



DOCTORAL THESIS

**Measurement of top quark pair
production in association with bosons
in multi-leptonic final states using
ATLAS Run 2 data**

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for the degree of Doctor of Philosophy*

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Physics and Astronomy Department
School of Mathematical and Physical Sciences
Experimental Particle Physics Research Group

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29th April 2025

I, Gianna LOESCHCKE CENTENO, hereby declare that this thesis has not been and will not be, submitted in whole or in part to another university for the award of any other degree.

Brighton,
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by Gianna LOESCHCKE CENTENO

ABSTRACT

In this thesis, two measurements of the top quark pair production in association with a boson in multi-leptonic final states are presented. Both have been performed using the 140 fb^{-1} of proton-proton collisions at a centre-of-mass energy of 13 TeV collected with the ATLAS detector during the Run 2 of the Large Hadron Collider. The first measurement corresponds to a search for physics beyond the Standard Model (SM) using an Effective Field Theory (EFT) approach in the high-mass $t\bar{t}\ell^+\ell^-$ regime. It is the first dedicated measurement, constraining the EFT four-fermion operators in the top quark sector. The data are measured to agree well with the SM expectation. New constraints are set on the flavour inclusive four-fermion EFT operators, improving the current limits. Additionally, the first flavour dependent measurement of the four-fermion operators in the $t\bar{t}\ell^+\ell^-$ vertex is performed, measuring the $t\bar{t}e^+e^-$ and $t\bar{t}\mu^+\mu^-$ rates separately, as well as measuring the relative electron muon rate. These flavour dependent measurements give access to a potential lepton flavour universality violation in the EFT operators. Similarly to the flavour inclusive case, no significant deviations from the SM expectations are observed for the electron and muon EFT operators. The second measurement targets the $t\bar{t}H$ process, having a direct sensitivity to the top Yukawa coupling. The results are compatible with the SM within 2σ and measure the $t\bar{t}H$ process in a multi-leptonic final state with a significance

of 3.2σ . Additionally, this measurement corresponds to the first ATLAS differential measurement of $t\bar{t}H$ in the multi-leptonic final state, bringing sensitivity to the Higgs self-coupling or the Higgs CP properties.

Keywords: *Particle Physics, ATLAS Experiment, Top Physics, Higgs Physics, Multi-leptonic final states, Effective Field Theory*

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INTRODUCTION

The Large Hadron Collider has introduced a new era of precision measurements in large areas of particle physics. By collecting an unmatched amount of proton-proton collision data and by reaching new energies, the increase in precision and in sensitivity to new processes might unveil physics beyond the Standard Model (SM). While it is known that the SM is not able to describe all observed phenomena, no concrete hints as to how the SM could be completed were found so far. The wide physics programme of the ATLAS collaboration therefore aims at testing the predictions of the SM on multiple fronts.

The unprecedented number of top quark events allows for a new level of precision in the measurement of the coupling of the top quark to the electroweak gauge bosons. The top quark, holding a special place because of its mass, plays an important role in many theories beyond the SM. No new physics having been found so far, a largely model independent search for new physics can be performed using an Effective Field Theory (EFT) approach. In this thesis, the high-mass regime is utilised to constrain the impact of potential new physics at a high-energy scale on the four-fermion $t\bar{t}\ell^+\ell^-$ vertex, where the invariant mass of the two leptons is above the Z peak. The measurement is performed in the EFT formalism, setting limits on the four-fermion operators. The author was the sole main analyser of this analysis, which led to a paper available in Reference [1] and submitted to the European Physical Journal C.

Additionally, the ATLAS experiment was able, after the discovery of the Higgs boson, to test the SM predictions in this new sector. Again, because of its high mass, the top quark has a key role in probing the Higgs sector, such as the top Yukawa coupling. This thesis presents a measurement of the $t\bar{t}H$ process in a multi-lepton final state, sensitive to the Higgs-top coupling. Additionally to the inclusive signal strength measurement, a differential measurement inside the Simplified Template Cross-Section framework is performed, the Higgs transverse momentum distribution, giving access to potential deviations from the Higgs self-coupling prediction or the

Higgs CP properties. The author was responsible for the implementation of the differential fit into the analysis channels, as well as for the combination of the analysis channels in the inclusive and differential fit. The analysis is in internal [ATLAS](#) review and expected to be submitted for publication later this year.

THE STANDARD MODEL OF PARTICLE PHYSICS

1

The Standard Model (SM) of particle physics, presented in Section 1.1, is a theoretical model which describes with high accuracy the observations made at particle physics experiments, such as the Large Hadron Collider (LHC). The SM was able to predict the existence of several particles, which were later found experimentally, the last one being the Higgs boson, described in Section 1.2, found at the LHC in 2012 independently by the two experiments ATLAS and CMS [2, 3]. Additionally, the couplings between the different particles are measured to be well in agreement with the predictions of the SM. There are, however, some observations which the SM fails to describe. Some of these shortcomings are described in Section 1.3 and a framework for the search for Beyond Standard Model (BSM) physics is presented in Section 1.4.

Sections 1.1 and 1.2 are based on explanations from Reference [4].

1.1 Content of the SM

The SM corresponds to a relativistic quantum field theory, which can be written in the Lagrangian formalism. Following the principle of minimisation of the action $S = \int d^4x \mathcal{L}$, where $\mathcal{L}$ is the Lagrange density, one obtains the Euler-Lagrange equation:

$$\partial_\mu \left(\frac{\partial \mathcal{L}}{\partial(\partial_\mu \psi)} \right) - \frac{\partial \mathcal{L}}{\partial \psi} = 0 \quad (1.1)$$

In the context of the SM, the Euler-Lagrange equation corresponds to the equation of motion of free fermion fields ψ . It is then imposed that the Lagrangian is invariant under local gauge transformations. In order to satisfy this invariance, gauge fields need to be introduced, which give rise to interaction terms between the fermion fields. The physical particles, the gauge bosons,

A summary of all the particles included in the SM is shown in Figure 1.1 and more details are given in Section 1.1.1 for the fermions, in Section 1.1.2 for the gauge bosons and in Section 1.2 for the Higgs boson.

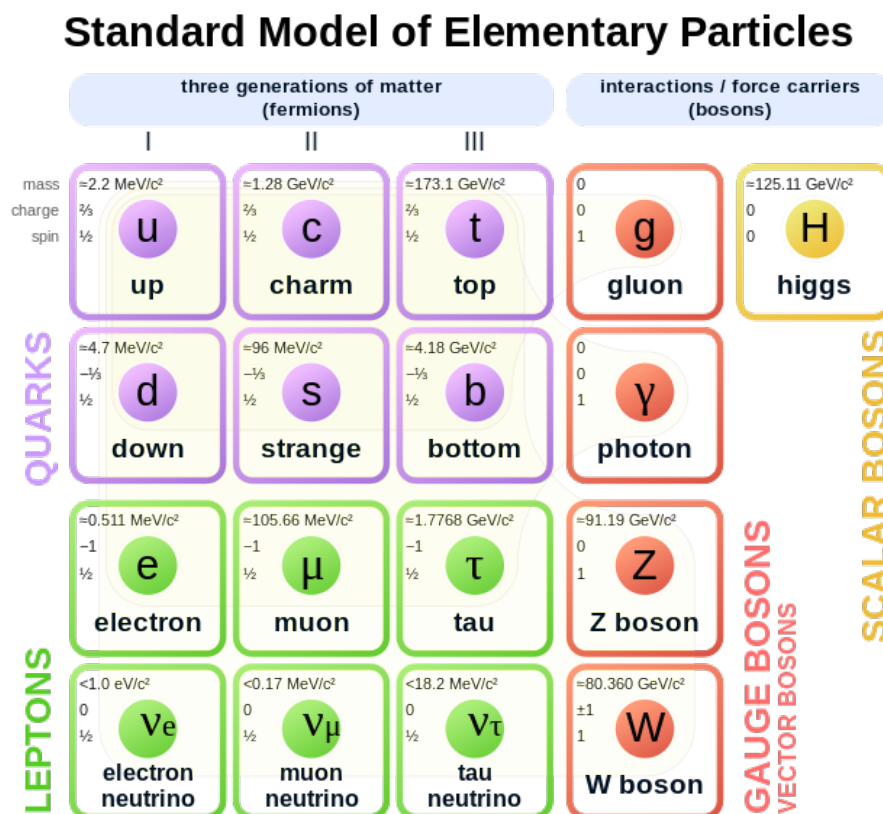


Figure 1.1: Content of the SM: the fermions composed of quarks and leptons, the gauge bosons and the Higgs boson [5]

1.1.1 Leptons and quarks

Matter is composed of spin $\frac{1}{2}$ particles, called fermions. These fermions are described by fields evolving as a function of space and time coordinates and are characterised by their symmetries called quantum numbers. Every fermion has a corresponding anti-fermion with the same properties (such as the mass and the lifetime) but opposite charges. The fermions are categorised into three generations, which heavily differ in mass, but are identical in all other respects. Each generation is composed of two leptons and two quarks.

- **Charged leptons:** these leptons have an electric charge of $-1e$, e being the elementary charge. The charged leptons correspond to the electron e (first generation), the muon μ

(second generation) and the tau τ (third generation). All three are massive, the electron being the lightest and the tau the heaviest. Additionally to the electric charge, leptons also couple to the weak force.

- **Uncharged neutrinos:** the charged leptons have a corresponding electrically uncharged neutrino, called electron, muon or tau neutrino (ν_i with $i = e, \mu, \tau$). Neutrinos only couple through the weak force and are considered to be massless.
- **Quarks:** each generation contains one up-type quark with electric charge $\frac{2}{3}e$ (up (u), charm (c) and top (t)) and one down-type quark with charge $\frac{-1}{3}e$ (down (d), strange (s) and bottom (b)). All quarks additionally interact via the weak and the strong force. Finally, quarks are massive particles and the mass strongly differs between the different quark types. More details on the properties of the top quark as well as the physics programme related to the measurement of top quark properties are given in Chapter 3.

1.1.2 Forces described by the SM

The symmetries of the SM lead to three fundamental forces: the electromagnetic force, the weak force and the strong force. All three forces are mediated by the gauge bosons with spin 1. The couplings of the gauge bosons to the other particles are described by the coupling constants g , which differ for the different forces. The couplings are also often expressed by the fine-structure constants, defined as $\alpha = \frac{g^2}{4\pi}$.

The symmetries imposed in the SM can be described by the following symmetry group:

$$SU(2)_L \otimes U(1)_Y \otimes SU(3)_C \quad (1.2)$$

The special unitary group $SU(2)_L$ acts on the weak isospin I_W (L denoting that it only acts on left-handed particles), the unitary group $U(1)_Y$ on the weak hypercharge Y and $SU(3)_C$ on the colour charge C . The symmetry groups have three, one and eight generators respectively, which can be absorbed into gauge fields.

Electroweak interaction

$U(1)_Y$ and $SU(2)_L$ interactions are sensitive to the chirality of the fermions. The $SU(2)_L$ interactions differentiate between left- and right-handed fermions by coupling exclusively to left-handed states. Under $SU(2)_L$, the fermions are therefore ordered into left-handed doublets and

right-handed singlets, meaning that the right-handed states are not affected by $SU(2)_L$ gauge transformations. Only left-handed neutrinos (and right-handed anti-neutrinos), which interact with the W and Z bosons, are included in the [SM](#).

The $SU(2)_L \otimes U(1)_Y$ symmetries require four gauge fields, three for $SU(2)_L$ called W_μ^k with $k = 1, 2, 3$ and one for $U(1)_Y$ called B_μ . The Electroweak ([EW](#)) Lagrangian can be written as follows, introducing the covariant derivative D_μ , which guarantees the invariance under the gauge transformations:

$$\mathcal{L}_{EW} = -\frac{1}{4}W^{i,\mu\nu}W_{i,\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} + \sum_{i=1}^3 [q_L^{i\dagger} \bar{\sigma}^\mu D_\mu q_L^i + u_R^{i\dagger} \sigma^\mu D_\mu u_R^i + d_R^{i\dagger} \sigma^\mu D_\mu d_R^i + l_L^{i\dagger} \bar{\sigma}^\mu D_\mu l_L^i + e_R^{i\dagger} \sigma^\mu D_\mu e_R^i] \quad (1.3)$$

$$D^\mu = \partial_\mu + igI_i W_\mu^i + i\frac{Y}{2}g'B_\mu \quad (1.4)$$

where q_L , u_R and d_R correspond to the left-handed quark doublet, the right-handed up-type quark singlet and the right-handed down-type quark singlet and l_L and e_R correspond to the left-handed lepton doublet and the right-handed charged lepton singlet. g and g' are the coupling constants of the $SU(2)_L$ and $U(1)_Y$ gauge interactions, I_i are the three generators of the $SU(2)_L$ symmetry, Y is the weak hypercharge of the $U(1)_Y$ symmetry, whereas $\sigma^\mu = (1_2, \sigma^i)$ and $\bar{\sigma}^\mu = (1_2, -\sigma^i)$ with σ^i the Pauli matrices.

The physical fields, which are observed in nature, correspond to the photon, mediating the electromagnetic force and the $W^\pm$ and Z bosons, mediating the weak force. These fields do not directly correspond to the gauge fields of $U(1)_Y$ and $SU(2)_L$ but can be described as a superposition:

$$\text{photon field: } A_\mu = B_\mu \cos \Theta_W + W_\mu^3 \sin \Theta_W \quad (1.5)$$

$$\text{Z boson field: } Z_\mu = -B_\mu \sin \Theta_W + W_\mu^3 \cos \Theta_W \quad (1.6)$$

$$\text{W boson fields: } W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp iW_\mu^2) \quad (1.7)$$

Θ_W corresponds to the Weinberg mixing angle, related to the couplings of the electromagnetic force and of the weak force ($\tan(\Theta_W) = \frac{g'}{g}$), and is determined by the observation that the photon is a pure vector field. Two of these three parameters are free parameters of the theory but can be measured experimentally.

The B_μ gauge field acts on the weak hypercharge Y and the W_μ^i fields act on the weak isospin I_W . The photon and Z fields consist, however, of a mixing of the $U(1)_Y$ and $SU(2)_L$ gauge bosons. The resulting photon is observed to couple to the electric charge, which can be identified as $Q = I_W^3 + \frac{Y}{2}$. As $SU(2)_L$ is a non-Abelian group, the $W^\pm$ and Z bosons are self-interacting, which is not the case for photons. Additionally the $W^\pm$ bosons carry an electric charge, allowing for a photon- $W^\pm$ vertex.

Strong interaction

$SU(3)_C$ is the symmetry group of Quantum Chromo Dynamics (QCD). It requires three colour states, referred to as red, blue and green. Quarks can adopt three colour states, behaving as triplets under $SU(3)_C$, while leptons behave as singlets, meaning that they do not couple via the strong interaction. The strong force is mediated by eight types of gluons, which carry colour and anti-colour.

Compared to the coupling constant of the electromagnetic interaction, the strength of the coupling in the strong interaction, usually called α_S , strongly depends on the energy. This behaviour is called running coupling. α_S increases for low energies, leading to the confinement of coloured particles. Because of this confinement, quarks cannot be observed as free particles but only as bound states in baryons (qqq) or in mesons ($q\bar{q}$). On the other hand, as the coupling constant decreases with higher energy, coloured particles are asymptotically free. For the description of the strong force, this means that perturbation theory can only be used for hard scales, while non-perturbative models have to be used for soft scales. More details on this are given in Chapter 4.

Similarly to the weak symmetry group, the group $SU(3)_C$ is non-Abelian, leading to the self-interaction of gluons.

Parity, charge conjugation and time reversal symmetries

Additionally to the continuous symmetries described so far, which give rise to the interactions between particles, observations show that the SM also satisfies some discrete symmetries. The considered symmetries are the charge conjugation (C), the parity (P) and the time reversal (T). The charge conjugation changes the sign of all charges, transforming a particle into its anti-particle. The parity inverts the spatial coordinates, $(t, \vec{x}) \rightarrow (t, -\vec{x})$. Finally, the time reversal inverts the time coordinate, $(t, \vec{x}) \rightarrow (-t, \vec{x})$.

While the electromagnetic and strong interactions are observed to be invariant under the P- and C-symmetry, the weak interaction was found to break them maximally [6]. The combined CP-symmetry almost restores the invariance in the weak interaction but was still found to be slightly violated [7]. Only the CPT-symmetry is currently believed to be satisfied by all interactions because of more fundamental principles.

1.2 Higgs mechanism

Experimentally, the $W^\pm$ and the Z bosons are found to be massive (around 80 GeV for the $W^\pm$ bosons and around 91 GeV for the Z boson). Adding a mass term to the Lagrangian, which could explain these masses, would, however, violate the gauge symmetry. Using the concept of spontaneous symmetry breaking, the Brout-Englert-Higgs mechanism [8, 9] is able to introduce the observed masses without breaking the gauge invariance.

1.2.1 Spontaneous symmetry breaking

In the Higgs mechanism, a doublet of two complex scalar fields is considered:

$$\Phi = \begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix} = \frac{1}{2} \begin{pmatrix} \Phi_1 + i\Phi_2 \\ \Phi_3 + i\Phi_4 \end{pmatrix} \quad (1.8)$$

In order to keep the Lagrangian of the Higgs field invariant under $SU(2)_L \otimes U(1)_Y$ symmetries, the same covariant derivative as in the electroweak Lagrangian has to be used in the Higgs Lagrangian:

$$\mathcal{L}_{Higgs} = (D^\mu \Phi)^\dagger (D_\mu \Phi) - V(\Phi) \quad (1.9)$$

$$D^\mu \Phi = (\partial_\mu + igI_i W_\mu^i + i\frac{Y}{2}g'B_\mu)\Phi \quad (1.10)$$

where W_μ^i and B_μ correspond again to the electroweak gauge fields. The first term in the Lagrangian therefore describes the interaction of the EW gauge bosons with the Higgs field. The second term corresponds to the Higgs potential and can be written as:

$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \quad (1.11)$$

In the case where μ^2 is negative, the vacuum state is degenerate. The form of such a potential is shown in Figure 1.2. The minimum of the potential is reached for all values of Φ satisfying the following criterion:

$$\Phi^\dagger \Phi = -\frac{\mu^2}{2\lambda} = \frac{v^2}{2} \quad (1.12)$$

where $v \neq 0$ is the vacuum expectation value. Adopting one of these minima induces the spontaneous symmetry breaking.

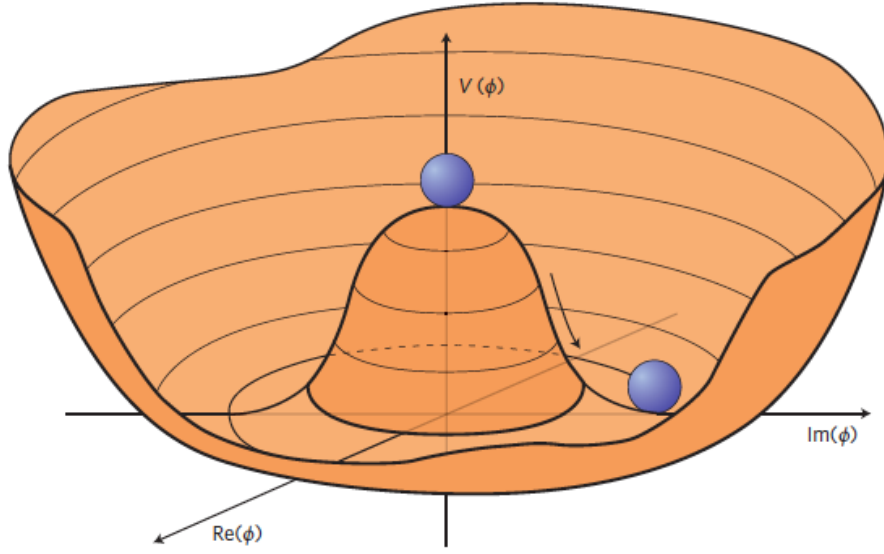


Figure 1.2: Form of the Higgs potential in the case of $\mu^2 < 0$, leading to a degenerate vacuum state [10]

As the neutral photon is required to remain massless, the potential minimum must be such that only the Φ^0 component of the doublet has a non-zero expectation value:

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad (1.13)$$

By expanding the Higgs field around its minimum and using the unitary gauge, the Higgs doublet becomes:

$$\Phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \quad (1.14)$$

Out of the symmetry breaking, three Goldstone bosons and a massive scalar particle appear. The Goldstone bosons become the longitudinal degrees of freedom of the $W^\pm$ and Z bosons.

The massive scalar particle, the Higgs boson, corresponds to field excitations in the direction of the physical vacuum.

When inserting the Higgs doublet after symmetry breaking into the Lagrangian, it becomes visible that the [EW](#) gauge bosons have acquired mass. The masses can be identified as:

$$m_W = \frac{1}{2}gv \quad (1.15)$$

$$m_A = 0 \quad (1.16)$$

$$m_Z = \frac{m_W}{\cos \Theta_W} \quad (1.17)$$

The Higgs model is described by four parameters: the coupling constants of $SU(2)_L$ and $U(1)_Y$ and the two free parameters of the Higgs potential μ and λ , related to the vacuum expectation value of the Higgs field and the mass of the Higgs by: $v^2 = \frac{-\mu^2}{\lambda}$ and $m_H^2 = 2\lambda v^2$.

1.2.2 Higgs self-coupling

After expanding the Higgs field around the vacuum expectation value v , the Higgs potential takes the form:

$$V(h) = \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4 \quad (1.18)$$

$$= \frac{1}{2}m_H^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4 \quad (1.19)$$

While the first term corresponds to the Higgs mass term, the second and third term give rise to the trilinear and the quartic self-interactions of the Higgs, as shown in Figure 1.3.

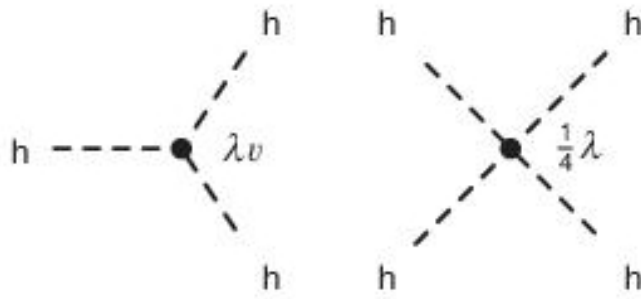


Figure 1.3: Trilinear and quartic Higgs self-coupling [4]

Through the interaction with other particles and appearing loop corrections, the scalar potential is modified to an effective potential, which can be written as:

$$V^{eff}(h) = \frac{1}{2}m_H^2(\mu_R)h^2 + \lambda(\mu_R)vh^3 + \frac{1}{4}\lambda(\mu_R)h^4 \quad (1.20)$$

where m_H and λ become running parameters depending on the physics scale μ_R .

1.2.3 Yukawa coupling

The Higgs mechanism described so far allows for massive gauge bosons, but does not explain the masses of the fermions. Another term describing the interaction of the Higgs field with the SM particles, called the Yukawa coupling, can be added to the Lagrangian, in order to add the fermion masses:

$$\mathcal{L}_{Yukawa} = -y_u \bar{q}_L \Phi_c u_R - y_d \bar{q}_L \Phi d_R - y_e \bar{l}_L \Phi e_R + \text{h.c.} \quad (1.21)$$

In the Yukawa term, the left-handed $SU(2)$ fermion doublets (q_L and l_L) and the right-handed $SU(2)$ fermion singlets (u_R , d_R and e_R) couple to the Higgs doublet Φ for charged leptons and down-type quarks or to the conjugate Higgs doublet Φ_c for up-type quarks. The Yukawa constant y_f regulates the strength of the coupling. Left-handed fermions and the Higgs doublet being both doublets under $SU(2)$, terms of the form $\psi^L \Phi$ are invariant under $SU(2)_L$ gauge transformations. ψ^R being a $SU(2)$ singlet, $\psi^L \Phi \psi^R$ terms are invariant under $SU(2)_L$ and $U(1)_Y$ gauge transformations, keeping the required gauge invariance of the SM Lagrangian. As the SM does not include right-handed neutrinos, neutrinos do not interact via the Yukawa coupling and remain massless. The coupling constant of the fermions to the Higgs field y_f is a free parameter of the theory, given by the observed fermion masses:

$$y_f = \sqrt{2} \frac{m_f}{v}$$

More details on the properties of the Higgs boson as well as the physics programme related to the measurement of Higgs properties are given in Chapter 3.

1.3 Limitations of the SM

Even though the SM provides an accurate description of most of the particle physics observations, it has apparent limitations in some areas.

Some observations are fully consistent with the SM but do not follow as requirements from the theoretical model:

- Fermion generations: the existence of three fermion generations and the important mass differences between the fermions is an observation but does not have a theoretical foundation in the SM.
- Hierarchy problem: the SM is considered to be valid until the Planck scale, defined as the scale where quantum effects of gravity become dominant. Loop corrections up to this scale can therefore contribute to the Higgs mass [11]. With about 125 GeV, the mass of the Higgs boson is, however, measured to be much smaller than the Planck mass, which is in the order of 10^{19} GeV. Within the SM, this small mass can only be obtained by numerical cancellations of terms which require a high degree of fine-tuning.

Additionally, some cosmological observations are not included in the SM:

- Dark matter: many cosmological observations, such as the measurement of rotational curves of galaxies [12], require the existence of dark matter, believed to make up around 25 % of the mass/energy content of the universe [13]. Thus far, no particles have been found which could be the components of dark matter and no other interaction than gravity was so far observed between dark matter and the baryonic matter.
- Dark energy: the expansion of the universe is observed to be accelerated [14, 15], which requires the presence of dark energy. It is expected that around 70 % of the mass/energy content of the universe corresponds to dark energy. This new form of energy is currently not understood and not included in the SM.
- Gravitation: the theory of general relativity, describing gravitation, and the SM can currently not be described in a unified theory.

Finally, some observations show that the SM description cannot be correct as is, even though most deviations from the SM could be explained by additions to the SM:

- Neutrino masses: the observation of neutrino oscillations [11] directly implies that the neutrinos have a non-zero mass, which is not included in the SM. The oscillation requires a mass difference between the different neutrino mass eigenstates, which can be determined experimentally. However, the current experiments are not sensitive to the very small neutrino masses, but were able to set an upper limit of around 0.8 eV [16].
- Matter-antimatter asymmetry: the universe is made up of matter, even though most physical processes are expected to be symmetric between matter and anti-matter. The require-

ments for the observed asymmetry are given by the Sakharov conditions [17] which are not met by the SM in such extent.

All these points hint to the fact that the SM has missing parts. However, so far no clear indication of what additions to SM are required have been found.

1.4 Effective field theory formalism

The SM Effective Field Theory (EFT) formalism is a way to characterise and to optimise the sensitivity to new physics in a relatively model independent way, in case the energy scale of the new interactions is above the reach of the experiment. In this EFT assumption, the SM Lagrangian is incomplete, missing BSM physics at a high-energy scale.

Missing contributions associated with physics at a high scale can be obtained by expanding the Lagrangian with effective coupling terms in a low energy limit compared to the mass of the new physics. The expansion is performed around $\frac{v}{\Lambda}$ where Λ is the scale of the new physics and v the vacuum expectation value.

The SM is then treated as a low-energy approximation of a higher-energy theory, which is described by additional higher-order terms. The Lagrangian can be written as:

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_{d,i} \frac{c_i^d}{\Lambda^{d-4}} \mathcal{O}_i^d \quad (1.22)$$

where $\mathcal{L}_{SM}$ has dimension ≤ 4 and where terms of higher dimension are added. $\mathcal{O}_i^d$ are the EFT operators of dimension d and c_i^d are the dimensionless Wilson Coefficients (WCs), which characterise the strength of the interactions at dimension d . The operators $\mathcal{O}_i^d$ form a basis, in this thesis the Warsaw basis [18] is used, which builds a complete set of operators allowed by SM gauge symmetries (must be conform to $SU(2)_L \otimes U(1)_Y \otimes SU(3)_C$). The WCs are the free parameters of the theory which are measured in experiments.

Operators of odd dimension violate baryon or lepton number [19], wherefore in the following only operators of even dimension are considered. As the contribution of an operator to the Lagrangian is suppressed by $1/\Lambda^{d-4}$, only the dimension 6 operators, which are the leading contribution from new physics, are considered in this thesis.

The cross-section of a specific process calculated within the EFT formalism, considering only dimension 6 EFT operators, can be written as:

$$\sigma = \sigma_{SM} + \sigma_{int} + \sigma_{BSM} \quad (1.23)$$

$$= \sigma_{SM} + \sum_i \frac{c_i a_i}{\Lambda^2} + \sum_{i,j} \frac{c_i c_j b_{ij}}{\Lambda^4} \quad (1.24)$$

where σ_{SM} is the cross-section predicted by the [SM](#), σ_{int} corresponds to the interference between the [SM](#) and the [BSM](#) physics and σ_{BSM} is the pure [BSM](#) part, which is suppressed by $\frac{1}{\Lambda^4}$. The coefficients a_i and b_{ij} are specific to each [EFT](#) operator and correspond to the strength of the impact of the operator on the cross-section. In case $i \neq j$, b_{ij} correspond to the interplay between the [EFT](#) operators $\mathcal{O}_i$ and $\mathcal{O}_j$. It is to be noted that the interference term between dimension 8 operators and the [SM](#) has the same $\frac{1}{\Lambda^4}$ suppression as the [BSM](#) only term of the dimension 6 operators. This has to be considered in the interpretation of results, where only dimension 6 operators were considered.

In the analysis presented in this thesis, the `SMEFTsim 3.0` model [\[20\]](#) is used. The [EFT](#) scale is set to an arbitrary value of 1 TeV and constraints on $\frac{c_i}{\Lambda^2}$ are derived.

THE ATLAS EXPERIMENT AT THE LARGE HADRON COLLIDER

2

The [ATLAS](#) experiment is one of the four large experiments located at the [LHC](#). In this chapter, a short description of the accelerator chain leading up to the [LHC](#) is given in Section [2.1](#). Additionally, the different components of the [ATLAS](#) detector are discussed in Section [2.2](#).

2.1 The Large Hadron Collider

The [LHC](#) [[21](#), [22](#)] is located at the European Organisation for Nuclear Research (CERN) in Geneva, Switzerland. In the accelerator complex located at CERN (see Figure [2.1](#)) protons and heavy ions are accelerated to energies of up to 6.5 TeV in a succession of different accelerators. In this thesis, only proton collisions are considered.

In the first instance, positive hydrogen ions, coming from a hydrogen bottle where the electron is stripped off the hydrogen, are accelerated in the linear accelerator 2 to an energy of 160 MeV. The protons are then injected into the Proton Synchrotron Booster and, after being accelerated to 2 GeV, are injected into the Proton Synchrotron. The last instance before the [LHC](#) is the Super Proton Synchrotron, where the beam is accelerated from 26 GeV to 450 GeV.

With its 26.7 km circumference, the [LHC](#) is the largest accelerator in the world and the collider with the highest energy. The protons entering the [LHC](#) are injected into two beam pipes, where they circulate in opposite directions and are accelerated to their final energy of 6.5 TeV. In order to bend and focus the protons at these high energies, magnetic fields of up to 8.3 T are required. These are obtained by superconducting dipole and quadrupole magnets, which are cooled down to a temperature of 1.9 K. Once the protons reach their final energy, they are brought to collision inside one of the four interaction points, where different experiments such as ALICE [[24](#)], [ATLAS](#), [CMS](#) [[25](#)] and LHCb [[26](#)] are located.

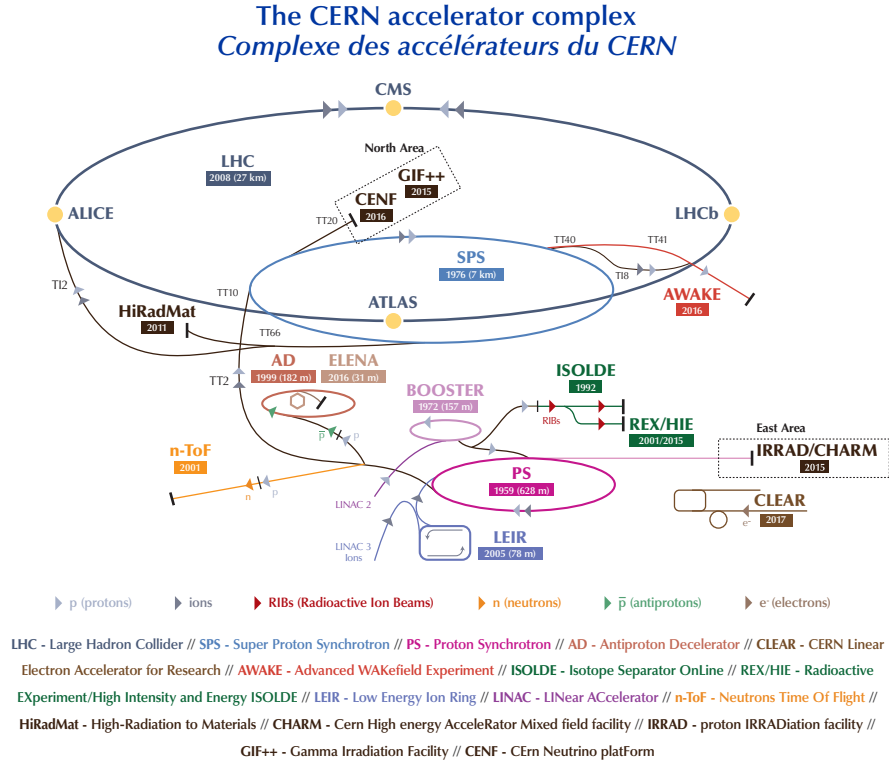


Figure 2.1: CERN accelerator complex in 2018 [23]

2.2 The ATLAS detector

The ATLAS detector [27] has a cylindrical shape around the LHC beam pipe with a length of 46 m and a diameter of 25 m. The central part of the detector is referred to as barrel and each side as end-caps. A schematic representation of the full detector is shown in Figure 2.2. The setup which is described in the following corresponds to the state in Run 2, as the analyses presented in this thesis are based on datasets collected in this specific run. More details on the current Run 3 detector configuration can be found in Reference [28].

2.2.1 Coordinate system

The ATLAS detector is symmetrical around the beam pipe line, with the interaction point in the centre. The coordinate system is therefore positioned, such that the origin corresponds to the nominal collision point. A Cartesian coordinate system is chosen, where the x-axis points towards the centre of the LHC and where the y-axis points upwards. The z-axis is then parallel to the beam line, forming a right handed coordinate system.

The kinematics of particles in the detectors are described by the four-momenta $\mathbf{p} = (E, \vec{p})$.

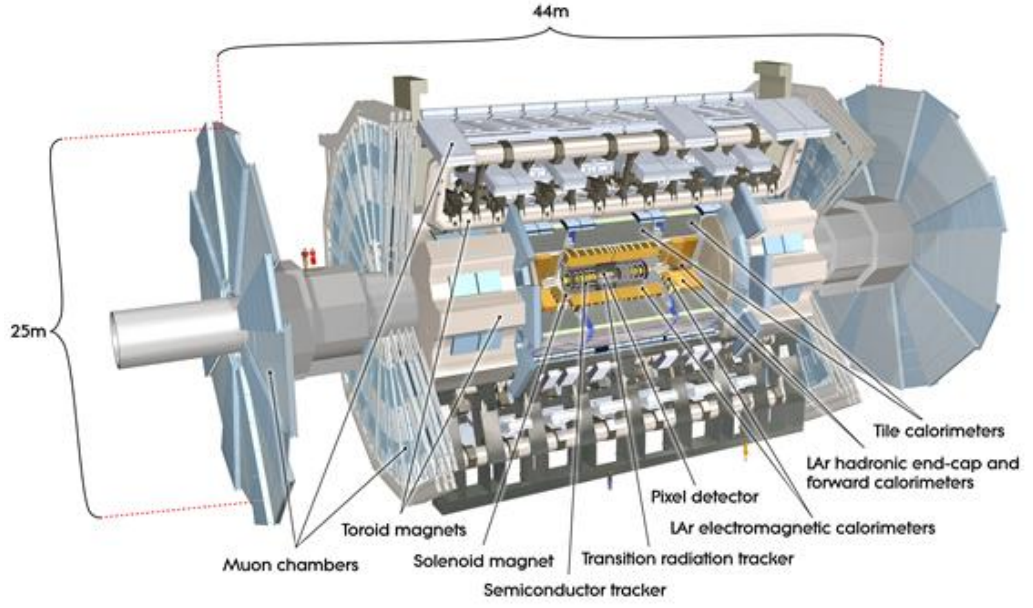


Figure 2.2: Schematic representation of the [ATLAS](#) detector [27]

In a proton-proton collision, the longitudinal momentum of the partons interacting in the hard interaction is not known. This means that p_z can in general not be used in order to describe the hard scattering. The transverse momentum though, defined by $p_T = \sqrt{p_x^2 + p_y^2}$ can be reconstructed, as the initial transverse momentum has to be zero and is conserved during the interaction.

Therefore, it can be helpful to describe the particle momenta in spherical coordinates, with p_T as the radius, an azimuthal angle ϕ and a polar angle θ .

A variable called rapidity can be introduced as:

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right) \quad (2.1)$$

This variable is defined in such a way that rapidity differences are Lorentz invariant under boosts along the z -axis. In the limit of massless or highly relativistic particles the rapidity simplifies to the pseudorapidity given by:

$$\eta = -\ln \left[\tan \left(\frac{\theta}{2} \right) \right] \quad (2.2)$$

The angular distance between two objects can then be expressed as:

$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} \quad (2.3)$$

2.2.2 Inner detector

The inner detector [29], depicted in Figure 2.3, is designed to provide precise tracking information. It covers the pseudo-rapidity range of $|\eta| < 2.5$ and is composed of three sub-detectors: the pixel detector, the semiconductor tracker and the transition radiation tracker. This subsystem is located inside a 2 T magnetic field which is produced by a solenoid magnet, located just outside of the inner detector. The magnetic field induces a bending of the tracks, which allows for a precise momentum reconstruction by measuring the curvature radius.

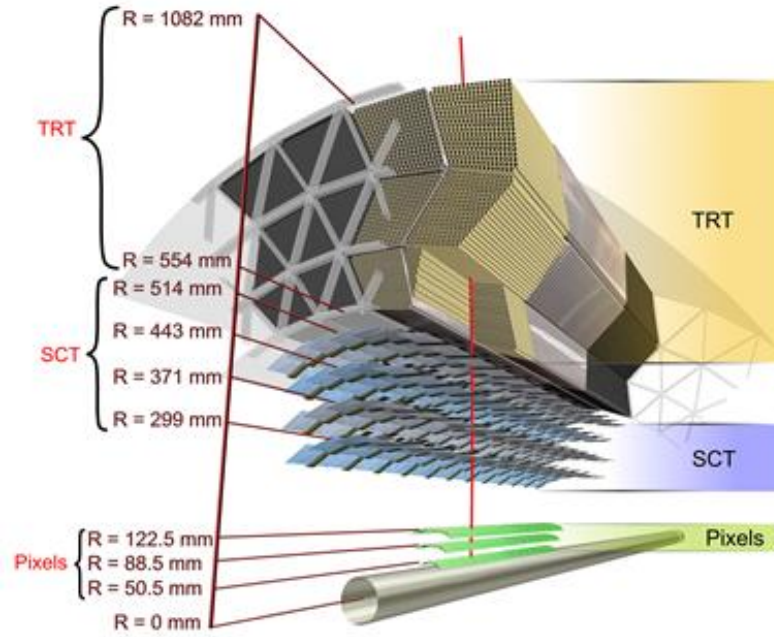


Figure 2.3: Schematic representation of the ATLAS inner detector [30]

Pixel detector

The pixel detector [31], located from 33 mm to 123 mm from the beam pipe, is the innermost component of the ATLAS detector. In the barrel region it consists of four layers of silicon pixels, where the innermost layer, called Insertable B-Layer [32, 33] was inserted for Run 2 to match the new requirements of the run. In the two end-caps, three pixel disks are placed to cover the

rest of the η range. The pixel detector is designed to reach an accuracy of $10\,\mu\text{m}$ in the $R - \phi$ direction and $115\,\mu\text{m}$ in the z direction.

Semiconductor Tracker

The semiconductor tracker [34], surrounding the pixel detector, corresponds to a silicon strip detector. It is composed of four double-layers in the barrel and nine double layers in each end-cap. This double layer structure with a small stereo angle between the sub-layers gives information about the z position. The strip design does not allow to reach the same spatial resolution as the pixel detector ($17\,\mu\text{m}$ in the $R - \phi$ direction and $580\,\mu\text{m}$ in the z direction). However, it helps to reduce the costs and the amount of material in front of the calorimeter compared to an all pixel detector.

Transition Radiation Tracker

The transition radiation tracker [35] is the outermost component of the inner detector, covering the radius from 554 mm to 1082 mm. It consists of layers of carbon-reinforced kapton drift tubes with gold-plated tungsten wires at the centre and filled with gas. The tubes are interlayered with polypropylene fibres, which allows for particle identification through transition radiation. In the barrel region the tubes are placed parallel to the beam pipe while they are perpendicular to the pipe in the end-caps.

The transition radiation tracker mainly works as a drift chamber, but was additionally designed for particle identification through transition radiation. However, important gas leaks required the use of an Argon based gas mixture instead of a Xenon based gas, leading to lower particle identification efficiencies than the design one.

2.2.3 Calorimeter system

After the inner detector, outside of the solenoid magnet, the calorimeter system, shown in Figure 2.4, is located. It is designed to measure the energy of most of the produced types of particles by absorbing them. The system is split into two parts: the Electromagnetic Calorimeter (ECal) targeting the energy measurement of electrons and photons and the Hadronic Calorimeter (HCal) providing the energy measurement of most particles which were not absorbed by the ECal.

The energy resolution of a calorimeter can be described as following:

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c \quad (2.4)$$

a corresponds to statistical fluctuations in the shower, b to the noise of the electronic readout system and c to a constant term describing artefacts of the calorimeter itself, such as non-uniformities.

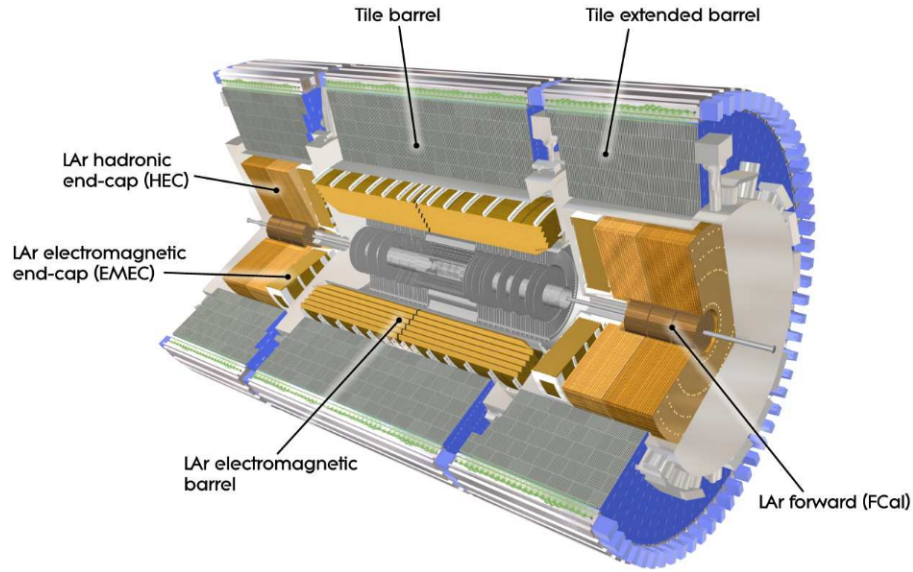


Figure 2.4: Schematic representation of the [ATLAS](#) calorimeter system [27]

Liquid argon calorimeter

The Liquid Argon Calorimeter ([LAr](#)) [36], targeting electrons and photons, is a sampling calorimeter composed of alternating layers of lead absorbers as absorbing material and liquid argon as active material. In the barrel region ($|\eta| < 1.475$) the absorber is placed in an accordion structure to maximise the interactions of the traversing particles. The design is such that electromagnetic showers are contained by the calorimeter. The achieved resolution corresponds to $\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}} \oplus 0.7\%$ [27].

Additionally to the barrel, [LAr](#) also includes electromagnetic and hadronic end-caps ($1.375 < |\eta| < 3.2$) as well as a forward calorimeter ($3.1 < |\eta| < 4.9$). In the hadronic end-caps copper is chosen as absorber while in the forward calorimeter copper is used for the first layer and tungsten for the following ones.

Tile hadronic calorimeter

The tile hadronic calorimeter [37], a sampling calorimeter as well, consists of iron and absorbs the hadrons which have passed the ECal. It is structured as three alternating layers of iron and scintillating plastic tiles. The depth of around 9.7 interaction lengths allows the calorimeter to fully contain most of the hadronic showers. The resolution of the HCal corresponds to $\frac{\sigma_E}{E} = \frac{50\%}{\sqrt{E}} \oplus 3\%$ [27].

The ferromagnetic iron used as absorber material is also used as flux return of the solenoidal magnetic field.

2.2.4 Muon system

The muon system, shown in Figure 2.5, is the outermost part of the ATLAS detector. As most particles are absorbed in the calorimeters, muons are the only particles leaving a track in the muon chambers. It consists of four different detectors, which are located inside a toroidal magnetic field bending the muon's trajectory, which, especially for high p_T muons, strongly improves the momentum resolution compared to inner detector measurements only.

While the Resistive Plate Chambers and the Thin Gap Chambers are designed for fast response used for muon triggers, the Monitored Drift Tubes and Cathode Strip Chambers provide precision tracking information. More details on the muon system can be found in the technical design report [38].

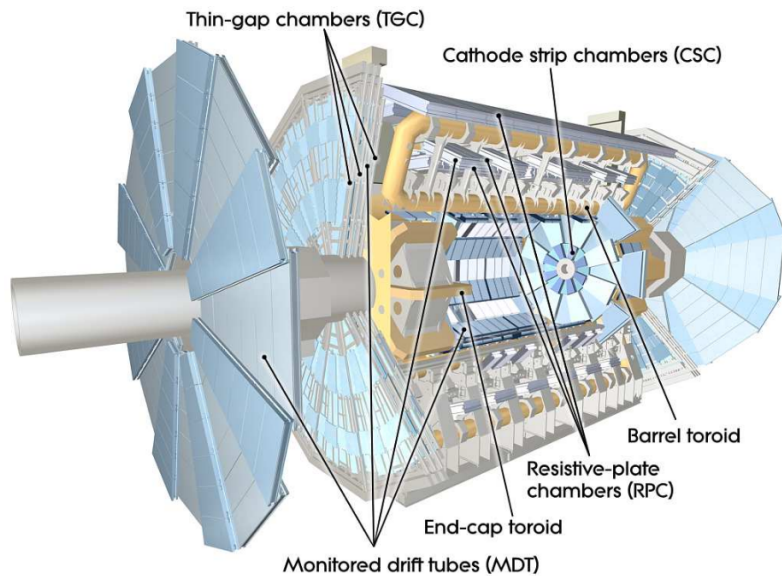


Figure 2.5: Schematic representation of the ATLAS muon system [27]

Resistive Plate Chambers

The resistive plate chambers are located in the barrel region. Each chamber has two independent detector layers, consisting of two resistive plates of phenolic-melaminic plastic laminate with gas in between. The plates have orthogonal read-out strips, providing a measurement in ϕ and η direction.

Thin Gap Chambers

The thin gap chambers are located in the end-cap regions. They correspond to multi-wire proportional chambers with gold-plated tungsten wires in between two cathode planes. The chambers are filled with a CO₂ and n-pentane gas mixture. The chambers are designed to have a very good timing resolution of about 4 ns.

Monitored Drift Tubes

The monitored drift tubes are located in the barrel as well as in the end-cap regions. They consist of drift tubes with a tungsten-rhenium wire and filled with a Argon CO₂ gas mixture. It provides high precision track coordinates.

Cathode Strip Chambers

In the end-caps, the monitored drift tubes are replaced by the cathode strip chambers in the innermost layer. It corresponds to a multi-wire proportional chamber filled with the same Argon CO₂ gas mixture as the monitored drift tubes. The cathodes are segmented into strips, resulting in a high spatial resolution.

PHYSICS WITH THE ATLAS DETECTOR

3

In this chapter, the data taking by the [ATLAS](#) detector and the physics interpretation of these data is described. First the concept of luminosity, describing the amount of delivered data by the [LHC](#), is introduced in Section [3.1](#), followed by a description of the [ATLAS](#) trigger system in Section [3.2](#) and the conditions in the different data-taking periods in Section [3.3](#). The physics of proton-proton collisions are then described in Section [3.4](#) and the algorithms to reconstruct physics events from the detector outputs as well as related systematics are detailed in Section [3.5](#). Finally, the top and Higgs physics programmes of the [ATLAS](#) collaboration are outlined in Sections [3.6](#) and [3.7](#).

3.1 Luminosity

The protons accelerated in the [LHC](#) do not form a continuous train but are grouped into bunches. These bunches are then brought into collision at the interaction points. The number of proton-proton collisions per unit of time is given by the luminosity, which is calculated as follows:

$$L = \frac{n_1 n_2 f_{coll} n_b}{4\pi \sigma_x \sigma_y} \quad (3.1)$$

where n_i are the number of protons in each bunch, f_{coll} is the collision frequency of the bunches, n_b is the number of bunches per train and $\sigma_{x,y}$ are the transverse dimensions of the beams.

The size of a collected dataset can then be indicated by the integrated luminosity, the integral of the luminosity over the recording time: $L_{int} = \int L dt$. Finally, the number of expected events of a given process is given by $N = \sigma L_{int}$, where σ is the cross-section of the process.

In each bunch crossing, several protons can interact. The average number of interactions per bunch crossing is called pile-up ($\langle \mu \rangle$). Pile-up can affect recorded events in two different ways, called in-time and out-of-time pile-up. In-time pile-up corresponds to additional proton-proton collisions happening in the same bunch-crossing as the recorded event. In out-of-time pile-up, the additional proton-proton collisions originate from the previous or following bunch-crossing, but can affect the recorded event if detector parts have a sensitive time longer than the spacing between the bunch-crossings.

3.2 Trigger

During data taking, the LHC delivers a collision rate inside ATLAS of 40 MHz. This results in a data volume which cannot be stored. Therefore a trigger [39] is applied, which filters the events in order to save only a subset of them. The decision is based on certain event criteria, selecting only events with a potential physics interest. The trigger is built out of two subsystems.

The first instance, called Level-1, performs a very fast reconstruction at hardware level, including calorimeter and muon system information. Level-1-calorimeter, using energy deposits in the calorimeters, and Level-1-muon, using coincidence patterns within defined regions of the resistive plate chambers and the thin gap chambers, are used to identify leptons, photons and jets. Level-1-topo receives this information and applies some kinematic and angular selection criteria. With a latency of only about $2.5 \mu\text{s}$ the event rate is reduced by the Level-1 trigger to around 100 kHz.

The second instance is called high-level trigger and is software based, using higher granularity information in order to reconstruct objects and apply selections. Higher granularity calorimeter information together with tracking information is used to reconstruct objects with simplified algorithms in the fast reconstruction, and with more precise but slower algorithms in the precision reconstruction. Using the partial reconstruction of an event allows saving events according to specific signatures defined in the trigger menu. With a processing time of around 0.2 s the high-level trigger brings the total event output rate down to around 1 kHz.

3.2.1 Trigger strategy

In the analyses described in this thesis, different triggers are used. Single lepton triggers (single electron or single muon triggers) save events with at least one lepton of the required flavour above a predefined p_T threshold. The di-lepton trigger stores events with at least two leptons

above certain p_T thresholds, the thresholds being in general lower than for the single lepton trigger. The exact p_T thresholds differ in the years of data-taking.

3.2.2 Trigger systematics

In order to account for differences in the trigger efficiency in data and simulation, scale factors are derived and applied on the simulated data. These scale factors come with systematic uncertainties applied in the analyses on the reconstructed objects.

3.3 ATLAS data-taking

3.3.1 Run 1

During the first phase of the [LHC](#) running, starting in 2010, [ATLAS](#) collected two datasets with different centre-of-mass energies. In 2010 and 2011 an integrated luminosity of 45.0 pb^{-1} and 5.1 fb^{-1} was collected respectively at a centre-of-mass energy of $\sqrt{s} = 7 \text{ TeV}$. In 2012 the centre-of-mass energy was slightly increased to $\sqrt{s} = 8 \text{ TeV}$, collecting a dataset with an integrated luminosity of 21.3 fb^{-1} . These three years of running correspond to the Run 1 of the [LHC](#).

3.3.2 Run 2

After a shutdown of three years, the [LHC](#) restarted in 2015 at a strongly increased centre-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$. Until the year 2018, [ATLAS](#) then collected in total $(140 \pm 1) \text{ fb}^{-1}$ of data, as shown in Figure 3.1. The breakdown corresponds to 3.2 fb^{-1} in 2015, 33.4 fb^{-1} in 2016, 44.6 fb^{-1} in 2017 and 58.8 fb^{-1} in 2018.

As shown in Figure 3.2, the pile-up is strongly dependent on the year of data-taking, with an average pile-up of $\langle \mu \rangle = 34.2$.

The analyses described in this thesis are performed on the full Run 2 dataset, tagged as suitable for physics analyses.

3.3.3 Run 3

After a second long shutdown, the current [LHC](#) run, called Run 3, started in summer 2022 and is planned to continue until the middle of 2026. The aim is to collect around 300 fb^{-1} of data

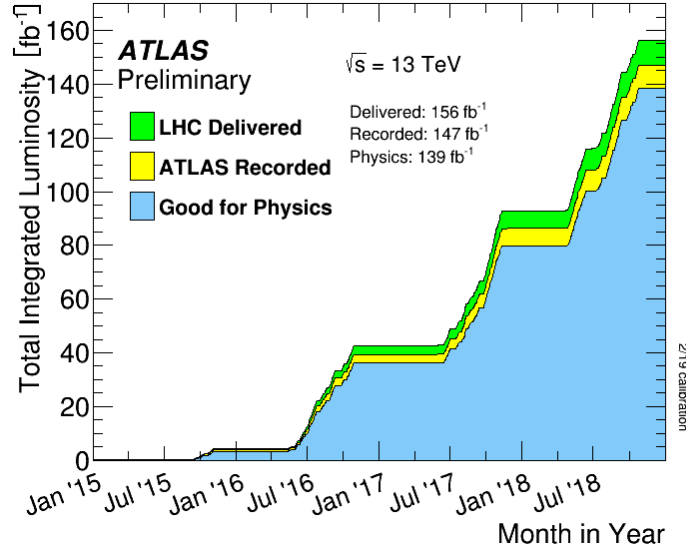


Figure 3.1: Integrated luminosity recorded by ATLAS during the Run 2 [40]

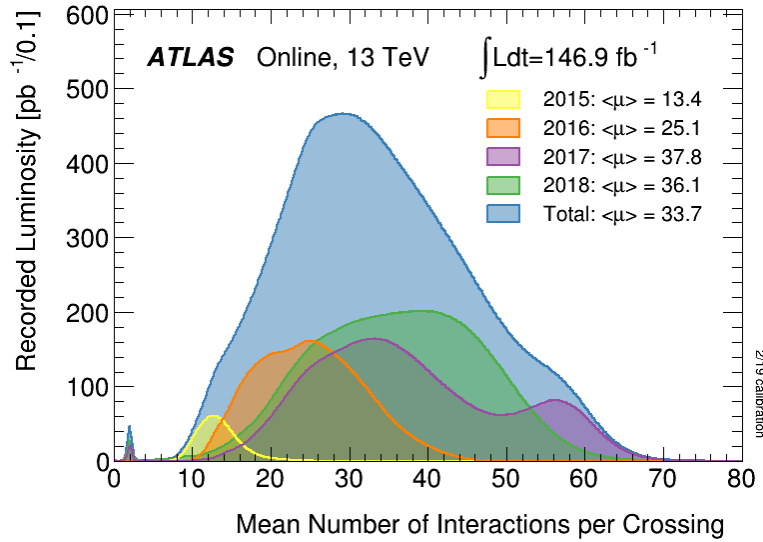


Figure 3.2: Average pile-up in the Run 2 split by years [40]

at a centre-of-mass energy of 13.6 TeV. Compared to the detector setup in Run 2, new muon end-caps were installed and several trigger upgrades were performed.

3.3.4 High-luminosity LHC

After Run 3, the LHC as well as the ATLAS detector will be upgraded [41] in order to run at much higher luminosities, the target baseline luminosity being $5 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$ and reaching up to an ultimate peak luminosity of $7.5 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$. Under these conditions, there will be an average of 140 to 200 proton-proton collisions per bunch crossing. Besides upgrades on the read-out electronics and the trigger, several muon chambers will be replaced, a new high-granularity

timing-detector will be inserted as well as the current inner detector will be replaced by the ITk detector, consisting of a silicon pixel and strip detector. This phase is often referred to as the high-luminosity [LHC](#). The plan is to run under these high-luminosity conditions between 2030 and 2041, collecting at least 3000 fb^{-1} proton-proton collision data at a centre-of-mass energy of $\sqrt{s} = 14 \text{ TeV}$.

3.4 Proton-proton collisions

In one proton-proton (pp) bunch crossing at the [LHC](#), several interactions can happen simultaneously: several protons in the bunches can interact, called pile-up, and several partons inside the protons can interact in one pp collision, referred to as multi-parton interactions.

The fact that protons are composite particles additionally means that the interactions happen between the quarks and the gluons which only carry a momentum fraction x of the proton momentum. Contrary to electron-electron collisions where the kinematics of the interaction are fully determined by the beam characteristics, in pp collisions, the longitudinal momentum of the centre-of-mass frame of the collision is unknown.

The distribution of the fraction x of the total proton momentum carried by a parton is given by the Parton Density Functions (PDFs). These functions depend on the type of the parton (gluon or flavour of the quark) and need to be determined experimentally. The proton PDFs for gluons and different quark flavours in the CT14 PDF set [42] are shown in Figure 3.3.

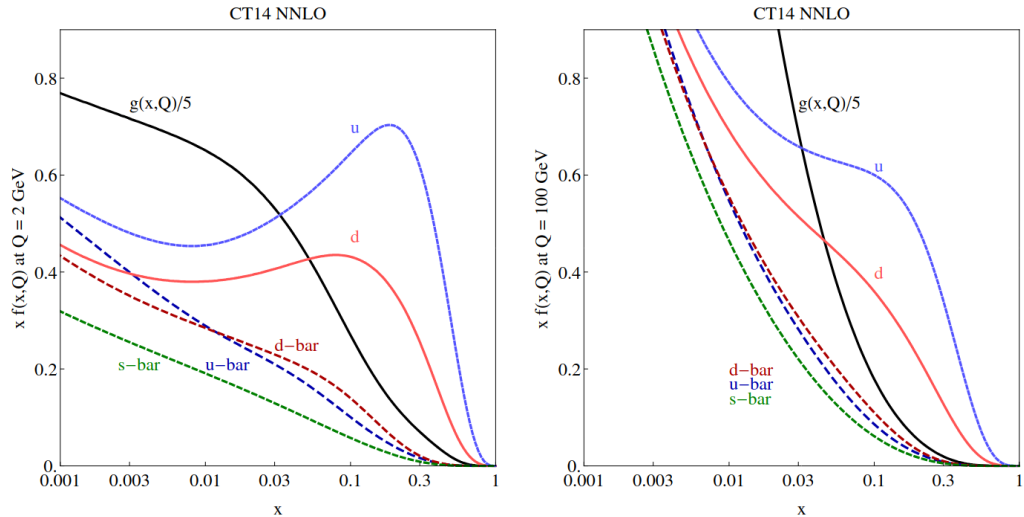


Figure 3.3: Proton PDFs in the CT14 set at 2 GeV (left) and at 100 GeV (right) [42]

While the centre-of-mass energy of the pp collision is given by $\sqrt{s} = E_1 + E_2$, where E_i is the energy of the i th proton, the actual centre-of-mass energy of the interaction is only $\hat{s} = x_1 x_2 s$.

The knowledge of the PDFs is therefore essential in order to model pp events with a given pp centre-of-mass energy. The PDFs are determined using deep inelastic scattering data, such as ep -collisions at HERA [43]. As the functional form of the PDFs is not known, a generic function is in principle required to be fitted to the measurements. Two different approaches are used for the fits: parametrisation with a hand-picked number of terms or the use of a neural network [44]. Most of the predictions used in the analyses described in this thesis use the NNPDF 3.0 [45] set of PDFs using the neural network approach. The PDFs are determined as a function of x at a specific momentum transfer Q^2 , but can be extrapolated to other Q^2 values using the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi evolution equation [46, 47, 48].

3.5 Object reconstruction

In all recorded and simulated events, a full offline event reconstruction is performed. The reconstructed objects are charged leptons, photons, jets, corresponding to the hadronic parts of the event, and missing transverse energy. The object reconstruction is based on the digital signals recorded by the different detectors. The hits, produced by charged particles interacting with the inner detector and the muon chambers, are used to reconstruct tracks through different fitting procedures. Combining these tracks allows searching for vertices and the vertex with the highest sum of transverse momentum is considered as the primary vertex where the hard interaction takes place. Additionally, energy deposits in the calorimeters are clustered and associated with the tracks in the inner detector. All this information is then combined to determine the trajectory of a particle, the transverse momentum and energy as well as the particle type.

Different criteria are applied on the objects, which, according to the chosen Working Point (WP), identify objects with a specific efficiency and reject backgrounds with a certain rejection rate. All these WPs are calibrated and come with scale factors, accounting for differences in the reconstruction between data and simulation.

A more detailed description of the reconstruction techniques for the different particle types is given in the following.

3.5.1 Electrons

The signature of electrons in the ATLAS detector are clusters in the ECal and HCal matched to at least one track in the inner detector. An energy calibration is performed on the clusters which

are used for the reconstruction in order to determine the initial electron energy. The charge is determined by the curvature of the track. [49]

Electrons are classified into prompt and non-prompt/fake electrons. While prompt electrons are produced in the hard interaction and therefore originate from the primary vertex, non-prompt electrons are produced in subsequent interactions such as photon conversions or in semileptonic decays inside jets and fake electrons are mimicked by jets. Based on the track quality and on the clusters and tracks around the electron candidate, different attributes are given to each electron candidate, such as the identification and the isolation, aiming at selecting prompt electrons.

For the requirement of the electron to arise from the primary vertex, selection cuts on the transverse (d_0) and longitudinal (z_0) impact parameters are applied [49]. d_0 is defined as the distance in the $x - y$ plane of closest approach between the track and the collision point and z_0 as the projection on the z axis of the distance between the primary vertex and the track point used for d_0 . Finally, electron candidates situated in the **LAr** crack-region ($1.37 < |\eta| < 1.52$) are vetoed in order to suppress non-prompt leptons.

Identification

The electron identification used in the analyses presented in this thesis is based on a likelihood approach [49, 50]. In this method, a likelihood discriminant between prompt and non-prompt electrons is built, which is based on a large number of different kinematic variables combining track and shower shape information.

Three different calibrated **WPs** are defined, corresponding to different prompt electron selection efficiencies and non-prompt/fake electron rejection power. For electrons above 40 GeV, the **Loose**, **Medium** and **Tight WPs** have a selection efficiency of 93 %, 88 % and 80 %.

Isolation

Additionally to the identification, isolation requirements can further suppress non-prompt leptons, rejecting especially electrons created in hadron decays. The isolation criterion is based on the amount of activity in the inner detector and in the calorimeter around the electron candidate. Two different approaches are used in the analyses presented in this thesis, based on cuts on kinematic variables or based on a Boosted Decision Tree (**BDT**).

In the purely cut based approach, the energy deposited in the calorimeter inside a cone with radius $R = 0.2$ around the electron candidate, after subtracting the energy of the electron itself

and the pile-up, has to be below a certain percentage of the electron p_T . Additionally, the sum of p_T of the tracks inside a cone of radius R around the electron candidate, R being the smaller of 0.3 and $10 \text{ GeV}/p_T^e$, has to be below an electron p_T dependent threshold. In the `LooseVar_Rad WP`, the thresholds are set to 20 % for the calorimeter isolation and 15 % for the track isolation.

In the `BDT` based approach, called Prompt Lepton Veto (`PLV`) [51] used in the analyses presented in this thesis, the input variables contain information about the track-jet associated to the electron candidate as well as the isolation of the calorimeter cluster of the electron candidate. Prompt electrons are selected by the `Tight WP` with an efficiency of about 60 % for $p_T \sim 10 \text{ GeV}$ and 96 % for $p_T \gtrsim 45 \text{ GeV}$ while having a rejection factor of about 20 against electrons from B-hadron decays. In addition to the `PLV` isolation, some parts of the analyses presented in the following make use of the Prompt Lepton Improved Veto (`PLIV`) [52], which has additional input variables targeting secondary vertices coming from potential B-hadron decays. The selection efficiencies are shown in Table 3.1. Rejection factors between 20 and 50 are achieved for the `Tight WP` and between 33 and 66 for the `VeryTight WP`.

Table 3.1: Selection efficiency of prompt leptons of the `Tight` and `Very Tight PLIV WPs` [52].

	$p_T^{e, barrel} \sim 20 \text{ GeV}$	$p_T^{e, barrel} \gtrsim 40 \text{ GeV}$	$p_T^{e, end-cap} \sim 20 \text{ GeV}$	$p_T^{e, end-cap} \gtrsim 65 \text{ GeV}$	$p_T^{\mu} \sim 20 \text{ GeV}$	$p_T^{\mu} \gtrsim 40 \text{ GeV}$
<code>Tight</code>	60 %	95 %	70 %	90 %	60 %	95 %
<code>VeryTight</code>	55 %	85 %	60 %	83 %	55 %	90 %

Charge misreconstructed electrons

Reconstructed electrons can have the wrong charge assigned to them. The misreconstruction of the charge can either happen for high p_T electrons where the curvature of the track is small or because of an opposite-sign electron created in the pair production of a bremsstrahlung photon. In order to suppress these charge flip electrons, the Electron Chargeflip Tagger ID Selector (`ECIDS`) [49] is used. It consists of a `BDT` trained on cluster and track related variables and variables describing the relation between track and cluster of the electron candidate.

The `WPs` for `ECIDS` have been derived with and without isolation requirements and achieve very high signal efficiencies of 97 % to 98 % and background rejection factors between 6 and 12.

Conversion electrons

Conversion electrons do not originate from the hard interaction but from photons undergoing pair production: internal conversions come from a virtual photon converting to a low-mass electron pair and material conversions originate from photons converting in the detector material. To suppress these, an ambiguity type cut can be applied, based on a procedure to remove ambiguities between overlapping objects. Additionally, conversion criteria are defined. If possible, a conversion vertex is reconstructed between the electron and the closest ΔR silicon track with opposite charge. Out of this vertex three variables are calculated, which provide good discrimination between material and internal conversions: the conversion radius as well as the invariant mass at the conversion vertex and at the primary vertex. At reconstruction level, the leptons are then classified following these cuts:

- as a material conversion: a conversion vertex is found with a radius above 20 mm and the invariant mass at the conversion vertex is between 0 MeV and 100 MeV
- as an internal conversion: a conversion vertex is found with a radius below 20 mm and the invariant mass at the primary vertex is between 0 MeV and 100 MeV
- as a prompt electron: is not classified as a material or an internal conversion

3.5.2 Muons

Muons are the only charged particles which are not absorbed in the calorimeter system, leaving a track in the muon system. The muon trajectory is reconstructed by matching tracks in the inner detector to tracks in the muon system. While in the first step, the inner detector and the muon system tracks are reconstructed independently, after a first matching a combined fit is performed, where single hits in the muon system can be removed to improve the quality of the fit [53].

Similar to electrons, selection cuts on the transverse and longitudinal impact parameters are applied and identification and isolation criteria are defined for muon candidates.

The identification [53] is based on the quality of the tracks in the inner detector and the muon system as well as the compatibility between those. Five identification **WPs** are defined for muons: **Loose**, **Medium**, **Tight**, **Low p_T** and **High p_T** . For muons with a transverse momentum between 20 GeV and 100 GeV, selection efficiencies of 93 % for the **Tight**, 97 % for the **Medium** and 99 % for the **Loose WPs** are obtained with light hadron misidentification rates of 0.12 %, 0.17 % and 0.25 % respectively.

For the isolation, the same tools as for electrons are used, namely the cut based isolation and the BDT based approach (PLV and PLIV). For PLV, the selection efficiency for prompt muons by the Tight WP corresponds to 70 % for $p_T \sim 10\text{GeV}$ and 98 % for $p_T \gtrsim 45\text{GeV}$ with a rejection factor of about 20 against muons from B-hadron decays. The selection efficiencies for the PLIV WPs are given in Table 3.1. The rejection to muons from B-hadron decays ranges from 33 to 50 for the Tight WP and between 50 and 100 for the VeryTight WP.

Charged lepton systematics

All the reconstruction and selection techniques for electrons and muons are susceptible to differences between data and simulation. These differences are corrected by performing calibrations or applying scale factors. Systematic uncertainties are applied in analyses accounting for uncertainties in the energy calibration, the lepton reconstruction, identification and isolation efficiencies, as well as in the ECIDS applied on electrons and the track-to-vertex association for muons.

Energy calibration Differences in the energy scale between data and simulation are corrected in data, while differences in the energy resolution are corrected in the simulation. $Z \rightarrow \ell\ell$ events are used to derive pseudo-rapidity dependent correction factors, adjusting the dileptonic invariant mass distribution in data and simulation. Two different fitting procedures are used to determine the correction factors and the difference is taken as an uncertainty [50]. The calibrated data and the corrected simulation is shown for electrons in Figure 3.4.

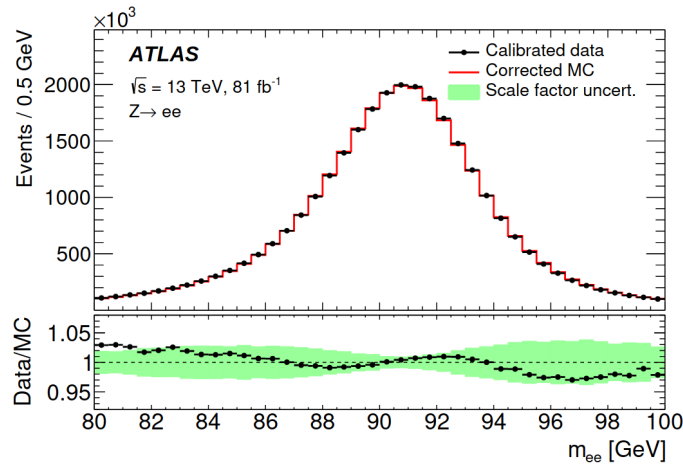


Figure 3.4: Calibrated energy scale and resolution in $Z \rightarrow ee$ events [50]

Reconstruction, identification and isolation efficiency Efficiency differences in the reconstruction, identification and isolation between data and simulation need to be corrected in simulation by applying scale factors. These scale factors are derived with a tag and probe method, by

comparing the lepton reconstruction, identification or isolation efficiency of the probe lepton in $Z \rightarrow \ell\ell$ and $J/\Psi \rightarrow \ell\ell$ events in data and simulation. The efficiencies in data and simulation as well as the ratio is shown for electrons in Figure 3.5. The uncertainties in the efficiency determination are approximated by varying the considered Z or J/Ψ mass windows (the peak region for the tag and probe method as well as the side-band regions used for the background estimation), the selection criteria for the tag lepton and the background template. The uncertainties are considered in the analyses as systematical uncertainties on the scale factors [49, 54, 53, 55, 51].

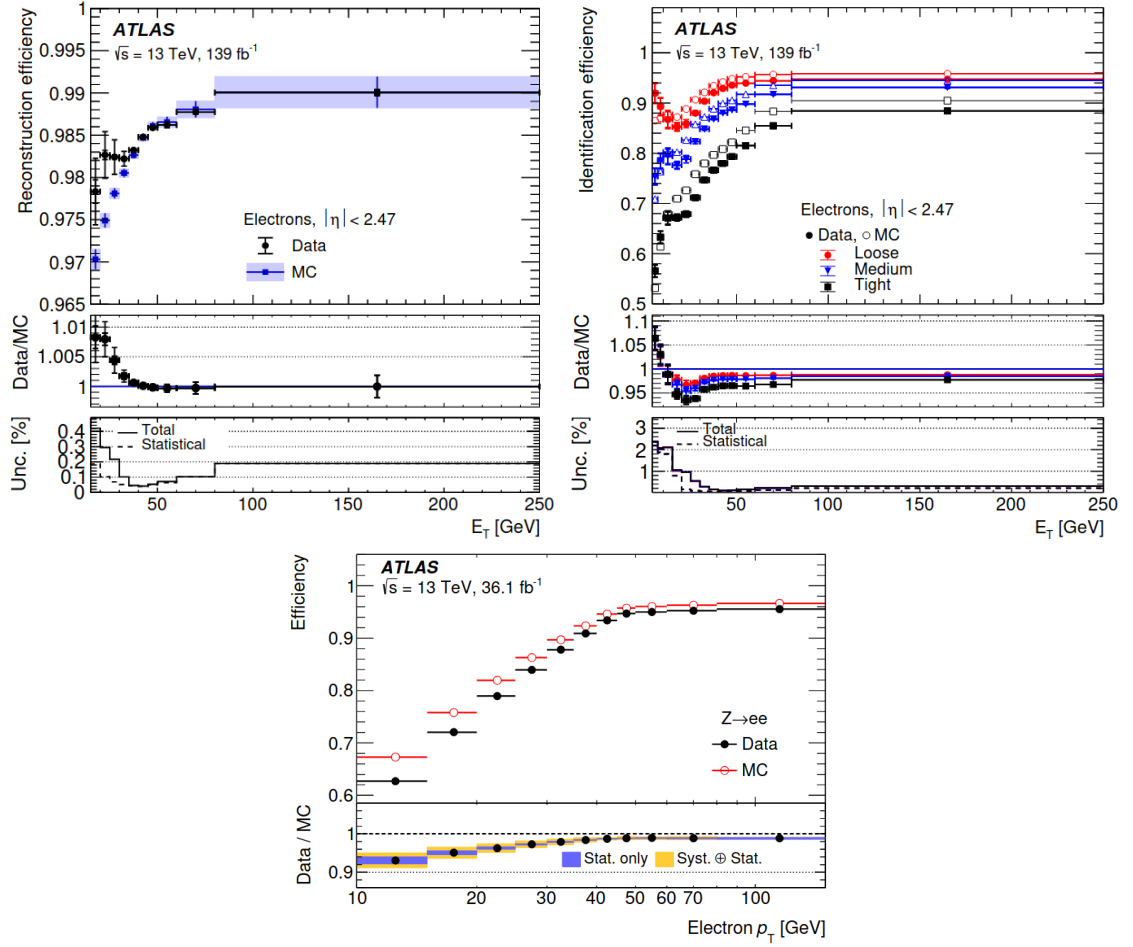


Figure 3.5: Efficiency of the electron reconstruction (top left), identification (top right) and isolation (bottom) from $Z \rightarrow ee$ events as a function of the electron transverse momentum [54, 51]

3.5.3 Jets

As described in Section 1.1, coloured objects (quarks and gluons) are confined and cannot be observed as free particles. Instead, high momentum coloured partons radiate gluons or undergo quark pair production leading to an accumulation of coloured partons in the detector, which can be categorised as an object referred to as a jet. This jet is defined by jet-finding algorithms. Experimentally, jets are formed of energy deposits in the **E**Cal and **H**Cal and potentially by tracks

in the inner detector. They are reconstructed using the anti- k_t algorithm [56] with the angular distance parameter $R = 0.4$. Particle-flow algorithms [57] are employed in order to improve the energy and angular resolution of the jet reconstruction. Additionally, the Jet Vertex Tagger [58] is used to suppress pileup jets, by considering variables regarding the tracks associated with the jet and which vertex they originate from.

Jet reconstruction

The energy deposits detected in the calorimeter cells are clustered into topo-clusters, which are seeded by cells with a large energy deposit. Neighbouring cells are added if their energy is above a pre-defined energy threshold. In particle-flow jets, which are used in the analyses described in this thesis, the jet reconstruction is performed on particle-flow objects. In these particle-flow objects, energy in the topo-cluster deposited by charged particles is replaced by the momenta of the tracks matched to the cluster. For high- p_T tracks, where the energy resolution of the calorimeter is better than the p_T resolution of the tracker, no inner detector information is used. A calibration is finally performed to obtain the jet energy scale and the jet energy resolution is measured in data [57].

Flavour tagging

Additionally to the jet reconstruction, flavour tagging is applied, which identifies from which quark a jet originates. The algorithm used in this thesis includes three categories: b -jets, c -jets and light-flavour jets.

For b -tagging, different properties of the B-mesons are utilised. Because of its relatively long lifetime of about 1.5 ps, the B-hadron travels a few millimetres before its decay, meaning that a secondary vertex can often be reconstructed, as shown in Figure 3.6. Its dominant decay modes include a C-hadron, which then decays again after a short time, producing a second displaced vertex. Furthermore, b -jets tend to be relatively wide because of the high mass difference between the B-meson and its decay particles, leading to high relative transverse momenta. Finally, nearly 40 % of the B-meson decays happen semi-leptonically, meaning that leptons are associated with the jet.

In Run 2, ATLAS uses a high-level b -tagging algorithm, DL1 [60], based on a deep feed-forward neural network with three output nodes giving the probability of a jet to be a b -, a c - or a light-flavour jet. Its input variables include the jet kinematics, some likelihood discriminant between

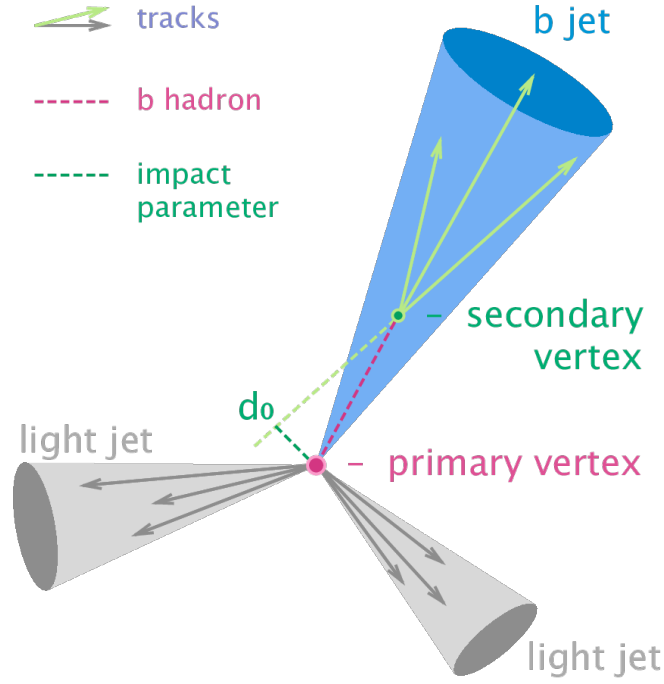


Figure 3.6: Schematic representation of a b-jet versus light jets [59]

jet-flavour hypotheses based on impact parameter information, and secondary and tertiary vertex information.

Different WPs are defined and calibrated. The main b -tagging WP used in the analyses presented in this thesis, is the WP with an 85 % b -tagging efficiency and a rejection of 2.6 for c -jets, 3.9 for τ -jets and 29 for light jets.

Jet systematics

Several uncertainties associated with a potential jet mismodelling are considered. Scale factors with associated uncertainties are derived to account for differences in data and simulation for the jet energy scale [57], using well-measured objects such as photons and Z bosons, and for the flavour-tagging [60], using $t\bar{t}$ events. Systematic uncertainties are applied on the jet energy scale and jet energy resolution [61], as well as on the jet vertex tagger.

Jet energy scale and resolution Correction factors, scaling the four-momentum of the jet, are derived to calibrate the reconstructed jet energy to the energy of jets reconstructed at particle level. A chain of calibration steps is performed, detailed in Reference [61], applying the corrections to data and simulation. The last step corresponds to a residual in situ calibration, which is only applied to data and corrects for differences between data and simulation. These in situ correction factors are shown in Figure 3.7. Systematic uncertainties arising in each step of the

calibration are propagated to the final jet energy scale correction, including uncertainties on the calibration method, the pile-up or the flavour composition. In order to match the jet energy resolution in simulation with the resolution in data, a smearing is applied in simulation for jets in a p_T region where the resolution in data is larger than in simulation. Systematic uncertainties are applied on this smearing procedure.

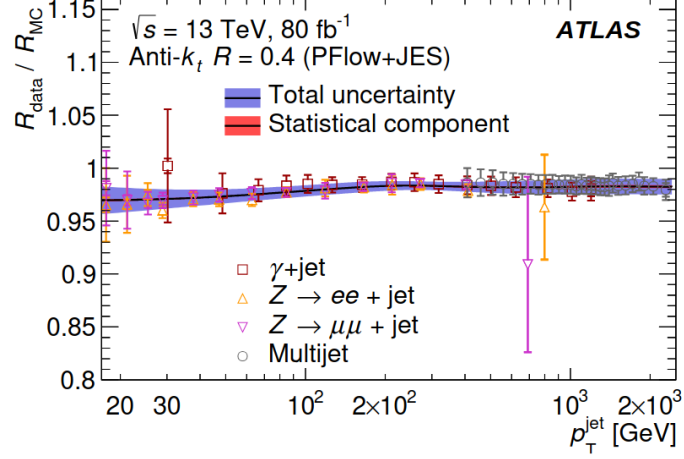


Figure 3.7: In situ jet calibration factors [61]

Flavour-tagging efficiency The flavour-tagging efficiency is measured for each jet flavour category in control samples in data as well as in simulation and correction factors are derived to correct the tagging rates in simulation. Systematic uncertainties on the flavour-tagging efficiency are derived by propagating simulation uncertainties of the considered processes to the final measurement [60].

