

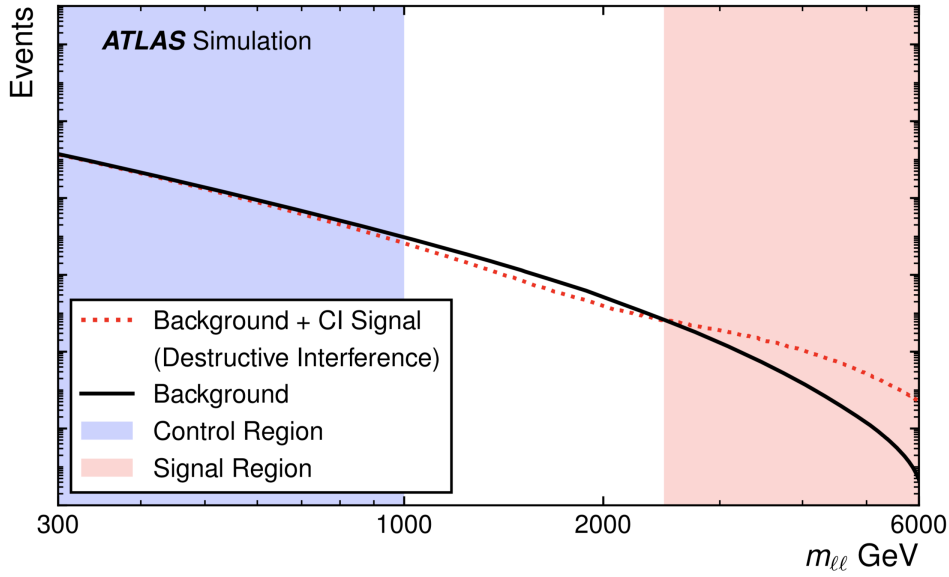


Figure 5.20. Illustration of the mass ranges in this analysis. The monotonically falling total background shape is shown by the solid black line, while an example of a contact interaction (CI) signal plus the total background shape is shown by the dotted red line. The data is fitted in a low mass control region (blue), and the background is extrapolated into a high mass signal region (red). The motivation for the extrapolation is evident here: in the CR where the data is fitted, the background shape is dominant and the presence of a signal has a smaller impact on the outcome of the fit. In the SR, the signal is expected to be larger. The gap illustrated between the CR and the SR is found to be the best solution for the destructive interference cases only.

extrapolated to the respective SRs. The background template is the same described in section 5.1.5. For any given test function, the distribution of the pulls, defined as $(\text{fit} - \text{simulation})/\text{fit}$, is evaluated bin per bin, for all the different CR and SR configuration taken into account. A function that results in pulls below 3 across all the ranges considered (CRs and SRs) is marked as acceptable. This criterion is needed in the SRs to veto functions that exhibit unphysical behaviour at the tail. Moreover, it guarantees a good description of the simulated background template in the CRs. The final function is chosen to be the same as the one used for the resonant search and it is given in Eq 5.9.

Extrapolation to signal region

Once the functional form of the background model has been fixed, the background model is extrapolated into the SR. The definition of the CR and SR are chosen to optimise the expected limits on each signal model.

CR and SR definitions

The CR and SR are defined by their respective minima and maxima in $m_{\ell\ell}$. In

all cases, the maximum of the SR (srMax) is fixed at 6 TeV. This leaves three mass points that must be selected: the CR minimum (fitMin), the CR maximum (fitMax), and the SR minimum (srMin). The definition of the CR has a major impact on the constraint of the fit. A CR that is too small, or is restricted to too low a mass, does not contain enough information to reliably extrapolate the background shape to the SR. Therefore the choice of CR influences the systematic uncertainty in the background as described in section 5.2.4. The choice of the CR was made through an optimization process that considered the following criterion: expected limits.

The definition of the SR has a lesser impact on the performance of the analysis, so it is picked after the choice of the CR. The main impacts of the choice of SR are: the resulting limit on the number of signal events in the SR, and the conversion of this limit to a limit on the contact interaction (CI) parameter Λ . A lower upper limit on signal events results in a stronger limit on Λ . Likewise, a larger expected yield from a signal model in the SR results a stronger limit on Λ . The criteria for selecting the SR for each signal model is therefore the resulting expected limit on Λ . As in the case of the CR, the different signal shapes means that different SRs are suitable for different signal models.

A possible gap between the end of the CR and the start of the SR is allowed when picking the ranges. This is mainly to benefit the destructive limits. If a signal region happens to include too much of the destructive component of the signal shape, as seen in the right plot in figure 5.21, the integral of the number of expected signal events in the SR can be reduced. In order to avoid this, a gap between the CR and SR is allowed. This enables the choice of a signal region with a large expected signal contribution that does not get canceled by the destructive component. Again, the criteria for this selection is the expected limit on Λ .

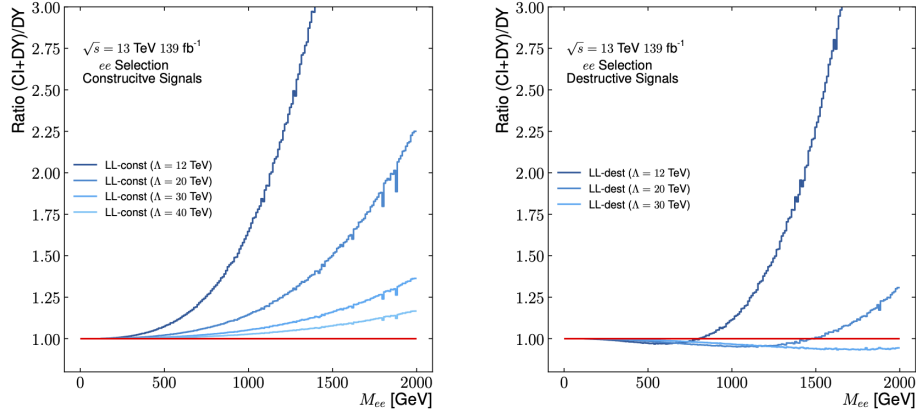


Figure 5.21. Signal templates for the CI LL model with constructive (left) and destructive (right) interference for the dielectron channel is presented for 4 Λ values. The reweighted templates are produced from the same DY sample, therefore the same statistical fluctuations of the underlying DY show up in the plots for each Λ . Also, while the ratio tends to blow up at high mass, this is due to the small number of events in the denominator (DY). In the destructive case, the $\Lambda = 30$ TeV signal is still primarily destructive at 2 TeV, but it also has a constructive component at ≈ 2.5 TeV.

The ranges used for the results shown here are given in table 5.10.

Channel	Chirality	Constructive interference			Destructive interference		
		CR Min	CR Max	SR Min	CR Min	CR Max	SR Min
e^+e^-	LL	280	2200	2200	310	1450	2770
e^+e^-	LR	280	2200	2200	310	1450	2770
e^+e^-	RL	280	2200	2200	310	1450	2770
e^+e^-	RR	280	2200	2200	310	1450	2770
$\mu^+\mu^-$	LL	310	2070	2070	320	1250	2570
$\mu^+\mu^-$	LR	310	2070	2070	320	1250	2570
$\mu^+\mu^-$	RL	310	2070	2070	320	1250	2570
$\mu^+\mu^-$	RR	310	2070	2070	320	1250	2570

Table 5.10. CR and SR ranges (in units of GeV). All SR terminate at 6000 GeV.

Validating the CR

In order for the background estimate described in this section to be useful to this analysis, it must be unaffected regardless of whether or not a signal is present in the control region. Whether the background estimate is biased by the presence of a signal depends both on the background model, and on the signal under consideration. The procedure described in this section is designed to:

- answer quantitatively whether the background estimate could be biased by the signal models under consideration.
- provide a method of adjusting the background model until the bias (if present) is no longer significant.

In this analysis, the primary focus is on contact interaction signals. Therefore, this procedure is built around the expected shape of the signals, and is applied to the background model in relation to contact interaction signals. The key feature of the signal shape is a large contribution to the spectra at large mass, and a relatively small contribution at small mass.

$$f_B(p'_i, m_{ll}, \Lambda') = N_{\text{bkg}} * B(p'_i, m_{ll}) \quad (5.16)$$

$$f_{\text{SB}}(p'_i, m_{ll}, \Lambda') = N_{\text{bkg}} * B(p'_i, m_{ll}) + N_{\text{sig}}(\Lambda') * S(\Lambda', m_{ll}) \quad (5.17)$$

The procedure requires two models: a background-only model (equation 5.16), and a signal+background model (equation 5.17). In each case, the background component $B(p'_i, m_{ll})$ is the same as defined in equations 5.9, with p'_i the fit parameters of the background function. Meanwhile, the signal component of equation 5.17, $N_{\text{sig}}(\Lambda')$ and $S(\Lambda', m_{ll})$ are the number of signal events and the signal probability density function in the CR, respectively. Both $N_{\text{sig}}(\Lambda')$ and $S(\Lambda', m_{ll})$ are determined from simulation. The parameter N_{bkg} is the number of background events in the CR

with the constraint $N_{bkg} + N_{sig}(\Lambda') = N_{CR}$. For a given CR both models in equations 5.17 and 5.16 are fitted. The background component estimate in the SR of the S+B model is compared to the B-only model. If the two background estimates *do not differ significantly*, then it is concluded that there is no bias in the background estimate from the presence of a signal. A significant difference is considered one that is larger than the 1σ uncertainty on the S+B background model. The S+B uncertainty is used as this is not expected to be effected by the potential presence of a signal in the CR, while the B-only background model is. This conclusion relies on the signal injection tests performed with the S+B model. These show that both in the presence and absence of a signal, the background component of the S+B model is not significantly deflected from the MC background.

An example of such a test on the compatibility of the S+B and B-only background models is shown in Figures 5.22, run on MC. Both plots report the total uncertainty (black), obtained by summing in quadrature the spurious signal (orange) and the fit (red) uncertainties, under the B-only background and signal plus background hypothesis. The left figure shows the case where the B-only background has not been biased by the presence of a $\Lambda = 20$ TeV signal in the CR. The right figure (in which the CR has been extended to an artificially high mass) shows the case where the B-only fit has been pulled upward by the 20 TeV signal, thus over-predicting the background contribution to the SR. The S+B model has not been biased in this way, and by comparing these it is clear that they are incompatible by $\approx 3\sigma$. In this case, the CR would be deemed invalid, and the "bootstrapping" procedure described below would be applied.

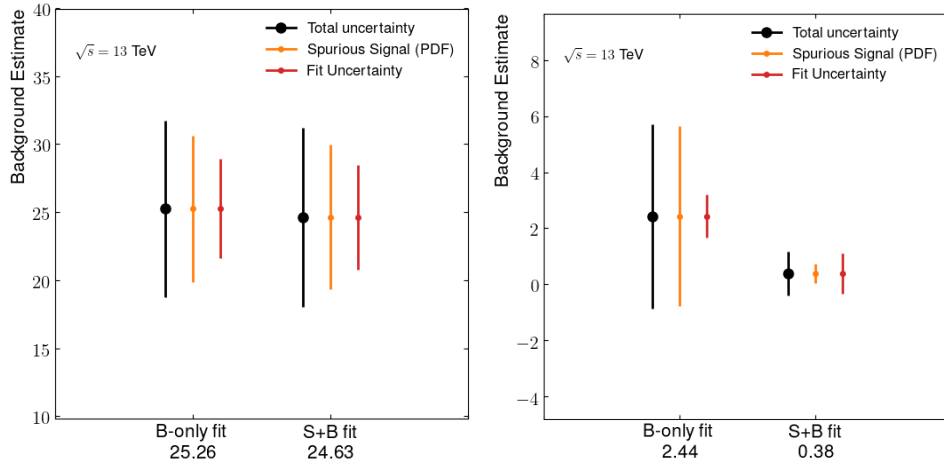


Figure 5.22. Background estimates from the S+B and B-only models. On the **left**, the estimates are compatible within the uncertainty on the S+B background estimate. On the **right**, the CR moved to a high mass to demonstrate how the estimates can be incompatible. In each case, the uncertainties used here are the CR uncertainty and the spurious signal uncertainty (Section 5.2.4).

Bootstrapping the CR

If the two background estimates *do differ significantly*, then it is concluded that the control region includes an invariant-mass range where a signal under consideration can impact the background fit. Due to the shape of the contact interaction signal (see Figure 5.21), such a mass range is expected to be caused by the CR extending to too high of a mass. In this case, the CR's high-mass end (fitMax) is reduced and a B-vs-S+B comparison is repeated until no bias is found, i.e. bootstrapping the "FitMax" to a lower mass range.

As an additional note, the mass ranges (CR and SR) have been selected such that a difference between the background components of equations 5.17 and 5.16 when fit to data is not expected unless a particularly large signal is present in the CR. A significant difference between the background components of the two models indicated the presence of a strong signal component in the CR. Therefore, the bootstrapping procedure is applied and the CR is moved back until the two background components of the models agree, but it is not expected to be needed.

Each chirality choice of the CI model is tested with an independent CR and SR configuration. The resulting ranges for the different chirality options are similar at the level of a few tens of GeV. The final result is not sensitive to the choice of CR within these small differences, and therefore these are merged as listed in Table 5.11 to simplify the subsequent procedures.

Channel	Constructive interference			Destructive interference		
	CR Min	CR Max	SR Min	CR Min	CR Max	SR Min
e^+e^-	280	2200	2200	310	1450	2770
$\mu^+\mu^-$	310	2070	2070	320	1250	2570

Table 5.11. CR and SR ranges (in units of GeV). All SR terminate at 6000 GeV.

Figure 5.23 shows the expectation of the background compatibility on background-only MC using the CR ranges reported in Table 5.11.

Fit to data

The fit is performed on data binned with linear spacing. This improves the constraint of the fit and avoids issues with logarithmic binning in RooFit, however it makes the display of data less appealing. Therefore this section shows the fits displayed in logarithmic bins for clarity. The fits and log binned data are shown in 5.24 5.25 5.26 5.27. These plots show fits to the data and the extrapolation.

5.2.4 Uncertainties

This section describes the uncertainties considered for the background model, and signal model.

The background estimate is obtained by integrating the extrapolated background model described in Section 5.2.3 within the signal region (SR). The following uncertainties (Stat Uncertainty on Fit, Induced SS, and CR Bias Uncertainty) impact this expected background yield.

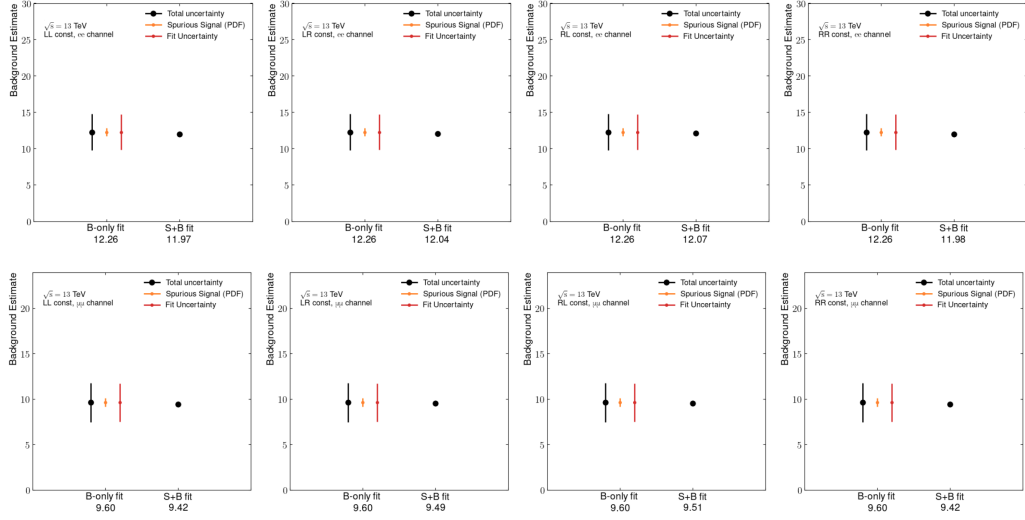


Figure 5.23. Background estimate compared in the SR, for B-only and S+B fits to data in the constructive ee (top) and $\mu\mu$ (bottom) channels.

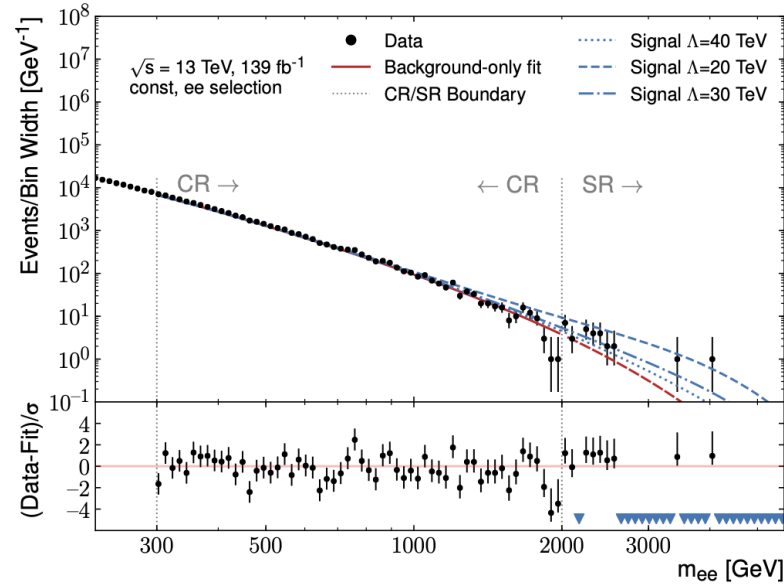


Figure 5.24. Fit for the ee constructive CR and SR. The data is shown in the log binning for better presentation, but the fit was performed on the linear binned data used in the analysis. The fit is the B-only model. The dotted grey lines show the CR/SR ranges for this channel. Imposed on top of the background model are three signal templates of different Λ for illustration purposes. Blue triangles represent empty bins.