3.5.4 Taus

With a lifetime of about 290×10^{-15} s [11], taus decay into a W and a tau neutrino before interacting with the detector. The subsequent W decay can then happen either leptonically, with a branching ratio of 35 %, or hadronically, with a branching ratio of 65 %. In the case of a leptonic decay, the taus are reconstructed as the light flavour lepton in which the tau decayed, losing the neutrinos for the kinematic information of the lepton. In hadronically decays, the tau (τ_{had}) decays into pions (one charged pion or three charged pions) as well as neutrinos.

The reconstruction of τ_{had} first follows the reconstruction procedure of jets. With a requirement of one or three tracks with a total charge of $\pm 1e$, a [BDT](#) is used to reconstruct τ_{had} candidates. A Recurrent Neural Network ([RNN](#)), which uses calorimeter and tracking based variables, is applied [62] to distinguish between τ_{had} candidates and generic jet backgrounds. Three iden-

tification **WPs** are defined based on the output of the **RNN**. The **Medium WP**, used in one of the analyses presented in this thesis, has an efficiency of 75 % with a background rejection of 35 for one-prong τ_{had} and of 60 % with a rejection of 240 for three-prong τ_{had} . Finally, a separate **BDT** is applied to reject τ_{had} candidates having one associated track which originates from an electron. Its efficiency for real τ_{had} is of 95 % with a p_T and η dependent rejection of 30 to 100.

Tau systematics

For hadronically decaying tau leptons, several uncertainties are associated with the τ_{had} reconstruction efficiency, the **RNN** identification efficiency, as well as the electron veto **BDT**. Additionally, similar to jets, the energy scale is calibrated, coming with a set of systematic uncertainties.

3.5.5 Missing transverse energy

The missing transverse energy (E_T^{miss}) is defined as the magnitude of the missing transverse momentum and exploits the fact that the p_T of the partons before the collision is negligible. By momentum conservation, all the transverse momenta of the particles produced in the interaction therefore have to sum to zero. The missing transverse momentum therefore corresponds to the p_T which was not detected by the detector, such as from neutrinos. It is defined as:

$$\vec{p}_T^{miss} = - \left(\sum_{i \in \text{hard}} \vec{p}_{T,i} + \sum_{j \in \text{soft}} \vec{p}_{T,j} \right) \quad (3.2)$$

The hard term corresponds to the reconstructed and calibrated electrons, muons, jets and photons, while the soft term [63] corresponds to tracks which point towards the primary vertex but are not associated with any object.

E_T^{miss} systematics

Uncertainties on all reconstructed objects used in the E_T^{miss} calculation are propagated. Additionally, uncertainties concerning the energy scale and resolution of the soft term are applied, derived in $Z \rightarrow \mu\mu$ events, where no missing transverse energy is expected.

3.6 Top physics programme

The top quark is the up-type quark of the third generation and therefore the weak isospin partner of the bottom quark. The existence of the top quark was predicted after the discovery of the b -quark in the 1970s before being discovered at the Tevatron in 1995 by the CDF and the DØ collaborations [64, 65].

The LHC is sometimes called a ‘top quark factory’, as an unmatched number of top quark events has been collected since its start in 2010, with around 100 million $t\bar{t}$ events in Run 2 only. This allows measuring different properties of the top quark with unique precision and to potentially unveil discrepancies from the SM predictions.

3.6.1 Decay

Because of its very large mass, the top quark has an extremely short lifetime of approximately 0.5×10^{-24} s [11]. Nearly 100 % of the time, the top decays into a W boson and a b -quark. While the W then decays further, either hadronically or leptonically, the b -quark is detected in the ATLAS detector as a jet. The variety of W decay modes leads to a rich phenomenology in the possible final states as well as in the top quark property measurements.

3.6.2 Production

The top production at the LHC is largely dominated by $t\bar{t}$ production, which in 90 % happens through gluon-gluon fusion and in 10 % via quark-antiquark annihilation.

The second largest cross-section is the production of a single top in association with another quark, a W or a Z boson.

Finally, there are much rarer processes which become accessible with the large amount of data collected in Run 2, such as $t\bar{t}V$ ($V = \gamma, Z, W, H$), tVq ($V = \gamma, Z$), tWZ or $t\bar{t}t\bar{t}$. Many of these were recently studied in ATLAS and CMS, corresponding to the experimental discovery of these processes.

A summary of all the inclusive cross-section measurements provided by ATLAS for top quark processes is shown in Figure 3.8.

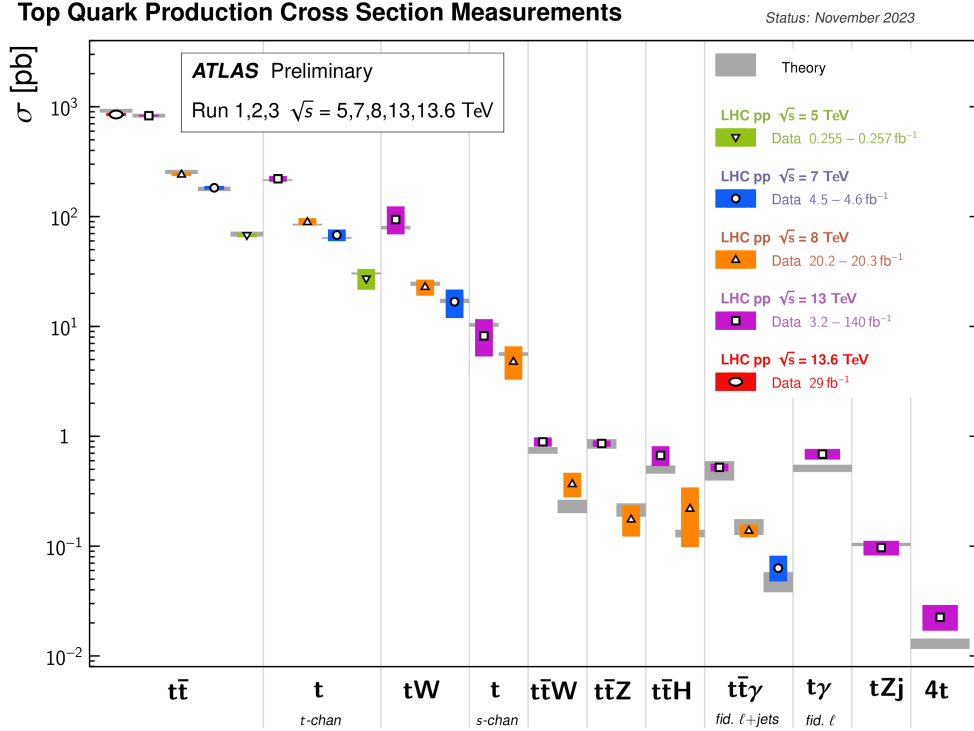


Figure 3.8: Summary plot of the inclusive cross-section of different top processes measured by ATLAS [66]

3.6.3 Physics goals

The very high statistics of $t\bar{t}$ production at the LHC allow for precise inclusive and differential cross-section measurements as well as studies of the decay width, the mass, the spin correlation or the charge/energy asymmetry. All these measurements represent important tests of the SM predictions [67].

The lifetime of the top quark is about one order of magnitude below the hadronisation time scale, meaning that the top decays before its hadronisation. All other quarks decaying only after hadronisation, this gives the unique possibility to study bare quark properties.

The top mass is a free parameter of the SM. It is measured to be 172.52(33) GeV [68], making the top quark the heaviest known elementary particle. It is in the order of the Z , W or H boson masses and much larger than for all other fermions (the bottom quark following with a mass of about 4.2 GeV [11]). Because of its size, the top mass also impacts through loop corrections the masses of the W , the Z and the Higgs boson and is therefore an important input to global EW fits.

The mass is a result of a very strong top Yukawa coupling of order 1. The top-Higgs coupling therefore has a special importance in the measurement of the Yukawa coupling and can be probed in a direct way in processes such as tH and $t\bar{t}H$.

The [EW](#) coupling of the top quark to the photon and the Z boson can be studied in $t\bar{t}V$ ($V = \gamma, Z$) processes. Inclusive and differential cross-section measurements are performed allowing for reinterpretations, such as the interpretations in the [EFT](#) framework to test for potential deviations from the [SM](#) prediction.

Top quark decays can also be used in the search for new [BSM](#) particles. It benefits from a sensitivity to a large mass range, as the large top quark mass allows for comparably heavy decay products.

Finally, besides the direct physical benefits of these top quark measurements, the better understanding of the processes helps to improve many other measurements. First, top processes correspond to a large source of background for many analyses, which makes it important to constrain them properly. Additionally, top-quark measurements can test the understanding of basic [QCD](#) and are therefore an important input for improving the simulation of physics processes.

3.7 Higgs physics programme

After the discovery of the Higgs boson in 2012 [[2, 3](#)] and the Nobel Prize being granted to François Englert and Peter Higgs in the following year, there has been a big effort in the [ATLAS](#) collaboration to make precision measurements on the properties of the Higgs boson as well as probing the Higgs sector for potential [BSM](#) physics.

3.7.1 Decay

The Higgs boson can decay via several decay channels with largely varying cross-sections. The different branching ratios of the Higgs decays are shown in Figure [3.9](#).

The measurements of different Higgs decay modes hold sensitivity to different parts of the Higgs transverse momentum distribution. Channels such as $H \rightarrow \gamma\gamma$ or $H \rightarrow ZZ \rightarrow 4l$ have a relatively small cross-section but also extremely clean signatures, allowing for a good background rejection. Therefore, these channels can be used for precision measurements at low Higgs p_T , the high Higgs production cross-section in this part of the phase-space counteracting the low branching ratios.

For higher Higgs p_T , where the Higgs production cross-section is relatively small, decay modes with high branching ratios are used, such as the dominant $H \rightarrow b\bar{b}$ decay or $H \rightarrow \tau\tau$. These modes suffer from large, poorly understood backgrounds, but benefit from the large statistics.

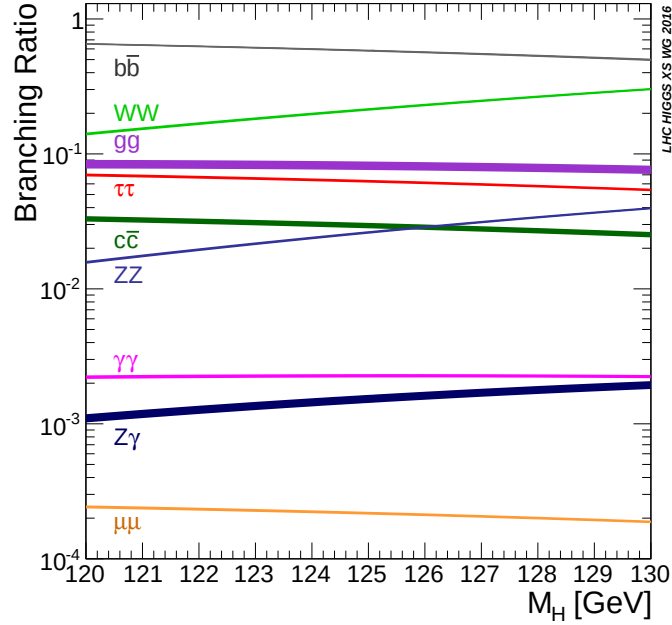


Figure 3.9: Branching ratios of the Higgs as a function of the Higgs mass with the corresponding uncertainties [69]

In between these two extremes, there are decay modes such as the Higgs decaying into multiple leptons ($H \rightarrow WW$ with at least one of W decaying leptonically and $H \rightarrow ZZ$, with exactly one of the Z decaying leptonically). These channels are not as clean as $H \rightarrow \gamma\gamma$ and have less statistics than $H \rightarrow b\bar{b}$, but with the increasing size of the collected datasets, these modes start to gain sensitivity in the higher Higgs p_T regimes.

3.7.2 Production

In hadron colliders, the Higgs can be produced via various modes. The cross-section of these different production channels are not only dependent on the coupling of the Higgs to the different particles, but also on the PDFs of the colliding protons. The main channels are via gluon-gluon fusion (ggF), via vector-boson fusion (VBF), via Higgs Strahlung by a vector boson (VH) or in association with one or two top quarks (tH and $t\bar{t}H$). The Feynman diagrams of these four production channels are shown in Figure 3.10 and their respective cross-sections in Figure 3.11.

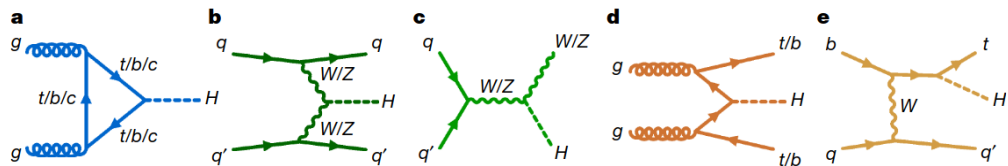


Figure 3.10: Feynman diagrams of the different processes including the Higgs at the LHC: a) ggF, b) VBF, c) VH, d) $t\bar{t}H$, e) tH [70]

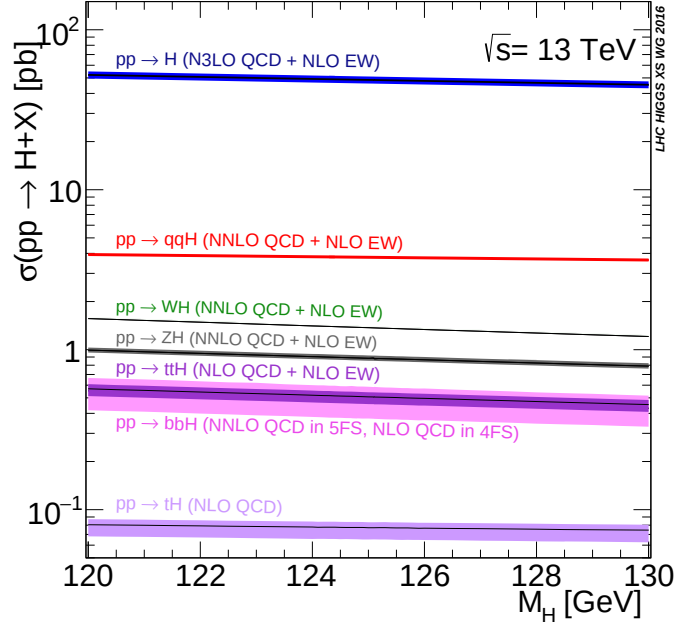


Figure 3.11: Cross-section of the different processes including the Higgs with the corresponding uncertainties [69]

The single Higgs production is dominated by the gluon-gluon fusion mode with a cross-section of $\sigma_{H,ggF} = 49 \text{ pb}$, due to the large contributions of the gluons at these high proton energies. As the Higgs boson does not couple to the massless gluons at leading order, this process mainly happens via quark loops. The second leading production channel is the vector boson fusion ($\sigma_{H,VBF} = 3.8 \text{ pb}$), where the Higgs is produced from two W or Z bosons radiated off from two quarks. The Higgs production via Higgs Strahlung ($\sigma_{H,W/Z+H} = 1.4/0.9 \text{ pb}$) and in association with top quarks ($\sigma_{H,t\bar{t}H} = 0.507 \text{ pb}$) have smaller cross-sections. The $t\bar{t}H$ production rate has been strongly increased from Run 1 to Run 2, as it is dependent on the centre-of-mass energy of the collision (the rate increased by a factor of 3.5 from $\sqrt{s} = 8 \text{ TeV}$ to $\sqrt{s} = 13 \text{ TeV}$).

Finally, in di-Higgs production, a pair of Higgs bosons is produced. This process has a cross-section about 1000 times smaller than the single Higgs cross-section. Its measurements are therefore still heavily statistics dominated.

3.7.3 Physics goals

While the existence of the Higgs boson was predicted in the [SM](#), the Higgs mass is a free parameter of the theory. The most precise mass measurement by [ATLAS](#) obtains a value of $m_H = 125.11(11) \text{ GeV}$ [71]. Additionally, measurements of the Higgs width are performed and found to agree with the [SM](#) prediction.

The other free parameter of the Higgs potential, the vacuum expectation value, can be derived from the value of the Fermi constant ($G_F = (\sqrt{2}v^2)^{-1}$), determined experimentally in the measurement of the muon lifetime.

Through the measurement of particle masses and their coupling to the Higgs, the W -Higgs and Z -Higgs coupling as well as the Yukawa coupling can be tested for potential deviations from the SM prediction. Figure 3.12 shows the ATLAS measurement described in [70] of the Higgs coupling to different bosons and fermions as a function of their mass. An impressive agreement with the SM is observed through several orders of magnitude, confirming so far the predicted behaviour of the Higgs mechanism by the SM.

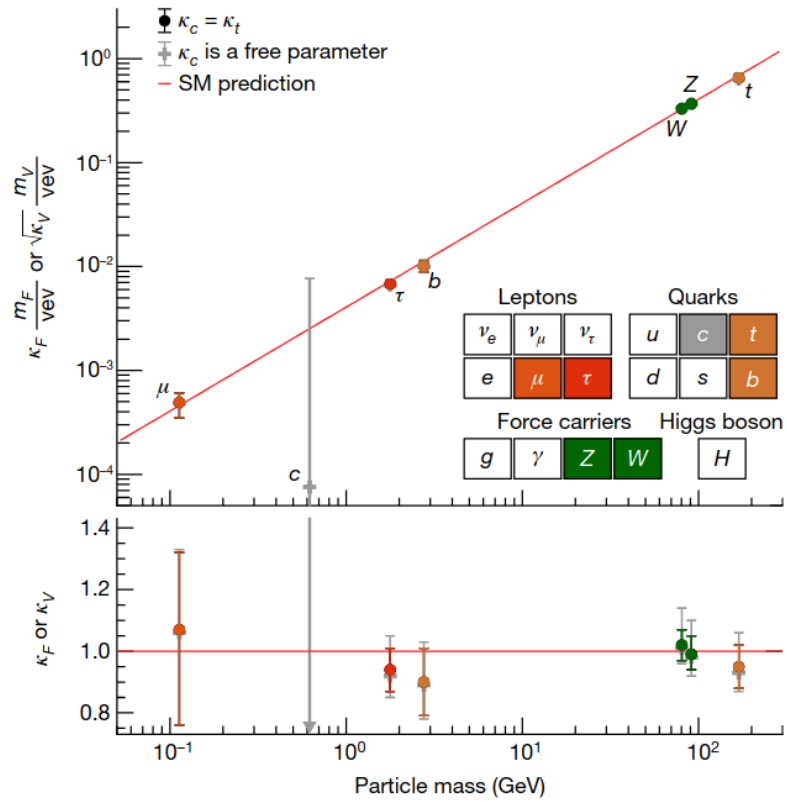


Figure 3.12: Summary plot of the ATLAS measurements of the coupling of different particles to the Higgs boson [70]

As described in Section 1.2, the effective Higgs potential, taking into account interactions with other particles, has a dependence on the physics scale. The top quark, being the heaviest known particle and coupling to the Higgs boson, loop corrections including the top are dominant. The running of the Higgs self-coupling λ as a function of the scale μ_R includes a term proportional to $-Y_t^4$, Y_t being the top Yukawa coupling. This term becomes dominant for large scales and results in the fact that λ can become negative. This effect is shown in Figure 3.13. However, a negative λ would result in a Higgs potential with additional minima to the EW minimum. In case the Higgs potential would take a smaller value in one of these minima compared to the current

one, the universe could tunnel between the current minimum and the true minimum. This would lead to a decay of the EW vacuum.

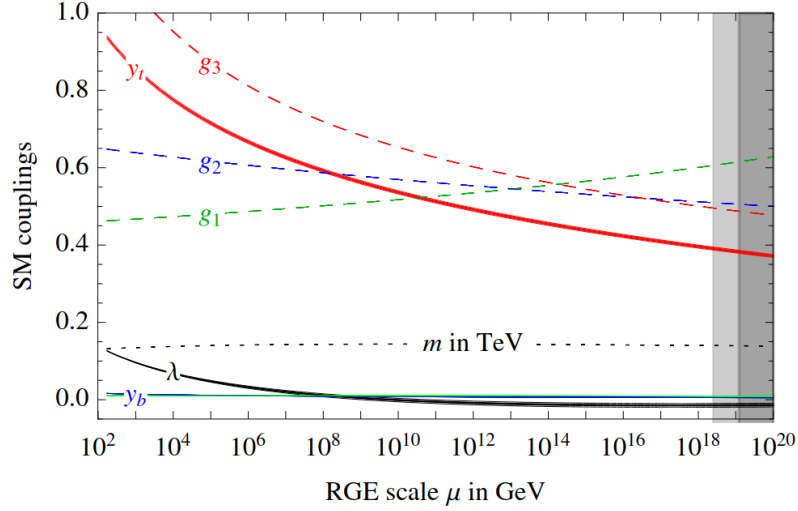


Figure 3.13: Running of different couplings as a function of the physics scale [72]

The stability of the universe can be expressed as a function of the Higgs and the top mass. Figure 3.14 shows the bands in which the universe would be stable, meta-stable or unstable. The current measurements of the masses hint that the universe is in a meta-stable state. A slightly lower top mass or new physics at a scale below the Planck scale could stabilise the vacuum state. This is, however, not strictly required, as the lifetime of the meta-stable state is much longer than the age of the universe. [73, 74, 75, 76, 77]

One way to test this picture is the direct measurement of the Higgs self-coupling λ . These measurements are mainly performed in di-Higgs measurements, where a trilinear Higgs vertex contributes to the cross-section as shown in Figure 3.15, but can also be done in differential measurements of single Higgs processes, such as $t\bar{t}H$. Current limits on the Higgs self-coupling modifier κ_λ , describing the deviation of λ from the SM prediction, set by the ATLAS experiment correspond to a 95 % confidence interval of $[-0.4, 6.3]$ with limits of $[-0.6, 6.6]$ from di-Higgs measurements and of $[-4.0, 10.3]$ from single-Higgs measurements [78].

3.7.4 Simplified template cross-section framework

The Simplified Template Cross-Section (STXS) framework [79] was developed in order to separate as much as possible measurement and interpretation steps to reduce the theory dependence folded into the measurements (both theoretical uncertainties and underlying physics models).

On a process by process basis, the phase-space is split into different regions. In each of these phase-space bins, separate normalisation measurements of the relevant Higgs process are per-

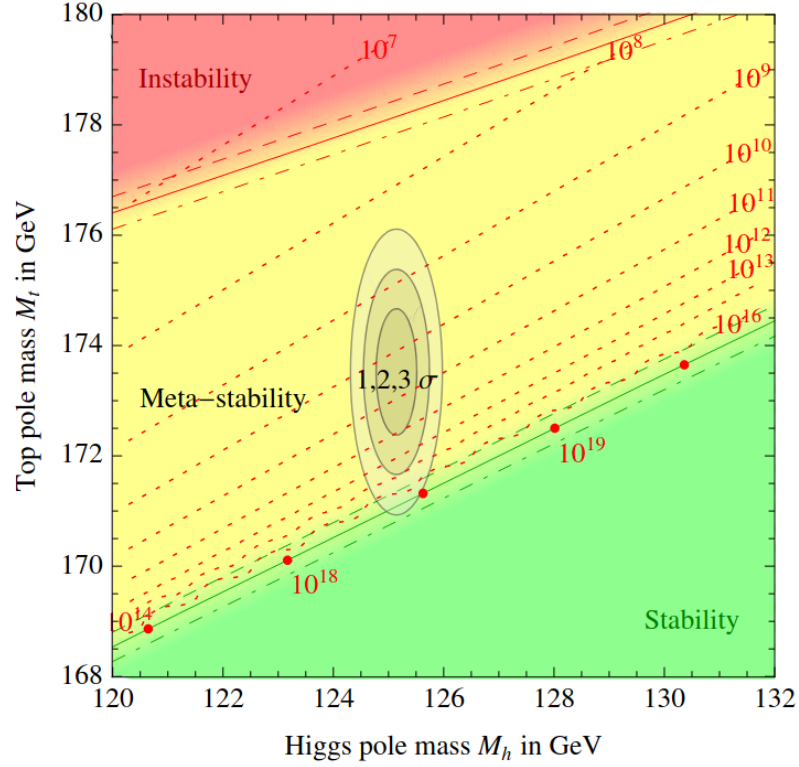


Figure 3.14: Phase diagram of the universe, including three stability regions as well as the current measurement of the top and Higgs masses [72]

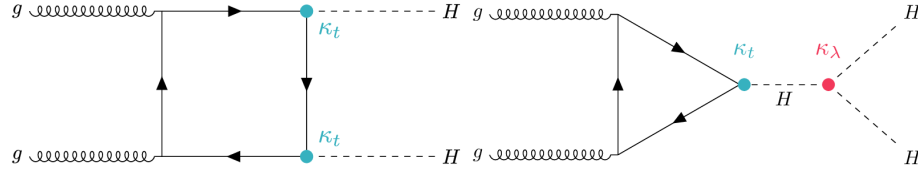


Figure 3.15: Feynman diagrams for Higgs pair production via the gluon-gluon fusion: contribution including the top-Higgs coupling (left) and contribution including the top-Higgs coupling as well as the Higgs self-coupling (right) [78]

formed. The choice of these bins takes into account the experimental sensitivity. The binning used in Run 2 (STXS framework version 1.2), and therefore also used in one of the analyses described in this thesis, is shown in Figure 3.16.

For the $t\bar{t}H$ process, the recommended binning scheme corresponds to the reconstructed Higgs p_T . For events where the Higgs has a rapidity of less than 2.5, the events are split into six p_T^H bins. The dashed bin boundary at 450 GeV is often omitted, as most analyses have a lack of statistics in this high p_T^H range. Additionally, one bin with the rapidity of the Higgs larger than 2.5, inclusive in p_T^H , is considered. However, most analyses do not have enough sensitivity to these forward Higgs events to provide a measurement in this bin.

The STXS measurement from a global Higgs combination [70] performed by ATLAS is shown in Figure 3.17.

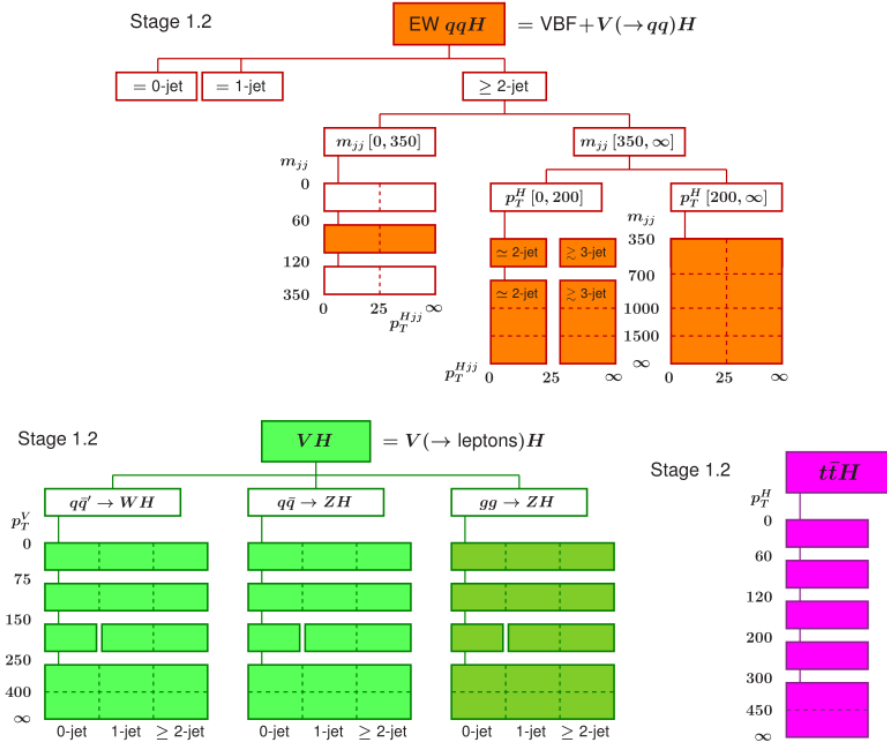


Figure 3.16: Binning in the STXS framework [80]

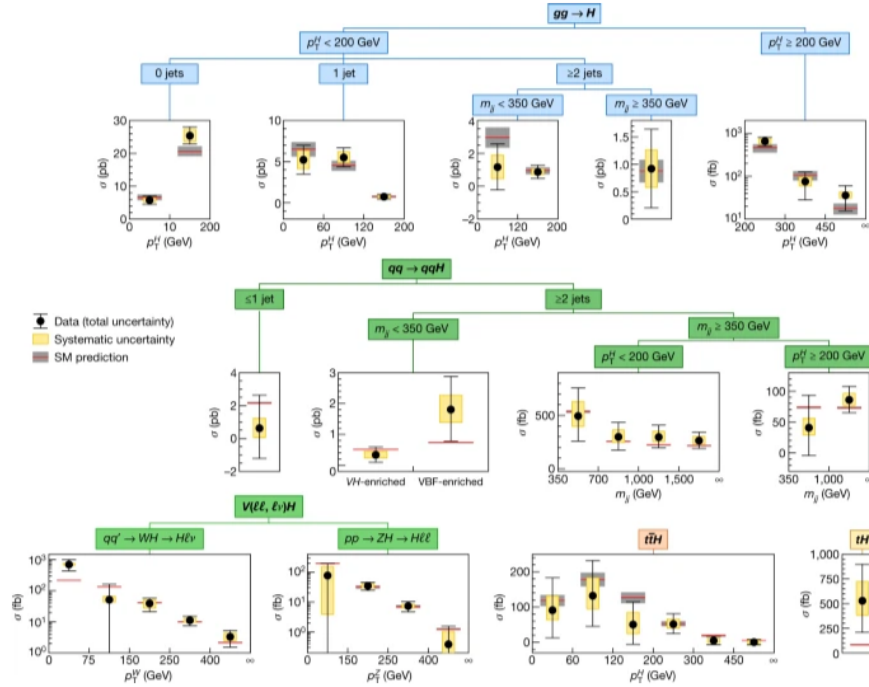


Figure 3.17: ATLAS measurements performed in the bins of the STXS framework [70]

MONTÉ CARLO GENERATION

4

Monte Carlo (MC) event generators are widely used in order to simulate the expected collected data in the assumption of a certain theoretical model. Most ATLAS analyses use these simulated data in order to maximise the signal sensitivity by optimising the event selection and in order to compare the measured data to the expected distributions.

Events for a chosen process are simulated in various steps, happening in different regimes of the running coupling α_S . The event generation starts in a perturbative regime with the hard scattering, followed by the Parton Shower (PS) and finally the hadronisation in a non-perturbative regime. A schematic representation of such an event simulation is shown in Figure 4.1. On top of the simulation at particle level, a full detector simulation is added, which simulates the propagation and material interactions of the particles in the detector.

In this chapter, the main steps of the MC generation are detailed in Sections 4.1 to 4.5, followed by the computation of MC uncertainties in Section 4.6. In this context, studies of the author on how to estimate PS and hadronisation uncertainties are presented. Additionally, studies were performed by the author on non-perturbative corrections and their uncertainties, which are described in Section 4.7. Finally, Section 4.8 gives a detailed description of the MC samples and MC uncertainties used in the analyses presented in this thesis.

4.1 Matrix element calculation

The cross-section of a hard scattering process of two protons p_1 and p_2 to a state X ($p_1 p_2 \rightarrow X$) is defined by [82]:

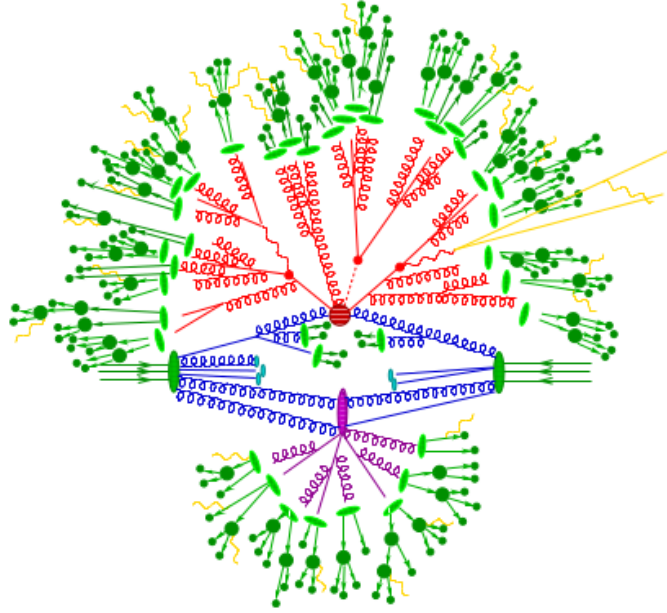


Figure 4.1: Schematic representation of the event simulation at particle level. The blue lines correspond to the incoming partons in the protons. These interact in the primary vertex of the hard interaction shown in the red circle as well as in a secondary interaction in purple. The red and purple lines then correspond to the parton shower. The transition from partons to hadrons which then decay are represented in green. Finally the yellow lines symbolise the soft photon radiation [81]

$$\begin{aligned}
 \sigma_{p_1 p_2 \rightarrow X} &= \sum_{a,b} \int_0^1 dx_a \int_0^1 dx_b f_a^{p_1}(x_a, \mu_F) f_b^{p_2}(x_b, \mu_F) \hat{\sigma}_{ab \rightarrow X}(\hat{s}, \mu_F, \mu_R) \\
 &= \sum_{a,b} \int_0^1 dx_a \int_0^1 dx_b \int d\Phi_X f_a^{p_1}(x_a, \mu_F) f_b^{p_2}(x_b, \mu_F) \frac{1}{2\hat{s}} |\mathcal{M}_{ab \rightarrow X}|^2(\hat{s}, \Phi_X; \mu_F, \mu_R)
 \end{aligned}
 \tag{4.1}$$

The PDFs $f_{a/b}^{p_1/p_2}$ of the partons a and b in the protons p_1 and p_2 can be factorised, as well as the cross-section of the parton-parton hard-scattering with final state X . The product is then summed over all partons and integrated over all momentum fractions x_i . The PDFs and the cross-section depend on the factorisation and renormalisation scales μ_R and μ_F . More details on these scales can be found in Section 4.6. The $ab \rightarrow X$ cross-section can be written in terms of the Matrix Element (ME) $\mathcal{M}_{ab \rightarrow X}$ and the parton-parton centre-of-mass energy squared $\hat{s}$, integrating over the momenta in the phase-space of the final state Φ_X .

For the calculation of the hard interaction cross-section, the ME of a specific process is therefore computed and the PDFs of the colliding protons are used as input for the initial state. Generally, the calculation of the cross-section cannot be performed analytically. The hard interaction happens, however, in a perturbative regime, where the cross-section can be expanded in powers of the coupling α_S . The accuracy of the calculations depends on the MC samples. While, due to the lower computing power, many background samples are available at Leading order (LO)

or Next to Leading Order (NLO), some signal samples are generated at Next to next to Leading Order (NNLO). LO takes into account tree-level Feynman diagrams, as shown in the left diagram of Figure 4.2, while NLO and NNLO include loop corrections as well as Initial State Radiation (ISR) and Final State Radiation (FSR), see the three right diagrams in Figure 4.2.

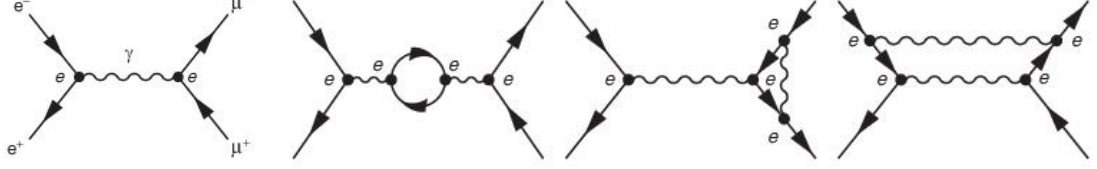


Figure 4.2: LO contribution to the $e^+e^- \rightarrow \mu^+\mu^-$ process (left diagram) and three of the NLO contributions (three right diagrams). [4]

In this thesis, different MC generator tools are used for the ME calculation, such as POWHEG 2 [83, 84, 85, 86], MADGRAPH 5 [87, 88] or SHERPA 2 [89]. These can be used in combination with specialised MC generators such as MADSPIN [90, 91] for top-spin correlations or EVTGEN [92] for decays of b - and c -hadrons.

4.2 Parton shower

After the computation of the hard interaction, the Parton Shower (PS) follows, which describes soft and collinear parton emissions. The events generated in the ME calculation are therefore interfaced with MC generators such as PYTHIA 8 [93, 94], HERWIG 7 [95, 96, 97] or with SHERPA's built-in PS [98] in case the ME was generated with SHERPA. In order to merge these two separate steps properly, matching and merging schemes were developed, which take care that there is no double counting. In general, rules are applied, requiring that all the hard emission originates from the ME, while the soft and collinear radiation is processed by the PS.

A PS arises when accelerated coloured partons are produced in the hard sub-process. These partons then emit QCD radiation in the form of partons, which are also coloured, and therefore create a shower. These showers represent higher order corrections to the interaction. It is, however, not feasible to perturbatively calculate the corrections to all orders in α_S . Therefore approximation schemes are used.

The exact model used is dependent on the generator and some allow changing between different shower models:

- **p_T ordered shower in PYTHIA [99]:** the PS in PYTHIA uses colour dipoles in a high number of colour approximation. All coloured partons are sorted into colour singlets which

then form a colour dipole. When a dipole radiates a gluon, the dipole is broken into two independent dipoles. The parton emissions follow a transverse momentum distribution, given by the probability of the Sudakov form factor. Once the p_T of a parton drops below a certain p_T threshold, the PS is terminated.

- **Angular ordered shower in HERWIG** [100, 101]: the default PS in HERWIG uses an angular ordered approach. The emission of a gluon is required to happen inside a cone with an opening angle equal to the emission angle of the previous gluon. Similar to the shower in PYTHIA, the emission follows the probability given by a Sudakov form factor, but ordered this time by angle.
- **Dipole shower in HERWIG** [102]: the dipole PS implemented in HERWIG follows the same structure as the PYTHIA PS

4.3 Hadronisation

At some point of the shower development, α_S enters a non-perturbative regime. In this phase, the observed final state hadrons are formed. Two main models exist, which describe this process, the cluster and the string model. Schematic representations of these models are shown in Figure 4.3.

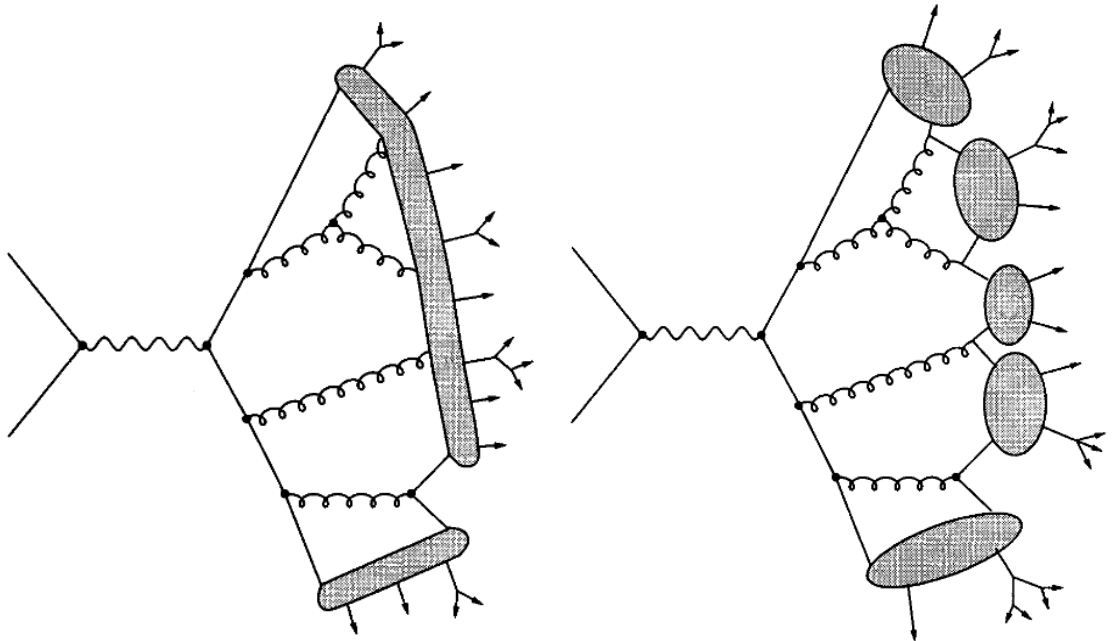


Figure 4.3: Schematic representations of the string (left) and cluster (right) hadronisation models. [82]

- **String (Lund) model** [103, 104]: In this model, light partons are connected by a string, forming an oscillator. This leads to statistical motions, where strings can break if the ten-

sion gets too large. The breaking of the strings corresponds to the creation of quark pairs, which then participate in the shower.

- **Cluster model** [105]: In this model, the showering is done, keeping track of all the colour connections. The partons are then clustered into colour neutral objects, which are projected onto high mass meson resonances. The last step of the shower is then the decay of these resonances.

4.4 Tuning

As described previously, some parts of the event simulation are described by models, which approximate processes happening in a perturbative regime but with high particle multiplicities (such as the PS) or in a non-perturbative regime (such as the hadronisation). These models generally include several parameters, which are determined by fitting MC distributions to data, called tuning.

In the analyses presented in this thesis, all MC generators include a tune. For most of the generators, the tune published alongside the MC generator is used, while for PYTHIA, an additional ATLAS specific tune, called A14 [106], is used. A14 includes a set of uncertainties on the parameter tuning.

4.5 Full detector simulation

In order to compare the MC predictions with data, the interaction of the final state particles with the detector and the detector response is simulated. This is done by implementing the whole ATLAS detector geometry into Geant4 [107]. This step allows the events obtained from the MC simulation to be treated similar to data, computing the different reconstructed variables.

As these full simulations are extremely computing power consuming, fast simulation procedures are available, which give approximations of the distributions. In this case, the full inner detector and muon system simulation is used, but the calorimeter simulation is simplified. Some of the backgrounds used in the analyses presented in this thesis, are simulated with fast simulation.

4.6 Monte Carlo uncertainties

4.6.1 Matrix element uncertainties

The **ME** calculation is dependent on many parameters which come with some uncertainties.

PDFs The **PDF** models, used to describe the interacting partons, are provided alongside uncertainties, which are propagated through weights to the final **MC** distributions.

Scales As shown in Section 4.1, the **ME** depends on two scales, the factorisation and the renormalisation scale:

- **Factorisation scale:** the **PDF** of a parton $f_i(x_i, \mu_F^2)$ is defined at a chosen factorisation scale μ_F . This scale can be interpreted as the scale separating short and long distance physics. While gluons with $p_T < \mu_F$ are part of the **PDF**, gluons with $p_T > \mu_F$ are part of the hard parton-parton scattering cross-section.
- **Renormalisation scale:** loop diagrams include two types of divergences: infrared and ultraviolet. Infra-red divergences cancel when taking into account real as well as virtual emissions. In order to remove the ultraviolet divergences, α_S has to be determined at a certain scale, called renormalisation scale μ_R .

In most cases, both scales are chosen to correspond to the hard scattering scale Q ($\mu_F = \mu_R = Q$). Uncertainties on the choice of the factorisation and renormalisation scales can be estimated in different ways: by varying the scales by a factor of two and by a factor of one half (2μ and $\frac{1}{2}\mu$) separately or by varying both scales simultaneously.

Other parameters Uncertainties in the **ME** algorithm coming from other choices, such as the merging schemes, are estimated by comparing different generators.

4.6.2 Parton shower and hadronisation uncertainties

$p_{T,hard}$ This parameter controls the matching between the **ME** and the **PS**. It regulates in which part of the phase-space the **PS** is allowed to emit parton radiation, by defining a criterion for the hardness of a parton.

Resummation scale h_{damp} This parameter also controls the matching between the [ME](#) and the [PS](#). It corresponds to the damping of the radiation with high transverse momentum, separating low and high transverse momentum and controlling the hardest radiation.

α_S in ISR and FSR The amount of [ISR](#) and [FSR](#) is impacted by the value of α_S and therefore by the choice of the scale at which α_S is computed. For α_S^{ISR} the scale is varied according to the values given by the A14 tune and α_S^{FSR} by a factor of two and one half.

PS and hadronisation model The uncertainties on the [PS](#) and hadronisation models themselves are often approximated by two-point variations between two generators. As POWHEG+PYTHIA and POWHEG+HERWIG, for example, use different [PS](#) and hadronisation models, the difference between them can be used as an approximation for the [PS](#) and hadronisation models uncertainty.

PS and hadronisation uncertainty studies

While these two-point variations between [MC](#) generators include the effect of switching [PS](#) and hadronisation models, they also include multiple other differences. As for many analyses the [PS](#) uncertainties correspond to the leading systematics, many efforts are ongoing to try to understand these uncertainties better and to reduce them if possible. In the context of this thesis, it was studied to compute these uncertainties inside one single generator. Such a method would allow having less other differences convoluted in the [PS](#) uncertainties.

Fully factorised [PS](#) and hadronisation uncertainties are studied, where uncertainties coming from different sources are estimated separately and then combined. The PYTHIA A14 tune variations are considered, which correspond to five independent variations targeting Multi-Parton Interactions ([MPI](#)) and the colour reconnection (in Var1) and different aspects of [ISR](#) and [FSR](#) (in Var2, Var3a, Var3b and Var3c). More details on these variations can be found in Reference [106]. Additionally, several generators allow generating events with different [PS](#) and hadronisation models. The main challenge, however, is that only the default generator setups are validated for physics. Developing a new uncertainty recipe making use of the alternative models therefore includes a thorough validation of all models. The aim of the studies summarised here, was to gather all the available [PS](#) and hadronisation models and to understand their status and any potential show stoppers. The studies were performed in the Z +jets and $t\bar{t}$ processes.

PS model In addition to the default p_T ordered [PS](#), PYTHIA comes with two alternative [PS](#) algorithms (DIRE and Vincia). HERWIG includes two [PS](#) models, the default angular ordered shower

and the dipole shower model. The alternative PS models in PYTHIA show unexpectedly large differences to the default PS model in distributions where the PS is not expected to have a large impact (such as the Z mass distribution in $Z(\rightarrow ee)+\text{jets}$). These models were therefore considered insufficiently validated to make sensible physics conclusions and were dropped.

The PS model switch in HERWIG also induces changes in distributions which are not expected to come from PS effects. Figure 4.4 for example, shows the Z mass distribution in $Z(\rightarrow ee)+\text{jets}$. The large deviation in the low mass tail comes from the fact that the dipole shower does not include Quantum Electro Dynamics (QED) radiation. It follows that the distributions from these two models can, in principle, not be compared on equal footing, without adding QED radiation to the dipole shower. In the following, the alternative PS in HERWIG is, however, used to study the behaviour of a factorised uncertainty.

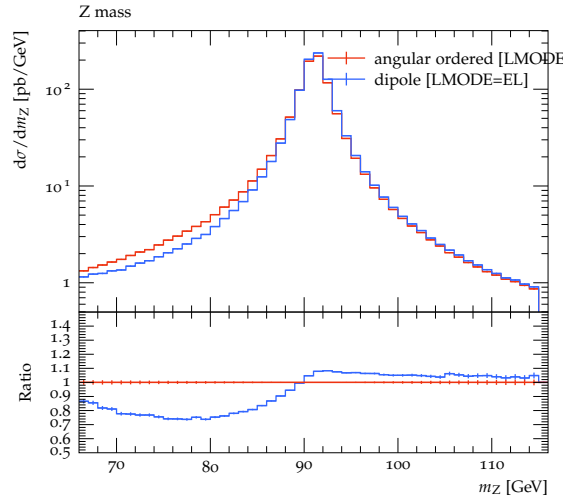


Figure 4.4: Z mass distribution computed with POWHEG+HERWIG with the angular ordered and the dipole shower model in the $Z(\rightarrow ee)+\text{jets}$ process. The distribution was computed with the Rivet routine [108] MC_ZINC.

Hadronisation model HERWIG and SHERPA include two different hadronisation models (cluster vs. string model). Similar effects as in the PS models can be observed when using alternative hadronisation models. Figure 4.5 for example, shows the comparison between the jet multiplicity distribution in POWHEG+PYTHIA (using the Lund model) and in POWHEG+HERWIG for the default setup (using the cluster model) and for the alternative setup (using the Lund model). While in the $t\bar{t}$ process (shown on the left), switching the hadronisation model in HERWIG to the same as in PYTHIA makes the POWHEG+HERWIG distribution more similar to the POWHEG+PYTHIA distribution, the opposite effect is observed in $Z+\text{jets}$ (shown on the right). This hints to the fact that other changes in the setup occur when using the alternative hadronisation model.

This is also supported by Figure 4.6 (left), showing the effect of the hadronisation model switch in the W mass distribution in the $t\bar{t}$ process for POWHEG+HERWIG and SHERPA. While the impact in SHERPA is relatively small and only visible, as expected, in the low mass tail, the impact in POWHEG+HERWIG is much larger and present in both the low-mass and the high-mass tail. Studies showing that the differences in POWHEG+HERWIG increase with larger jet radii underline that these are not hadronisation effects. One difference which was noticed, is that the Lund model does not include colour reconnection. As shown in Figure 4.6 (right), switching off the colour reconnection in the default setup strongly reduces the differences between the hadronisation models in the low-mass tail, but the differences in the high-mass tail remain. These are not understood and still under investigation.

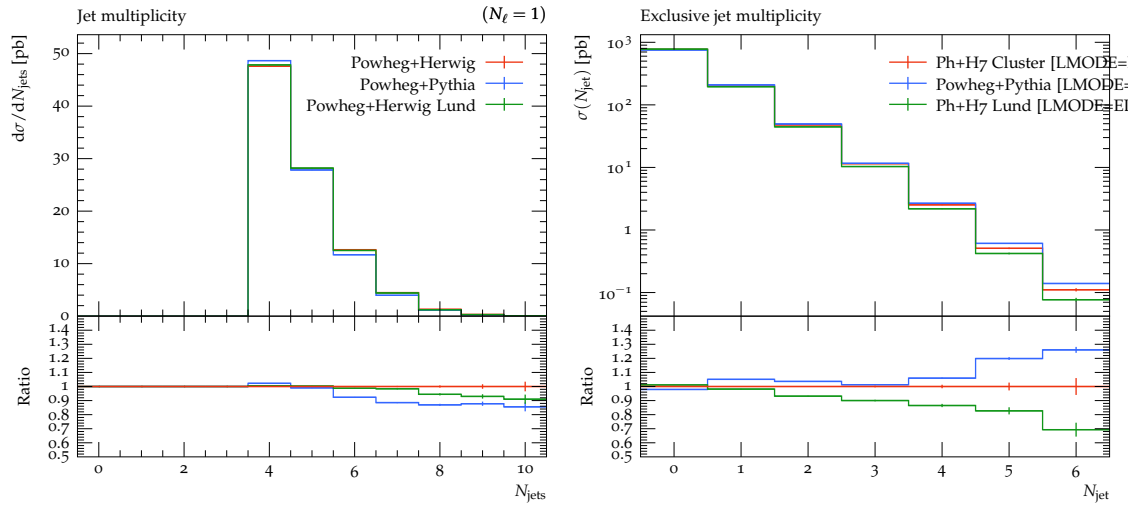


Figure 4.5: Jet multiplicity distribution computed with POWHEG+HERWIG with the cluster and the Lund model and with POWHEG+PYTHIA with the Lund model for the $t\bar{t}$ process (left) and for the $Z(\rightarrow ee)+\text{jets}$ (right) process. The distributions were computed with the Rivet routine [108] MC_TTBAR and MC_ZJETS.

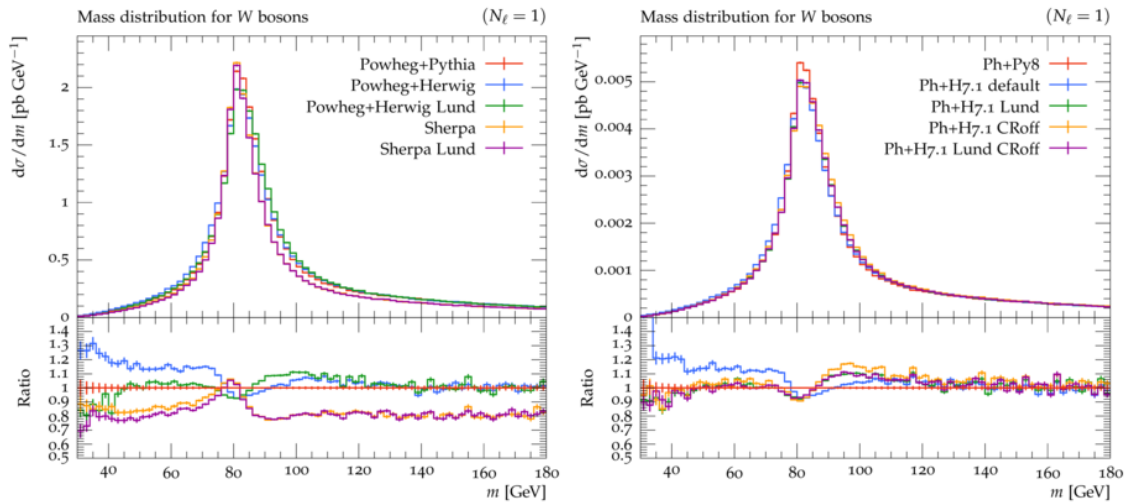


Figure 4.6: W mass distribution computed with POWHEG+PYTHIA with the Lund model, with POWHEG+HERWIG with the cluster and the Lund model and with SHERPA with the cluster and the Lund model in the $t\bar{t}$ process. On the right plot, the POWHEG+HERWIG distributions are additionally shown when removing the colour reconnection. The distribution was computed with the Rivet routine [108] MC_TTBAR.

Factorised uncertainty In order to translate the performed variations into uncertainties, the envelopes of the different distributions are considered. The POWHEG+PYTHIA sample is used as the nominal sample. For the tune variations, where each parameter variation has a down and an up variation around the nominal setting, the envelope between the down and the up sample is taken. This method allows for possibly asymmetric uncertainties. In case of the model switches, only two independent samples are obtained. Therefore, the envelope between these two samples is taken, which is then symmetrised around the nominal distribution. The total uncertainty is finally obtained by adding the individual contributions in quadrature.

This method assumes a complete factorisation and therefore that the different uncertainties are fully independent. This assumption is valid for the tune variations, as these are defined such that they are orthogonal to each other. However, it cannot be determined, to what extent this holds for the PS and the hadronisation model. A potential interplay between these components would lead to a double counting, artificially increasing the overall uncertainty.

In the following, some results are shown for the Z +jets process. The coloured bands correspond to the individual uncertainties, added linearly in order to show their contribution to the overall uncertainty, and the dashed line represents the total sum in quadrature. For the PS uncertainty, the switch between the angular ordered and dipole shower in POWHEG+HERWIG is used, while for the hadronisation uncertainty, the switch between the cluster and Lund model in SHERPA is used.

In Figure 4.7, the uncertainty for the angular distance ($\Delta\phi$) distribution between the two leading jets is shown. It can be seen that especially for back-to-back jets, the factorised approach leads to a much larger total uncertainty (up to 20 %) than the two-point uncertainty between POWHEG+PYTHIA and POWHEG+HERWIG (below 10 %).

Figure 4.8 shows the uncertainty bands for the leading jet rapidity, the leading jet being calculated in the ME. While Var1 and Var2 have a similar impact as on the $\Delta\Phi$ distribution, the ISR and FSR variations (Var3a, Var3b, Var3c), the PS model and the hadronisation model only have very small uncertainties. Therefore, the uncertainties obtained with the factorised approach and the two-point variation between POWHEG+PYTHIA and POWHEG+HERWIG are relatively similar at about 5 % in the transverse region. In addition, both methods show similarities in the shape of the uncertainties. For forward jets, the factorised uncertainty increases. This increase is mainly driven by Var1, as the MPI has a strong impact on low p_T jets. This 5 % increase of the uncertainty in the forward regions is also seen in the two-point variation between

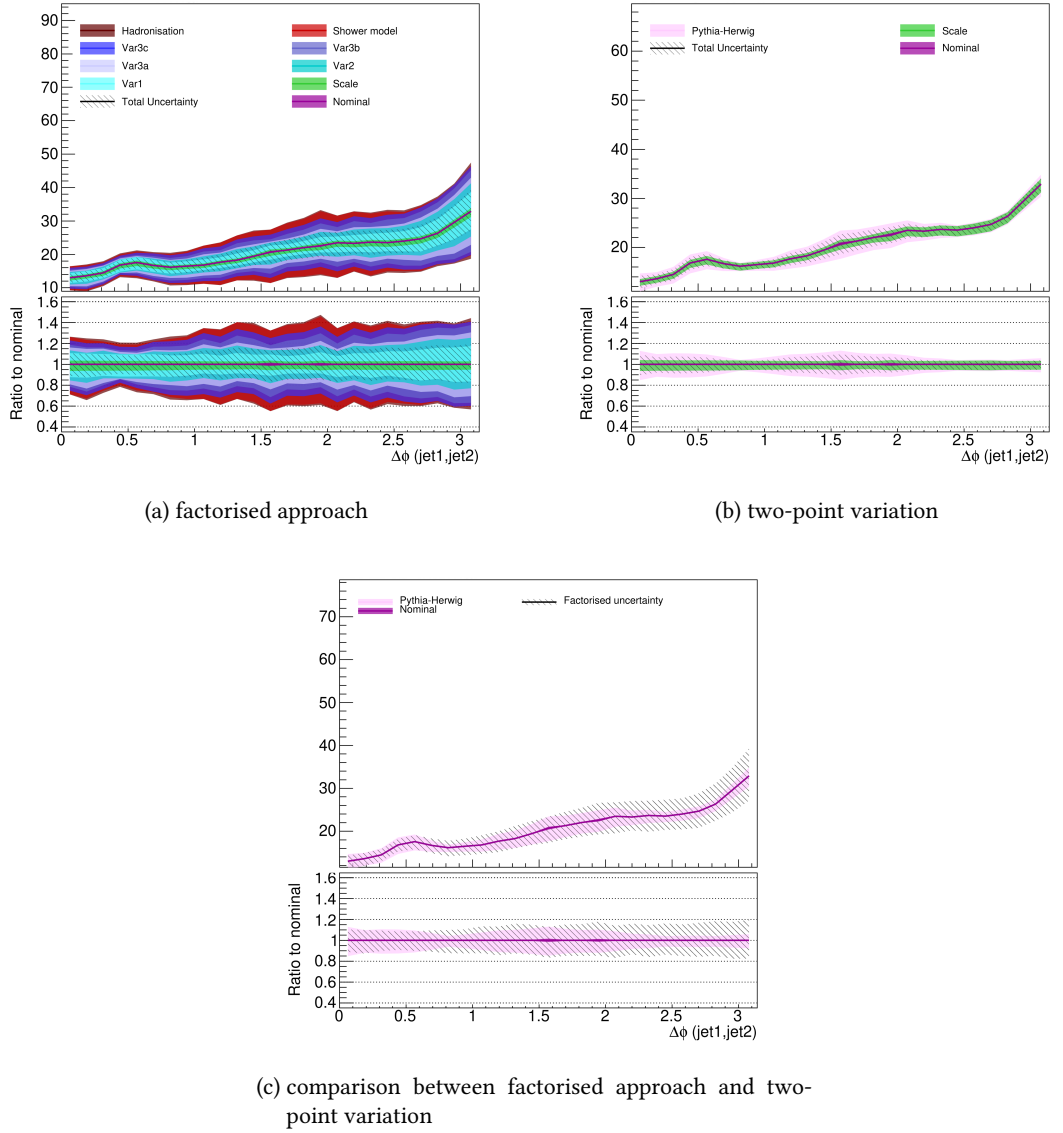


Figure 4.7: Factorised uncertainties and uncertainties from the two-point variation between POWHEG+PYTHIA and POWHEG+HERWIG for the $\Delta\Phi$ (jet1,jet2) distribution in the Z +jets channel. Figure a) shows the different components of the factorised uncertainties as coloured bands and the quadratic sum of these components as dashed lines. Figure b) shows the two-point variation between POWHEG+PYTHIA and POWHEG+HERWIG. Figure c) compares the two-point variation uncertainty between POWHEG+PYTHIA and POWHEG+HERWIG with the total factorised uncertainty.

POWHEG+PYTHIA and POWHEG+HERWIG, indicating that the difference in the MPI model between the generators could be responsible for these deviations.

The uncertainties are also shown for the transverse momentum of the Z in Figure 4.9, where the impact of Var1 and Var2 to the factorised uncertainty is very small. This is expected, as for the reconstruction of the p_T of the Z only the leptons are used, meaning that MPI is not expected to contribute significantly. Overall, the uncertainties are much smaller than for the other distributions (less than 5 %), the two-point uncertainty being slightly larger than the factorised uncertainty. The total uncertainty increases with higher p_T of the Z for both methods. As the Z

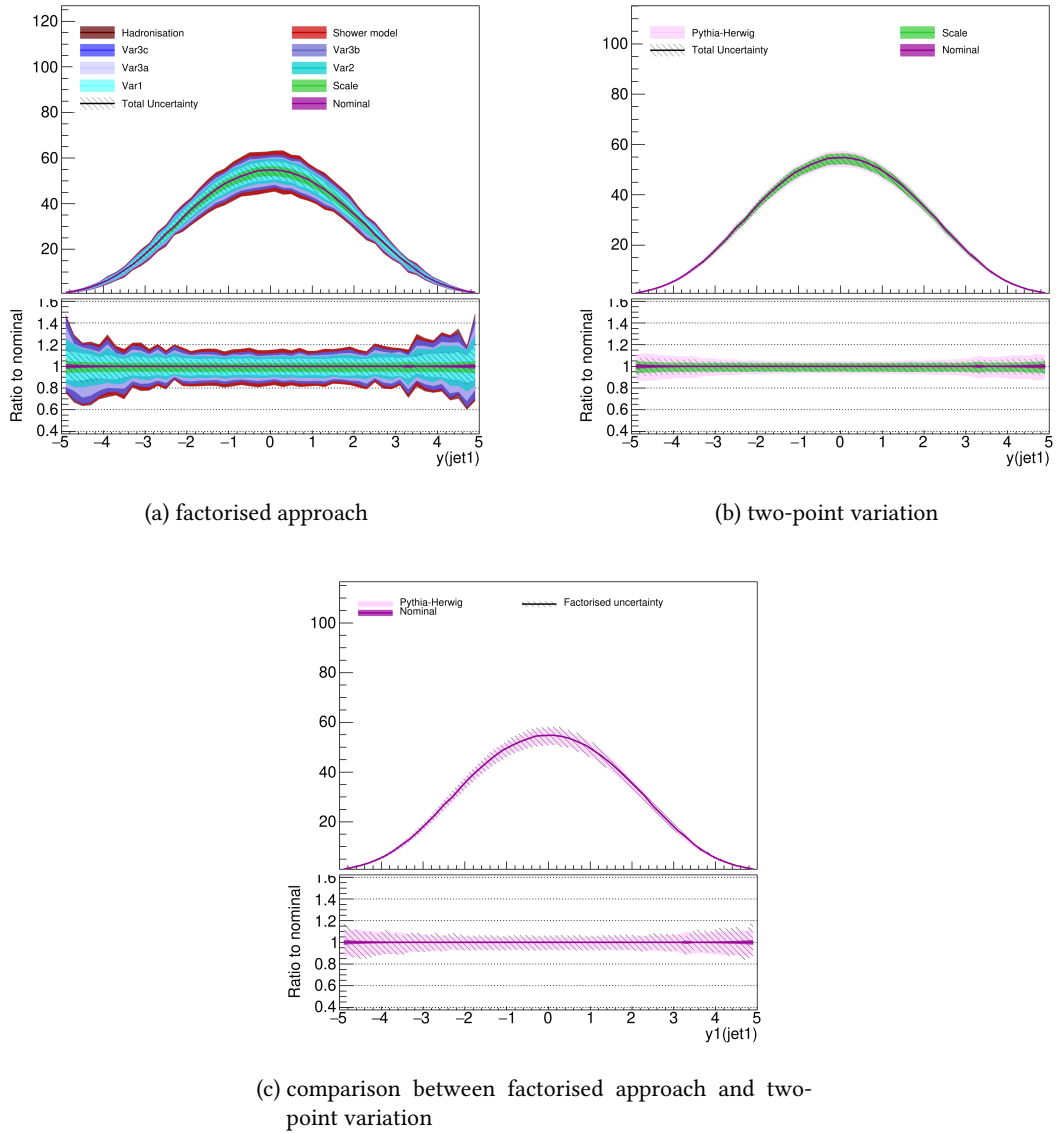


Figure 4.8: Factorised uncertainties and uncertainties from the two-point variation between POWHEG+PYTHIA and POWHEG+HERWIG for the leading jet rapidity distribution in the Z +jets channel. Figure a) shows the different components of the factorised uncertainties as coloured bands and the quadratic sum of these components as dashed lines. Figure b) shows the two-point variation between POWHEG+PYTHIA and POWHEG+HERWIG. Figure c) compares the two-point variation uncertainty between POWHEG+PYTHIA and POWHEG+HERWIG with the total factorised uncertainty.

boson only gets transverse momentum, if additional jets are produced in the event, a correlation between the Zp_T and the jet multiplicity could explain the increase in uncertainty in the high p_T region.

Finally, the jet multiplicity distribution in Figure 4.10 shows a clear dependence of the factorised uncertainties on the number of jets in the event. For events with zero or one jet, the uncertainties from the factorised approach and from the two-point variation between POWHEG+PYTHIA and POWHEG+HERWIG have a similar size of about 5 %. For higher jet multiplicities, the factorised uncertainties strongly increase (over 60 % for four-jet events), while the difference between

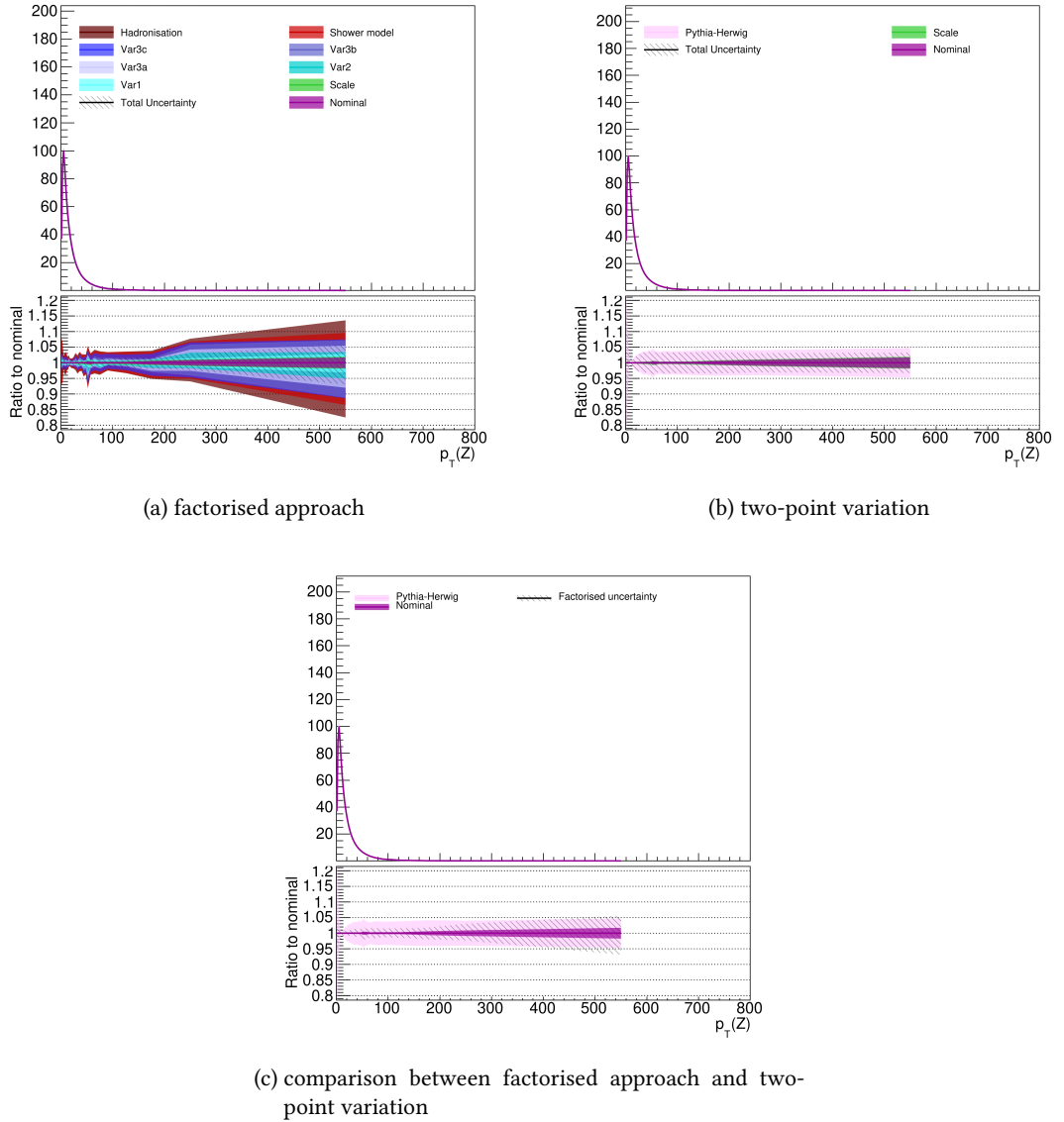
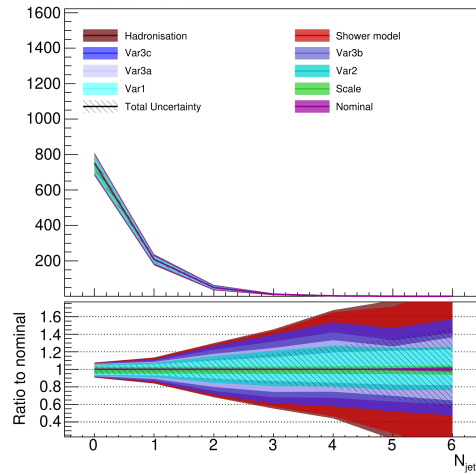


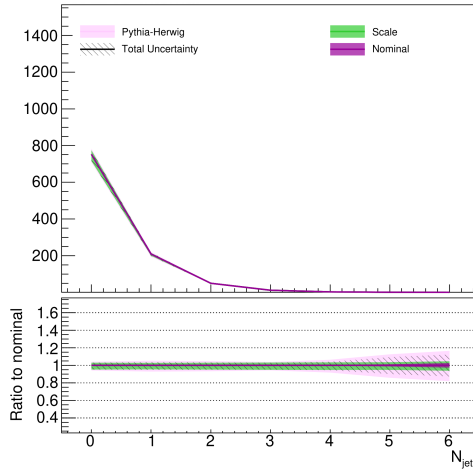
Figure 4.9: Factorised uncertainties and uncertainties from the two-point variation between POWHEG+PYTHIA and POWHEG+HERWIG for the Z transverse momentum distribution in the Z +jets channel. Figure a) shows the different components of the factorised uncertainties as coloured bands and the quadratic sum of these components as dashed lines. Figure b) shows the two-point variation between POWHEG+PYTHIA and POWHEG+HERWIG. Figure c) compares the two-point variation uncertainty between POWHEG+PYTHIA and POWHEG+HERWIG with the total factorised uncertainty.

POWHEG+PYTHIA and POWHEG+HERWIG stays approximately constant up to about four jets. One possible explanation for this effect is the [MC](#) tuning. While PYTHIA and the default HERWIG setup are tuned to data, the alternative HERWIG models are not tuned at all or at least not to the same extent. In order to compute a proper uncertainty from the different models, all the alternative setups would therefore ideally be required to be tuned consistently.

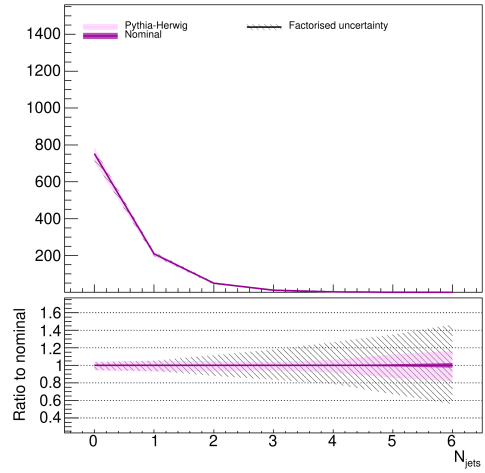
Studies were also performed, where potential dependencies between the [PS](#) and the hadronisation are taken into account. A four-point variation of the distributions with all possible combinations of [PS](#) and hadronisation models inside HERWIG, see Table [4.1](#), is considered. The colour



(a) factorised approach



(b) two-point variation



(c) comparison between factorised approach and two-point variation

Figure 4.10: Factorised uncertainties and uncertainties from the two-point variation between POWHEG+PYTHIA and POWHEG+HERWIG for the jet multiplicity distribution in the Z +jets channel. Figure a) shows the different components of the factorised uncertainties as coloured bands and the quadratic sum of these components as dashed lines. Figure b) shows the two-point variation between POWHEG+PYTHIA and POWHEG+HERWIG. Figure c) compares the two-point variation uncertainty between POWHEG+PYTHIA and POWHEG+HERWIG with the total factorised uncertainty.

reconnection was removed in all samples, in order to compare them on equal footing. Such an uncertainty band is shown in Figure 4.11 for the jet multiplicity distribution in $t\bar{t}$. For comparison, the two-point variation between POWHEG+PYTHIA and POWHEG+HERWIG is also shown. A similar behaviour as in the fully factorised approach is observed.

All these studies do not result in a clear proposal for a new, fully factorised uncertainty approach. They serve, however, as a starting point for other investigations currently pursued in ATLAS. A strong collaboration with the MC generator authors is required to obtain comparable setups, where all observed differences can be attributed to the model switch. Additionally, a con-

Table 4.1: [PS](#) and hadronisation model setups in the samples used for the four-point variation approximating the [PS](#) and hadronisation uncertainty.

	Angular ordered PS	Dipole PS
Cluster hadronisation	Angular ordered + Cluster	Dipole + Cluster
Lund hadronisation	Angular ordered + Lund	Dipole + Lund

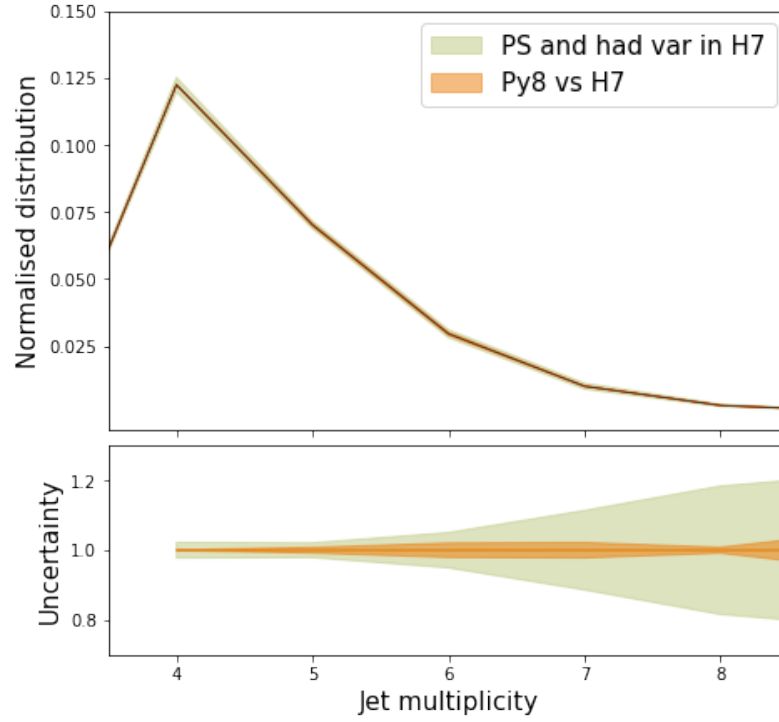


Figure 4.11: Uncertainty band for the jet multiplicity distribution in the $t\bar{t}$ process. A four-point variation between HERWIG distributions with cluster, Lund, angular ordered and dipole [PS](#) model is compared to the two-point variation between POWHEG+PYTHIA and POWHEG+HERWIG. The distribution was computed with the Rivet routine [\[108\]](#) MC_TTBAR.

sistent tuning of all alternative samples seems to be inevitable to guarantee a sensible comparison of the different models.

4.7 Non-perturbative corrections

In order to compare experimental measurements with theoretical predictions, the measured data are unfolded to particle level, computing a transformation of the data which removes the detector dependence. Many theoretical predictions, however, are only computed at parton level, not including the non-perturbative parts of the [PS](#). Therefore, non-perturbative corrections need to be applied to the predictions, including the effects of the [MPI](#), the hadronisation and the primordial k_T .

The corrections are defined by $\frac{\sigma_{particle-level}}{\sigma_{parton-level}}$, where the predictions at parton and particle level are both produced by MC generators, and MPI, hadronisation and primordial k_T are switched off at parton level. Uncertainties on these corrections are approximated by the difference of the non-perturbative corrections in two different generators. These can be relatively large, with relative uncertainties of up to 100 %, as many choices inside the MC generators can affect the size of the corrections. An example of the non-perturbative corrections computed in different generators can be seen in Figure 4.12 for an ATLAS Z +jets analysis [109].

Some phenomenological studies [110], however, obtain smaller non-perturbative corrections and smaller differences between the generators, as shown in Figure 4.13. When comparing both results, it is to be noted that a slightly different definition of the non-perturbative corrections is used in Reference [110] ($\frac{(\sigma_{particle-level} - \sigma_{parton-level})}{\sigma_{parton-level}}$).

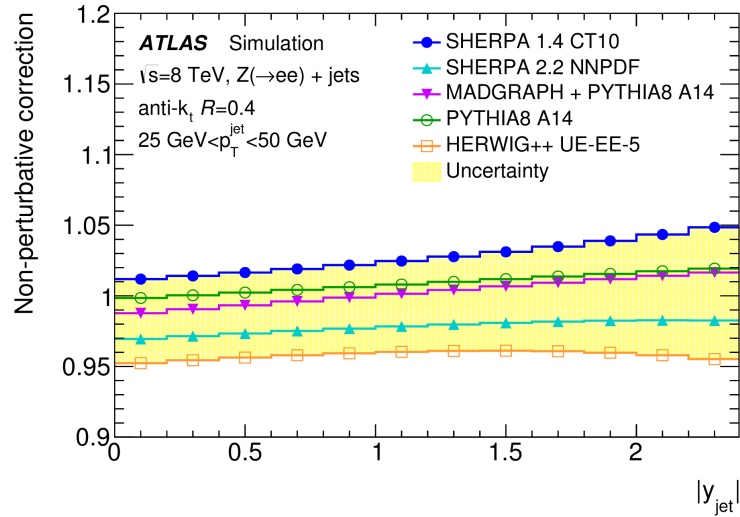


Figure 4.12: Non-perturbative corrections as a function of the jet rapidity in the Z +jets final state for the jet momentum bin from 25 GeV to 50 GeV for different generators. [109]

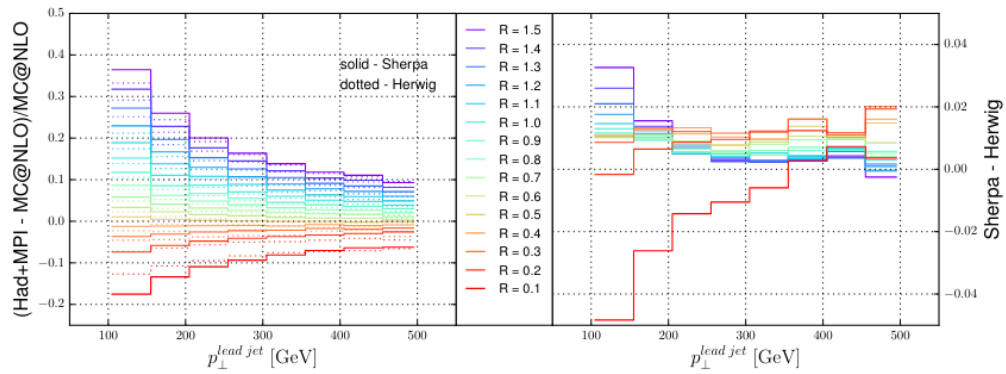


Figure 4.13: Non-perturbative corrections (here a slightly different definition is used) as a function of the leading jet transverse momentum and different jet radii in the Z +jets final state for POWHEG+HERWIG and SHERPA [110]

In the context of this thesis, some studies were performed in order to understand the composition and the uncertainties on the non-perturbative corrections, using the Z +jets process. One of the main outcomes is that these corrections are heavily jet p_T dependent. Figure 4.14 shows the non-perturbative corrections for a large range of the leading jet p_T . While for small jet p_T the non-perturbative corrections are very large and strongly depend on the generator, the corrections decrease with p_T , as well as the absolute differences between the generators.

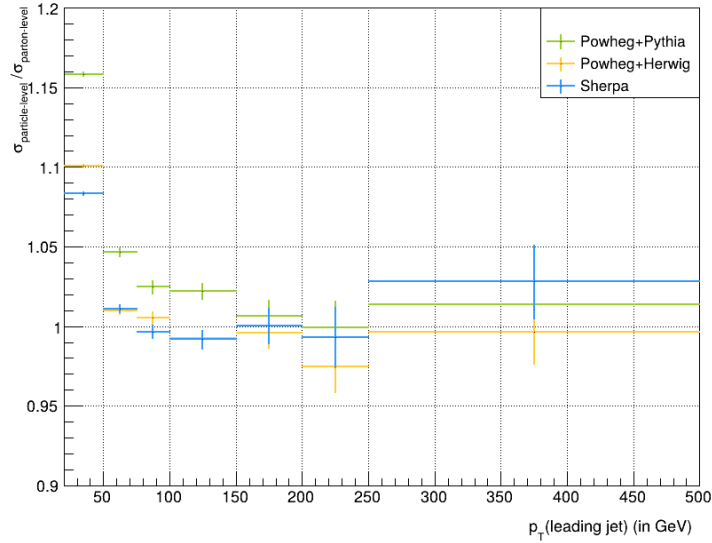


Figure 4.14: Non-perturbative corrections as a function of the leading jet transverse momentum in the Z +jets final state for different generators. The distribution was computed with the Rivet routine [108] MC_ZJETS.

Additionally, the non-perturbative corrections were found to be largely dominated by the **MPI**. This effect is shown in Figure 4.15, where the leading jet p_T distribution is shown. The distributions at particle level, at parton level and at parton level where the **MPI** is considered are compared. The differences between particle and parton level strongly decrease as a function of jet p_T meaning that the non-perturbative corrections get small for high p_T . Additionally it can be seen that the difference between the distributions with and without **MPI** are much larger than the difference between the distributions with and without hadronisation and primordial k_T .

In addition to the non-perturbative corrections decreasing with jet p_T , the absolute uncertainties also get smaller with increasing jet p_T . A full understanding of the non-perturbative corrections and the differences between the generators is, however, difficult, as a strong interplay between the **MPI** and the showering is observed. Figure 4.16 shows the leading (top) and sub-leading (bottom) jet p_T distributions at parton (left) and particle (right) level for POWHEG+PYTHIA and POWHEG+HERWIG. For leading jet distributions, with the leading jet being generated in the **ME** by POWHEG, the two generators are very close at parton level and deviate a bit more at particle level. For sub-leading jet distributions or correlations between jets, sub-leading jets

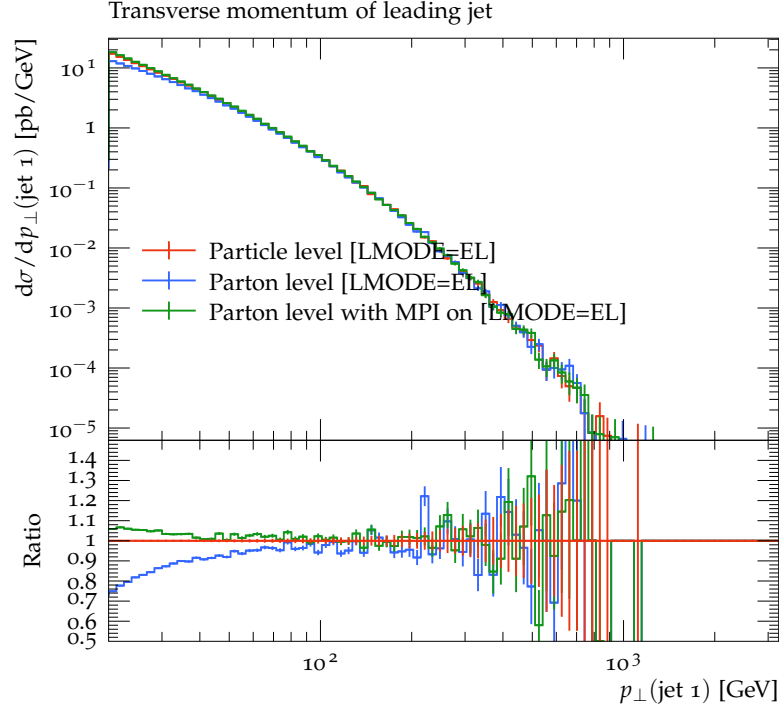


Figure 4.15: Leading jet p_T distribution computed with POWHEG+PYTHIA at particle level, parton level and parton level including **MPI** in the $Z(\rightarrow ee)$ +jets process. The distribution was computed with the Rivet routine [108] MC_ZJETS.

being produced by the **PS**, the two generators are closer at particle than at parton level. This interplay between **MPI** and showering is likely introduced by the tuning, which artificially makes the particle level distributions match the data.

4.8 MC samples and modelling systematics

In the following, the **MC** samples used in the analyses presented in this thesis are described. Most of the samples are common to both analyses.

$t\bar{t}\ell^+\ell^-$ MADGRAPH5_AMC@NLO 2.8.1 is used to generate the **ME** of $t\bar{t}\ell^+\ell^-$ at **NLO** in α_S , with the NNPDF3.0NLO **PDF** set. For the functional form of the renormalisation and factorisation scale, the default scale $0.5 \times \sum_i \sqrt{m_i^2 + p_{T,i}^2}$ is used, where the sum runs over all particles i in the **ME**. Top quarks, with a mass set to 172.5 GeV, are decayed with MADSPIN. The **PS** and hadronisation is performed by PYTHIA 8.244, with the A14 set of tuned parameters and the NNPDF2.3LO **PDF** set. B- and C-hadron decays are simulated with the EVTGEN 1.7.0 program. The sample is normalised according to the MADGRAPH5_AMC@NLO cross-section at **NLO QCD** and **NLO EW** accuracies [69], taking into account the contribution from γ^* and the interference between the Z and the γ^*

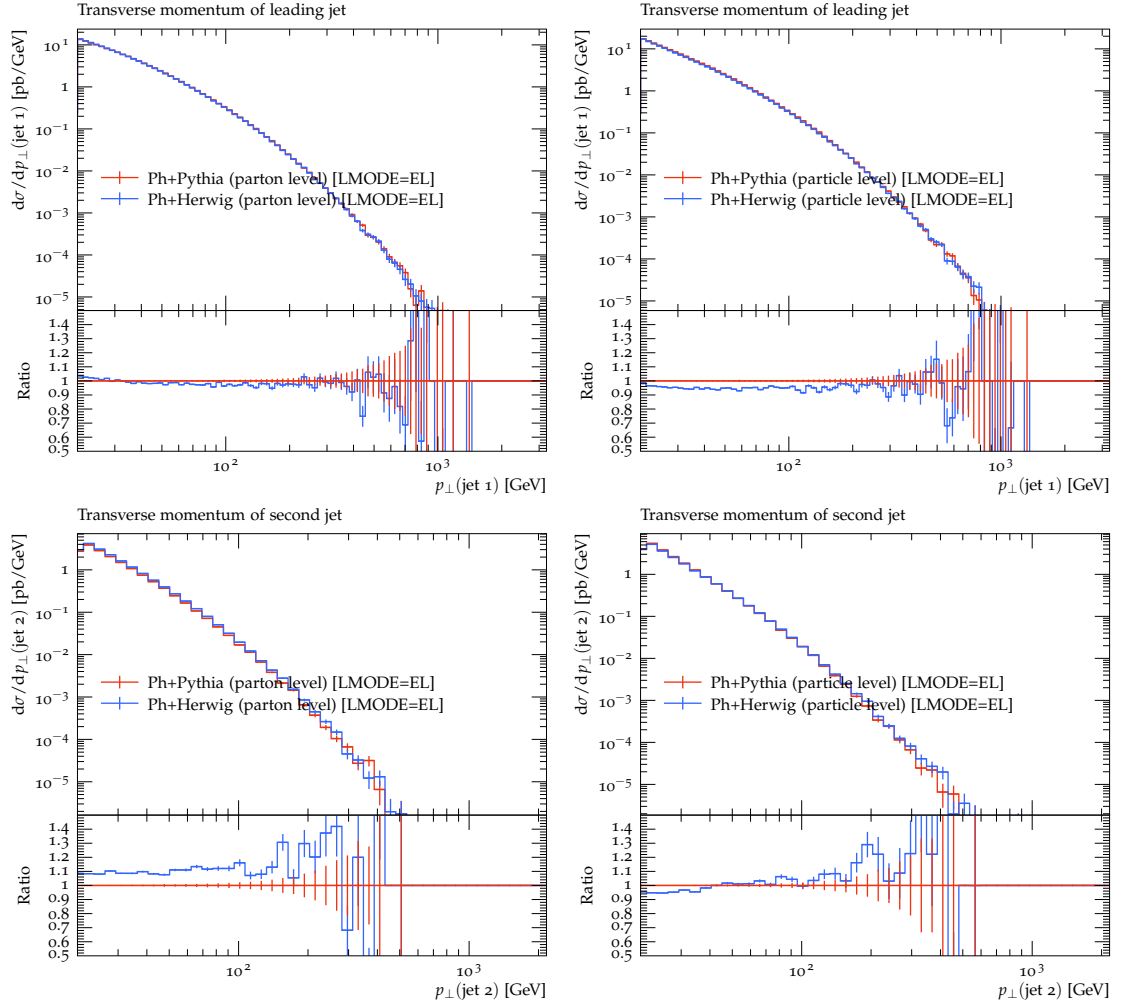


Figure 4.16: Leading (top) and sub-leading (bottom) jet p_T distribution computed with POWHEG+PYTHIA and POWHEG+HERWIG at parton level (left) and particle level (right) in the $Z(\rightarrow ee)$ +jets process. The distribution was computed with the Rivet routine [108] MC_ZJETS.

as well as off-shell correction down to 5 GeV[111]. The resulting cross-section corresponds to $0.88^{+0.09}_{-0.10}\text{pb}$.

The renormalisation and factorisation scale uncertainties are obtained by simultaneously varying up and down both parameters by a factor of two and comparing them to the nominal prediction. Additionally, PDF uncertainties are considered following the PDF4LHC prescription. For the PS algorithm and underlying event model uncertainty, the nominal sample is compared to a MADGRAPH5_AMC@NLO sample interfaced to HERWIG instead of PYTHIA. Finally, the Var3c A14 tune variations are applied as uncertainty in the modelling on the initial-state radiation.

$t\bar{t}H$ For the sample used in the $t\bar{t}H$ analysis, POWHEG 2 [112] is used to generate the ME at NLO in α_s , with the NNPDF3.0NLO PDF set. The h_{damp} parameter is chosen as $\frac{3}{4}(m_t + m_{\bar{t}} + m_H) = 352.5\text{ GeV}$ and for the functional form of the renormalisation and factorisation scale, the default scale $\sqrt[3]{m_T(t)m_T(\bar{t})m_T(H)}$ is used with $m_T = \sqrt{m^2 + p_T^2}$. The PS and hadronisation

is handled by PYTHIA 8.230, with the A14 set of tuned parameters and the NNPDF2.3LO PDF set. The sample is normalised according to the NLO cross-section [69].

The renormalisation and factorisation scale uncertainties as well as the PDF uncertainties are considered and constructed in the same way as for the $t\bar{t}\ell^+\ell^-$ sample. For the PS algorithm and underlying event model uncertainty, the nominal sample is compared to a POWHEG sample interfaced to HERWIG instead of PYTHIA and an uncertainty in the ME and PS matching is obtained through varying $p_{T,hard}$. Finally, the Var3C A14 tune variations are applied as uncertainty in the modelling on the initial-state radiation and α_s^{FSR} is varied by factor of two up and down as uncertainty in the final-state radiation. Theoretical uncertainties are additionally covered by a scale uncertainty of $\pm 9.2\%$, a PDF + α_S uncertainty of $\pm 3.6\%$ [113]. Branching ratio uncertainties are applied on the $H \rightarrow WW$, $H \rightarrow \tau\tau$, $H \rightarrow ZZ$, $H \rightarrow bb$ and $H \rightarrow other$ branching ratios.

For the $t\bar{t}\ell^+\ell^-$ analysis, another sample is used, where the ME for $t\bar{t}H$ is calculated at NLO with MADGRAPH5_AMC@NLO 2.6.0 with the NNPDF3.0NLO PDF set. It is then interfaced with PYTHIA 8.230 using the A14 tune.

The $t\bar{t}H$ theoretical uncertainties are only covered by a scale uncertainty of $5.8\% - 9.2\%$ and a PDF + α_S uncertainty of $\pm 3.6\%$ [113].

tHq, tWH The samples are produced with MADGRAPH5_AMC@NLO 2.6 in the four (tHq) and five (tWH) flavour scheme at NLO accuracy with the NNPDF3.0NLO PDF set and interfaced with PYTHIA 8.230, with the A14 set of tuned parameters and the NNPDF2.3LO PDF set. The decay of the top quark and of the W boson are performed by MADSPIN. The overlap between $t\bar{t}H$ and tWH is removed [114, 115].

In the $t\bar{t}H$ analysis, the theoretical uncertainties are covered by a scale uncertainty of $\pm 15\%$ and $\pm 7\%$ respectively and a PDF + α_S uncertainty of $\pm 4\%$ and $\pm 6\%$ respectively [113].

$t\bar{t}W$ The $t\bar{t}W$ background is generated with SHERPA 2.2.10 using the default PS at NLO accuracy in QCD with MEPS@NLO merging [116] of up to one additional parton at NLO and up to two additional partons at LO using COMIX [117] and OPENLOOPS [118, 119, 120]. Additionally, a LO $t\bar{t}Wj$ sample is also generated with SHERPA 2.2.10, including the sub-leading EW corrections with $\alpha_S\alpha^3$ couplings [121, 122]. In the $t\bar{t}\ell^+\ell^-$ analysis, the samples are normalised separately to a total reference cross-section of 722.4fb [123], while in the $t\bar{t}H$ analysis the cross-sections are normalised to 745fb [124].

Similar to $t\bar{t}\ell^+\ell^-$ and $t\bar{t}H$, renormalisation and factorisation scale uncertainties are considered for $t\bar{t}W$. For the PDF uncertainties, the PDF4LHC prescription is used and α_S is varied. The ME and PS uncertainties are estimated by a two-point variation between the nominal SHERPA sample and a MADGRAPH5_AMC@NLO sample interfaced with PYTHIA 8 using the FxFx merging scheme, as well as by a two-point variation between a POWHEG+PYTHIA 8 and a POWHEG+HERWIG 7 sample. Lastly, an uncertainty in the relative yields of the EW component inside the QCD +EW template is considered, by varying the EW fraction between the values of SHERPA and MADGRAPH5_AMC@NLO.

tZq and tWZ tZq and tWZ are generated at NLO using MADGRAPH5_AMC@NLO 2.9.5 and MADGRAPH5_AMC@NLO 2.2.2 respectively with the NNPDF3.0NLO PDF set. The events are then interfaced with PYTHIA 8.245 for tZq and PYTHIA 8.212 for tWZ , both using the A14 tune and the NNPDF2.3LO PDF set. tZq is simulated in the four-flavour scheme and normalised to a cross-section obtained in the five-flavour scheme, including off-shell corrections down to 5 GeV. tWZ is modelled according to the diagram removal scheme 1 [115], not including processes with two resonant top quarks.

In the $t\bar{t}\ell^+\ell^-$ analysis, several uncertainties are considered. For tZq , the same uncertainties as for $t\bar{t}\ell^+\ell^-$ are applied. For tWZ , the modelling uncertainties are estimated by the difference between samples using the DR1 and DR2 diagram removal scheme [115]. Additionally, the same PDF and scale uncertainties are considered as for $t\bar{t}\ell^+\ell^-$.

$t\bar{t}$ $t\bar{t}$ is modelled using POWHEG 2 at NLO with the NNPDF3.0NLO PDF set. The damping factor h_{damp} is set to 1.5 times the top mass. The PS and hadronisation is performed by PYTHIA 8.230 with the A14 tune and the NNPDF2.3LO PDF set. The top quark decays, with the mass set to 172.5 GeV, are modelled at LO and decays of B- and C-hadrons are modelled using EVTGEN 1.2.0.

For $t\bar{t}$, the PS uncertainty is estimated by a two-point variation between a POWHEG+PYTHIA 8 and a POWHEG+HERWIG 7 sample. Additionally, matching uncertainties are considered by varying the h_{damp} and $p_{T,hard}$ parameters in PYTHIA. Finally, in the $t\bar{t}H$ analysis, renormalisation and factorisation scale and initial-state and final-state radiation uncertainties are considered.

$t\bar{t} \rightarrow W^+bW^-b\ell^+\ell^-$ This sample is only used in the $t\bar{t}H$ analysis and includes rare $t \rightarrow Wb\gamma^*(\rightarrow \ell^+\ell^-)$ radiative decays with $m(\ell^+\ell^-) > 1$ GeV. The photon radiation is allowed to originate from the t - or b -quark or the W boson. For the generation of the $t\bar{t}$ process at LO accuracy in α_s MADGRAPH5_AMC@NLO 2.8.1 is used. The PS and hadronisation is performed

by PYTHIA 8.244, with the A14 set of tuned parameters and the NNPDF2.3LO PDF set. Internal photon conversion contributions with $m(\ell^+\ell^-) < 1$ GeV are added via an inclusive $t\bar{t}$ sample, where the conversions are modelled with QED multiphoton radiation in the PS. Overlap between the different samples is removed.

$t\bar{t}t\bar{t}$ $t\bar{t}t\bar{t}$ is produced with MADGRAPH5_AMC@NLO 2.6.2 at NLO in α_s , with the NNPDF3.0NLO PDF set. For the functional form of the renormalisation and factorisation scale, the default scale $\frac{m_T}{4}$ is used. The top quarks are decayed with MADSPIN at LO. The sample is interfaced with PYTHIA 8.230 with the A14 tune and the NNPDF2.3LO PDF set. The sample is normalised to a NLO cross-section including EW corrections of 12 fb [122].

The PS uncertainty for $t\bar{t}t\bar{t}$ is estimated by a two-point variation between MADGRAPH5_AMC@NLO +PYTHIA and MADGRAPH5_AMC@NLO +HERWIG. Additionally, in the $t\bar{t}H$ analysis, renormalisation and factorisation scale uncertainties are considered.

Diboson Diboson processes with additional jets, up to one additional parton at NLO and up to two additional partons at LO, resulting in three charged leptons and one neutrino or four charged leptons are generated with SHERPA 2.2.2, using the default PS. The OPENLOOPS library is used for virtual QCD corrections.

Renormalisation and factorisation scale uncertainties and PDF uncertainties are included. Additionally, in the $t\bar{t}\ell^+\ell^-$ analysis, alternative truth level samples are used to estimate the CKKW matching scale in SHERPA, the resummation scale and the alternative recoil scheme uncertainties.

Single boson Single boson processes are generated in the same way as diboson events but with SHERPA 2.2.1. The samples include up to two additional partons at NLO and up to two additional partons at LO.

Pile-up and detector simulation In order to model the pile-up, all MC samples are overlayed with soft QCD samples generated with PYTHIA 8.186 with the A3 tune [125] and the MSTW2008LO PDF set [126]. The pile-up is modelled separately for the different data taking years in order to match the requirements. Additionally, the detector response is simulated using Geant4.

STATISTICAL INTERPRETATION

5

All of the particle interactions described previously occur according to probabilities given by their cross-sections. Statistical tools and methods are therefore essential for analysing the collected data. In general, these data are compared to the predictions of a considered theoretical model, which requires quantifying how compatible the model is with the experimental data, taking into account uncertainties. The comparisons can either be used to identify shortcomings of the theory or to measure free parameters of the model. In the analyses presented in this thesis, signal strength measurements are performed using binned profile likelihood fits, described in Section 5.1. The uncertainties on these measurements are then estimated with confidence intervals, described in Section 5.2.

5.1 Profile likelihood fit

Binned histograms are filled with templates for all expected background components and the considered signal. For all of these templates uncertainties are considered. The statistical uncertainties originate from the finite number of simulated MC events. The systematic uncertainties come from theoretical or instrumental uncertainties and can impact the normalisation as well as the shape of the distributions. Shape uncertainties can be constructed by considering alternative distributions and interpolating between them. The interpolation happens between the nominal distribution and $+1\sigma$ and/or -1σ variations via a bin-by-bin interpolation, allowing intermediate values. Finally, the observed data are added to the histograms with statistical uncertainties following Poisson distributions. Each bin of the histogram is considered to be independent.

A fit is then performed in order to determine the signal strength μ , corresponding to the normalisation of the signal component, where the model is best described by the data. A likelihood function is built, which is then maximised (or the negative logarithm of the likelihood is

minimised) during the fit procedure. The likelihood describes the probability for measuring the observed data, given the simulated templates in each bin in each analysis region. It is defined as follows:

$$L\left(\vec{n}|\mu, \vec{\theta}, \vec{k}\right) = \prod_{r \in \text{regions}} \prod_{i \in \text{bins}} \text{Pois}\left(n_{i,r} | \mu S_{i,r}(\vec{\theta}) + B_{i,r}(\vec{\theta}, \vec{k})\right) \times \prod_{j \in NP} \text{Gaus}(\theta_j) \quad (5.1)$$

$\vec{n}$ corresponds to the observed data, $\vec{k}$ to the free floating Normalisation Factors (NFs) of the background components and $\vec{\theta}$ to the Nuisance Parameters (NPs), describing the uncertainties on the templates [127]. While free floating NFs have a flat prior and can therefore freely be adjusted in the fit, NPs have a Gaussian prior, giving penalty terms to the fit if they are pulled away from the nominal value.

From the fit, the best-fit values of the signal strength, the background NFs and the NPs can be extracted, as well as the agreement of the observed data with the fitted MC templates. When NPs take a value different to their nominal one they are called ‘pulled’ and when their uncertainty determined by the fit is smaller than the uncertainty used as input for the NP, they are called ‘constrained’.

5.2 Confidence intervals

In order to determine uncertainties on the best-fit values, Confidence Intervals (CIs) are computed. A CI corresponds to an interval, which contains the true value of the estimated parameter with a certain probability.

The CI can be computed using Wilks’ theorem [128], stating that in the asymptotic limit, the test statistic follows a χ^2 distribution with the number of profiled parameters as the number of degrees of freedom. Another assumption of this theorem is that the best-fit value lies in the bulk of the parameter space and not at the boundary. In case all assumptions are valid, the 68 % CI would then correspond to the interval, where the test statistic is below 1.

In the profile likelihood fit, the test statistic is given by the profile likelihood ratio, which, at a specific signal strength μ_{test} , is defined as:

$$-2 \ln \left(\frac{\text{likelihood with } \mu \text{ fixed to } \mu_{test}}{\text{likelihood with } \mu \text{ free floating}} \right) \quad (5.2)$$

The 68 % CI limits, being approximately 1σ limits, would therefore correspond to the μ_{test} values, for which the profile likelihood ratio is equal to 1.

CONSTRAINING FOUR-FERMION EFT OPERATORS IN THE HIGH-MASS $t\bar{t}\ell^+\ell^-$ VERTEX

6

This chapter describes the measurement of the $t\bar{t}\ell^+\ell^-$ process, focussing on the high di-lepton invariant mass region, with emphasis on the unique sensitivity to the four-fermion EFT operators this provides. It is based on the ATLAS $t\bar{t}Z$ analysis [129] but targets a higher di-lepton invariant mass regime. The low statistics in this part of the phase-space require different background estimation techniques, which partially align with the ATLAS $t\bar{t}W$ analysis [52].

The author was the sole main analyser of this analysis and worked on all the studies presented in the following. The paper resulting from this work can be found in Reference [1].

6.1 Motivation

With the increasing amount of data collected with the LHC, the measurement of rare top processes becomes accessible, providing a stringent test of the SM by measuring the coupling of the top quark to bosons, such as the Z boson or the photon. Both processes have recently been measured with the ATLAS detector [129, 130]. The focus of the ATLAS $t\bar{t}Z$ analysis was on measuring the inclusive and differential cross-section of $t\bar{t}Z$ with the Z decaying to a charged lepton pair ($t\bar{t}\ell^+\ell^-$) in the on-shell Z mass region. Deviations in the coupling between the top and the Z boson from the SM could be a sign of new physics in the EW symmetry breaking mechanism [131, 132, 133, 134, 135, 136, 137, 138].

However, there has not been yet any dedicated measurement of the off-shell $t\bar{t}\ell^+\ell^-$ process, where the opposite-sign lepton pair originates from the Z/γ^* decay, with an invariant mass above the Z peak (Feynman diagram shown in Figure 6.1). This part of the phase-space is particularly interesting to study in the context of EFT, as many EFT $t\bar{t}\ell^+\ell^-$ couplings show an increasing impact with growing energy in the event. Constraints have been set so far by CMS in the context

of a global top [EFT](#) measurement [139], but no dedicated measurement has been performed to date.

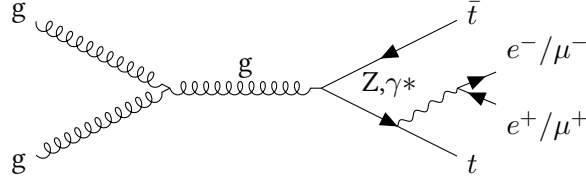


Figure 6.1: Feynman diagram of one of the possible $t\bar{t}Z$ production channels

Furthermore, the measurement of the $t\bar{t}\ell^+\ell^-$ coupling for $t\bar{t}e^+e^-$ and $t\bar{t}\mu^+\mu^-$ separately, could give access to some lepton flavour universality violating processes in the [EFT](#).

6.2 Strategy

In this analysis, a first dedicated measurement of the high di-leptonic invariant mass phase-space of the $t\bar{t}\ell^+\ell^-$ process is performed, with an interpretation in terms of four-fermion [EFT](#) operators. The measurement is made in the 3ℓ channel, providing good statistics (the $t\bar{t}$ branching ratio into a final state with exactly one lepton being about 44 %) and comparably low backgrounds.

The following four-fermion operators are considered:

- O_{Qe} with [WC](#) c_{Qe} : $(\bar{e}_i\gamma^\mu e_j)(\bar{Q}_k\gamma^\mu Q_\ell)$ corresponding to a coupling of right handed leptons and left handed quarks
- $O_{t\ell}$ with [WC](#) $c_{t\ell}$: $(\bar{\ell}_i\gamma^\mu \ell_j)(\bar{t}_k\gamma^\mu t_\ell)$ corresponding to a coupling of left handed leptons and right handed quarks
- $O_{Q\ell}^1$ with [WC](#) $c_{Q\ell}^1$: $(\bar{\ell}_i\gamma^\mu \ell_j)(\bar{Q}_k\gamma^\mu Q_\ell)$ corresponding to a coupling of left handed leptons and left handed quarks, weak singlet
- $O_{Q\ell}^3$ with [WC](#) $c_{Q\ell}^3$: $(\bar{\ell}_i\gamma^\mu \tau^I \ell_j)(\bar{Q}_k\gamma^\mu \tau^I Q_\ell)$ corresponding to a coupling of left handed leptons and left handed quarks, weak triplet
- O_{te} with [WC](#) c_{te} : $(\bar{e}_i\gamma^\mu e_j)(\bar{t}_k\gamma^\mu t_\ell)$ corresponding to a coupling of right handed leptons and right handed quarks
- $O_{\ell e Q t}^1$ with [WC](#) $c_{\ell e Q t}^1$: $(\bar{\ell}_i e_j)\epsilon(\bar{Q}_k t_\ell)$ corresponding to a coupling of right and left handed leptons and right and left handed quarks
- $O_{\ell e Q t}^3$ with [WC](#) $c_{\ell e Q t}^3$: $(\bar{\ell}_i \sigma^{\mu\nu} e_j)\epsilon(\bar{Q}_k \sigma_{\mu\nu} t_\ell)$ corresponding to a coupling of right and left handed leptons and right and left handed quarks, tensor $\times$ tensor Lorentz structure

As O_{Ql}^1 and O_{Ql}^3 are degenerate in $t\bar{t}\ell^+\ell^-$, both operators cannot be constrained at the same time. A linear combination is therefore considered: $O_{Ql}^\pm = O_{Ql}^1 \pm O_{Ql}^3$. O_{Ql}^- corresponds to the interaction between two up-type quarks with two charged leptons or two down-type quarks with two neutrinos, while O_{Ql}^+ describes the interaction between two down-type quarks with two charged leptons or two up-type quarks with two neutrinos. This analysis therefore only holds sensitivity to O_{Ql}^- , and O_{Ql}^+ is dropped.

The analysis will provide constraints on the following:

- flavour inclusive WCs considering linear and quadratic EFT contributions (terms proportional to c_i and c_i^2)
- flavour inclusive WCs considering only linear EFT contributions, namely only the interference of the EFT with the SM and not BSM only effects (only terms proportional to c_i)
- flavour dependent WCs (for electrons and muons) considering linear and quadratic EFT contributions (terms proportional to c_{i11} and c_{i11}^2 as well as to c_{i22} and c_{i22}^2)
- the difference between the electron and muon WCs considering linear and quadratic EFT contributions (parameterise the flavour dependent fit in terms of $c_{tl22} - c_{tl11}$)

The default EFT results are obtained without applying any upper m_{ll} cut. In order to increase the interpretability of the results, the constraints on the WCs are additionally presented with different upper m_{ll} cuts, as suggested by the LHC EFT working group [140]. By clipping on a specific m_{ll} value, any potential EW corrections or contributions from higher order EFT operators are restricted to a well defined maximum contribution. The clipping values are chosen to be 550 GeV, 800 GeV and 1 TeV.

6.3 Data and simulated event samples

In this analysis, the full 140 fb^{-1} dataset of pp collisions collected in Run 2 is used. More details about this run period can be found in Section 3.3.2.

A summary of the MC samples used in this analysis is given in Table 6.1. A more detailed description can be found in Section 4.8. Additionally, the alternative samples considered for modelling systematics are listed.

For the EFT interpretation of the measurement, additionally to the SM $t\bar{t}\ell^+\ell^-$ sample, a sample at LO is considered, which includes a reweighting to different WC values for several dimension

Table 6.1: MC configurations used for the signal and background MC samples. The configurations in grey and parentheses correspond to MC samples used to compute the modelling systematics.

Process	Generator	ME order	Parton shower	PDF	Tune
$t\bar{t}\ell^+\ell^-$	MG5_aMC	NLO	PYTHIA 8	NNPDF3.0NLO	A14
	(MG5_aMC)	(NLO)	(HERWIG 7)	(NNPDF3.0NLO)	(H7-UE-MMHT)
$t\bar{t}W$	SHERPA 2.2.10	MePs@NLO	SHERPA	NNPDF3.0NNLO	SHERPA default
	(MG5_aMC)	(FxFx NLO)	(PYTHIA 8)	(NNPDF3.0NLO)	(A14)
	(POWHEG)	(NLO)	(PYTHIA 8)	(NNPDF3.0NLO)	(A14)
	(POWHEG)	(NLO)	(HERWIG 7)	(NNPDF3.0NLO)	(H7-UE-MMHT)
$t\bar{t}W$ (EW)	SHERPA 2.2.10	LO	SHERPA	NNPDF3.0NNLO	SHERPA default
	(MG5_aMC)	(LO)	(PYTHIA 8)	(NNPDF3.0NLO)	(A14)
$t\bar{t}H$	MG5_aMC	NLO	PYTHIA 8	NNPDF3.0NLO	A14
$t\bar{t}t\bar{t}$	MG5_aMC	NLO	PYTHIA 8	NNPDF3.1NLO	A14
	(MG5_aMC)	(NLO)	(HERWIG 7)	(NNPDF3.0NLO)	(H7-UE-MMHT)
$t\bar{t}$	POWHEG-BOX	NLO	PYTHIA 8	NNPDF3.0NLO	A14
	(POWHEG-BOX)	NLO	(HERWIG7.1.3)	(NNPDF3.0NLO)	(H7-UE-MMHT)
	(POWHEG-BOX $2h_{damp}$)	NLO	(PYTHIA 8)	(NNPDF3.0NLO)	(A14)
	(POWHEG-BOX)	NLO	(PYTHIA 8 $p_{T,hard} = 1$)	(NNPDF3.0NLO)	(A14)
$t\bar{t}t$	MG5_aMC	LO	PYTHIA 8	NNPDF2.3LO	A14
$V, VV, qqVV, VVV$	SHERPA 2.2.2(1)	MePs@NLO	SHERPA	NNPDF3.0NNLO	SHERPA default
$Z \rightarrow \ell^+\ell^-$	SHERPA 2.2.1	MePs@NLO	SHERPA	NNPDF3.0NNLO	SHERPA default
$Z\gamma$	Sherpa 2.2.4	MePs@NLO	SHERPA	NNPDF3.0NNLO	SHERPA default
VH	PYTHIA 8	LO	PYTHIA 8	NNPDF2.3LO	A14
$t\bar{t}WW$	MG5_aMC	LO	PYTHIA 8	NNPDF2.3LO	A14
$t\bar{t}\gamma$	MG5_aMC	NLO	PYTHIA 8	NNPDF3.0NLO	A14
$t\bar{t}qq$	MG5_aMC	NLO	PYTHIA 8	NNPDF3.0NLO	A14
$t\bar{t}\nu\nu$	MG5_aMC	NLO	PYTHIA 8	NNPDF3.0NLO	A14
tZq, tWZ	MG5_aMC	NLO	PYTHIA 8	NNPDF2.3LO	A14

6 EFT operators. This sample is produced with MADGRAPH5_AMC@NLO 2.9.3 and PYTHIA 8.245 with the A14 tune. The reweighting is done according to the SMEFTsim 3.0 model, in the M_W EW input scheme [141] with the top flavour restrictions [20]. In the quark sector, this flavour model requires some symmetries in the first two generations, but none in the third generation. Additionally, top is slightly more restrictive in the lepton sector than the general model. The EFT scale is set to 1 TeV. As this analysis targets the high di-lepton invariant mass regime, two separate dedicated samples were generated: one covering the mass range between 5 GeV and 150 GeV and one covering everything above 150 GeV. Additionally, the samples are not generated at SM level, as it is usually done, but with all WCs set to some non zero value and then reweighted back to SM or points where only one WC has a non-zero value. Both, the mass cut and this different way of generating the sample, help to strongly enhance the high m_{ll} regime in the

MADGRAPH5_AMC@NLO calculations in order to obtain better accuracy in the EFT reweighting. In Figure 6.2 the m_{ll} distribution of $t\bar{t}\ell^+\ell^-$ is shown for c_{tll11} set to -2.4 for a default sample, generated at SM and covering the entire mass range (left), and for the dedicated samples used in this analysis (right). It can be observed that the EFT enhancement of the distribution at high m_{ll} is much more pronounced in the dedicated samples, while having significantly smaller statistical uncertainties. Additionally the default sample is showing very large weight fluctuations with a few very strongly weighted events. This issue is not observed in the dedicated samples.

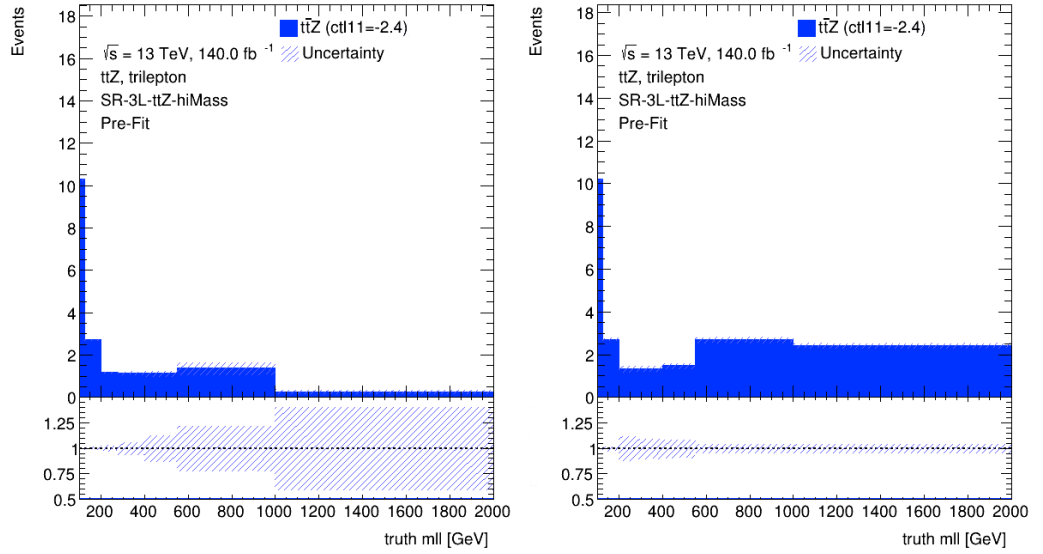


Figure 6.2: m_{ll} distribution of $t\bar{t}\ell^+\ell^-$ with the WC c_{tll11} set to -2.4 in a default EFT sample (left) and in the dedicated samples used in this analysis (right)

6.4 Object identification and reconstruction

The physics objects used in this analysis are reconstructed using the techniques described in Section 3.5.

6.4.1 Trigger strategy

Events used in this analysis must have been selected by either the single electron or the single muon trigger. Additionally, the lepton passing the trigger requirements must be matched to one of the pre-selection leptons reconstructed in the event. This matching is done using dedicated matching tools with the angular distance as metric.

6.4.2 Charged leptons

Two different categories of leptons are defined: pre-selected leptons, which are used for overlap removal and a subset of analysis regions for the non-prompt/fake background estimation, and signal leptons, passing tighter cuts than the pre-selected leptons and which are used for the majority of the analysis regions.

For electrons, the pre-selection requires an electron candidate to pass the `LooseAndBLayerLH` isolation WP. Additionally, cuts excluding the `LAr` crack-region ($1.37 < |\eta| < 1.52$) are applied as well as requirements on the transverse (d_0) and longitudinal (z_0) impact parameter ($|d_0/\sigma(d_0)| < 5.0$ and $|z_0 \cdot \sin(\theta)| < 0.5$ mm) in order to reduce the contributions from fake/non-prompt electrons and pile-up. Finally, the `ECIDS` and ambiguity type cut are applied in order to reduce charge-misidentified electrons and conversion electrons. Signal electrons are additionally required to pass the `MediumLH` identification cut and the `PLVTight` isolation cut.

Pre-selected muons need to pass the `Medium` quality requirement. Cuts on the transverse momentum ($p_T > 7$ GeV), the pseudo-rapidity ($|\eta| < 2.5$) and the impact parameter ($|d_0/\sigma(d_0)| < 3.0$ and $|z_0 \cdot \sin(\theta)| < 0.5$ mm) are also applied. Signal muons additionally need to pass the `PLVTight` WP cut.

The selection cuts for electrons and muons are summarised in Table 6.2.

Table 6.2: Summary of the electron and muon object definitions. The selection requirements for signal electrons and muons are applied in addition to the pre-selection cuts.

	Pre-selected Electron	Pre-selected Muon
Acceptance	$p_T > 7$ GeV, $ \eta^{clust} < 2.47$ except $1.37 < \eta^{clust} < 1.52$	$p_T > 7$ GeV, $ \eta < 2.5$
Quality	<code>LooseAndBLayerLH</code>	<code>Medium</code>
Impact parameter	$ d_0/\sigma(d_0) < 5.0$ $ z_0 \cdot \sin(\theta) < 0.5$ mm	$ d_0/\sigma(d_0) < 3.0$ $ z_0 \cdot \sin(\theta) < 0.5$ mm
	Signal Electron	Signal Muon
Quality	<code>MediumLH</code>	<code>Medium</code>
Isolation	<code>PLVTight</code>	<code>PLVTight</code>
<code>ECIDS</code>	Loose WP	
Ambiguity type	applied	

6.4.3 Jets

Jets which enter this analysis are required to pass a transverse momentum cut ($p_T > 25$ GeV), a pseudo-rapidity cut ($|\eta| < 2.5$) as well as a cut on the jet vertex tagger (reject jets with $p_T < 60$ GeV, $|\eta| < 2.4$ and $JVT < 0.5$ after overlap removal).

b -tagged jets have the same kinematic requirements as other jets and are considered as b -jet if they pass the 85 % DL1r b -tagging WP.

The jet selection criteria are summarised in Table 6.3.

Table 6.3: Summary of the jet selection criteria and the b -tagging requirement.

Selected jet	
Collection	Ant iKt 4EMPF low
Acceptance	$p_T > 25$ GeV, $ \eta < 2.5$
Jet Vertex Tagger	reject jets with $p_T < 60$ GeV, $ \eta < 2.4$ and $JVT < 0.5$ after overlap removal
b -tagged jet	
b -tagging	85% efficiency

6.4.4 Overlap removal

An overlap removal is applied on pre-selected objects in order to avoid the double-counting of objects.

Different removal steps are applied, removing objects in the following order from the event:

- electrons which have a shared track or overlapping cluster to any other electron
- calorimeter muons which share a track with an electron
- electrons which share a track with a muon
- jets within an angular distance of 0.2 of an electron
- electrons within an angular distance of 0.4 of a jet
- jets with less than 3 tracks within an angular distance of 0.2 of a muon
- jets with less than 3 tracks which have a inner-detector muon track ghost-associated to them

- muons within an angular distance of 0.4 of a jet

6.5 Definition of analysis regions and MC templates

In this analysis, two regions target the signal process, being the high-mass component of $t\bar{t}\ell^+\ell^-$: the high-mass $t\bar{t}e^+e^-$ and high-mass $t\bar{t}\mu^+\mu^-$ Signal Regions (SRs). Additionally to $t\bar{t}\ell^+\ell^-$, several background processes enter the SRs. They can be divided in irreducible and reducible backgrounds. In irreducible backgrounds, the reconstructed leptons are prompt and the final state is the same as the signal. For reducible backgrounds, the same final state as for the signal is reconstructed because of fake/non-prompt leptons. In order to enhance the sensitivity to the signal, the normalisation of the dominant backgrounds is measured in data. Two $t\bar{t}Z$ Control Regions (CRs), one WZ +jets CR and four 2ℓ SS CRs are defined, targeting the on-shell $t\bar{t}Z$ process, the WZ +jets process and the $t\bar{t}W$ process respectively. Finally, six CRs target different fake/non-prompt backgrounds: events containing conversion leptons or Heavy Flavour (HF) and Light Flavour (LF) fakes. The regions are summarised in Figure 6.3 and the cuts used to define the SRs and CRs are detailed in the following.

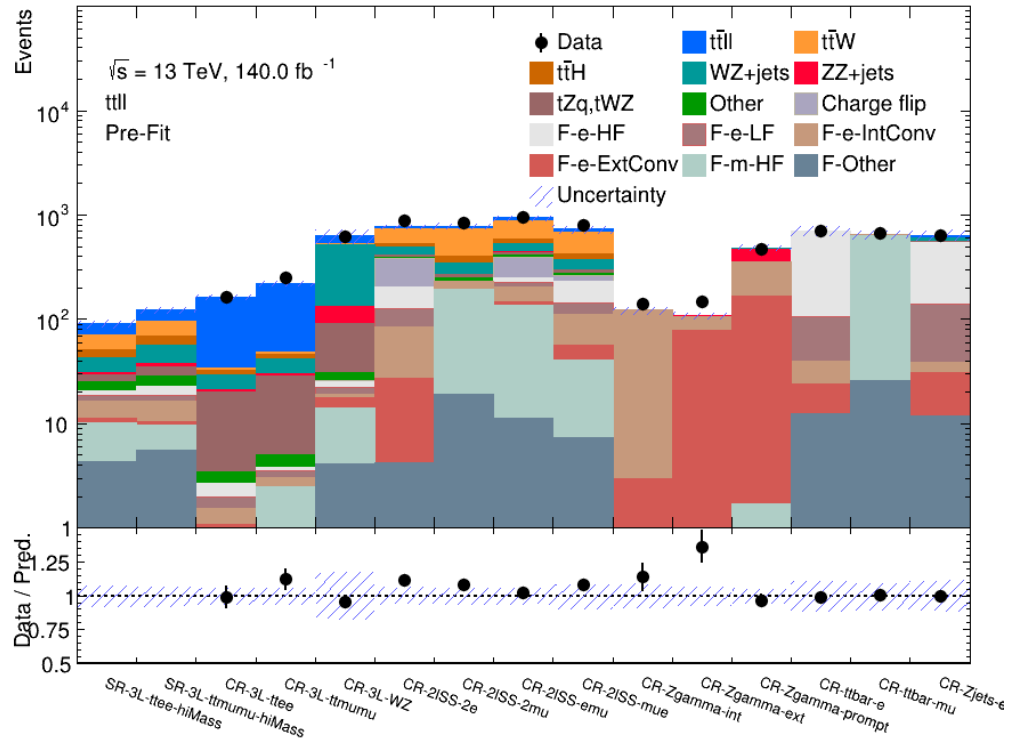


Figure 6.3: Summary of the SRs and CRs included in the fit. The different processes are defined in Section 6.5.1. The uncertainty bands include statistical and systematic uncertainties.

6.5.1 Event categorisation

The signal and the backgrounds are split into different templates, which are affected separately by **NFs** and **NPs**. In the following, events are categorised according to different criteria:

- if all leptons in the events are categorised as prompt, the event is classified according to its process (rare processes are grouped together as **Other**, including $t\bar{t}t\bar{t}$, $t\bar{t}t$, VH , WW , VVV , $t\bar{t}WW$, $t\bar{t}qq$ and $t\bar{t}\nu\nu$).
- if one lepton is categorised as fake/non-prompt, the event is classified according to the type of the fake lepton
- if several leptons are categorised as fake/non-prompt, the event is classified into the ‘Other fakes’ category. This contribution is, however, very small. In the plots, the template is called **F-Other**.

The classification of leptons into prompt or fake/non-prompt leptons is performed according to the truth information in the event, matched to the reconstructed objects using the angular distance. If a lepton is categorised as fake/non-prompt the following categories are considered:

- Heavy Flavour (**HF**) fakes: originate from a strange, charmed or bottom meson or baryon, a J/Ψ or $B\bar{B}$ meson. In the plots, the templates are called **F-e-HF** for **HF** electron fakes and **F-m-HF** for **HF** muon fakes.
- Light Flavour (**LF**) fakes: originate from a light baryon or meson. In the plots, the template is called **F-e-LF** for **LF** electron fakes.
- Conversion leptons: originate from a photon conversion (internal or material). In the plots, the templates are called **F-e-IntConv** for internal conversion fakes and **F-e-ExtConv** for material (external) conversion fakes.
- Charge flip electrons: electrons with misidentified charge

6.5.2 Signal regions

The **SRs** require exactly three signal leptons with at least one Opposite-Sign Same-Flavour (**OSSF**) pair. Their transverse momentum must be greater than 27 GeV, 20 GeV and 15 GeV. In order to suppress the conversion background, none of the leptons should pass the conversion cuts described in Section 3.5.1. All **OSSF** lepton pairs in the event must have an invariant mass above

10 GeV in order to remove contributions from low mass resonances, which are not included in the simulations. Finally, at least three jets with at least one being b -tagged are required.

The **SRs** target the high-mass component of $t\bar{t}\ell^+\ell^-$, where the mass of the **OSSF** pair closest to the Z mass (called m_{z1}) has to be above 101.1876 GeV. This mass cut corresponds to $m_Z + 10$ GeV, which selects events above the Z -peak. The **SRs** are split by flavour into $t\bar{t}e^+e^-$ and $t\bar{t}\mu^+\mu^-$ **SRs**, increasing the sensitivity to the flavour dependent **WCs**. This splitting is obtained by requiring at least two electrons or at least two muons respectively.

The selection cuts are summarised in Table 6.4. Additionally, the resulting **SRs** are shown in Figure 6.4 and the event yields for each process are detailed in Table 6.5.

Table 6.4: Summary of the selection criteria for the 3ℓ **SRs** and **CRs**. The neural network used for the splitting between the $t\bar{t}Z$ **CR** and the WZ +jets **CR** is introduced in Section 6.5.3.

$t\bar{t}\ell^+\ell^-$	$t\bar{t}Z$	WZ +jets
SR-3L-ttZ-hiMass	CR-3L-ttZ	CR-3L-WZ
exactly 3 tight leptons		
$p_T(1lep) > 27$ GeV, $p_T(2lep) > 20$ GeV, $p_T(3lep) > 15$ GeV		
at least one OSSF pair		
$m_{ll} > 10$ GeV for all OSSF pairs		
$n_{jets} \geq 3$ and $n_{B-jets} \geq 1$ at the 85 % efficiency WP		
none of the leptons passes the conversion cuts		
$m_{z1} > m_Z + 10$ GeV	$ m_{z1} - m_Z < 10$ GeV	
	$NN(VV) < 0.22$	$NN(VV) \geq 0.22$
	$NN(tZq) < 0.43$	

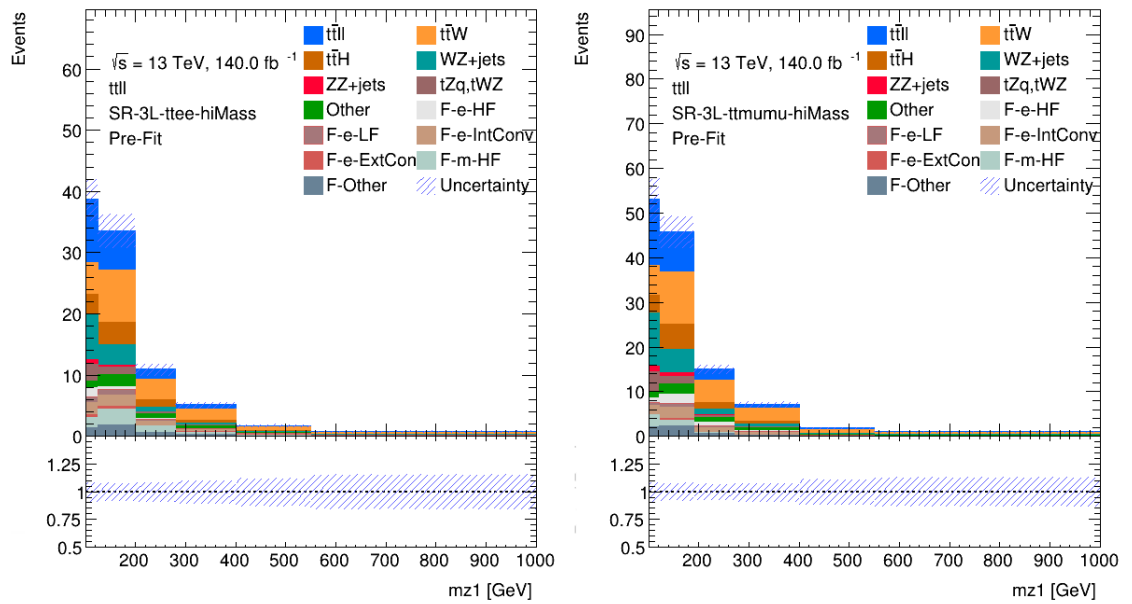


Figure 6.4: Expected distributions in the $t\bar{t}e^+e^-$ (left) and $t\bar{t}\mu^+\mu^-$ (right) **SRs** binned in the di-lepton invariant mass closest to the Z mass. The uncertainty bands include statistical and systematic uncertainties.

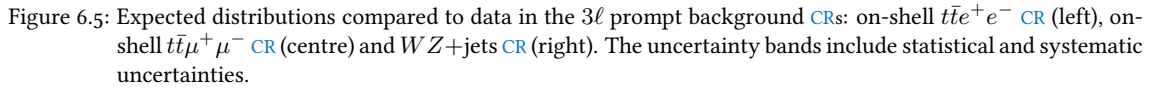
Table 6.5: Expected yields taken from MC of the different processes in the $t\bar{t}e^+e^-$ and $t\bar{t}\mu^+\mu^-$ SRs.

Process	$t\bar{t}e^+e^-$ SR	$t\bar{t}\mu^+\mu^-$ SR
$t\bar{t}\ell^+\ell^-$	19.4 ± 1.7	27.4 ± 1.9
$t\bar{t}W$	19.9 ± 2.3	27.5 ± 4.3
$t\bar{t}H$	8.6 ± 0.9	11.9 ± 1.2
WZ +jets	12.0 ± 3.2	19.5 ± 5.2
ZZ +jets	1.4 ± 0.4	2.4 ± 0.7
tZq, tWZ	4.2 ± 0.9	6.5 ± 0.7
Other	4.7 ± 1.6	5.7 ± 2.1
Ext e Conv	1.2 ± 1.2	0.7 ± 0.3
Int e Conv	4.9 ± 1.3	6.2 ± 2.7
e HF	2.1 ± 1.5	4.5 ± 0.8
e LF	2.4 ± 0.9	2.0 ± 0.6
μ HF	5.9 ± 1.5	4.2 ± 0.7
Other fakes	4.4 ± 2.2	5.6 ± 3.6
Total	91.1 ± 8.0	124.1 ± 10.4

6.5.3 Control regions targeting prompt backgrounds

CRs targeting the $t\bar{t}Z$ and the WZ +jets contributions are obtained by using the same selection as for the SRs, but requiring the invariant mass of the OSSF pair to lie inside of the Z peak, namely $81.1876 \text{ GeV} < m_{Z1} < 101.1876 \text{ GeV}$. The $t\bar{t}Z$ and the WZ +jets CRs are split by a cut on a Deep Neural Network (DNN) output, the DNN being taken from the refined $t\bar{t}Z$ analysis [129]. The DNN was trained to separate between $t\bar{t}Z$, tZq and diboson events, using different lepton- and jet-related variables, as well as properties of the reconstructed Z or top. In this analysis, the tZq region is not considered. Otherwise, the same DNN output cuts are used to define the $t\bar{t}Z$ and WZ +jets CRs. For the $t\bar{t}Z$ CR, the output node for tZq must be below 0.43 and the VV output node below 0.22. For the WZ +jets CR the output node for VV is required to be larger than 0.22. In the $t\bar{t}Z$ analysis, the WZ +jets CR targets specifically the $WZ + b$ process, wherefore a tighter b -tagging WP of 60 % efficiency is used. In this analysis, a general WZ +jets CR, with a similar diboson composition as in the SRs, is considered and the default 85 % tagging WP is used. In the same way as for the SRs, the $t\bar{t}Z$ CR is split by flavour into a $t\bar{t}e^+e^-$ and a $t\bar{t}\mu^+\mu^-$ CR. Both $t\bar{t}Z$ CRs and the WZ +jets are not binned in any variable but only contain the overall event yield. A summary of the cuts defining these CRs is shown in Table 6.4.

The 3ℓ prompt CRs with data are shown in Figure 6.5. A very good data MC agreement already at pre-fit level can be observed.

Table 6.6: Summary of the selection criteria for the 2 ℓ SS CRs.

The resulting CRs are shown in Figure 6.6. As already seen in several previous ATLAS analyses, an excess in data compared to MC is observed. The results of the inclusive and differential $t\bar{t}W$ analysis [52] are discussed in Section 7.3.2.

In order to get a better control of the dominant non-prompt and fake lepton backgrounds, the template fit method is applied. In this method, it is assumed that the shape of these backgrounds

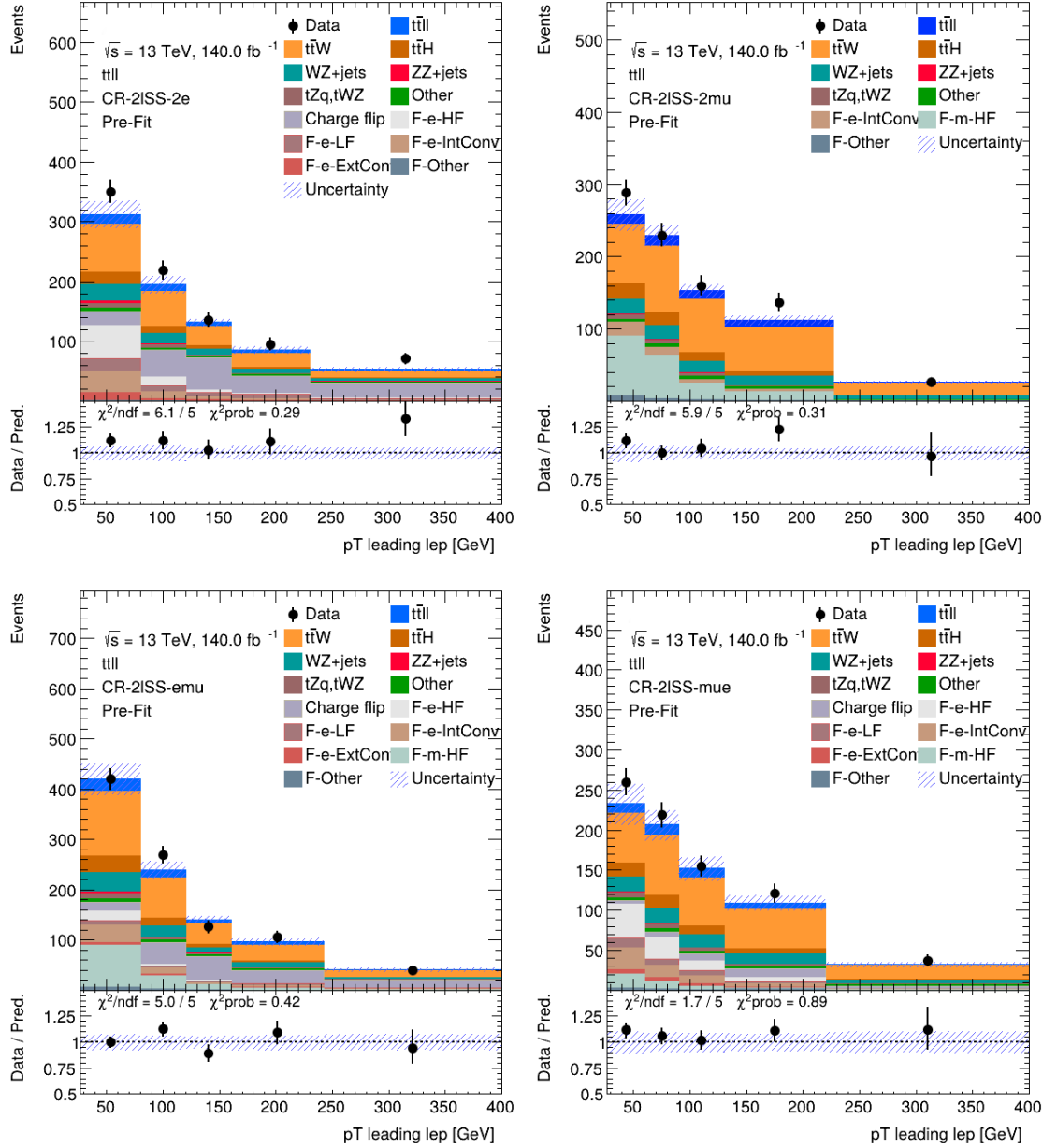


Figure 6.6: Expected distributions compared to data in the 2ℓ SS prompt CRs: $2e$ SS CR (top left), 2μ SS CR (top right), $e\mu$ SS CR (bottom left) and μe SS CR (bottom right). The uncertainty bands include statistical and systematic uncertainties.

is well modelled in simulation within the considered uncertainties. Therefore, the shape of these backgrounds is taken from MC but the normalisation is determined in data. This is done through adding CRs targeting these backgrounds to the fit and keeping the normalisation of the templates as free floating parameters.

Fake lepton MC templates in the signal regions

In this analysis, the fake/non-prompt lepton backgrounds are dominated by the $t\bar{t}$ process. In order to enhance the MC statistics, $t\bar{t}$ samples with a di-lepton filter are used. The MC statistics in the SRs are, however, still observed to be very low for the fake background templates. These are therefore replaced by templates with looser selection criteria. Instead of the requirement of three signal leptons, only three pre-selected leptons are required in the SRs and the new loose templates are normalised to the distribution with the tight selection. The impact of using pre-selected leptons instead of signal leptons on the m_{ll} distribution is shown in Figures 6.7 and 6.8. Additionally to the tight and loose selection, the χ^2 probability is given for the agreement of both distributions. In general, the shape in m_{ll} agrees well between both distributions, with high χ^2 probabilities. Some discrepancies can be observed, which are, however, compatible with statistical fluctuations in the distribution with the tight selection. Additionally, conservative uncertainties are applied, described in Section 6.6. This method is observed to strongly increase the MC statistics of the fake templates, allowing for a binning optimisation towards EFT sensitivity.

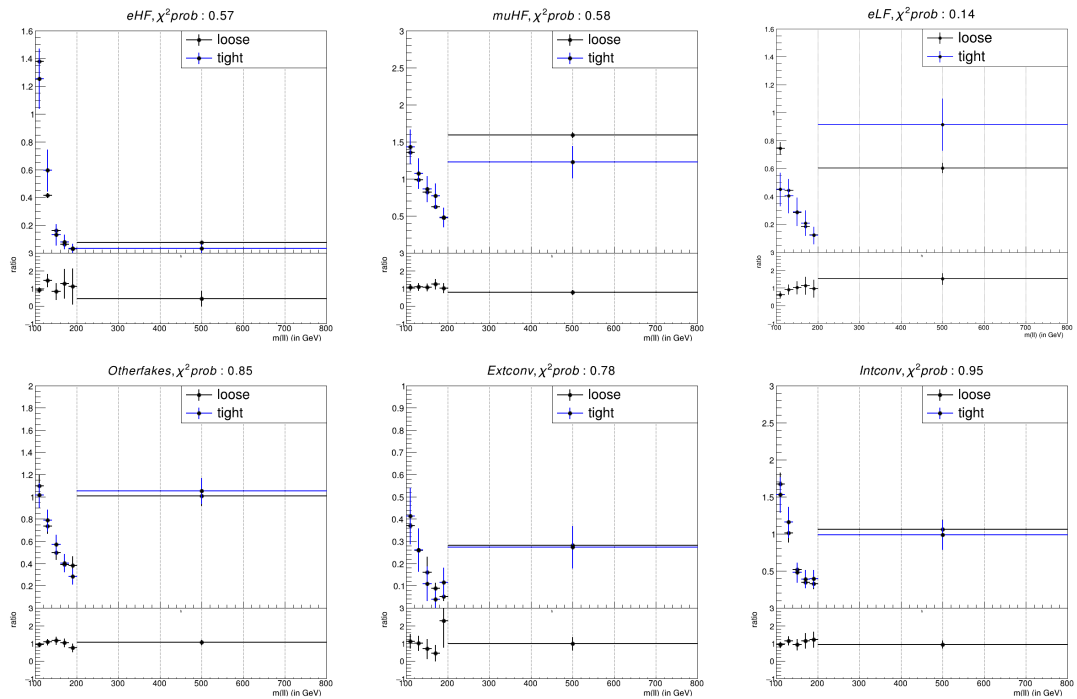


Figure 6.7: Comparison of the expected m_{ll} distribution of the loose and tight fake templates in the $t\bar{t}e^+e^-$ SR

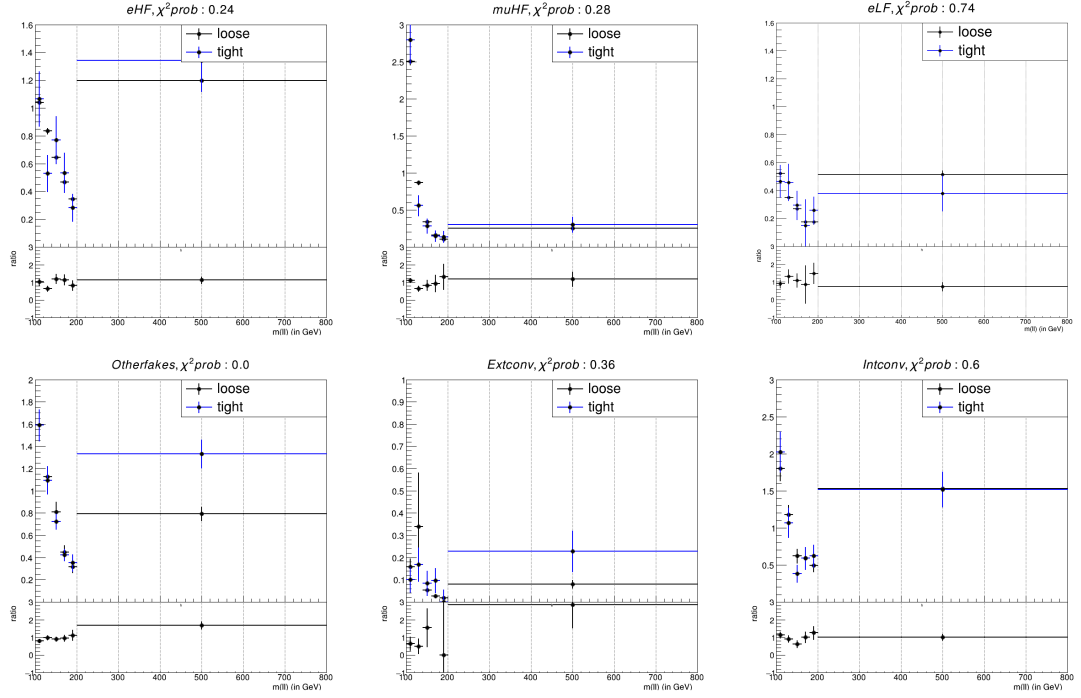


Figure 6.8: Comparison of the expected m_{ll} distribution of the loose and tight fake templates in the $t\bar{t}\mu^+\mu^-$ SR

Control regions targeting heavy flavour and light flavour fake backgrounds

In order to target the HF and LF electron and muon fakes, three CRs are defined, using looser requirements on the leptons. They require exactly three leptons, two signal leptons and one pre-selected-non-signal lepton, with a sum of charges of $+1e$ or $-1e$. Additionally, similar to the SRs, the transverse momentum must be greater than 27 GeV, 20 GeV and 15 GeV. Finally, at least three jets, with at least one of them being b-tagged, are required.

The three regions are split by the following selection cuts:

- HF electron CR: the loose non-tight lepton is an electron, no OSSF pair
- HF muon CR: the loose non-tight lepton is a muon, no OSSF pair
- LF electron CR: three electrons, $E_T^{miss} < 80$ GeV

A summary of these cuts is shown in Table 6.7.

Similar to the $t\bar{t}Z$ analysis, the HF electron and HF muon CRs only contain one bin and the LF electron CR is binned in the transverse mass of the W , using the electron not associated to a Z and the missing transverse energy, as it provides a good discrimination between LF electron fakes and other fakes.

Table 6.7: Summary of the selection criteria for the heavy and light flavour fake CRs.

e HF CR-ttbar-e	μ HF CR-ttbar-mu	e LF CR-Zjets-e
2 tight and 1 loose non-tight lepton		
$p_T(1lep) > 27 \text{ GeV}, p_T(2lep) > 20 \text{ GeV}, p_T(3lep) > 15 \text{ GeV}$		
Sum of lepton charges equal plus or minus 1		
$n_{jets} \geq 3$ and $n_{B-jets} \geq 1$ at the 85 % efficiency WP		
no OSSF pair		
loose lep is an e	loose lep is a μ	3 e
		$E_T^{miss} < 80 \text{ GeV}$

The resulting CRs are shown in Figure 6.9, all three having a good data MC agreement at pre-fit level.

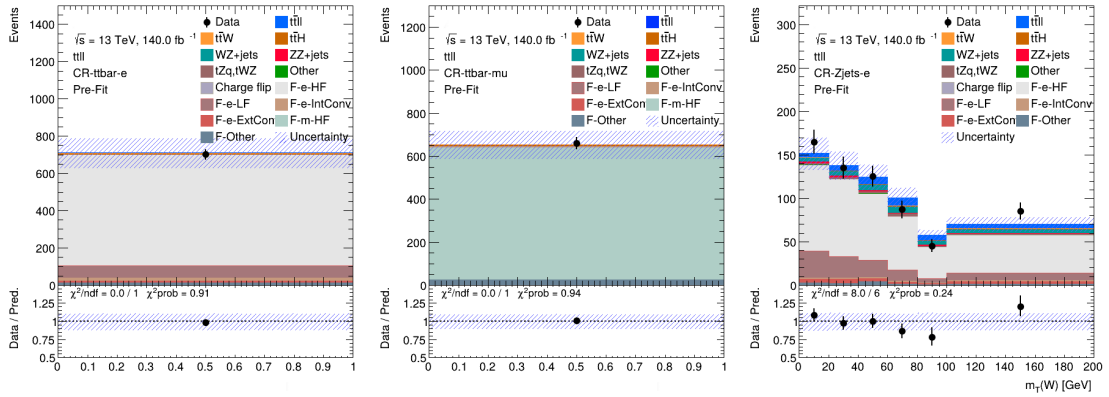


Figure 6.9: Expected distributions compared to data in the fake background CRs: HF e CR (left), HF μ CR (centre), LF e CR (right). The uncertainty bands include statistical and systematic uncertainties.

In the template fit, only the normalisation is derived from data, the shape being determined by the MC predictions. In order to check that any potential shape mismodelling would not affect the $t\bar{t}\ell^+\ell^-$ measurement, the MC shape of the fake templates is compared between the HF and LF CRs and the SRs. The fake lepton rates being heavily p_T dependent, the p_T distribution of the HF and LF fake leptons in the fake CRs and in the SRs is shown in Figures 6.10 to 6.12. The distributions appear to be very similar between the CRs and the SRs. Additionally, as seen in Figure 6.13, the shape of the fake lepton p_T inside different $m_{\ell\ell}$ regimes in the SRs does not show important shape differences.

Control regions targeting conversion fake backgrounds

CRs are defined to constrain the conversion fake background. These CRs target the $Z(\rightarrow \mu\mu)\gamma$ process, where the photon converts into electrons. Therefore, an opposite-sign muon pair and

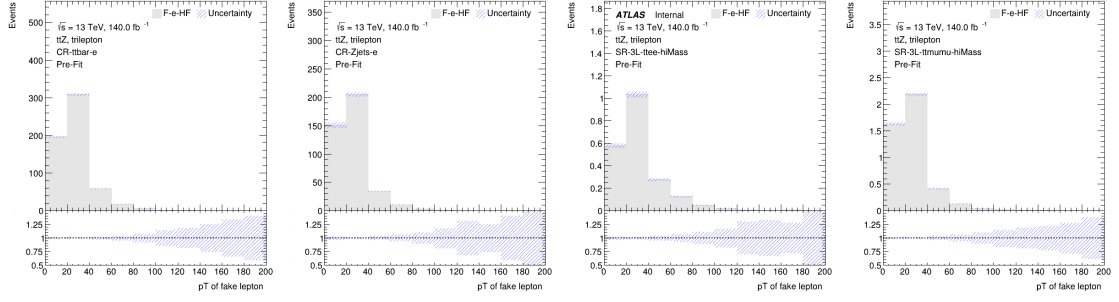


Figure 6.10: Expected p_T distribution of the HF fake electron in the HF and LF electron CRs (two left plots) and in the SRs (two right plots)

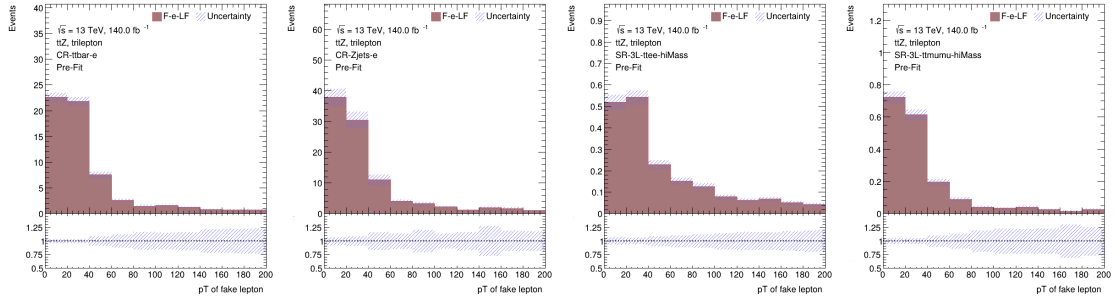


Figure 6.11: Expected p_T distribution of the LF fake electron in the HF and LF electron CRs (two left plots) and in the SRs (two right plots)

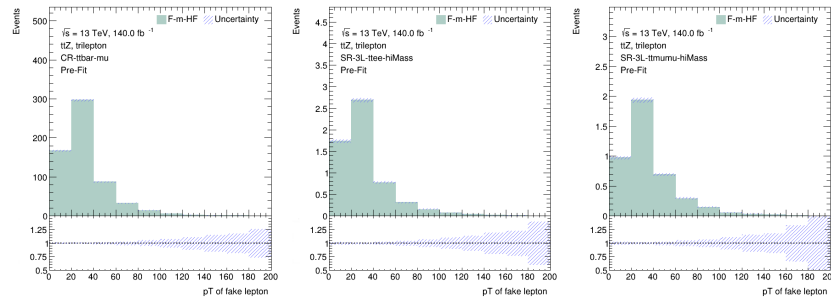


Figure 6.12: Expected p_T distribution of the HF fake muon in the HF muon CR (left) and in the SRs (two right plots)

an electron are required, all leptons passing the tight WP. In order to isolate the events where the photon is radiated of the Z , an invariant mass above 20 GeV but outside of the Z peak is required for the muon pair, with at the same time an invariant mass of the three leptons lying within the Z peak. An upper cut on E_T^{miss} of 50 GeV is applied and events containing a b -tagged jet are vetoed.

Compared to the SRs, the conversion requirements described in Section 3.5.1 are inverted, asking for the electron to be conversion-like. The CRs are split into an internal and a material conversions CR depending on the conversion type of the electron. Both of these conversion CRs only contain one bin. They are shown in Figure 6.14. Both CRs show an excess of data compared to MC, which is particularly pronounced in the material conversion CR. In order to understand this

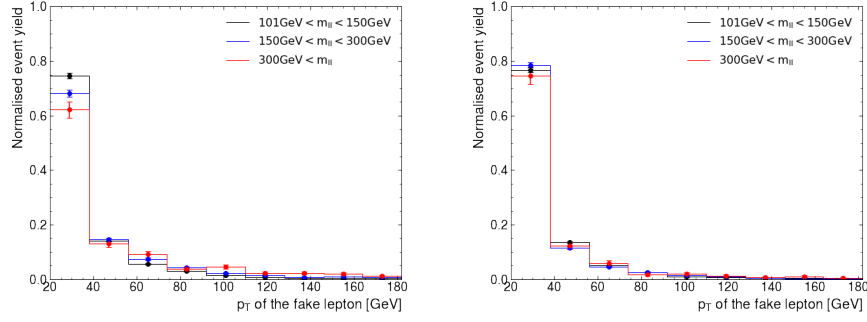


Figure 6.13: Expected p_T distribution of the fake lepton in the SRs ($t\bar{t}e^+e^-$ left and $t\bar{t}\mu^+\mu^-$ right) for different m_{II} regions.

mismodelling better, Figure 6.15 shows an inclusive $Z\gamma$ CR (left), an inclusive $2\ell\text{SS}$ CR (centre) and an inclusive SR (right) where the default CRs and SRs are used without lepton flavour splitting and where at least one lepton must pass the internal or material conversions cut. All three regions are binned in the conversion radius of the conversion fake lepton. While the region obtained from the SR does not have enough statistics to make a clear statement, the region obtained from the $2\ell\text{SS}$ CRs shows a similar mismodelling as in the $Z\gamma$ region, where the MC clearly underestimates the data for high conversion radii. No particular cut was observed to introduce this mismodelling.

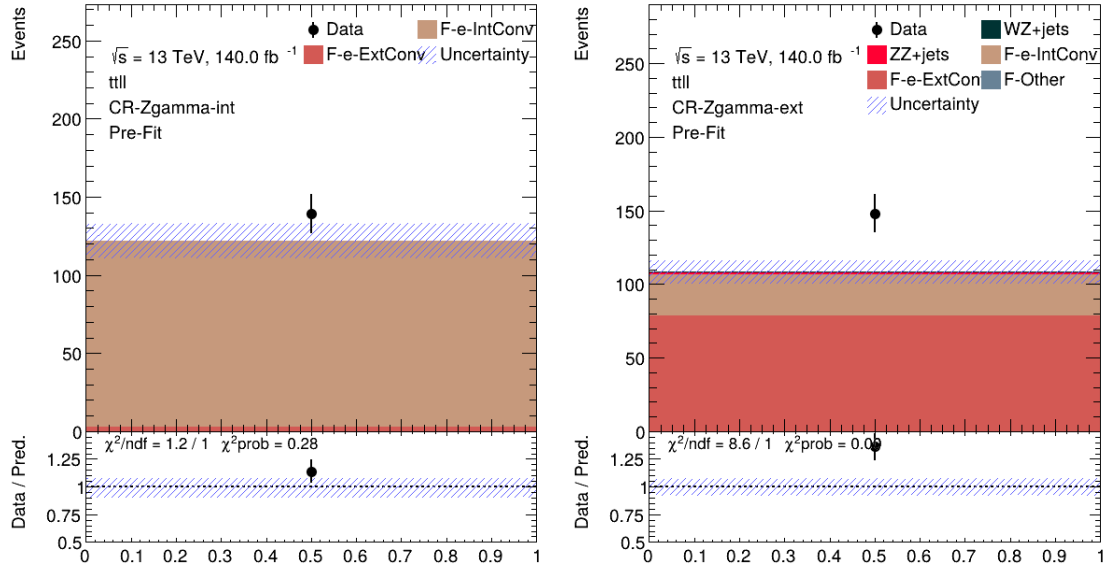


Figure 6.14: Expected distributions compared to data in the internal (left) and material (right) conversion fake CRs . The uncertainty bands include statistical and systematic uncertainties.

A third $Z\gamma$ region is considered, where instead of selecting events containing an electron which passes either the internal or material conversion cuts, events without any conversion-like electrons are selected. This $Z\gamma$ region therefore has the same conversion cuts applied as all other

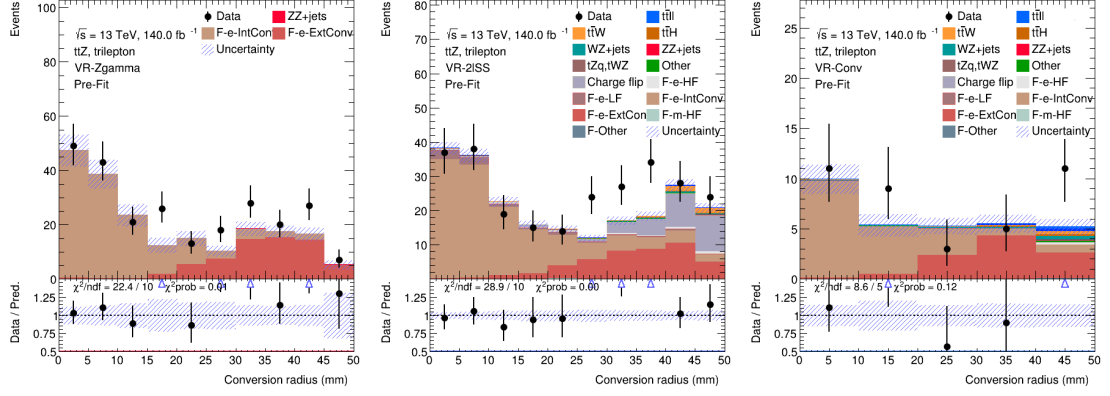


Figure 6.15: Expected distributions compared to data in an inclusive $Z\gamma$ region (left), an inclusive $2\ell\text{SS}$ region (centre) and an inclusive SRs (right) selecting events containing at least one conversion-like lepton. The uncertainty bands include statistical uncertainties.

prompt CRs and the SRs . The MC modelling in this region is checked for different variables such as the p_T of the fake lepton and m_{ll} (see Figure 6.16). The data MC agreement is improved compared to the other two $Z\gamma$ CRs .

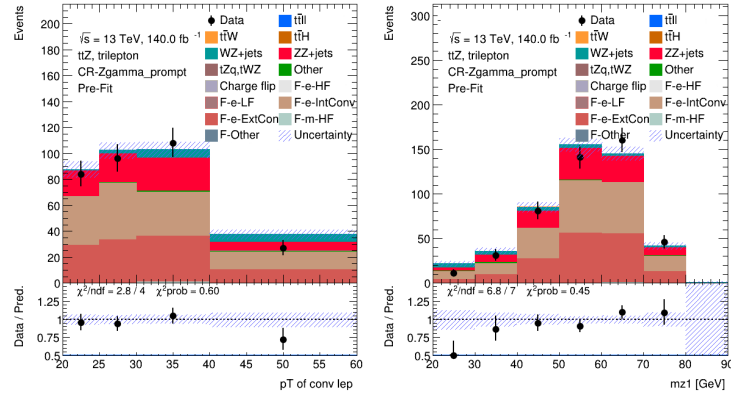


Figure 6.16: Expected distributions compared to data in a prompt $Z\gamma$ region binned in the p_T of the fake lepton (left) and m_{ll} (right). The uncertainty bands include statistical uncertainties.

This prompt $Z\gamma$ region is, however, less pure than the dedicated internal and material conversion CRs and no variable was found, allowing to separate well between internal and material conversions. It was therefore decided to include all three $Z\gamma$ regions in the fit. The prompt $Z\gamma$ CR is shown in Figure 6.17 and, as the other $Z\gamma$ CRs , contains one bin. The internal and material conversion CRs allow to separate the normalisation of internal and material conversions but show some mismodelling which is not fully understood. The prompt CR , being closer in the selection to the SRs , can counterbalance the mismodelling. Additionally, the difference in mismodelling in the different CRs introduces a penalty in the fit, by leading to higher uncertainties on the conversion NFs .