Statistical uncertainty of fit

Since the background model is fitted to the observed data in the CR, statistical

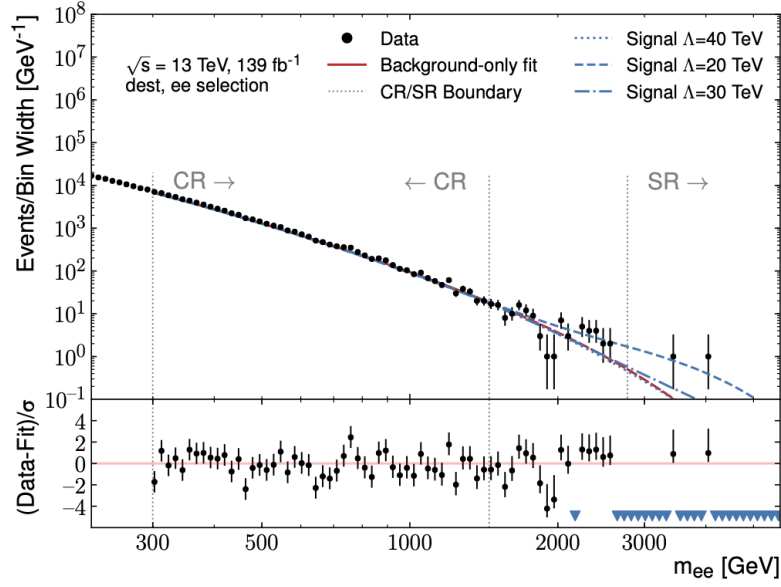


Figure 5.25. Fit for the ee destructive CR and SR. The data is shown in the log binning for better presentation, but the fit was performed on the linear binned data used in the analysis. The fit is the B-only model. The dotted grey lines show the CR/SR ranges for this channel. Imposed on top of the background model are three signal templates of different Λ for illustration purposes. Blue triangles represent empty bins.

fluctuations in the CR data result in variation in the fitted background model. This in turn has an impact on the extrapolated model, and therefore the background estimate in the SR. “**Statistical uncertainty of fit**”, σ_b^{Stat} , is the name given to the variation in the background estimate caused by statistical fluctuations. It is the dominant uncertainty in the expected background.

To estimate the statistical uncertainty of fit, the following procedure is done for each of the signal models. Data is used for the final analysis results, while for the optimization studies, the nominal MC was used in place of data, where the normalization of the MC has been set to match that of the corresponding data (ee or $\mu\mu$).

1. Fit the **data** template in the CR using the B-only background model, and extrapolate it to get the yield in the SR. This is the *nominal background expectation*.
2. Use the nominal background template as a Probability Density Function (PDF), and from it generate a toy dataset in the CR corresponding to the expected luminosity.
3. Fit the background model to the toy dataset, and extrapolate it to get the yield in the SR. This is the *toy background expectation*.
4. Repeat steps 2 and 3 to produce a distribution of toy background expectations.

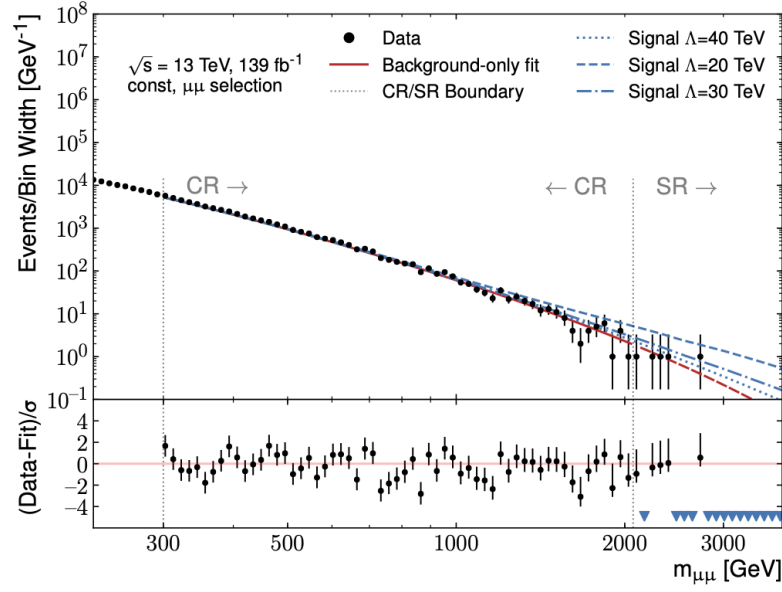


Figure 5.26. Fit for the $\mu\mu$ constructive CR and SR. The data is shown in the log binning for better presentation, but the fit was performed on the linear binned data used in the analysis. The fit is the B-only model. The dotted grey lines show the CR/SR ranges for this channel. Imposed on top of the background model are three signal templates of different Λ for illustration purposes. Blue triangles represent empty bins.

The distribution of toy background expectations is confirmed to be centered around the nominal background expectation.

The width of the distribution (σ) corresponds to the width of a Gaussian constraint on a nuisance parameter multiplying the background expectation. For the dielectron and dimuon channels, the statistical uncertainty ranges from 14% to 20% (34% to 60%) of the nominal background for the constructive (destructive) SRs of the analysis.

Induced Spurious signal uncertainty in the expected background

The sub-dominant uncertainty in the background arises from systematic mismodeling of the background contribution to the SR. For a given underlying PDF that generates an m_{ll} spectrum, the extrapolation from the low-mass region to the high-mass region will naturally deviate from the underlying distribution. In this analysis, this deviation is given the name **induced spurious signal uncertainty** or σ_b^{ISS} . This name is used since the deviation of the background expectation from the true background contribution in the SR is regarded as signal (partially, since it also impacts the background's nuisance parameters as well).

To estimate the magnitude of σ_b^{ISS} is challenging since there is no way to know exactly what the underlying distribution is in nature. The measure of the induced spurious signal with respect to the nominal MC samples, would result in making an assumption about the underlying distribution (ie assuming that the nominal PDF used to generate the MC is the true one). To avoid this, the uncertainties associated

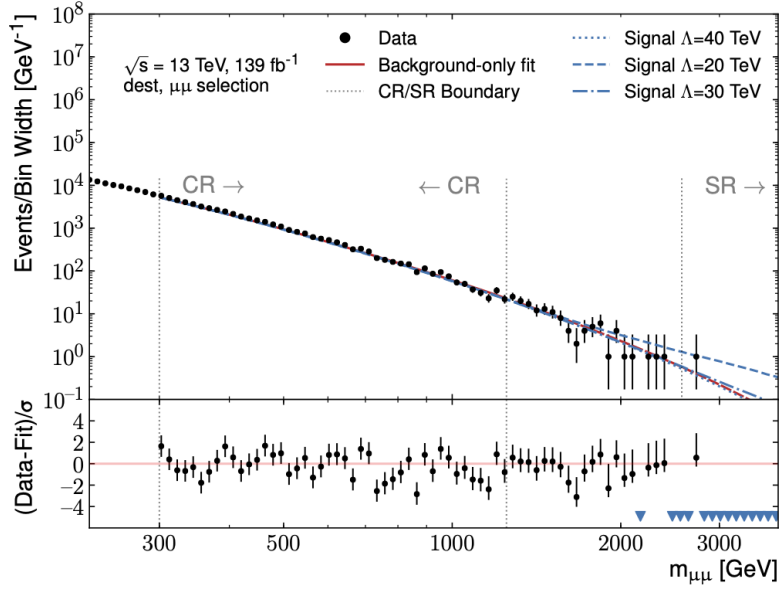


Figure 5.27. Fit for the $\mu\mu$ destructive CR and SR. The data is shown in the log binning for better presentation, but the fit was performed on the linear binned data used in the analysis. The fit is the B-only model. The dotted grey lines show the CR/SR ranges for this channel. Imposed on top of the background model are three signal templates of different Λ for illustration purposes. Blue triangles represent empty bins.

with the simulated background shape are derived from simulated variations on the background shape. These uncertainties are used to generate a number of MCs of possible background shapes. Each of these is fitted in the CR, and the background estimate is compared to the SR yield of the corresponding MC template. The greatest deviation found this way is considered as the spurious signal from PDF variations.

The largest source of uncertainty in the simulated background is theoretical, and it is particularly large at the high end of the dilepton mass spectrum. The following variations are considered for the theoretical uncertainties for the DY component only: the eigenvector variations of the nominal PDF set, variations of PDF scales, the strong coupling ($\alpha_S(M_Z)$), electroweak corrections, photon-induced corrections [76], as well as the effect of choosing different PDF sets. For all PDF variations, the modified DY component is used along with the other nominal background components. These theoretical uncertainties are the same for both dilepton channels at generator level, but they result in different uncertainties at reconstruction level due to the different resolutions of the dielectron and dimuon channels. Further details of this procedure can be found in Ref [23].

The experimental uncertainty is mostly due to the q/p criterion related to the high- p_T muon identification in the dimuon channel. For this reason a new study, with the aim of minimizing this source of uncertainty, is undertaken and is detailed in the following paragraph.

Among the experimental uncertainty sources in the dielectron channel, the

dominant ones are the electron identification at low dielectron masses ($\leq 5\%$, below 2000 GeV) and the uncertainty in the electromagnetic energy scale at higher dielectron masses ($\leq 15\%$). In the muon channel, the dominant experimental uncertainties arise from the muon reconstruction efficiency at low dimuon masses (20% , below 4000 GeV) and from the identification of high- p_T muons at higher dimuon masses (50%). Figure 5.28 presents the illustration of experimental systematic variation shapes, showing the impact of the uncertainty that grows with mass.

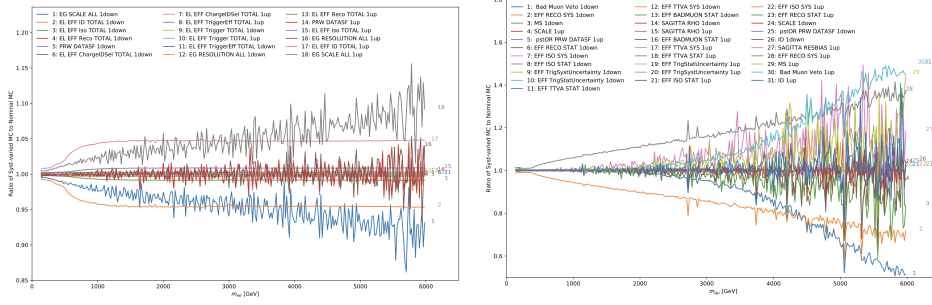


Figure 5.28. Illustration of systematic variation shapes, shown as a ratio to the nominal MC, for ee channel (left) and $\mu\mu$ channel (right).

The σ_b^{ISS} is 4% (6%) for the constructive e^+e^- ($\mu^+\mu^-$) channels, and 7% (24%) for the destructive channels. The large difference, in terms of induced spurious-signal uncertainty, between the two channels under the destructive signal hypothesis is due to the different size of the CR (see Table 5.11). Indeed, the best choice of CR in the dimuon channel has a smaller size so it constrains less the background fit in the CR, allowing more freedom in the extrapolation.

New systematics for high- p_T muons

A systematic uncertainty is applied on the rate of simulated events to account for possible differences of the q/p criteria, described in section 5.1.2, between data and MC in the high- p_T selection. The efficiency of the q/p criteria has been evaluated separately in data and in MC samples in the following way:

$$\epsilon^{data} = \frac{n_{data}^{pass\ cut}}{n_{data}}; \quad \epsilon^{MC} = \frac{n_{MC}^{pass\ cut}}{n_{MC}} \quad (5.18)$$

where n_{data} and n_{MC} represent respectively the number of candidates included in the high- p_T selection in data and MC, while $n_{data}^{pass\ cut}$ and $n_{MC}^{pass\ cut}$ are the high- p_T candidates accepted by the q/p criteria. The systematic uncertainty on the q/p criteria has been calculated as:

$$1 - \frac{\epsilon^{data}}{\epsilon^{MC}}. \quad (5.19)$$

Considering that the data-MC agreement depends on the η region, the q/p criteria uncertainties have been evaluated in three different slices: $|\eta| < 1.3$, $1.3 < |\eta| < 2.0$ and $2.0 < |\eta| < 2.5$. In Figure 5.29 the q/p criteria uncertainties are presented as a function of the muon transverse momentum. The old uncertainties (blue) have

been evaluated for the 2015-2016 Run2 dataset (36 fb^{-1}) using the initial value of $C(p_T)$ equal to 1.8 at 1 TeV, while new uncertainties (red) have been evaluated for the full Run2 dataset (139 fb^{-1}), deploying the new q/p criterion optimization (paragraph 5.1.2). In the p_T range between 1–3 TeV, the new systematic uncertainties (red) are two times smaller than the old ones (blue).

The impact of the new high- p_T systematics on the sensitivity of this search in terms of expected and observed limit on the CI scale is discussed in the next section 5.2.6.

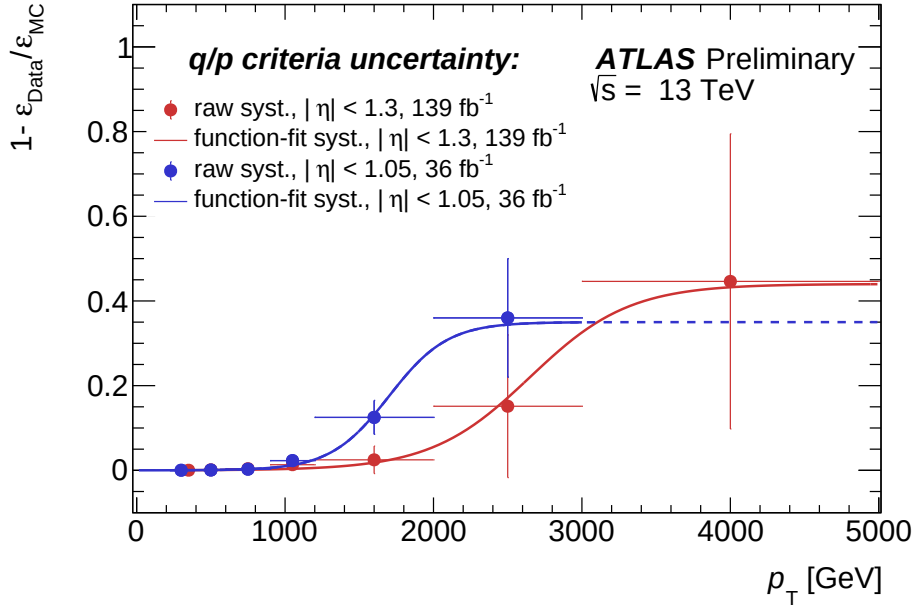


Figure 5.29. The systematic uncertainty on the q/p criteria, derived from the difference in selection efficiency between data and MC, reported as a function of the p_T of the reconstructed muon. The systematic points are presented as computed for an early Run-2 dataset (blue), corresponding to 36 fb^{-1} of pp collision data, and for the full Run-2 dataset (red), amounting to 139 fb^{-1} using a new cut. The data points are fitted with a sigmoid function. The extrapolation of the fitted curve of the early Run-2 dataset for p_T values larger than 3 TeV is shown with a dashed curve.

CR bias uncertainty

The last important source of uncertainty is the "CR Bias Uncertainty", σ_b^{CRB} , that describes the small discrepancy expected between the (nominal) background model using the B-only fit, and the background model using the S+B fit. The procedure, described in section 5.2.3, ensures that both background models will be compatible within the appropriate uncertainty. A very small difference between the models is expected, and this is used to define an additional uncertainty in the B-only fit background estimate. This uncertainty is expected to be small, but it describes the potential degree to which a signal-like shape exist in the CR. This uncertainty is not considered for the model independent limits on the number of signal events

since the impact on the final results is $< 2\%$. They will only be included for the results for the CI energy scale Λ . The σ_b^{CRB} uncertainty is smaller than 4% of the nominal background for all SRs of the analysis.

Uncertainty in the signal yield

The expected number of simulated CI signal events in the SR is affected by theoretical and experimental uncertainties (σ_s^{Theory} and $\sigma_s^{Experiment}$). In order to obtain the signal yield, the simulated signal in the single bin has to be integrated. The signal yield is evaluated for all the theoretical and experimental uncertainties variations of the signal. σ_s^{Theory} and $\sigma_s^{Experiment}$ are taken as the sum in quadrature of the differences between the yields obtained in all variations and the nominal yield and are evaluated with the same procedure as discussed above for the background in the context of σ_b^{ISS} (see paragraph 5.2.4).

The experimental uncertainties in the signal yield ($\sigma_s^{Experiment}$) are smaller than 9% (22%) for the electron (muon) channel.

The theoretical uncertainties in the signal yield are only used when studying the sensitivity of the analysis in term of CI scale (Λ) and are smaller than 15% (14%) for the electron (muon) channel.

The breakdown of the relative uncertainty in both the background estimate and the expected signal yield is shown in Table 5.12, sorted by impact.

channel	interference	Background uncertainties			Signal uncertainties	
		σ_b^{Stat}	σ_b^{ISS}	σ_b^{CRB}	$\sigma_s^{Experiment}$	σ_s^{theory}
e^+e^-	constructive	14%	4%	2%	8%	+11%
						-10%
e^+e^-	destructive	34%	7%	1%	8%	+14%
						-13%
$\mu^+\mu^-$	constructive	21%	6%	2%	+20%	+10%
						-17%
$\mu^+\mu^-$	destructive	58%	24%	4%	+27%	+13%
						-22%

Table 5.12. Summary of the relative uncertainties in the background estimate and signal in each SR, where σ_b^{Stat} , σ_b^{ISS} and σ_b^{CRB} represents the "statical uncertainty", the experimental and theoretical "induced spurious signal uncertainty" and the "control region bias uncertainty", respectively. Experimental and theoretical uncertainties are shown as well, quoted for $\Lambda = 30$ TeV only.

5.2.5 Statistical analysis

In the previous analysis the Bayesian Analysis Toolkit (BAT) [77] for the statistical analysis, which uses a Markov Chain Monte Carlo technique to integrate over the nuisance parameters was used. In this analysis, frameworks based on RooFit and RooStats were chosen as the analysis strategy changed to a data-driven background estimation. RooStats is based on the Frequentist approach. No significant differences in the results between the Bayesian and Frequentist approaches are observed.

The compatibility of finding the observed data and the background-only hypothesis is tested by fitting the data with the background model. The p-value of each observation is defined as the probability, given the background-only hypothesis, of observing an excess at least as large as that seen in the data.

In the presence of a Contact Interaction signal, an excess of candidate events is expected in the dilepton invariant mass distribution in the signal region, compared to the background estimation. A single bin counting experiment is used to analyse the data and set a limit for each assumed Contact Interaction chiral and interference model using the observed number of events in the signal region where the number of signal events depends on a Contact Interaction hypothesis. The total number of expected events μ is given by Equation 5.20.

$$\mu = n_s(\Omega) + n_b(\theta) \quad (5.20)$$

where, $n_s(\Omega)$ is the number of signal events for a particular choice of model parameter Ω , while $n_b(\theta)$ is the total number of background events, and θ represents the set of Gaussian nuisance parameters that describes the systematic and statistical uncertainties on the number of signal and background events. The parameter Ω represents the choice of the energy scale Λ and interference parameter η_{il} as described in Section 2.2.2.

Using Poisson statistics the likelihood to observe n events given θ and Ω is:

$$\mathcal{L}(n | \mu, \theta) = \prod_{i=1}^{N_{channel}} \frac{\mu_i^{n_i} e^{-\mu_i}}{n_i!} \prod_{j=1}^{N_{sys}} G(\theta_{ij}, \sigma_{ij}) \quad (5.21)$$

where, n_i is the number of observed events in data, μ_i is the total number of expected signal and background, both for a given channel i (ee or $\mu\mu$), and $N_{channel}$ is equal 2 and represent the number of channel (ee or $\mu\mu$). $G(\theta_{ij}, \sigma_{ij})$ represents the Gaussian constraint for each uncertainty.

The strategy to search for a deviation from the SM prediction is the likelihood ratio test, the same used by the resonant search and its definition is described in 5.1.7.

5.2.6 Results

The invariant-mass distributions for the dielectron and dimuon channel considering only events that satisfy all the selection requirements are shown in Figures 5.30, 5.31.

The number of events in the SR for data and background and the corresponding significance are reported in Table 5.13. No significant deviation is observed.

The direct result of the limit setting procedure is a limit on the number of signal events in the SR. Explicitly the claim is that the contribution from a non-background process to the number of expected events in the SR is *less* than a given number, N_{excl} , with 95% confidence. This means that signal models predicting *more* than N_{excl} in the SR are excluded with 95% confidence. Limits on N_{excl} can therefore be converted into limits on the contact interaction scale Λ by considering the number of predicted signal events in the SR from a given Λ model. Model-independent upper

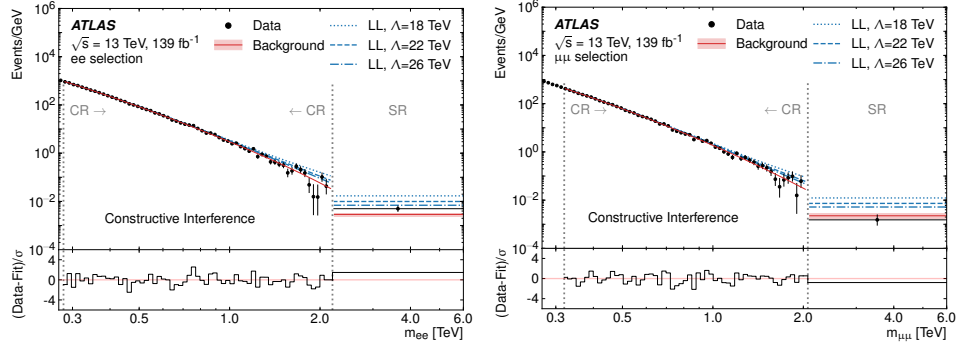


Figure 5.30. Distributions of the invariant mass of dilepton pairs passing the full selection for dielectrons (top) and dimuons (bottom), and showing CR and SR for constructive interference. The data points are plotted at the centre of each bin as the number of events divided by the bin width, which is constant in $\log(m_{ll})$. The error bars indicate statistical uncertainties only. A few CI benchmark signal shapes are shown, scaled to the data luminosity and superimposed by subtracting the LO DY component and adding the resulting shape to the background shape obtained from the fit. These signals have LL chirality with $\Lambda = 18, 22$, and 26 TeV for the constructive case and $\Lambda = 16, 20$, and 26 TeV for the destructive case. The background-only fit is shown in solid red, with the light red area being its uncertainty. The boundaries of the CR and SR corresponding to the signals used are shown in dotted vertical lines for reference and marked by arrows. The differences between the data and the fit results in units of standard deviations of the statistical uncertainty are shown in the bottom panels.

Signal Region	Data	Background	Significance	p-value
e^+e^- Const.	19	12.4 ± 1.9	1.28	0.10
e^+e^- Dest.	2	3.1 ± 1.1	-0.19	0.42
$\mu^+\mu^-$ Const.	6	9.6 ± 2.1	-0.99	0.15
$\mu^+\mu^-$ Dest.	1	1.4 ± 0.9	-0.58	0.28

Table 5.13. The dielectron and dimuon event yields for the data, the expected background and the respective significance in the different SRs used in the analysis. The p-value of each observation is defined as the probability, given the background-only hypothesis, of an observation at least as large as that seen in the data. The significance is the Gaussian cumulative density function of the p-value, and negative significances correspond to deficits.

limits at 95% CL on N_{excl} are illustrated in Figure 5.32 and the conversion of these to limits on Λ are shown in Figures 5.33, 5.34.

As discussed in the previous section 5.2.4, a very important role on the sensitivity of this analysis is played by the uncertainty associated with the q/p criterion cut ($\sigma_s^{q/p}$) about the high- p_T muon identification. The impact of the q/p criterion uncertainty on the limits of this analysis is given in Table 5.14. A comparison of lower limits at 95% for the LL signal chirality in the constructive interference, obtained by considering both the old q/p criterion uncertainty and the new uncertainties evaluated specially for this analysis and already described in section 5.2.4, is reported for both the dimuon and the combined dilepton channel. Notice that the old q/p

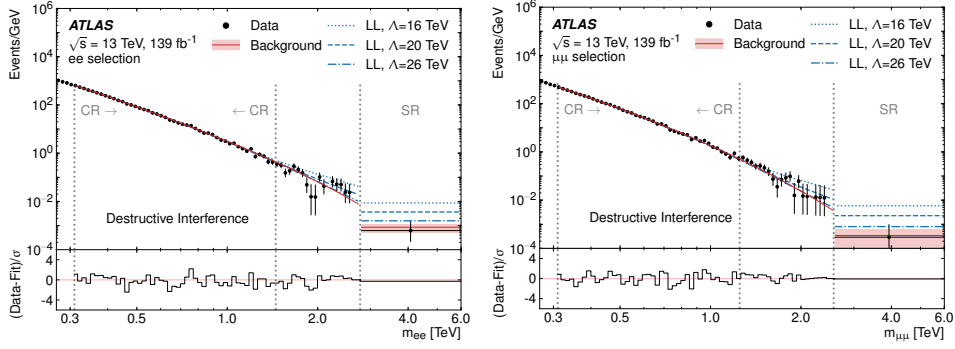


Figure 5.31. Distributions of the invariant mass of dilepton pairs passing the full selection for dielectrons (top) and dimuons (bottom). CR, SR and the region in the middle, that is not used by the fit, for destructive interference are shown. The data points are plotted at the centre of each bin as the number of events divided by the bin width, which is constant in $\log(m_{\ell\ell})$. The error bars indicate statistical uncertainties only. A few CI benchmark signal shapes are shown, scaled to the data luminosity and superimposed by subtracting the LO DY component and adding the resulting shape to the background shape obtained from the fit. These signals have LL chirality with $\Lambda = 18, 22$, and 26 TeV for the constructive case and $\Lambda = 16, 20$, and 26 TeV for the destructive case. The background-only fit is shown in solid red, with the light red area being its uncertainty. The boundaries of the CR and SR corresponding to the signals used are shown in dotted vertical lines for reference and marked by arrows. The differences between the data and the fit results in units of standard deviations of the statistical uncertainty are shown in the bottom panels.

criterion uncertainty are the one used for the resonant search and reported in Table 5.7. Both expected and observed lower limits on the contact interaction scale improve using the new $\sigma_s^{q/p}$, in particular the observed lower limit in the combined dilepton channel results to be increase of 1.3 TeV. Finally Table 5.15 summarises the lower limits on Λ for the different SRs used in the analysis. Observed lower limits on Λ goes from 22.3 TeV, for the CI signal hypotheses with destructive interference and LL chirality in the dimuon channel, up to 35.8 TeV for the CI signal hypotheses with constructive interference and LL chirality in the combined dilepton channel [78].

Limits for a LL signal chirality on Λ in TeV			
Channel Interference	Exp./Obs.	New $\sigma_s^{q/p}$	Old $\sigma_s^{q/p}$
$\mu^+\mu^-$ Constructive	Expected	28.1	27.1
	Observed	31.8	30.9
l^+l^- Constructive	Expected	36.7	36.3
	Observed	35.0	33.7

Table 5.14. Lower limits at 95% for LL signal chirality on Λ TeV. New $\sigma_s^{q/p}$ and old $\sigma_s^{q/p}$ are the expected/observed limits using the new and the old uncertainty on the q/p criterion, respectively.

Channel Interference	Exp./Obs.	LL	LR	RL	RR
e^+e^- Constructive	Expected	31.1	28.9	28.7	30.9
	Observed	26.1	24.7	24.6	26.0
$\mu^+\mu^-$ Constructive	Expected	29.2	27.1	27.0	29.0
	Observed	32.7	30.0	29.8	32.6
l^+l^- Constructive	Expected	37.6	34.0	33.7	37.3
	Observed	35.8	32.5	32.3	35.5
e^+e^- Destructive	Expected	23.0	24.4	24.4	23.2
	Observed	23.5	25.1	25.1	23.7
$\mu^+\mu^-$ Destructive	Expected	22.0	23.6	23.6	22.2
	Observed	22.3	23.9	23.9	22.5
l^+l^- Destructive	Expected	25.6	28.0	28.0	25.9
	Observed	26.0	28.8	28.8	26.5

Table 5.15. Expected and observed lower limits at 95% CL on Λ in TeV for the dielectron and dimuon channels separately and the combined dilepton channel and for CI signal hypotheses with constructive and destructive interference and different chiralities.

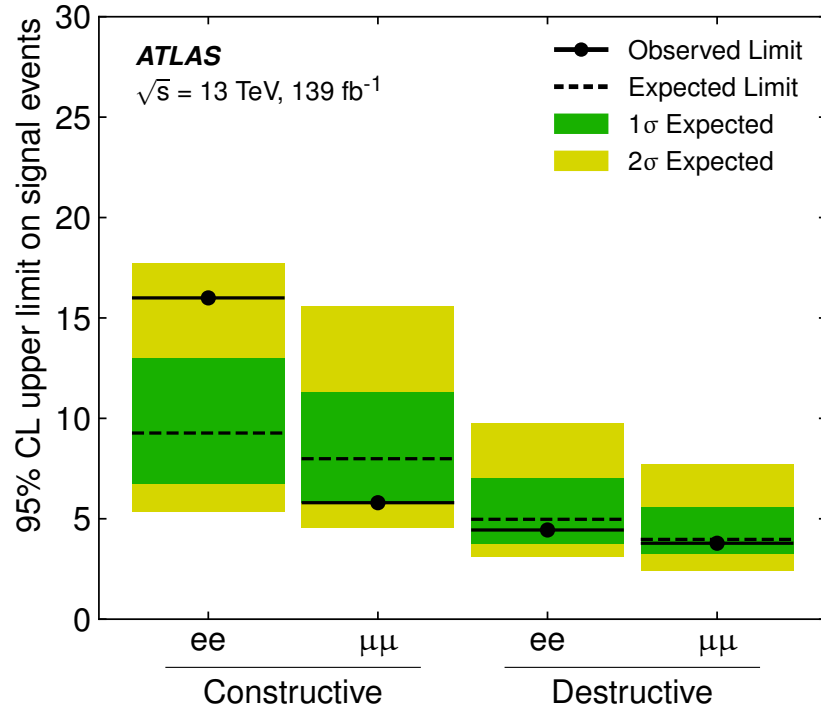


Figure 5.32. Model-independent upper limits at 95% CL on the number of signal events for the constructive/destructive interference in the SRs used in the analysis for dielectron and dimuon channels [78].

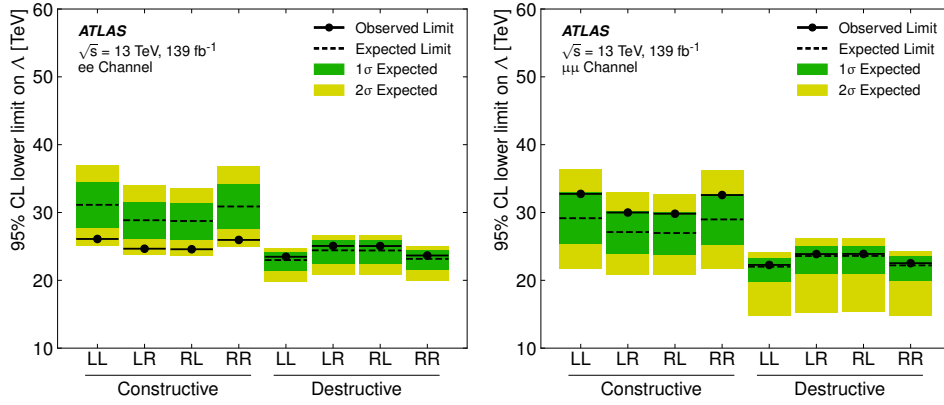


Figure 5.33. Lower limits at 95% CL on the contact interaction scale Λ for the electron (top) and muon (bottom) channel. For each different signal chiralities, in the (constructive/destructive interference) SRs of the analysis, shown in the bottom axis, the expected and observed limits are shown. The dotted line shows the expected limits and the green and yellow error bars show the 1 and 2 σ uncertainty bands on the expectation. The black points show the observed limits [78].

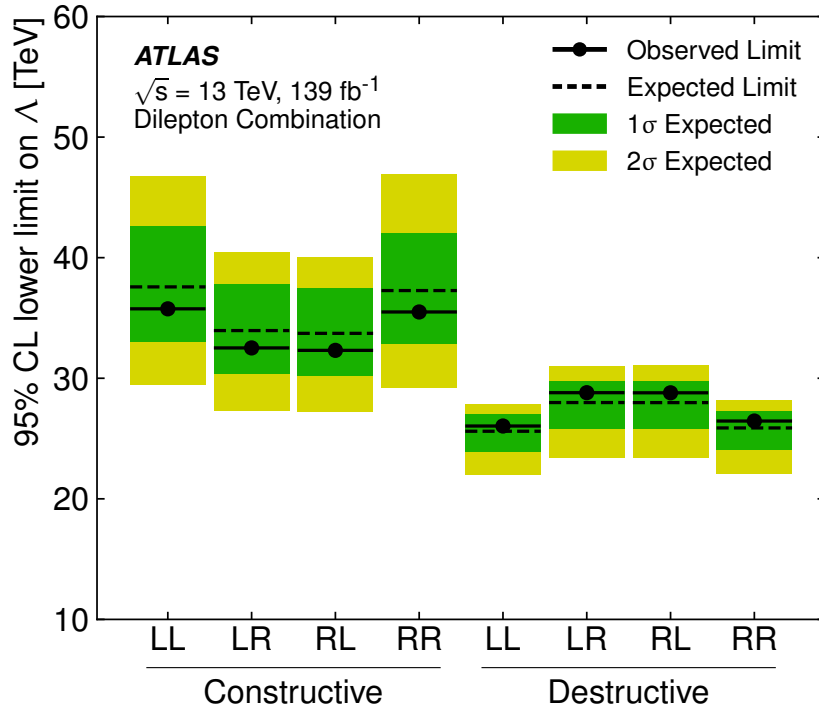


Figure 5.34. Lower limits at 95% CL on the contact interaction scale Λ for the combined dilepton channel. For each different signal chiralities, in the (constructive/destructive interference) SRs of the analysis, shown in the bottom axis, the expected and observed limits are shown. The dotted line shows the expected limits and the green and yellow error bars show the 1 and 2 σ uncertainty bands on the expectation. The black points show the observed limits [78].

5.3 Analyses improvement prospects

5.3.1 High- p_T working point extension

Exotics searches for new physics at the TeV scale, in particular the $W' \rightarrow \mu\nu$ and $Z' \rightarrow \mu\mu$ searches, benefit from as good as possible momentum resolution for muons with a transverse momentum greater than 200 GeV. As described in section 3.3.2, only CB muons are used in the high- p_T working point. Requiring three precision layers ensures that the muon spectrometer is used to its full potential in the measurement, and this requirement is a central ingredient in the high- p_T selection.

2 station muons studies

A dedicated study was undertaken to improve the efficiency of the high- p_T working point by including a subset of the muons reconstructed with only two precision layers [52]. For this purpose the muon performance has been studied using Monte Carlo samples that take into account the relative misalignment between the ID and MS and contains muons with a transverse momentum in the range between 0.3 and 3 TeV. In particular the characteristics of muons with more than two hits in two MS precision layers (*two-station muons*) have been evaluated only. To really understand if some two-station muons can be recovered, a first preliminary q/p resolution comparison between muons belonging to the standard high- p_T working point and two-station muons has been performed. In Figure 5.35 the result of this comparison, for three different η regions, is reported.

After this preliminary study, three different two-station muons sub-selections have been analyzed. The criterion used to divide muons in the three sub-groups is the missing precision layer:

- missing inner layer,
- missing middle layer,
- missing outer layer.

In Figure 5.36, the q/p resolution as a function of the transverse momentum of the three sub-groups defined before is shown. The selection with the best resolution is the one in which the missing precision layer is the innermost one, and this is the selection considered further in this section. These muons are referred to in the following as “missing-inner muons”.