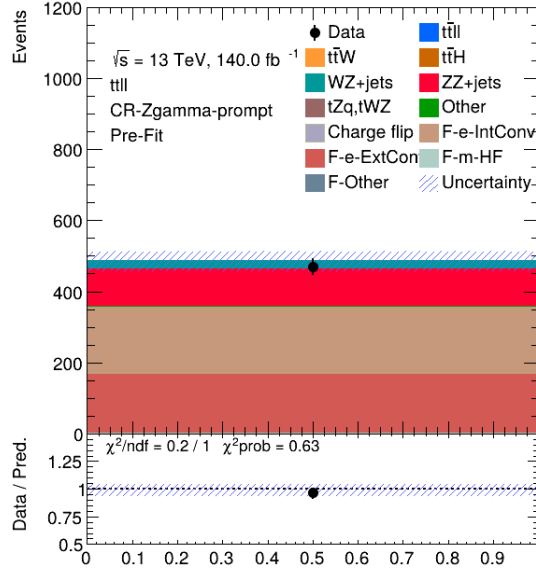


Figure 6.17: Expected distributions compared to data in the prompt conversion fake CRs with data included. The uncertainty bands include statistical and systematic uncertainties.

The conversion variables used to define the conversion CRs can only be computed for electrons. Therefore, only conversion electrons are considered in the CRs. The derived NF for internal conversions is, however, also applied on conversion muons, the physics process being independent of the flavour.

A summary of the cuts defining the three conversion CRs is given in Table 6.8.

Table 6.8: Summary of the selection criteria for the conversion fake CRs.

Material conversions CR-Zgamma-ext	Internal conversions CR-Zgamma-int	Prompt CR-Zgamma-prompt
3 tight leptons		
2 opposite-sign μ and 1 e		
for same-sign leptons: $p_T > 20$ GeV & for opposite-sign lepton: $p_T > 10$ GeV		
$E_T^{miss} < 50$ GeV		
$m_{\mu\mu} > 20$ GeV & $ m_{\mu\mu} - m_Z > 10$ GeV		
$ m_{ll} - m_Z < 10$ GeV		
no b-jet at the 85 % efficiency WP		
A conversion vertex is found for the electron		No conversion vertex is found
$r_{conv} > 20$ mm	$r_{conv} < 20$ mm	
$m_{ll} < 100$ MeV wrt conversion vertex	$m_{ll} < 100$ MeV wrt primary vertex	

Data-driven charge flip estimation in the $2\ell SS$ control regions

The $2\ell SS$ CRs are heavily impacted by events including charge flip electrons. Most of the SM processes generate opposite-sign leptons, leading to significantly higher cross-sections for opposite-sign leptons compared to same-sign leptons. This results in the fact that even if the charge flip rates are small and the charge flip contributions are suppressed with tools such as ECIDS, the same-sign selection has a non-negligible contamination from opposite-sign processes through charge flip electrons. As the charge misreconstruction relies on particle interactions with the detector material, a data-driven estimation of this background is chosen in the $2\ell SS$ CRs, to avoid a potential mismodelling in simulation.

Data-driven charge flip factors are computed in two $Z \rightarrow ee$ regions, which require exactly two tight electrons, which pass the ECIDS cut and fail the conversion cuts. Events with more than one jet or any b -jet are vetoed. An opposite-sign lepton region and a same-sign region are considered, both being dominated by $Z \rightarrow ee$, one of the electrons having a misreconstructed charge in the same-sign region.

Both regions are then split into three m_{ee} bands: the peak region between 71 GeV and 101 GeV and two side-bands (61 GeV to 71 GeV and 101 GeV to 111 GeV). The Z peak region is not centred around the Z mass, but shifted towards smaller values, as the reconstructed p_T of the charge misidentified electrons is often slightly smaller than the truth p_T of the actual electron. Assuming a linear background distribution under the Z peak, a background subtraction is performed in the peak region by subtracting the event yield in the side-bands from yields in the central region.

The charge flip factors are then extracted in bins of electron p_T and η , using the number of same-sign events, given the number of opposite-sign events, by minimising the following function:

$$-\ln L_{CF} = - \sum_{i,j,k,l} \ln Po(N_{ijkl}^{SS} | (\epsilon_{1,ij} + \epsilon_{2,kl}) N_{ijkl}^{tot}) \quad (6.1)$$

Po corresponds to a Poisson distribution, $\epsilon_{1,ij}$ and $\epsilon_{2,kl}$ to the charge flip rate of the leading electron with p_T in the i^{th} bin and η in the j^{th} bin and the sub-leading electron with p_T in the k^{th} bin and η in the l^{th} bin respectively. N_{ijkl}^{SS} and N_{ijkl}^{OS} correspond to the number of events in the same-sign and opposite-sign region respectively, with electrons in the i, j, k and l bins and $N_{ijkl}^{tot} = N_{ijkl}^{OS} + N_{ijkl}^{SS}$.

The computed charge flip rates are shown in Figure 6.18. In order to estimate the event yields containing charge flip electrons in the 2ℓ SS CRs, the charge flip factors are applied on regions with the same selections as the 2ℓ SS CRs except for an opposite-sign lepton requirement. In the 3ℓ SRs and CRs, where the charge flip background is minor, the charge flip estimate is taken from MC.

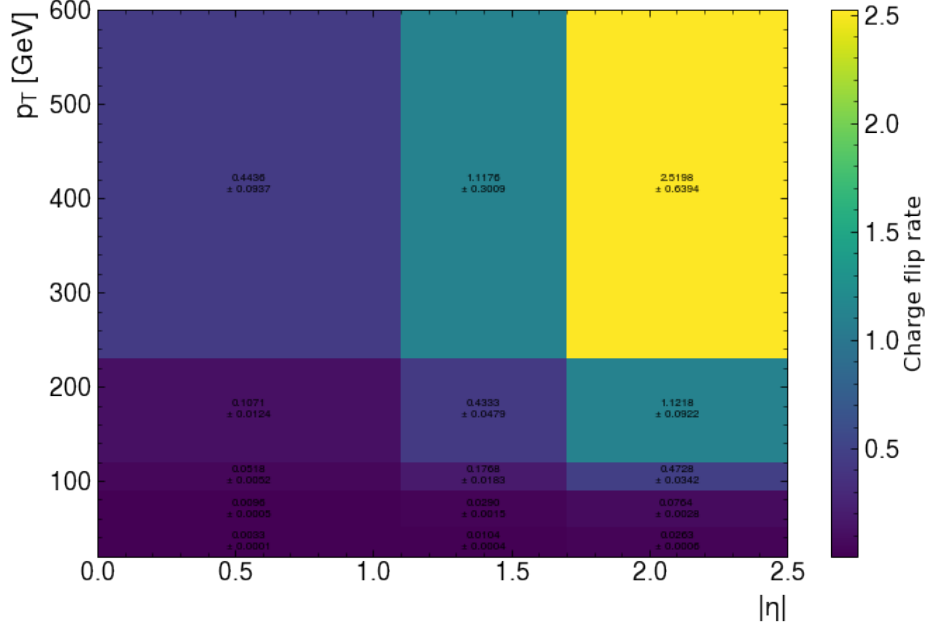


Figure 6.18: Data-driven charge flip rates with their statistical uncertainties as a function of electron p_T and $|\eta|$.

6.5.5 Validation regions

Several Validation Regions (VRs) are considered, which are not included in the fit, but are aimed at cross-checking the post-fit data MC agreement for the main backgrounds in regions describing a part of the phase-space relatively similar to the one in the SRs.

As VR for $t\bar{t}W$ and $t\bar{t}H$ the low-mass $t\bar{t}\ell^+\ell^-$ region is used. The same selection cuts as for the SR are applied but with a mass-cut of the OSSF pair closest to the Z mass of below 81.1876 GeV and above 30 GeV. This lower mass cut is applied to cut out any potential backgrounds arising at very low masses.

The pre-fit data MC agreement in the low-mass $t\bar{t}\ell^+\ell^-$ VRs is shown in Figure 6.19. A slightly larger normalisation discrepancy is observed in the $t\bar{t}e^+e^-$ VR compared to the $t\bar{t}\mu^+\mu^-$ VR.

Additionally, two VRs for the conversion leptons are considered. These regions have the same selection as the SRs but with inverted conversion cuts. For the material conversion VR, at least one of the leptons needs to pass the material conversion cuts. For the internal conversion VR, the

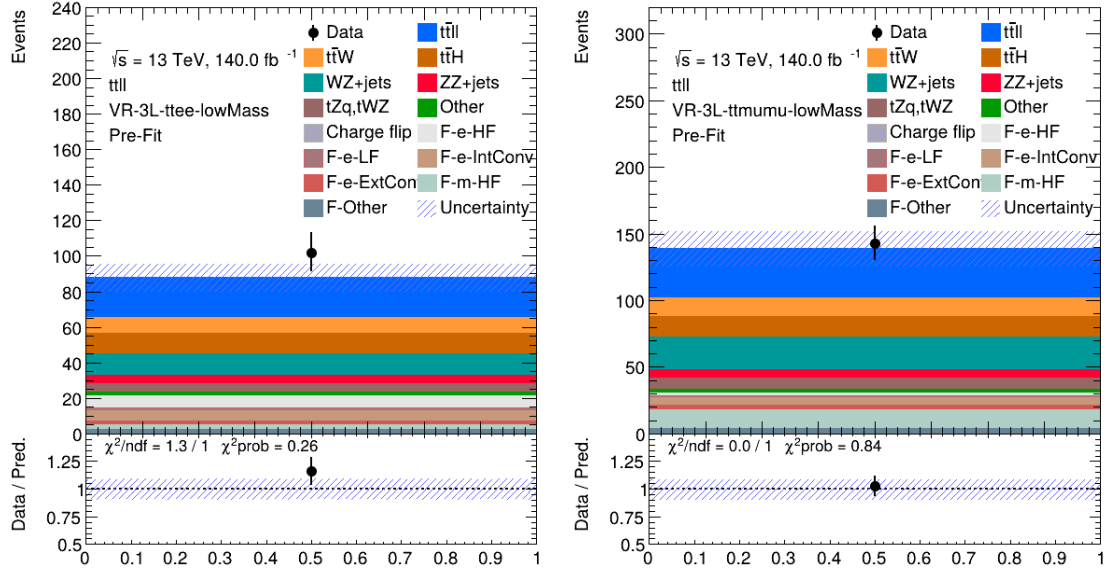


Figure 6.19: Expected distributions compared to data in the low-mass $t\bar{t}e^+e^-$ (left) and $t\bar{t}\mu^+\mu^-$ (right) VRs. The uncertainty bands include statistical and systematic uncertainties.

event must not enter the material conversion VR and at least one lepton must pass the internal conversion cuts. Additionally the di-lepton invariant mass cuts are relaxed to enhance the statistics. For the internal conversion VR no mass cut is applied, while for the material conversion VR, m_{ll} needs to lie outside of the Z mass peak to keep the purity. In the material conversion VR, it is observed that after the ECIDS and ambiguity type cuts on the leptons, only a small number of material conversion events enter the region. As the NFs for the conversion fakes are not significantly impacted by these cuts, the ECIDS and ambiguity type cuts are removed for the material conversion VR. Finally for the internal conversion VR, only the $t\bar{t}\mu\mu$ region can be considered, as the $Z\gamma$ sample, including internal conversions, only exists for $Z(\rightarrow \mu\mu)\gamma$.

Figure 6.20 shows the pre-fit data MC agreement in the conversion fake VRs. No important discrepancies are observed.

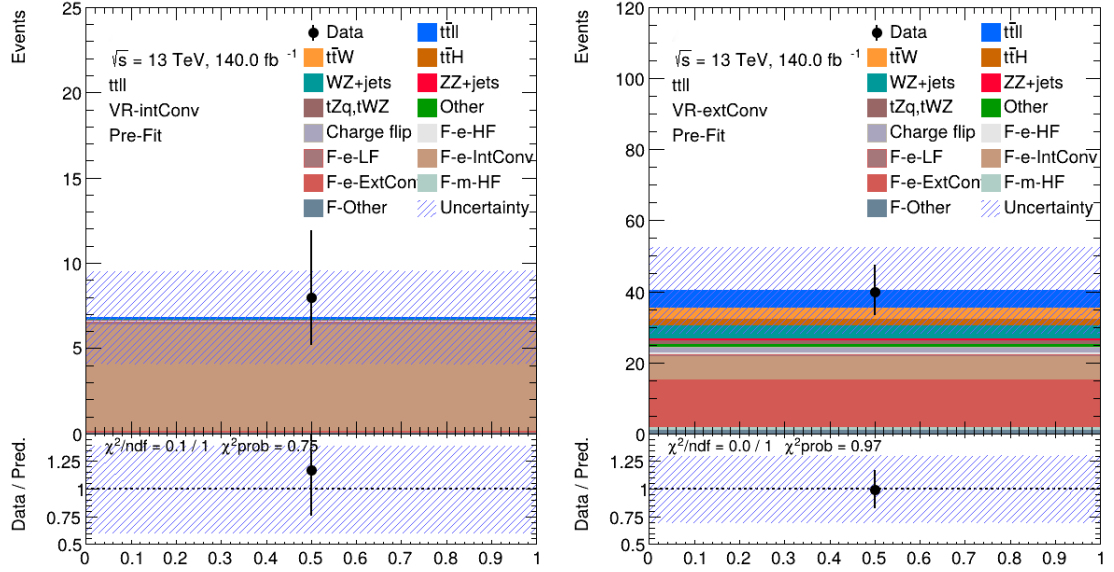


Figure 6.20: Expected distributions compared to data in the internal (left) and material (right) conversion fake VRs. The uncertainty bands include statistical and systematic uncertainties.

6.6 Systematic uncertainties

6.6.1 Detector uncertainties

All of the relevant detector systematics described in Section 3.5 are considered in the fit and briefly summarised as follows.

For all events an uncertainty in the integrated luminosity, in the trigger efficiency and in the pile-up modelling is applied. On leptons, systematic uncertainties in the reconstruction efficiency, the identification and the isolation scale factors are applied, as well as in the momentum scale and resolution. Additionally, for electrons ECIDS uncertainties and for muons uncertainties in the track-to-vertex association are considered. For jets, uncertainties in the jet energy scale and resolution, jet-vertex-tagging and flavour tagging are applied. Finally, uncertainties in the missing transverse energy are considered such as the scale and the resolution of the soft track component.

6.6.2 Modelling uncertainties

Modelling uncertainties are considered for the dominant MC templates and are described in Section 4.8.

Additionally to the modelling systematics, normalisation uncertainties are added to several processes. For tZq , an uncertainty of 14 % is applied, based on the [ATLAS](#) measurement of tZq [142] and for tWZ of 30 %. For the diboson samples, uncertainties of 10 % are applied on $ZZ+l$, 30 % on $WZ+l$, $WZ+c$ and $ZZ+c$ and 50 % on $WZ+b$ and $ZZ+b$. These numbers are based on measurements in the first Run 2 and the refined Run2 $t\bar{t}Z$ [ATLAS](#) analyses [143, 129]. The normalisation uncertainty on $t\bar{t}t\bar{t}$ is chosen to be very conservative with $^{+70}_{-15}\%$, defined such that it covers the latest $t\bar{t}t\bar{t}$ [ATLAS](#) cross-section measurement [144]. Finally, for all minor backgrounds grouped in the ‘other’ category, a conservative uncertainty of 50 % is applied.

6.6.3 Non-prompt/fake background uncertainties

For all non-categorised non-prompt/fake backgrounds, a normalisation uncertainty of 30 % is applied.

For the [MC](#) based charge flip templates in the 3ℓ regions, a normalisation uncertainty of 30 % is applied. For the data-driven charge flip estimation in the $2\ell SS$ [CRs](#), three uncertainties are considered: a statistical uncertainty, a binning uncertainty as well as an extrapolation uncertainty. For the statistical uncertainties, toy charge flip rates are generated, where in each electron p_T and η bin, a charge flip rate is chosen according to a Gaussian shaped probability having the nominal rate as mean value and the statistical uncertainty as its width. In the $2\ell SS$ [CRs](#), the standard deviation of all the distributions produced according to these toy rates is then taken as an uncertainty. The binning uncertainty, describing the impact of the size of the p_T and η bins on the charge flip estimation, is estimated by comparing the default charge-flip distribution in the [CRs](#) with a distribution produced with charge flip rates derived in p_T and η bins with half the bin width. These alternative rates are shown in Figure 6.21. Finally, the extrapolation uncertainty approximates the impact of extrapolating the charge flip rates from the Z peak region to the analysis [CRs](#). It is based on the assumption that the extrapolation is similar in data and in [MC](#). The difference between the charge flip distributions computed with rates derived in [MC](#) in the Z peak region and in the $2eSS$ [CR](#) is therefore taken as uncertainty. Both these charge flip rates are shown in Figure 6.22.

Finally, an uncertainty is applied on the estimation of the fake templates in the [SRs](#). The difference between the nominal fake distributions (using the Loose selection and reweighted to the overall normalisation of the Tight selection) and the fake distributions using the Tight selection is taken as uncertainty. A two-sided symmetrisation is applied to remove large statistical fluctuations while keeping some shape information.

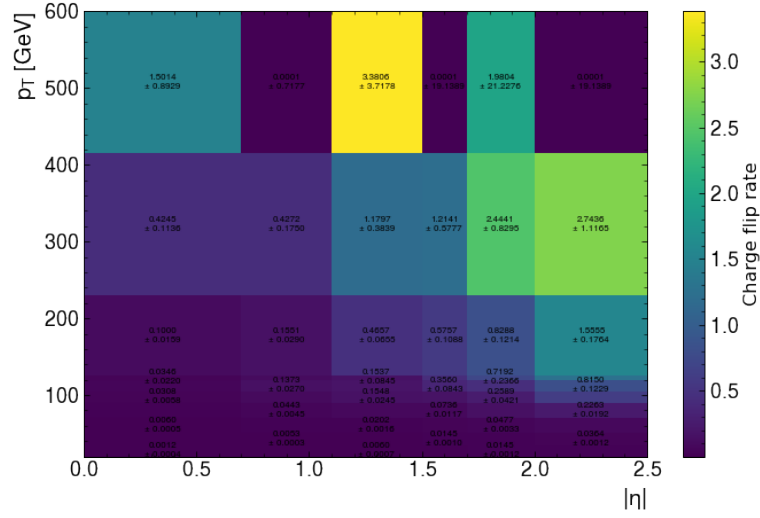


Figure 6.21: Data-driven charge flip rates derived in a setup with half the electron p_T and η bin width as a function of electron p_T and $|\eta|$.

6.7 Fit setup

For this measurement, a binned profile likelihood fit is used, as described in Section 5.1. On a region by region basis, systematic uncertainties which have a normalisation and shape impact of less than 0.1 % are pruned, in order to simplify the fit by removing NPs with negligible effect. Additionally, systematics with a normalisation effect above 90 % are removed. It was checked that these are fully statistics dominated and that removing them does not significantly impact the fit result. Additionally, most systematic uncertainties are smoothed in order to remove statistical fluctuations. This is also not observed to have any significant effect on the fit.

6.7.1 $t\bar{t}\ell^+\ell^-$ signal strength fit

In order to study the behaviour of the fit, an inclusive signal strength measurement is performed. The full $t\bar{t}Z/\gamma^*$ sample is split at reconstruction-level into a high-mass $t\bar{t}\ell^+\ell^-$ sample and an on-shell $t\bar{t}Z$ sample, each with separate NFs. This fit setup allows studying the expected sensitivity of the different regions to $t\bar{t}\ell^+\ell^-$.

6.7.2 EFT fit

The EFT fits, in which the WCs are constrained, are performed using a $t\bar{t}\ell^+\ell^-$ sample including the reweighted distributions for different values of the WCs. The EFT variation is included at

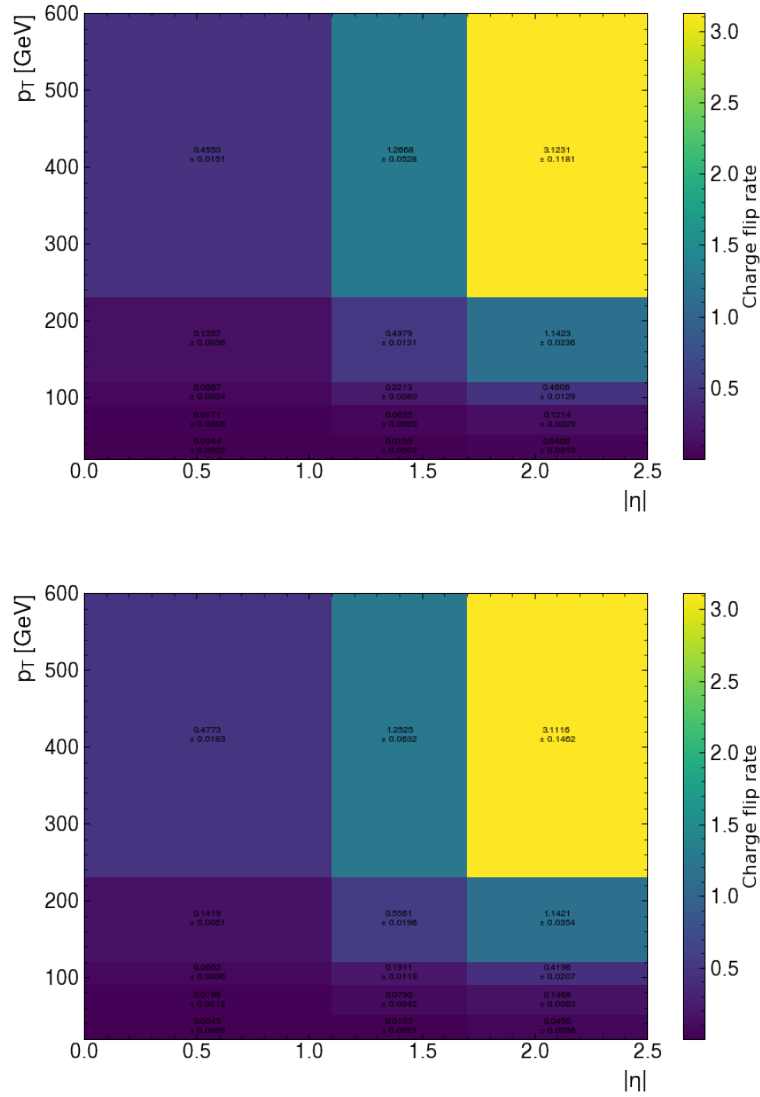


Figure 6.22: Data-driven charge flip rates derived in MC in the Z peak region (top) and in the $2eSS$ CR as a function of electron p_T and $|\eta|$.

truth level, split by flavour. For O_{tl} for example, the c_{tl11} weights are applied to truth $t\bar{t}e^+e^-$ events, c_{tl22} weights to truth $t\bar{t}\mu^+\mu^-$ events and c_{tl33} weights to truth $t\bar{t}\tau^+\tau^-$ events. In the flavour dependent fit, the WCs are fitted separately for the different flavours, while the WCs are treated as one parameter in the flavour inclusive fit. For each value of the WCs, the event yield in each bin is normalised to the $t\bar{t}\ell^+\ell^-$ SM NLO cross-section, in order to take into account SM NLO effects. The variation of the cross-section of the EFT reweighted distributions compared to the SM is then considered in each bin of the regions, in order to determine the parametrisation of the cross-section as a function of the WC value. In this analysis, a quadratic dependence of the cross-section to the WCs is assumed and a second degree polynomial is fitted to the cross-section variation in each bin. This is shown in Figure 6.23 for the $t\bar{t}e^+e^-$ and $t\bar{t}\mu^+\mu^-$ SRs with

c_{ll} as example. The dependence of the $t\bar{t}e^+e^-$, $t\bar{t}\mu^+\mu^-$ and $t\bar{t}\tau^+\tau^-$ yields on c_{tl11} , c_{tl22} and c_{tl33} respectively is shown for each of the **SR** bins. Because of very low statistics of $t\bar{t}\mu^+\mu^-$ in the $t\bar{t}e^+e^-$ **SR** and of $t\bar{t}e^+e^-$ in the $t\bar{t}\mu^+\mu^-$ **SR**, no important **EFT** sensitivity is observed for these templates. Additionally, the **EFT** sensitivity of the $t\bar{t}\tau^+\tau^-$ templates is minimal, as no dedicated τ reconstruction is performed.

In the fit setup where only the linear part is considered, the quadratic **EFT** term from the parametrisation is dropped in the fit.

Once the **EFT** parametrisation is obtained, a profile-likelihood fit is performed, where the considered **WC** is treated as free floating parameter of the fit.

In order to simplify the fit, the **EFT** variations are not included in all regions but only in regions where some sensitivity to the **EFT** operators is observed or where $t\bar{t}\ell^+\ell^-$ (or $t\bar{t}Z$) has a considerable contribution, namely the **SRs**, the $t\bar{t}Z$ **CRs** and the 2ℓ SS **CRs**. The 2ℓ SS **CRs** are binned in the leading lepton p_T . The choice of this variable is based on the attempt to recover the **EFT** sensitivity from high-mass $t\bar{t}\ell^+\ell^-$ events with one non-reconstructed lepton. The p_T of the leading lepton is found to be a good approximation for the energy in the event, m_{Z1} not being possible to reconstruct. However, as the sensitivity is relatively small, a conservative binning is chosen, making sure to have reasonable **MC** statistics in the highest bins (the **MC** statistical uncertainties in the highest bins are below 5 %). In the **SRs**, the binning is done in m_{ll} , or more precisely in m_{Z1} . The optimisation procedure of the binning is detailed in Section 6.7.3. As the considered **EFT** operators have a strong shape dependence but only very small normalisation effects, the normalisation of **SM** $t\bar{t}\ell^+\ell^-$ is kept free floating (including on-shell $t\bar{t}Z$ as well as high-mass $t\bar{t}\ell^+\ell^-$) in addition to free floating the **EFT** operators.

In Figures 6.24 to 6.26, the **EFT** dependence of the cross-section is shown in all the considered **CRs** for c_{tl} as example.

6.7.3 Binning optimisation in the signal regions

Choice of the binning variable

The impact of the four-fermion operators grows with the invariant mass of the two leptons originating from the **EFT** vertex (m_{ll}). The **SRs** should therefore be binned in a variable highly correlated with m_{ll} . m_{Z1} is defined by the invariant mass of the **OSSF** lepton pair in the event. In the case where several pairs are found, the mass closest to the Z mass is chosen.

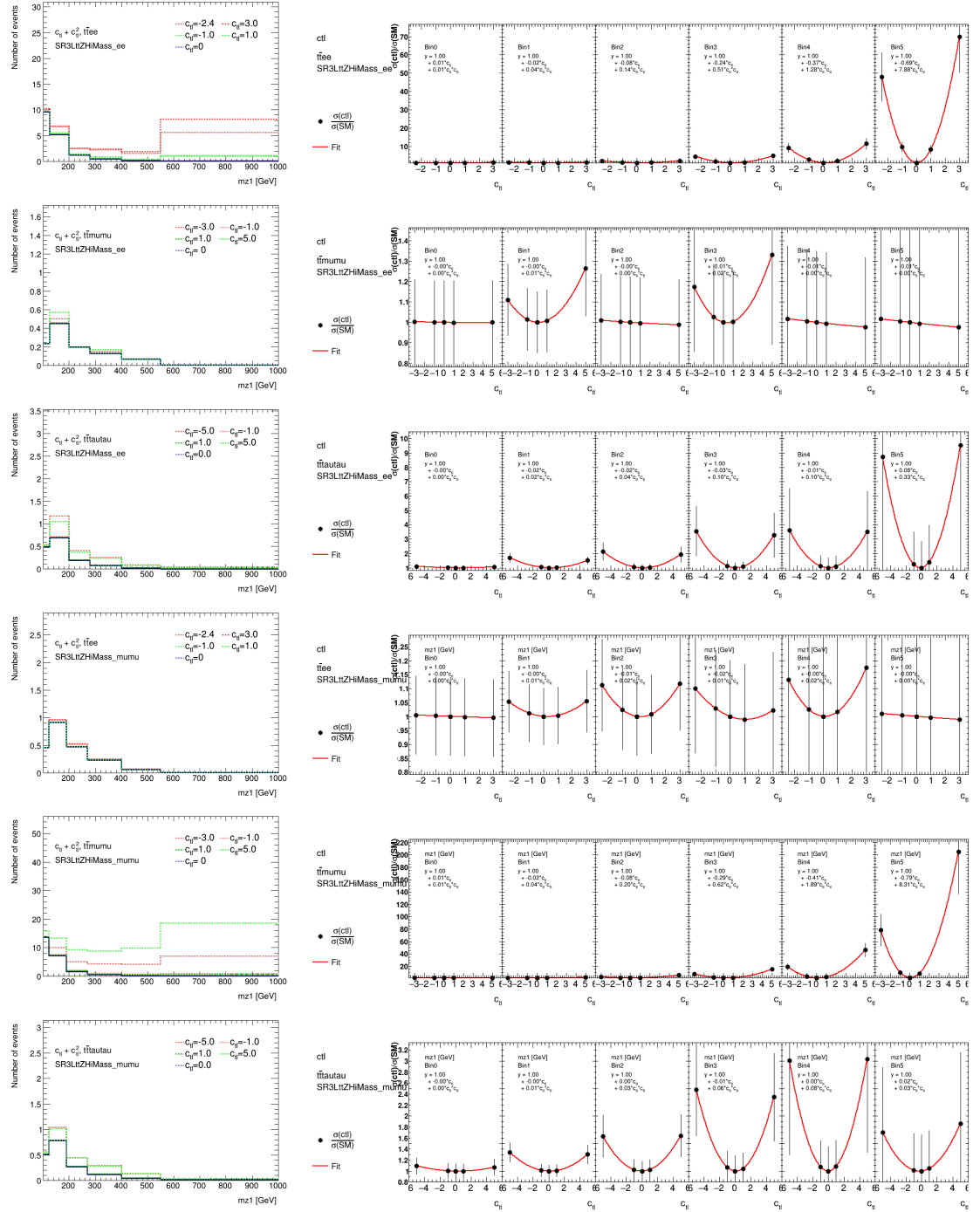


Figure 6.23: EFT parametrisation in the SRs: $t\bar{t}e^+e^-$, $t\bar{t}\mu^+\mu^-$ and $t\bar{t}\tau^+\tau^-$ yields in the $t\bar{t}e^+e^-$ and $t\bar{t}\mu^+\mu^-$ SRs for different values of c_{tI} (left) and corresponding parametrisation of the cross-section variation as a function of c_{tI} for each bin of the SRs for $t\bar{t}e^+e^-$, $t\bar{t}\mu^+\mu^-$ and $t\bar{t}\tau^+\tau^-$ (right).

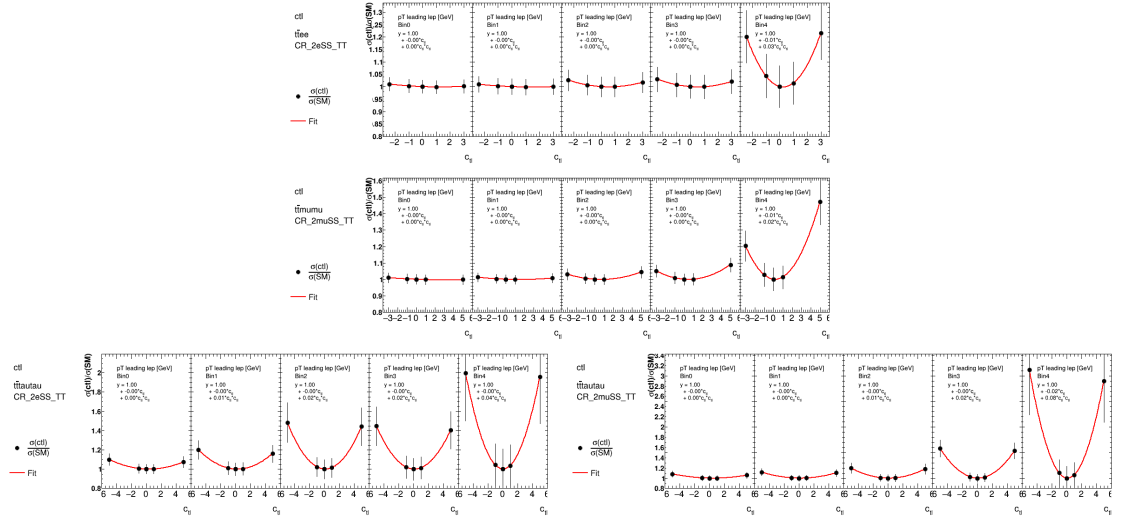


Figure 6.24: Parametrisation of the cross-section variation as a function of c_{tl} for each bin of the same flavour $2\ell SS$ CRs for $t\bar{t}e^+e^-$, $t\bar{t}\mu^+\mu^-$ and $t\bar{t}\tau^+\tau^-$. The contributions of $t\bar{t}e^+e^-$ in the $2\mu SS$ CR and of $t\bar{t}\mu^+\mu^-$ in the $2e SS$ CR are negligible.

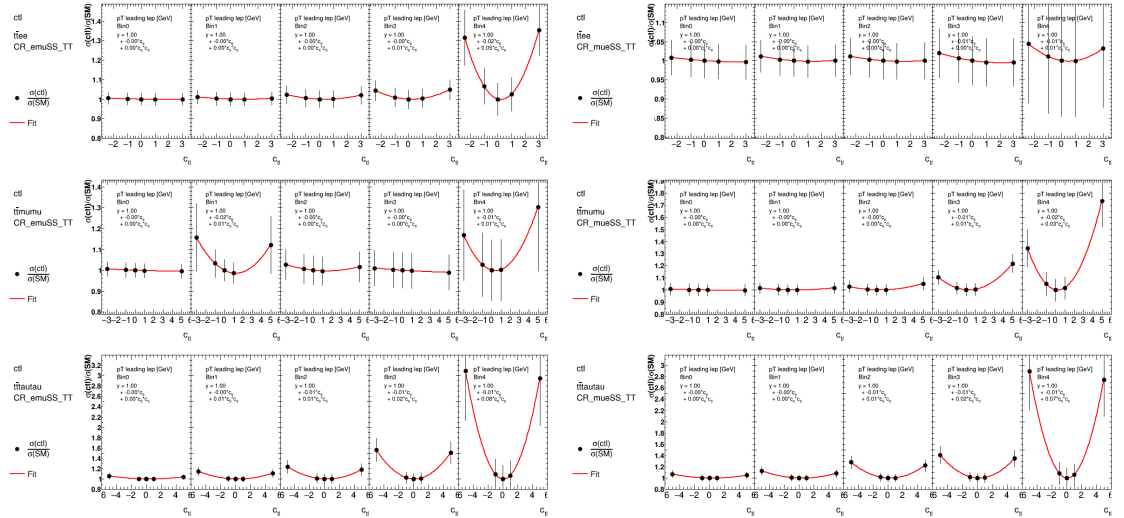


Figure 6.25: Parametrisation of the cross-section variation as a function of c_{tl} for each bin of the opposite flavour $2\ell SS$ CRs for $t\bar{t}e^+e^-$, $t\bar{t}\mu^+\mu^-$ and $t\bar{t}\tau^+\tau^-$.

Figure 6.27 shows the truth m_{ll} and the m_{Z1} distribution separately for $t\bar{t}ee$, $t\bar{t}\mu\mu$ and $t\bar{t}\tau\tau$. As expected, the truth m_{ll} distribution shows a clear peak around the Z mass and is independent of the lepton channel. m_{Z1} shows a very similar shape for $t\bar{t}ee$ and $t\bar{t}\mu\mu$ but the peak is very smeared out for $t\bar{t}\tau\tau$. This is due to the fact that the leptonic τ decay includes two neutrinos which are not reconstructed.

In the case where all three leptons in the $t\bar{t}\ell^+\ell^-$ event have the same flavour, the definition of m_{Z1} introduces a bias towards the Z mass. In the truth high-mass region, in 20 % of the events where both leptons from the Z decay are correctly reconstructed, a wrong pairing of leptons is chosen to reconstruct the Z . In the truth on-shell region, this only happens in about 3 % of the events.

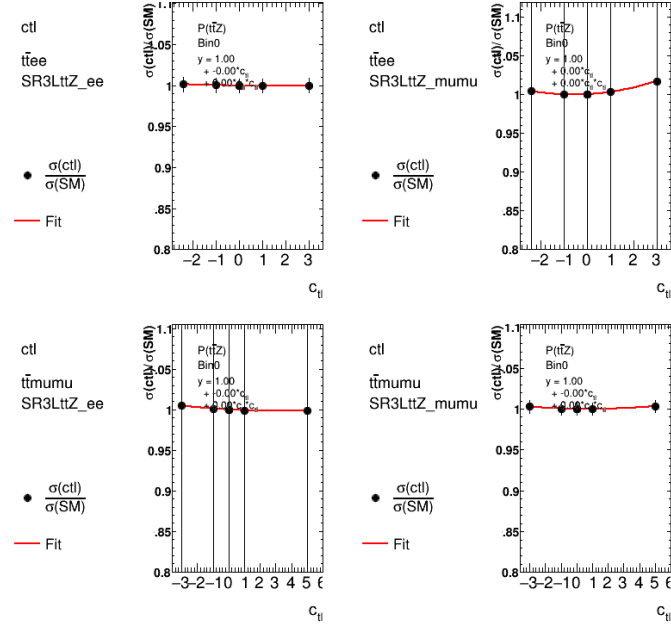


Figure 6.26: Parametrisation of the cross-section variation as a function of $c_{t\bar{t}}$ for the $t\bar{t}Z$ CRs for $t\bar{t}e^+e^-$, $t\bar{t}\mu^+\mu^-$ and $t\bar{t}\tau^+\tau^-$.

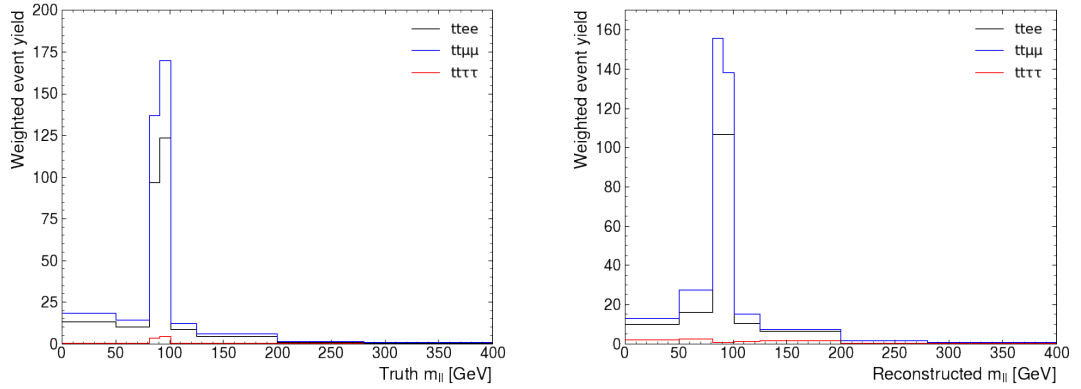


Figure 6.27: Truth m_{ll} and $mz1$ distribution of $t\bar{t}e^+e^-$, $t\bar{t}\mu^+\mu^-$ and $t\bar{t}\tau^+\tau^-$ in a mass and flavour inclusive $t\bar{t}\ell^+\ell^-$ region ($t\bar{t}Z$ CRs and $t\bar{t}\ell^+\ell^-$ SRs merged)

The migration of the events between reconstructed mass bins is shown in Figure 6.28. The bias towards smaller $mz1$ values for truth high-mass events can clearly be seen, as only 58 % of the events which belong to the highest mass bin are classified into the highest mass bin at reconstruction level. Instead, many of these events migrate into lower $mz1$ bins or the on-shell region. Even though the migration of high-mass events to lower masses is much higher than the other way around, the cross-section of on-shell $t\bar{t}Z$ events is much larger than the high-mass $t\bar{t}ll$ cross-section. Therefore, the on-shell contribution in the high-mass bins is non-negligible. In the highest mass bin, where the main EFT sensitivity lies, about 60 % of the $t\bar{t}\ell^+\ell^-$ events are in this highest bin at truth level and about 35 % are events with a truth invariant mass lying in the Z peak or below.

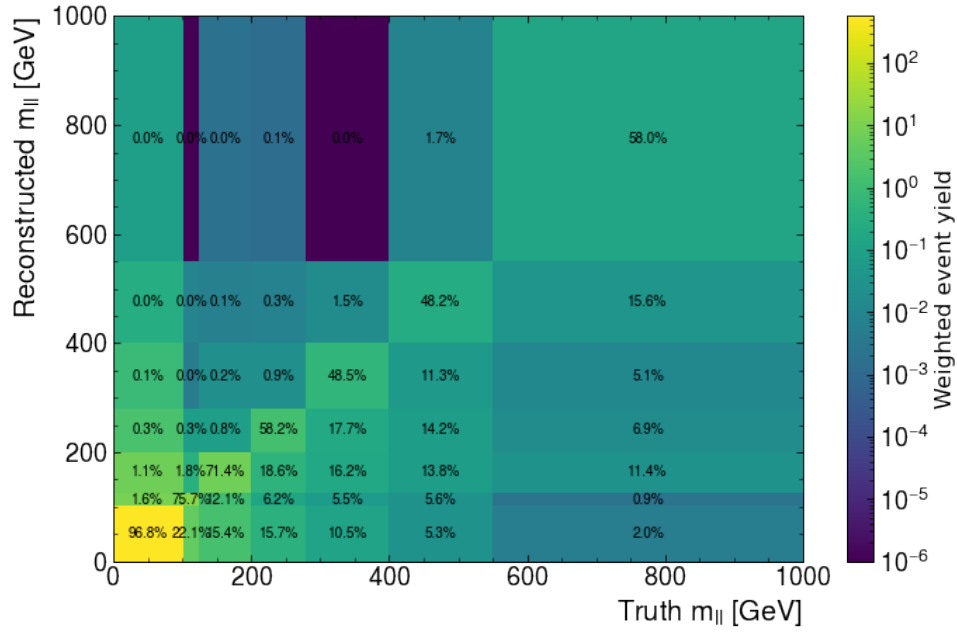


Figure 6.28: m_{z1} as a function of the truth m_{ll} in a mass and flavour inclusive $t\bar{t}\ell^+\ell^-$ region ($t\bar{t}Z$ CRs and $t\bar{t}\ell^+\ell^-$ SRs merged)

Additionally to m_{z1} , other variables were studied but none of them was found to bring better sensitivity:

- leading lepton p_T : this kinematic variable is less affected by reconstruction effects and has a better signal to background rejection but shows a smaller correlation to the energy in the event, leading to diluted EFT effects.
- p_T of the object pair with the highest p_T in the event: this variable was used by CMS, but does not show better sensitivity than m_{z1} .
- Neural Network (NN) approaches: different approaches were tested, where a regression NN was trained to predict m_{ll} or a classification NN was trained to classify events into SRs and $t\bar{t}Z$ CRs. However, these methods did not show large improvements compared to m_{z1} , and it was therefore decided to keep the purely cut based variable.

Binning optimisation

As the impact of the EFT operators grows with energy, an aggressive binning in the highest m_{z1} bins of the SRs increases the sensitivity. This effect is counterbalanced by the need of statistical power in the highest bin. The bin boundary of the highest bin is therefore optimised (in the optimisation a higher m_{ll} cut of 800 GeV is applied). Figure 6.29 shows the expected uncertainty

Figure 10 consists of two vertically stacked panels sharing a common x-axis. The x-axis is labeled 'Lower boundary of the highest $m_{\parallel}$ bin [GeV]' and ranges from 460 to 620 with major ticks every 20 units. The top panel's y-axis is labeled 'Upper 68% CI limit' and ranges from 1.55 to 1.65 with major ticks every 0.05 units. It contains four red 'x' data points at approximately (480, 1.67), (510, 1.62), (550, 1.58), and (600, 1.57). The bottom panel's y-axis is labeled 'Lower 68% CI limit' and ranges from -1.40 to -1.30 with major ticks every 0.02 units. It contains four red 'x' data points at approximately (480, -1.39), (510, -1.35), (550, -1.32), and (600, -1.32).

Lower boundary of the highest $m_{\parallel}$ bin [GeV]	Upper 68% CI limit	Lower 68% CI limit
480	1.67	-1.39
510	1.62	-1.35
550	1.58	-1.32
600	1.57	-1.32

The shape of $t\bar{t}\ell^+\ell^-$ compared to the backgrounds is shown in Figure 6.30 for the SM case as well as for two different values of $c_{t\ell}$, showing a good separation between the backgrounds and the EFT signal.

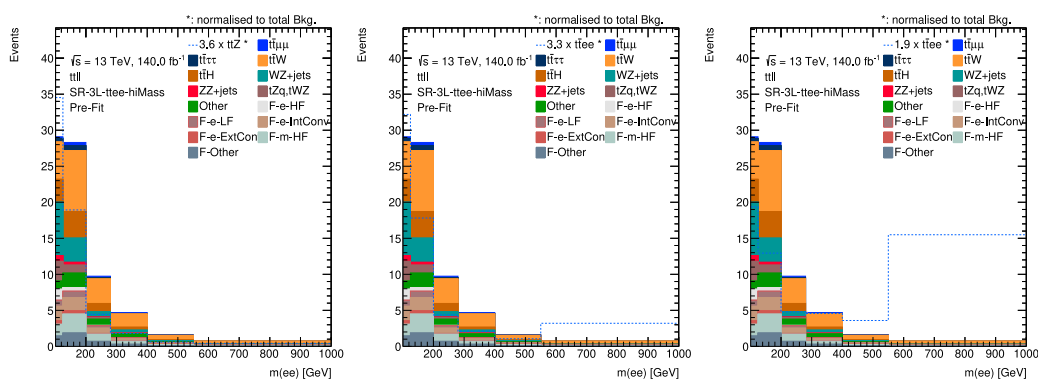


Figure 6.30: Shape of the $t\bar{t}\ell^+ \ell^-$ signal distribution (blue dotted line) in the $t\bar{t}\ell^+ e^-$ SR compared to the backgrounds for the SM case (left), for $c_{t\ell} = 1.0$ (centre) and for $c_{t\ell} = 3.0$ (right).

6.8 Dedicated statistical treatment for EFT fits

In the EFT fits, both the SM interference and the pure BSM part of the EFT are considered, corresponding to linear and quadratic yield dependencies. As described in Chapter 5, one of the assumptions of Wilks' theorem is that the best-fit value does not lie at the boundary of the parameter space. In the case of a strong quadratic EFT dependence with an expected value of 0 for the WC, this assumption is not valid. Wilks' theorem therefore does not hold in quadratic dominated fits. This can lead to under- or over-coverage of the computed CI from the likelihood scan, when determining the 68 % CI assuming that the profile likelihood ratio is χ^2 distributed [145].

In this analysis, the true coverage of the CI limits computed from the likelihood scans is determined. Additionally, the asymptotic CI limits are corrected using toy pseudo-data in order to obtain a true 68 % coverage. The method used for the correction is described in Section 6.8.1.

Additionally, Section 6.8.2 describes studies performed in order to understand the sensitivity of the EFT fits to potential signal and the correlations between the WCs when several EFT operators are constrained at the same time. As the generation of toy pseudo-data is computationally expensive, all the studies shown in the following are performed with EFT fits considering only statistical uncertainties.

6.8.1 Correction of the CI limits using toy pseudo-data

Generating toy pseudo-data

Toy pseudo-data are generated according to the expected distribution but take into account statistical fluctuations which would be present in measured data. Instead of using the nominal values of the parameters describing the fit model, like it is done in the generation of Asimov data, the NFs and NPs are fluctuated around the initial values. Generating toy pseudo-datasets with different random numbers therefore allows to obtain pseudo-data following the same model but being statistically independent.

In the context of this analysis, toy pseudo-data are only generated in the SRs, while the measured data are used in the CRs. Additionally, the NFs and NPs are fluctuated around the fit results from the background estimation with data presented in Section 6.9. Only the parameters of interest, being the WCs, are fluctuated around a given injected signal value.

Corrected 1σ contour

In this analysis, the correction of the CI is only performed in one-dimensional EFT fits, constraining one WC at a time. The corrected 1σ contour is computed using the Neyman construction [146]. Figure 6.31 shows the likelihood scan distribution for a fit constraining c_{tl} . While the horizontal line at $-\Delta \ln(L) = 0.5$ corresponds to the 1σ contour in the case Wilks' theorem holds, the interpolation between the red markers corresponds to the corrected 1σ contour. The corrected 68 % CI limits correspond to the crossing points between the likelihood scan distribution and the corrected 1σ contour.

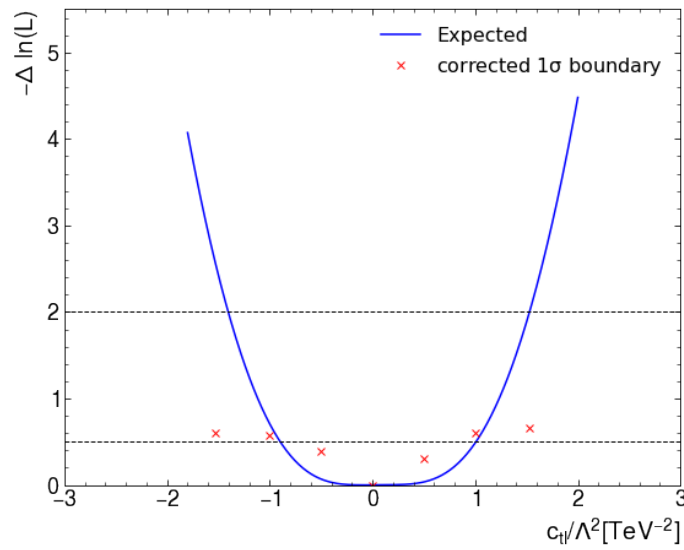


Figure 6.31: Expected likelihood scan for c_{tl} and corrected 1σ contour for a fit constraining c_{tl} with the corrected 1σ contour. This fit only takes statistical uncertainties into account.

Each of the points of the corrected 1σ contour is computed using 5000 toy pseudo-data. For the contour at μ_{test} , toy pseudo-data are generated around a distribution with an injected signal strength of μ_{test} . For each of the pseudo-datasets, the fit is performed and the test statistic, given in Formula 5.2, is computed. The corrected 1σ contour then corresponds to the 68 % percentile of the test statistics of all pseudo-data. It is to note that in this analysis, the convention does not consider the factor of 2 in front of the test statistic compared to the definition in Section 5.2. In the case where Wilks' theorem holds, the distribution of the test statistics would follow a χ^2 distribution with one degree of freedom, while in fits with dominant quadratic contributions, the distribution of the test statistics can significantly deviate from a χ^2 distribution.

The corrected 1σ contour shown in Figure 6.31 shows strong deviations from the contour under the assumptions of Wilks' theorem at $-\Delta \ln(L) = 0.5$. Especially for $c_{tl} = 0$, a strong over-coverage of the asymptotic limit is observed. This point corresponds to the value where

Wilks' theorem is maximally violated, as 0 corresponds to the boundary. For large c_{tl} , the corrected contour should converge towards the $-\Delta \ln(L) = 0.5$ line, as the fitted parameter would be shifted away from the boundary of the parameter space.

The corrected CI limits are then obtained by interpolating between the computed contour points in order to determine the crossing point between the likelihood scan and the 1σ contour. As for the full fit, including systematics, each of the contour points requires a lot of computing power, only four contour points are generated for the final results: two points around both of the expected crossing points.

6.8.2 Sensitivity of the EFT fits to potential signal

In the following, toy pseudo-data are used to test the sensitivity of the fit to potential EFT signals, in the case where a single EFT operator is considered, as well as in the case where multiple EFT operators are constrained at a time. Toy pseudo-data, generated with different values of injected EFT signal, are used to test the capability of the fit to recover the signal.

First, a one-dimensional fit constraining c_{tl} is considered. Figure 6.32 shows the best fit value distribution for all toy pseudo-datasets and the likelihood scans for the c_{tl} fit with Asimov data in the SRs, in case of no injected signal, $c_{tl} = 0.0$ (top), and for an injected signal of $c_{tl} = 1.53$ (bottom), which corresponds approximately to the 95 % CI limit in the fit. Without injected signal, the main peak of the best fit values is centred around 0 with two additional small peaks appearing, where the pseudo-data lead to a non-zero fitted value of the WC. The distribution is symmetric around 0 due to the quadratic behaviour. The likelihood scan has its minimum at $c_{tl} = 0$, recovering the truth c_{tl} value. With an injected signal of $c_{tl} = 1.53$, the number of toys where the fit detects a non-zero EFT contribution increases, shown by the additional peaks becoming more prominent. Additionally, the likelihood scan shows a minimum at the injected value and $c_{tl} = 0$ is not included in the 95 % CI. These studies show that the fit setup has the ability to detect a potential EFT signal and behaves according to the computed limits in the case of a single EFT operator.

Additionally to the fits where one single WC is constrained, fits can be performed where several WCs are constrained at the same time. One way of presenting the measured limits, is to set one-dimensional limits, obtained by a one-dimensional likelihood scan, where only one of the considered WCs is fixed and the others are free floating.

For the following studies, a two-dimensional fit, constraining c_{tl} and c_{Qe} , is considered. Similar to the one-dimensional fit, toy pseudo-data with no injected signal, $c_{tl} = 0.0$, and with an

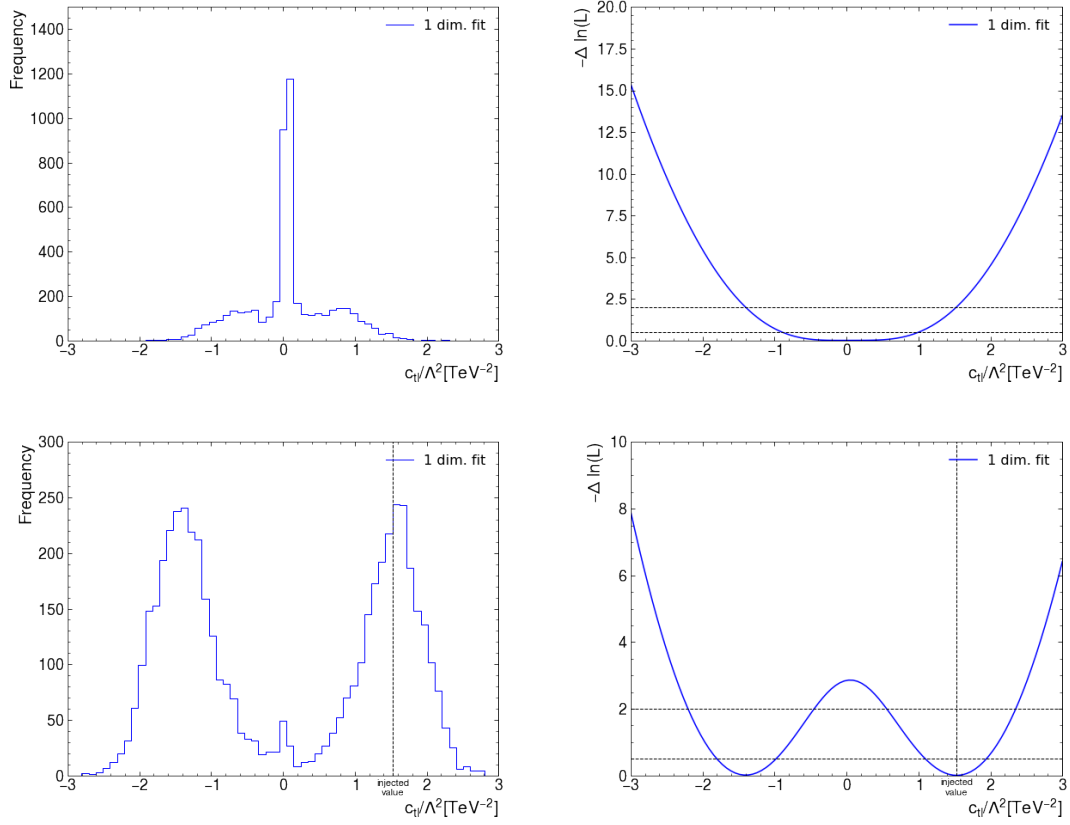


Figure 6.32: Distribution of the fitted c_{tl} values for all generated toy pseudo-datasets (left) and expected likelihood scan of c_{tl} (right) for a fit constraining c_{tl} for different injected signal values of c_{tl} : $c_{tl} = 0.0$ (top) and $c_{tl} = 1.53$ (bottom)

injected signal of $c_{tl} = 1.53$ are considered. The second $\text{WC } c_{Qe}$ has no injected signal in all cases. Comparing the best fit value distributions for all toy pseudo-datasets in the two-dimensional and one-dimensional fit in Figure 6.33 shows a clear loss in the ability to detect the injected signal in c_{tl} . While the number of toy pseudo-datasets where no signal is identified in c_{tl} increases, a considerable number of toy pseudo-data induces a fake signal in c_{Qe} . This behaviour clearly indicates that the WCs are largely correlated in the fit, which washes out the detected signal.

The likelihood scans are shown in Figure 6.34. In the case where no signal is injected, it can be observed that the asymptotic CI limits are the same in the one-dimensional and two-dimensional fit. For an injected signal in c_{tl} approximately 2σ away from the SM expectation, the CI interval for the two-dimensional fit is still centred around 0 and does not capture the signal. These studies show that even though the two-dimensional EFT fit sets comparable limits on the WCs in case of no EFT signal, it would not be able to detect a potential EFT signal.

This is due to correlations between the WCs which only become apparent in case of the presence of an EFT signal. Because of the dominant quadratic behaviour of the considered EFT operators, the correlations between the WCs depend on the injected signal. The correlation between c_{tl}

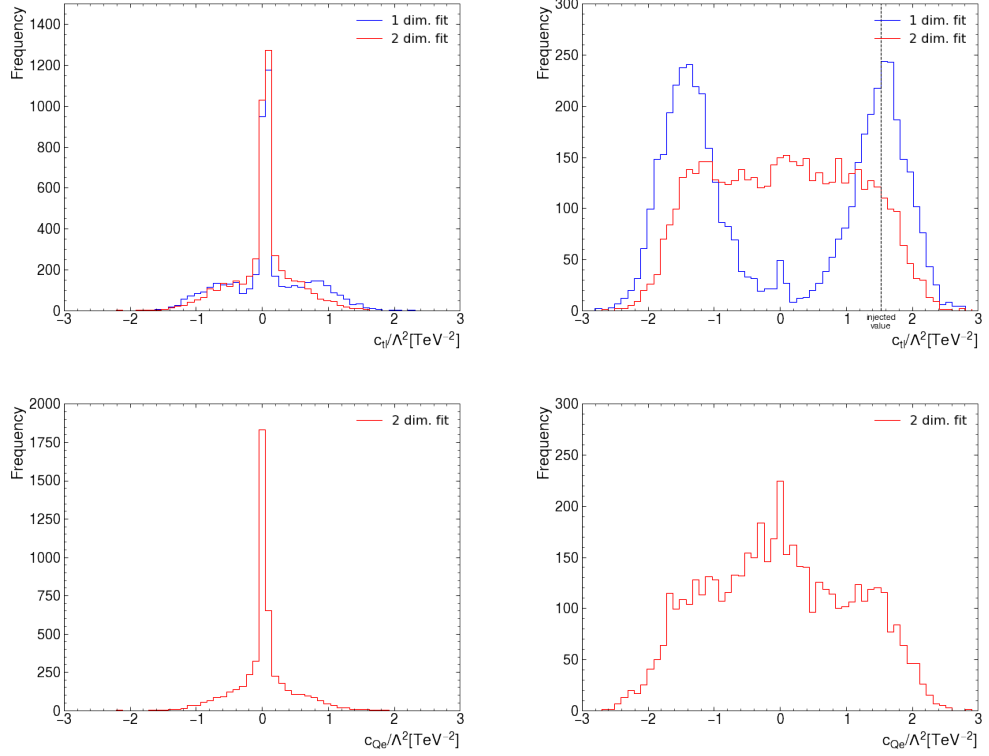


Figure 6.33: Distribution of the fitted c_{tl} values (top) and c_{Qe} values (bottom) for all generated toy pseudo-datasets for a fit constraining c_{tl} (one-dimensional fit) and for a fit constraining c_{tl} and c_{Qe} (two-dimensional fit) for different injected signal values of c_{tl} : $c_{tl} = 0.0$ (left) and $c_{tl} = 1.53$ (right)

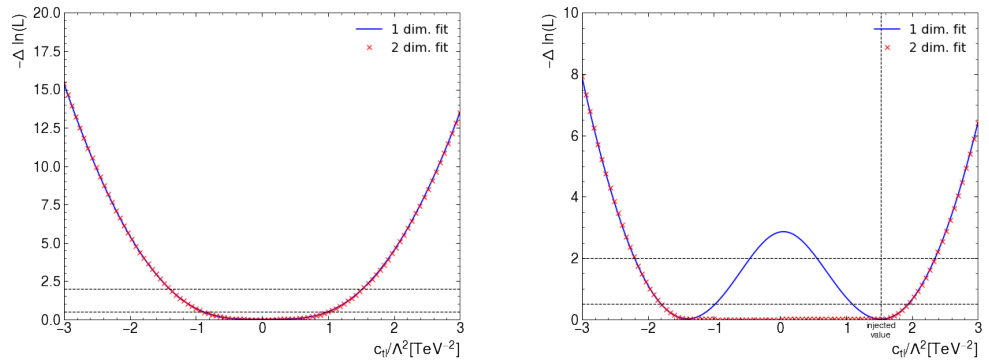


Figure 6.34: Expected likelihood scan of c_{tl} for a fit constraining c_{tl} (one-dimensional fit) and for a fit constraining c_{tl} and c_{Qe} (two-dimensional fit) for different injected signal values of c_{tl} : $c_{tl} = 0.0$ (left) and $c_{tl} = 1.53$ (right)

and c_{Q_e} is shown in Figure 6.35 in case of no signal injection (left) and for a signal of $c_{t_l} = 1.53$ (right). While without any injected signal both WC s appear to be largely uncorrelated, higher order correlations appear with an injected signal. The reason for this behaviour is that both WC s predict a minimum event yield when set to 0. In the case without any injected signal, the Asimov data follow a distribution where both WC s are set to their minimum. Any effect of moving one of WC s away from 0 therefore cannot be counteracted by moving the other WC . Both WC s appear to be uncorrelated. As soon as a signal is injected, the Asimov distribution has an increased event yield. In the fit setup of this analysis, there is not enough separation power between the WC s, so that different combinations of c_{t_l} and c_{Q_e} values lead to the same goodness of fit, meaning that they are highly correlated.

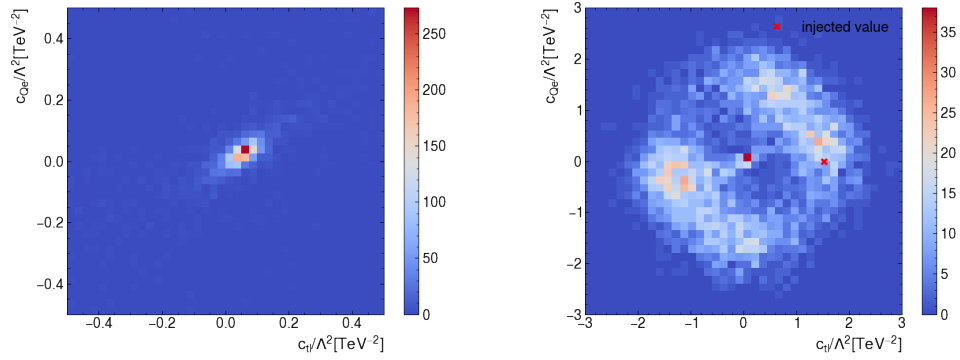


Figure 6.35: Fitted c_{t_l} and c_{Q_e} values for all generated toy pseudo-datasets for a fit constraining c_{t_l} and c_{Q_e} (two-dimensional fit) for different injected signal values of c_{t_l} : $c_{t_l} = 0.0$ (left) and $c_{t_l} = 1.53$ (right)

This explains the behaviour in the likelihood scans in Figure 6.34. For the likelihood scan without injected signal, c_{t_l} and c_{Q_e} are fully uncorrelated, meaning that likelihood scans for the one-dimensional and two-dimensional EFT fits are identical. For the likelihood scan with an injected signal of $c_{t_l} = 1.53$, the two WC s are uncorrelated for $|c_{t_l}| > 1.53$, c_{t_l} being larger than the injected signal, meaning that c_{Q_e} must be in its minimum for the best fit value. For $|c_{t_l}| < 1.53$ the two WC s are correlated, as c_{Q_e} can absorb the part of the injected signal which is not accounted for by c_{t_l} . For these c_{t_l} values, the $-\Delta \ln(L)$ values are therefore much lower in the two-dimensional fit than in the one-dimensional fit.

The same effects are observed in two-dimensional likelihood scans where two- and three-dimensional fits are considered. As shown in Figure 6.36, two-dimensional likelihood scans can be used to recover some sensitivity to injected signal in two-dimensional fits, which is lost in one-dimensional likelihood scans in two-dimensional fits (top). The signal can, however, not be attributed to one specific WC . Higher dimensional fits (such as three-dimensional fits in this case) show the same behaviour as previously, where the signal cannot be detected (bottom).

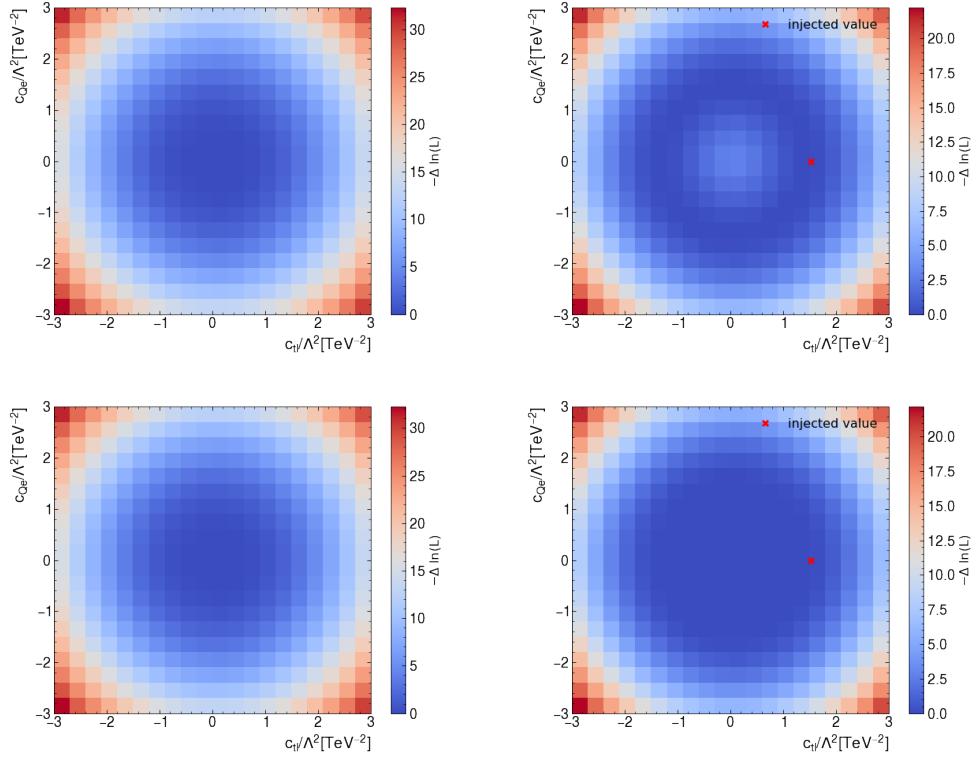


Figure 6.36: Expected two-dimensional likelihood scan of c_{Qe} versus c_{tl} for a fit constraining c_{tl} and c_{Qe} (two-dimensional fit) (top) and for a fit constraining c_{tl} , c_{Qe} and c_{te} (three-dimensional fit) (bottom) for different injected signal values of c_{tl} : $c_{tl} = 0.0$ (left) and $c_{tl} = 1.53$ (right)

These studies show that because of the high quadratic correlations, the common method of setting one-dimensional limits on **WCs** would only be sensitive to potential **EFT** signal in fits constraining one **WC** at a time. For fits constraining two **WCs**, two-dimensional likelihood scans can be plotted, capturing the presence of potential signal. Constraining more than two **WCs** at the same time, however, becomes difficult, because of the drastic increase in computing power to compute n -dimensional likelihood scans and the lack of possibility to properly display them. One-dimensional limits can still be quoted for n -dimensional **EFT** fits, but it seems questionable how interpretable they are for this analysis.

6.8.3 Two-dimensional flavour dependent EFT fits

Because of the fit setup, where the **SRs** are split by lepton flavour (one $t\bar{t}e^+e^-$ **SR** and one $t\bar{t}\mu^+\mu^-$ **SR**), the flavour dependent **WCs** have relatively low correlations. Figures 6.37 and 6.38 show the one-dimensional and the two-dimensional likelihood scans for a fit constraining c_{tl11} and c_{tl22} without any injected signal, $c_{tl11} = 0.0$ (left), and with an injected signal of $c_{tl11} = 1.87$ (right), corresponding approximately to the 95% **CI** limit for c_{tl11} in the fit. In both cases no signal is injected for c_{tl22} . It can be seen that the correlation between both flavour parts of the **WCs** are

very low and that the injected signal in c_{tl11} can be recovered in the correct WC. Therefore, the limits on the flavour dependent WCs are computed in EFT fits constraining both flavours at the same time.

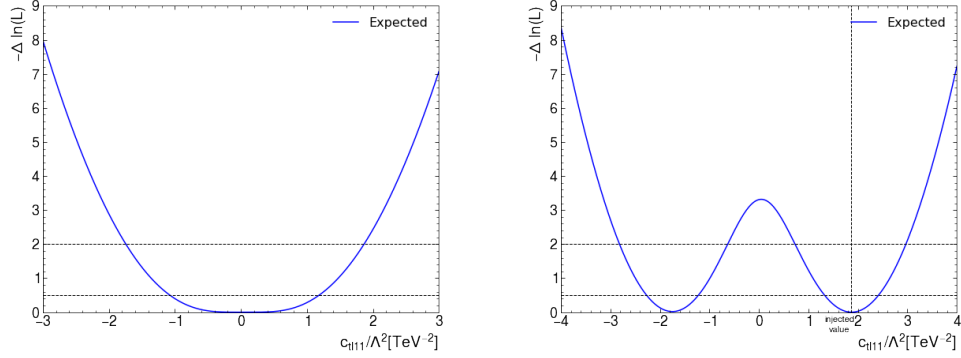


Figure 6.37: Expected likelihood scan of c_{tl11} for a fit constraining c_{tl11} and c_{tl22} for different injected signal values of c_{tl11} : $c_{tl11} = 0.0$ (left) and $c_{tl11} = 1.87$ (right)

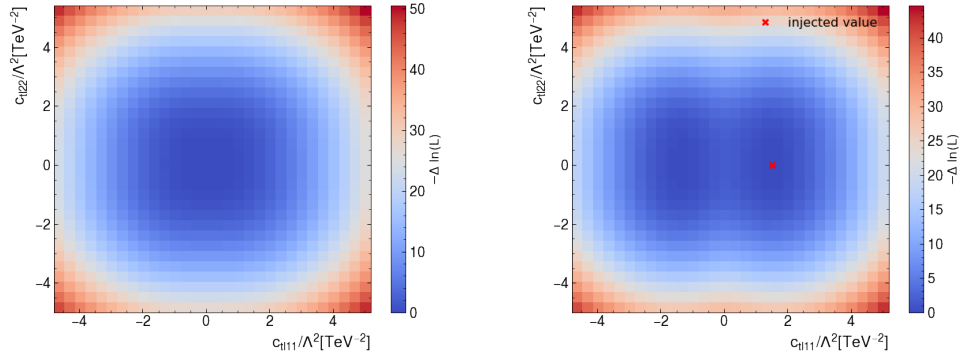


Figure 6.38: Expected two-dimensional likelihood scan of c_{tl22} versus c_{tl11} for a fit constraining c_{tl11} and c_{tl22} for different injected signal values of c_{tl11} : $c_{tl11} = 0.0$ (left) and $c_{tl11} = 1.87$ (right)

6.9 Validation of the background estimation in the CRs

In this section, the normalisation of the backgrounds is studied in a fit to data including only the CRs and fitting only the background NFs. As the CRs are designed to target specific backgrounds, they are expected to drive the sensitivity to the background NFs. The results for the background NFs from this fit are therefore expected to be very similar to the final fit, where the backgrounds are constrained at the same time as the signal.

6.9.1 Background only fit results

The resulting NFs are shown in Figure 6.39. As expected, the NF for $t\bar{t}W$ is significantly above 1. With the fitted value of $1.20^{+0.11}_{-0.11}$, the NF is similar to the measurement in the dedicated $t\bar{t}W$

analysis ($1.22^{+0.12}_{-0.12}$) [52]. The $t\bar{t}Z$ NF ($1.08^{+0.10}_{-0.10}$) is equally compatible with the measurement of the dedicated $t\bar{t}Z$ analysis ($1.02^{+0.08}_{-0.08}$ for the 3ℓ channel) [129].

The fake NFs slightly deviate from 1, especially for the material conversions. The uncertainties on the NFs of the internal and material conversions are improved by about 30 % to 40 % compared to the $t\bar{t}W$ analysis, which is mainly due to the looser lepton definition, considerably increasing the statistics in the conversion CRs. It is though to be noted that the fitted NFs are further away from 1 compared to the $t\bar{t}W$ analysis.

Even though similar CRs were used for the estimation of HF and LF electron and HF muon fakes than in the dedicated $t\bar{t}Z$ analysis, the NFs do not perfectly agree with the results obtained there. This is partly caused by the sensitivity of the 2ℓ SS CRs to these fake components and partly by the different electron isolation WP which is used.

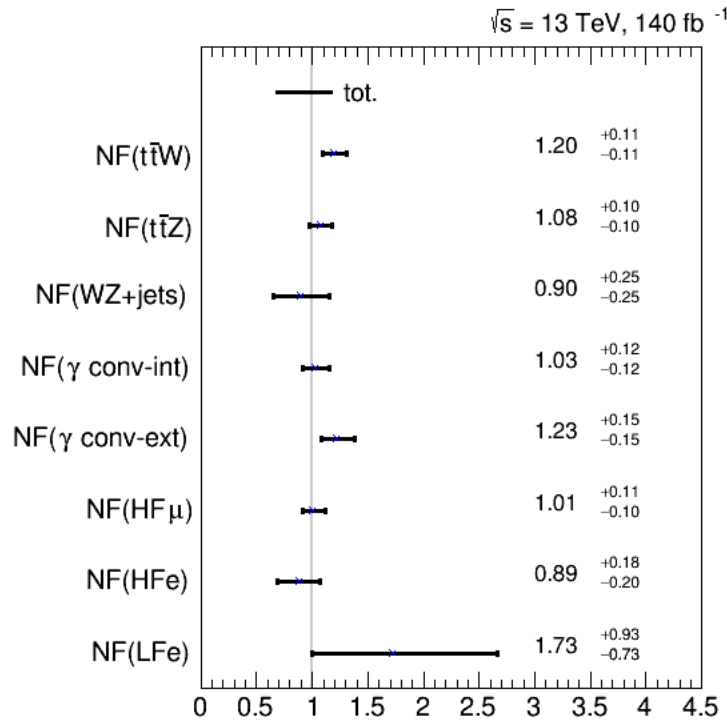


Figure 6.39: Background NFs obtained in a fit to data including only the CRs.

The correlations between the NFs and NPs are shown Figure 6.40. A good separation between most of the NFs and NPs is achieved by the fit. The larger correlations, which can be seen in Figure 6.40, are mostly between NFs and modelling systematics affecting the same templates or between the fake/non-prompt lepton NFs.

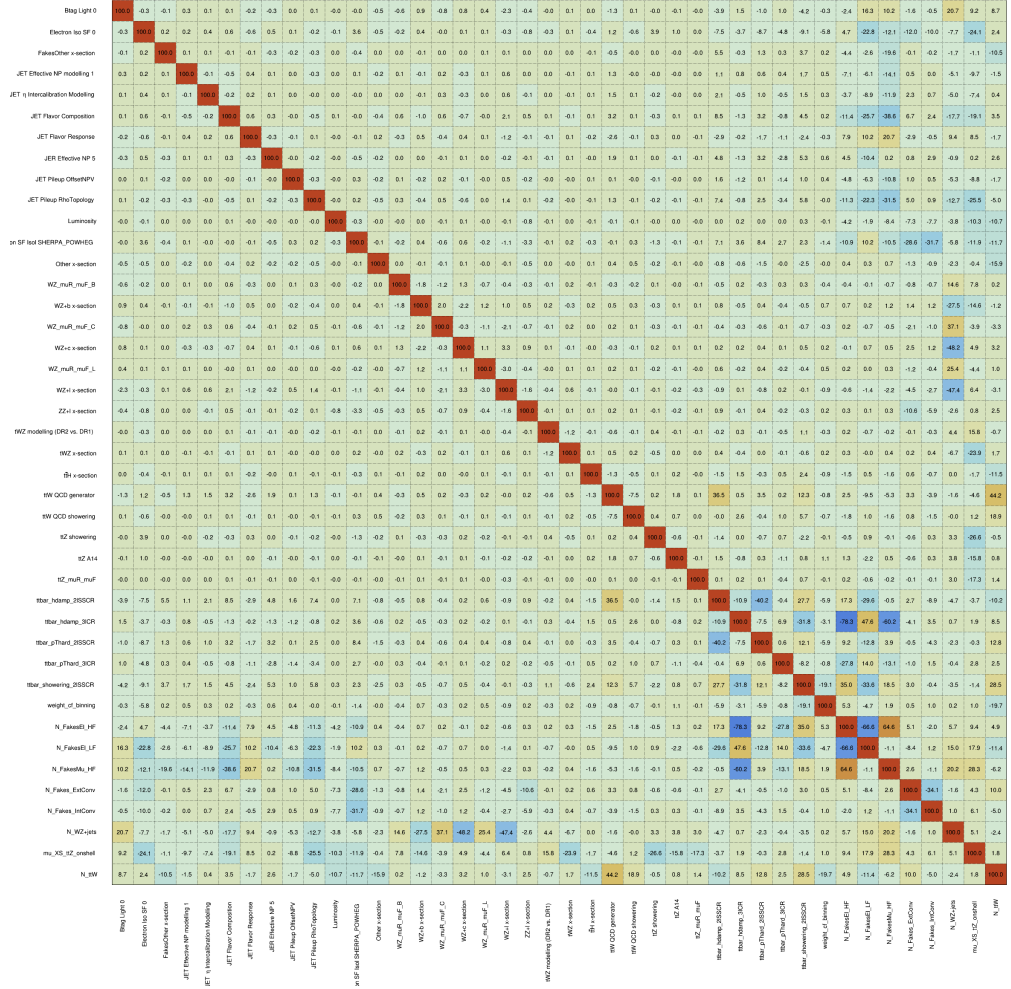


Figure 6.40: Correlation matrix of the NFs and NPs in a fit to data including only the CRs (correlation threshold set to 10 %).

The pulls and constraints of the NPs in the fit are shown in Figure 6.41. Some small pulls such as in the $t\bar{t}Z$ showering or in some experimental uncertainties are introduced from the fact that no symmetrisation is applied on systematics with up and down variations. A pull is observed for the $t\bar{t}W$ QCD generator uncertainty, which corresponds to the two-point variation between SHERPA and the MADGRAPH5_AMC@NLO +PYTHIA sample. This pull is found to be created by the $2\ell SS$ CRs. Additionally, small pulls of the $ZZ + l$ cross-section and PDF scale are introduced by the prompt conversions CR. This is due to the fact that the ZZ process has a relatively large contribution in this prompt $Z\gamma$ CR, but not in any other region.

Pulls and constraints are also observed in the charge flip systematics. Especially the extrapolation uncertainty, targeting the extrapolation from the Z peak region, where the charge flip rates are computed, into the $2eSS$ CR, is pulled and constrained. The fit pulls this NP towards the distribution computed with charge flip rates derived in MC in the $2eSS$ CR. This is caused by the fact that the Z region and the $2\ell SS$ CRs have slight kinematic differences in the low electron p_T



regime. As the charge flip rate is electron p_T dependent, the p_T distribution inside a p_T bin impacts the computed charge flip factor. The pull in the fit therefore seems to be physically sensible. The same arguments hold for the slight pull and constraint of the binning systematic towards the distribution with more lepton p_T and η bins. In both cases, using smaller electron p_T and η bins in the charge flip rate computation would help solve the tensions with the data. However, the charge flip rates being heavily statistics dominated, more bins are not feasible. Finally, a slight pull is observed in the statistical uncertainty, which also reflects that the data driven charge flip estimation is very statistics limited. Overall, it was studied that these pulls do not have an effect on any NFs or other NPs and they are not part of the leading systematics.

Finally, large pulls and constraints are observed on the $t\bar{t}$ modelling systematics ($t\bar{t}$ showering, $t\bar{t} h_{damp}$ and $t\bar{t} p_{T,hard}$). These uncertainties are highly affected by low MC statistics in some of the bins. As the pulls appear to be much stronger in the 2 ℓ SS CRs than in the 3 ℓ CRs, it was decided to choose a more conservative approach and to decorrelate the $t\bar{t}$ NPs between the 2 ℓ SS CRs, the 3 ℓ CRs and the SRs, leading to separate $t\bar{t}$ showering, $t\bar{t} h_{damp}$ and $t\bar{t} p_{T,hard}$ uncertainties for these different groups of regions. This decorrelation prevents that constraints and pulls on the NPs coming from the 2 ℓ SS CRs are propagated into the other regions. This corresponds to a more conservative approach, as the pulls could come from a mismodelling in the p_T distribution in the 2 ℓ SS CRs, which is not necessarily correlated with the m_{Z1} distribution in the SRs.