2 station muons q/p criterion

A dedicated q/p criterion (see paragraph 5.1.2) for this two-station muon selection has been developed. The cut ensures that only the best 2 station candidates are selected and it is defined as follows:

$$\frac{\sigma(q/p)}{(q/p)} < C_{2Station}(p_T) \cdot \frac{\sigma(q/p)^{exp}}{(q/p)} \quad (5.22)$$

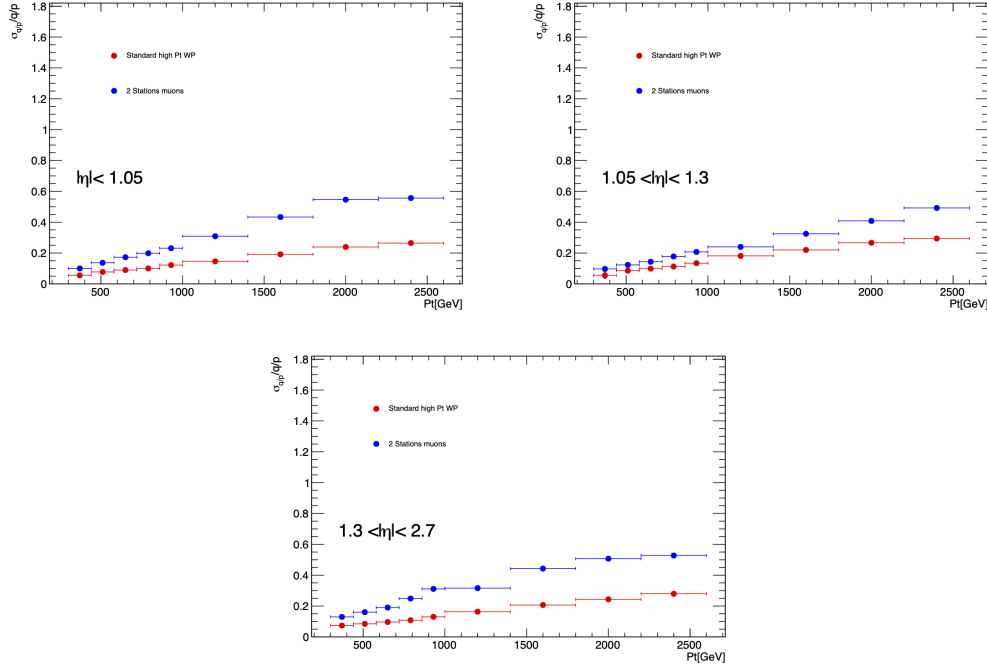


Figure 5.35. The q/p resolution as a function of the transverse momentum. The red and blue dots represent respectively muons belonging to the standard High- p_T working point and two-station muons.

where $C_{2Station}(p_T)$ is a p_T -dependent coefficient, which is constant for $p_T < 1.1$ TeV and decreases linearly if $p_T > 1.1$ TeV as:

$$C_{2Station}(p_T) = 1.2 - 10^{-4} \text{ GeV}^{-1} \cdot p_T \quad (5.23)$$

and settling $C_{2Station}(p_T) = 0.7$ for $p_T \geq 5$ TeV.

Figure 5.37 shows the effect of this dedicated cut on the two-station muon selection. A very good discrimination between well reconstructed muons and the others is offered by the dedicated q/p criterion. A muon is considered well reconstructed if it belongs to the core of the q/p resolution distribution (i.e. within three standard deviations from the mean value of the distribution) or bad if it does not (i.e. it is in the tail of the q/p resolution distribution). In Figure 5.38 an example of the q/p resolution distribution is given. Before including two-station missing-inner muons in the final selection all the other standard High- p_T requirements³, described in section 3.3.2, must be satisfied.

Following checks on the quality of two-station muons in 2015 and 2016 data, pathological structures were observed, pointing to a bug in the treatment of ID/MS misalignment in the reconstruction. The issue is related to the fact that, for missing-inner muons, the distance between the hits in the ID and MS is increased compared to 3-station muons, and this effect is not properly accounted for in the reconstruction. The ATLAS Muon Combined Performance group is working to fix this problem,

³Of course this does not include the 3-station requirement.

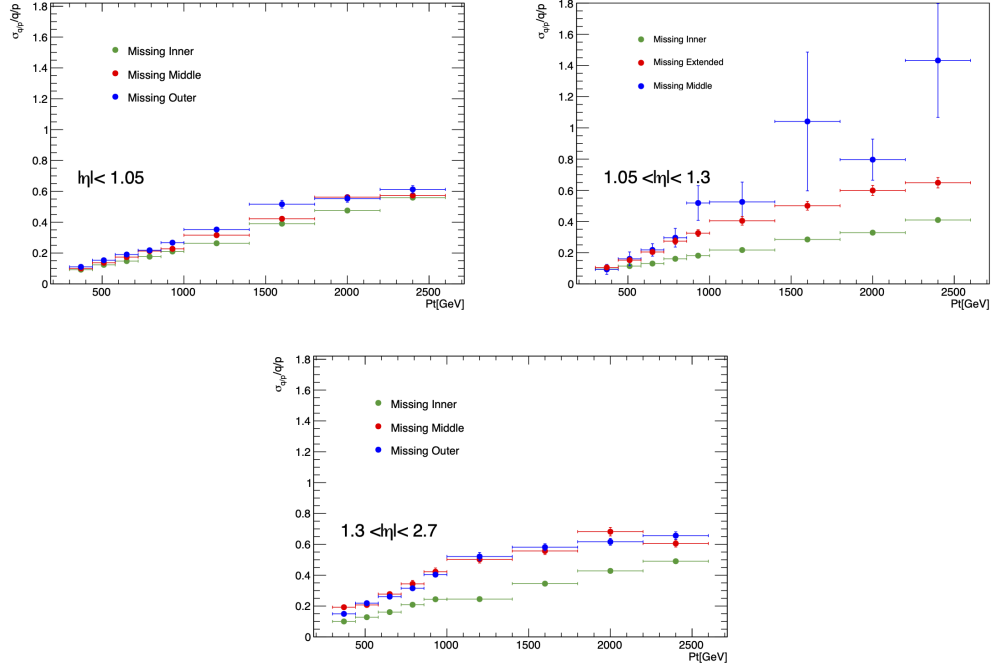


Figure 5.36. The q/p resolution as a function of the transverse momentum. The green, red and blue points represent respectively muons belonging to the missing inner, middle and outer category.

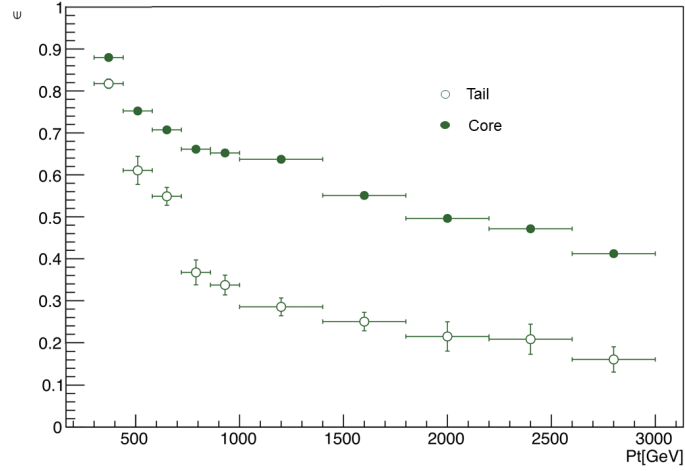


Figure 5.37. Charge over momentum criterion efficiency as a function of the transverse momentum. Empty and full bullets represent respectively the muon fraction within tail and core of the q/p resolution distribution able to pass the dedicated q/p cut.

meanwhile, some additional selection is applied to the two-station muons to avoid the impact of the bug (pending its proper resolution in reprocessed data):

- The “standard” q/p criterion targeting ID/MS misalignment effects (see paragraph 5.1.2) is applied (in addition to the dedicated error cut described above).

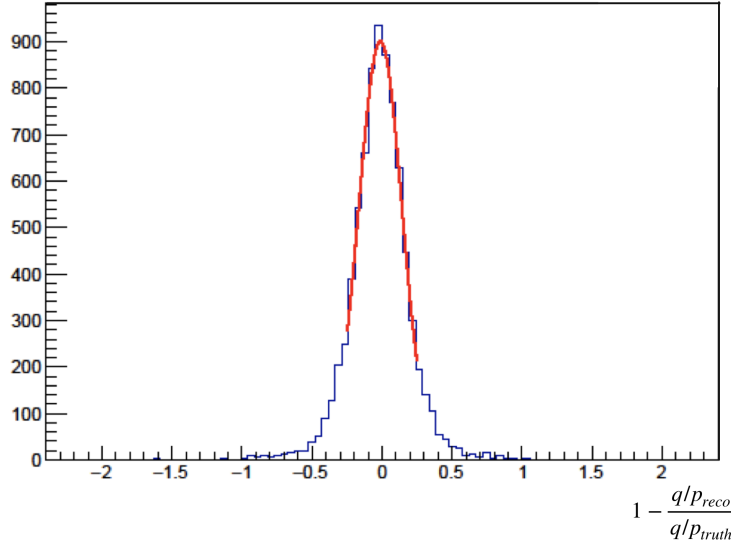


Figure 5.38. Charge over momentum resolution distribution of muons with transverse momentum in the range of [600; 700] GeV. The distribution points are fitted with a gaussian function.

- Muons having their precision hits in the EM+EO layers are vetoed, which essentially limits the acceptance to $|\eta| \lesssim 1.3$, as the distance from the ID to the first MS hits is particularly large in this region. This also corresponds to the region where the MS alone cannot reliably measure the muon p_T due to the magnetic field configuration.

In Figure 5.39 a q/p resolution comparison between muons belonging to the standard *High- p_T* working point (red) and to the final *two-station missing-inner muons* selection (green) as a function of the transverse momentum is reported, showing the quality of the new selection. The new selection resolution is only 1.2 – 1.5 (p_T -dependent) times larger than the standard one.

Impact on the high-mass searches

Finally, the impact on efficiency and resolution for the dimuon selection used in the searches for new high-mass phenomena is evaluated. To evaluate the efficiency gain, the (perfect alignment) NLO Drell Yan MC samples listed in Tables 5.3 were used. The event selection efficiency times acceptance as a function of the dimuon invariant mass is shown in Figure 5.40. A relative efficiency gain of 5 – 6% is obtained when including the new selection in the *High- p_T* working point. The reconstructed invariant mass peak corresponding to a Z' with a mass of 2 TeV is shown in Figure 5.41 both for muon pairs where both muons satisfy the 3-station requirement and for the case where one of the muons is a two-station missing-inner muon. The standard deviation of the fitted distribution is only about 10% higher in the case of 3-station plus 2-station pairs.

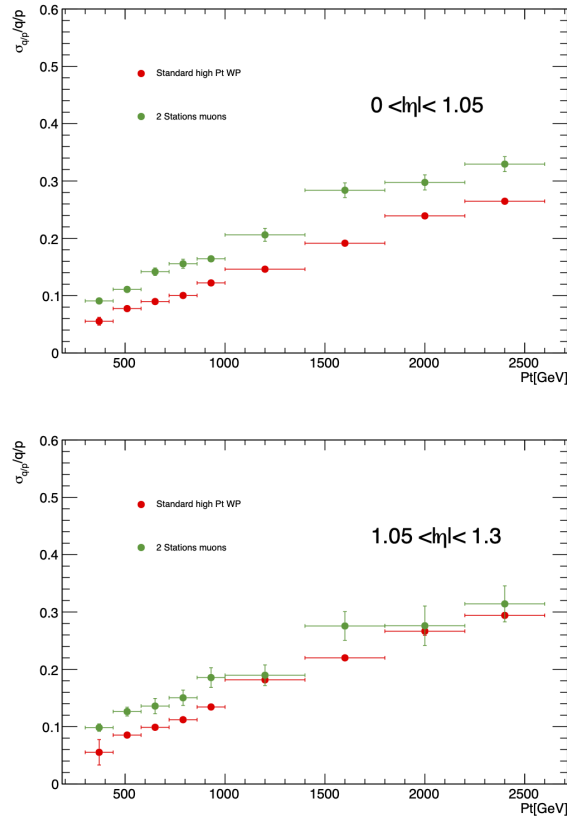


Figure 5.39. The q/p resolution as a function of the transverse momentum for muons in the barrel (top) and end-caps (bottom). Respectively in red and green the resolution of muons belonging to the standard $High-p_T$ WP and to the *two stations missing-inner muons* selection.

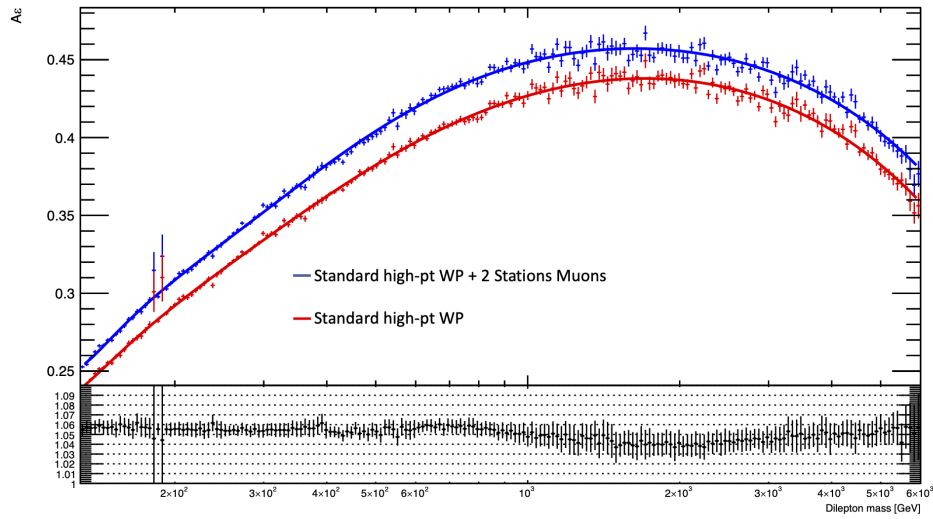


Figure 5.40. Top: Acceptance $\times$ efficiency as a function of the dimuon invariant mass. The red curve includes only muons belonging to the standard *High- p_T* working point, the blue curve contains both standard *High- p_T* muons and two-station muons. Bottom: Ratio of the two curves, the error bars are due to MC statistics.

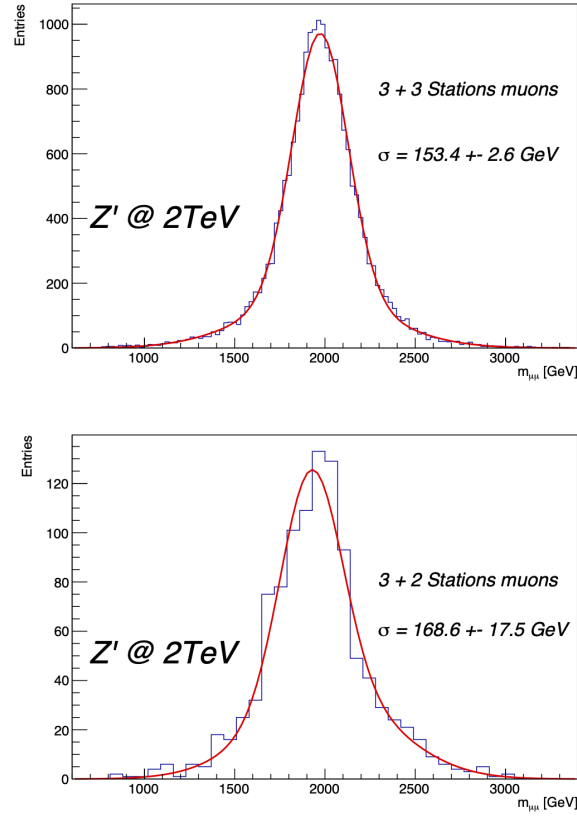


Figure 5.41. The reconstructed invariant mass peak corresponding to a Z' ($\Gamma/M = 0\%$) with a mass of 2 TeV for muon pairs where both muons satisfy the 3-station requirement (top) and for the case where one of the muons is a two-station missing-inner muon (bottom).

Chapter 6

Search for a narrow resonance decaying to a pair of muons

ATLAS has been pushing the search for new dilepton resonances to very high masses, excluding resonances up to 5.1 TeV [79] for Standard-Model-Like couplings. While the mass spectrum below the Z mass peak has been largely studied in the past, the large luminosity collected in LHC Run-2 gives now the possibility to search for resonances with very small couplings to Standard Model particles with improved sensitivity. A typical candidate for low-mass resonances is the Dark Photon, Z_D , a hypothetical vector particle from a Dark Sector which mixes kinematically with SM γ/Z and can be produced in the Drell-Yan (DY) process (section 2.2.3).

In this section the search for dimuon resonances with the full Run-2 ATLAS pp collisions data is described. The analysis is focusing on the dimuon spectrum in the mass range 35 – 80 GeV: below this range the acceptance is reduced by trigger limitations; above this range the background increases due to the Z pole and for this reason it is difficult to control.

This analysis utilizes data collected by the ATLAS detector in years 2015-2018 (Run-2) at a center-of-mass energy of 13 TeV. The dataset comprised of an integrated luminosity of 139 fb^{-1} .

The dataset along with the Monte Carlo simulated samples used for background and signal study in the analysis are detailed in Section 6.1.

The event selection is motivated and described in Section 6.2.

In Section 6.3, the corrections applied to MC to reproduce the data are discussed and comparisons between the simulated samples and data are shown.

Section 6.4 discusses the methodology used for the signal and background modelling, moreover a detailed description about the signal extraction is provided.

The systematic uncertainties and their impact on the sensitivity of the search are presented in Section 6.5.

A description of the statistical analysis is given in section 6.6.

Although Run-2 data are still officially blinded and the internal ATLAS review process is still ongoing preliminary expected results can be obtained. In detail, in Section 6.7 the expected limits on the fiducial cross-section for zero-width resonance is reported. In addition interpretation is given in the context of a Dark-Photon signal model.

Process	Generator	Generator cuts (GeV)	Filter cuts (GeV)
$Z/\gamma^* \rightarrow \mu\mu$	Sherpa 2.2.1	$10 < M < 40$	-
	Sherpa 2.2.1	$M > 40$	-
$Z/\gamma^* \rightarrow \tau\tau$	Sherpa 2.2.1	$10 < M < 40$	-
	Sherpa 2.2.1	$M > 40$	-
$t\bar{t}$	Powheg+Pythia8	-	dileptonic
$W \rightarrow \mu\nu$	Sherpa 2.2.1	-	-
VV leptonic	Sherpa 2.2.2	-	$p_T(l_{1,2}) > 5, M_{l_1, l_2} > 4$
	Sherpa 2.2.2	-	lowPtMllComplement
semi-leptonic	Sherpa 2.2.1	-	-
$b\bar{b}$	Pythia8	$p_T(b) > 3$	$p_T(\mu_{1,2}) > 3.5, M_{\mu_1, \mu_2} > 6$
$c\bar{c}$	Pythia8	$p_T(c) > 4$	$p_T(\mu_{1,2}) > 3.5, M_{\mu_1, \mu_2} > 6$

Table 6.1. MC Generators used for different background processes. The columns report the process, the MC generator, the generator-level and filter cuts.

6.1 Data and MC samples

The analysis is based on Run-2 pp data at $\sqrt{s} = 13$ TeV. The total integrated luminosity of the dataset is determined to be $139.0 \pm 2.4 fb^{-1}$ (Figure 3.2).

The main background of the analysis is dimuon production from the DY process: $Z/\gamma^* \rightarrow \mu^+\mu^-$. This process is an irreducible background that was simulated with SHERPA 2.2.1.

Other backgrounds, simulated using MC samples are, in order of relevance:

- $Z/\gamma^* \rightarrow \tau\tau$ with subsequent τ decays into μ ;
- $t\bar{t}$ production, in which muons are mainly produced from W decays;
- $b\bar{b}$ with muons from heavy flavour decays;
- Multi-boson production VV ($=WW, ZZ, ZW$);
- single top production;
- W + jet with a muon from W decay and one fake or non-isolated muon from jets.

Multijet QCD processes have huge cross sections and can not be practically simulated. A dedicated study aiming at the QCD background events rejection is discussed in Section 6.3.1.

Table 6.1 reports the generators and the filters used for the different background processes.

6.1.1 Dark-Photon Signal MC

Signal samples have been generated with the HAHM v3 implemented in MADGRAPH5 [13]. The input parameters for MADGRAPH5 are calculated starting from the input mass m_{Z_D} and from the corresponding width Γ_{Z_D} and branching ratio $B_{Z_D \rightarrow \mu\mu}$ calculated with 3-loop QCD corrections as reported in Table 2 of [13]. The value of the kinetic mixing coefficient, ϵ , is set at 0.01.

Table 6.2 shows the generated mass points, with the corresponding width and $\sigma_{Z_D} \times B_{Z_D \rightarrow \mu\mu}$ as calculated with LO by MADGRAPH5, the filter efficiency, ε_{Filter} , and the NLO/LO k-factor calculated with DYNNLO [80, 81]. The filter efficiency is defined as the fraction of events that pass the following MadGraph cuts:

- $p_T(\mu_{1,2}^{truth}) > 4 \text{ GeV}$
- $|\eta_{\mu_{1,2}}^{truth}| < 3$

m_{Z_D} (GeV)	ϵ	Γ_{Z_D}/ϵ^2 (GeV)	$B_{Z_D \rightarrow \mu\mu}$	$\sigma_{Z_D} \times B_{Z_D \rightarrow \mu\mu}/\epsilon^2$ (nb)	ε_{Filter}	k
30	0.01	0.564	0.280	8.403	0.446	1.037
35	0.01	0.607	0.274	5.728	0.463	1.052
40	0.01	0.797	0.267	4.128	0.485	1.066
45	0.01	0.878	0.257	3.069	0.500	1.079
50	0.01	1.120	0.244	2.373	0.510	1.091
60	0.01	1.680	0.206	1.567	0.533	1.113
75	0.01	4.932	0.119	1.163	0.578	1.139

Table 6.2. Generated MC dark photon mass points. The table shows the input parameters: mass m_{Z_D} , ϵ , the width Γ_{Z_D} , the muon branching ratio $B_{Z_D \rightarrow \mu\mu}$ taken from [13], the LO cross section calculated with MADGRAPH5, ε_{Filter} is the signal efficiency within the p_T and $|\eta|$ cuts, and the NLO/LO k -factor calculated with DYNNLO in the same fiducial region.

6.1.2 Drell-Yan background super-fast MC

The cross section of the DY process is too large to permit to produce standard MC samples corresponding to a luminosity much larger than that of the data. A super-fast simulation is used to provide a high-statistic template for the study of the functional forms to be used to reproduce the background in the fits. This approach is similar to that of the Higgs to $\mu\mu$ analysis [82]. The super-fast simulation is obtained by generating truth-level events and by applying parametrized resolutions and efficiencies. The super-fast simulation was used for the two DY processes $Z/\gamma^* \rightarrow \mu\mu$ and $Z/\gamma^* \rightarrow \tau\tau$ that comprise more than 95% of background.

The simulation is performed with PYTHIA 8.244. Only decays of Z to muon (or tau) pairs are activated; Multi-Parton-Interactions and hadronization are switched off to speed-up, without affecting the final muon kinematics. A **nominal** super-fast simulation, obtained by using the PYTHIA8 parameter tuned on ATLAS data [83], is used as the central prediction. The **up var-down var** super-fast simulation, which correspond to variations of the α_S value used in initial-state parton showers, are

used to vary the transverse momentum shape. The **eta var** super-fast simulation, produced by setting the NNPDF2.3 QCD+QED NLO PDF, is needed to vary the shape of the η distribution. The FSR photon radiation is simulated with the default Pythia QED parton shower.

Detector effects are included as follows: muon momentum is smeared according to the muon momentum smearing functions developed for the $H \rightarrow \mu\mu$ analysis [82] which include non-Gaussian tails. The efficiency for muon reconstruction, isolation, track to vertex association and trigger is applied as an event weight:

$$\epsilon = \epsilon_1^{\text{rec}} \epsilon_1^{\text{iso}} \epsilon_1^{\text{TTVA}} \epsilon_2^{\text{rec}} \epsilon_2^{\text{iso}} \epsilon_2^{\text{TTVA}} \epsilon^{\text{trig}}$$

where ϵ_i^{rec} , ϵ_i^{iso} and ϵ_i^{TTVA} are reconstruction, isolation and track to vertex association efficiencies in data for muon i . The event trigger efficiency in data, ϵ^{trig} , is obtained from the combination of single-leg efficiencies, taken from the official tools, as explained in Par. 6.2.2.

6.2 Event selection

Events are required to be triggered by at least one of the unprescaled single-muon or dimuon trigger chains shown in table 6.3.

Type	Period	Chain	L1	p_T^{off}
Isolated Single Muon	2015	HLT_mu20_iloose_L1MU15	MU15	27
	2016-2018	HLT_mu26_ivarmedium	MU20	
Non-Isolated Single Muon	2015-2018	HLT_mu50	MU20	27
Symmetric Dimuon	2015	HLT_2mu10	2MU10	15, 15
	2016-2018	HLT_2mu14	2MU14	
Asymmetric Dimuon	2015	HLT_mu18_mu8noL1	MU15	24, 10
	2016-2018	HLT_mu22_mu8noL1	MU20	

Table 6.3. Triggers chains used in the analysis. The trigger type, the period, the name of the trigger chain, the corresponding L1 item are shown. The last column shows the p_T cuts applied in the analysis on the offline reconstructed muons matching the trigger. For the asymmetric dimuon trigger, the first cut is for the L1-seeded candidate (mu18/mu22) and the second is for the full-scan candidate (mu8noL1).

The lowest- p_T unprescaled muon trigger requires isolation at HLT. To recover efficiency, a non-isolated single muon trigger with higher p_T threshold (HLT_mu50) is also used in OR, according to the standard recommendation. Two types of dimuon triggers are used: Symmetric, which requires two muons found at L1 and confirmed at HLT, and Asymmetric, which requires one muon found at L1 and confirmed at HLT plus a second muon reconstructed at HLT by the full-scan algorithm (mu8noL1). For ATLAS Run 2, full-scan algorithm was performed in the MS, followed by track reconstruction in small ID projections of each MS muon candidate. In the 2015 running period the triggers had slightly different thresholds and definitions, as reported in the table.

6.2.1 Dimuon Selection

Only events with two muons that satisfy the following cuts, according to the standard recommendations, are selected:

- **Medium working point** This is the standard muon identification working point, it selects combined muons reconstructed in the Muon Spectrometer and in the ID, plus Calorimeter tagged ID tracks in the region corresponding to the MS acceptance hole of $|\eta| < 0.1$;
- This isolation working point has a fixed cut on the sum of track isolation and neutral energy flow
- **Track To Vertex Association** the ID track associated to the muon should have $|d_0^{BL}/\sigma_{d0}| < 3$ and $|\Delta z_0^{BL} \sin(\theta)| < 0.5mm$ according to MCP recommendations;
- $|\eta| < 2.5$, $p_{T\text{leading}} > 15 \text{ GeV}$, $p_{T\text{subleading}} > 5 \text{ GeV}$.

The invariant mass of the pair have to be within $35 - 80 \text{ GeV}$. The Opposite-Charge (OC) requirement is not applied because the Same-Charge (SC) events are needed to reject the QCD background events (Sec. 6.3.1).

6.2.2 Trigger matching

The event is accepted if at least one of the trigger chains that selected the event is matched to the selected muon pair, according to the standard recommendation. A single-muon chain is matched if at least one of the two selected muons is matched to the HLT object corresponding to the trigger chain. A di-muon chain is matched if the two selected muons are matched to two HLT objects corresponding to the two legs of the dimuon chain. The matching between a reconstructed muon and an HLT object is defined as:

- the HLT object is within a cone of radius 0.1 in $\eta - \phi$ around the reconstructed muon;
- the reconstructed muon transverse momentum pass the cuts reported in Tab. 6.3 for each trigger object: $p_T > p_T^{\text{off}}$.

Trigger scale factor

The trigger scale factor is defined as the trigger efficiency on data, $\epsilon_{\text{Data}}^{\text{trig}}$, over the trigger efficiency on MC, $\epsilon_{\text{MC}}^{\text{trig}}$ and is given in the following equation.

$$SF^{\text{trig}} = \epsilon_{\text{data}}^{\text{trig}} / \epsilon_{\text{MC}}^{\text{trig}} \quad (6.1)$$

Trigger scale factor requires to calculate separately the data and MC efficiencies and has been computed specifically for different regions, depending by the transverse momentum of the two muons, as illustrated on Table 6.4.

A, B, C, AB, BC, ABC refer to the symmetric dimuon chain (2mu10 – 2mu14), the asymmetric dimuon chain (mu18_mu8noL1 – mu22_mu8noL1), the single muon

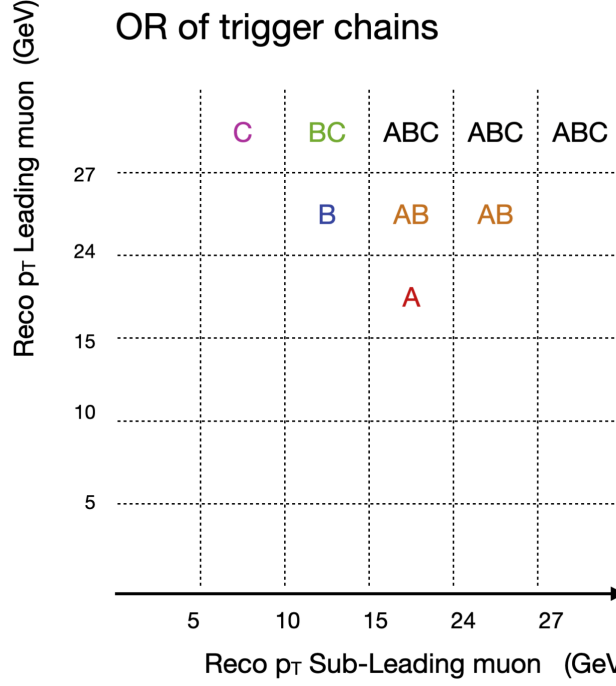


Table 6.4. Six different region: A, B, C, AB, BC, and ABC defined by the transverse momentum of the leading (y axis) and sub-leading (x axis) muon and corresponding to different trigger chain configurations are shown. A, B, C, AB, BC, ABC refer to the symmetric dimuon, the asymmetric dimuon, the single muon, the or of symmetric and asymmetric dimuon, the or of asymmetric dimuon and single muon and the or of all the three trigger chain, respectively.

chain (`mu26_iloose_L1MU15` – `mu26_ivarmedium`), the or of symmetric and asymmetric dimuon, the or of asymmetric dimuon and single muon and the or of all the three trigger chain, respectively. Data and MC trigger efficiencies are computed as the probability that the trigger chain fires and are obtained by combining the information from of all the single lepton legs trigger involved. The calculation can be done easily because the correlation between different single-leg trigger efficiencies is simplified thanks to the inclusive definition of single-leg triggers, i.e. the muons selected by tighter triggers are always a subset of the muons selected by looser triggers:

$$(\text{mu20_iloose_L1MU15} \parallel \text{mu50}) \subset \text{mu18} \subset \text{mu10} \subset \text{mu8noL1}$$

.

$$(\text{mu26_ivarmedium} \parallel \text{mu50}) \subset \text{mu22} \subset \text{mu14} \subset \text{mu8noL1}$$

. Single-leg trigger efficiencies are set equal zero if the muon p_T is smaller than the respective threshold given in Table 6.3. Efficiencies are then calculated as follows:

- $P(A)_{2015} = p_{\mu 1}(\text{mu10}) p_{\mu 2}(\text{mu10})$
- $P(A)_{2016-2018} = p_{\mu 1}(\text{mu14}) p_{\mu 2}(\text{mu14})$

- $P(B)_{2015} = p_{\mu 1}(\text{mu18}) p_{\mu 2}(\text{mu8noL1}) + p_{\mu 1}(\text{mu8noL1}) p_{\mu 2}(\text{mu18}) - p_{\mu 1}(\text{mu22}) p_{\mu 2}(\text{mu22})$
- $P(B)_{2016-2018} = p_{\mu 1}(\text{mu22}) p_{\mu 2}(\text{mu8noL1}) + p_{\mu 1}(\text{mu8noL1}) p_{\mu 2}(\text{mu22}) - p_{\mu 1}(\text{mu22}) p_{\mu 2}(\text{mu22})$
- $P(C)_{2015} = p_{\mu 1}(\text{mu20i}) + p_{\mu 2}(\text{mu20i}) - p_{\mu 1}(\text{mu20i}) p_{\mu 2}(\text{mu20i})$
- $P(C)_{2016-2018} = p_{\mu 1}(\text{mu26i}) + p_{\mu 2}(\text{mu26i}) - p_{\mu 1}(\text{mu26i}) p_{\mu 2}(\text{mu26i})$
- $P(A|B|C)_{2015} = P(A) + P(B) + P(C) - p_{\mu 1}(\text{mu10}) p_{\mu 2}(\text{mu18}) - p_{\mu 1}(\text{mu18}) p_{\mu 2}(\text{mu10}) + p_{\mu 1}(\text{mu18}) p_{\mu 2}(\text{mu18}) - p_{\mu 1}(\text{mu20i}) p_{\mu 2}(\text{mu8noL1}) - p_{\mu 1}(\text{mu8noL1}) p_{\mu 2}(\text{mu20i}) + p_{\mu 1}(\text{mu20i}) p_{\mu 2}(\text{mu20i})$
- $P(A|B|C)_{2016-2018} = P(A) + P(B) + P(C) - p_{\mu 1}(\text{mu14}) p_{\mu 2}(\text{mu22}) - p_{\mu 1}(\text{mu22}) p_{\mu 2}(\text{mu14}) + p_{\mu 1}(\text{mu22}) p_{\mu 2}(\text{mu22}) - p_{\mu 1}(\text{mu26i}) p_{\mu 2}(\text{mu8noL1}) - p_{\mu 1}(\text{mu8noL1}) p_{\mu 2}(\text{mu26i}) + p_{\mu 1}(\text{mu26i}) p_{\mu 2}(\text{mu26i})$

where the subscripts 2015 and 2016-2018 refer to the data taking year, while $\mu 1$ and $\mu 2$ are the leading and subleading muon.

Impact of trigger on the analysis sensitivity

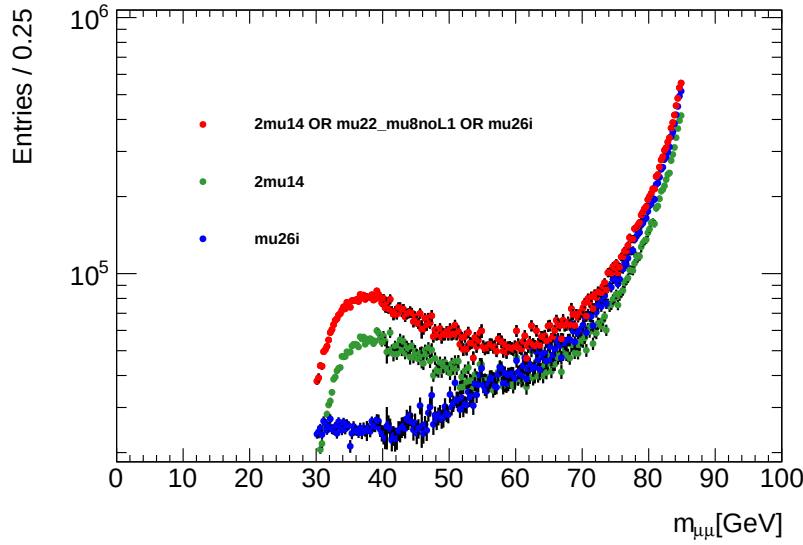


Figure 6.1. Number of events as a function of the dimuon invariant mass for the single muon (blue), for the symmetric dimuon (green) and for the optimized (red) trigger selection.

The average scale factor evaluated for the different regions defined above is reported in Table 6.5.

After building the trigger scale factor, the impact of applying the event selection cuts was tested on the $Z/\gamma^* \rightarrow \mu\mu$ Sherpa 2.2.1., since the signal is kinematically similar to the SM DY $\mu\mu$ process. In Figure 6.1 a comparison between the single muon (blue), the symmetric dimuon (green) and the optimized (red) trigger selection is given, where optimized refer to the trigger chain defined in Table 6.3.

Region	Scale Factor
A	0.931
B	0.947
C	0.950
AB	0.965
ABC	0.970

Table 6.5. Average trigger scale factor for the A, B, C, AB and ABC regions.

In the 40-70 GeV dimuon mass range, a relative efficiency gain of 61% (35%) with respect to in the number of reconstructed events is obtained when using the optimized trigger chain instead of the single muon (symmetric dimuon) trigger chain. The search is not performed in the dimuon mass range < 35 GeV, since due to the trigger limitation, the statistic is still not enough to be competitive with previous results (Sec. 2.2.3) at searching for very small couplings.