6.9.2 Post-fit data MC agreement

The goodness-of-fit corresponds to 30 %. The post-fit data MC agreement for the $t\bar{t}Z$ and WZ +jets CRs can be seen in Figure 6.42, for the fakes CRs in Figure 6.43 and for the 2 ℓ SS CRs in Figure 6.44. All these plots show an improvement of the agreement compared to the pre-fit case. Especially in the 2 ℓ SS CRs, the discrepancies are strongly reduced. In the conversion VRs, shown in Figure 6.45, a very good agreement can be observed in the internal conversions CR, however, the agreement in the material conversion VR slightly decreases. This is likely due to the very low purity of this VR and the fact that the NFs for the prompt background components are not computed for this very specific part of phase-space. Finally, in both low-mass $t\bar{t}\ell^+\ell^-$ VRs, an improvement is seen for post-fit case. Especially for $t\bar{t}\mu\mu$, the post-fit data MC agreement is very good.

Finally, the data MC agreement is also checked in the CRs as a function of the fake lepton p_T . In order to do so, the HF and LF fake lepton CRs are binned in the loose lepton p_T , as shown in Figure 6.47, and the 2 ℓ SS CRs are binned in subleading lepton p_T , see Figure 6.48. The softest

leptons in the event are the most likely to correspond to the fake lepton. In all of these regions, the post-fit MC distribution describes data very well.

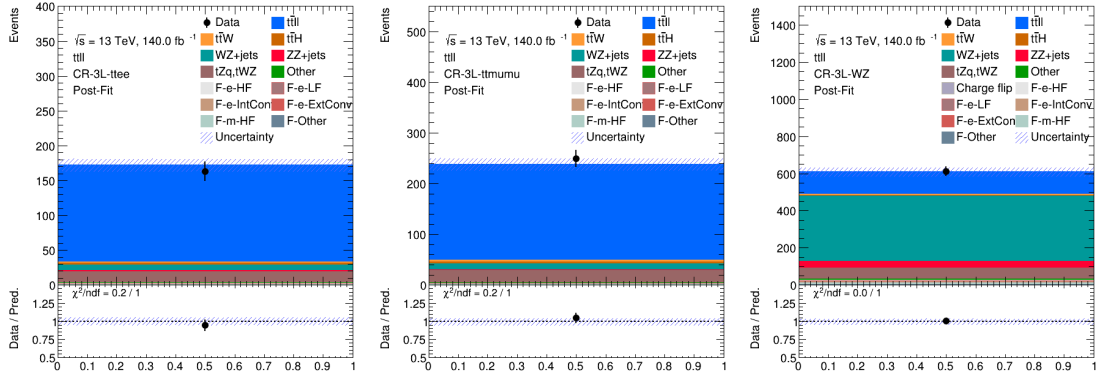


Figure 6.42: Post-fit distributions compared to data in the 3ℓ prompt background CRs: on-shell $t\bar{t}e^+e^-$ CR (left), on-shell $t\bar{t}\mu^+\mu^-$ CR (centre) and WZ +jets CR (right). The uncertainty bands include statistical and systematic uncertainties.

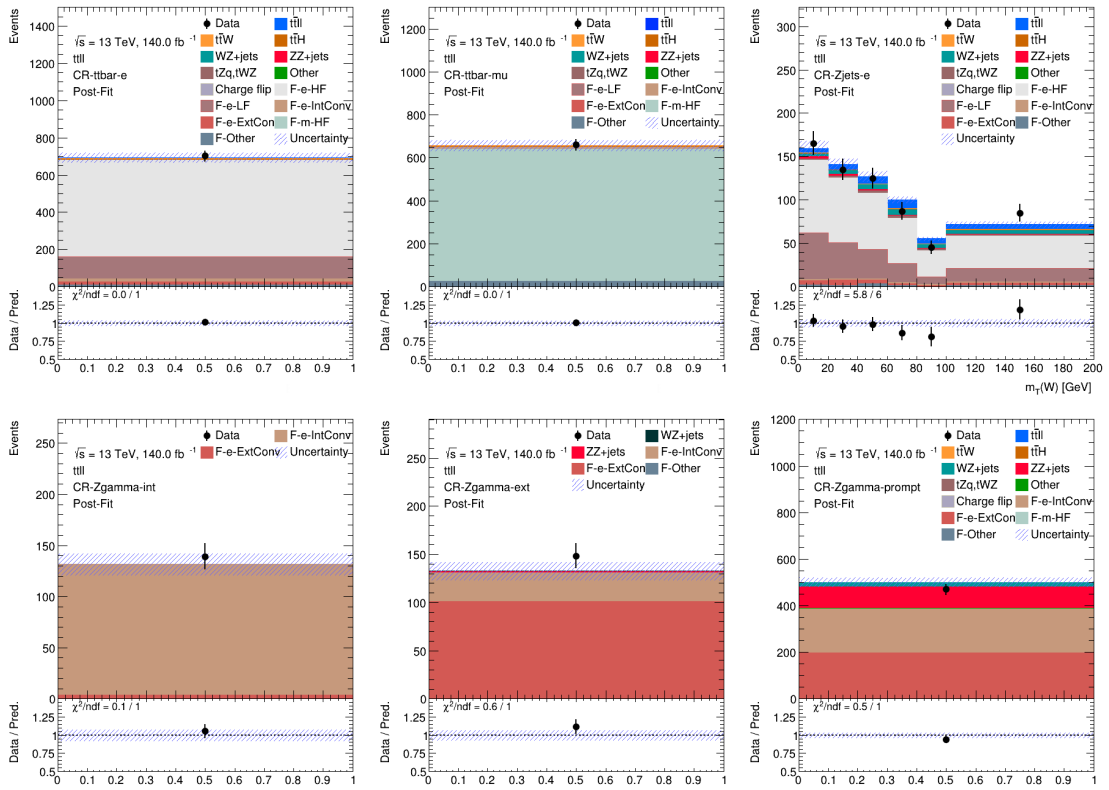


Figure 6.43: Post-fit distributions compared to data in the fake background CRs: $\text{HF } e$ CR (top left), $\text{HF } \mu$ CR (top centre), $\text{LF } e$ CR (top right), internal conv. CR (bottom left), material conv. CR (bottom centre) and prompt conv. CR (bottom right). The uncertainty bands include statistical and systematic uncertainties.

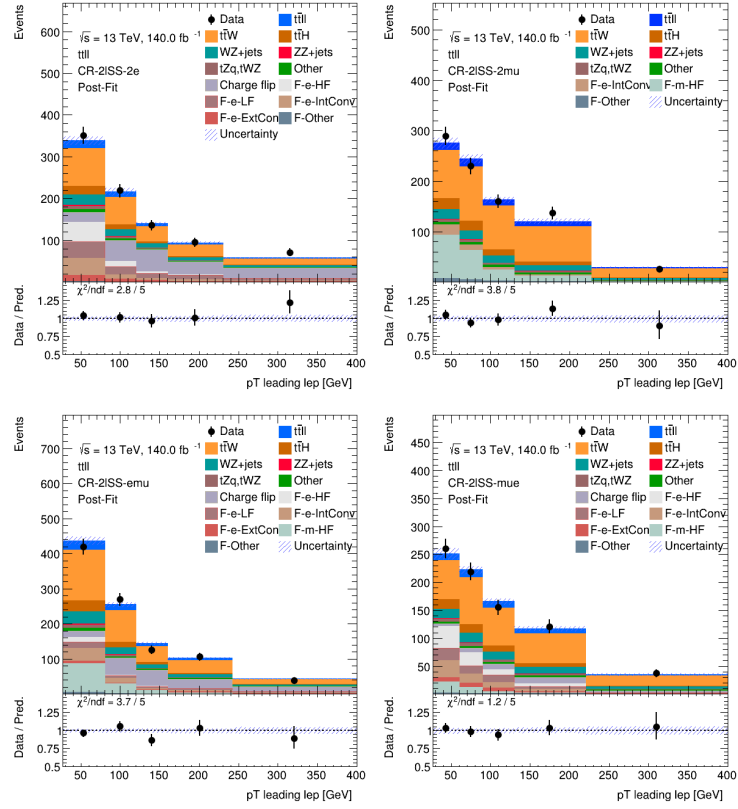


Figure 6.44: Post-fit distributions compared to data in the $2\ell SS$ CRs: $2eSS$ CR (top left), $2\mu SS$ CR (top right), $e\mu SS$ CR (bottom left) and $\mu e SS$ CR (bottom right). The uncertainty bands include statistical and systematic uncertainties.

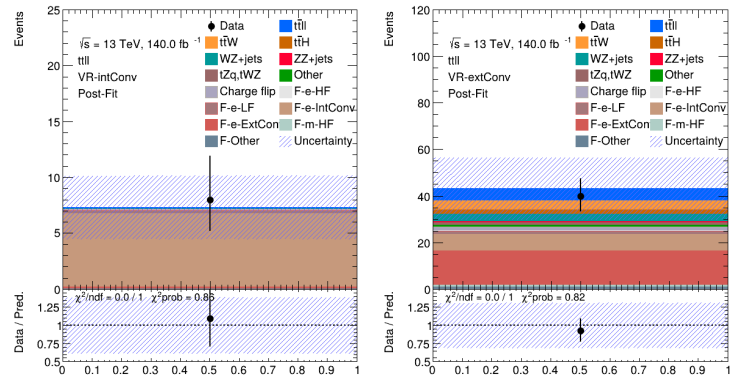


Figure 6.45: Post-fit distributions compared to data in the internal (left) and material (right) conversion VRs. The uncertainty bands include statistical and systematic uncertainties.

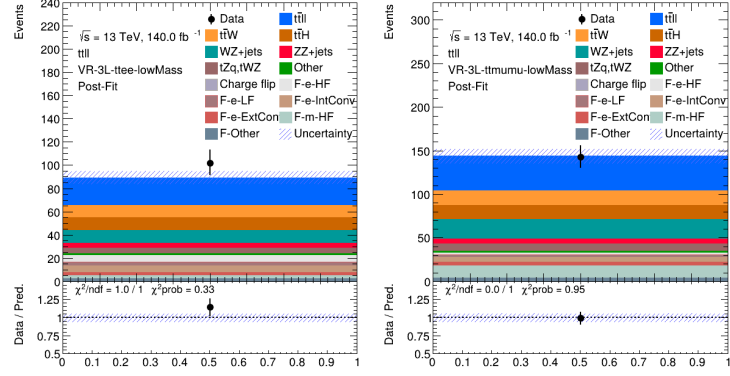


Figure 6.46: Post-fit distributions compared to data in the low-mass $t\bar{t}e^+e^-$ (left) and $t\bar{t}\mu^+\mu^-$ (right) VRs. The uncertainty bands include statistical and systematic uncertainties.

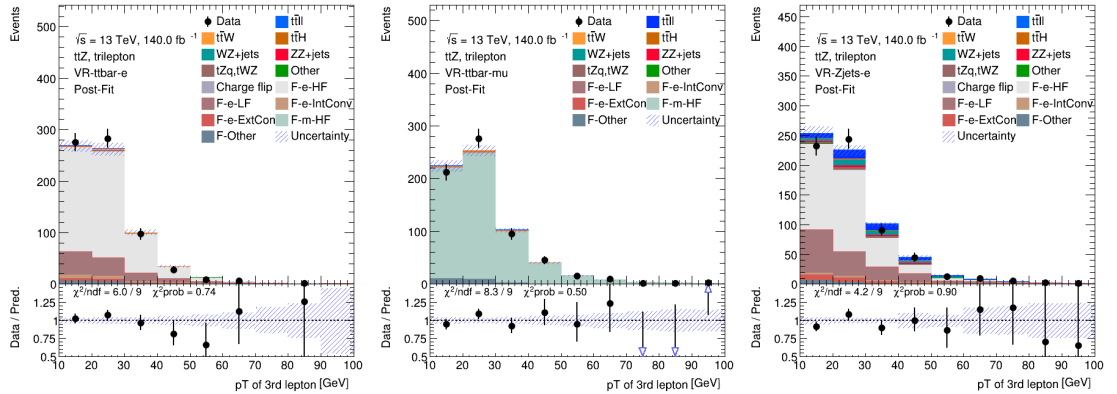


Figure 6.47: Post-fit distributions compared to data in the fake background CRs binned in the loose lepton p_T : HF e CR (left), HF μ CR (centre) and LF e CR (right). The uncertainty bands include statistical and systematic uncertainties.

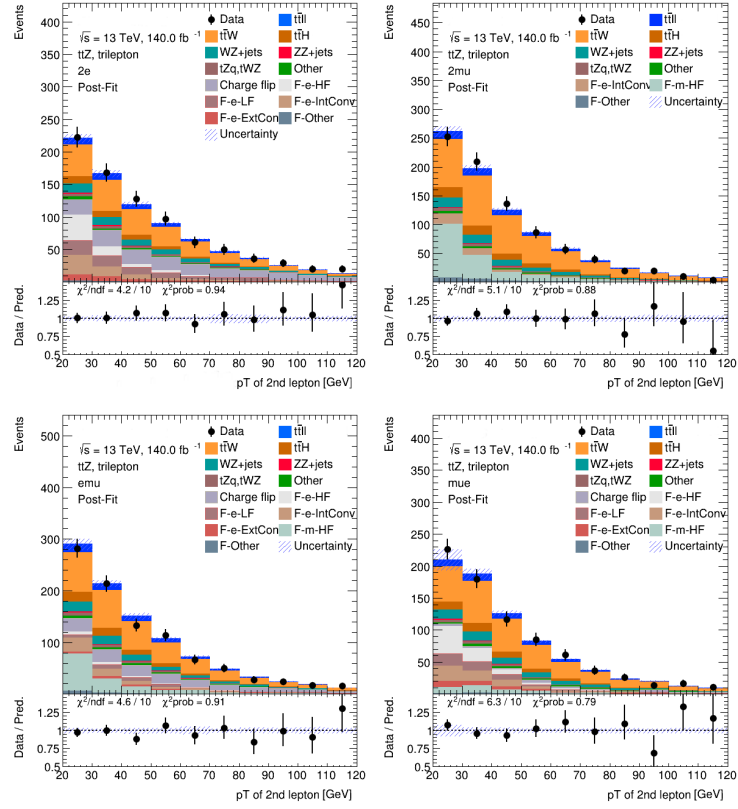


Figure 6.48: Post-fit distributions compared to data in the 2ℓ SS CRs binned in the subleading lepton p_T : $2e$ SS CR (top left), 2μ SS CR (top right), $e\mu$ SS CR (bottom left) and μe SS CR (bottom right). The uncertainty bands include statistical and systematic uncertainties.

6.10 Expected results

In the following sections, the expected results for the signal strength fit (see Section 6.10.1) and the EFT fits (see Section 6.10.2) are studied, where data are fitted in the CRs but the SRs are fully blinded. The fits, called hybrid Asimov fits, are performed in two steps. First, a background only fit is performed, including only the CRs, where the background NFs are fitted to the data. This first step is similar to the fit setup described in Section 6.9. The fit results are then propagated into an Asimov dataset in the SRs. The fit is then reperformed using the data in the CRs and the Asimov data in the SRs, constraining the background NFs and the signal strength at the same time. By construction, the fitted parameters of interest, which should mainly be constrained by the SRs, should take values close to the injected value, namely 1 for the signal strength and 0 for the WCs. Compared to pure Asimov fits or background only fits, including only the CRs, the hybrid Asimov fits have the advantage that the expected sensitivity to the parameters of interest can be studied, while taking into account the observed normalisation of the background NFs and the pulls and constraints on the NPs.

The CI limits given in the following for the expected WC results correspond to the limits assuming the validity of Wilks' theorem.

6.10.1 $t\bar{t}\ell^+\ell^-$ signal strength fit

In the following, a signal strength fit of the high-mass component of $t\bar{t}\ell^+\ell^-$ is studied. Figure 6.49 shows the fitted NFs and their uncertainties. As expected, the background NFs stay nearly unchanged compared to the background only fit, as the CRs give much stronger constraints than the SRs. For the NF of the high-mass component of $t\bar{t}\ell^+\ell^-$, a value of $0.99^{+0.40}_{-0.37}$ is fitted, 1 being the injected signal value. The lower sensitivity to high-mass $t\bar{t}\ell^+\ell^-$ compared to the on-shell $t\bar{t}Z$ contribution, with a sensitivity of about 10 %, is caused by the considerably lower data statistics in the high m_{ll} regime than in the Z peak.

With a statistical impact on the uncertainty of $\mu_{t\bar{t}\ell^+\ell^-}$ of around 0.3 and a systematical impact of about 0.2, the data statistics component has the largest impact on the fit. A breakdown of the impact of different groups of systematics is shown in Figure 6.50. The dominant systematics are the NFs of the non-prompt/fake and prompt backgrounds.

Additionally, the high-mass $t\bar{t}\ell^+\ell^-$ signal-strength is measured separately for electrons and muons, constraining $\mu_{t\bar{t}e^+e^-}$ and $\mu_{t\bar{t}\mu^+\mu^-}$ in one fit. The fit results are shown in Figure 6.51. No changes in the background NFs are observed and $\mu_{t\bar{t}e^+e^-}$ and $\mu_{t\bar{t}\mu^+\mu^-}$ are not shifted significantly

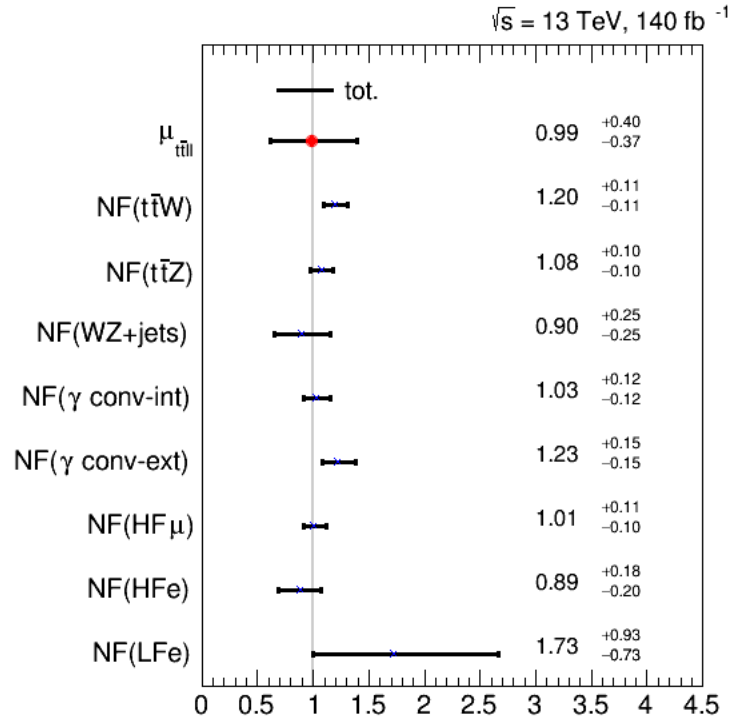


Figure 6.49: NF results of a signal strength fit to data in the CRs and to Asimov data in the SRs .

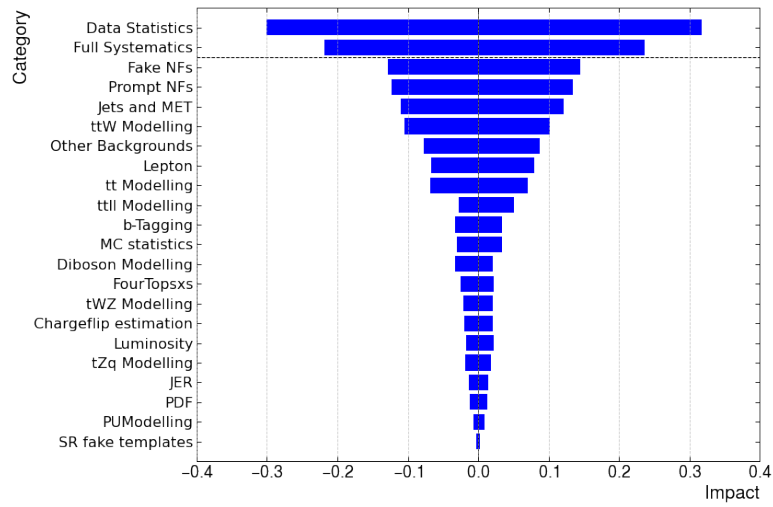


Figure 6.50: Ranking of the impact of grouped systematics on $\mu_{t\bar{t}\ell\ell+\ell-}$ in a signal strength fit to data in the CRs and to Asimov data in the SRs .

away from 1, as expected in the hybrid Asimov fit. The uncertainties on $\mu_{t\bar{t}e^+e^-}$ and $\mu_{t\bar{t}\mu^+\mu^-}$ are increased with respect to $\mu_{t\bar{t}\ell^+\ell^-}$ because of the split of data statistics between the flavours. As the $t\bar{t}\mu^+\mu^-$ SR has slightly larger $t\bar{t}\ell^+\ell^-$ statistics than the $t\bar{t}e^+e^-$ SR, the sensitivity is slightly better for $\mu_{t\bar{t}\mu^+\mu^-}$ than for $\mu_{t\bar{t}e^+e^-}$.

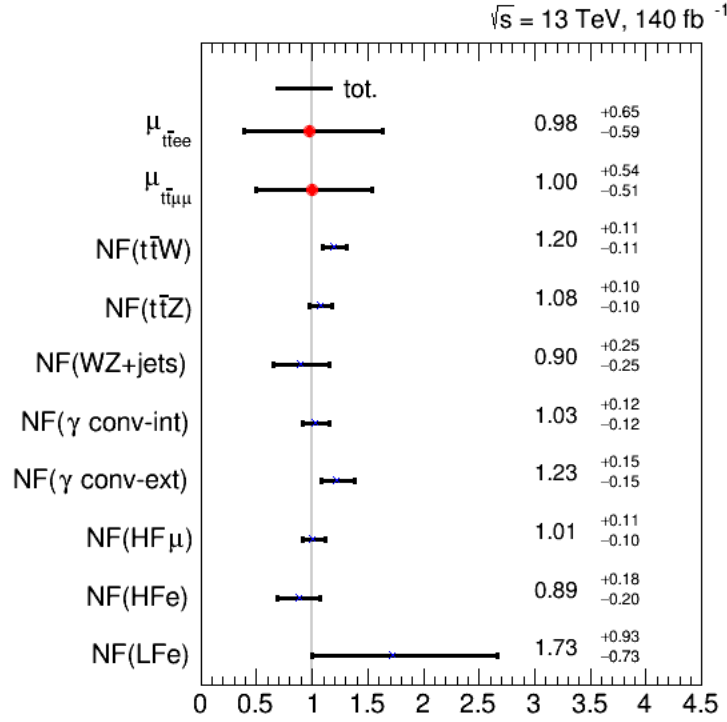


Figure 6.51: NF results of a signal strength fit to data in the CRs and to Asimov data in the SRs splitting the normalisation of the electron and muon flavour components of $t\bar{t}\ell^+\ell^-$.

6.10.2 EFT fits

Fit constraining one EFT operator at a time

The EFT fit setup, described previously, is then performed in order to constrain the six considered WCs. Only one WC is fitted at a time and all others are fixed to the SM.

The obtained results for the background NFs are very similar in all the EFT fits. Figure 6.52 shows as example the NFs in the fit constraining $c_{t\ell}$. The uncertainties agree with the results obtained in the signal strength fit.

The impact of different groups of systematics on the uncertainties of $c_{t\ell}$ is shown in Figure 6.53. The EFT fit is fully data statistics dominated, the data statistical contribution being

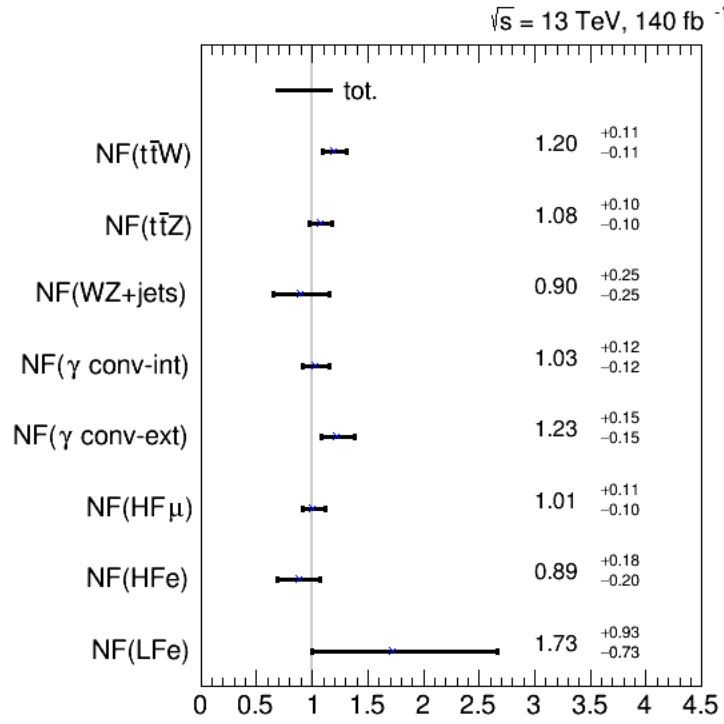


Figure 6.52: Background NF results of an EFT fit to data in the CRs and to Asimov data in the SRs with $c_{t\ell}$ free-floating.

$(-0.88, 1.03)$ compared to $(-0.22, 0.22)$ as systematics contribution. The dominant systematics contribution corresponds to the modelling uncertainties on $t\bar{t}\ell^+\ell^-$.

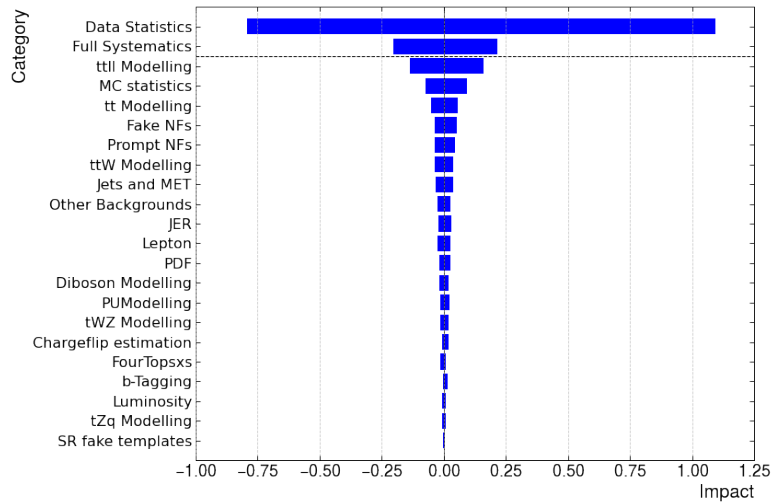


Figure 6.53: Ranking of the impact of grouped systematics on $c_{t\ell}$ in an EFT fit to data in the CRs and to Asimov data in the SRs constraining $c_{t\ell}$.

The expected results for the different WCs are summarised in Tables 6.9 to 6.11 for the flavour dependent case, the flavour inclusive case and the flavour inclusive case where only the linear

EFT contribution is considered (c_{leQt^1} and c_{leQt^3} are dropped in this case as they only have a quadratic EFT contribution).

Table 6.9: Expected best fit results and asymptotic 68 % CI limits for the flavour dependent WCs in EFT fits to data in the CRs and to Asimov data in the SRs. Only one EFT operator is constrained at a time but both flavour components are fitted simultaneously.

WC/ Λ^2	Best fit	68 % asym. CI
c_{tl11}	0.05	$[-1.19, 1.30]$
c_{tl22}	-0.14	$[-1.19, 1.42]$
c_{te11}	-0.06	$[-1.09, 1.33]$
c_{te22}	-0.08	$[-1.07, 1.34]$
c_{Qe11}	-0.10	$[-1.26, 1.32]$
c_{Qe22}	-0.07	$[-1.32, 1.37]$
c_{Ql-11}	0.21	$[-1.10, 1.42]$
c_{Ql-22}	-0.09	$[-1.14, 1.47]$
c_{leQt^111}	0.0	$[-1.59, 1.59]$
c_{leQt^122}	0.0	$[-1.69, 1.69]$
c_{leQt^311}	0.0	$[-0.27, 0.27]$
c_{leQt^322}	0.0	$[-0.27, 0.27]$

Table 6.10: Expected best fit results and asymptotic 68 % CI limits for the flavour inclusive WCs in EFT fits to data in the CRs and to Asimov data in the SRs. Only one EFT operator is constrained at a time.

WC/ Λ^2	Best fit	68 % asym. CI
c_{tl}	-0.09	$[-0.91, 1.02]$
c_{te}	-0.07	$[-0.82, 1.05]$
c_{Qe}	-0.10	$[-0.99, 1.05]$
c_{Ql-}	-0.03	$[-0.85, 1.14]$
c_{leQt1}	0.00	$[-1.26, 1.26]$
c_{leQt3}	0.00	$[-0.21, 0.21]$

As expected, the best-fit values of the WCs are fully compatible with the injected value of 0. The gain in data statistics when fitting the WCs in a flavour inclusive way instead of separately improves the obtained limits. The two flavour dependent WCs can, however, be well separated and constrained, the electron and muon WC having at most a correlation of about 6 %.

In the case where only the linear EFT dependence is considered, an important loss in sensitivity is observed for the majority of the WCs. As shown in the EFT parametrisation of c_{tl} in Figure 6.54 (left), c_{tl} has a dominant quadratic contribution which strongly increases with m_{ll} , while the linear contribution is much smaller. In Figure 6.54 (right), showing the EFT paramet-

Table 6.11: Expected best fit results and asymptotic 68 % CI limits for the flavour inclusive WCs considering the linear EFT dependence in EFT fits to data in the CRs and to Asimov data in the SRs. Only one EFT operator is constrained at a time.

WC/ Λ^2	Best fit	68 % asym. CI
c_{tl}	-0.33	$[-6.98, 5.07]$
c_{te}	-0.12	$[-2.98, 2.15]$
c_{Qe}	-0.64	$[-12.24, 10.57]$
c_{Ql^-}	-0.04	$[-2.56, 2.08]$

risation of c_{te} , a much larger linear contribution can be seen compared to c_{tl} , explaining the fact that the linear only limits are much stronger for c_{te} than for c_{tl} .

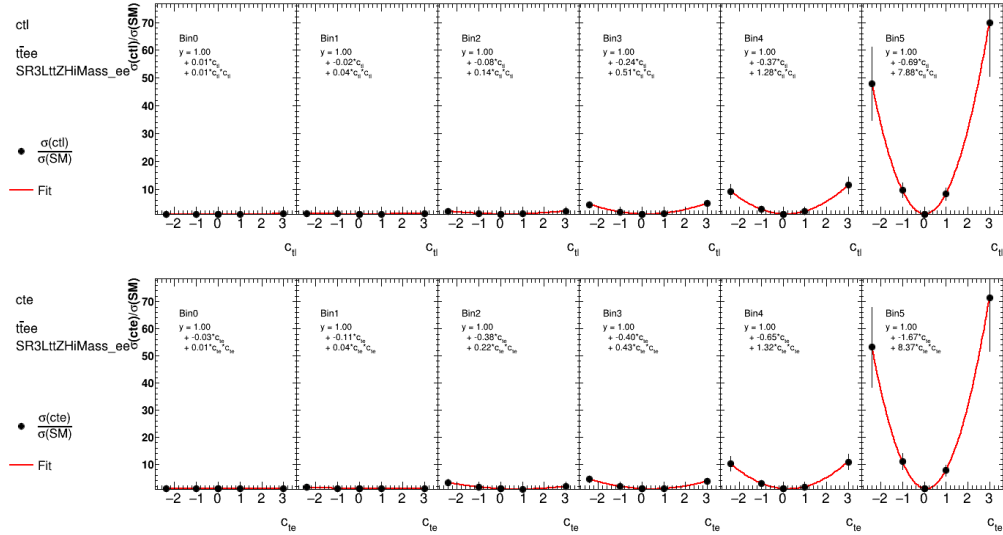


Figure 6.54: EFT parametrisation of the cross-section variation as a function of c_{tl} (top) and of c_{te} (bottom) for each bin of the $t\bar{t}e^+e^-$ SR

Finally, fits are also performed, where, instead of constraining the different flavour dependent WCs separately, the difference between the muon and the electron WC is constrained. This setup would be sensitive to lepton flavour universality violating effects. At the same time, the electron WC is chosen to free float in the fit as the second free parameter. The fit results are shown in Table 6.12. It can be observed that the uncertainties on the difference of WCs are larger than for the individual flavour dependent results. Even though fitting the flavour difference allows for some flavour independent systematics to cancel, the fact that the fit is statistics dominated means that this cancelling effect is small and both flavour dependent WC measurements are mostly independent.

Table 6.12: Expected best fit results and asymptotic 68 % CI limits for the flavour dependent WCs in EFT fits to data in the CRs and to Asimov data in the SRs. Only one EFT operator is constrained at a time and the electron component as well as the relative rate between the electron and muon components are fitted.

WC/ Λ^2	Best fit	68 % asym. CI
c_{tl11}	0.08	$[-1.19, 1.30]$
$c_{tl22} - c_{tl11}$	-0.22	$[-1.93, 2.38]$
c_{te11}	-0.06	$[-1.08, 1.33]$
$c_{te22} - c_{te11}$	-0.02	$[-1.85, 1.88]$
c_{Qe11}	-0.10	$[-1.26, 1.32]$
$c_{Qe22} - c_{Qe11}$	0.02	$[-2.05, 2.04]$
c_{Ql-11}	0.20	$[-1.42, 1.11]$
$c_{Ql-22} - 2c_{Ql-11}$	-0.29	$[-1.99, 1.99]$
c_{leQt^111}	0.05	$[-1.69, 1.49]$
$c_{leQt^122} - 2c_{leQt^111}$	-0.07	$[-2.53, 2.53]$
c_{leQt^311}	0.01	$[-0.27, 0.27]$
$c_{leQt^322} - 2c_{leQt^311}$	-0.02	$[-0.46, 0.42]$

EFT fit constraining several EFT operators at the same time

EFT fits are also considered, where several EFT operators are constrained at the same time. Different combinations of two-dimensional EFT fits are considered. As described in Section 6.8.2, the WCs appear uncorrelated in the lack of signal. Two-dimensional likelihood scans, such as the one shown in Figure 6.55 therefore do not show any interesting behaviour for expected results in the assumption of the SM.

A fit constraining all six WCs at the same time does not converge properly in the case where Asimov data are used for the fit in the SRs.

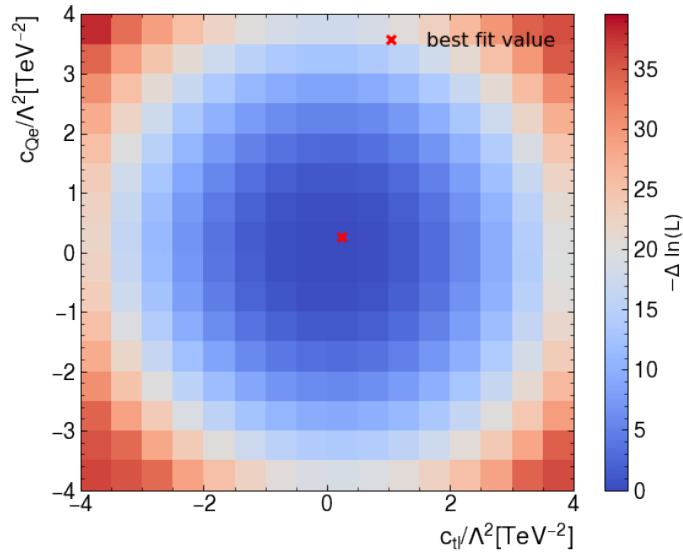


Figure 6.55: Expected two-dimensional likelihood scan of c_{Qe} versus c_{tl} in an EFT fit to data in the CRs and to Asimov data in the SRs constraining c_{tl} and c_{Qe} at the same time.

6.11 Observed results

In the following, the final results are shown including the data in the SRs.

6.11.1 Pre-fit distribution

Figure 6.56 shows the pre-fit data MC agreement in the SRs. Overall, the data are compatible with the expectations, with a χ^2 probability of 24 % in the $t\bar{t}e^+e^-$ SR and of 30 % in the $t\bar{t}\mu^+\mu^-$ SR. While the highest m_{ll} bin in both SRs shows a very good data MC agreement, the second to highest bin shows some expected statistical fluctuations in data compared to MC. In the $t\bar{t}e^+e^-$ SR this bin does not contain any data events and in the $t\bar{t}\mu^+\mu^-$ SR a slight upward fluctuation of the data compared to MC is observed. These disagreements are, however, not significant, as these bins have very low expected statistics.

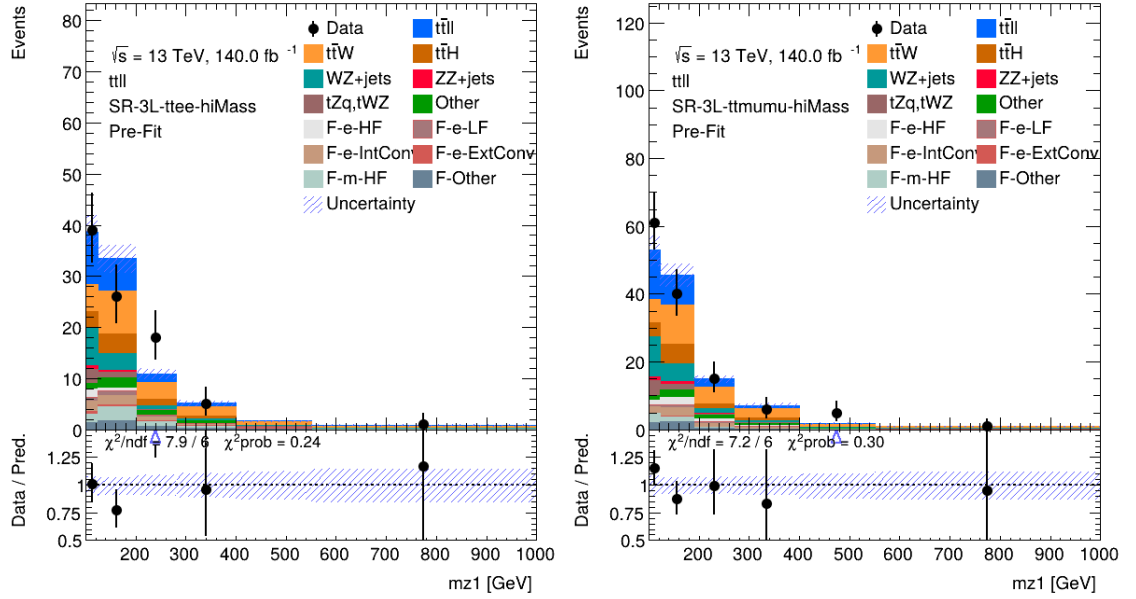


Figure 6.56: Expected distributions compared to data in the $t\bar{t}e^+e^-$ (left) and $t\bar{t}\mu^+\mu^-$ (right) SRs. The uncertainty bands include statistical and systematic uncertainties.

6.11.2 $t\bar{t}\ell^+\ell^-$ signal strength fit

A signal strength fit is performed and the results for the NFs of the high-mass $t\bar{t}\ell^+\ell^-$ component and the backgrounds are shown in Figure 6.57 (left). The background NFs are not significantly impacted by the data in the SRs compared to the background only fit. Additionally, the high-mass $t\bar{t}\ell^+\ell^-$ flavour inclusive signal strength is measured to be $1.03^{+0.39}_{-0.37}$, being very compatible with the SM expectation. The goodness-of-fit corresponds to 16 %. In a flavour dependent signal strength fit, shown in Figure 6.57 (right), a slight pull of the $t\bar{t}e^+e^-$ normalisation to smaller values and of the $t\bar{t}\mu^+\mu^-$ normalisation to higher values is observed. However, these pulls are not significant and the measurement is again very compatible with the SM expectation. The post-fit distributions are shown in Figure 6.58.

Additionally, Figure 6.59 shows all NPs which are pulled or over/underconstrained by more than 0.1 and compares them in the unblinded signal strength fit and the hybrid Asimov signal strength fit. No new pulls or constraints are observed compared to the ones in the background only fit with data.

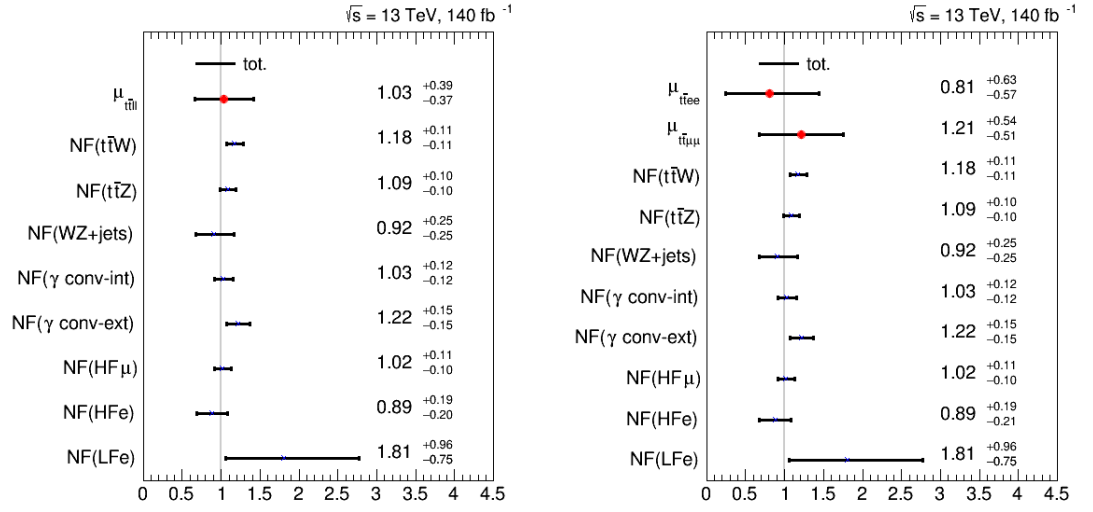


Figure 6.57: NF results of a signal strength fit to data with a flavour inclusive signal strength (left) and splitting the signal strength of the electron and muon flavour components of $t\bar{t}\ell^+\ell^-$ (right).

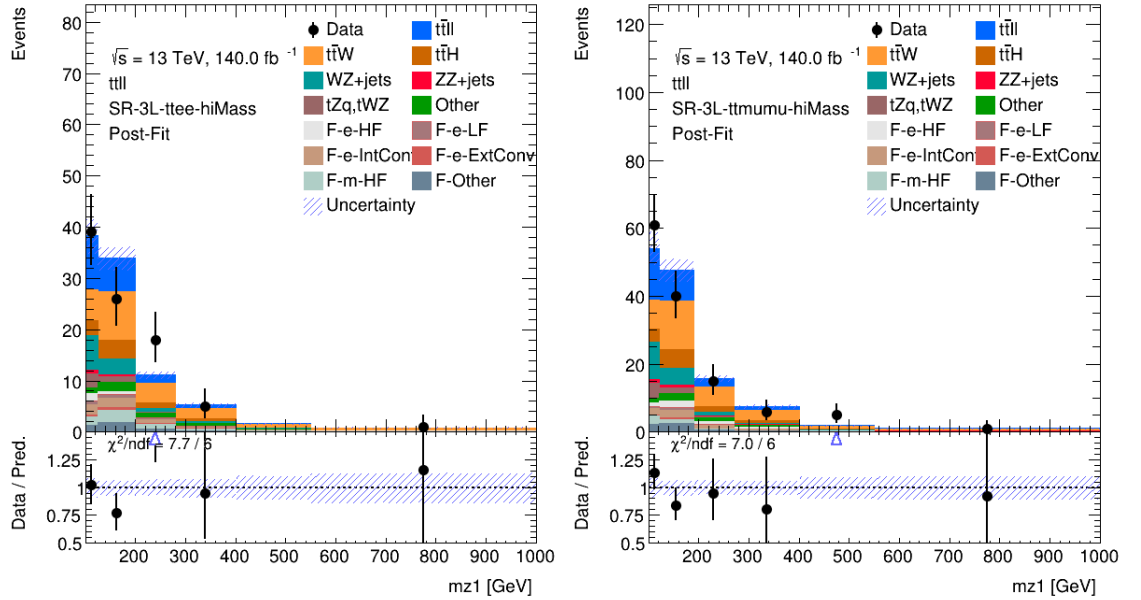


Figure 6.58: Post-fit distributions compared to data in the $t\bar{t}\ell^+\ell^-$ (left) and $t\bar{t}\mu^+\mu^-$ (right) SRs. The uncertainty bands include statistical and systematic uncertainties.

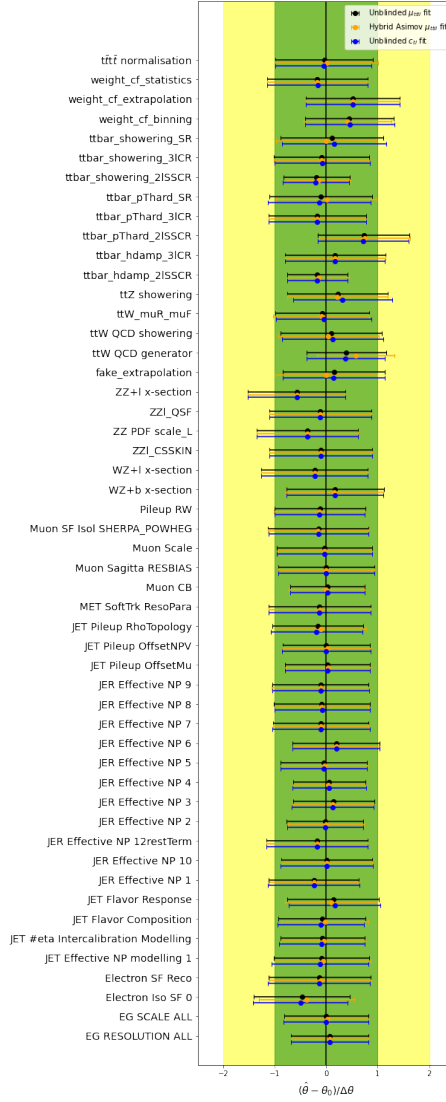


Figure 6.59: Comparison of the constraints and pulls of the **NPs** in a signal strength fit to data, a signal strength fit to data in the **CRs** and to Asimov data in the **SRs** and an **EFT** fit to data constraining $c_{t\ell}$.

6.11.3 EFT fits

Fit constraining one EFT operator at a time

In the following, the results of the **EFT** fits constraining one **WC** at a time are discussed. Figure 6.60 shows the background **NFs** in a fit constraining $c_{t\ell}$ and no significant changes are observed compared to the signal strength fit. Additionally, Figure 6.59 shows that no pulls are introduced by the **EFT** fit.

In Figure 6.61, the impact of different groups of systematics on the uncertainties of $c_{t\ell}$ can be seen. Similar to the expected results, the sensitivity to $c_{t\ell}$ is limited by the statistical uncertainty and the dominating systematic uncertainty is the modelling of $t\bar{t}\ell^+\ell^-$.

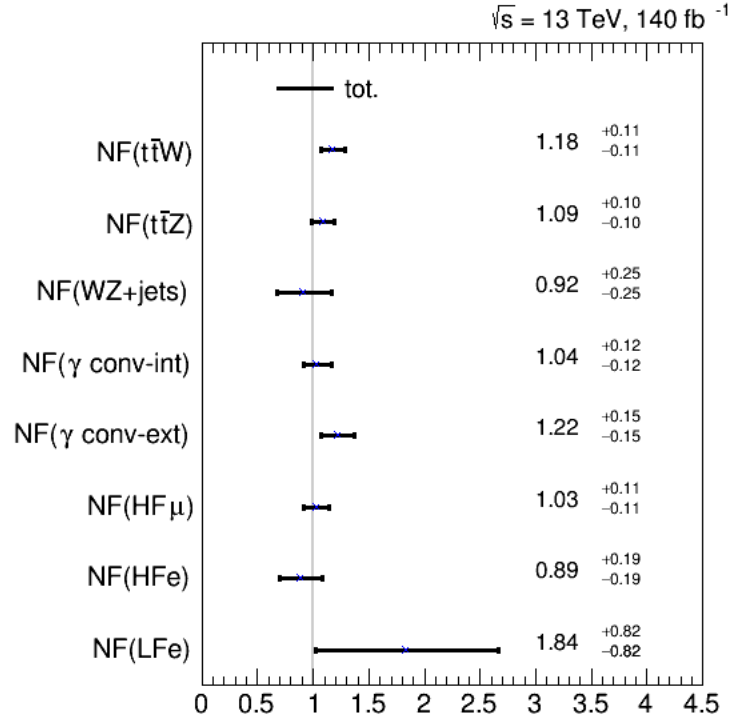


Figure 6.60: Background NF results of an EFT fit to data in the CRs and to Asimov data in the SRs with c_{tI} free-floating.

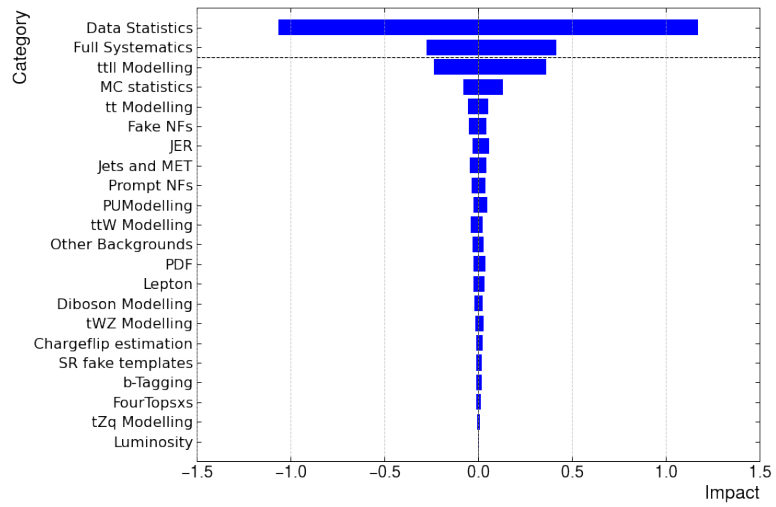


Figure 6.61: Ranking of the impact of grouped systematics on c_{tI} in an EFT fit to data constraining c_{tI} .

The [EFT](#) results for the flavour inclusive results are listed in Table 6.13. Additionally to the best fit result, the 1σ [CI](#) in the assumption of Wilk's theorem and the toy corrected [CI](#) limits are shown. The likelihood scans for the different [WCs](#) are shown in Figure 6.62 together with the corrected 1σ contour and the coverage in the asymptotic assumption. It can be noted that the breaking of Wilk's theorem leads to an under-coverage and the corrected [CI](#) limits are therefore looser than the asymptotic [CI](#) limits.

Table 6.13: Best fit results, asymptotic 68 % [CI](#) limits and corrected 68 % [CI](#) limits for the flavour inclusive [WCs](#) in [EFT](#) fits to data. Only one [EFT](#) operator is constrained at a time.

WC / Λ^2	Best fit	68 % asym. CI	68 % corr. CI
c_{tl}	-0.44	$[-1.10, 1.24]$	$[-1.17, 1.31]$
c_{te}	-0.45	$[-1.05, 1.18]$	$[-1.21, 1.41]$
c_{Qe}	-0.54	$[-1.23, 1.19]$	$[-1.32, 1.32]$
c_{Ql-}	0.69	$[-0.98, 1.41]$	$[-1.15, 1.74]$
c_{leQt1}	-0.61	$[-1.51, 1.50]$	$[-1.55, 1.54]$
c_{leQt3}	-0.12	$[-0.26, 0.26]$	$[-0.27, 0.27]$

In Figure 6.63 the asymptotic observed results are compared to the expected results (left) and with the results obtained by [CMS](#) (right). Due to the data fluctuations with respect to the [MC](#) prediction, a slight loss in sensitivity compared to the expected results is observed. An improvement in the limits is still, however, observed with respect to the [CMS](#) results.

In Table 6.14 the fit results are shown for the case, where the quadratic [EFT](#) contribution is dropped. Again a small loss in sensitivity compared to the expected results is observed. Additionally the [CIs](#) are shifted towards negative values, even though the results are still consistent with the [SM](#) expectation. Finally the data distribution seems to allow for much stronger positive limits than negative ones.

Table 6.14: Best fit results and asymptotic 68 % [CI](#) limits for the flavour inclusive [WCs](#) considering only the linear [EFT](#) dependence in [EFT](#) fits to data. Only one [EFT](#) operator is constrained at a time.

WC / Λ^2	Best fit	68 % asym. CI
c_{tl}	-1.21	$[-8.23, 4.22]$
c_{te}	-1.42	$[-4.45, 1.09]$
c_{Qe}	-11.65	$[-25.75, 0.98]$
c_{Ql-}	-0.16	$[-2.66, 1.91]$

In Table 6.15 the results for the flavour dependent [WCs](#) are presented using the asymptotic assumption and correcting the limits with toys. The two-dimensional likelihood scans, see Fig-

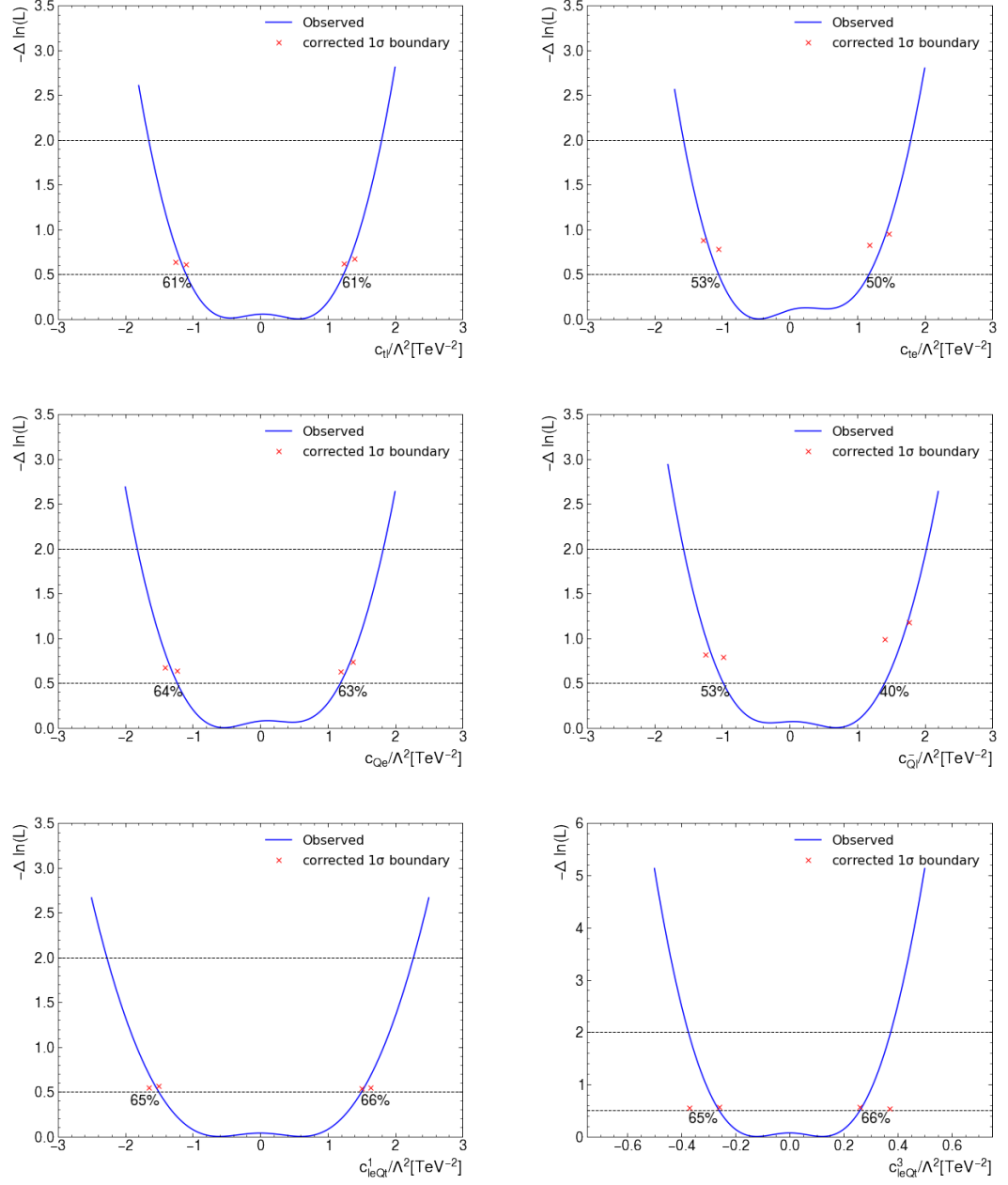


Figure 6.62: Likelihood scans for the flavour inclusive WCs in EFT fits to data with the corrected 1σ contour and the true coverage at the asymptotic 1σ CI limits.

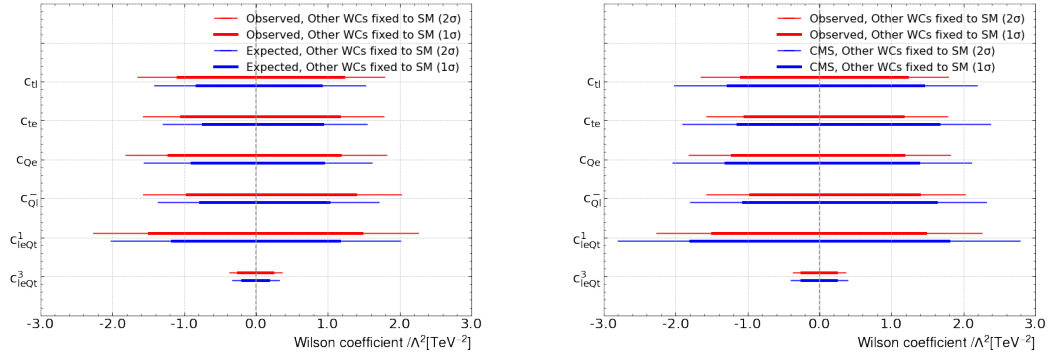


Figure 6.63: Asymptotic 68 % and 95 % CI limits for the flavour inclusive WCs in EFT fits to data compared to EFT fits to data in the CRs and to Asimov data in the SRs (left) and compared to the results obtained by CMS (right) [139].

Figure 6.64, show that the flavour components of the WCs are largely uncorrelated. Splitting the WCs by flavour demonstrates that the loss in sensitivity in the observed results with respect to the expected results is driven by the muon operators. This is likely due to the upwards fluctuation of the data in the second highest bin in the $t\bar{t}\mu^+\mu^-$ SR. All results are again compatible with the SM. Similar to the flavour inclusive CI limits, the toy corrected limits are looser than the asymptotic ones.

Table 6.15: Best fit results, asymptotic 68 % CI limits and corrected 68 % CI limits for the flavour dependent WCs in EFT fits to data. Only one EFT operator is constrained at a time but both flavour components are fitted simultaneously.

WC/ Λ^2	Best fit	68 % asym. CI	68 % corr. CI
c_{tl11}	0.22	$[-1.10, 1.24]$	$[-1.20, 1.36]$
c_{tl22}	-0.81	$[-1.57, 1.79]$	$[-1.64, 1.85]$
c_{te11}	-0.24	$[-1.19, 1.21]$	$[-1.44, 1.55]$
c_{te22}	-0.67	$[-1.40, 1.79]$	$[-1.56, 2.07]$
c_{Qe11}	-0.24	$[-1.28, 1.22]$	$[-1.40, 1.31]$
c_{Qe22}	-0.89	$[-1.72, 1.77]$	$[-1.76, 1.84]$
c_{Ql-11}	0.48	$[-1.00, 1.49]$	$[-1.30, 2.09]$
c_{Ql-22}	-0.66	$[-1.46, 1.99]$	$[-1.65, 2.44]$
c_{leQt^111}	-0.22	$[-1.57, 1.58]$	$[-1.67, 1.70]$
c_{leQt^122}	-1.08	$[-2.21, 2.20]$	$[-2.27, 2.26]$
c_{leQt^311}	0.0	$[-0.26, 0.26]$	$[-0.28, 0.27]$
c_{leQt^322}	-0.20	$[-0.35, 0.35]$	$[-0.36, 0.35]$

Table 6.16 shows the fitted difference between the muon and electron operators. Again all results are compatible with the SM expectation.

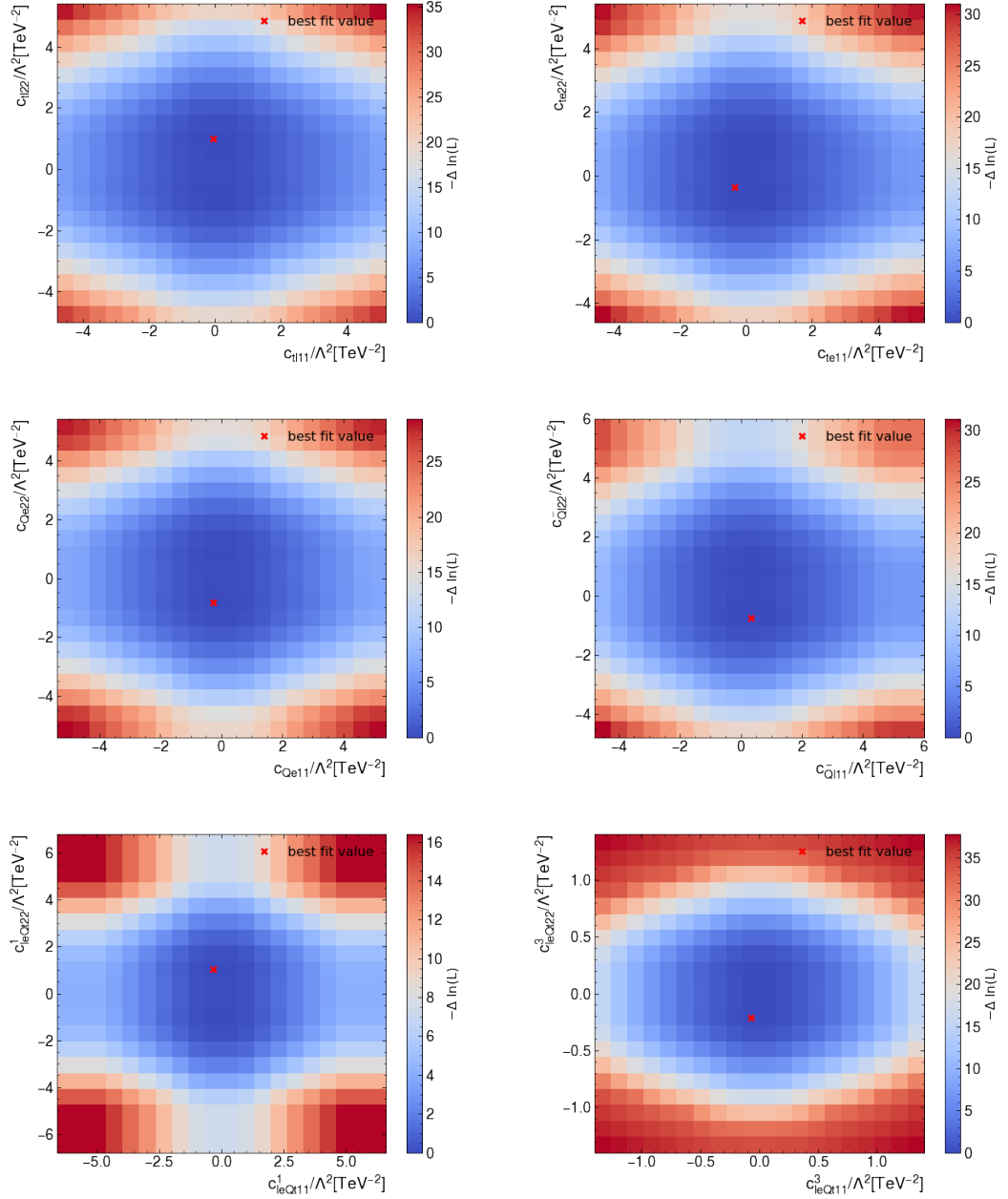


Figure 6.64: Two-dimensional likelihood scans of the muon component versus the electron component for the flavour dependent WCs in EFT fits to data.

Table 6.16: Best fit results and asymptotic 68 % CI limits for the flavour dependent WCs in EFT fits to data. Only one EFT operator is constrained at a time and the electron component as well as the relative rate between the electron and muon components are fitted.

WC/Λ^2	Best fit	68 % asym. CI
$c_{tl22} - c_{tl11}$	0.79	$[-2.28, 2.32]$
$c_{te22} - c_{te11}$	-0.43	$[-2.10, 2.36]$
$c_{Qe22} - c_{Qe11}$	-0.66	$[-2.39, 2.43]$
$c_{Ql-22} - c_{Ql-11}$	-1.14	$[-2.38, 2.37]$
$c_{leQt^1 22} - c_{leQt^1 11}$	-1.32	$[-3.03, 3.03]$
$c_{leQt^3 22} - c_{leQt^3 11}$	-0.20	$[-0.50, 0.50]$

All the asymptotic results are summarised in Figure 6.65. Finally, the asymptotic limits for the flavour inclusive WCs are shown for different upper limits on m_{ll} in Figure 6.66. While a cut on m_{ll} at 1 TeV does not significantly impact the sensitivity, cuts at lower values show an important impact. Especially removing the highest m_{ll} bin loosens significantly the limits. For c_{Ql}^- , removing the highest bin shifts the CI away from the expected value of 0 because of the data MC discrepancy in the second highest bin. The tension to the SM expectation is, however, not significant.

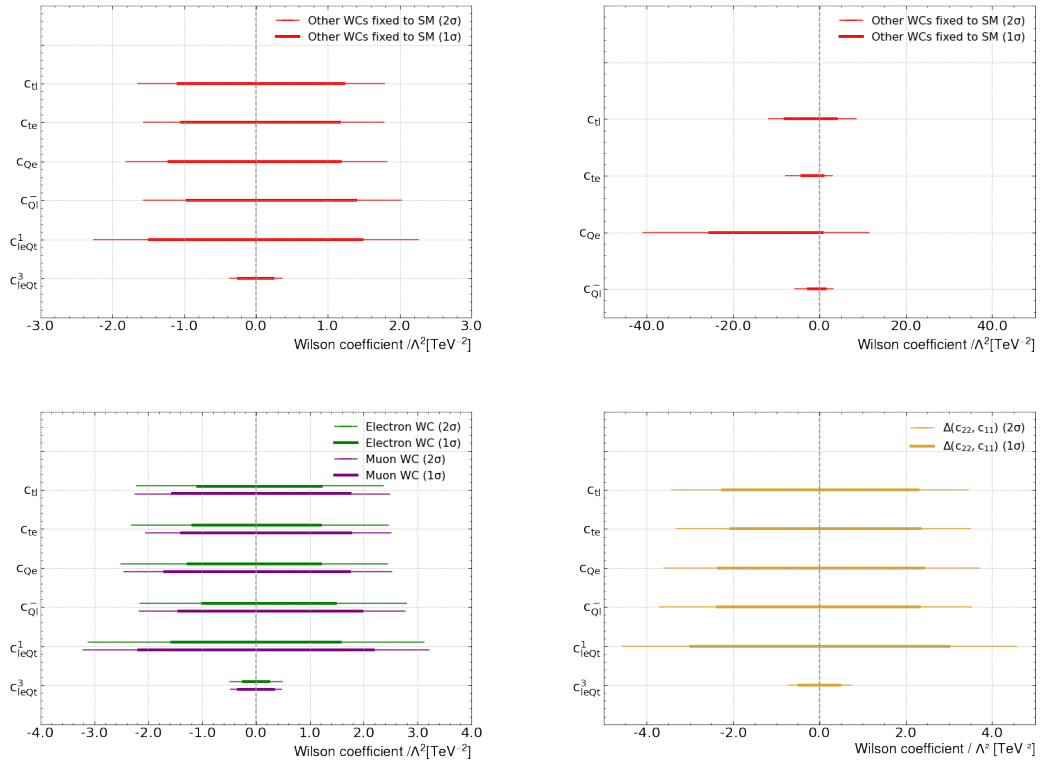


Figure 6.65: Summary plot of the asymptotic 68 % and 95 % CI limits: flavour inclusive WCs with quadratic dependence (top left), flavour inclusive WCs considering only the linear EFT dependence (top right), flavour dependent WCs (bottom left) and difference of the flavour dependent WCs (bottom right).

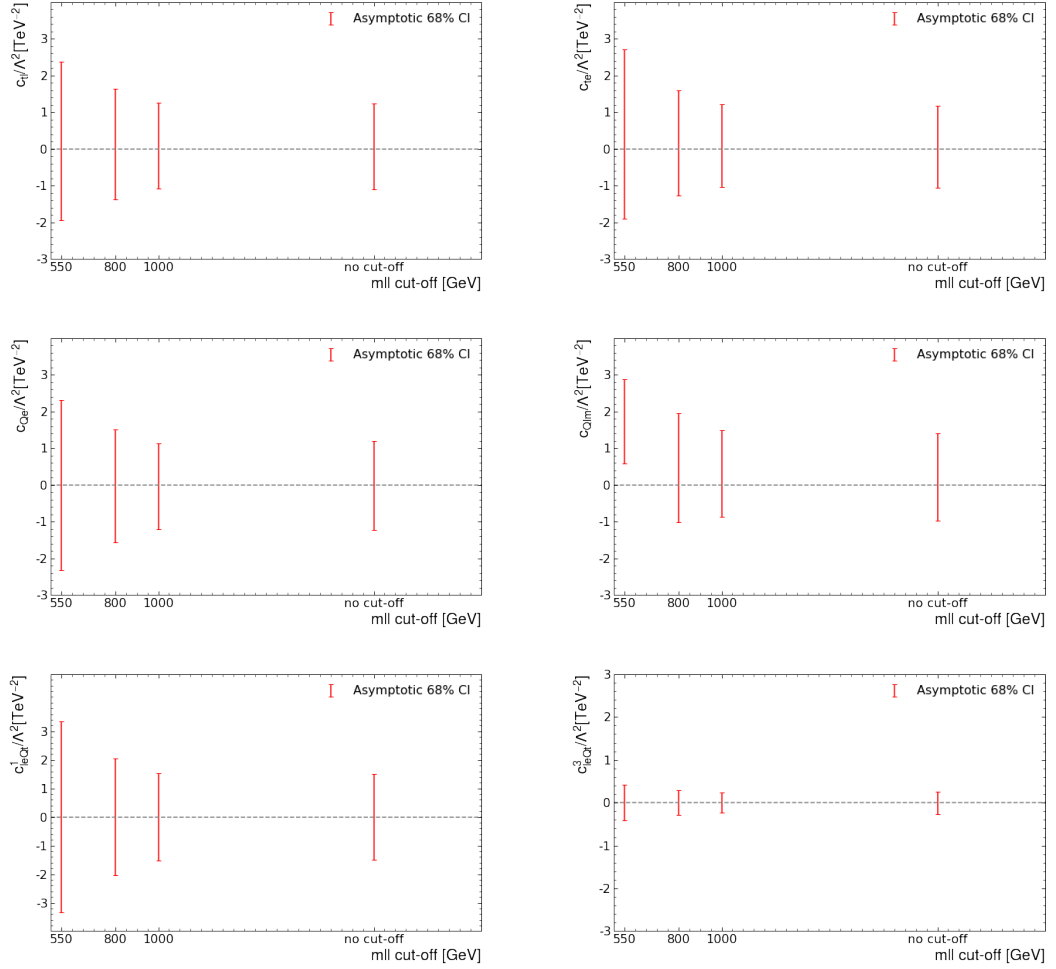


Figure 6.66: Asymptotic 68 % CI limits for the flavour inclusive WCs in EFT fits to data with different m_{ll} cut-offs.

Fit constraining several EFT operators at a time

In the case where Asimov data are used in the SRs, the EFT fit, where all six WCs are constrained at the same time, does not converge. However, adding the data in the SRs helps the fit to converge properly. The results are shown in Table 6.17 and compares them to the results from the one-dimensional EFT fits. The CI limits are relatively consistent between both fit setups. As described in Section 6.8, the fact that no loss in sensitivity is observed when fitting six WCs at the same time instead of one, comes from the fact that no EFT signal is observed. The quadratic behaviour of the WCs therefore leads to very low perceived correlations between the WCs.

Additionally, all fifteen possible combinations of two-dimensional EFT fits are considered. The two-dimensional likelihood scans are shown for three of these in Figure 6.67. As no EFT signal is observed, the WCs are largely uncorrelated and these results do not generally show noteworthy trends.

Table 6.17: Fit results for the considered [EFT](#) flavour inclusive Wilson coefficients and their asymptotic 1σ uncertainty intervals, where all six [EFT](#) operators are kept free floating at the same time compared to the case where only one [WC](#) is constrained.

WC / Λ^2	Best fit (other WC s free floating)	68 % asym. CI (other WC s free floating)	68 % asym. CI (other WC s fixed to SM)
$c_{t\ell}$	0.15	$[-0.97, 1.22]$	$[-1.10, 1.24]$
c_{te}	-0.54	$[-1.13, 1.03]$	$[-1.05, 1.18]$
c_{Qe}	-0.18	$[-1.13, 1.16]$	$[-1.23, 1.19]$
c_{Ql^-}	0.61	$[-1.27, 1.45]$	$[-0.98, 1.41]$
c_{leQt1}	-0.49	$[-1.66, 1.53]$	$[-1.51, 1.50]$
c_{leQt3}	-0.02	$[-0.27, 0.24]$	$[-0.26, 0.26]$

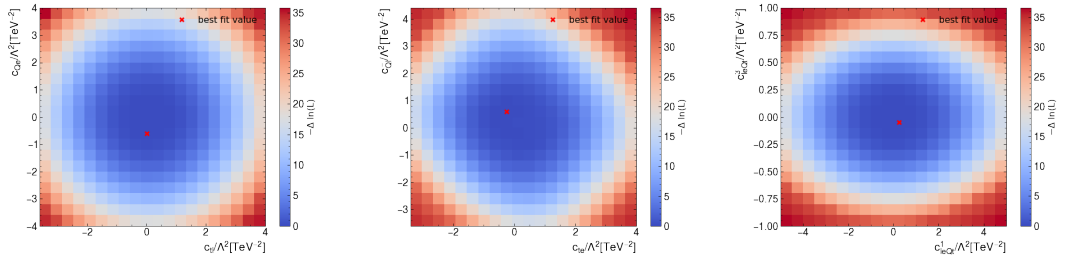


Figure 6.67: Two-dimensional likelihood scans in [EFT](#) fits to data constraining $c_{t\ell}$ and c_{Qe} (left), c_{te} and c_{Ql^-} (centre) and c_{leQt}^1 and c_{leQt}^3 (right) at the same time.

6.12 Conclusion

The high-mass $t\bar{t}\ell^+\ell^-$ analysis corresponds to a search for physics beyond the [SM](#) making use of the [EFT](#) formalism. It is the first dedicated measurement by [ATLAS](#) in the high-mass regime of $t\bar{t}\ell^+\ell^-$.

The analysis is optimised for its sensitivity to the four-fermion operators in the $t\bar{t}\ell^+\ell^-$ vertex. This includes designing the analysis in a way, to maximise the impact of a potential [EFT](#) signal on the measured $t\bar{t}\ell^+\ell^-$ distribution. Additionally, a good understanding of the backgrounds is required, which is obtained by the definition of [CRs](#), a significant extension of the on-shell $t\bar{t}Z$ analysis. Finally, the statistical interpretation of the results was studied, revealing the need to correct the [CI](#) limits with toys and showing quadratic correlations between different [WCs](#), appearing in the case of [EFT](#) signal.

The [EFT](#) coefficients are measured flavour inclusively as well as separately for electrons and muons including the relative rates between both flavours, giving access to potential lepton flavour universality violation. The obtained results are fully consistent with the [SM](#) expectations. Constraints on the [WCs](#) are therefore derived, setting the current strongest limits on the four-fermion operators, improving upon previous measurements.

MEASUREMENT OF THE INCLUSIVE AND DIFFERENTIAL CROSS-SECTION OF $t\bar{t}H$ IN A MULTI-LEPTONIC FINAL STATE



This chapter presents the $t\bar{t}H$ Multi Lepton (ML) analysis, an inclusive and differential measurement of the top-pair production in association with the Higgs boson in a multi-leptonic final state. Additionally, the ATLAS $t\bar{t}W$ measurement, which served as input to this analysis, is briefly described.

The author was responsible for the combination of the five different analysis channels including the harmonisation of the templates and systematics. Additionally, the author was responsible for the combined STXS fit, as well as the setup of the STXS fits in the single channels. This included some Higgs p_T reconstruction studies in the $0\tau_{\text{had}}$ channels (but not the training of the Graph Neural Network (GNN)), the binning optimisation of the STXS SRs and the treatment of the signal templates and uncertainties.

Finally, the author was involved in the preceding inclusive and differential $t\bar{t}W$ measurement [52], by implementing the differential distributions in the fiducial phase-space of the analysis into a Rivet routine and deriving non-perturbative corrections for the comparison of the unfolded differential measurement to full off-shell theory calculations.

7.1 Motivation

Measuring the top-Yukawa coupling, the top quark being the SM particle with the strongest coupling to the Higgs, provides a test of EW symmetry breaking. While the top-Higgs coupling contributes to the dominant Higgs production cross-section via gluon-gluon fusion through loops, the $t\bar{t}H$ process probes the top Yukawa coupling in a direct way. Additionally, as shown in Figure 7.1, a $t\bar{t}H$ process including a trilinear Higgs coupling vertex contributes to the $t\bar{t}H$ cross-section. This contribution does not only affect the inclusive cross-section of $t\bar{t}H$ but also the

shape of some differential distributions, such as the transverse momentum of the Higgs shown in Figure 7.2. Even though di-Higgs processes hold much larger sensitivity to the Higgs self-coupling, $t\bar{t}H$ is the single Higgs process which is affected the most by the Higgs self-coupling in its differential distributions [147], which allows for an important complementary measurement.

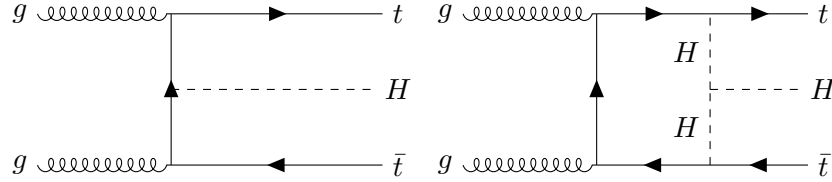


Figure 7.1: Two of the Feynman diagrams contributing to the $t\bar{t}H$ cross-section: LO (left) and higher order contribution including the trilinear Higgs self-coupling (right).

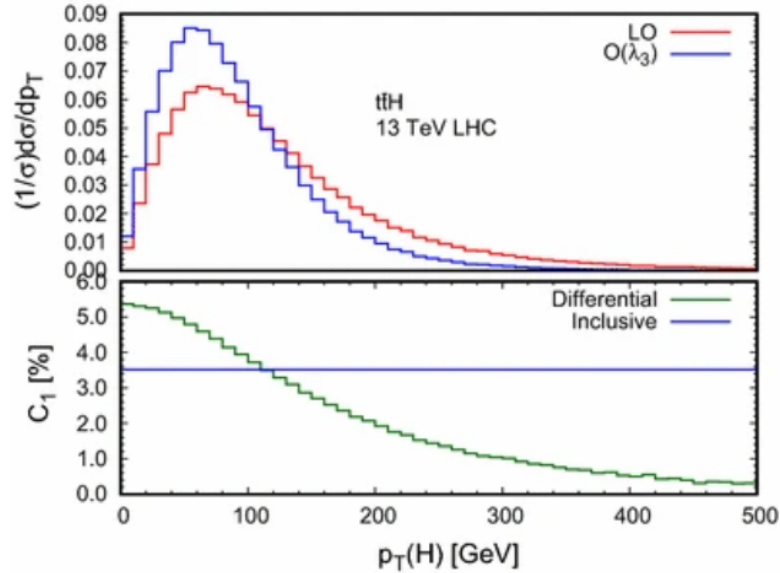


Figure 7.2: Upper panel: differential shape of $t\bar{t}H$ as a function of Higgs p_T at LO and shape induced by NLO EW corrections adding the impact of the trilinear Higgs coupling; Lower panel: process- and kinematic-dependant part (C_1) of the NLO EW corrections sensitive to the Higgs self-coupling [147]

Finally, the $t\bar{t}H$ process can be used to test the Higgs sector as a source of CP violation in a direct way. Whether CP is broken by the Yukawa coupling or not impacts the $t\bar{t}H$ production rate as well as some differential distributions. As can be seen in Figure 7.3, a combined measurement of the $t\bar{t}H$ and the $tHj\bar{b}$ cross-section can give an important constraint on the degree of CP breaking, described by the CP mixing angle α .

The $t\bar{t}H$ process was first discovered at the LHC by the ATLAS and CMS collaborations using the data collected in Run 1 and a partial Run 2 dataset, combining different decay channels of the Higgs boson [149, 150]. With the full Run 2 dataset, inclusive and first differential cross-section measurements of single channels become possible, such as the first observation of $t\bar{t}H$ ($\rightarrow b\bar{b}$) with ATLAS [151].

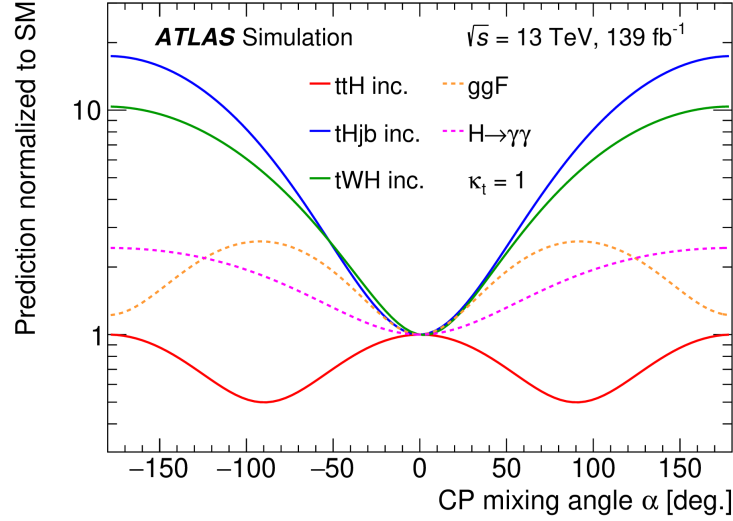


Figure 7.3: Inclusive cross-section of $t\bar{t}H$ and $tHj\bar{b}$ as a function of the CP mixing angle α [148]

The analysis described in the following studies the $t\bar{t}H$ process in a ML final state, considering different hadronically decaying tau multiplicities and numbers of light leptons.