6.3 Data-MC comparisons

To improve the agreement between data and simulation, the standard MCP corrections have been applied to the simulation:

- Muon momentum smearing and corrections;
- Pileup Reweighting, to reweight the pileup distribution in MC to reproduce that of data, `pileupWeight`.
- Muon efficiency data/MC scale factors, which include corrections for muon reconstruction, isolation and track-to-vertex association, `leptonWeight`.
- Trigger data/MC scale factor SF^{trig} , calculated as described in the previous section.

Therefore MC event receives the following event weight:

$$w = \text{eventWeight} \times \text{pileupWeight} \times \text{leptonWeight}(\mu_1) \times \text{leptonWeight}(\mu_2) \times SF^{\text{trig}}$$

where $\text{eventWeight} = \sigma \epsilon^{\text{filter}} k^{\text{NLO}}$ is the weight associated to the event MC generator cross section σ , the generator-level filter efficiency ϵ^{filter} and the NLO/LO k-factor k^{NLO} . SF^{trig} and `leptonWeight` depend by the kinematic of the reconstructed muons and are different for each event.

6.3.1 QCD background

Standard multi-Jet QCD events can produce so-called “fake muon”, comprising muons originating from punch-through, K and π decays, etc..

To improve the agreement between data and simulation, the standard multi-Jet QCD events have to be rejected. Since “fake” dimuons are mostly charge symmetric can be considered by subtracting SC dimuons from OC dimuons. Figures 6.2 shows the Data-MC comparison for the OC and OC - SC as a function of the transverse

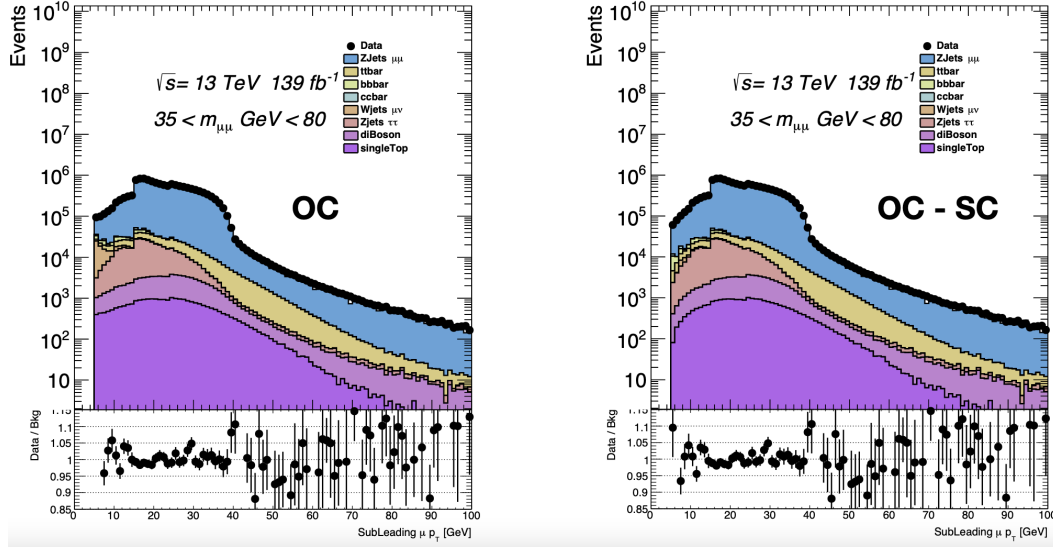


Figure 6.2. Data-MC comparison for the transverse momentum of the sub-leading muon: OC (left) and OC - SC (right).

momentum of the sub-leading muon. The effect of subtracting SC from OC is visible mostly at low p_T values (5-20 GeV) where the probability of reconstructing fake muons is higher. In Table 6.6 the fraction of rejected events by applying the OC-SC selection is presented for all the background processes reported in Table 6.1. An estimate of the QCD background in this analysis is obtained as the difference between the Data-MC SC distribution and is given in Table 6.7, together with the other background processes considered. As a consequence of the SC subtraction the $W \rightarrow \mu\nu$ process is mostly rejected (0.2 % of the total background) and will be neglected for following studies.

MC Sample	1 - (OS-SC)/OC (%)
$Z/\gamma^* \rightarrow \mu\mu$	0.02
$Z/\gamma^* \rightarrow \tau\tau$	0.19
$t\bar{t}$	0.85
VV	5.42
$W \rightarrow \mu\nu$	67.35
$b\bar{b}$	7.49
single Top	4.82
Dark-Photon	< 0.001

Table 6.6. Fraction of rejected events by applying OC-SC selection for the different background and signal processes with $35 < m_{\mu\mu} < 80$ GeV.

6.3.2 Data - MC comparisons

After applying all the cuts described in Sec. 5.1.2 and subtracting the SC dimuon from the OC dimuon, a comparison of the distributions obtained with the ATLAS standard simulation with data for the main variables is shown in Figure 6.3. ATLAS

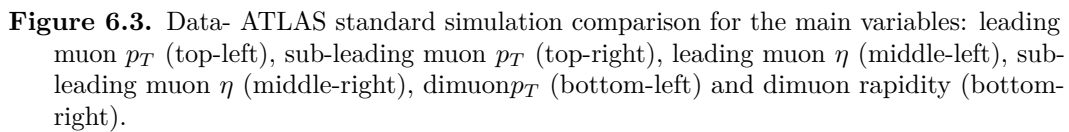
MC Sample	events	fraction of total background (%)
$Z/\gamma^* \rightarrow \mu\mu$	13383414	93.3
$Z/\gamma^* \rightarrow \tau\tau$	343885	2.4
$t\bar{t}$	304016	2.1
VV	61284	0.4
$W \rightarrow \mu\nu$	26693	0.2
$b\bar{b}$	73322	0.5
single Top	26195	0.2
QCD	129038	0.9

Table 6.7. Number of total events expected for different background processes.

standard simulation is referring to a simulation obtained by simulating the detector response of the ATLAS experiment running ATLAS Geant4 simulation software [84]. A good agreement between data and ATLAS standard simulation is obtained ensuring the high quality of the event weight correction described above. Since the luminosity of the DY ATLAS standard simulation is much smaller than that of the data, the background cannot be modelled by using the ATLAS standard DY MC samples. A validation of the high-stat DY super-fast simulations with the data distributions is therefore needed.

High-stat background template includes the two DY processes $Z/\gamma^* \rightarrow \mu\mu$ and $Z/\gamma^* \rightarrow \tau\tau$ generated using the super-fast simulation (Sec. 6.1.2) and $t\bar{t}$, VV and single top processes generated by the ATLAS standard simulation, comprising more than 99% of background. Figures 6.4 show a comparison of the distributions obtained with the different high-stat background templates (nominal, down var, up var, eta var) and ATLAS standard sim (violet) with data for the main variables. The ATLAS standard sim (violet) error bars are much larger than the high-stat ones because of the lower luminosity of the ATLAS DY MC samples, as expected. Possible disagreements between data and nominal high-stat template (blue) are covered by the three high-stat variations: **down var** (green), **up var** (red) and **eta var** (azure). This comparisons ensure that the data distributions are well described by all the high-stat background templates. The high-stat background templates can be used for the background modelling studies described in the following section.

The discrepancies observed at transverse momentum larger than 45 GeV and at small values of the dimuon pt distribution are expected as Sherpa and Pythia are effectively LO in α_S at large p_T (Figure 6.5) [85]. Moreover, the disagreement present at low dimuon pt values is not a concern since it is fully covered by all the variations produced (down var, up var, nominal, eta var and ATLAS standard simulation).



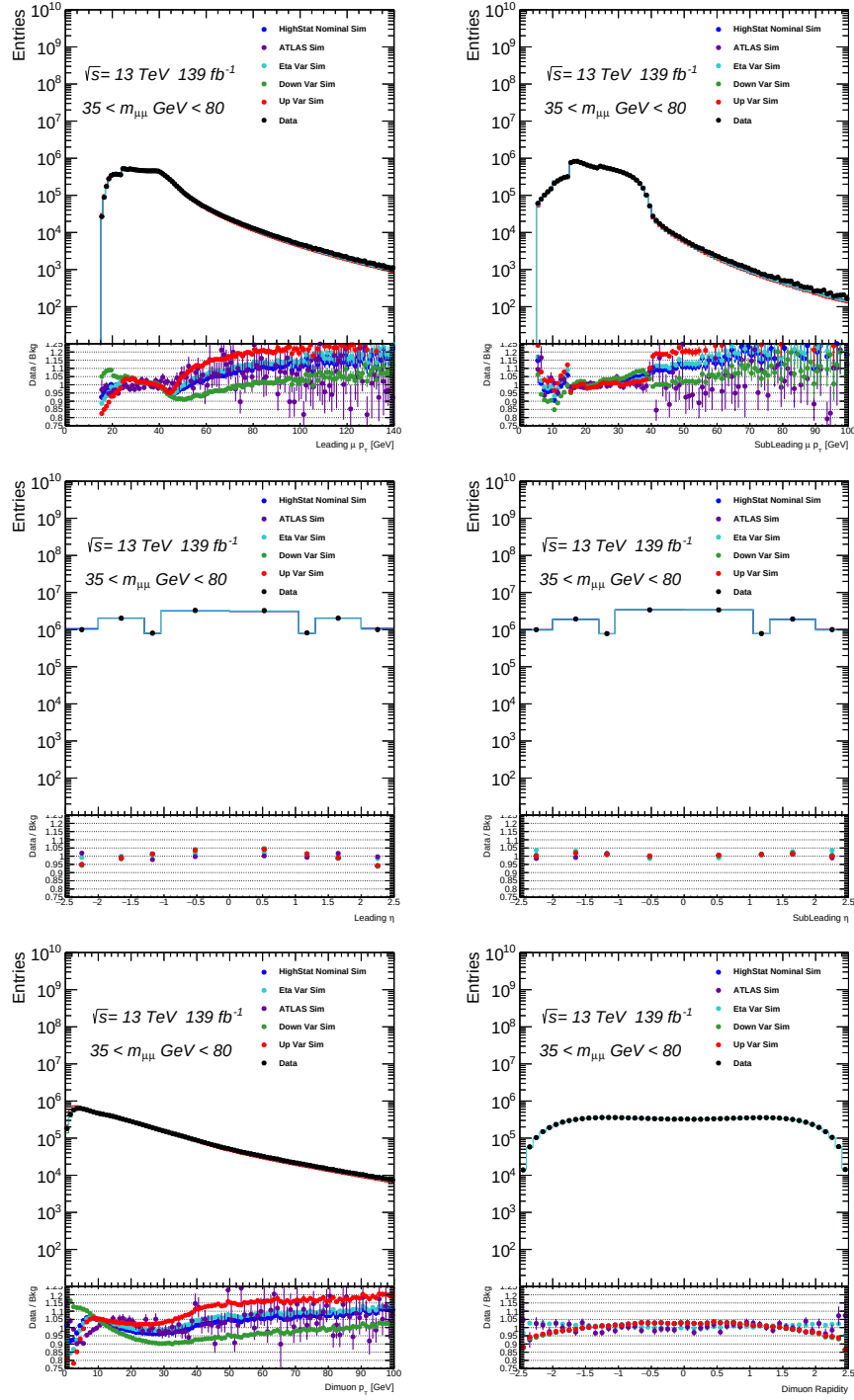


Figure 6.4. High-stat sim: nominal (blue), down var (green), up var (red), eta var (azure) - Data comparison for the main variables; leading muon p_T (top-left), sub-leading muon p_T (top-right), leading muon η (middle-left), sub-leading muon η (middle-right), dimuon p_T (bottom-left) and dimuon rapidity (bottom-right). ATLAS sim (violet) corresponds to the results given in Fig 6.3.

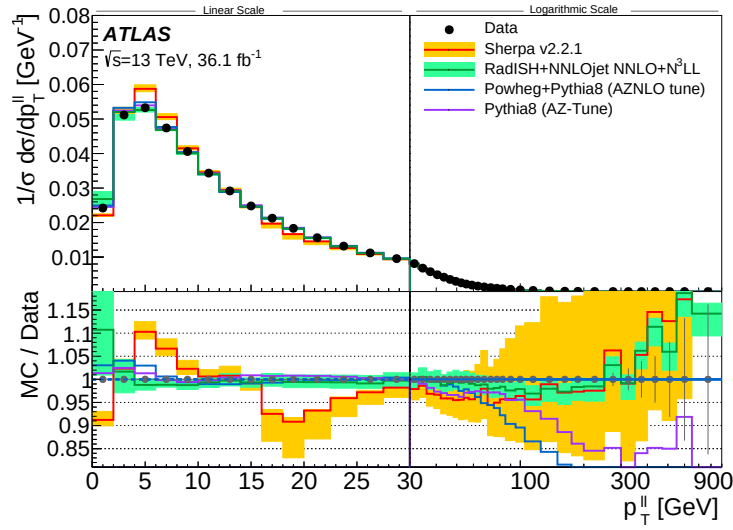


Figure 6.5. Comparison of the normalized p_T^{ll} distribution predicted by different computation. The uncertainties of the measurement are shown as vertical bars and uncertainties of the Sherpa and RadISH predictions are indicated by the coloured bands [85].

6.4 Signal and background modelling

6.4.1 Acceptance and efficiency for dark photon signal

In order to interpret the results and compare them to any model, the fiducial volume for the signal model and cross section calculations is:

- $p_T(\mu_1) > 15$ GeV- $p_T(\mu_2) > 5$ GeV, applied to the leading and subleading muon on truth-level.
- $|\eta_{\mu_{1,2}}| < 2.5$, applied to the leading and subleading muon on truth-level.

The acceptance, A , can then be defined as number of generated events within the fiducial volume ($n_{visible}$) over the total number of events generated (n_{tot}). The signal efficiency ϵ has been calculated from the Signal MC as the fraction of events within the fiducial cross section that pass the full event selection:

$$\epsilon = \frac{n_{reco}}{n_{visible}}$$

Figure 6.6 shows the acceptance (top) and efficiency (bottom) for the different signal MC samples. The curves show a fit of the form $p_1 + p_2/m_{Z_D} + p_3/m_{Z_D}^2 + p_4 \cdot m_{Z_D}$ that provides continuous values as a function of m_{Z_D} .

6.4.2 Signal mass distribution

The generic signal shapes are constructed from non-relativistic Breit-Wigner functions of various widths convolved with the detector resolution ($m_{\mu\mu}$).

Several function choices have been tested to obtain a good description of the detector resolution throughout the full $m_{\mu\mu}$ spectrum. finally the sum of two Crystal-Ball (CB) is used. Since the Crystal-Ball has longer tails on one side of the distribution with respect to the Gaussian, the sum of two Crystal-Ball (CB) is used to describes both the tails of the response. The function is thus given as shown in equation 6.2 and has in total 7 parameters.

$$P(m_{\mu\mu}) = \kappa \cdot \text{CB}_1(m_{\mu\mu}|\mu, \sigma, \alpha_1, n_1) + (1 - \kappa) \cdot \text{CB}_2(m_{\mu\mu}|\mu, \sigma, \alpha_2, n_2) \quad (6.2)$$

The parameters inside equation 6.2 have the following properties:

- μ is a common parameter of the two CB and describes the central value expected to be close to $m_{Z_D}^{true}$.
- σ , as for μ , is a common parameter which refers to the width of the two CB. Its value corresponds to the uncertainty of the response. An increasing behaviour, as a function of m_{Z_D} , is expected, as described in eq. 5.1.
- α_1 and α_2 define the cut-off in the Crystal-Ball function after which the Gaussian behaviour is replaced by a power-law. No strong m_{Z_D} -dependence is expected.

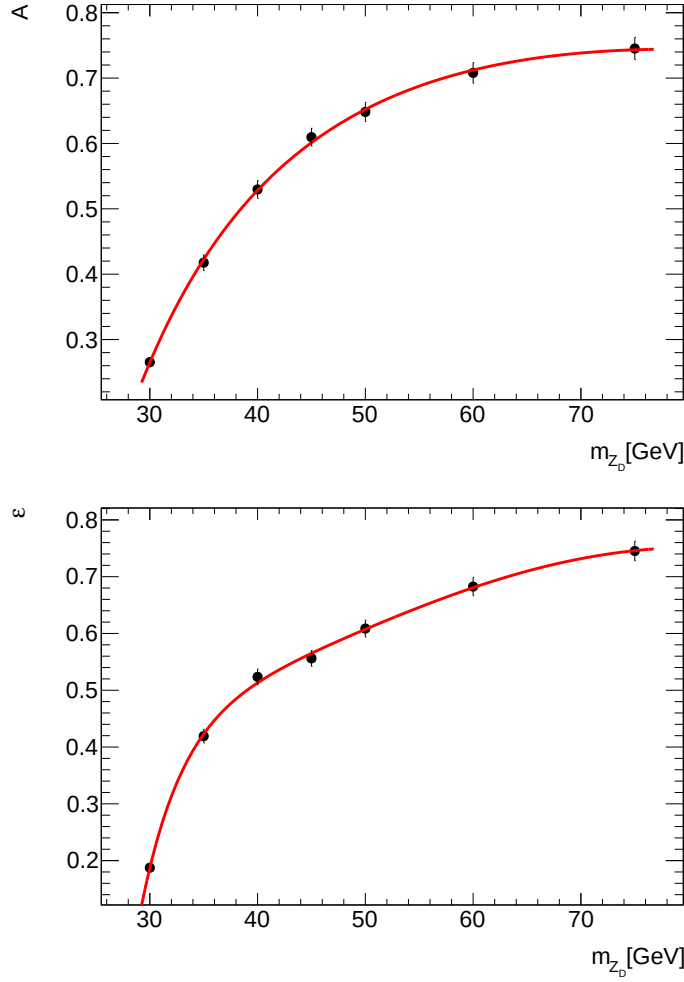


Figure 6.6. Signal acceptance and efficiency as a function of the Dark-Photon mass. A polynomial fit (red line) is performed to the values obtained from signal MC samples (black points). χ^2/NDF for the signal acceptance (efficiency) fit of 0.23 (0.47) is obtained. The error bars are due to MC statistics.

- n_1 and n_2 are the exponents in the power-law region of the Crystal-Ball function. No strong m_{Z_D} -dependence is expected.
- κ defines the fraction of the CB_1 function in the total pdf. No m_{Z_D} -dependence is expected, since the relative importance of the tails should be constant in the range investigated.

Figures 6.7 show the mass distributions obtained for signal MC samples corresponding to different M_{Z_D} bins. Mass distributions are fitted with eq. 6.2. The χ^2 values normalized to the number of degrees of freedom (NDF) for each fit (Figure 6.7) is given in Table 6.8.

The σ and μ dependencies with m_{Z_D} are shown in figures 6.8, while α_1 , α_2 , n_1 , n_2 and κ are not found to depend with m_{Z_D} and are then set constant at 1.15, -1.25, 1.8, 23 and 0.5, respectively. The functional form of σ and μ parametrisations is

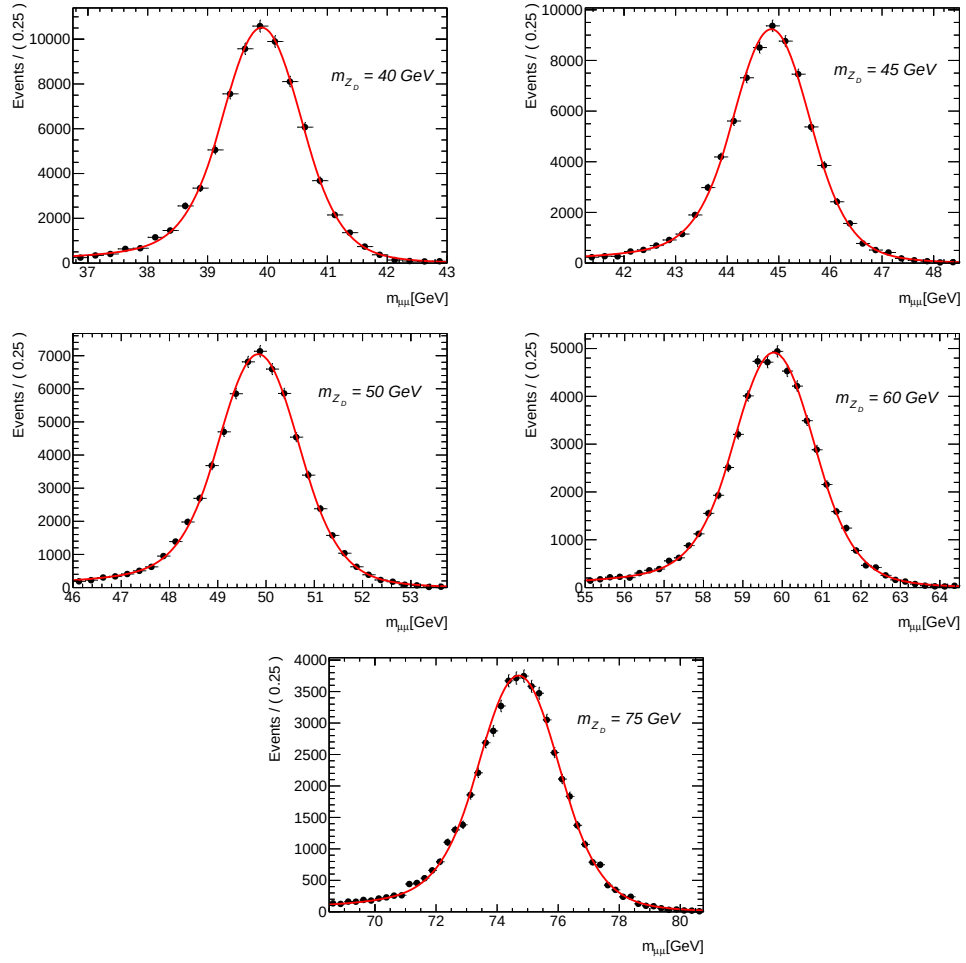


Figure 6.7. Five different mass distributions corresponding to different truth Dark-Photon mass bins are shown. The red line corresponds to the functional description by the sum of two Crystal-Ball.

m_{Z_D} [GeV]	χ^2/NDF
40	1.93
45	1.70
50	1.67
60	1.51
75	1.97

Table 6.8. χ^2/NDF values of the response description after the fit for the Signal MC samples.

given in tables 6.9. These values provide a continuous parametrisations for the signal shape as a function of m_{Z_D} .

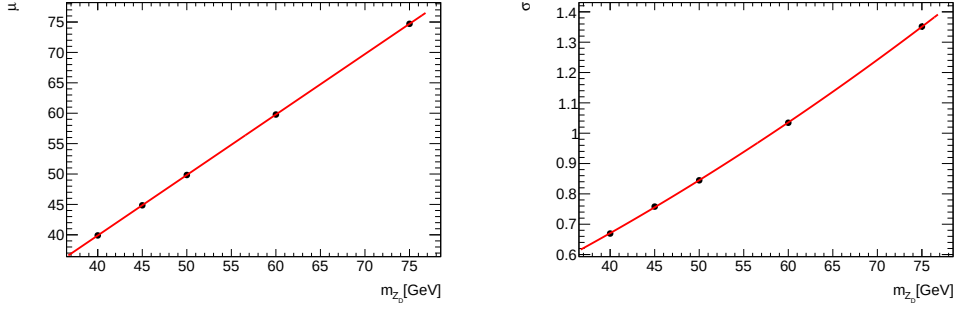


Figure 6.8. m_{Z_D} -dependence of the signal modelling parameters. The shown variables are, μ (left - $\chi^2/NDF = 1.91$) and σ (right - $\chi^2/NDF = 0.96$). The parameter points are fitted with a pol1 (top) and pol2 (bottom) function (red line).

Parameter m_{Z_D} -dependence	Fit result
$\mu(m_{Z_D}) = p_{\mu,1} + p_{\mu,2} \cdot m_{Z_D}$	$p_{\mu,1} = 0.112516$
	$p_{\mu,2} = 0.994535$
$\sigma(m_{Z_D}) = p_{\sigma,1} + p_{\sigma,2} \cdot m_{Z_D} + p_{\sigma,3} \cdot m_{Z_D}^2$	$p_{\sigma,1} = 0.131054$
	$p_{\sigma,2} = 0.010311$
	$p_{\sigma,3} = 0.000079$

Table 6.9. Description of the m_{Z_D} -dependence for σ and μ signal function parameters.

6.4.3 Background mass distribution

The observed mass distribution of the data should be fitted with a signal plus background function, to extract the signal yield or set limits. As the analysis is dominated by background, with $S/B \ll 1$, it is important to find a functional form that is able to fit the background with a limited number of degrees of freedom. Since it may be difficult to find a suitable function that can fit simultaneously the whole mass range, sliding window fits are performed. The sliding window fit tries to obtain the background estimate in each bin by fitting a constrained region which is referred to as a window, instead of fitting the full spectrum.

To search for the optimal functional form, fits have been done on high-stat mass distribution histograms generated with the super-fast MC and corresponding to approximately 60 times the number of events expected in the data. The distribution has been normalized to the data luminosity. Since the number of SC events is negligible with respect to the number of OC events (Tab 6.6), the error bars have been calculated as the square root of the normalized OC events in each bin. In this way a distribution is produced that has similar error bars as expected in data but much lower fluctuations, which is equivalent to an Asimov dataset [73].

For each mass hypothesis a signal+background fit is performed and the following quantities are plotted : the fit χ^2 and the signal, expressed in number of standard deviations from 0 : S/σ_S . The latter quantity is known as the “spurious signal” (SS) in the sense that it is the amount of signal found by a signal+background fit on a background-only distribution when statistical fluctuations are negligible, and is used to estimate the systematic uncertainties related to the functional shape of

the background. In general, functions with more free parameters will produce a smaller SS because can fit more complex shapes, but at the same time will have reduced sensitivity because the background function will be able to reproduce part of the signal. The capability to observe a significant signal, or the strength of the limit if no signal is found, will increase for smaller σ_S , and a compromise should be found between minimizing σ_S and the SS. As an empirical rule (see for example [79]) a function with minimal σ_S while keeping $S/\sigma_S < 0.5$ is searched for. The choice of the fit window range aims at the simultaneous optimization of σ_S and S/σ_S . Fit windows of 7.5, 7 and 5 times the signal width are found to be the best simultaneous optimization of σ_S and S/σ_S for the mass regions in the range of 39-60 GeV, 60-62 GeV and 62-75 GeV, respectively.

$$f_{LowMass}(\mu\mu) = a_1/(m_Z - m_{\mu\mu})^{a_2} + a_3 \cdot m_{\mu\mu}^{a_4}(1 - a_5/m_{\mu\mu}^{a_6}) \quad (6.3)$$

$$f_{MiddleMass}(\mu\mu) = a_1 \cdot m_{\mu\mu}/(m_Z^2 - m_{\mu\mu}^2)^{a_2} + a_3 \cdot m_{\mu\mu}^{a_4}(1 - a_5/m_{\mu\mu}^{a_6}) \quad (6.4)$$

$$f_{HighMass}(\mu\mu) = a_1 \cdot m_{\mu\mu}/(m_Z - m_{\mu\mu})^{a_2} + a_3 \cdot m_{\mu\mu}^{a_4}(1 - a_5/m_{\mu\mu}^{a_6}) \quad (6.5)$$

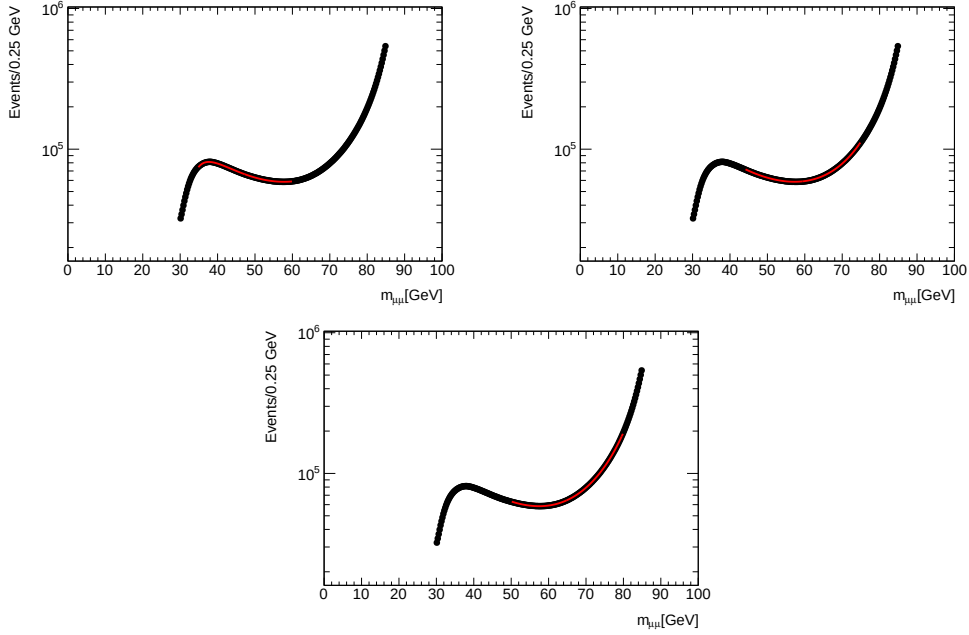


Figure 6.9. High-stat nominal background template as a function of the dimuon invariant mass. The distribution are fitted (red line) with the functional form described by eq. 6.3 (top-left), eq. 6.4 (top-right) and by eq. 6.5 (bottom).

In order to find a function or several functions that fulfill these requirements, a number of functional forms were considered. Given the challenging shape of the background, the functional forms reported in eq. 6.3- 6.5 are chosen to fit the mass range 39 – 48 GeV, 48 – 62 GeV and 62 – 75 GeV, respectively. The first term is used to accommodate for the Z boson peak, while the second term describes the turn on of the trigger. Figure 6.9 shows the shape of the nominal high-stat background template fitted with eq. 6.3 (top-left), with eq. 6.4 (top-right) and with eq. 6.5

(bottom). The χ^2/NDF for the low-mass, middle-mass and high-mass fit are 0.19, 0.62 and 0.65, respectively.

Statistical uncertainty

A dedicated study aiming at evaluating the statistical uncertainty, σ_S , is performed. 380000 toy background templates are obtained by applying, bin per bin, random Poissonian fluctuations starting from the high-stat nominal background template. All the toy background templates are fitted following the sliding window fit strategy described above. For each local fit the corresponding fitted signal, S , is taken and its distribution for each bin is therefore obtained. Gaussian S distributions centered at 0 with sigma equal to the statistical uncertainty, σ_S , are expected. In Figure 6.10 examples of the S distributions for the local fits centered at $m_{\mu\mu}$ equal to 40, 50, 60 and 70 GeV are given. The S distributions are fitted with a Gaussian function (red line). This procedure was applied for each bin of the dimuon mass distribution and the values of the fitted sigma are taken as σ_S . In Figure 6.11 the χ^2/NDF corresponding to the Gaussian fits is shown. Values of χ^2/NDF smaller than 1.4 are obtained for all the dimuon mass range ensuring all the fitted signal events distributions are well described by Gaussian functions.

Figure 6.12 shows χ^2/NDF (top) and spurious signal values (bottom) for the Zero-Width resonance case obtained by fitting the different high-stat template in the range of reconstructed $m_{\mu\mu} \in [39 \text{ GeV}, 75 \text{ GeV}]$. χ^2/NDF values are resulted to be much smaller than 1 ensuring a good fit quality. S/σ_S values close to 0.5 are obtained in the central dimuon mass (40-73 GeV) for all the high-stat background template variations (nominal, down var, up var, eta var). S/σ_S values are significantly higher than 0.5 in the region below 40 GeV and above 70 GeV. As expected, the sensibility of the analysis decreases in both these regions because the smooth monotone background hypothesis cannot be applied: the trigger turn on is in fact represented by a step rise and a smoother descent, while the high-mass region above 70 GeV is contaminated by the Z resonance contribution.

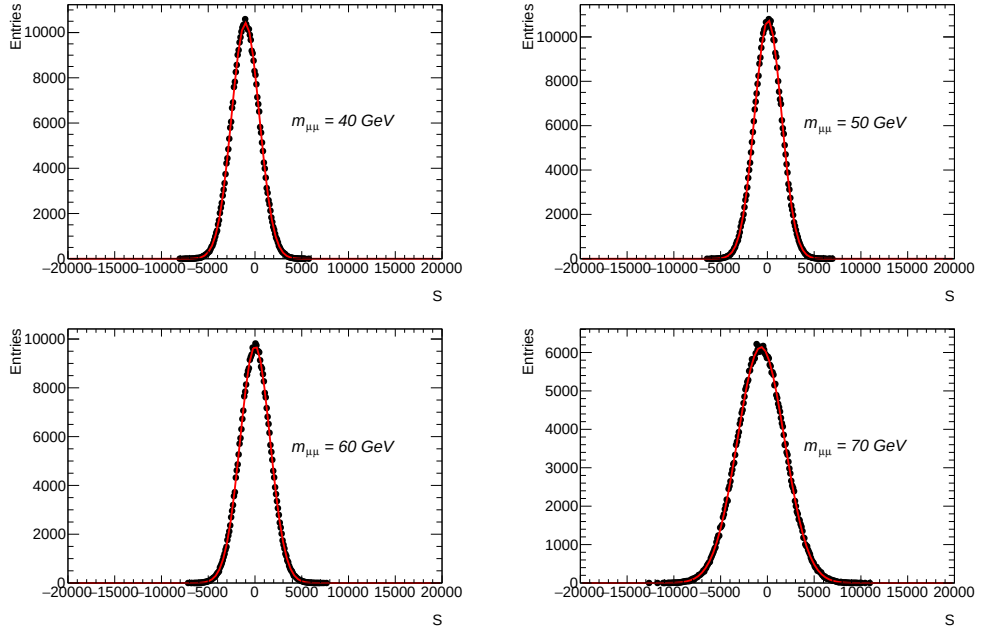


Figure 6.10. S/σ_S distributions for the local fits centered at $m_{\mu\mu}$ equal to 40 (top-left), 50 (top-right), 60 (bottom-left) and 70 (bottom-right) GeV fitted with a Gaussian function (red line).

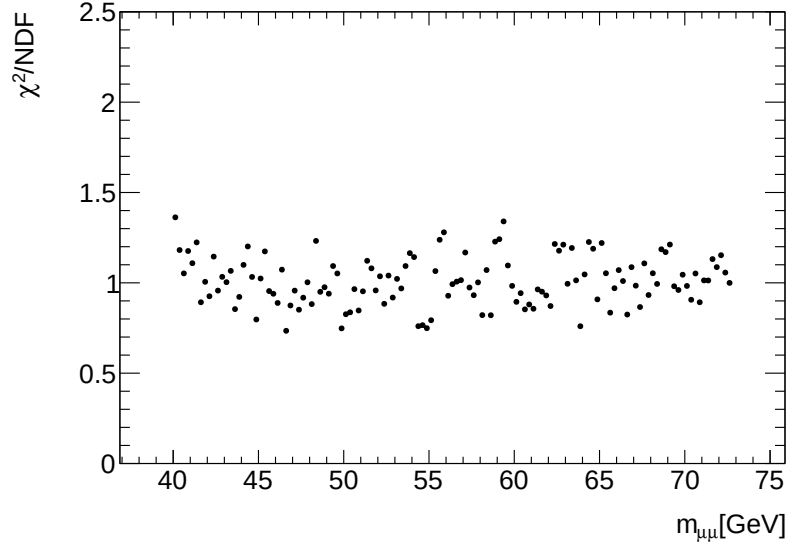


Figure 6.11. χ^2/NDF as a function of the dimuon mass corresponding to the signal distributions fitted with a Gaussian functions.