7.2 Strategy

The $t\bar{t}H$ ML analysis provides an inclusive signal strength measurement of $t\bar{t}H$ production at $\sqrt{s} = 13 \text{ TeV}$. Additionally, a differential signal strength measurement inside the STXS framework is performed. As the required Higgs transverse momentum reconstruction is challenging in a final state with several leptons, including neutrinos, the differential measurement is done with a lower granularity than is suggested in the STXS formalism by merging some of the STXS $t\bar{t}H$ signal strengths. Finally a CP interpretation of the measurement is provided, where the parametrisation of the event yields is done as a function of the CP mixing angle α . This interpretation will, however, not be covered in this thesis.

The analysis considers six different channels shown in Figure 7.4. Two channels require zero hadronically decaying taus (τ_{had}) and two same-sign light leptons ($2\ell_{\text{SS}} + 0\tau_{\text{had}}$) or three light leptons ($3\ell + 0\tau_{\text{had}}$) in the final state, one channel requires one τ_{had} and two same-sign light leptons ($2\ell_{\text{SS}} + 1\tau_{\text{had}}$), two channels require two τ_{had} with one light lepton ($1\ell + 2\tau_{\text{had}}$) or two light leptons ($2\ell + 2\tau_{\text{had}}$) and finally one channel applies no requirement on the number of τ_{had} but asks for four light leptons in the final state (4ℓ). As these six channels are orthogonal by construction they can be combined into one global fit.

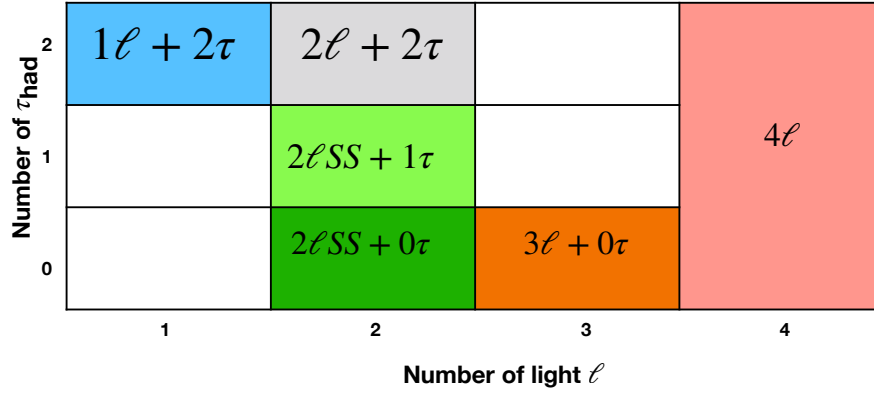


Figure 7.4: Channels considered in the $t\bar{t}H$ ML analysis in terms of the number of hadronically decaying τ and light leptons [152]

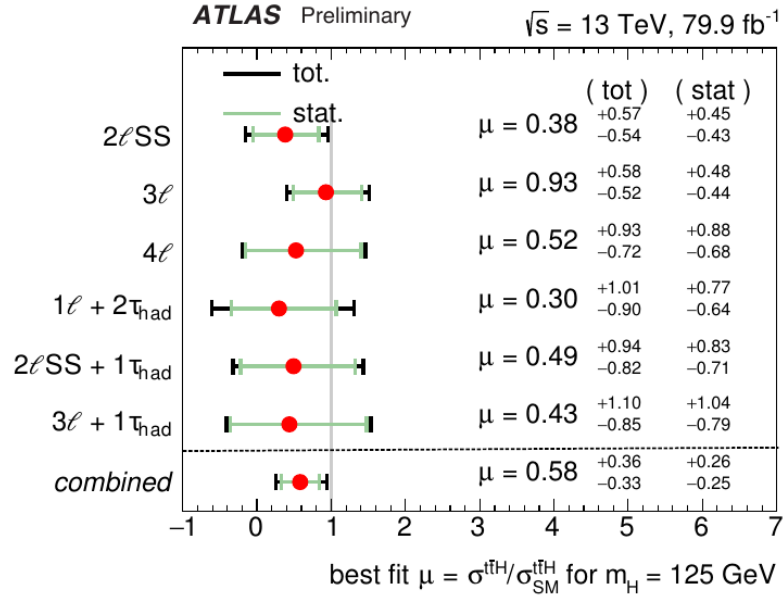
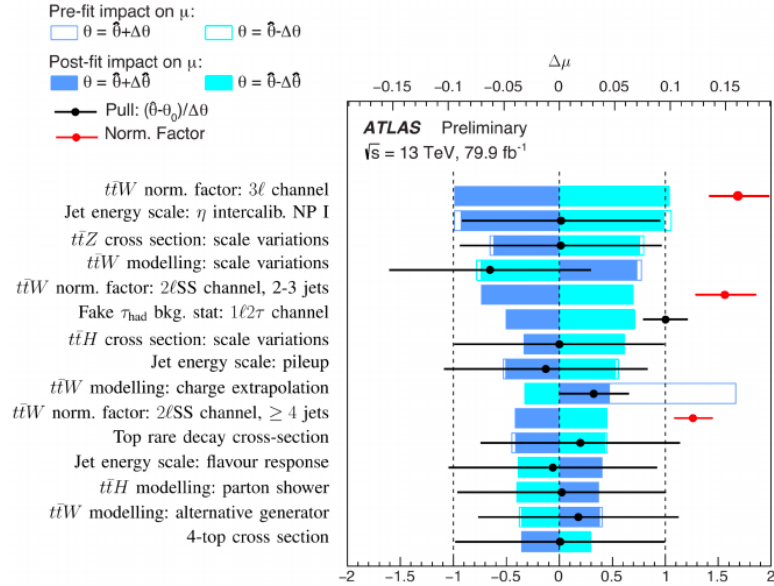
7.3 Previous $t\bar{t}H$ and $t\bar{t}W$ efforts in multi-lepton final states

7.3.1 Partial Run 2 $t\bar{t}H$ measurement

A first Run 2 $t\bar{t}H$ ML measurement as been performed by ATLAS [51], using 36.1 fb^{-1} of data, measuring a signal strength of $\mu_{t\bar{t}H} = 1.6^{+0.5}_{-0.4}$ with respect to the SM cross-section with a significance of 4.1σ . While the nominal fit uses the $t\bar{t}W$ and $t\bar{t}Z$ normalisation from the SM expectation with attached systematic uncertainties, an alternative fit setup has free floating $t\bar{t}W$ and $t\bar{t}Z$ normalisation factors, fitting a normalisation of 0.92 ± 0.32 and $1.17^{+0.25}_{-0.22}$ respectively and a signal strength of $\mu_{t\bar{t}H} = 1.6^{+0.6}_{-0.5}$, fully compatible with the nominal fit result.

A following ATLAS $t\bar{t}H$ ML analysis [153] with partial Run 2 data (80 fb^{-1}), having an improved treatment of $t\bar{t}W$ and of non-prompt light leptons, has measured the $t\bar{t}H$ signal strength to be relatively low, with $\mu_{t\bar{t}H} = 0.58^{+0.36}_{-0.33}$ with respect to the SM cross-section expectation. This corresponds to measuring $t\bar{t}H$ with a significance of 1.8σ . The results for the different considered channels as well as for the combined fit are shown in Figure 7.5.

The ranking of the impact of the systematics on the signal strength is shown in Figure 7.6. Several systematic uncertainties related to $t\bar{t}W$ are highly ranked, such as $t\bar{t}W$ NFs and $t\bar{t}W$ modelling uncertainties. The NF for $t\bar{t}W$ was measured to be $1.39^{+0.17}_{-0.16}$ compared to the SHERPA cross-section of 600.8 fb .

Figure 7.5: Results on the $t\bar{t}H$ signal strength in the ATLAS partial Run 2 $t\bar{t}H$ ML analysis [153]Figure 7.6: Ranking of the impact of the systematics on the $t\bar{t}H$ signal strength in the ATLAS partial Run 2 $t\bar{t}H$ ML analysis [153]

7.3.2 Inclusive and differential $t\bar{t}W$ measurement

A dedicated analysis targeting $t\bar{t}W$ [52] was performed by [ATLAS](#), including thorough studies of the fake backgrounds. The full Run 2 $t\bar{t}H$ analysis presented in this chapter is making use of the background treatment developed for the $t\bar{t}W$ analysis.

The inclusive measurement confirms the observed excess compared to the SHERPA cross-section, measuring a cross-section of $\sigma(t\bar{t}W) = 880 \pm 50(\text{stat.}) \pm 70(\text{syst.}) = 880 \pm 80 \text{ fb}$. The result is shown in Figure 7.7 with comparisons to several cross-section calculations. More recent cross-section calculations, such as the NNLO cross-section of $745 \pm 50(\text{scale}) \pm 13(2\text{-loop approx.}) \pm 19(\text{PDF}, \alpha_S) \text{ fb}$ [124], reduce the tension to the observed $t\bar{t}W$ NF, the $t\bar{t}W$ measurement having a 1.4σ compatibility with the SM NNLO cross-section.

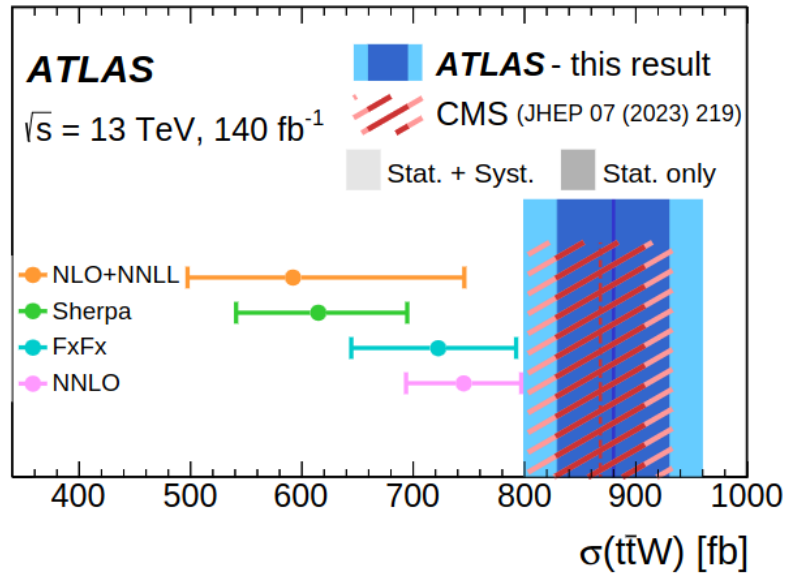


Figure 7.7: Inclusive $t\bar{t}W$ cross-section measured by [ATLAS](#) and [CMS](#) compared to different cross-section calculations [52]

The differential measurement, performed in six different variables, shows the same normalisation offset as in the inclusive measurement. Once removing this normalisation effect, no significant deviation from the SM expectations are observed. It is, however, to be noted that most measurements are heavily statistics limited.

As described previously, $t\bar{t}W$ is an important background for the $t\bar{t}H$ measurement. One way to separate both processes is by the jet multiplicity, $t\bar{t}H$ including more jets at tree level in a $2\ell\text{SS}$ or 3ℓ final state than $t\bar{t}W$. Having a well understood modelling of $t\bar{t}W$ +jets is therefore crucial to guarantee a good modelling of $t\bar{t}W$ in the $t\bar{t}H$ SRs. The differential measurement in the number of jets can be seen in Figure 7.8. The agreement between the expected and measured jet multiplicity distributions unfolded to particle level is shown as is on the left and removing

normalisation effects on the right. It can be seen that the predicted shapes agree well with the measurement within the uncertainties.

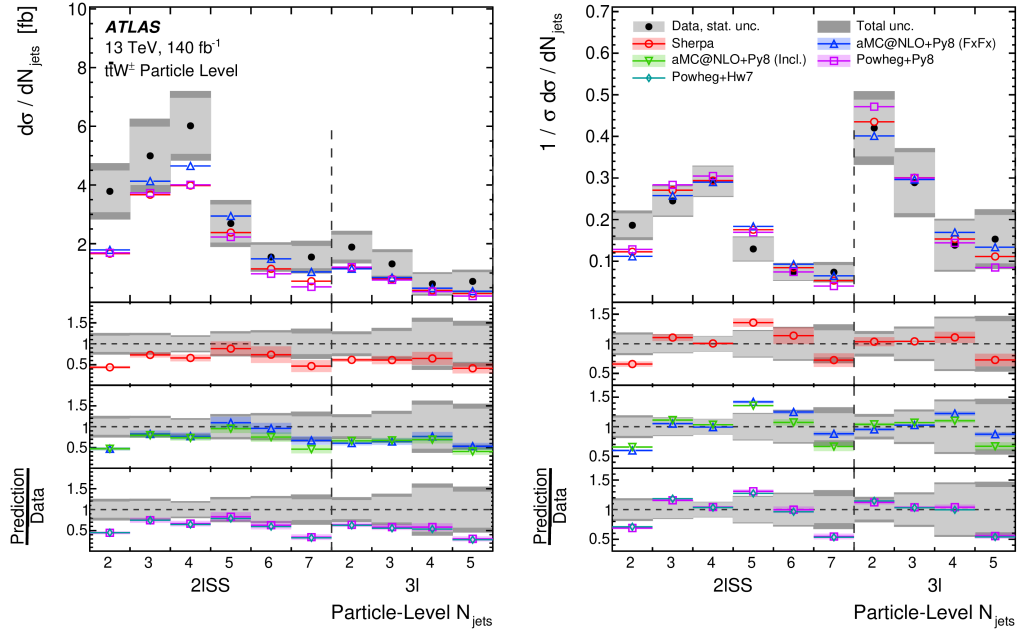


Figure 7.8: Differential $t\bar{t}W$ cross-section measured in jet multiplicity compared to predictions of different MC generators. The plot on the left corresponds to the actual measurement, while the plot on the right removes normalisation differences between data and MC. [52]

7.4 Data and simulated event samples

In this analysis, the full 140 fb^{-1} dataset of pp collisions collected in Run 2 is used. More details about this run period can be found in Section 3.3.2.

The MC samples used in this analysis are summarised in Table 7.1 and described in more detail in Section 4.8.

7.5 Object identification and reconstruction

The physics objects used in this analysis are reconstructed using the techniques described in Section 3.5. The selection of the objects, specific to this analysis, is described in the following. The selection criteria are in general similar to the high-mass $t\bar{t}\ell^+\ell^-$ measurement, but with slightly tighter requirements on leptons in order to get a higher rejection of fake backgrounds.

Table 7.1: MC configurations used for the signal and background MC samples. The configurations in grey and parentheses correspond to MC samples used to compute the modelling systematics described in Section 7.7 [152].

Process	Generator	ME order	Parton shower PDF		Tune
$t\bar{t}H$	POWHEG-BOX	NLO	PYTHIA 8	NNPDF3.0NLO	A14
	(POWHEG-BOX)	(NLO)	(HERWIG7.0.4)	(NNPDF3.0NLO)	(H7-UE-MMHT)
	(MG5_aMC)	(NLO)	(PYTHIA 8)	(NNPDF3.0NLO)	(A14)
tHq, tWH	MG5_aMC	NLO	PYTHIA 8.2	NNPDF3.0NLO	A14
$t\bar{t}W$	SHERPA 2.2.10	MEPs@NLO	SHERPA	NNPDF3.0NNLO	SHERPA default
	(MG5_aMC)	(FxFx NLO)	(PYTHIA 8)	(NNPDF3.0NLO)	(A14)
	(POWHEG)	(NLO)	(PYTHIA 8)	(NNPDF3.0NLO)	(A14)
	(POWHEG)	(NLO)	(HERWIG 7)	(NNPDF3.0NLO)	(H7-UE-MMHT)
$t\bar{t}W$ (EW)	SHERPA 2.2.10	LO	SHERPA	NNPDF3.0NNLO	SHERPA default
	(MG5_aMC)	(LO)	(PYTHIA 8)	(NNPDF3.0NLO)	(A14)
$t\bar{t}\ell^+\ell^-$	MG5_aMC	NLO	PYTHIA 8	NNPDF3.0NLO	A14
	(MG5_aMC)	(NLO)	(HERWIG 7)	(NNPDF3.0NLO)	(H7-UE-MMHT)
	(MG5_aMC)	(NLO)	(PYTHIA 8)	(NNPDF3.0NLO)	(A14 VAR3C)
$t\bar{t} \rightarrow W^+bW^-\bar{b}\ell^+\ell^-$	MG5_aMC	LO	PYTHIA 8	NNPDF3.0LO	A14
$t\bar{t}t\bar{t}$	MG5_aMC	NLO	PYTHIA 8	NNPDF3.1NLO	A14
	(MG5_aMC)	(NLO)	(HERWIG 7)	(NNPDF3.0NLO)	(H7-UE-MMHT)
	(SHERPA 2.2.11)	(MEPs@NLO)	(SHERPA)	(NNPDF3.0NNLO)	(SHERPA default)
$t\bar{t}$	POWHEG-BOX	NLO	PYTHIA 8	NNPDF3.0NLO	A14
	(POWHEG-BOX)	NLO	(HERWIG7.1.3)	(NNPDF3.0NLO)	(H7-UE-MMHT)
$t\bar{t}t$	MG5_aMC	LO	PYTHIA 8	NNPDF2.3LO	A14
Single top (t -, Wt -, s -channel)	POWHEG-BOX	NLO	PYTHIA 8	NNPDF3.0NLO	A14
$VV, qqVV, VVV$	SHERPA 2.2.2(1)	MEPs@NLO	SHERPA	NNPDF3.0NNLO	SHERPA default
$Z \rightarrow \ell^+\ell^-$	SHERPA 2.2.1	MEPs@NLO	SHERPA	NNPDF3.0NNLO	SHERPA default
$Z \rightarrow \ell^+\ell^-(\gamma \rightarrow e^+e^-)$	POWHEG-BOX	NLO	PYTHIA 8	CTEQ6L1NLO	A14
$Z \rightarrow \ell^+\ell^-(\gamma^* \rightarrow e^+e^-)$	POWHEG-BOX	NLO	PYTHIA 8	CTEQ6L1NLO	A14
$t\bar{t}WW$	MG5_aMC	LO	PYTHIA 8.186	NNPDF2.3LO1	A14
VH	POWHEG-BOX	NLO	PYTHIA 8.230	NNPDF3.0NLO	AZNLO

7.5.1 Trigger strategy

The trigger selection of the events used in this analysis is based on a combination of single lepton and di-lepton triggers. For most analysis channels, an event is selected if it passes the single electron or muon trigger, the di-lepton trigger or both. For the $1\ell+2\tau_{\text{had}}$ channel, only the single lepton trigger is used.

Two different categories of leptons are defined: loose leptons, which are used for overlap removal, the split of the events into the different channels and in some of the analysis regions, and tight leptons, with tighter cuts than the loose leptons, which are used for the majority of the analysis regions. The lepton selection cuts are summarised in Table 7.2.

Loose muons, also denoted as L [WP](#), have similar kinematic requirements as electrons ($p_T > 10\text{GeV}$ and $|\eta| < 2.5$), a slightly tighter transverse (d_0) impact parameter selection ($|d_0/\sigma(d_0)| < 3.0$) and the same longitudinal (z_0) impact parameter selection ($|z_0 \cdot \sin(\theta)| < 0.5\text{ mm}$). Finally, loose muons have to pass the Loose identification and LooseVar_Rad isolation [WPs](#). For tight muons, the additional requirement of the Medium identification [WP](#) is added. Similar to electrons, tight muons are split into M, M_{ex} and T [WPs](#) depending on the [PLIV WP](#) (Tight, Tight-not-VeryTight and VeryTight).

Table 7.2: Loose (L or L'), Medium (M), Medium exclusive (M_{ex}), and Tight (T) light lepton definitions. [152]

	e					μ			
	L	L'	M	M _{ex}	T	L	M	M _{ex}	T
LooseVar_Rad isolation	Yes					Yes			
Non-prompt lepton BDT (PLIV)	No		<i>Tight</i>	<i>Tight-not-VeryTight</i>	<i>VeryTight</i>	No	<i>Tight</i>	<i>Tight-not-VeryTight</i>	<i>VeryTight</i>
Identification	Loose		Tight			Loose		Medium	
Charge mis-assignment veto (ECIDS)	No		Yes			N/A			
Conversion rejection	No		Yes			N/A			
Transverse impact parameter significance $ d_0 /\sigma_{d_0}$	< 5					< 3			
Longitudinal impact parameter $ z_0 \sin \theta $	$< 0.5 \text{ mm}$								

7.5.3 Jets

Selected jets are required to pass the $p_T > 25 \text{ GeV}$ and $|\eta| < 2.5$ cuts. Some variables used in the analysis take into account forward jets with $|\eta|$ up to 4.5. Additionally, the tight WP cut on the jet vertex tagger and forward jet vertex tagger is applied on jets and forward jets respectively after overlap removal.

b-tagged jets have the same selection requirements as other jets, but need to pass pseudo-continuous b -tagging WPs with efficiencies of about 60 %, 70 %, 77 % and 85 %. The WPs used differ for different analysis channels.

7.5.4 Hadronically decaying taus

τ_{had} candidates are considered if they satisfy the requirement of $p_T > 20 \text{ GeV}$ and $|\eta| < 2.5$. Additionally a Medium identification WP cut is applied.

7.5.5 Overlap removal

In order to remove any potential double-counting of objects, an overlap removal is applied on loose leptons and jets. The following steps are performed in the following order, removing from the event:

- electrons which have a shared track or overlapping cluster ($\Delta R < 0.1$) to any other electron and a smaller p_T than this electron
- taus within $\Delta R < 0.2$ of an electron or muon
- muons overlapping within $\Delta R < 0.1$ with an electron, if the muons are reconstructed from a track and calorimeter deposits consistent with a minimum ionising particle. Otherwise the electron is removed.
- jets within $\Delta R < 0.2$ of an electron, if the jets are not b -tagged or have a $p_T > 200 \text{ GeV}$
- jets, to which a muon is ghost-matched within $\Delta R < 0.4$, if the jets are not b -tagged or have less than three tracks with $p_T > 500 \text{ GeV}$
- jets within $\Delta R < 0.2$ of a tau
- leptons overlapping with a jet in a cone with a radius of $R = 0.04 + \frac{10 \text{ GeV}}{p_{T,lep}}$ or of $R = 0.4$, whatever is smaller

7.6 Definition of the analysis channels

All six analysis channels measure $t\bar{t}H$ in ML final states, but target different Higgs decay modes. As shown in Figure 7.9 (top), the $0\tau_{\text{had}}$ and 4ℓ channels are dominated by $t\bar{t}H$ events where the Higgs decays into two W bosons. Events with subsequent leptonic W decays are selected. The τ_{had} channels mainly target events where the Higgs decays to two tau leptons. The $1\tau_{\text{had}}$ and $2\tau_{\text{had}}$ channels are complementary, targeting events where only one or both taus decay hadronically.

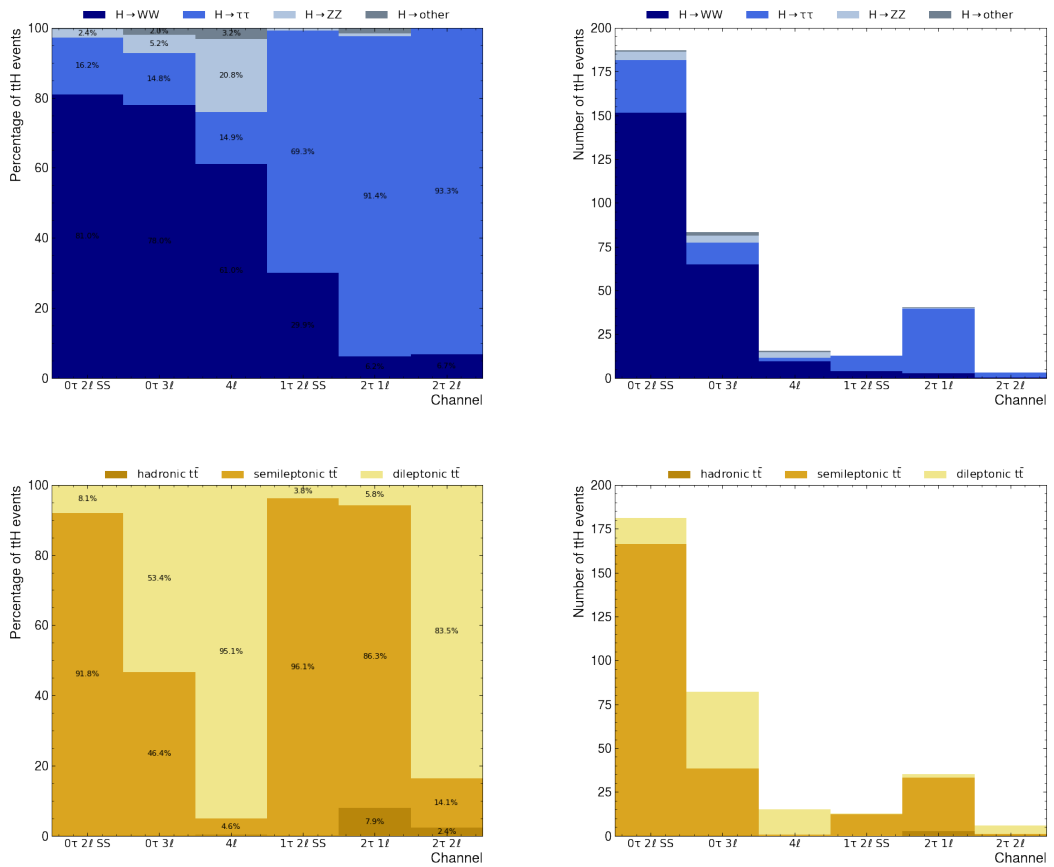


Figure 7.9: Contribution of the different $t\bar{t}H$ decay channels to the analysis channels: Higgs decay mode (top) and $t\bar{t}$ decay mode (bottom). On the left, the relative contributions and on the right the absolute contributions are shown.

Different lepton requirements allow to reject SM backgrounds. The $2\ell SS + 0\tau_{\text{had}}$ and $2\ell SS + 1\tau_{\text{had}}$ channels make use of the fact that most SM processes, such as the dominant $t\bar{t}$ process, have an opposite-sign final state. Requiring exactly two-same sign leptons therefore heavily reduces the contribution of backgrounds. The $3\ell + 0\tau_{\text{had}}$ and 4ℓ channels target final states with higher lepton multiplicities, which reduces the signal statistics but also significantly increases the purity. $1\ell + 2\tau_{\text{had}}$ and $2\ell + 2\tau_{\text{had}}$ channels cover the final states, where one or both top quarks in the

In the following, a short description of the different channels is given, describing the event selection and treatment of the backgrounds. An overview over all the analysis regions included in the different channels is shown in Figure 7.10.

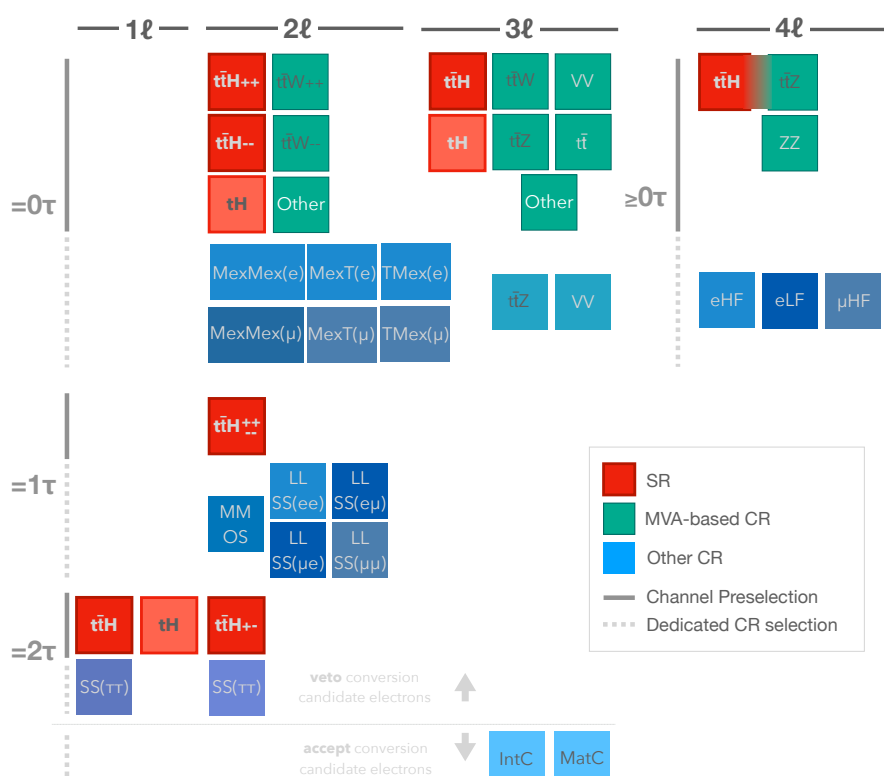


Figure 7.10: Summary of all the regions (SRs and CRs) included in the analysis. [152]

7.6.1 $0\tau_{\text{had}}$ channels

The analysis includes two channels which veto τ_{had} candidates at a medium WP and which require two light same-sign loose (L) leptons and three light loose (L) leptons respectively. Both channels are heavily based on the $t\bar{t}W$ analysis using similar lepton WPs, selection criteria and a similar fake treatment.

$2\ell\text{SS} + 0\tau_{\text{had}}$ channel

The $2\ell\text{SS} + 0\tau_{\text{had}}$ channel requires two same-sign light leptons with a tight WP and a p_T greater than 15 GeV. Additionally, at least three jets, from which at least one must be tagged as a b-jet at a 85% WP, are required. The selection criteria are summarised in Table 7.3.

Table 7.3: Selection criteria for the $2\ell\text{SS} + 0\tau_{\text{had}}$ channel SRs and BDT CRs

	$2\ell\text{SS}+0\tau_{\text{had}}$
τ_{had} candidates	0 M
Lepton candidates	2 T: $p_T > 15$ GeV
Lepton details	same-sign
Number of jets	≥ 3
Number of b-jets (at 85% WP)	≥ 1

In this channel, $t\bar{t}W$ and $t\bar{t}Z$ are the dominant backgrounds. $t\bar{t}W$ has a similar final state as $t\bar{t}H$, while $t\bar{t}Z$ enters when one of the leptons from the Z decay is not reconstructed. In order to suppress these processes, a four-dimensional multiclass BDT is trained with output nodes tagging events as $t\bar{t}H$, $tHjb$, $t\bar{t}W$ or Other. The BDT is then used to attribute events to four different analysis regions ($t\bar{t}H$ SR and $tHjb$, $t\bar{t}W$ and Other CRs) according to the highest output score. The $t\bar{t}H$ and $t\bar{t}W$ regions are then split further by charge, in order to benefit from the charge asymmetry of $t\bar{t}W$. Finally, in order to suppress the contribution from $t\bar{t}t\bar{t}$, events with more than six jets and more than three b-jets are vetoed in the SR. The SR and CRs are binned in their corresponding BDT output.

An overview over all these regions is shown in Figure 7.11.

$3\ell + 0\tau_{\text{had}}$ channel

In the $3\ell + 0\tau_{\text{had}}$ channel, three light leptons are required. The leptons, forming the same-sign pair, are required to pass the tight WP and to have a transverse momentum larger than 15 GeV. The opposite-sign lepton only needs to pass the loose (L) WP and a p_T cut of 10 GeV. In order to

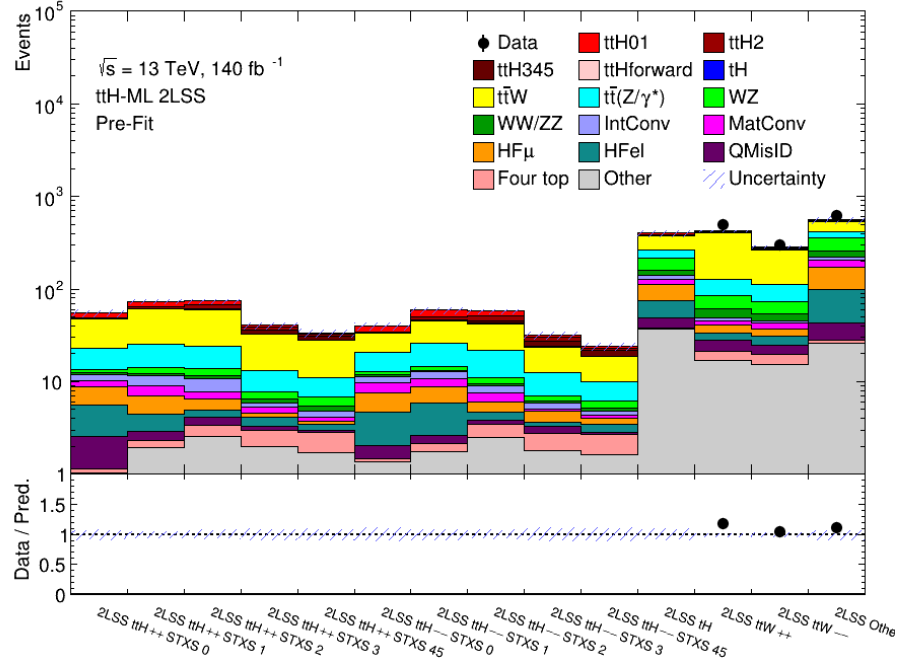


Figure 7.11: Event yields in all regions included in the $2\ell\text{SS} + 0\tau_{\text{had}}$ channel. Additionally to the SRs , the $tHjb$ CR is blinded. The uncertainty bands include statistical and systematic uncertainties.

suppress the $t\bar{t}Z$ background, opposite-sign lepton pairs are required to have an invariant mass outside a 10 GeV window around the Z peak. Additionally, an invariant mass cut of at least 12 GeV removes any potential low mass resonances which are not well modelled in MC . Finally, at least two jets and at least one b-tagged jet at a 85% WP are required and events with more than six jets and more than three b-jets are vetoed in the SR to suppress the $t\bar{t}t\bar{t}$ contribution. The selection cuts are summarised in Table 7.4.

Table 7.4: Selection criteria for the $3\ell + 0\tau_{\text{had}}$ channel SRs and BDT based CRs

	$3\ell + 0\tau_{\text{had}}$
τ_{had} candidates	0 M
Lepton candidates	3 (T,T,L): $p_T > 15, 15, 10$ GeV
Lepton details	opposite-sign to others: L $p_T > 10$ GeV same-sign pair: T $p_T > 15$ GeV OSSF pair: $ m(ll) - m_Z > 10$ GeV and $m(ll) > 12$ GeV
Number of jets	≥ 2
Number of b-jets (at 85% WP)	≥ 1

Similar to the $2\ell\text{SS} + 0\tau_{\text{had}}$ channel, the dominant backgrounds are $t\bar{t}W$ and $t\bar{t}Z$, both channels having very similar reconstructed final states as $t\bar{t}H$. For this channel, a multi-class BDT is trained, with six different output nodes, differentiating between $t\bar{t}H$, $tHjb$, $t\bar{t}W$, $t\bar{t}Z$, VV and $t\bar{t}$ events. The events are then attributed to the different regions ($t\bar{t}H$ SR and $tHjb$, $t\bar{t}W$, $t\bar{t}Z$,

VV , $t\bar{t}$ and Other CRs) based on the BDT outputs. A region optimisation is performed. First a cut on the $t\bar{t}H$ output is used to split the SR from all other CRs and the cut is chosen, such that the signal to background ratio in the SR is maximised. For the remaining events, a $tHjb$ cut is then defined in a similar way optimising the sensitivity of the $tHjb$ CR to the $tHjb$ process. This step is then repeated for the $t\bar{t}W$ CR, the $t\bar{t}Z$ CR, the VV CR and lastly for the $t\bar{t}$ CR. All remaining events are then attributed to the Other CR. The SR and CRs are binned in their corresponding BDT output.

An overview over the SRs and CRs is shown in Figure 7.12.

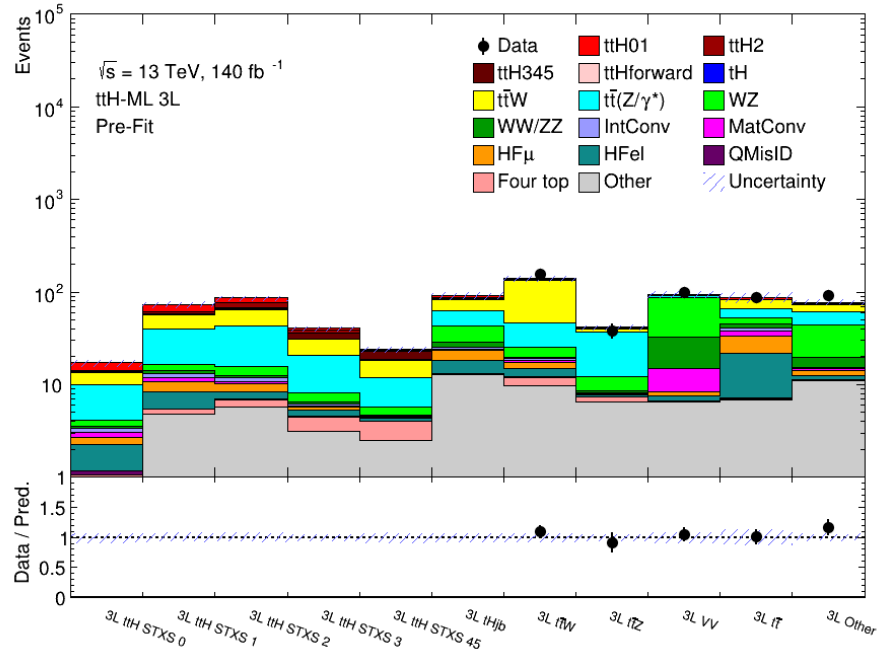


Figure 7.12: Event yields in all regions included in the $3\ell + 0\tau_{\text{had}}$ channel. Additionally to the SRs, the $tHjb$ CR is blinded. The uncertainty bands include statistical and systematic uncertainties.

Common prompt background estimation

The $0\tau_{\text{had}}$ channels additionally share two cut based prompt background CRs: a VV CR and a $t\bar{t}Z$ CR. A jet multiplicity dependent diboson reweighting is performed, in order to fix some mismodelling issues. Both CRs require three light leptons passing the medium WP and a p_T cut of 15 GeV for the opposite-sign lepton pair and the loose (L for electrons and L' for muons) WP and a p_T cut of 10 GeV for the same-sign lepton. The invariant mass of the OSSF lepton pair has to lie inside of the Z peak and the three lepton invariant mass outside of the Z peak. Finally, at least one b-tagged jet is required with a 85 % WP. The VV and $t\bar{t}Z$ CRs are separated by asking for two or three jets in the VV CR and at least four jets in the $t\bar{t}Z$ CR.

Common non-prompt background estimation

The $0\tau_{\text{had}}$ channels have a common fake/non-prompt background estimation, using the template fit method. The dominant process, from which originate the fake/non-prompt leptons, is the $t\bar{t}$ process, which, together with the fake lepton, has a similar final state as $t\bar{t}H$. It is followed by V +jets which has, however, much smaller contributions. Fake/non-prompt leptons are classified as HF fakes if they originate from bottom or charm decays, as conversion leptons if they originate from a photon conversion (internal or material) and as leptons with misidentified charge if the wrong charge is assigned to them. The normalisation of HF electrons and muons and of internal and material conversion leptons are constrained in the template fit.

Six $2\ell SS$ CRs, enriched in contributions from HF fakes in $t\bar{t}$ events, are used to constrain the HF electron and muon fake normalisation in data. The CRs require two same-sign leptons with a p_T of at least 15 GeV and at least two jets with one of them being b-tagged at a WP of 85%. The regions are split depending on the WP passed by the leptons: the leading lepton passing the tight WP and the subleading passing the medium exclusive WP, the leading lepton passing the medium exclusive WP and the subleading passing the tight WP, both leptons passing the medium exclusive WP. Lastly the CRs are split by the flavour of the subleading lepton.

Finally, two conversion fake CRs (internal and material) are defined. The CRs target the $Z(\rightarrow \mu\mu)\gamma$ process, including an electron originating from the photon conversion. Two opposite-sign muons and one electron are required, passing the medium WP and a p_T cut of 15 GeV for the opposite-sign muons and the loose (L) WP and a p_T cut of 10 GeV for the electron. In order to select $Z\gamma$ events, the invariant mass of the muon pair has to lie outside of the Z peak and the three lepton invariant mass inside of the Z peak. Finally, events including b-tagged jets at a WP of 85% are vetoed. The CRs are then split into an internal and a material conversions CR depending on the conversion type of the electron using the cuts described in Section 3.5.1.

An overview over all the regions common to the $0\tau_{\text{had}}$ channels is shown in Figure 7.13.

7.6.2 $2\ell SS + 1\tau_{\text{had}}$ channel

The $2\ell SS + 1\tau_{\text{had}}$ channel requires one hadronically decaying τ with medium WP and p_T greater than 20 GeV and two same-sign light leptons with a medium WP and p_T greater than 15 GeV. The invariant mass of the same-sign leptons must lie outside of the Z peak if they have the same flavour. Additionally, at least four jets, from which at least one must be tagged as a b-jet at a 85% WP, are required. The selection criteria are summarised in Table 7.5.

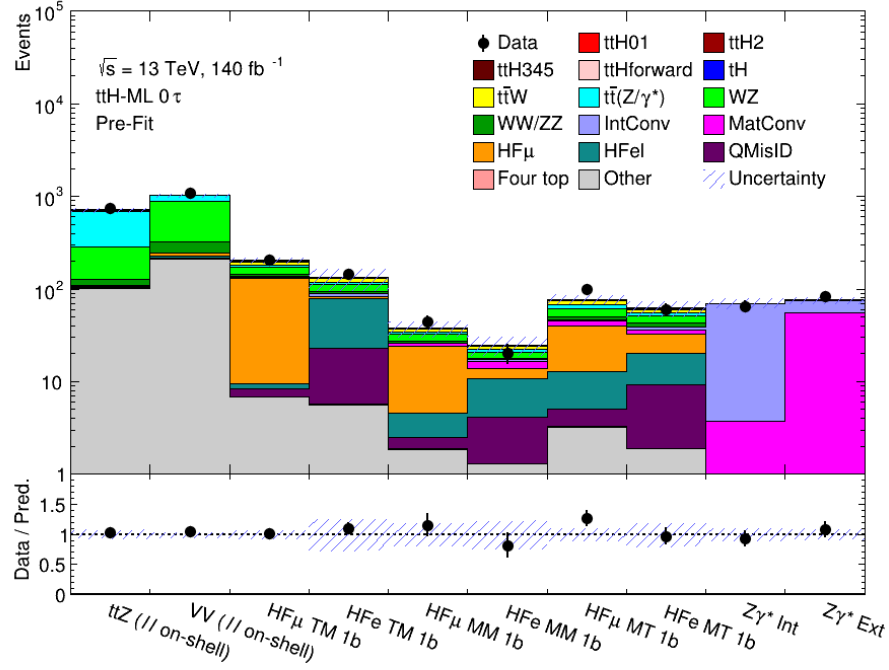


Figure 7.13: Event yields in all regions common to the $2\ell\text{SS} + 0\tau_{\text{had}}$ and $3\ell + 0\tau_{\text{had}}$ channels. The uncertainty bands include statistical and systematic uncertainties.

Table 7.5: Selection criteria for the $2\ell\text{SS} + 1\tau_{\text{had}}$ channel [SR](#)

	$2\ell\text{SS} + 1\tau_{\text{had}}$
τ_{had} candidates	1 M: $p_T > 20$ GeV
Lepton candidates	2 M: $p_T > 15$ GeV
Lepton details	same-sign same-flavour pair: $ m(\ell\ell) - m_Z > 10$ GeV
Number of jets	≥ 4
Number of b-jets	≥ 1 (at 85% WP)

The dominant backgrounds are $t\bar{t}W$, with a similar final state as $t\bar{t}H$, and fake/non-prompt leptons originating from $t\bar{t}$, satisfying the $2\ell\text{SS}$ requirement. A [BDT](#) is trained to discriminate between signal and background (including only $t\bar{t}W$ and $t\bar{t}$ as backgrounds). The [SR](#) is then binned in the [BDT](#) output.

Non-prompt background estimation

The $2\ell\text{SS} + 1\tau_{\text{had}}$ channel uses an extended template fit method to constrain the normalisation of the dominant fake/non-prompt backgrounds. The fake templates are classified according to the flavour and the number of fake leptons. Electron and muon fakes are dominated by leptons originating from B-hadron decays, while tau fakes mostly correspond to mis-reconstructed quark

or gluon jets. The normalisation of fake electrons, muons and taus are constrained in the fit. Events with several fake/non-prompt leptons are scaled by the product of the relevant NFs .

The CR s targeting fake electrons and muons are split from the SR by requiring only two or three jets. Additionally, the statistics are enhanced by loosening the requirement on the leptons to the loose (L') WP . The CR s are then split by flavour into four different CR s ($\mu\mu$, ee , $e\mu$, μe) and are binned in the subleading lepton p_T .

The CR targeting fake taus is split from the SR by requiring only two or three jets and by requiring opposite-sign instead of same-sign leptons. The CR is binned in the ratio between the τ width and the τ p_T .

All regions included in the $2\ell SS+1\tau_{had}$ channel are summarised in Figure 7.14.

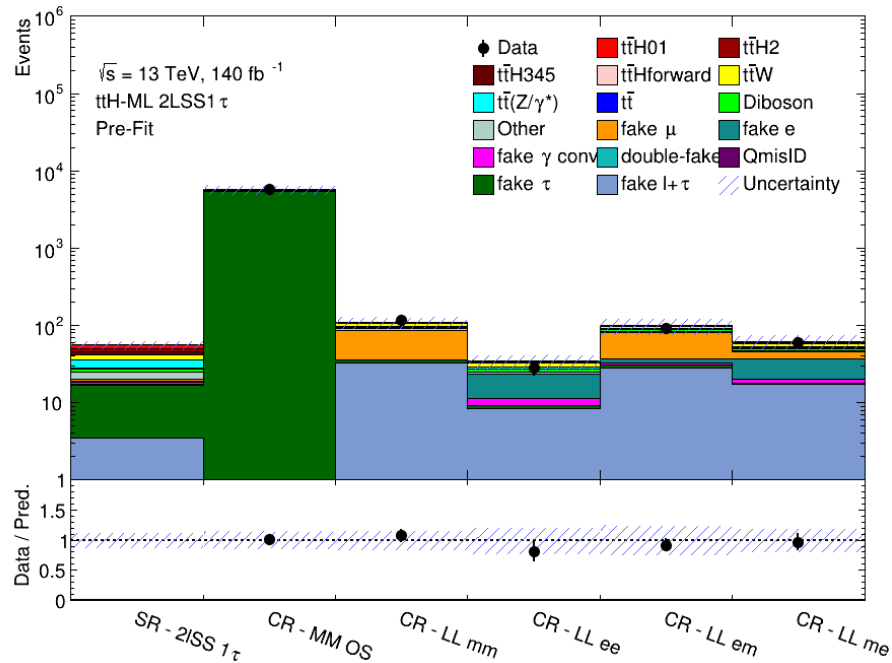


Figure 7.14: Event yields in all regions included in the $2\ell SS+1\tau_{had}$ channel. The uncertainty bands include statistical and systematic uncertainties.

7.6.3 $2\tau_{had}$ channels

The $2\tau_{had}$ channels require two opposite-sign hadronically decaying taus, both passing the medium WP and having a p_T greater than 20 GeV.

Additionally, the $1\ell+2\tau_{had}$ requires one loose (L) light lepton with p_T greater than 27 GeV and at least three jets, where at least one of the jets must be b-tagged at a WP of 77 %. The SR is split from the $tHj\bar{b}$ CR according to the number of jets, requiring less than three jets in the CR .

The $2\ell+2\tau_{\text{had}}$ channel requires two opposite-sign loose (L) light leptons with p_T greater than 20 GeV, a di-lepton invariant mass above 12 GeV and outside the Z peak, and at least one b-tagged jet at a WP of 77 %. The selection criteria are summarised in Table 7.6.

Table 7.6: Selection criteria for the $1\ell+2\tau_{\text{had}}$ and $2\ell+2\tau_{\text{had}}$ channel SRs

	$1\ell+2\tau_{\text{had}}$	$2\ell\text{OS}+2\tau_{\text{had}}$
τ_{had} candidates	2 opposite-sign M $p_T > 20$ GeV	2 opposite-sign M $p_T > 20$ GeV
Lepton candidates	1 L $p_T > 27$ GeV	2 opposite-sign L $p_T > 10$ GeV
Lepton details		$ m(ll) - m_Z > 10$ GeV and $m(ll) > 12$ GeV
Number of jets	≥ 3	–
Number of b-jets	≥ 1 (at 77% WP)	> 0 (at 77% WP)

The SRs and $tHjb$ CR are binned in a binary BDT, trained separately for the regions, rejecting the fake tau background.

Non-prompt background estimation

The fake τ_{had} process is by far the dominant background and a fake factor method is used to estimate its contribution.

The fake factors are computed in a $Z(\rightarrow ll)+\text{jets}$ regions, where the real τ contribution is subtracted from data using the MC estimate. The fake factor is then defined as the ratio between the number of events with a τ_{had} passing the medium WP and the number of events with a τ_{had} passing the very loose but not the medium WP. The fake τ_{had} contribution in the analysis regions is then estimated by applying the fake factors on events in a region with the same selection as the analysis regions, but where at least one of the τ_{had} only passes the loose WP.

A summary of the regions included in the $2\tau_{\text{had}}$ channel are summarised in Figure 7.15.

7.6.4 4ℓ channel

The 4ℓ channel is inclusive in τ_{had} . It requires four loose (L) leptons with p_T greater than 10 GeV and a sum of charge of zero. All opposite-sign pairs are required to have an invariant mass above 12 GeV and the four lepton invariant mass must be outside of a Higgs mass window of 115 GeV to 130 GeV, in order to exclude the part of the phase-space covered by the ATLAS $H \rightarrow 4\ell$ analysis [155]. Additionally, the events are required to contain at least two jets of which at least one must be b-tagged at a WP of 85 %. The selection criteria are summarised in Table 7.7.

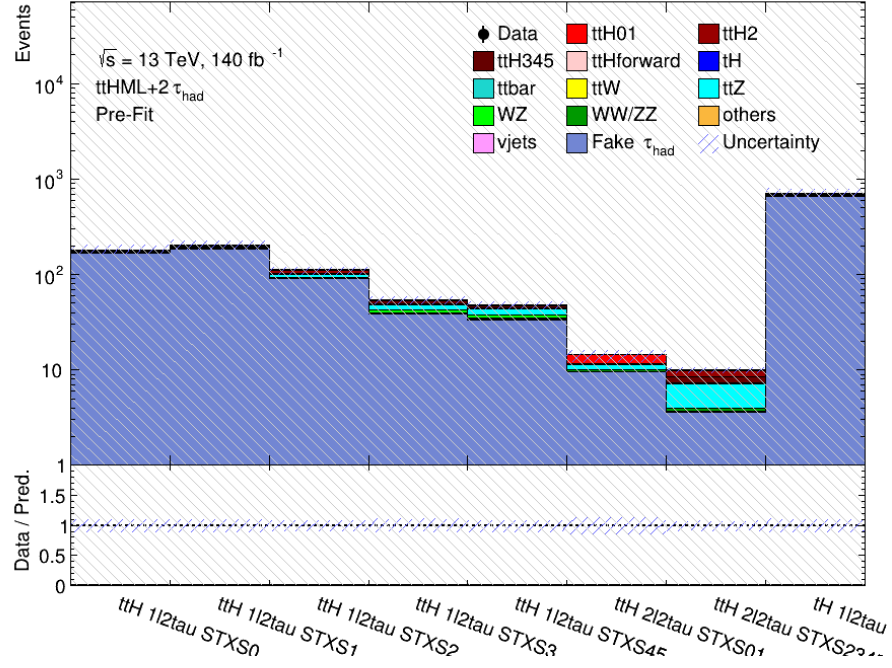


Figure 7.15: Event yields in all regions included in the $2\tau_{\text{had}}$ channels. Additionally to the highest bins in the SRs, the highest bin of the $tHj\bar{b}$ CR is blinded. The uncertainty bands include statistical and systematic uncertainties.

Table 7.7: Selection criteria for the 4ℓ channel SR and prompt background CR

	4ℓ
τ_{had} candidates	–
Lepton candidates	4 L: $p_T > 10$ GeV
Lepton details	Sum charge = 0 OS pairs: $m(ll) > 12$ GeV $m(llll) \notin [115 \text{ GeV}, 130 \text{ GeV}]$
Number of jets	≥ 2
Number of b-jets (at 85% WP)	≥ 1

The dominant backgrounds of the 4ℓ channel are $t\bar{t}Z$ and ZZ , both being channels which can include four prompt leptons. A three dimensional multiclass DNN is trained to separate $t\bar{t}H$, $t\bar{t}Z$ and ZZ . The ZZ output is used to separate between the SR and the ZZ CR. The SR is then binned in the $t\bar{t}H$ output score and the ZZ CR in the b-jet multiplicity.

Non-prompt background estimation

In order to estimate the normalisation of the dominant fake backgrounds, the template fit method is used. Three CRs are defined, constraining HF electrons and muons and LF electrons.

The CRs targeting the HF fakes require three loose (L) light leptons with p_T greater than 10 GeV, a sum of charge of plus or minus one and no OSSF lepton pairs. The events must contain

at least one jet with at least one being b-tagged at a **WP** of 85 %. Additionally, events included in the $3\ell + 0\tau_{\text{had}}$ channel are vetoed. The **CRs** are binned in the p_T of the subleading same-sign lepton p_T .

The **CR** targeting the **LF** electrons requires three loose (L) light leptons with p_T greater than 10 GeV, a sum of charge of plus or minus one and one **OSSF** lepton pair with an invariant mass inside the Z peak. The invariant mass of the three leptons has to lie outside of a 15 GeV window around the Z mass. The events must contain at least one jet but no b-tagged jet at a **WP** of 85 %. Additionally, events included in the $3\ell + 0\tau_{\text{had}}$ channel are vetoed, in order to be fully orthogonal to all other channels. Finally, the missing transverse energy must be below 20 GeV. The **CR** is binned in E_T^{miss} .

The **SR** and **CRs** of the 4ℓ channel are summarised in Figure 7.16.

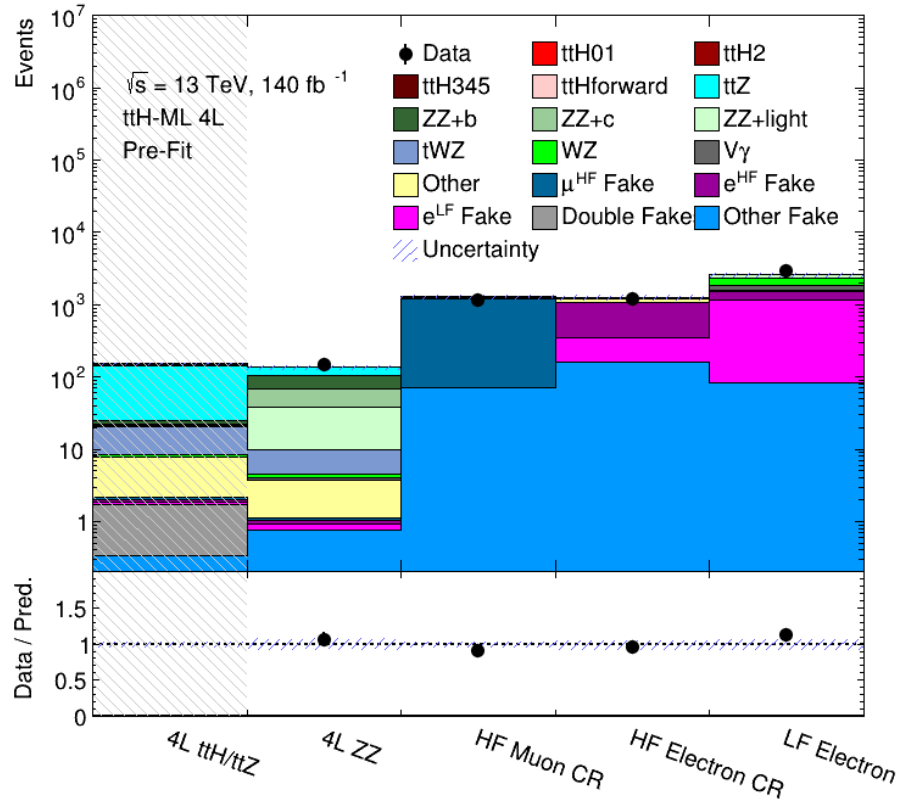


Figure 7.16: Event yields in all regions included in the 4ℓ channel. The uncertainty bands include statistical and systematic uncertainties.

7.7 Systematic uncertainties

7.7.1 Detector uncertainties

All of the relevant detector systematics, described in Section 3.5, are considered in the fit.

For all events, an uncertainty on the integrated luminosity, on the trigger efficiency and on the pile-up modelling is applied. On leptons, systematic uncertainties on the reconstruction efficiency, the identification and the isolation scale factors are applied, as well as on the momentum scale and resolution. Additionally, for muons, uncertainties on the track-to-vertex association are considered. For jets, uncertainties on the jet energy scale and resolution, jet-vertex-tagging and flavour tagging are applied. Tau uncertainties are covered by systematics on the reconstruction and identification efficiency, as well as on the energy scale. Finally, uncertainties on the missing transverse energy are considered such as the scale and the resolution of the soft track component.

7.7.2 Modelling uncertainties

The modelling uncertainties considered for the dominant MC templates are described in Section 4.8.

On the $t\bar{t}H$ modelling, in addition to the uncertainties mentioned previously, STXS uncertainties are considered, which consider event migrations between the STXS bins in the reference cross-sections [156].

For several backgrounds, normalisation uncertainties are applied: $^{+70}_{-15}\%$ for $t\bar{t}t\bar{t}$, 5 % on tV , 30 % on triboson and VH , 35 % on $t\bar{t}\bar{t}$ and 50 % on $t\bar{t}WW$ and $V\gamma$.

7.7.3 Non-prompt/fake background uncertainties

On the fake/non-prompt leptons, extrapolation uncertainties are applied accounting for the extrapolation of the normalisation from the CRs to the SR.

Additionally, uncertainties on the data-driven fake τ_{had} estimation in the $2\tau_{\text{had}}$ channels are considered.

7.8 Reconstruction of the Higgs transverse momentum

As described in Section 3.7.4, the differential distribution in the STXS framework for the $t\bar{t}H$ channel corresponds to the transverse momentum of the Higgs (p_T^H). The reconstruction of p_T^H is, however, challenging in the multi-lepton final state because of the presence of neutrinos in the leptonic Higgs and $t\bar{t}$ decays. It was therefore decided to reconstruct the Higgs p_T only in the

$0\tau_{\text{had}}$ channels, which are the channels with the most statistics, and the $2\tau_{\text{had}}$ channels, where the hadronically decaying di-tau system can be used for the reconstruction of the variable.

7.8.1 $0\tau_{\text{had}}$ channels

For the $0\tau_{\text{had}}$ channels, initial studies were performed in order to understand the composition of the $2\ell\text{SS} + 0\tau_{\text{had}}$ and $3\ell + 0\tau_{\text{had}}$ channels and potential ways of reconstructing the transverse momentum of the Higgs.

Reconstruction efficiency studies

In the following, the kinematics of the events as well as the reconstruction efficiency of the objects are considered.

$2\ell\text{SS} + 0\tau_{\text{had}}$ Because of the same-sign requirement on the leptons and the hadronically decaying τ veto, only events with a Higgs decaying to WW , one W subsequently decaying leptonically and the other hadronically, can corresponds to $2\ell\text{SS} + 0\tau_{\text{had}}$ events at truth level. As shown in Figure 7.17 (left), only 75 % of the selected $2\ell\text{SS} + 0\tau_{\text{had}}$ events contain exactly two light leptons at truth level. 25 % of the events have three or more truth leptons, where at least one lepton did not pass the selection criteria. The high number of truth-leptons in the final state leads to an average number of 2.7 neutrinos per event (shown in Figure 7.17 (right)), producing significant missing transverse energy.

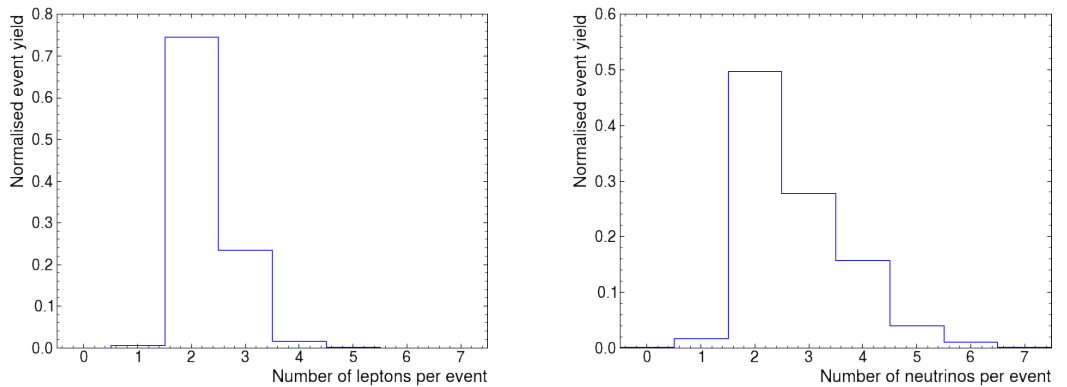


Figure 7.17: Number of leptons (left) and of neutrinos (right) per event in the $2\ell\text{SS} + 0\tau_{\text{had}}$ channel.

In order to understand in which part of the selection objects are lost, a simple truth-matching is performed separately for leptons and jets. A truth-object and an object at reconstruction level, called reco-object, are considered as truth-matched if $\Delta R < 0.3$. In the case where several

objects lie in the $R = 0.3$ cone, the object pair with the smallest ΔR is chosen. In the Higgs decay, 85 % of the truth-leptons and 43 % of the truth-jets have a truth matched reco-object. In the top/anti-top decays, 88 % of the truth-leptons and 69 % of the truth-jets have a truth matched reco-object. Additionally, in the top decay, 85 % of the truth-b-jets have a truth matched reco-jet. This shows that the reconstruction efficiency for leptons is very similar in the Higgs and in the top decays and inefficiencies mainly seem to be driven by leptons lying outside of the acceptance (p_T lying below 15 GeV or the pseudo-rapidity lying outside of the accepted range). For the jet reconstruction, the efficiency is much smaller in the Higgs than in the top decay. This is mainly caused by very low p_T jets in the Higgs decay, not passing the applied p_T cut.

$3\ell + 0\tau_{\text{had}}$ In the $3\ell + 0\tau_{\text{had}}$ channel, several Higgs decay modes can contribute to a three lepton $t\bar{t}H$ final state at truth level, such as $H \rightarrow WW$, $H \rightarrow ZZ$, $H \rightarrow \tau\tau$ and $H \rightarrow \mu\mu$. Compared to the $2\ell\text{SS} + 0\tau_{\text{had}}$ channel, most events are reconstructed with the correct number of light leptons, with 94 % of the events being truth 3ℓ events, only 5 % of the events having two or less truth leptons and only less than 1 % of the events having four or more truth leptons (see Figure 7.18 (left)). The $3\ell + 0\tau_{\text{had}}$ final state, as shown in Figure 7.18, includes in the majority of events three neutrinos.

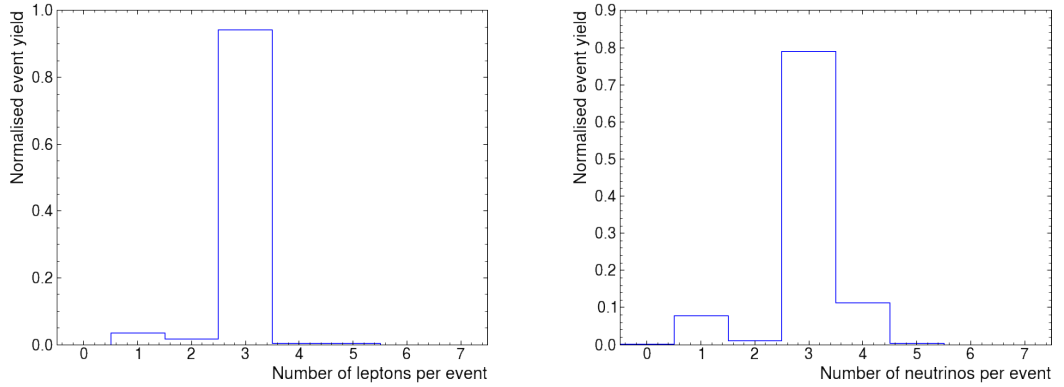


Figure 7.18: Number of leptons (left) and of neutrinos (right) per event in the $3\ell + 0\tau_{\text{had}}$ channel.

Looking at the truth-matching, the lepton reconstruction efficiency in the $3\ell + 0\tau_{\text{had}}$ channel is higher than in the $2\ell\text{SS} + 0\tau_{\text{had}}$ channel, with 92 % of the truth-leptons having a truth matched reco-lepton in the Higgs decay and 96 % in the top decay. In the jet reconstruction the behaviour is very similar to the $2\ell\text{SS} + 0\tau_{\text{had}}$ channel, as only 44 % of the truth-jets in the Higgs decay have a truth matched reco-jet, while 71 % of the truth-jets in the top decay have a truth matched reco-jet.

Higgs p_T reconstruction studies

As most events include at least two neutrinos coming from the Higgs as well as from the top decay, the $t\bar{t}H$ ML channel does not allow for an exact p_T^H reconstruction. Therefore, a first step was to look at variables which are highly correlated to the Higgs p_T . The low-level variable with the highest correlation is found to be the scalar sum of the two leading leptons, the two leading jets and the missing transverse energy with an overall correlation of 50 %. Other variables, such as the vector sum of the p_T of different objects, show smaller correlations. Additionally, it is observed that including the missing transverse energy into the variable is having a large impact on the correlation.

Another approach, is to try a partial reconstruction of either the Higgs or the $t\bar{t}$ system. At truth-level, combining the visible final state particles from the Higgs decay leads to a correlation of 75 % to the Higgs p_T , showing a potential increase of the correlation compared to low-level variables. However, the low reconstruction efficiency of jets in the Higgs decay makes a partial reconstruction of the Higgs difficult. In the $2\ell\text{SS} + 0\tau_{\text{had}}$ channel for example, in over 45 % of the events, none of the two jets from the Higgs decay are reconstructed, leaving only one lepton for the Higgs reconstruction. The other approach of trying to at least partially reconstruct the $t\bar{t}$ system already shows at truth-level a relatively low correlation to the Higgs p_T . Even a full reconstruction of both the top and the anti-top, including neutrinos which could not be used at reconstruction level, only has a correlation of 64 %, as the p_T of the $t\bar{t}$ system is not only correlated to the Higgs p_T but to the p_T^H in addition to the p_T of all additional jets.

Different neural network approaches were then tested, in order to try to combine the information from the Higgs and the $t\bar{t}$ system in the best possible way. Different approaches were considered: a regression DNN predicting the Higgs p_T , a classifier DNN, attributing each event to an STXS bin and a GNN, also classifying the events into the different STXS bins. The GNN showed the highest performance and is therefore retained for this analysis.

Higgs p_T reconstruction with a GNN

Separate GNNs are trained for the Higgs p_T reconstruction in the $2\ell\text{SS} + 0\tau_{\text{had}}$ and $3\ell + 0\tau_{\text{had}}$ channels. All events are represented with graphs. The nodes correspond to the kinematics of the final state particles, such as the p_T or η of leptons, jets and E_T^{miss} . The edges correspond to the kinematics of all object pairs, such as ΔR and p_T of all object pairs. Finally some global information are included, which describe global event variables, such as the jet multiplicity, the scalar sum of the p_T of all objects or the p_T or invariant mass of different combinations of objects.

The **GNN** classifies the events into the six different **STXS** bins. As expected from the previous studies, relatively large migrations between the **STXS** bins are observed. More details on the behaviour of the p_T^H reconstruction and of its impact on the fit are described in Sections 7.9 and 7.10.

7.8.2 $2\tau_{\text{had}}$ channels

The $2\tau_{\text{had}}$ channels predominantly target $t\bar{t}H$ events with $H \rightarrow \tau_{\text{had}} \tau_{\text{had}}$ decays. This allows the p_T^H reconstruction to be based on the di-tau visible p_T . A **BDT** is trained using the visible p_T , the angular distance, as well as the invariant mass of the two τ_{had} . Compared to the $0\tau_{\text{had}}$ channels, this yields a very accurate p_T^H reconstruction. More details on the behaviour of the p_T^H reconstruction and of its impact on the fit are described in Sections 7.9 and 7.10.

7.9 STXS fit setup studies

The analysis strategy was first developed in a Higgs p_T inclusive setup, where the **SRs** are split from the **CRs** with a signal to background discrimination **BDT** and are binned in the $t\bar{t}H$ output score of this same **BDT**. With this setup a good sensitivity to the inclusive $t\bar{t}H$ signal strength can be obtained. As these **SRs**, however, do not allow for any separation between the different **STXS** templates, this fit setup does not have any sensitivity to the **STXS** signal strengths. In order to perform the **STXS** measurement, the dedicated p_T^H reconstruction, described in Section 7.8, is therefore used in the $0\tau_{\text{had}}$ and $2\tau_{\text{had}}$ channels for the definition of the **SRs**. The 1τ and 4ℓ channels are included in the fit but do not have any p_T^H related binning. Studies on how to define the $0\tau_{\text{had}}$ and $2\tau_{\text{had}}$ **SRs** are described in Section 7.9.1.

As seen in Figure 7.19, showing the migration matrix between truth and reconstructed **STXS** bins in the **SRs**, the Higgs p_T reconstruction in the $0\tau_{\text{had}}$ channels is challenging and large **STXS** bin migrations are observed. This introduces correlations between the **STXS** signal strengths and the fit does not have enough separation power to constrain all six **STXS** signal strengths. Several of the **STXS** signal strengths are therefore merged. The decision on which **STXS** signal strengths to fit is based on studies described in Section 7.9.2.

Many of the studies presented below were performed with preliminary fit setups and without including systematic uncertainties. The conclusions taken from these studies are, however, not expected to change in the final fit setup.

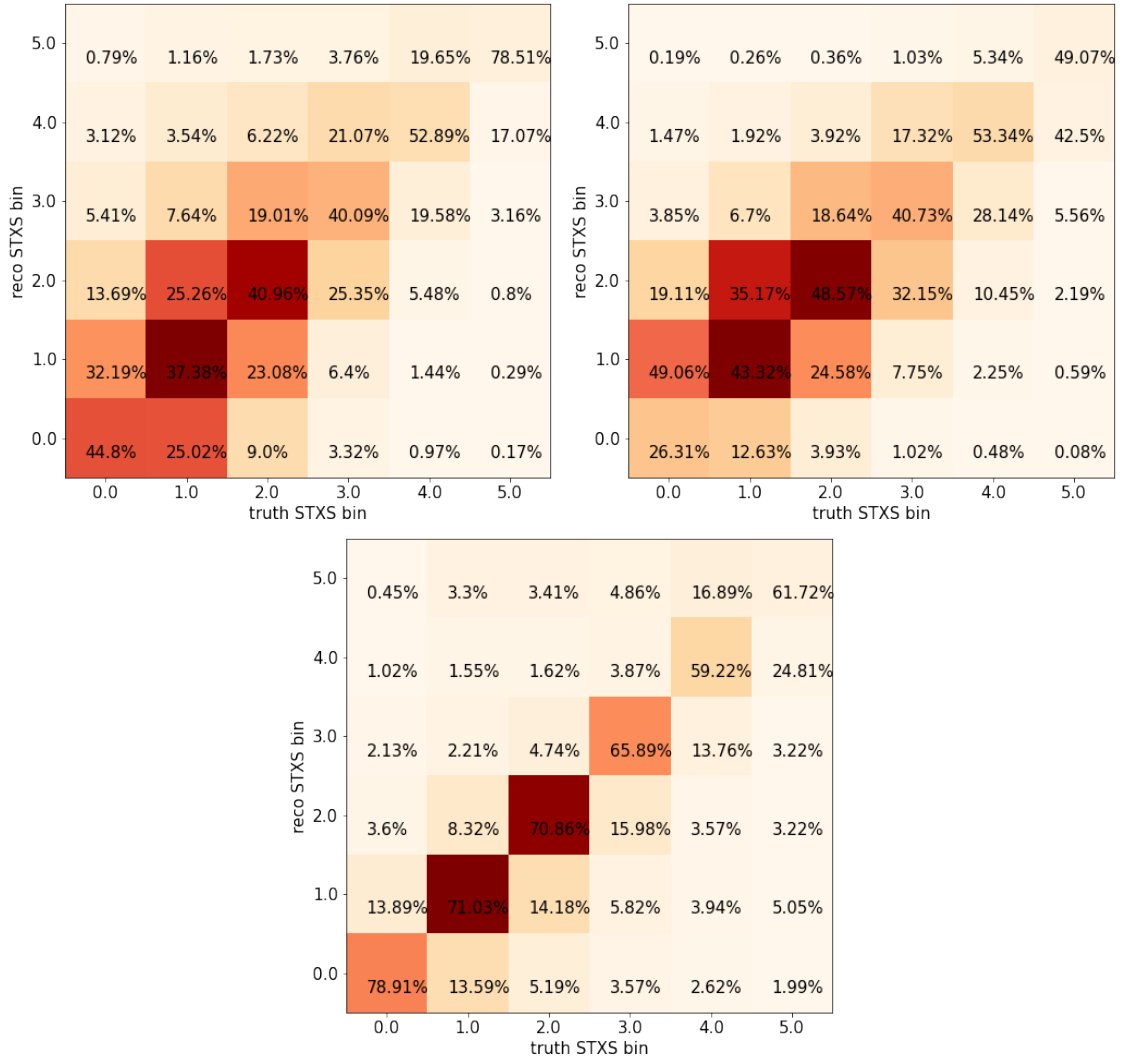


Figure 7.19: Migration matrices between truth and reconstructed **STXS** bins for the $2\ell\text{SS} + 0\tau_{\text{had}}$ channel (top left), the $3\ell + 0\tau_{\text{had}}$ channel (top right) and the $2\tau_{\text{had}}$ channels (bottom)

7.9.1 STXS signal region definition

Adding the p_T^H information to the fit was considered in two different ways:

- use the p_T^H inclusive **SRs** and bin them in reconstructed Higgs p_T . In the following these **SRs** will be referred to as inclusive-**STXS**-binned **SRs**.
- split the p_T^H inclusive **SRs** by reconstructed **STXS** bins and bin each **SR** in the signal to background classification **BDT**. In the following these **SRs** will be referred to as **STXS**-split-**BDT**-binned **SRs**.

Figure 7.20 shows the inclusive-**STXS**-binned **SRs** for the $2\ell\text{SS} + 0\tau_{\text{had}}$ and $3\ell + 0\tau_{\text{had}}$ channels. As the highest p_T^H bin has only very small statistics, the two highest **STXS** bins are merged for the following studies. The fits are performed with different numbers of reconstructed **STXS** bins,

different binning inside of each STXS SR and for different numbers of fitted STXS signal strengths. Only the setup with five reconstructed STXS bins and three STXS signal strengths ($p_T^H < 120$ GeV and $120 \text{ GeV} < p_T^H < 200$ GeV and $p_T^H > 200$ GeV) is shown here.

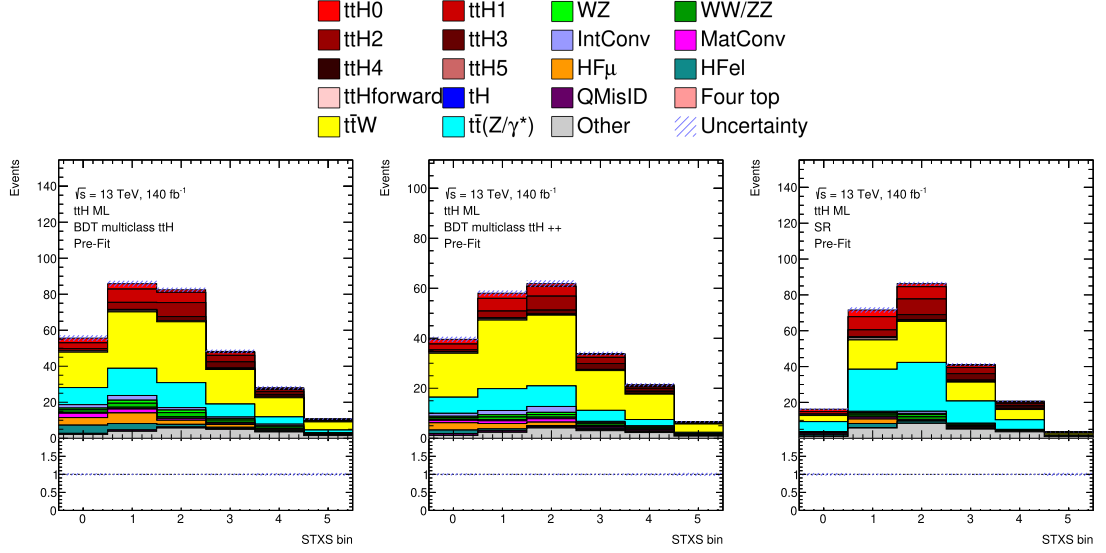


Figure 7.20: Inclusive-STXS-binned SRs for the $2\ell\text{SS} + 0\tau_{\text{had}}$ ($t\bar{t}H$ — left and $t\bar{t}H$ ++ centre) and $3\ell + 0\tau_{\text{had}}$ (right) channels.

The STXS fit setup with the STXS-split-BDT-binned SRs is shown in Figure 7.21 for $2\ell\text{SS} + 0\tau_{\text{had}}$ as example. The number of bins in each of the split SRs was chosen according to the number of events in the region and the binning was done with an auto-binning functionality of the fitting tool. Further binning optimisations were performed later, but the exact binning choice was not found to have a significant effect on the results.

The fit results for both approaches are shown in Figure 7.22. The fit setup with the STXS-split-BDT-binned SRs shows similar results for the background NFs to the other fit setup, but slightly improves the sensitivity to the different STXS signal strengths.

Additionally to these STXS fits, inclusive $t\bar{t}H$ signal strength fits are performed with both fit setups as well as with a fit where no Higgs p_T reconstruction is used. The fit results are shown in Figure 7.23. While the STXS fit with inclusive-STXS-binned SRs shows a small loss of sensitivity to $\mu_{t\bar{t}H}$ compared to a non STXS setup, the fit with STXS-split-BDT-binned SRs shows the same uncertainty on $\mu_{t\bar{t}H}$. Therefore, using this second STXS fit setup would allow using the same setup for the inclusive and the STXS fit.

Similar studies were performed for the $2\tau_{\text{had}}$ channel showing similar results. The setup where the SRs are split into several STXS SRs and then binned in the classification BDT is therefore chosen for the final fit.

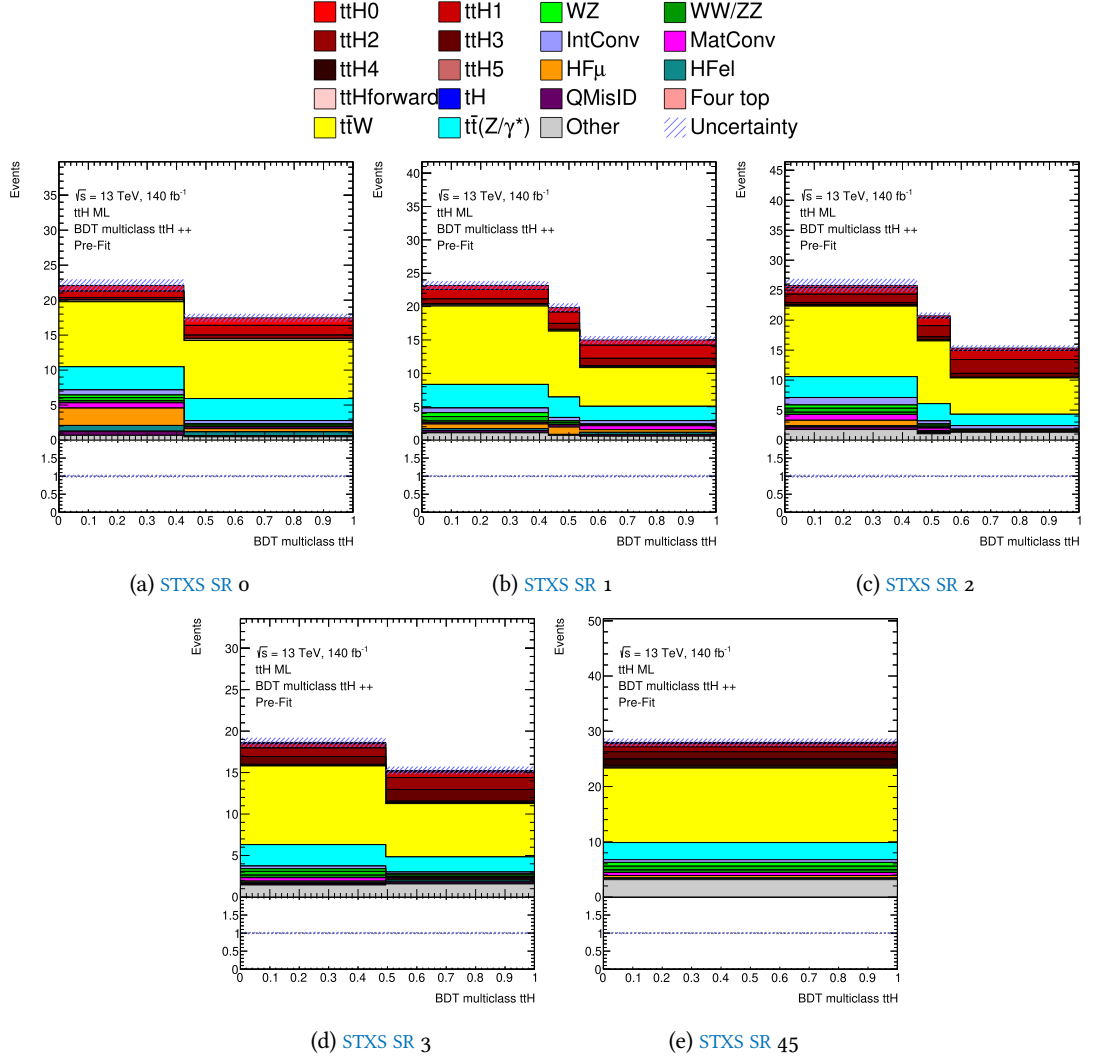
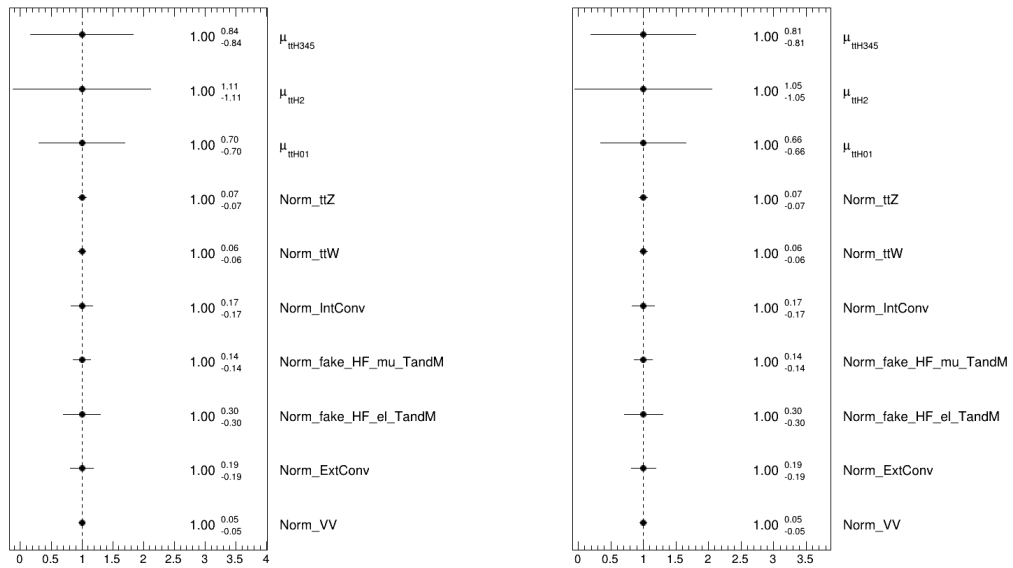
Figure 7.21: $t\bar{t}H$ ++ STXS-split-BDT-binned SRs of the $2\ell\text{SS} + 0\gamma_{\text{had}}$ channel.

Figure 7.22: NF results for the two fit setups of the STXS fit: inclusive-STXS-binned SRs (left) and STXS-split-BDT-binned SRs (right)

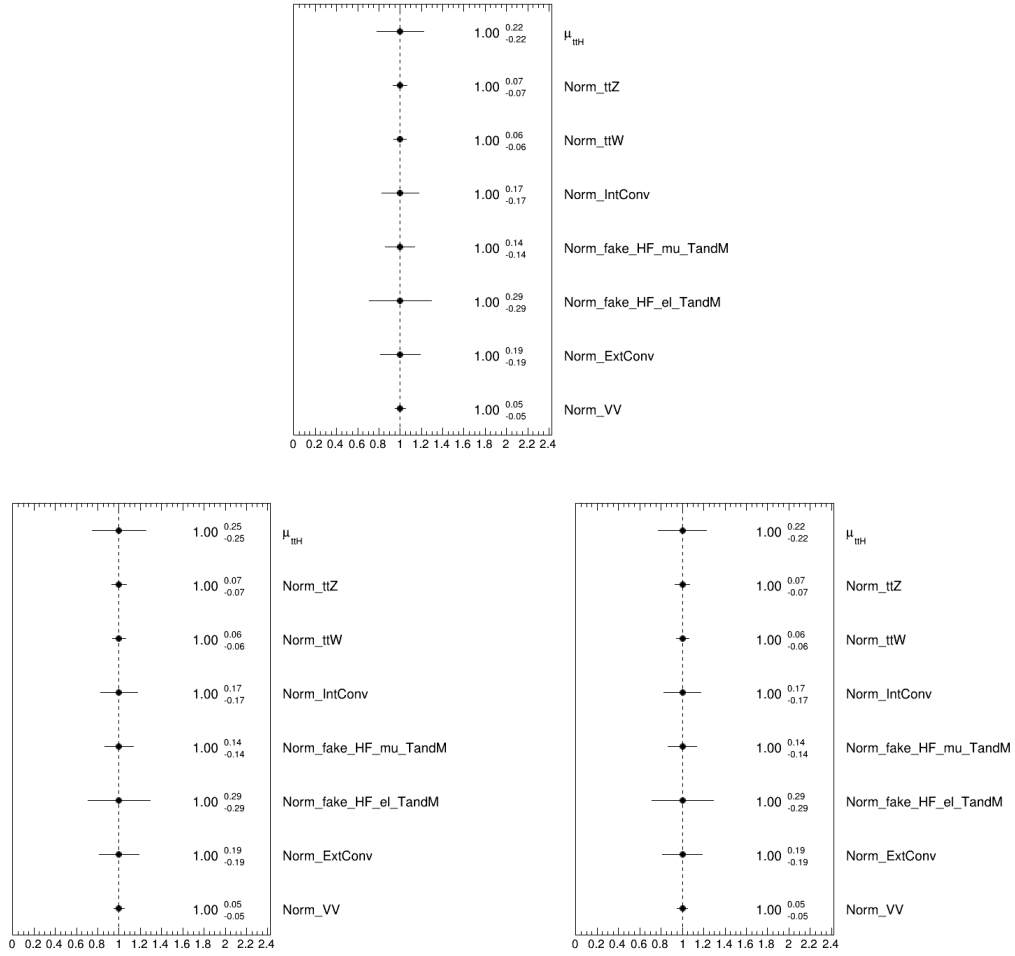


Figure 7.23: NF results for three fit setups of the inclusive fit: inclusive SRs (top), inclusive-STXS-binned SRs (bottom left) and STXS-split-BDT-binned SRs (bottom right)

7.9.2 Choice of the fitted STXS signal strengths

The STXS framework includes six STXS bins for $t\bar{t}H$. However, the large migrations between truth and reconstructed STXS bins lead to high correlations between the STXS signal strengths and the fit is not sensitive enough to constrain all six of them. In order to reduce the correlations, some of the STXS signal strengths need to be merged.

Impact of the Higgs p_T mis-reconstruction on the STXS sensitivity in the $0\tau_{\text{had}}$ channels

The impact of the p_T^H migrations on the STXS fit is studied, by comparing the sensitivity to three STXS signal strengths in the default fit to the sensitivity in a fit where the STXS SRs are split by truth p_T^H for the $t\bar{t}H$ component, the backgrounds still being attributed to the different SRs based on the reconstructed p_T^H . The comparison of the fit results in the $2\ell\text{SS} + 0\tau_{\text{had}}$ channel are

shown in Figure 7.24 and in the $3\ell + 0\tau_{\text{had}}$ channel in Figure 7.25. Additionally, the correlation between the $t\bar{t}H$ STXS signal strengths is shown. It can be seen that in both channels, the p_T^H mis-reconstruction highly increases the correlation between the $t\bar{t}H$ STXS signal strengths and therefore decreases the sensitivity at reconstruction level compared to truth level. The p_T^H being more diagonal in the $2\tau_{\text{had}}$ channel, the combination with this channel counteracts this effect by decorrelating the STXS signal strengths.

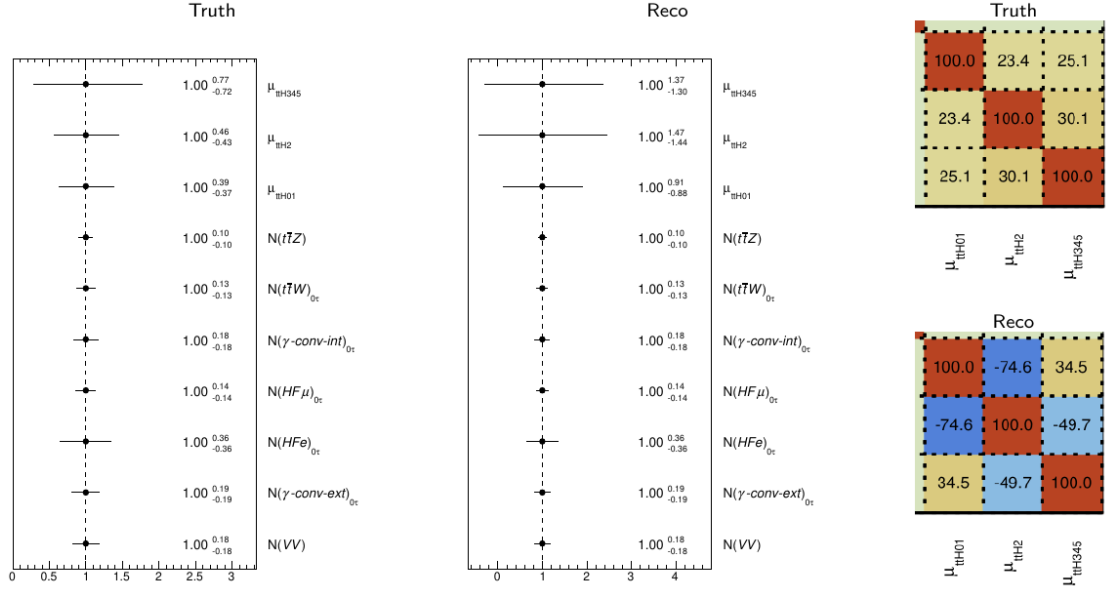


Figure 7.24: Comparison of the fit results in the $2\ell\text{SS} + 0\tau_{\text{had}}$ channel, where the STXS SRs are split by truth level p_T^H for the $t\bar{t}H$ components (left) and in the default fit setup, where the STXS SRs are split by p_T^H at reconstruction level for the $t\bar{t}H$ components (right). Additionally the comparison of the correlations between the $t\bar{t}H$ STXS signal strengths is shown for both setups.

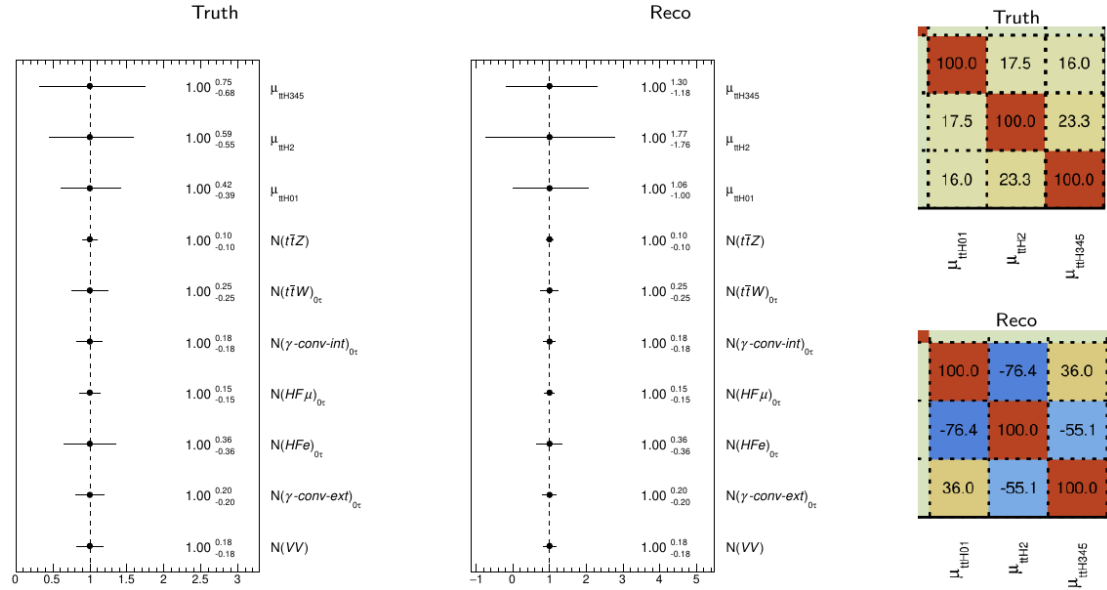


Figure 7.25: Comparison of the fit results in the $3\ell + 0\tau_{\text{had}}$ channel where, the STXS SRs are split by truth level p_T^H for the $t\bar{t}H$ components (left) and in the default fit setup, where the STXS SRs are split by p_T^H at reconstruction level for the $t\bar{t}H$ components (right). Additionally the comparison of the correlations between the $t\bar{t}H$ STXS signal strengths is shown for both setups.

Number of fitted STXS signal strengths

Figures 7.26 and 7.27 show the migration matrices for two different ways of merging the STXS bins:

- 3 STXS signal strengths: merge the first two and last three STXS bins ($p_T^H < 120$ GeV and $120 \text{ GeV} < p_T^H < 200$ GeV and $p_T^H > 200$ GeV)
- 4 STXS signal strengths: merge the first two and last two STXS bins ($p_T^H < 120$ GeV and $120 \text{ GeV} < p_T^H < 200$ GeV and $200 \text{ GeV} < p_T^H < 300$ GeV and $p_T^H > 300$ GeV)

In both cases, the migration matrices become more diagonal compared to the case with six STXS bins shown in Figure 7.19. Because of the very large migrations in the low p_T^H regime, the setup where the first two STXS bins are split is not considered.

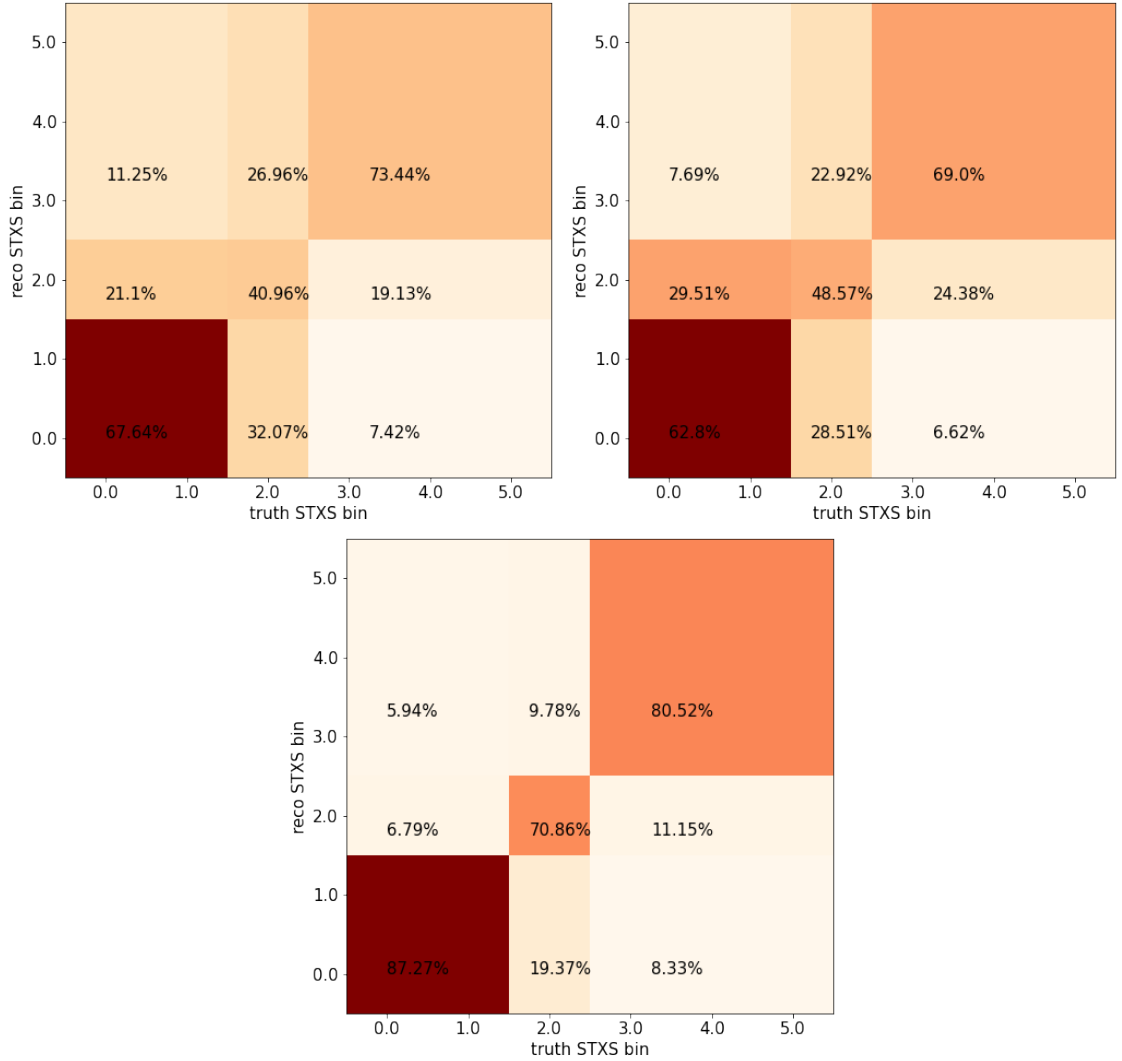


Figure 7.26: Migration matrices between truth and reconstructed STXS bins for the $2\ell\text{SS} + 0\tau_{\text{had}}$ channel (top left), the $3\ell + 0\tau_{\text{had}}$ channel (top right) and the $2\tau_{\text{had}}$ channels (bottom) binned in three STXS bins.

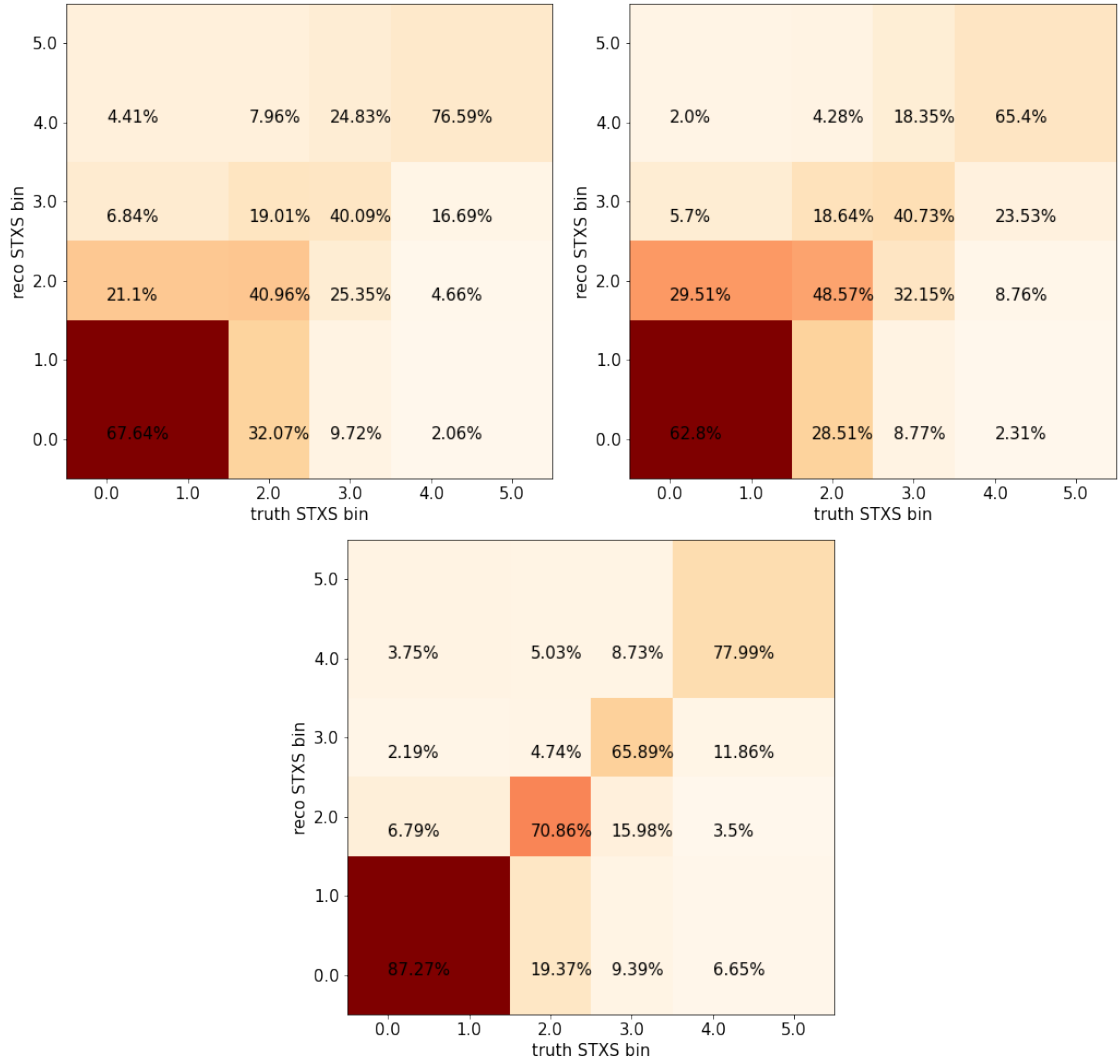


Figure 7.27: Migration matrices between truth and reconstructed $STXS$ bins for the $2\ell_{SS} + 0\tau_{had}$ channel (top left), the $3\ell + 0\tau_{had}$ channel (top right) and the $2\tau_{had}$ channels (bottom) binned in four $STXS$ bins.

Figure 7.28 shows the fit results for both setups in a fit combining the $0\tau_{had}$ and $2\tau_{had}$ channels. It can be seen that the fit is not able to separate the fourth $STXS$ bin properly from the two highest $STXS$ bins. The fit setup with three $STXS$ signal strengths is therefore chosen.

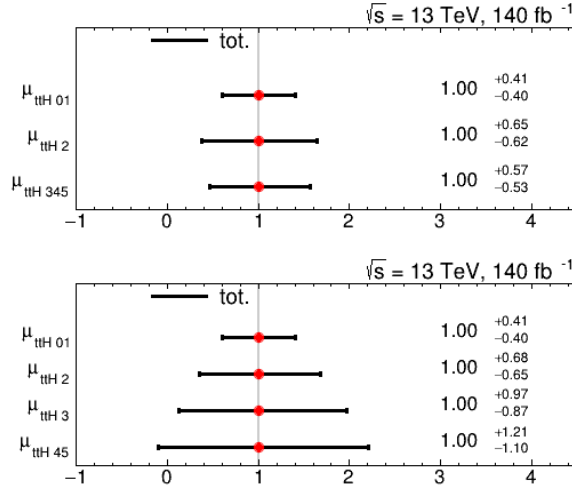


Figure 7.28: Fit results for the two fit setups of the STXS fit: three STXS signal strengths (top), four STXS signal strengths (bottom)

7.10 Impact of the Higgs p_T reconstruction on the fit

The final STXS setup consists of splitting the inclusive SRs into five STXS SRs, defined at reconstruction level, except for the $2\ell+2\tau_{\text{had}}$ channel, where the statistics only allow for two STXS SRs. The STXS template composition of the final STXS SRs is shown in Figure 7.29. Additionally, three STXS signal strengths are constrained in the fit.

In the following, studies on the impact of this setup on the physics results are shown. First, efficiency differences of the p_T^H reconstruction for different Higgs decay modes are studied in Section 7.10.1. Then the interplay of the signal to background classification with the p_T^H and the p_T^H reconstruction is described in Section 7.10.2, followed by the behaviour of the p_T^H reconstruction in data in Section 7.10.3. Finally, the impact of the STXS setup on the background estimation is studied in Section 7.10.4.

7.10.1 Efficiency of the Higgs p_T reconstruction for different Higgs decay modes

In this analysis, $t\bar{t}H$ is considered inclusively in Higgs decay mode. It was shown previously that the $0\tau_{\text{had}}$ channels mainly target $H \rightarrow WW$ and the $2\tau_{\text{had}}$ channels $H \rightarrow \tau\tau$. In the following, the Higgs decay mode composition of the SRs in the different channels is studied as well as the p_T^H reconstruction efficiency depending on the Higgs decay mode.

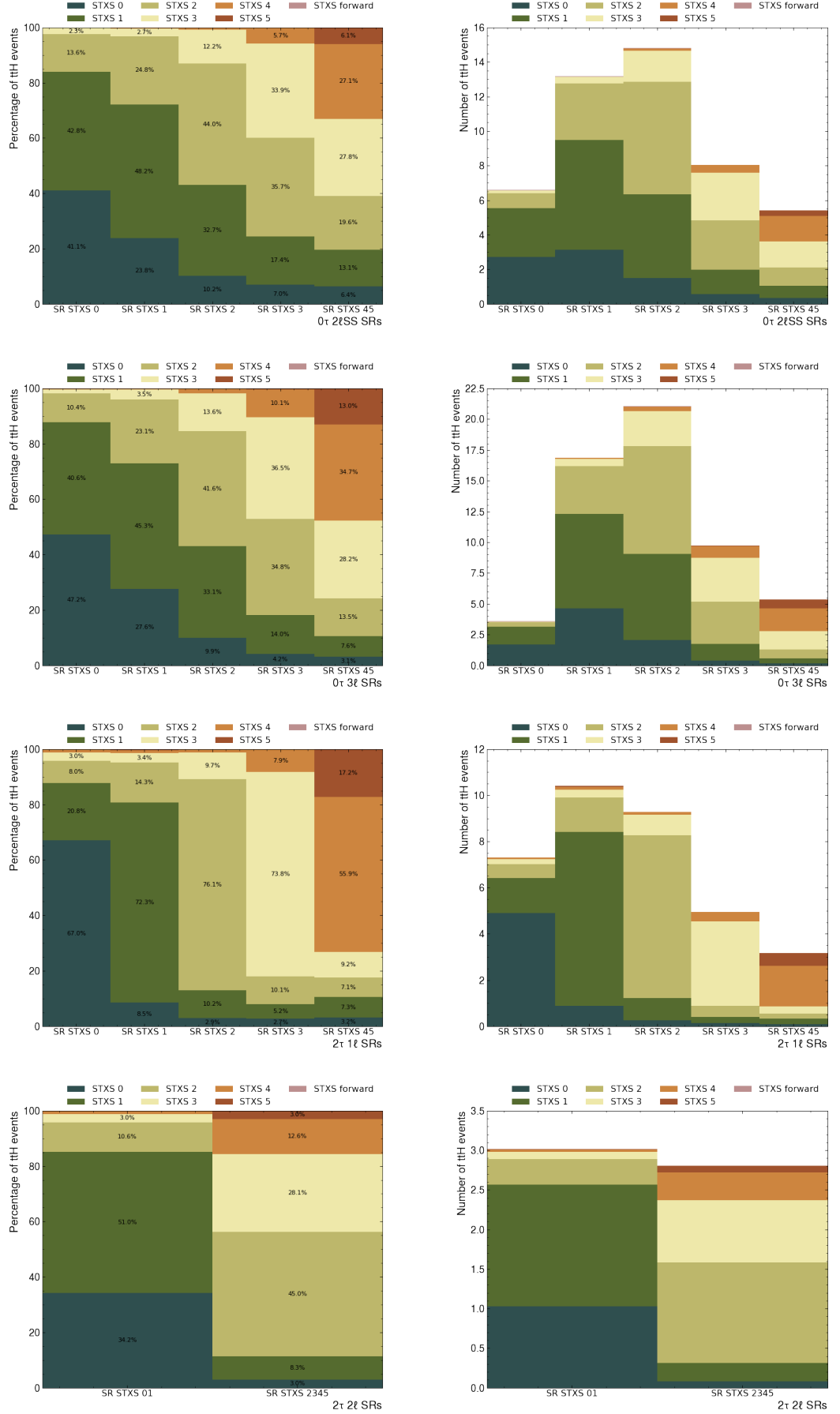


Figure 7.29: Contribution of the different $t\bar{t}H$ STXS templates to the STXS SRs for the $2\ell\text{SS} + 0\tau_{\text{had}}$ channel (top row), the $3\ell + 0\tau_{\text{had}}$ channel (second row), the $1\ell + 2\tau_{\text{had}}$ channel (third row) and the $2\ell + 2\tau_{\text{had}}$ channel (bottom row). On the left, the relative contributions and on the right the absolute contributions are shown.

$0\tau_{\text{had}}$ channels

The SRs are split from the CRs using the output scores of multi-dimensional classifier BDTs . The $t\bar{t}H$ output nodes (see Figure 7.30) do not show any strong dependence on the Higgs decay mode, keeping the percentage of $H \rightarrow WW$ relatively constant throughout the CRs and SRs . Additionally, the splitting of the SRs into the STXS bins, as shown in Figure 7.31, does not introduce any significant changes in the Higgs decay mode composition.

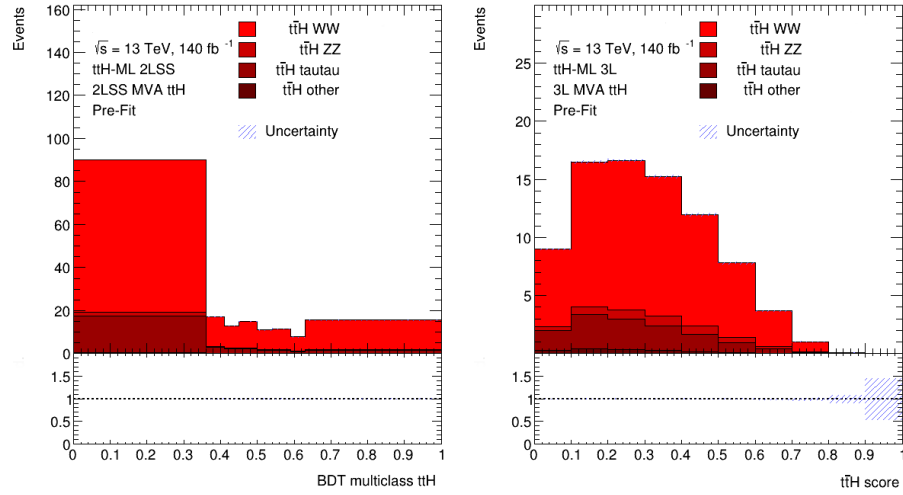


Figure 7.30: $t\bar{t}H$ output score of the signal to background classification BDT in the $2\ell\text{SS} + 0\tau_{\text{had}}$ channel (left) and the $3\ell + 0\tau_{\text{had}}$ channel (right) for the different Higgs decay modes.

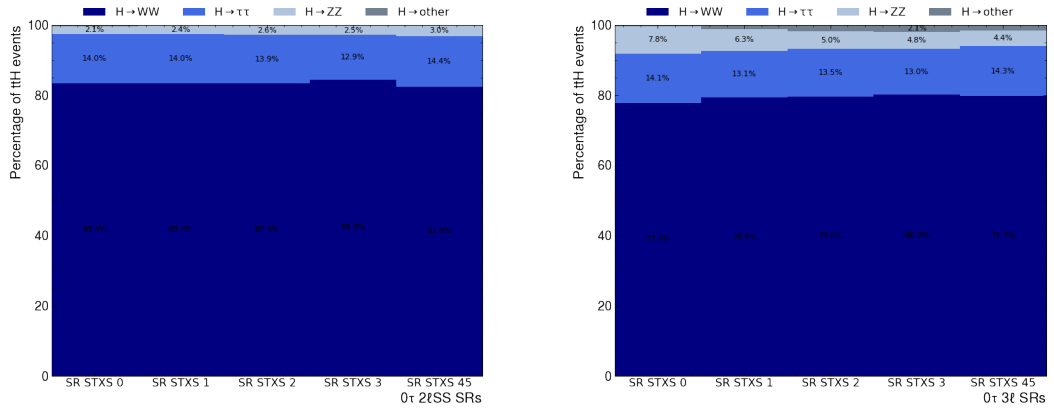


Figure 7.31: Relative contribution of the different Higgs decay modes in $t\bar{t}H$ to the STXS SRs for the $2\ell\text{SS} + 0\tau_{\text{had}}$ channel (left) and the $3\ell + 0\tau_{\text{had}}$ channel (right).

Finally, the accuracy of the Higgs p_T reconstruction is considered for the different Higgs decay modes. Figures 7.32 and 7.33 show the migration matrices between truth and reconstructed STXS bins for the $2\ell\text{SS} + 0\tau_{\text{had}}$ and $3\ell + 0\tau_{\text{had}}$ channels, for the three main decay channels as well as for the inclusive case. The migrations are relatively similar for all decay modes, a small loss

in diagonality can, however, be seen for non $H \rightarrow WW$ events, $H \rightarrow WW$ being the dominant decay mode and therefore dominating the training of the GNN.

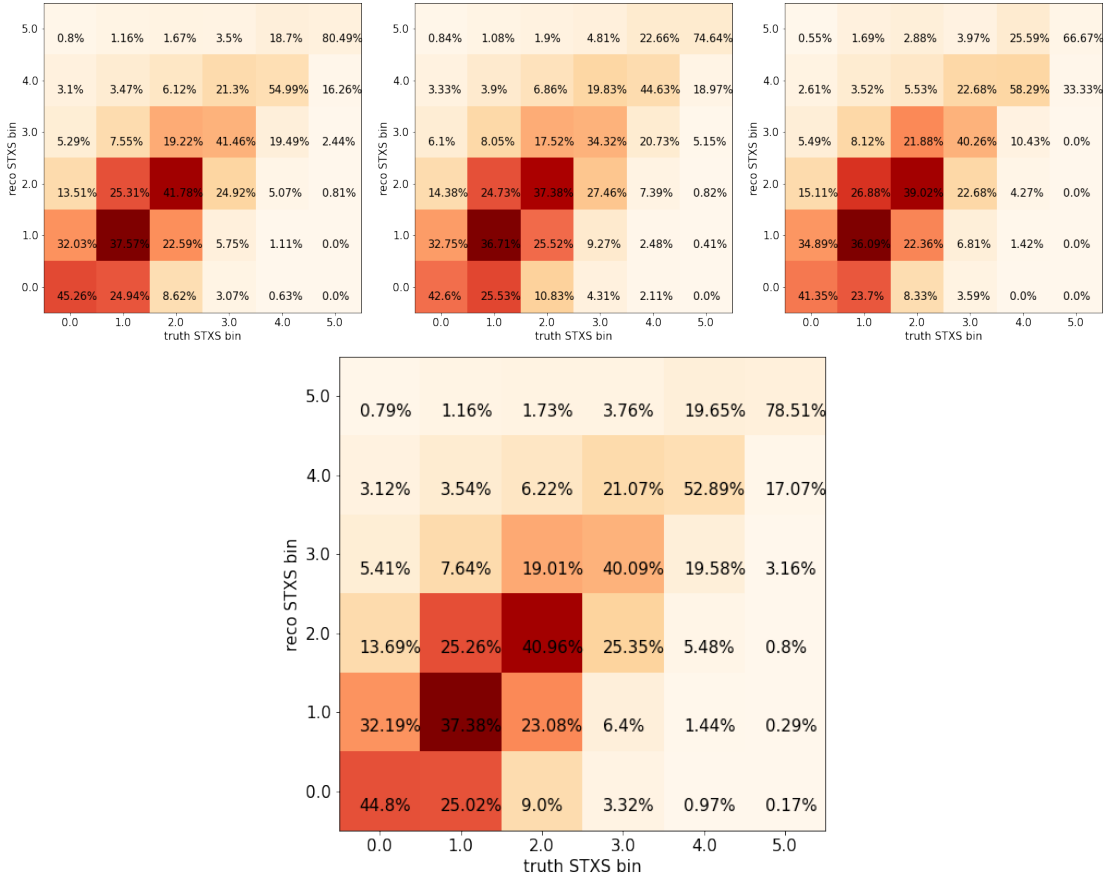


Figure 7.32: Migration matrices between truth and reconstructed STXS bins for $t\bar{t}H \rightarrow WW$ events (top left), $t\bar{t}H \rightarrow \tau\tau$ events (top centre), $t\bar{t}H \rightarrow ZZ$ events (top right) and inclusive in Higgs decay mode (bottom) for the $2\ell_{SS} + 0\tau_{had}$ channel.

2 τ_{had} channels

The picture seen in the $0\tau_{had}$ channels changes in the $2\tau_{had}$ channels. In these channels, the SRs are not defined with any cuts on the classifier BDT but are binned in the output score. Figure 7.34 shows the BDT score distribution for the different Higgs decay channels. While $H \rightarrow \tau\tau$ events peak for high scores, the $H \rightarrow WW$ distribution is relatively flat. This hints to the fact that the signal to background rejection heavily relies on the di-tau system of the Higgs decay. This inefficiency in the classification of $H \rightarrow WW$ events means that the sensitivity to the $H \rightarrow WW$ events will be suppressed with respect to $H \rightarrow \tau\tau$ events.

As shown in Figure 7.35, the split of the SRs into STXS bins introduces slightly larger variations in the Higgs decay composition than in the $0\tau_{had}$ channels, but the differences are still relatively small.

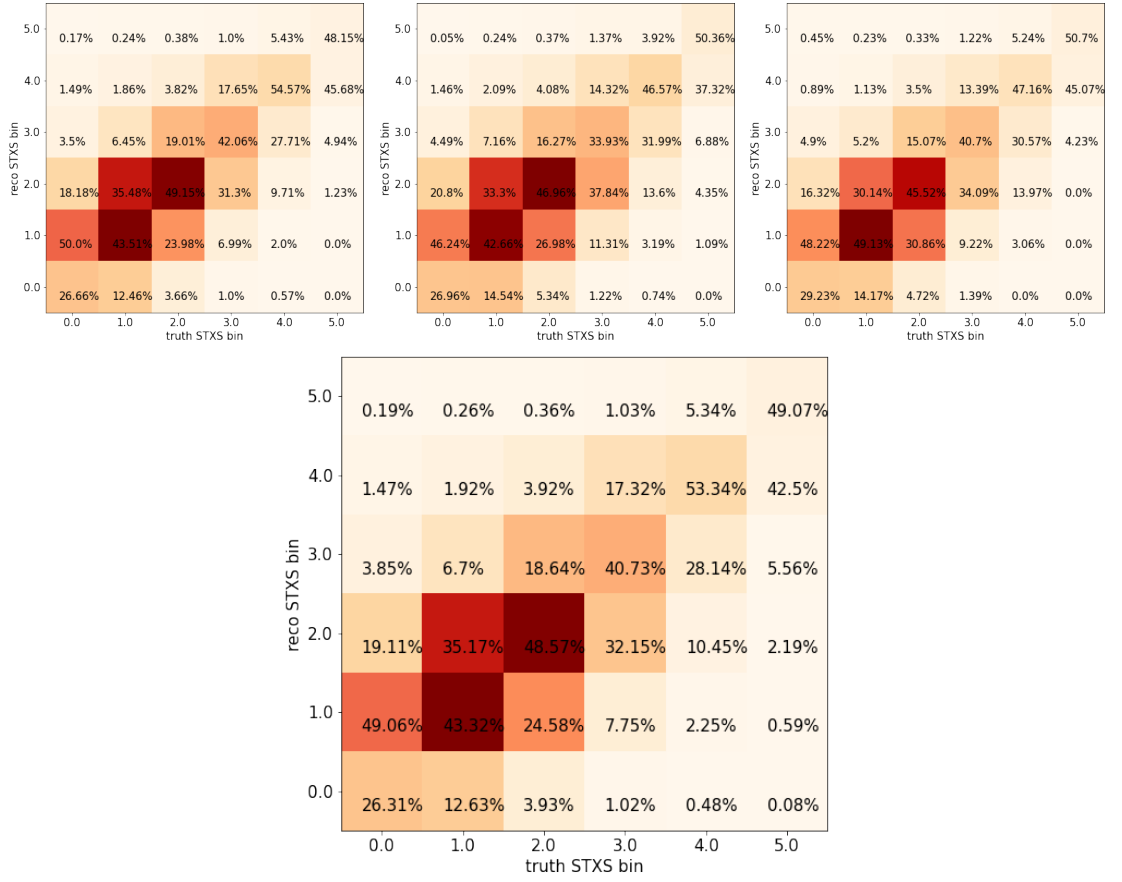


Figure 7.33: Migration matrices between truth and reconstructed STXS bins for $t\bar{t}H \rightarrow WW$ events (top left), $t\bar{t}H \rightarrow \tau\tau$ events (top centre), $t\bar{t}H \rightarrow ZZ$ events (top right) and inclusive in Higgs decay mode (bottom) for the $3\ell + 0\tau_{\text{had}}$ channel.

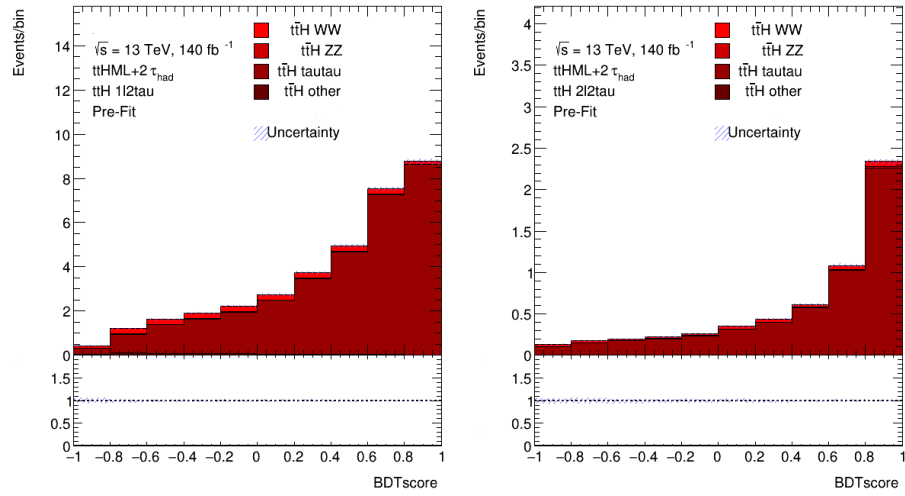


Figure 7.34: $t\bar{t}H$ output score of the signal to background classification BDT in the $1\ell + 2\tau_{\text{had}}$ channel (left) and the $2\ell + 2\tau_{\text{had}}$ channel (right) for the different Higgs decay modes.

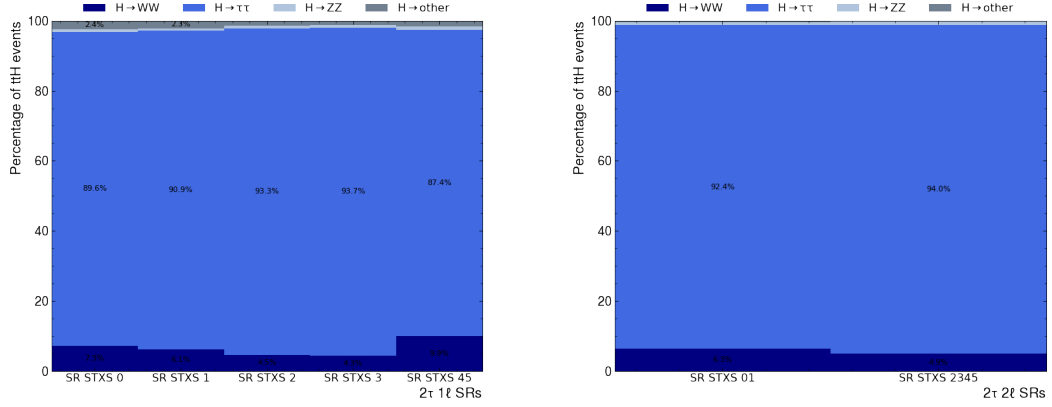


Figure 7.35: Relative contribution of the different Higgs decay modes in $t\bar{t}H$ to the **STXS** SRs for the $1\ell+2\tau_{\text{had}}$ channel (left) and the $2\ell+2\tau_{\text{had}}$ channel (right).

The migration matrices between truth and reconstructed p_T^H (see Figure 7.36) show, however, again very large efficiency differences between $H \rightarrow \tau\tau$ and $H \rightarrow WW$ events. While the matrix for $H \rightarrow \tau\tau$ is very diagonal, the reconstruction being based on the visible di- τ p_T , the p_T^H reconstruction in $H \rightarrow WW$ events seems mainly flat. $H \rightarrow WW$ events will therefore increase the correlations between the **STXS** signal strengths. However, the fraction of $t\bar{t}H \rightarrow WW$ being small compared $t\bar{t}H \rightarrow \tau\tau$, this does not have a large impact on the overall p_T^H resolution.

7.10.2 Interplay between the classification BDTs and the Higgs p_T reconstruction

Different studies are performed in order to understand the Higgs p_T distribution inside the SRs and the interplay between the p_T^H reconstruction and the signal to background classification BDTs.

$0\tau_{\text{had}}$ channels

First, it is tested how well the classification BDTs, trained in the $2\ell\text{SS} + 0\tau_{\text{had}}$ and $3\ell + 0\tau_{\text{had}}$ channels, behave as a function of the truth Higgs p_T . Figure 7.37 shows the $t\bar{t}H$ output distribution for the two channels for the six **STXS** truth bins. Additionally, the tables show which percentage of events in the truth **STXS** bins are classified into the SRs and into the CRs. Although no strong shape differences are observed for the different p_T^H regimes, events with low or high p_T^H are less likely to be attributed to the SRs than events with p_T^H in an intermediate region. This leads to a slight loss in sensitivity to the low and high **STXS** bins.

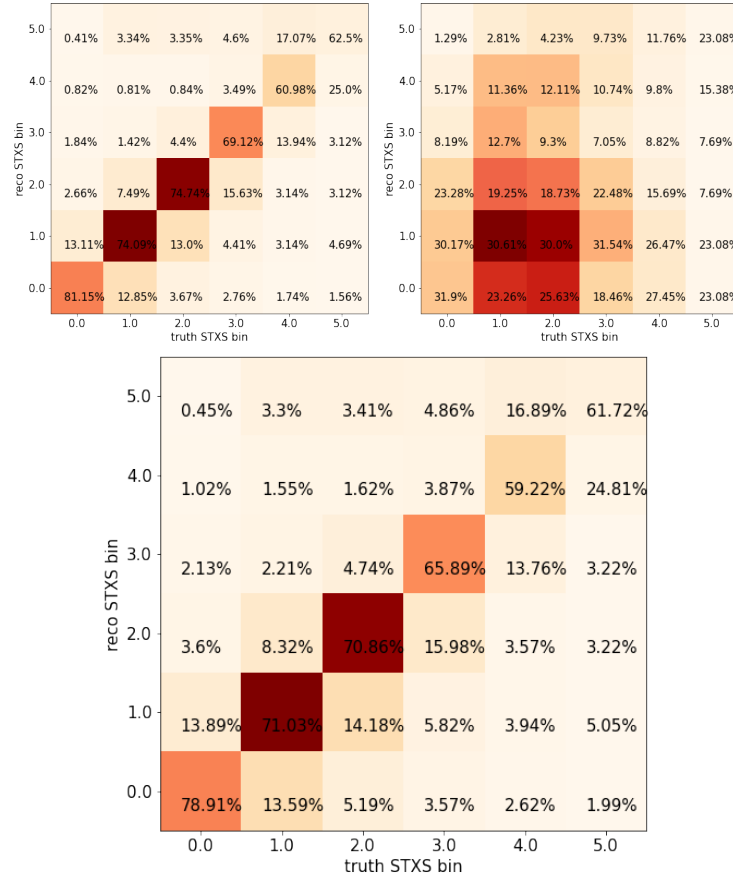


Figure 7.36: Migration matrices between truth and reconstructed STXS bins for $t\bar{t}H \rightarrow \tau\tau$ events (top left), $t\bar{t}H \rightarrow WW$ events (top right) and inclusive in Higgs decay mode (bottom) for the $2\tau_{\text{had}}$ channels.

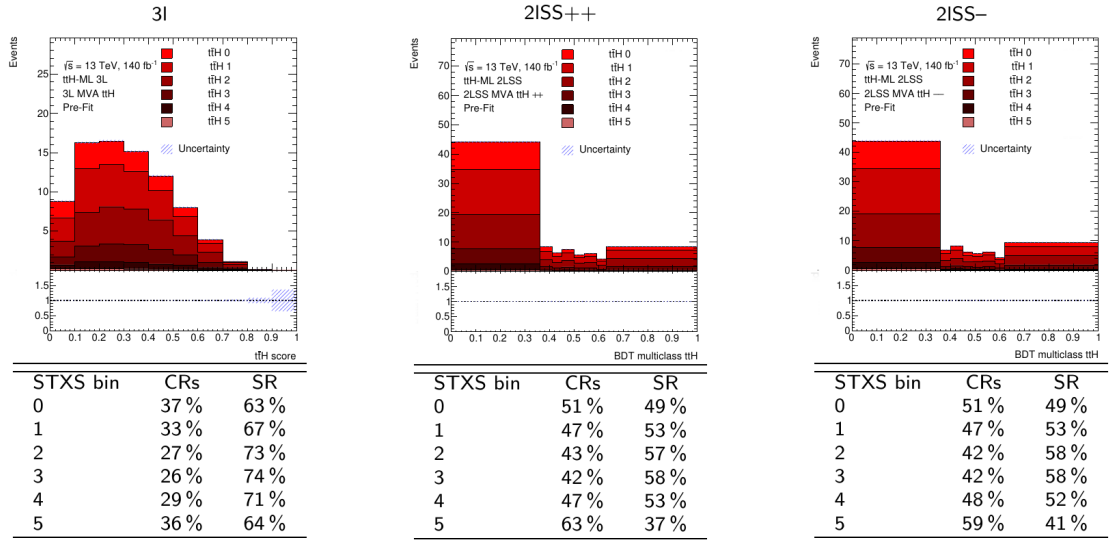


Figure 7.37: $t\bar{t}H$ output score of the signal to background classification BDT in the $3\ell + 0\tau_{\text{had}}$ channel (left) and the $2\ell\text{SS} + 0\tau_{\text{had}}$ channel ($t\bar{t}H ++$ (centre) and $t\bar{t}H --$ (right)) for the different STXS templates (top) and percentage of the $t\bar{t}H$ events classified into the SR and CRs for the different STXS templates (bottom)

Figure 1 displays four stacked histograms showing the reco HpT distribution for ttH production at $\sqrt{s} = 13$ TeV, 140 fb^{-1} . The top row shows the full distribution with various background components (ttH 0-5, ttH-ML 2LSS, 2LSS MVA ttH, Pre-Fit, and Uncertainty). The bottom row shows the same distribution with the ttH-ML 2LSS fit overlaid. The x-axis is reco HpT (0 to 5) and the y-axis is Events (0 to 25 for the top row, 0 to 1.5 for the bottom row).

These studies show that performing the signal to background rejection and the p_T^H reconstruction in a fully separate way leads to losses in the sensitivity to the [STXS](#) signal strengths, especially for [STXS](#) bins with lower statistics. In future efforts, it would be beneficial to study approaches where both, the event classification and the p_T^H reconstruction, are interlinked. One first approach could be to perform the p_T^H reconstruction first and train a signal to background

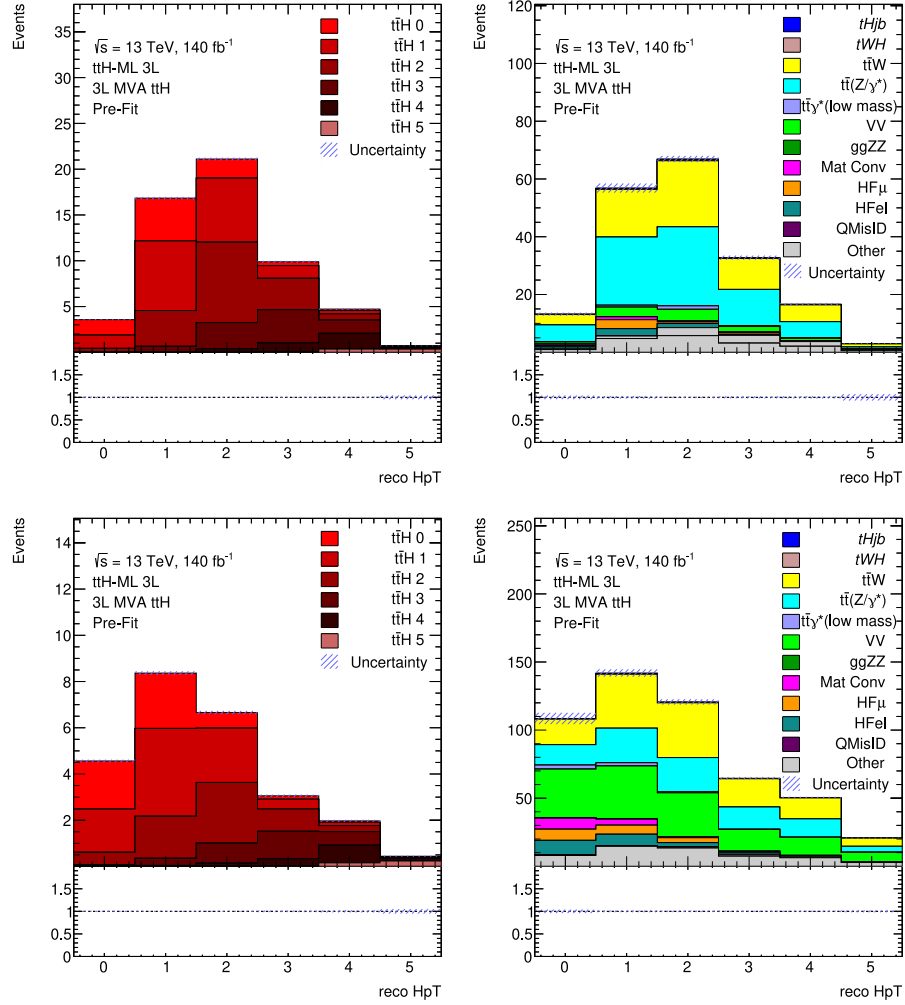


Figure 7.39: Reconstructed p_T^H distribution for the $3\ell + 0\tau_{\text{had}}$ SR (top) and for the $3\ell + 0\tau_{\text{had}}$ SR with inverted $t\bar{t}H$ BDT output cut (bottom) ($t\bar{t}H$ (left) and backgrounds (right)).

classification inside different STXS bins. Another approach could be to perform the signal to background rejection and the p_T^H reconstruction simultaneously, by training one single GNN, which classifies events into backgrounds as well into different STXS bins. Both these approaches would allow to optimise the sensitivity to the different STXS signal strengths separately and to study the sculpting of the backgrounds inside the training.

$2\tau_{\text{had}}$ channels

A very similar behaviour is observed in the $2\tau_{\text{had}}$ channels. In Figure 7.40, it can be seen that high p_T^H events seem to have a more prominent peak at high BDT scores than low p_T^H events. As the SRs are binned in the BDT score, this will lead to a loss in sensitivity for the low STXS bins.

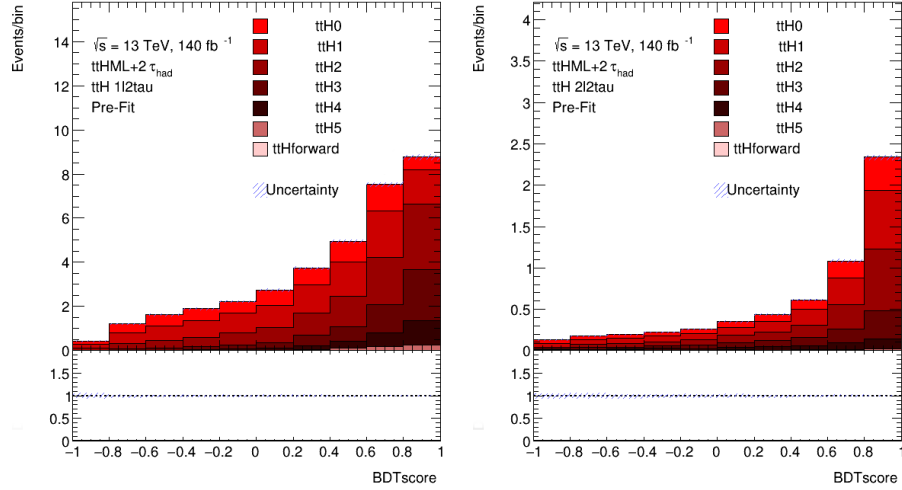


Figure 7.40: $t\bar{t}H$ output score of the signal to background classification BDT in the $1\ell+2\tau_{\text{had}}$ channel (left) and the $2\ell+2\tau_{\text{had}}$ channel (right) for the different $STXS$ templates.

Additionally, the same sculpting of the backgrounds is observed in Figures 7.41 and 7.42, showing the signal and background p_T^H distributions in a signal-like regime with a classifier BDT score above 0.1 and in a background-like regime with a BDT score below 0.1.

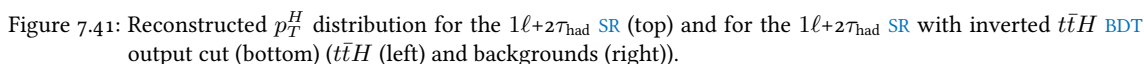
7.10.3 Behaviour of the Higgs p_T reconstruction in data

The behaviour of the Higgs p_T reconstruction in data is studied. To gain understanding of the GNN before unblinding, only the unblinded regions of the fit can be used. In order to extrapolate the conclusions of these studies to the parts directly relevant for the signal, the assumption has to be made that the data MC agreement is smooth throughout the classifier BDT output.

$0\tau_{\text{had}}$ channels

First, the data MC agreement is checked in the existing CR s for both $0\tau_{\text{had}}$ channels, when binning them in the GNN output instead of their usual binning in the classifier BDT output. This is shown in Figure 7.43 for the $2\ell SS + 0\tau_{\text{had}}$ channel. For none of the CR s major discrepancies are observed between the GNN shape in data and in MC .

Second, a similar $STXS$ binning approach is used in the CR s as in the SR s, to check that no unexpected behaviour is introduced by using the $STXS$ setup. To do so, the different $STXS$ SR s are used with inverted $t\bar{t}H$ BDT classification cut. These different $STXS$ CR s are then binned in the $t\bar{t}H$ BDT output. As shown in Figure 7.44 for the $3\ell + 0\tau_{\text{had}}$ channel, no significant data mismodelling is introduced by this setup.



As the $2\tau_{\text{had}}$ channels do not include any CRs, the data MC is checked in a background-like regime of the SRs with a BDT score below 0.1, binned in reconstructed p_T^H . The distributions are shown in Figure 7.45. No significant mismodelling is observed.

$t\bar{t}W$ being an important background for the measurement of the $t\bar{t}H$ normalisation, extensive studies are performed in the [STXS](#) fit, in order to understand if the $t\bar{t}W$ normalisation shows some dependence on the reconstructed p_T^H , introducing a potential bias on the results of the [STXS](#) $t\bar{t}H$ signal strengths, as only one inclusive $t\bar{t}W$ [NF](#) is fitted.

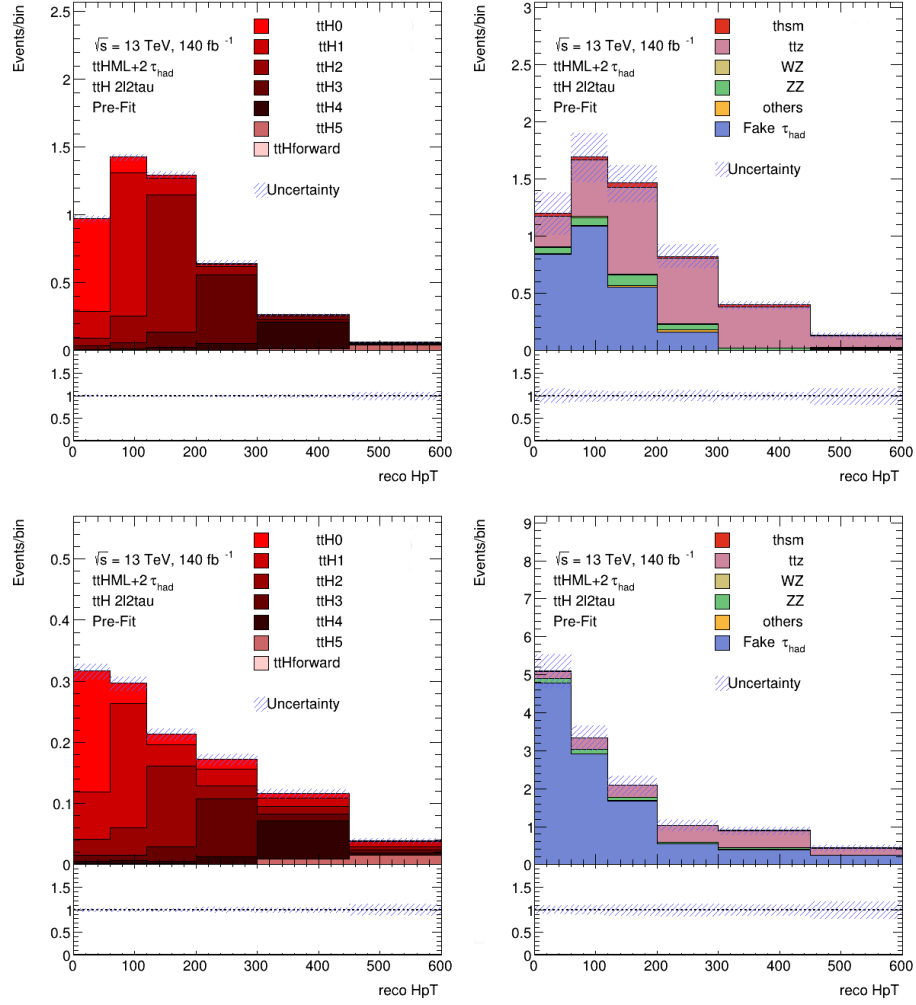


Figure 7.42: Reconstructed p_T^H distribution for the $2\ell+2\tau_{\text{had}}$ SR (top) and for the $2\ell+2\tau_{\text{had}}$ SR with inverted $t\bar{t}H$ BDT output cut (bottom) ($t\bar{t}H$ (left) and backgrounds (right)).

Figure 7.46 shows the $t\bar{t}W$ CRs of the 0τ channels binned in the reconstructed p_T^H . Overall, no strong mismodelling is introduced, even though some bins show a stronger underestimation of MC with respect to data compared to others, such as the second STXS bin. In order to check the impact of this reconstructed p_T^H dependence, the $t\bar{t}W$ CRs and $t\bar{t}W$ templates are split by reconstructed p_T^H . The CRs are split into three STXS regions (the first two bins, the third bin, and the last three bins) following the merging of the fitted $t\bar{t}H$ STXS signal strengths. The resulting $t\bar{t}W$ CRs are shown in Figure 7.47.

A background only fit with data, including only the CRs, is then performed for the $2\ell\text{SS} + 0\tau_{\text{had}}$ and $3\ell + 0\tau_{\text{had}}$ channel, where three STXS $t\bar{t}W$ NFs are fitted and the results are shown in Figure 7.48. Especially for the $2\ell\text{SS} + 0\tau_{\text{had}}$ channel, the $t\bar{t}W$ NFs show some large p_T^H dependence, however, the three NFs are strongly correlated with each other. A compatibility test between this fit setup and a fit setup with only one inclusive $t\bar{t}W$ NF shows a compatibility of 25 % for the $2\ell\text{SS} + 0\tau_{\text{had}}$ channel and a compatibility of 40 % for the $3\ell + 0\tau_{\text{had}}$ channel.

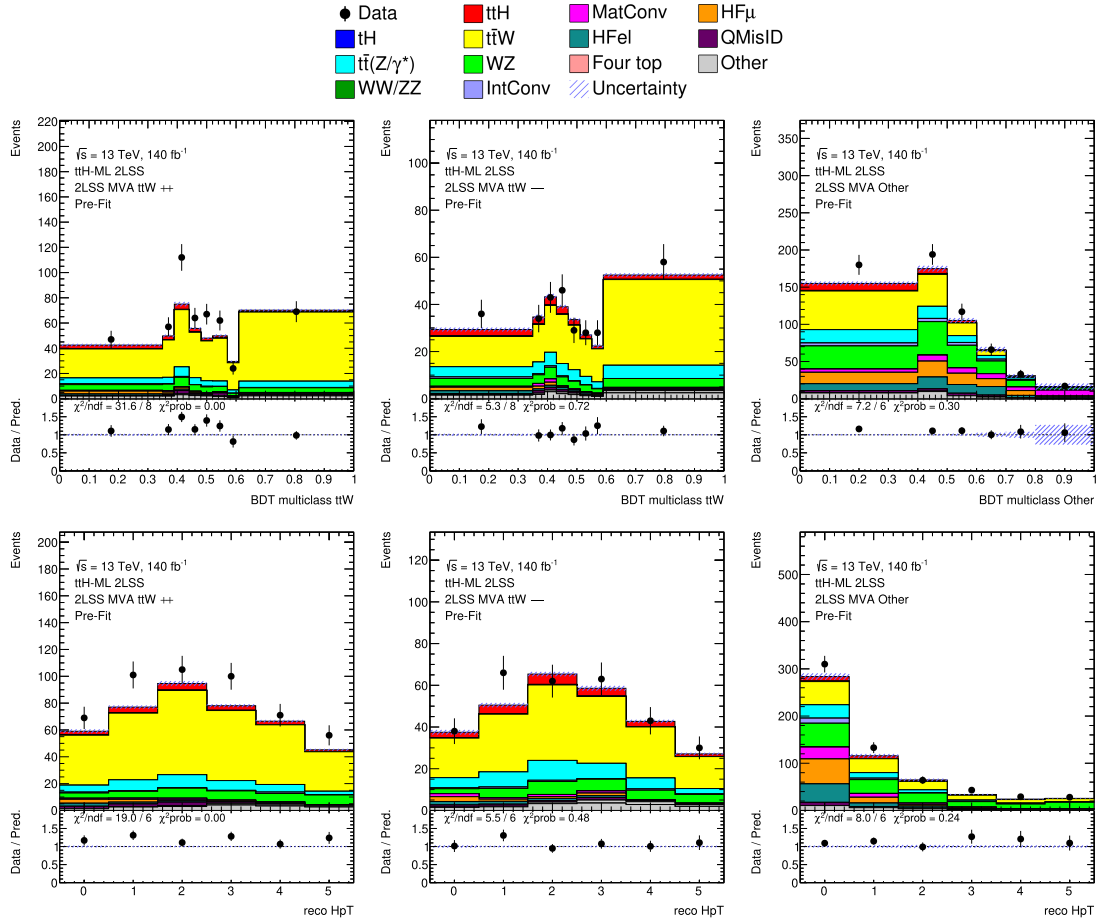


Figure 7.43: Prompt BDT based CRs for the $2\ell\text{SS} + 0\tau_{\text{had}}$ channel: default binning in the classification BDT outputs (top) and binning in the reconstructed p_T^H distribution (bottom).

As a second step, the impact of this effect on the fitted $t\bar{t}H$ STXS signal strengths is studied. In order to do so, it needs to be assumed that the normalisation differences of $t\bar{t}W$ are similar in the CRs and in the SRs. A pseudo-dataset is built, propagating the corresponding STXS $t\bar{t}W$ NFs into the $t\bar{t}H$ STXS SRs. The resulting SRs are shown in Figure 7.49. The bias of only fitting one inclusive $t\bar{t}W$ NF can then be tested, by fitting these pseudo-data with the default fit setup. The results are shown in Figure 7.50. Especially in the $2\ell\text{SS} + 0\tau_{\text{had}}$ channel, some pulls of the STXS $t\bar{t}H$ NFs away from 1 are observed. However, the different STXS signal strengths show again very high correlations between each other. The compatibility with a fit where all three $t\bar{t}H$ STXS signal strengths are fixed to 1 is of 55 % for the $2\ell\text{SS} + 0\tau_{\text{had}}$ channel and of 87 % for the $3\ell + 0\tau_{\text{had}}$ channel, showing that the pulls in the NFs are not significant.

In order to reduce the correlations between the $t\bar{t}H$ STXS signal strengths, both channels are combined with the $2\tau_{\text{had}}$ channels. The $t\bar{t}W$ NFs from the $2\ell\text{SS} + 0\tau_{\text{had}}$ channel are injected as pseudo-data into the SRs of the $2\tau_{\text{had}}$ channels. The $t\bar{t}H$ STXS signal strengths of the combined fit are shown in Figure 7.51. First of all, it is to be observed that the reconstructed p_T^H dependence of the $t\bar{t}W$ NF has nearly no effect on the $2\tau_{\text{had}}$ results, the $t\bar{t}W$ contribution in the $2\tau_{\text{had}}$ channels

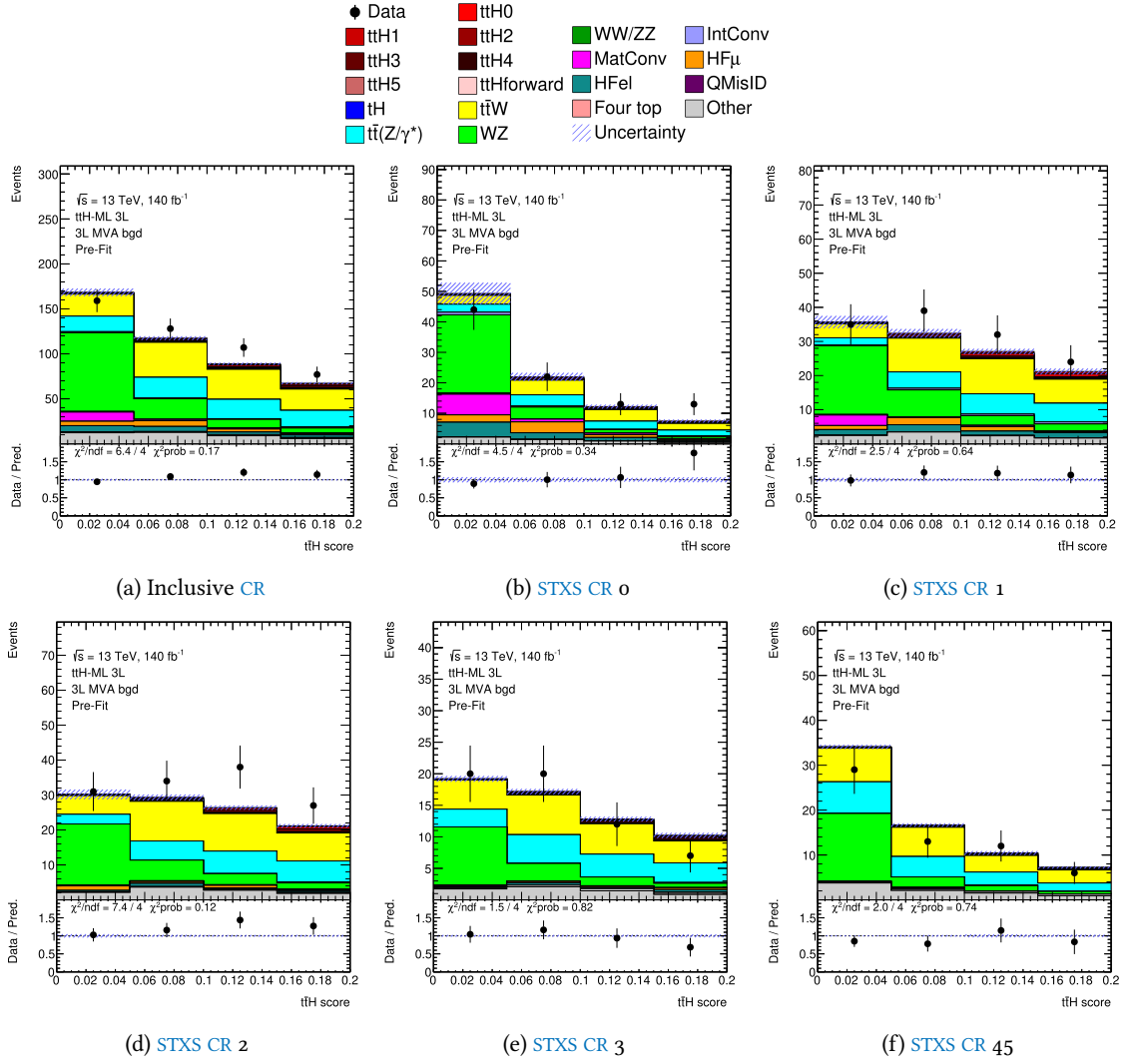


Figure 7.44: Merged prompt BDT based CRs for the $3\ell + 0\tau_{\text{had}}$ channel split by reconstructed p_T^H and binned in the ttH output node of the classification BDT.

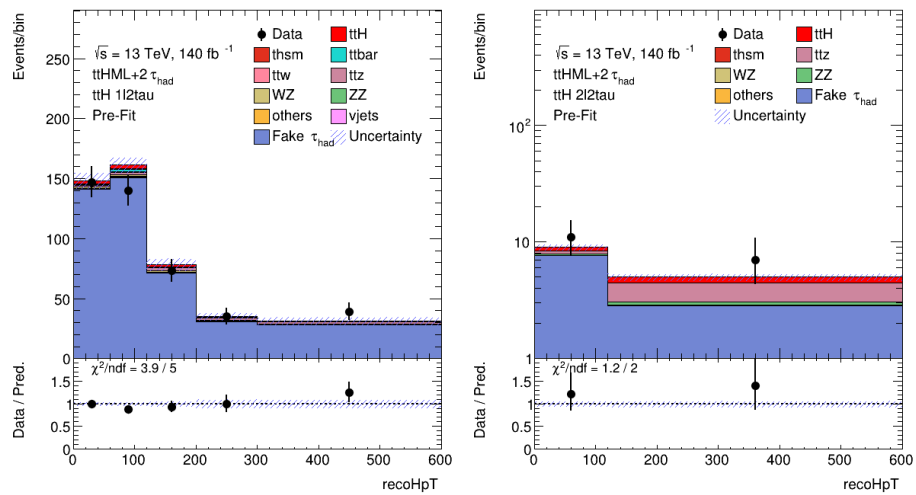


Figure 7.45: Background-like part of the $1\ell + 2\tau_{\text{had}}$ (left) and $2\ell + 2\tau_{\text{had}}$ (right) SRs, where a cut on the BDT score of maximum 0.1 is applied.

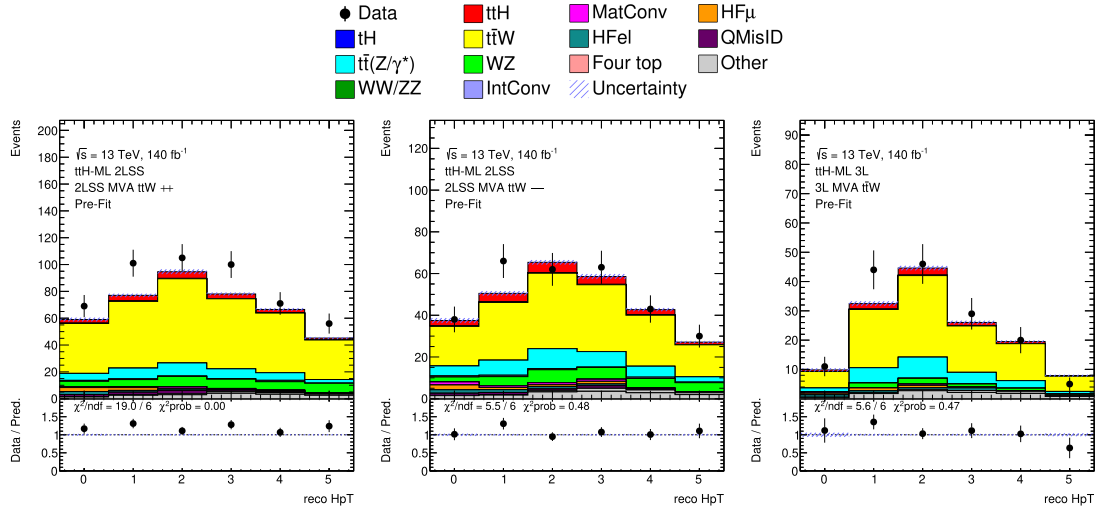


Figure 7.46: Reconstructed p_T^H distribution for the $t\bar{t}W$ CRs of the $2\ell\text{SS} + 0\tau_{\text{had}}$ channel ($t\bar{t}W$ ++ (left) and $t\bar{t}W$ -- (centre)) and of the $3\ell + 0\tau_{\text{had}}$ channel (right).

being very small. Additionally, it can be observed that the combined STXS signal strengths are compatible with 1. The compatibility test with a combined fit with the STXS signal strengths fixed to 1 is of 79 %. The potential bias on the STXS signal strengths of only fitting one inclusive $t\bar{t}W$ NF is therefore assessed to be minimal. As it is difficult to extrapolate the seen reconstructed p_T^H dependence from the CRs into the SRs, it was decided to keep one inclusive $t\bar{t}W$ NF.

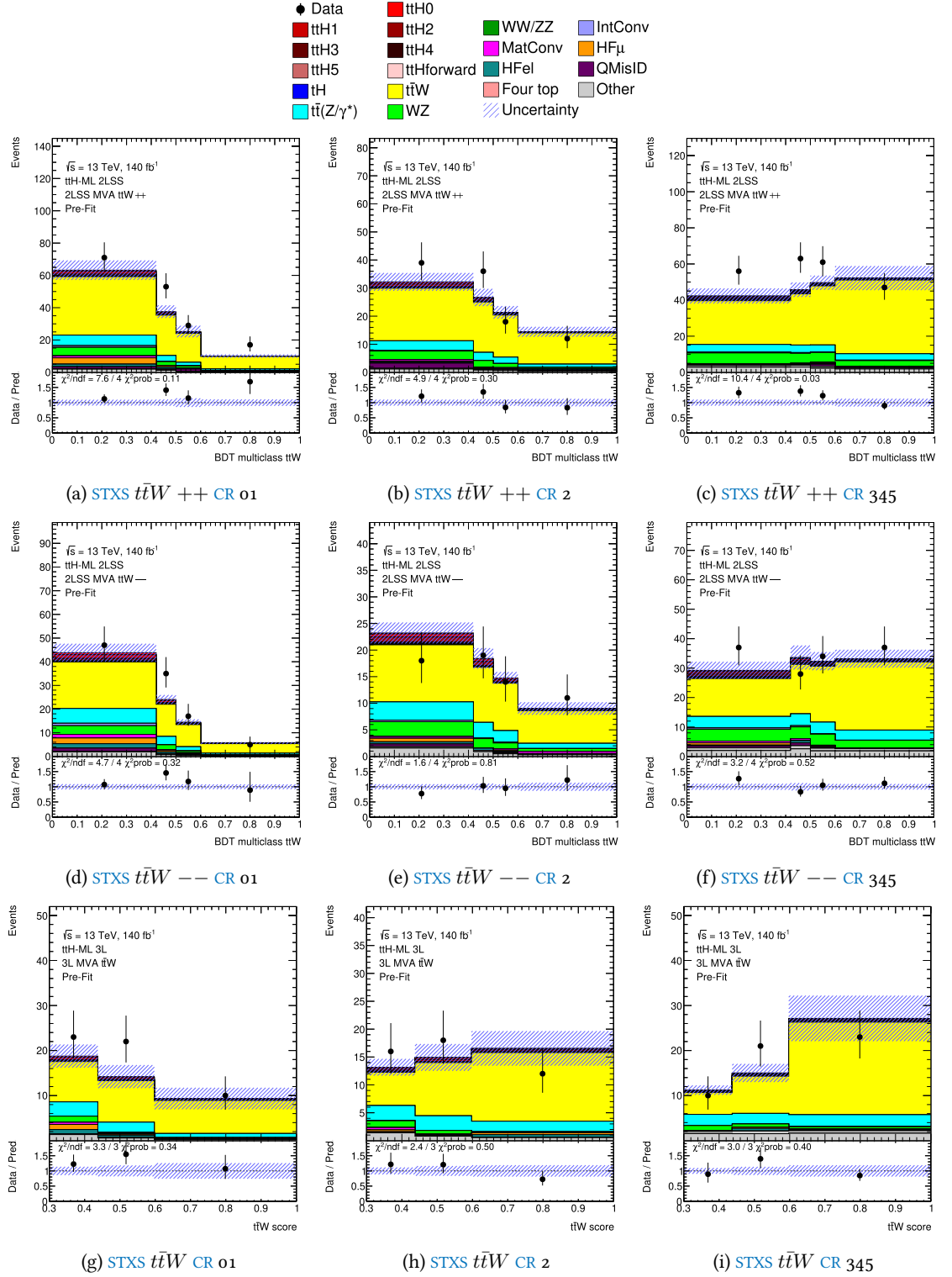


Figure 7.47: $t\bar{t}W$ CRs of the $2\ell\text{SS} + 0\tau_{\text{had}}$ channel ($t\bar{t}W$ ++ (top row) and $t\bar{t}W$ -- (second row)) and of the $3\ell + 0\tau_{\text{had}}$ channel (bottom row) split by reconstructed p_T^H .