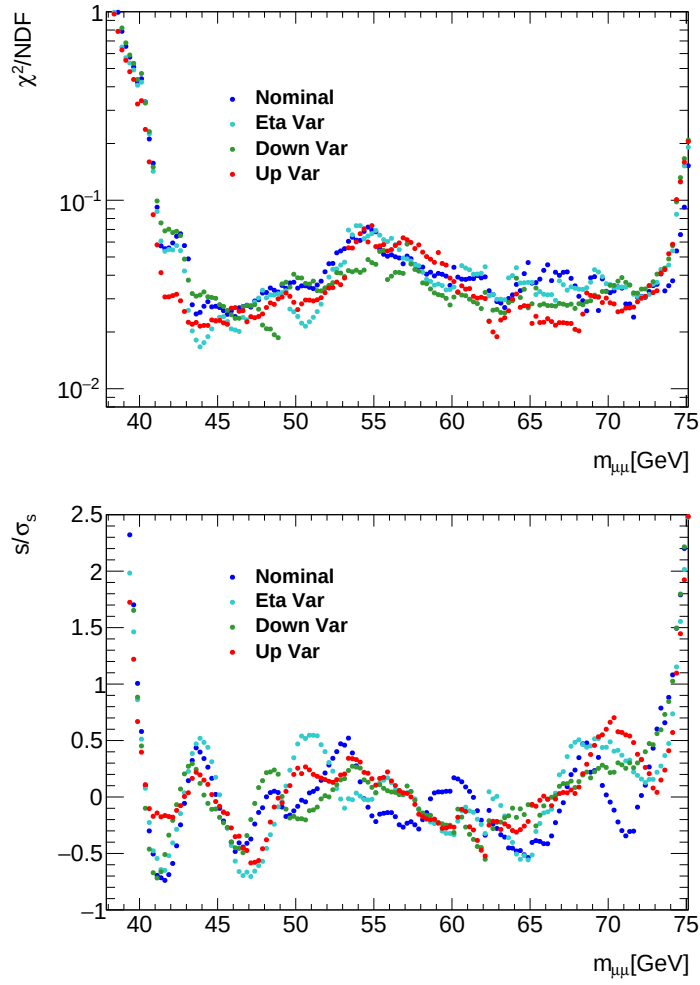


Figure 6.12. χ^2/NDF (top) and spurious signal (bottom) distribution obtained by fitting super-fast nominal (blue), down var (green), up var (red) and eta var (azure) background template.

6.5 Systematic uncertainties

Since the analysis is carried out entirely in a data-driven way, as far as the uncertainties related to the background modelling concern, the criterion is the same used in the resonant analysis and presented in section 5.1.6 that is summarized here.

The functional form used for the data-driven fits has to accommodate for possible shape changes, so spurious signal estimates are performed for each high-stat background template variation (Figure 6.12 - bottom). For the chosen function, at each $m_{\mu\mu}$ value the largest of all the spurious signal values is taken as the background modelling uncertainty (σ_{SS}) for the zero-width signal. Figure 6.13 shows the σ_{SS} uncertainty (envelope) as a function of the $m_{\mu\mu}$ mass range. Background modelling uncertainty is resulted to be between the 10% and 70% of the statistical uncertainty (σ_{stat}) in the fitted signal yield for the zero-width signal in the central dimuon mass range (40-73 GeV).

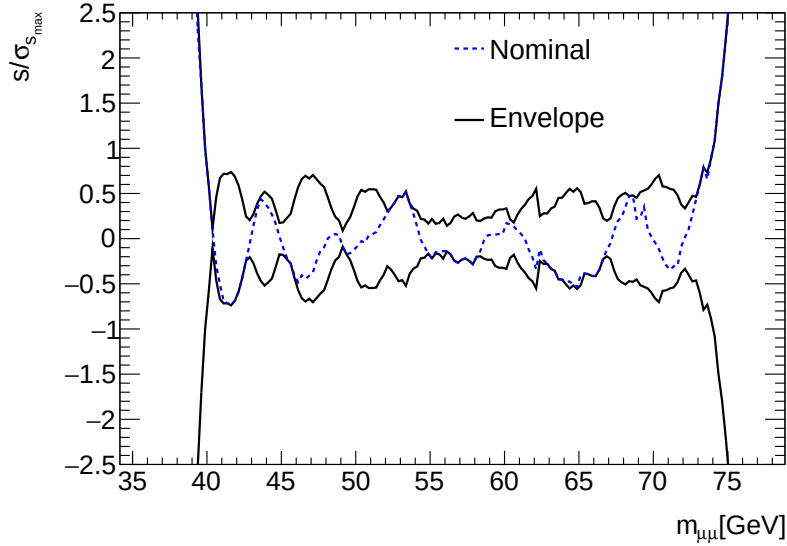


Figure 6.13. Background modelling uncertainty (black line) and nominal spurious signal uncertainty (blue dashed line) as a function of the $m_{\mu\mu}$ mass.

The experimental sources of systematic uncertainties come from efficiency (σ_ϵ), while the theoretical uncertainties are due to the signal cross-section (σ_σ). Also the uncertainty on the luminosity ($\sigma_{\mathcal{L}}$) is considered.

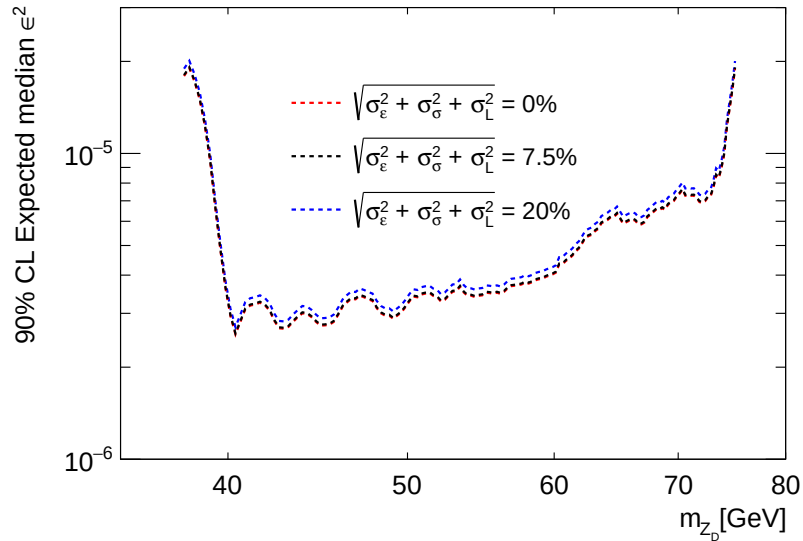
The theoretical uncertainty is dominated by the scale variations (δ_{scale}) which can reach 4% in the lowest mass region. Reasonable value for $\sqrt{\sigma_\epsilon^2 + \sigma_\sigma^2 + \sigma_{\mathcal{L}}^2}$ are provided by ATLAS Drell-Yan $\mu\mu$ paper [86] and are reported in Table 6.10 for different dimuon mass ranges.

The impact of σ_ϵ , σ_σ and $\sigma_{\mathcal{L}}$ on the signal is shown in Figure 6.14. The sensitivity of the search is expressed in terms of expected upper limits at 90% CL on the square of the kinetic mixing coefficient (ϵ Sec. 2.2.3), calculated following the procedure described in section 6.6. No visible changes of signal sensitivity at any point in the mass spectrum are observed by setting $\sqrt{\sigma_\epsilon^2 + \sigma_\sigma^2 + \sigma_{\mathcal{L}}^2}$ from 0% to 7.5%.

Table 6.10. The relative impact of 1σ variation of systematic uncertainties on the signal yield in percent for zero relative width.

Systematic uncertainties				
$m_X [\text{GeV}]$	$\sigma_{SS} [\%]$	$\sigma_\epsilon [\%]$	$\sigma_\sigma [\%]$	
			δ_{pdf}	δ_{scale}
< 46	15	2.1	2.6	+4.0 −4.4
46-51	15	1.9	2.4	+2.8 −3.0
51-56	12	1.7	2.4	+2.8 −3.0
56-61	6	1.6	2.4	+2.8 −3.0
> 61	15	1.5	2.4	+2.8 −3.0

The only relevant systematic uncertainty comes from the background modelling, σ_{SS} . The sensitivity of this search is therefore mostly limited by the statistical uncertainty, σ_{stat} .

**Figure 6.14.** Expected upper limits at 90% CL on ϵ^2 as a function of the Z_D mass corresponding to $\sqrt{\sigma_\epsilon^2 + \sigma_\sigma^2 + \sigma_L^2}$ equal to 0% (red), 5% (black) and 20% (blue).

6.6 Statistical analysis

Model independent expected upper limits on the visible cross section, s , of a generic vector boson mediator, χ , as a function its mass, are estimated from simultaneous maximum-likelihood fits of the signal-plus-background models to the nominal high-stat template $m_{\mu\mu}$ distribution. A Bayesian approach was used assuming a prior, $f_0(s)$, equal to 0 or 1 if s is < 0 or ≥ 0 , respectively. In the Gaussian approximation, the credibility limit obtained with this prior is numerically equivalent to the frequentist confidence limit obtained with the CL_s prescription. The uncertainty on s is obtained by summing in quadrature σ_{SS} and σ_{stat} , while the other systematic uncertainties are included in the fits via nuisance parameters constrained by a Gaussian pdf. The parameter s , and the nuisance parameter, θ_a , are defined as follows:

$$s = \sigma_\chi A \cdot B_{\chi \rightarrow \mu\mu} \quad (6.6)$$

$$\theta_a = \varepsilon \cdot \mathcal{L} \quad (6.7)$$

where σ_χ and $B_{\chi \rightarrow \mu\mu}$ refer to the cross section of the mediator χ and its branching fraction, respectively.

The probability of observing n events given a certain value of s is expressed by the Likelihood as:

$$L_{m_\chi}(n | s, \theta_a) = \text{Gaus}(n; \mu = s/\theta_a, \sigma = \sigma_s) \quad (6.8)$$

Finally, the expression of the Likelihood used to calculate the expected upper limits, obtained by marginalizing on θ_a the eq. 6.8, is given as:

$$L'_{m_\chi}(n | s) = \int d\theta_a L_{m_\chi}(n | s, \theta_{a0}) \cdot \text{Gaus}(\theta_a; \mu = 1, \sigma = \sigma_{\theta_a}/\theta_{a0}) \quad (6.9)$$

The subscript, a_0 , refers to the nominal value. The posterior probability for s given a number of observed events, n_{obs} , is calculated as:

$$f(s | n_{obs}) = L'(n_{obs} | s) \cdot f_0(s) \quad (6.10)$$

In order to interpret the upper limits in terms of the square of the kinetic mixing coefficient s and a have to be redefined as follows:

- $s = \epsilon^2$
- $a = \frac{\sigma_{Z_D} A \cdot B_{Z_D \rightarrow \mu\mu} \cdot \varepsilon \cdot \mathcal{L}}{\epsilon_0^2}$

where ϵ^2 is the square of the kinetic mixing coefficient, ϵ_0^2 is the square of the value used to generate Dark-Photon signal with MadGraph (sec. 6.1.1), while σ_{Z_D} and $B_{Z_D \rightarrow \mu\mu}$ are the Dark-Photon cross section and its branching fraction.

The expected median model independent upper limits and their reinterpretation in term of Dark-Photon signal model are presented in the following section and are obtained by setting n_{obs} at zero.

Since the spurious signal values at low-mass (< 40 GeV) and at high-mass (> 73 GeV) are much larger than 0.5, the statistical analysis is restricted to the 40-73 GeV dimuon mass range.

6.7 Results

The present section contains the expected upper limits of the resonant search obtained by sliding window fit background estimation.

Figure 6.15 shows the model-independent expected upper limit at 95% CL on the fiducial cross-section times branching ratio as a function of m_χ for zero-width signal.

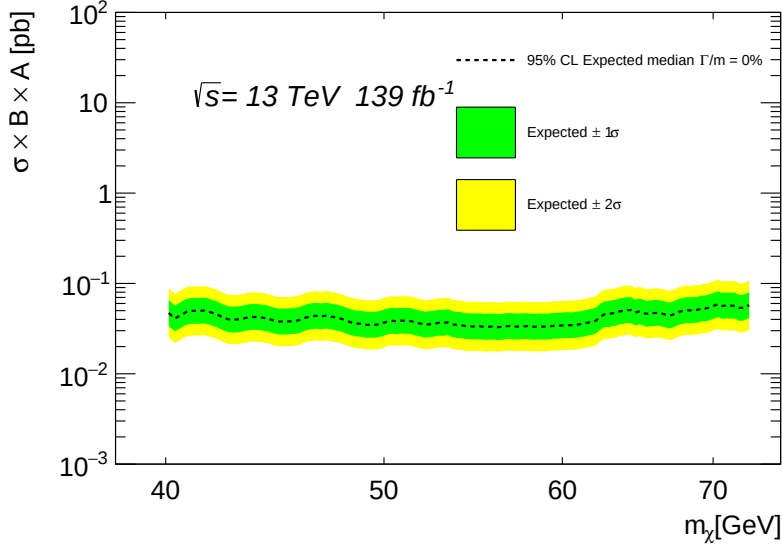


Figure 6.15. Model-independent expected upper limits at 95% CL on the fiducial cross-section times branching ratio as a function of the Z_D mass for zero-width signal. The dotted line shows the expected limits and the green and yellow error bars show the 1 and 2 σ uncertainty bands on the expectation.

Figure 6.16 shows the expected upper limit at 90% CL on the square of the kinetic mixing coefficient as a function of pole mass for zero-width signal. Expected upper limit are compared with the results obtained by the LHCb Collaboration (red) [38] and by CMS Collaboration (blue) [37]. Although the ATLAS transverse momentum resolution for p_t muons of 5-150 GeV is limited by a factor two with respect to CMS muon p_t resolution [87], the optimization studies and the analysis strategy, discussed above, allowed to set expected upper limits on the kinetic mixing coefficient of a dark photon in the mass range 39, 75 GeV competitive with the most stringent limit to date.

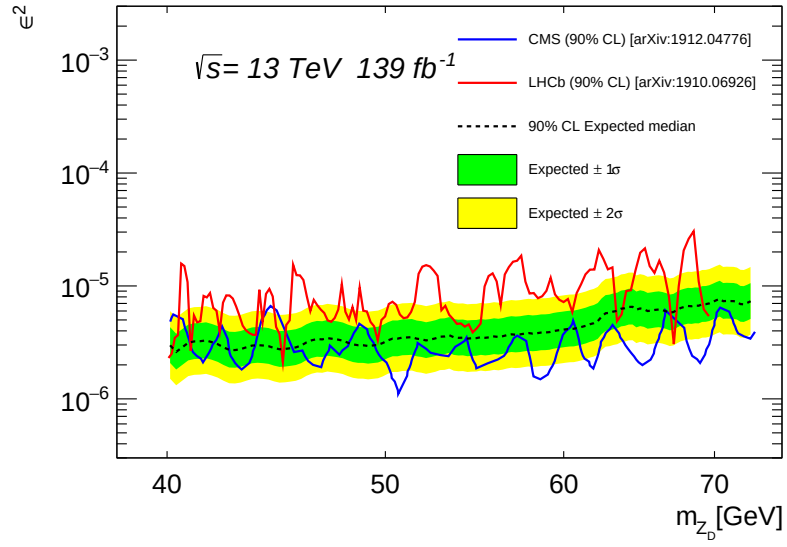


Figure 6.16. Expected upper limits at 90% CL on ϵ^2 , the square of the kinetic mixing coefficient, as a function of the Z_D mass for zero-width signal. The dotted line shows the expected limits, the green and yellow error bars show the 1 and 2 σ uncertainty bands on the expectation. Observed limits at 90% CL from the search performed by the LHCb Collaboration [38] and by CMS Collaboration [37] are shown in red and blue, respectively.

Chapter 7

Conclusions

Several promising theories beyond the Standard Model predict the existence of new particles decaying in a dilepton final state. These models can provide a solution to many open questions in particle physics such as Dark Matter and naturalness.

The dark photon mixes kinetically with the SM photon and depending on the structure of the hidden sector can decay to SM particles.

This work presents the most recent ATLAS results [75] [78] for the search for resonant and non resonant high-mass states decaying into a pair of leptons, based on 139 fb^{-1} of data collected at LHC in proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$. No significant excess of events compared with the background expectation is observed. Model independent upper limits at 95% CL are set on the fiducial cross-section times branching ratio of generic resonances by the resonant search (Sec 5.1), as well as on the number of signal events by the non resonant search (Sec 5.2). These results imply a lower limit at 95% CL of 4.5 (5.1) TeV on the $m_{Z'}$ for the Z'_ψ (Z'_{SSM}) boson (Sec 5.1) and exclude the contact interaction model for Λ up to 35.8 TeV at 95% CL.

Dedicated studies aiming at increasing the efficiency selection of high- p_T muon WP without worsening the transverse muon momentum resolution are provided. They will lead to a significantly increased sensitivity compared to the present searches for high-mass phenomena decaying in a final state with muons.

This document investigates the extension of the high-mass searches to the lower mass scale (40-73) GeV. Since the internal ATLAS review process is still ongoing, Run-2 data are still officially blinded. Preliminary results are discussed. Expected model independent upper limits are set on the fiducial cross-section times branching ratio to dimuons for generic narrow resonances ($\Gamma/m = 0\%$) at 95% CL. This result is interpreted in the context of dark photon model. Expected upper limits are set on the square of the kinetic mixing coefficient, ϵ^2 at 90% CL. The sensitivity of the search for the dark photon model is found to be competitive with the most stringent limit to date [37].

A new interesting idea to extend the sensitivity of the search would be to include the dark photon decaying into electrons and taus. In general, exploring the gauge couplings to SM particles could dramatically reshape the landscape of Dark sectors, and LHC searches could be complementary to dedicated dark photon experiments.

In the long-term picture, with the planned LHC increase of the luminosity, more data will allow to enhance the sensitivity of the searches. In particular, a crucial

role is played by the New Small Wheel upgrade that will allow ATLAS to cope with harsher experimental conditions. Micromegas and sTGC chambers will provide trigger and tracking capabilities aiming at maximising the impact on the muon system performance in terms of reconstruction efficiency and p_T resolution. The sensitivity of all the searches presented in this document will benefit from the New Small wheel upgrade.

This work reports a description of the design, construction and assembly procedures of the Micromegas modules with particular emphasis to the drift panels of the SM1 chambers built in Italy. The total number of drift panels needed for the SM1 micromegas project is 96. Rome1 and Cosenza INFN teams built 105 drift panels, nine more of the needed number, to ensure the highest possible quality for the final MM quadruplet assembly. Micromegas High voltage studies and efficiencies results are also presented. In particular the target 95% efficiency has been achieved for all the small double wedges that are installed on New Small Wheel A.

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