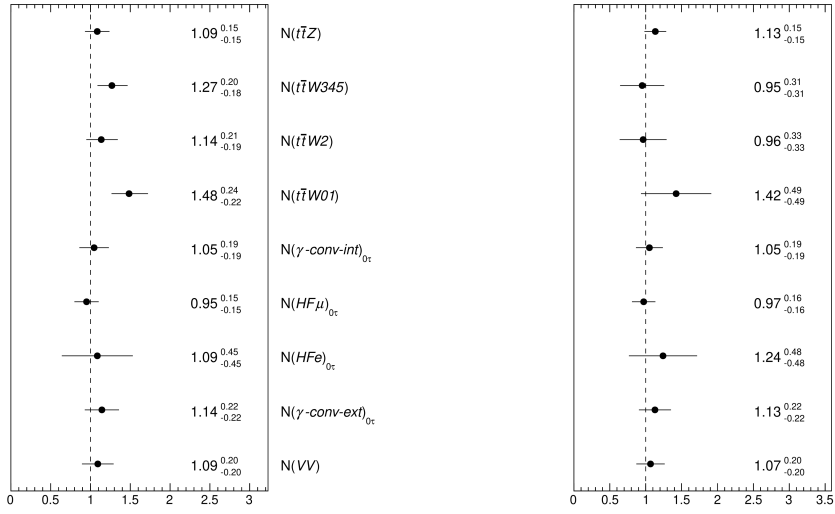


Figure 7.48: Fit results in the $2\ell_{SS} + 0\tau_{\text{had}}$ (left) and $3\ell + 0\tau_{\text{had}}$ (right) channels in a fit to data including only CRs with three STXS $t\bar{t}W$ NFs.

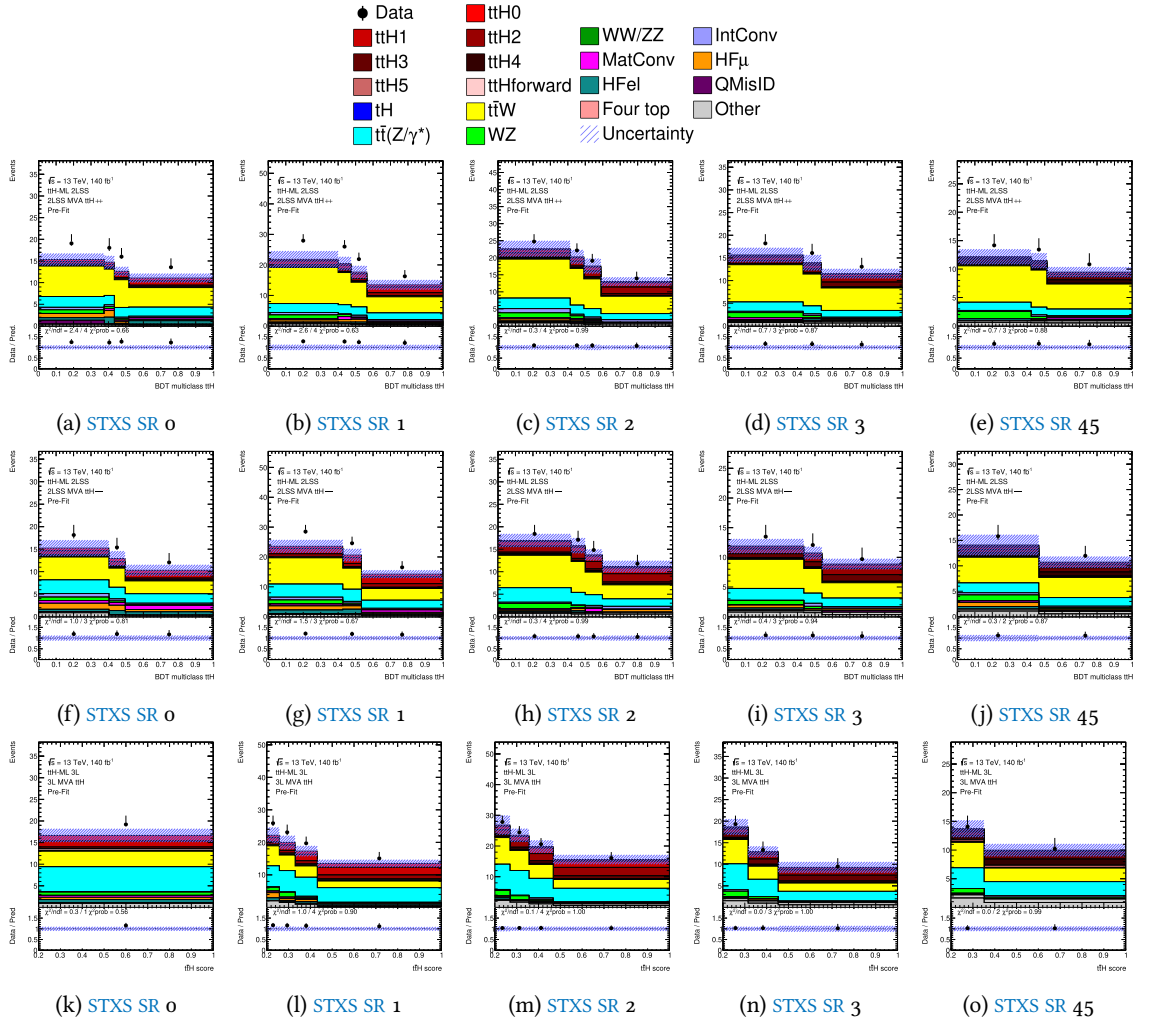


Figure 7.49: $t\bar{t}H$ STXS SRs of the $2\ell_{SS} + 0\tau_{\text{had}}$ channel ($t\bar{t}H$ ++ (top row) and $t\bar{t}H$ -- (second row) and of the $3\ell + 0\tau_{\text{had}}$ channel (bottom row) with pseudo-data, constructed by propagating the STXS $t\bar{t}W$ NFs into the SRs.

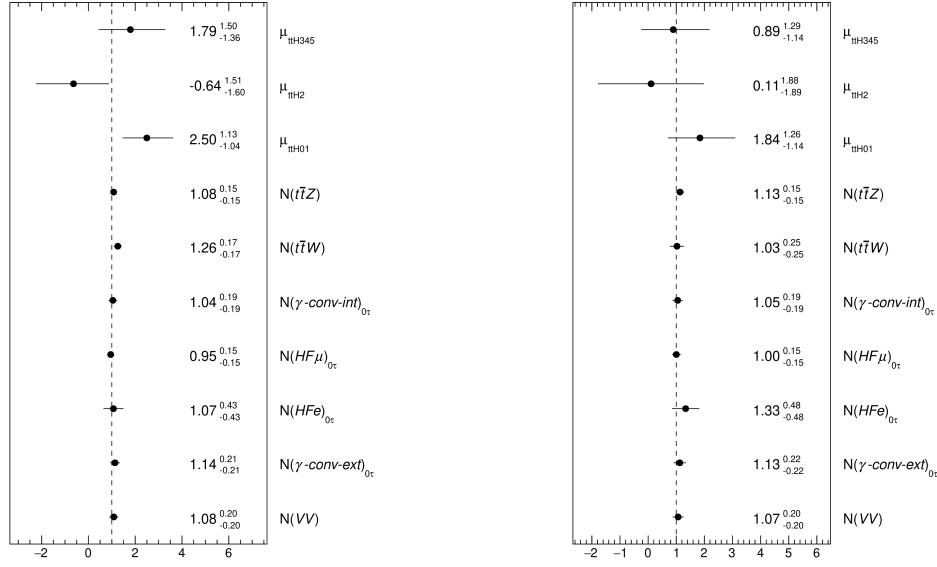


Figure 7.50: Fit results in the $2\ell_{\text{SS}} + 0\tau_{\text{had}}$ (left) and $3\ell + 0\tau_{\text{had}}$ (right) channels in a fit including data in the [CRs](#) and the pseudo-data in the [SRs](#).

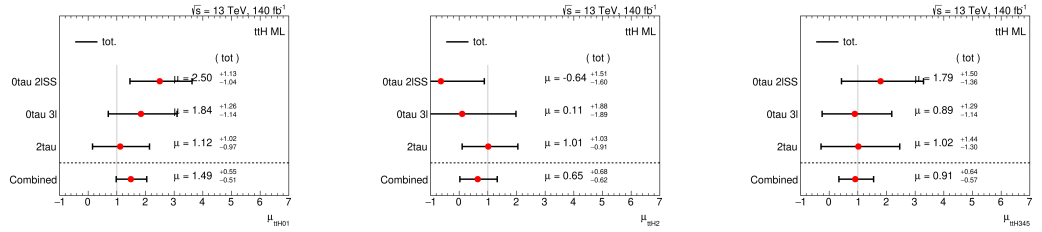


Figure 7.51: [STXS](#) signal strength results in a combined fit including data in the [CRs](#) and the pseudo-data in the [SRs](#).

7.11 Fit setup of the combined fit

All six analysis channels are combined into one global fit, where all the [NFs](#) and [NPs](#) are constrained simultaneously using all [SRs](#) and [CRs](#). For the [STXS](#) fit, as well as for the inclusive $t\bar{t}H$ signal strength measurement, the [STXS](#) setup, presented above, is used. In the inclusive fit, the different $t\bar{t}H$ [STXS](#) templates are scaled by one single $t\bar{t}H$ signal strength, while they are scaled by three separate signal strengths in the [STXS](#) fit.

All the included [SRs](#) are shown in Figures 7.52 to 7.56. Additionally, the [CRs](#) for $tHjb$ are shown in Figure 7.57. In the $0\tau_{\text{had}}$ and $1\tau_{\text{had}}$ channels, the backgrounds are constrained in separate regions and the [SRs](#) and $tHjb$ [CRs](#) are fully blinded. In the $2\tau_{\text{had}}$ and 4ℓ channels, where the [SRs](#) include bins sensitive to the backgrounds, only bins with a signal to background ratio above 15 % are blinded.

The combined fit requires the full harmonisation of all the [NFs](#) and [NPs](#). For prompt background processes being an important contribution in at least one of the channels, a free floating

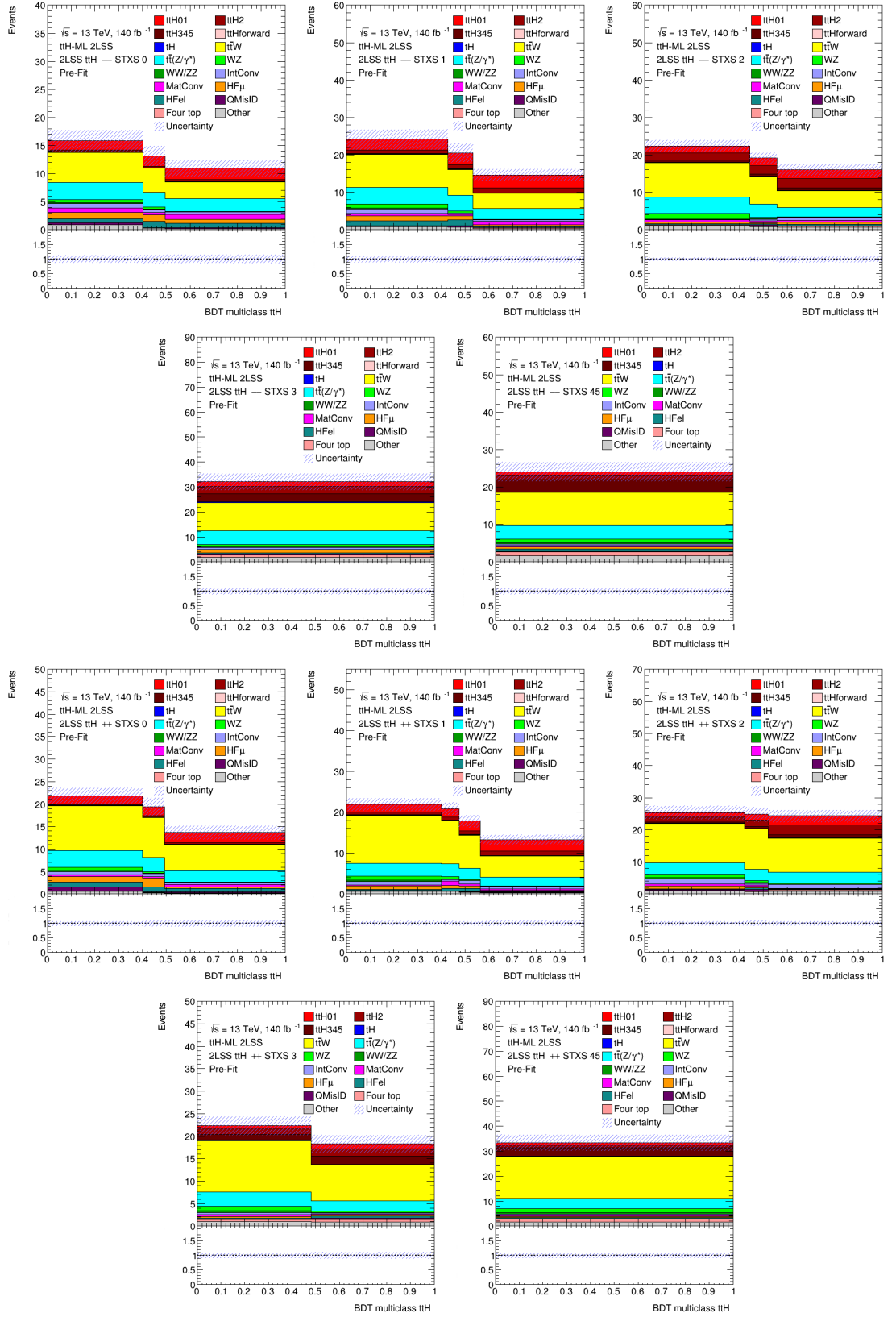


Figure 7.52: STXS SRs for the $2\ell SS + 0\tau_{had}$ channel. The uncertainty bands include statistical and systematic uncertainties.

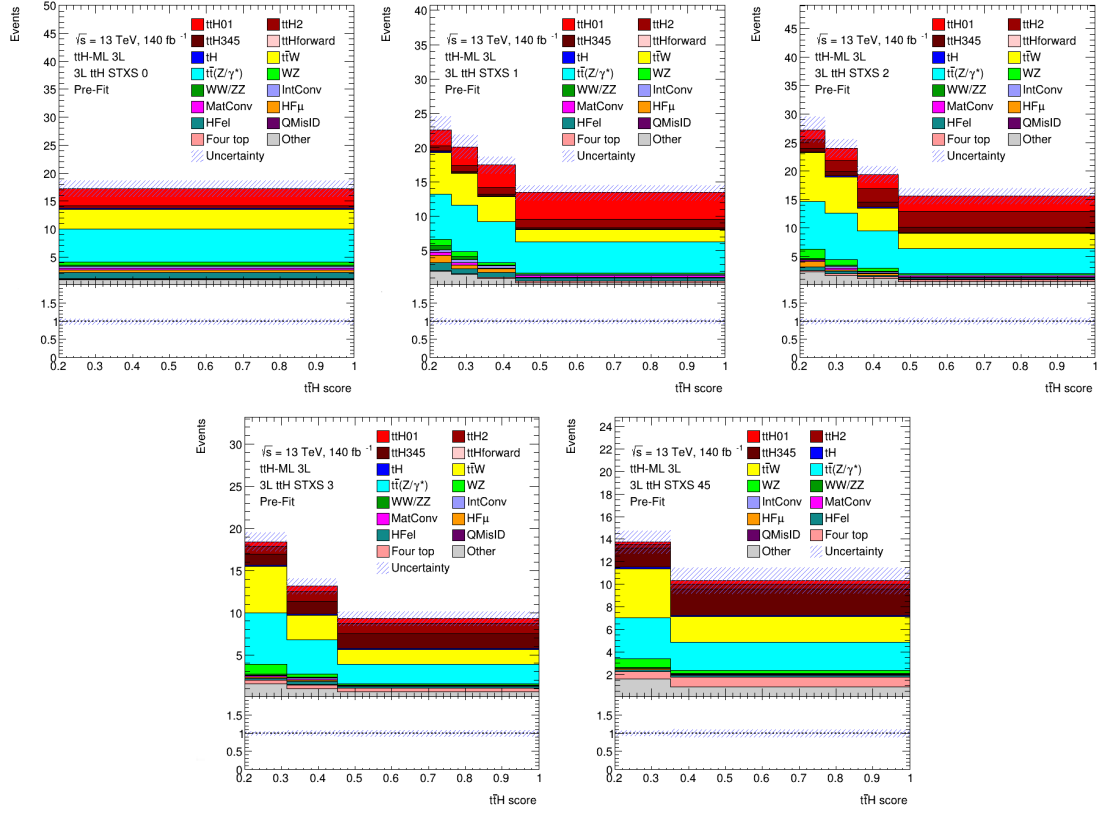


Figure 7.53: STXS SRs for the $3\ell+0\tau_{\text{had}}$ channel. The uncertainty bands include statistical and systematic uncertainties.

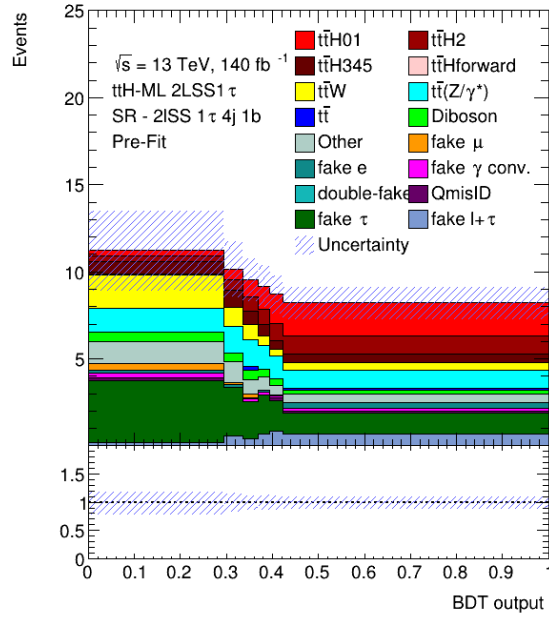
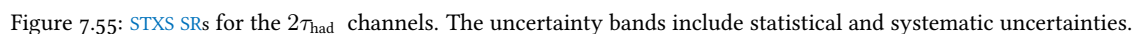


Figure 7.54: SR for the $2\ell\text{SS}+1\tau_{\text{had}}$ channel. The uncertainty bands include statistical and systematic uncertainties.



NFs scaling fake backgrounds are kept uncorrelated across all channels, as the origin of the fake/non-prompt leptons in the different channels heavily differs. As a result, different fake estimation techniques and different fake lepton working points are used. Studies where the fake NFs are correlated were performed and no large impact was seen. In the $1\tau_{\text{had}}$ channel, the fake components of $t\bar{t}W$ and $t\bar{t}Z$ are, additionally to the dedicated fake NFs , scaled with the global $t\bar{t}W$ and $t\bar{t}Z$ NFs .

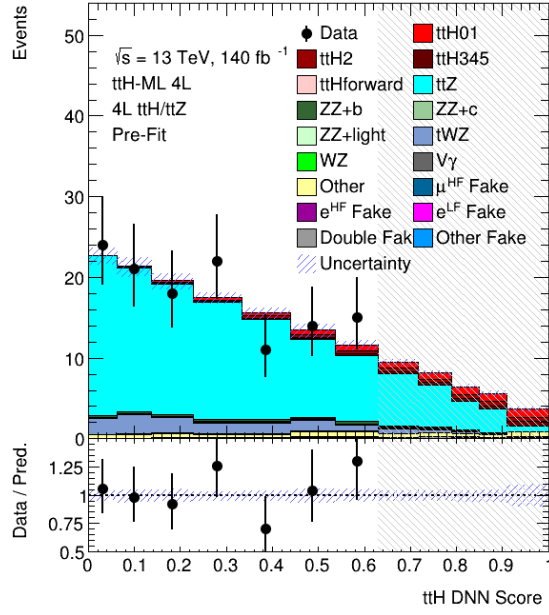


Figure 7.56: SR for the 4ℓ channel. The uncertainty bands include statistical and systematic uncertainties.

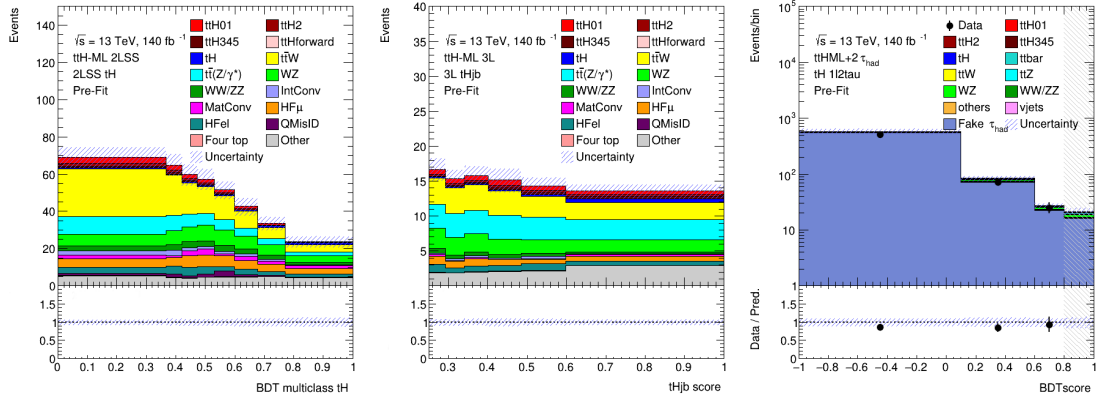


Figure 7.57: CRs for $tHj\ell b$ for the $2\ell_{\text{SS}} + 0\tau_{\text{had}}$ (left), $3\ell + 0\tau_{\text{had}}$ (centre) and $1\ell + 2\tau_{\text{had}}$ (right) channels. The uncertainty bands include statistical and systematic uncertainties.

Additionally, the systematics models of the different channels are fully harmonised. Corresponding systematic uncertainties between the channels are treated as fully correlated, except if they are related to fake backgrounds.

7.12 Validation of the background estimation in the CRs

In this section, the normalisation of the backgrounds is studied in a combined fit to data including only the CRs and fitting only the background NFs, the $t\bar{t}H$ NF being fixed to 1. As the CRs are designed to target the different backgrounds, they are expected to drive the sensitivity to the background NFs. The CRs have $t\bar{t}H$ signal yields corresponding to less than 15 % of the total event yield in every bin. For the $2\tau_{\text{had}}$ and 4ℓ channels, where some of the CRs are included in the SRs, additionally to the CRs, the SRs are added to the fit with a blinding threshold of 15 %. Bins with a signal to background ratio above 15 % are dropped.

7.12.1 Background only fit results

The observed values for the NFs of the background components are shown in Figure 7.58. Most of the NFs are, as expected, compatible with 1, and compatible with the results obtained from the single channel fits. The obtained $t\bar{t}W$ and $t\bar{t}Z$ NFs are additionally in agreement with the results obtained in the dedicated $t\bar{t}W$ analysis ($N(t\bar{t}W) = 1.18 \pm 0.11$ and $N(t\bar{t}Z) = 1.16 \pm 0.15$).

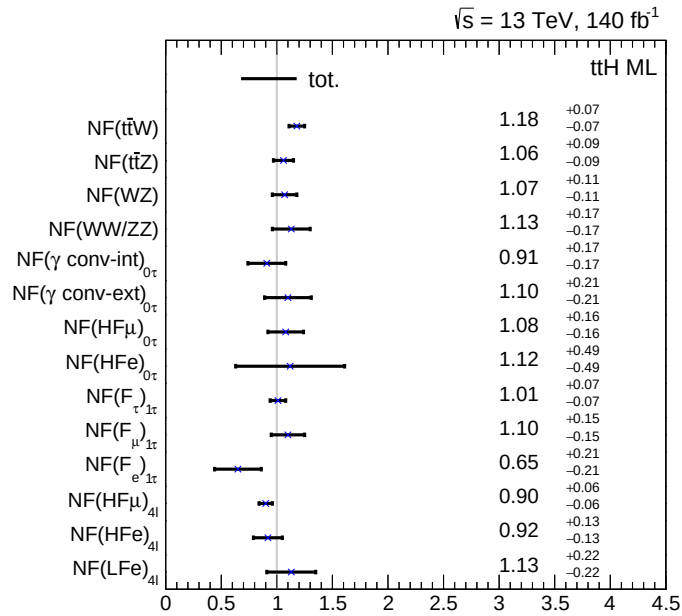


Figure 7.58: Background NFs obtained in a combined fit to data including only the CRs.

Figure 7.59 shows the correlation of the NFs and NPs in the combined fit. Due to the construction of the CRs, most of the NFs and NPs are well separated. Some high correlations are observed, which, however, mainly appear between NPs and NFs inside a single analysis channel. These cor-

relations are understood and originate from small backgrounds which are not well separated or from normalisation effects.

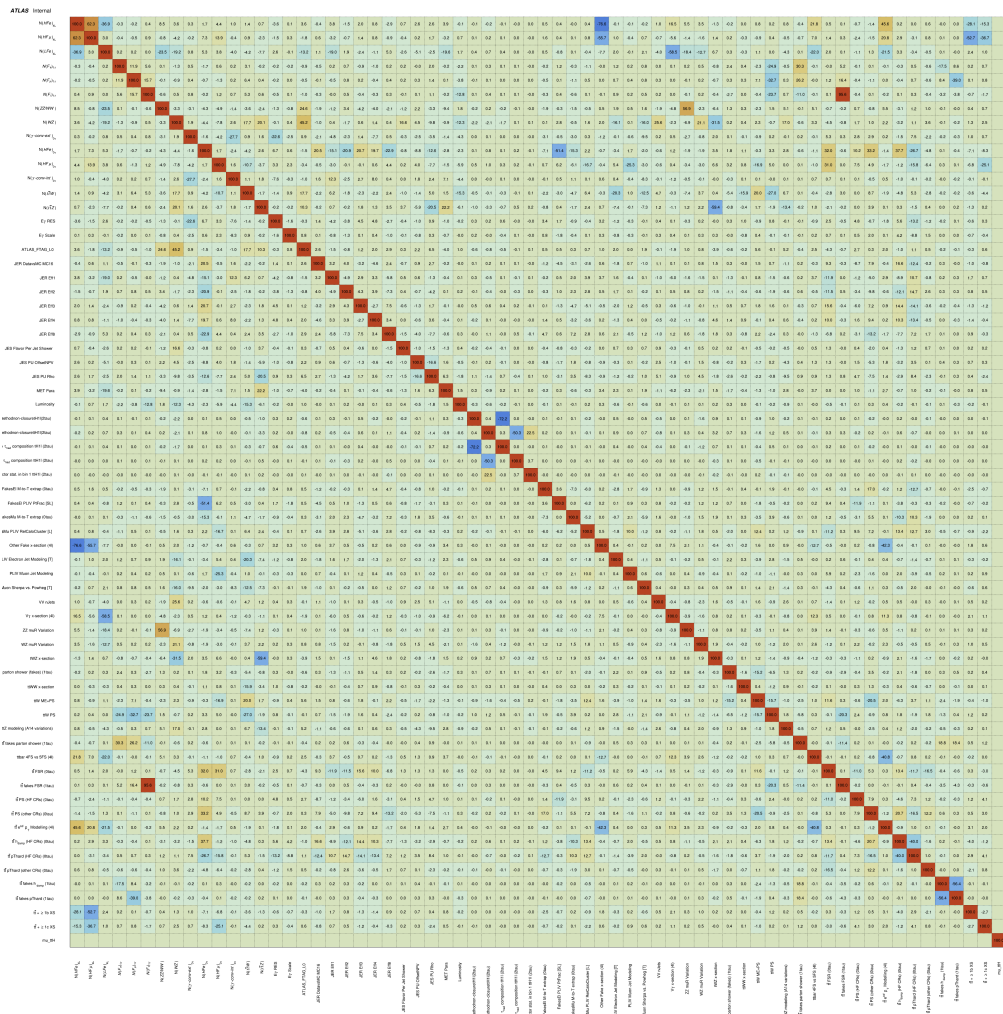


Figure 7.59: Correlation matrix of the NFs and NPs in a fit to data including only the CRs (correlation threshold set to 10%).

As seen in Figure 7.60, a few pulls and constraints in the systematics are observed. Figure 7.61 shows a comparison between the NPs in the single channels and in the combined fit, only for the NPs where some constraints or pulls are observed. These pulls and constraints were investigated in detail by the individual channels but are beyond the scope of this discussion. No large pulls or constraints are induced by the combination of the channels.

7.12.2 Post-fit data MC agreement

The goodness-of-fit corresponds to 94.4%. The post-fit data MC agreement is shown in the following for all the CRs included in the fit.

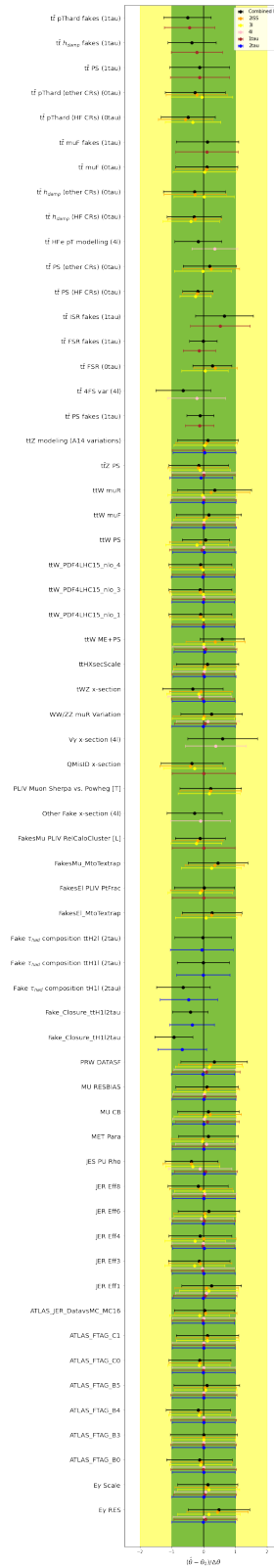


Figure 7.61: Comparison of the constraints and pulls of the NPs in the combined and single channel fits to data including only the CRs. Only NPs which are either pulled or over/under-constrained by more than 0.1 are shown.

$0\tau_{\text{had}}$ channels

The post-fit data **MC** agreement in the prompt $0\tau_{\text{had}}$ **CRs**, sharing the same pre-selection as the **SRs** but split by **BDT** output cuts, are shown in Figure 7.62 for the $2\ell\text{SS} + 0\tau_{\text{had}}$ channel and in Figure 7.63 for the $3\ell + 0\tau_{\text{had}}$ channel. No significant mismodelling is observed, the important $t\bar{t}W$ normalisation mismodelling being corrected by the fit.

Figure 7.64 shows the common $0\tau_{\text{had}}$ cut-based prompt **CRs** and Figures 7.65 and 7.66 the fake/non-prompt **CRs**. Most of these **CRs** only contain the event yield or very few bins, but overall a good post-fit agreement between the data and expectation is found.

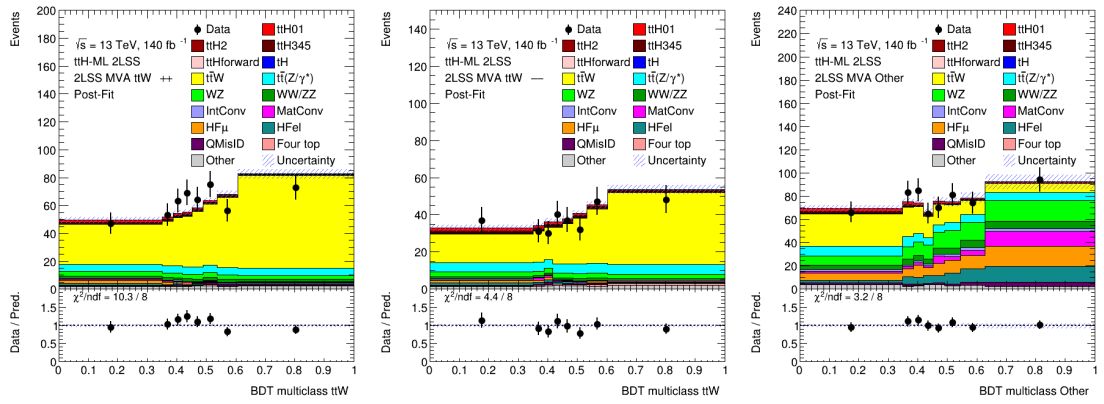


Figure 7.62: Post-fit distributions compared to data in the $2\ell\text{SS} + 0\tau_{\text{had}}$ prompt **BDT** based **CRs**. The uncertainty bands include statistical and systematic uncertainties.

$1\tau_{\text{had}}$ channel

The post-fit agreement between data and **MC** in the $1\tau_{\text{had}}$ fake/non-prompt **CRs** is shown in Figure 7.67. Overall a very good modelling of the data is observed.

$2\tau_{\text{had}}$ channel

The $2\tau_{\text{had}}$ regions are shown in Figures 7.68 and 7.69. The $2\tau_{\text{had}}$ channels do not have dedicated **CRs**, except for $tHj\bar{b}$, which is also blinded, but the **SRs** are binned in the **BDT** output, with the low **BDT** bins being dominated by backgrounds. The dominant fake τ_{had} background is fully data-driven and implement at pre-fit level. All other backgrounds constrained in the fit are subdominant, leading to no large changes pre and post background only fit.

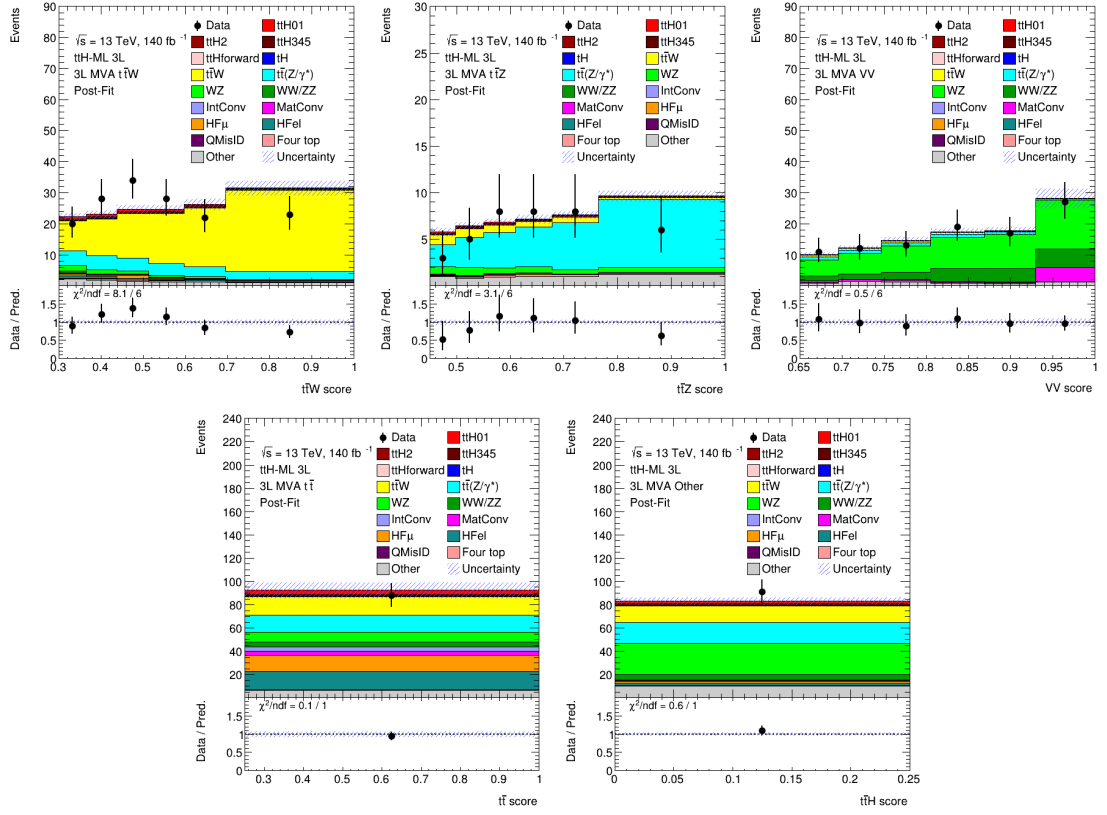


Figure 7.63: Post-fit distributions compared to data in the $3\ell + 0\tau_{\text{had}}$ prompt BDT based CRs. The uncertainty bands include statistical and systematic uncertainties.

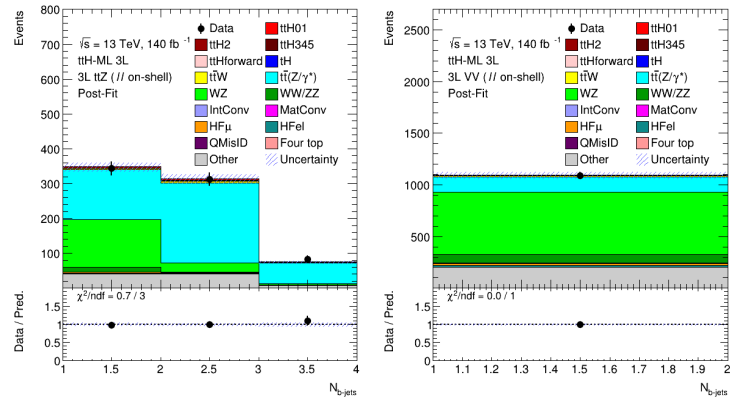


Figure 7.64: Post-fit distributions compared to data in the $0\tau_{\text{had}}$ prompt cut-based CRs. The uncertainty bands include statistical and systematic uncertainties.

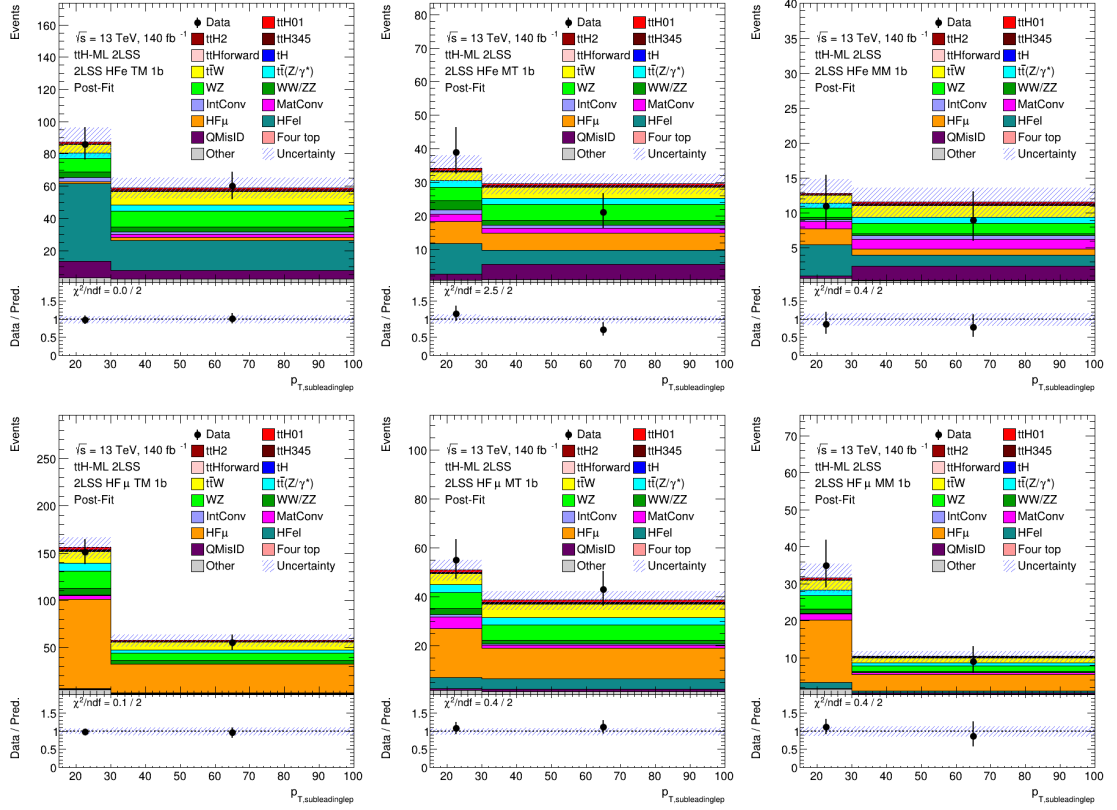


Figure 7.65: Post-fit distributions compared to data in the 07_{had} HF fake CRs. The uncertainty bands include statistical and systematic uncertainties.

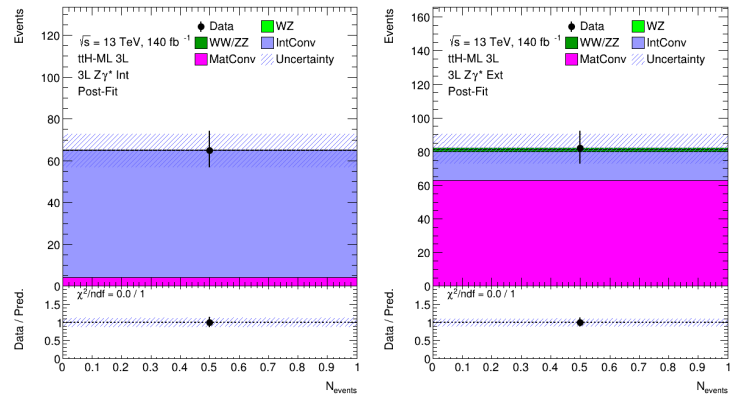


Figure 7.66: Post-fit distributions compared to data in the 07_{had} conversion fake CRs. The uncertainty bands include statistical and systematic uncertainties.

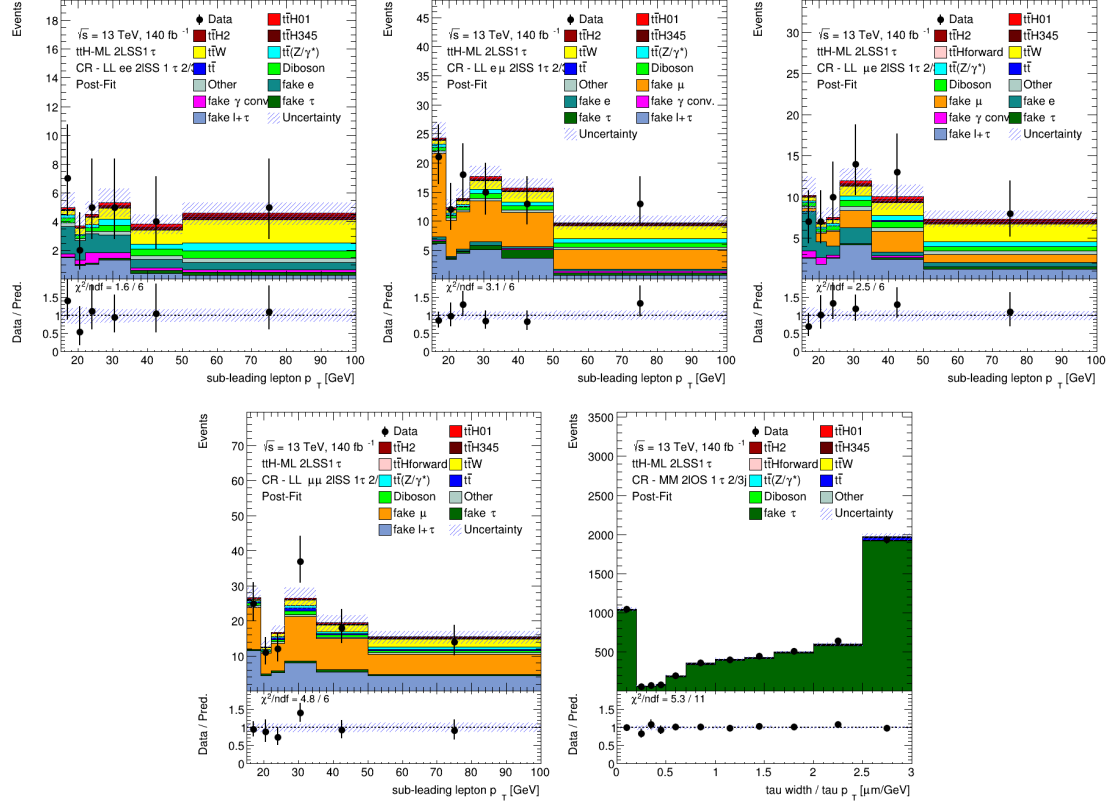


Figure 7.67: Post-fit distributions compared to data in the $2\ell\text{SS}+1\tau_{\text{had}}$ fake/non-prompt CRs. The uncertainty bands include statistical and systematic uncertainties.

4ℓ channel

Finally, the post-fit data MC agreement for the 4ℓ channel is shown in Figure 7.70. While the highest DNN bins of the SRs are blinded, all other bins and the CRs show a good agreement between the data and the MC.

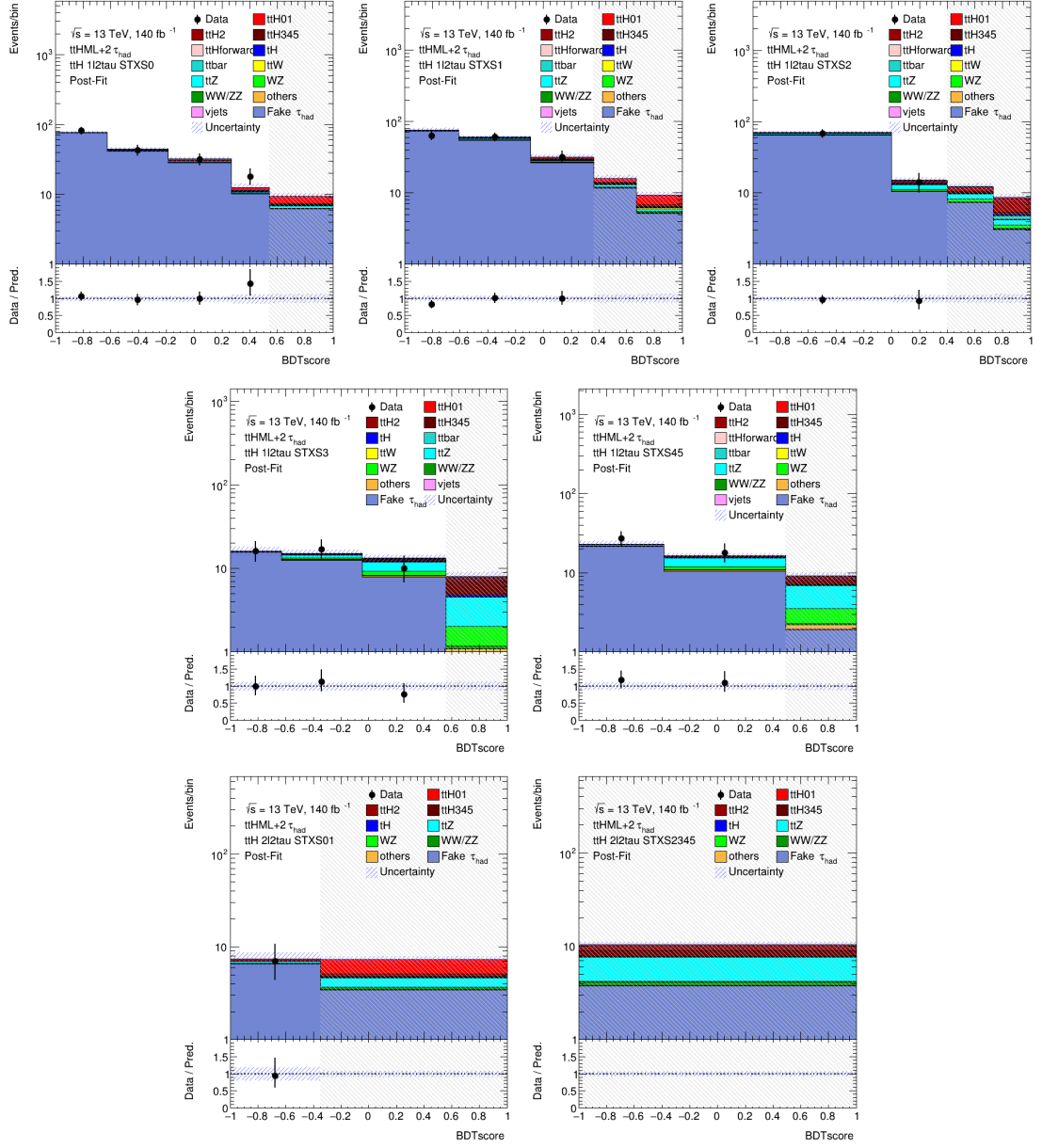


Figure 7.68: Post-fit distributions compared to data in the $1\ell+27_{\text{had}}$ and $2\ell+27_{\text{had}}$ SRs, with unblinded background-like bins. The uncertainty bands include statistical and systematic uncertainties.

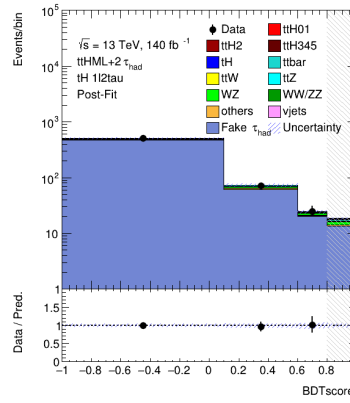


Figure 7.69: Post-fit distributions compared to data in the $1\ell+27_{\text{had}}$ CR, with unblinded background-like bins. The uncertainty bands include statistical and systematic uncertainties.

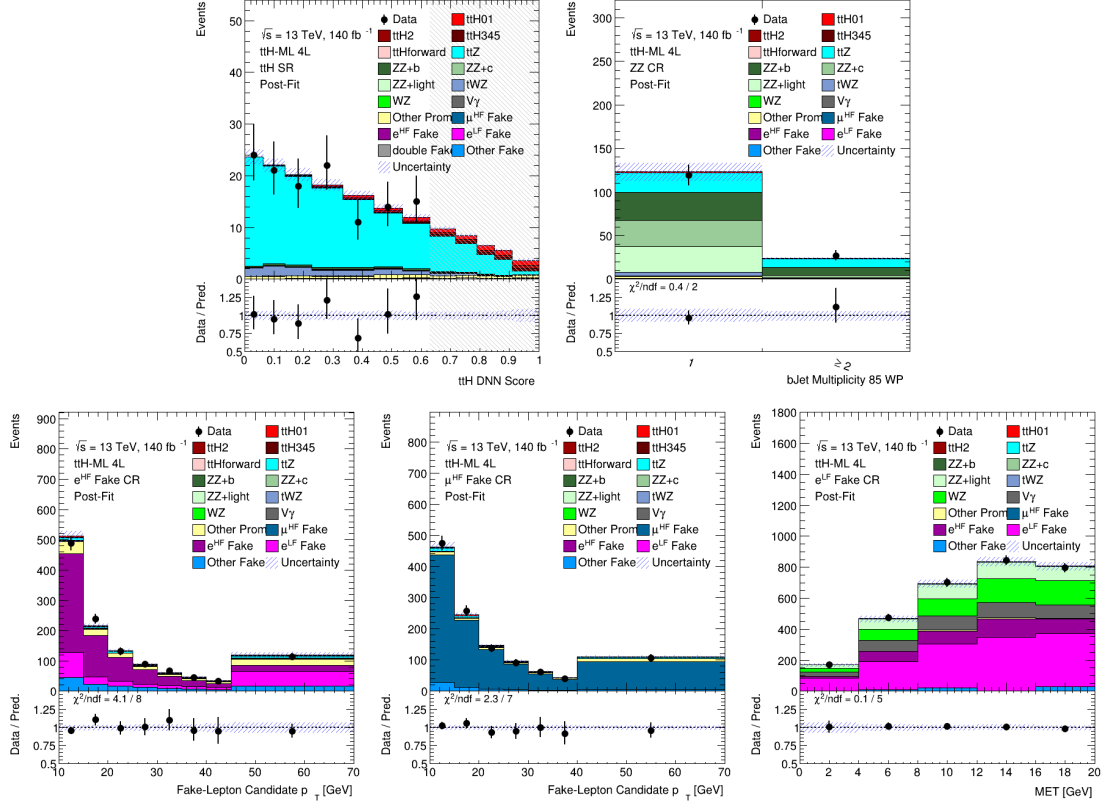


Figure 7.70: Post-fit distributions compared to data in the 4ℓ SR, with unblinded background-like bins and in the HF and LF fake CRs. The uncertainty bands include statistical and systematic uncertainties.

7.13 Expected results

In the following section, the expected sensitivity of different fit setups is shown. The fit is fully blinded and only Asimov data are used. First, the inclusive $t\bar{t}H$ signal strength fit is considered (see Section 7.13.1) in a setup where the normalisation of the $tHjb$ process is fixed to SM and in a setup where the $tHjb$ normalisation is determined by the fit. Finally, the expected results for the STXS fit are considered in Section 7.13.2.

7.13.1 Inclusive $t\bar{t}H$ signal strength measurement

Fit free floating the $t\bar{t}H$ signal strength with fixed $tHjb$ signal strength

First, a combined inclusive signal strength measurement is considered, where the sensitivity to the $t\bar{t}H$ normalisation is studied.

The fitted $t\bar{t}H$ signal strengths are shown in Figure 7.71. Additionally to the combined result, the sensitivity of the different channels to $\mu_{t\bar{t}H}$ is shown. These numbers are computed by defining separate $t\bar{t}H$ signal strengths per analysis channel but constraining the backgrounds

simultaneously in all channels. The expected uncertainty of $\mu_{t\bar{t}H} = 1.0^{+0.24}_{-0.21}$ shows a large improvement of the combined result with respect to the results of the individual channels. This result would correspond to the measurement of $t\bar{t}H$ with a significance of 5.3σ .

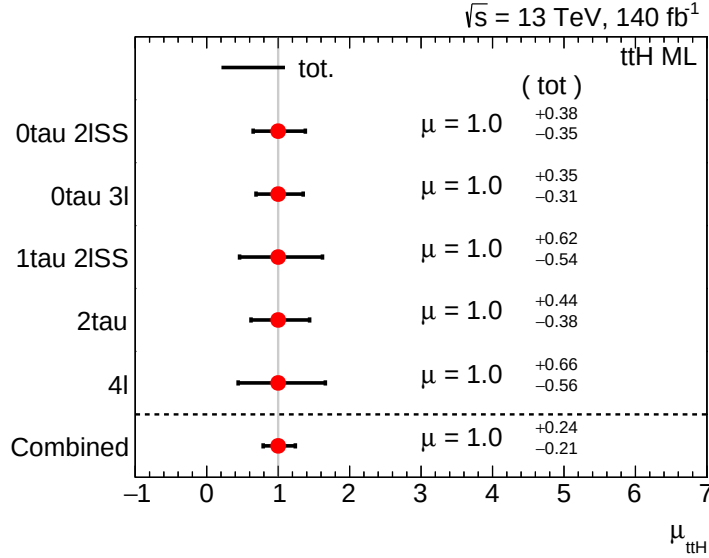


Figure 7.71: $t\bar{t}H$ signal strength results of a combined inclusive signal strength fit to Asimov data.

The NFs of the free floating background components are shown in Figure 7.72. This setup cannot be directly compared with the results in the background only fit in Section 7.12, as in this case Asimov data instead of real data were used. The uncertainties on the background NFs are, however, mainly unchanged when adding the SRs to the fit.

The correlation matrix, shown in Figure 7.73, shows some large anti-correlations of the $t\bar{t}H$ normalisation with the $t\bar{t}W$ and $t\bar{t}Z$ NFs , as well as with the $t\bar{t}H$ theory cross-section scale uncertainty. These correlations are expected and observed to be reduced with respect to the partial Run 2 *ATLAS* $t\bar{t}H$ ML analysis, demonstrating that the additional data statistics have been exploited. The background NFs and NPs show similar correlations as in the background only fit to data.

The ranking of the impact of the systematic uncertainties is shown in Figure 7.74. The highest ranked uncertainties are the $t\bar{t}H$ theory cross-section scale and PDF α_S uncertainties, which affect the $t\bar{t}H$ normalisation, as well as the $t\bar{t}W$ and $t\bar{t}Z$ NFs , $t\bar{t}W$ and $t\bar{t}Z$ being dominant backgrounds in several analysis channels.

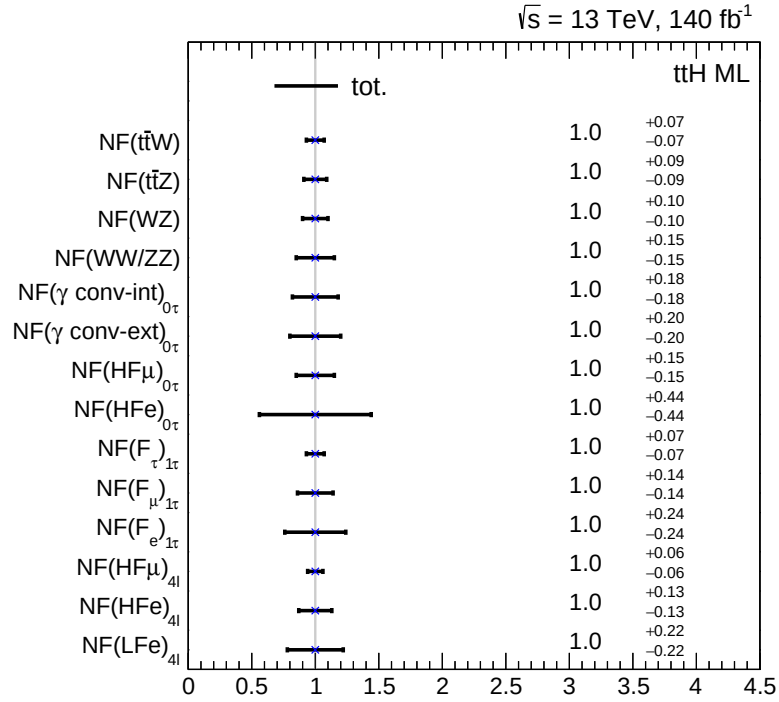


Figure 7.72: Background NF results of a combined inclusive signal strength fit to Asimov data.

Fit free floating the $t\bar{t}H$ and $tHjb$ signal strengths

Compared to the fit setup presented above, where the $tHjb$ normalisation is fixed to SM, another fit is performed where additionally to $\mu_{t\bar{t}H}$, the sensitivity to μ_{tHjb} is determined. The results are shown in Figure 7.75. The expected uncertainties on μ_{tHjb} are $1.0^{+4.13}_{-3.92}$. Additionally, free floating the $tHjb$ normalisation only slightly decreases the sensitivity to $\mu_{t\bar{t}H}$ ($1.0^{+0.24}_{-0.22}$ instead of $1.0^{+0.24}_{-0.21}$) and has no effect on the determination of the background NFs (see Figure 7.76).

Figure 7.77 shows the ranking of the impact of the systematics on $\mu_{t\bar{t}H}$ and μ_{tHjb} . The ranking for $\mu_{t\bar{t}H}$ is very similar to the case where μ_{tHjb} is fixed to SM, except that μ_{tHjb} is now ranked third (having a correlation of -19% to $\mu_{t\bar{t}H}$). For μ_{tHjb} , the $t\bar{t}$ modelling uncertainties in the $0\tau_{\text{had}}$ $tHjb$ CRs, as well as $\mu_{t\bar{t}H}$ have the highest impact.

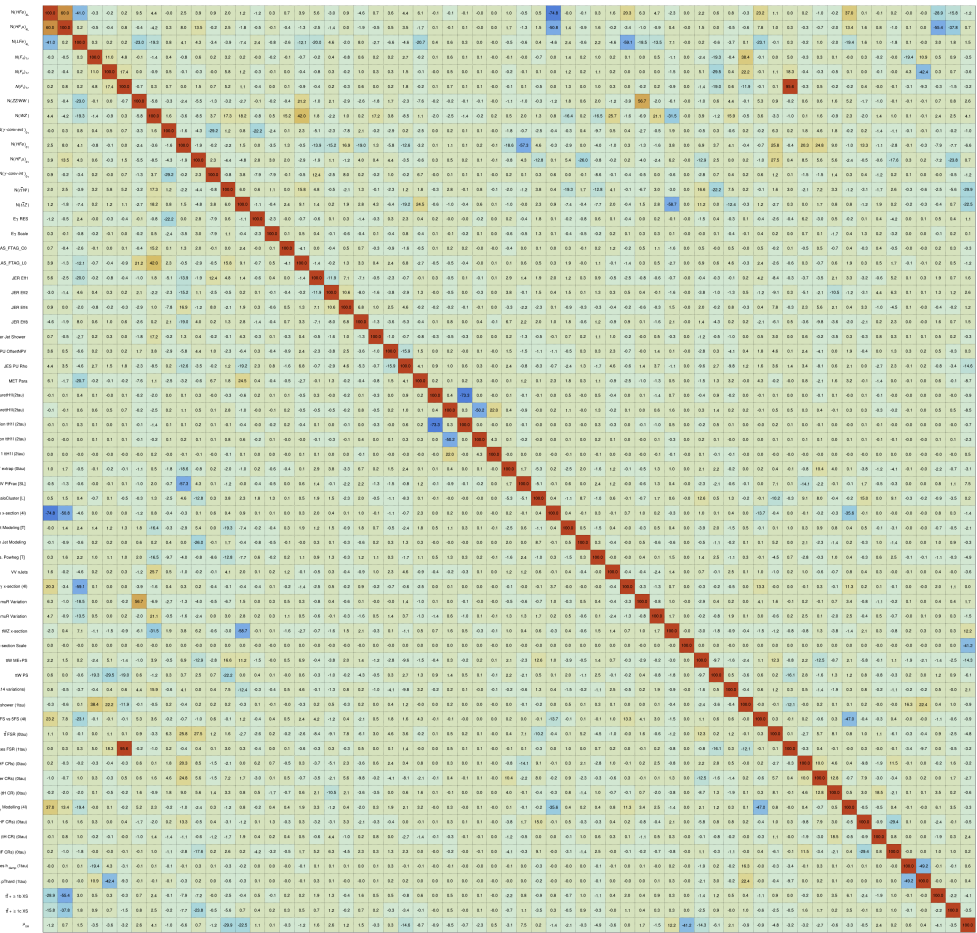


Figure 7.73: Correlation matrix of the **NFs** and **NP**s in a combined inclusive signal strength fit to Asimov data (correlation threshold set to 10 %).

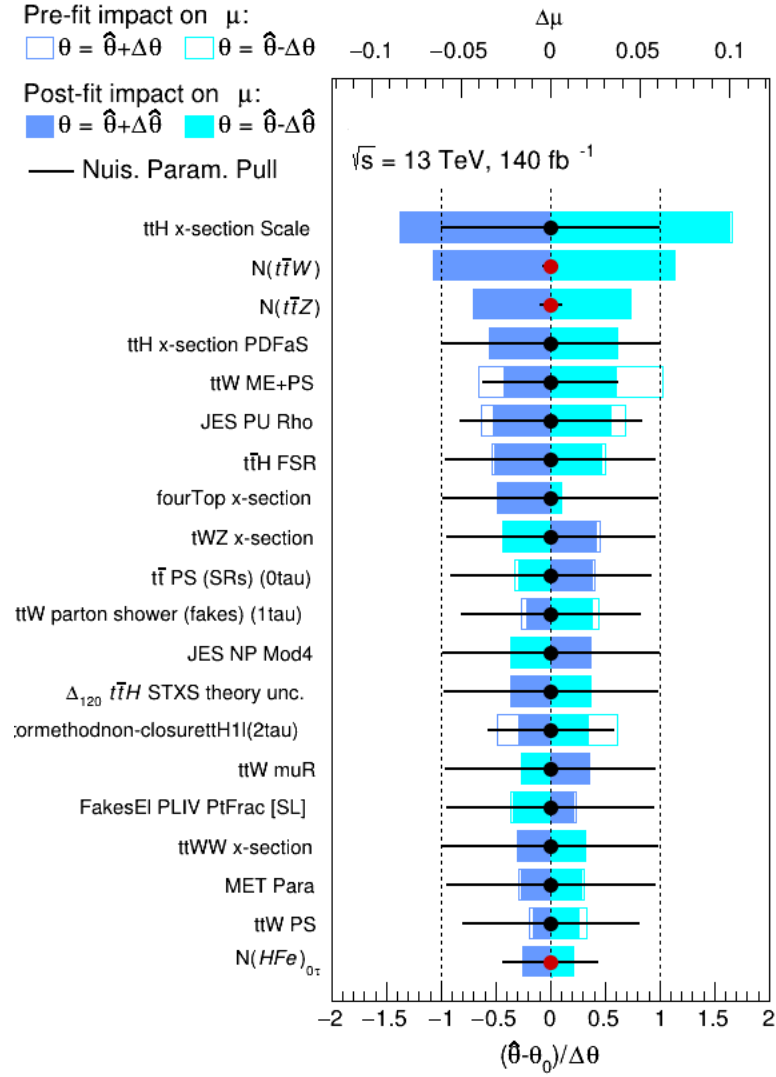


Figure 7.74: Ranking of the impact of the 20 leading systematic uncertainties on the $t\bar{t}H$ signal strength in a combined inclusive signal strength fit to Asimov data. The blue empty and solid rectangles show the impacts on $\mu_{t\bar{t}H}$ at pre-fit and post-fit level respectively, with respect to the axis at the top. The impact is defined as the difference between the fitted values of $\mu_{t\bar{t}H}$ in a nominal fit and in a fit where the NP is fixed to its best-fit value plus or minus its uncertainty. The black points correspond to the pulls of the NPs relative to zero and the red points to the fitted values of the background NFs with relative to one, with respect to the bottom axis.

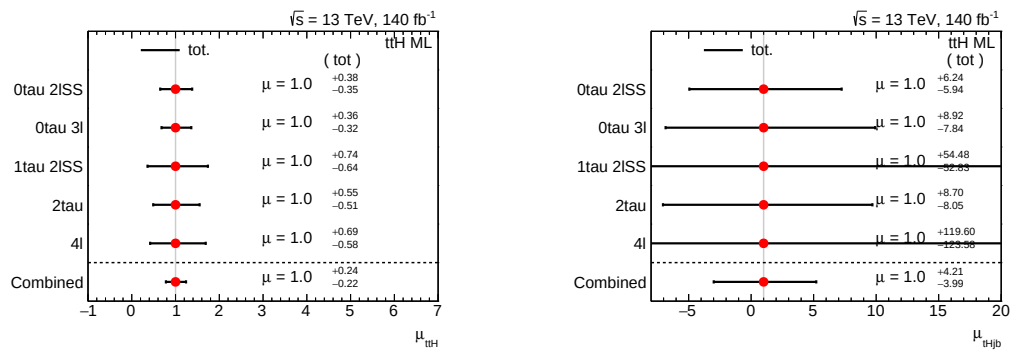


Figure 7.75: $t\bar{t}H$ and $tHjb$ signal strength results of a combined inclusive signal strength fit to Asimov data with μ_{tHjb} free floating.

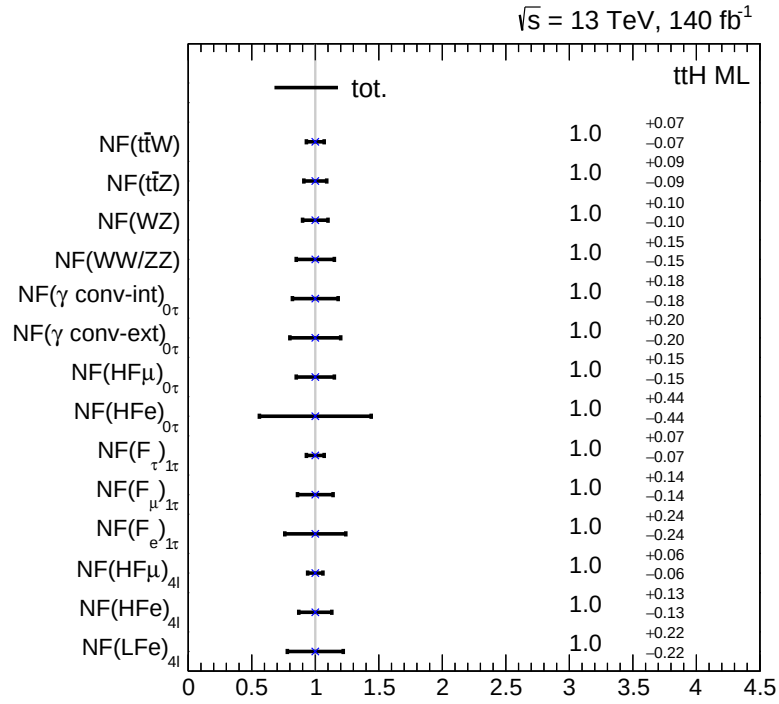


Figure 7.76: Background NF results of a combined inclusive signal strength fit to Asimov data with μ_{tHjb} free floating.

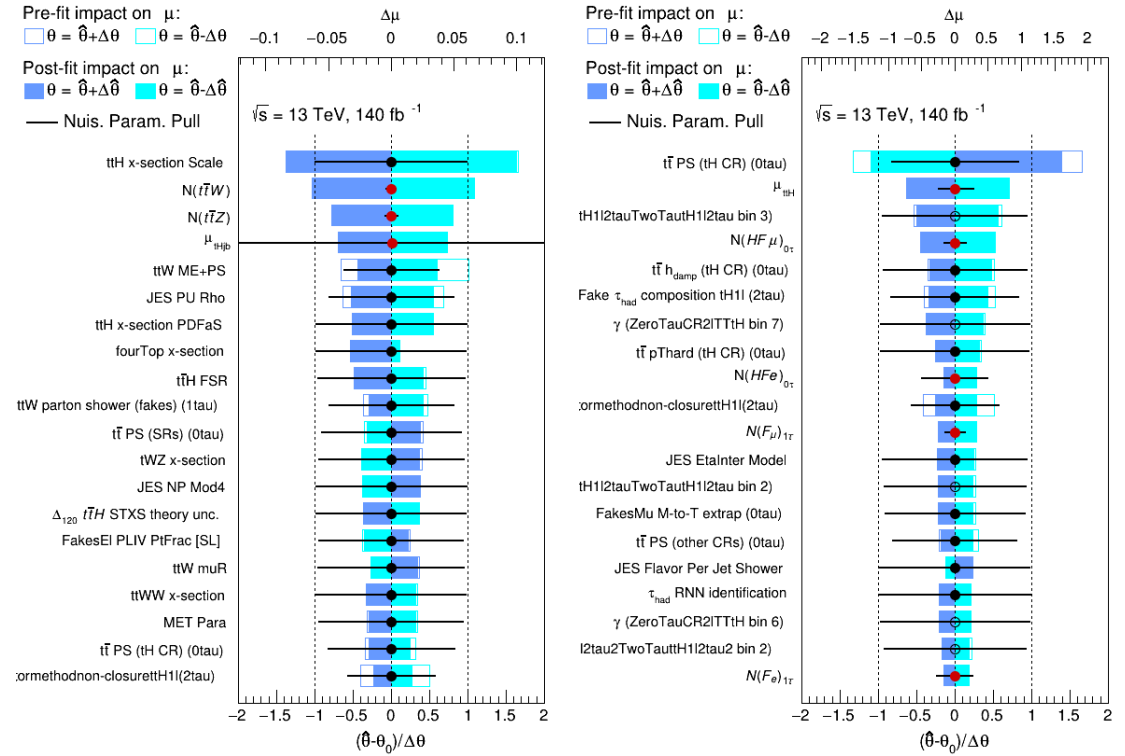


Figure 7.77: Ranking of the impact of the systematic uncertainties on the $t\bar{t}H$ and $tHjb$ signal strengths in a combined inclusive signal strength fit to Asimov data with μ_{tHjb} free floating.

7.13.2 STXS measurement

The expected results for the three measured **STXS** signal strengths are shown in Figure 7.78. As the $1\tau_{\text{had}}$ and 4ℓ channels do not include a dedicated p_T^H reconstruction, they are not sensitive to the **STXS** signal strengths. It can be seen that the combination of the channels brings a large improvement in all three **STXS** signal strengths. As described previously, the $2\tau_{\text{had}}$ channels have a much smaller statistical power than the $0\tau_{\text{had}}$ channels, but a more diagonal Higgs p_T reconstruction. The low migrations between the different **STXS** bins help to reduce the correlations between the **STXS** signal strengths introduced by the $0\tau_{\text{had}}$ channels. Similar to the inclusive fit, a relatively large anti-correlation of the **STXS** signal strengths to the $t\bar{t}H$ cross-section normalisation uncertainty and to the $t\bar{t}W$ and $t\bar{t}Z$ **NFs** can be observed in Figure 7.79.

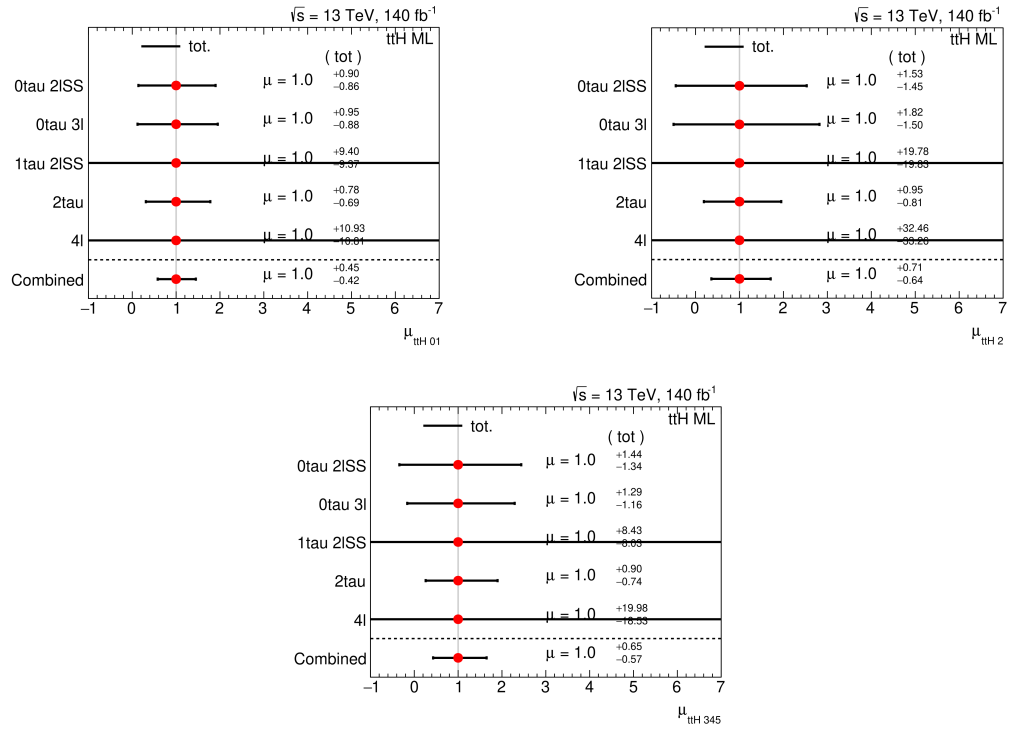
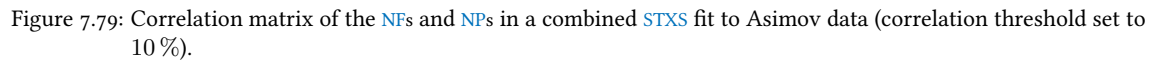


Figure 7.78: $t\bar{t}H$ **STXS** signal strength results of a combined **STXS** fit to Asimov data.

The ranking of the impact of the systematics on the different **STXS** signal strengths is shown in Figure 7.80. As expected from the correlations, the other **STXS** signal strengths, the $t\bar{t}H$ cross-section scale uncertainty, as well as the $t\bar{t}W$ and $t\bar{t}Z$ **NFs** are the dominant uncertainties. Compared to the inclusive measurement, the **HF** electron fake **NF** appears relatively high in the ranking. This is caused by the p_T dependence of the **HF** electron fakes and induced correlations to the **STXS** signal strengths (-10.6% to $\mu_{t\bar{t}H01}$ and 7.8% to $\mu_{t\bar{t}H2}$) which cancel out in the inclusive fit.



The sensitivity to the NFs of the background components, shown in Figure 7.81, are similar to the results in the inclusive fit.

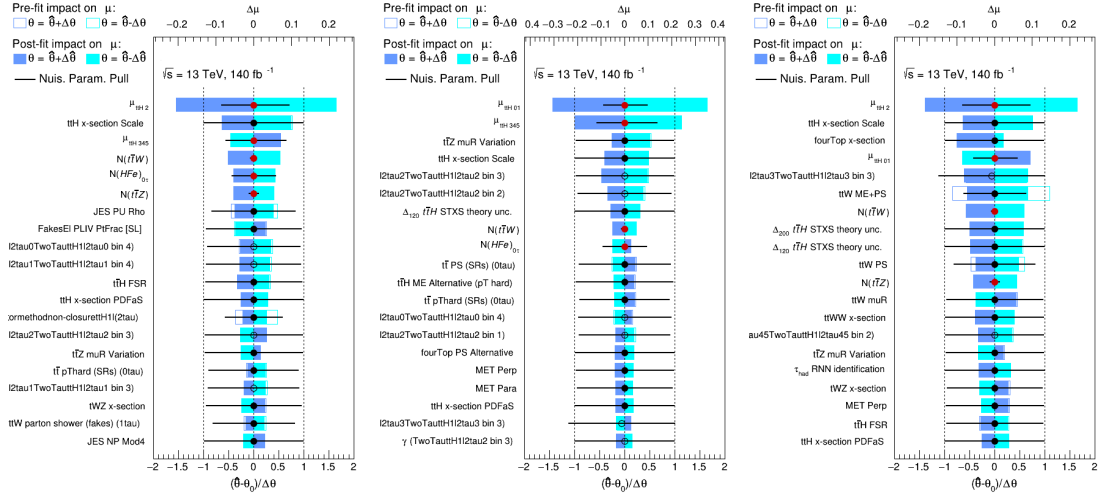


Figure 7.80: Ranking of the impact of the systematic uncertainties on the $t\bar{t}H$ STXS signal strengths in a combined STXS fit to Asimov data.

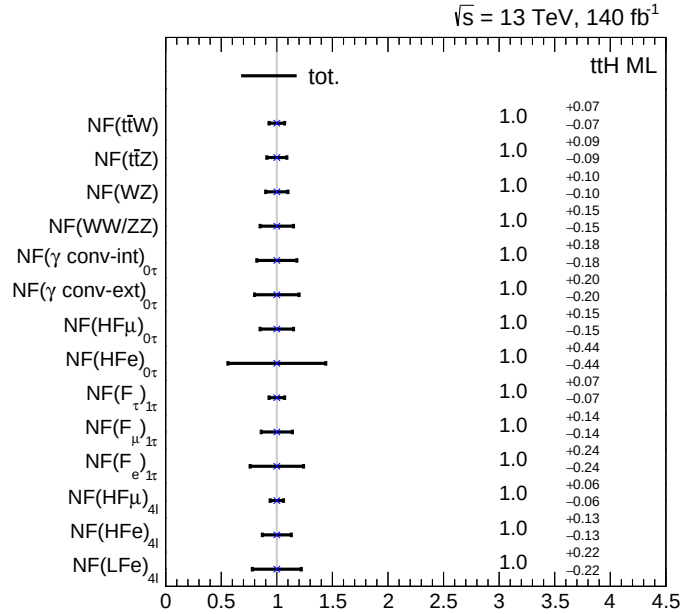


Figure 7.81: Background NF results of a combined STXS fit to Asimov data.

7.14 Observed results

In the following, the final results, including the data in the [SRs](#), are shown. The analysis was unblinded for the purpose of this thesis, and the presented results therefore correspond to preliminary results and should not be considered final or approved by [ATLAS](#).

7.14.1 Pre-fit distribution

Figures [7.82](#) to [7.86](#) show the pre-fit data [MC](#) agreement in the [SRs](#) of the different channels. Overall, a slight underestimation of the data is observed.

In the $0\tau_{\text{had}}$ and $2\tau_{\text{had}}$ channels, where the [SRs](#) are split by reconstructed Higgs p_T , slight differences in the data [MC](#) agreement are observed for the different [STXS SRs](#), but no major trend seems to be introduced by the p_T^H reconstruction.

The $2\ell\text{SS}+1\tau_{\text{had}}$ channel shows a clear data [MC](#) discrepancy in the two highest [BDT](#) bins of the [SR](#), both bins including significantly less data events than [MC](#) events. While the first four bins show a sensible modelling, the observed data yields in the two highest bins do not even cover the backgrounds, resulting in an overall χ^2 probability of 7 %. This could either correspond to a statistical fluctuation or to a mismodelling of the data in the [BDT](#) output. The [MC](#) modelling of all [BDT](#) input variables was tested in data in a region close to the [SR](#) but with looser selection cuts, in order to validate the [BDT](#) prior to unblinding. More studies are, however, required to get a better understanding of this observed discrepancy. The overestimation of [MC](#) compared to data being in the two bins with the highest $t\bar{t}H$ sensitivity, the mismodelling is expected to have a significant impact on the fit results.

In the 4ℓ channel, statistical fluctuations of the data are observed in the high [DNN](#) bins, but none of the deviations is significant.

Finally, Figure [7.87](#) shows the unblinded $tHjb$ [CRs](#). No important pre-fit data [MC](#) disagreements are observed.

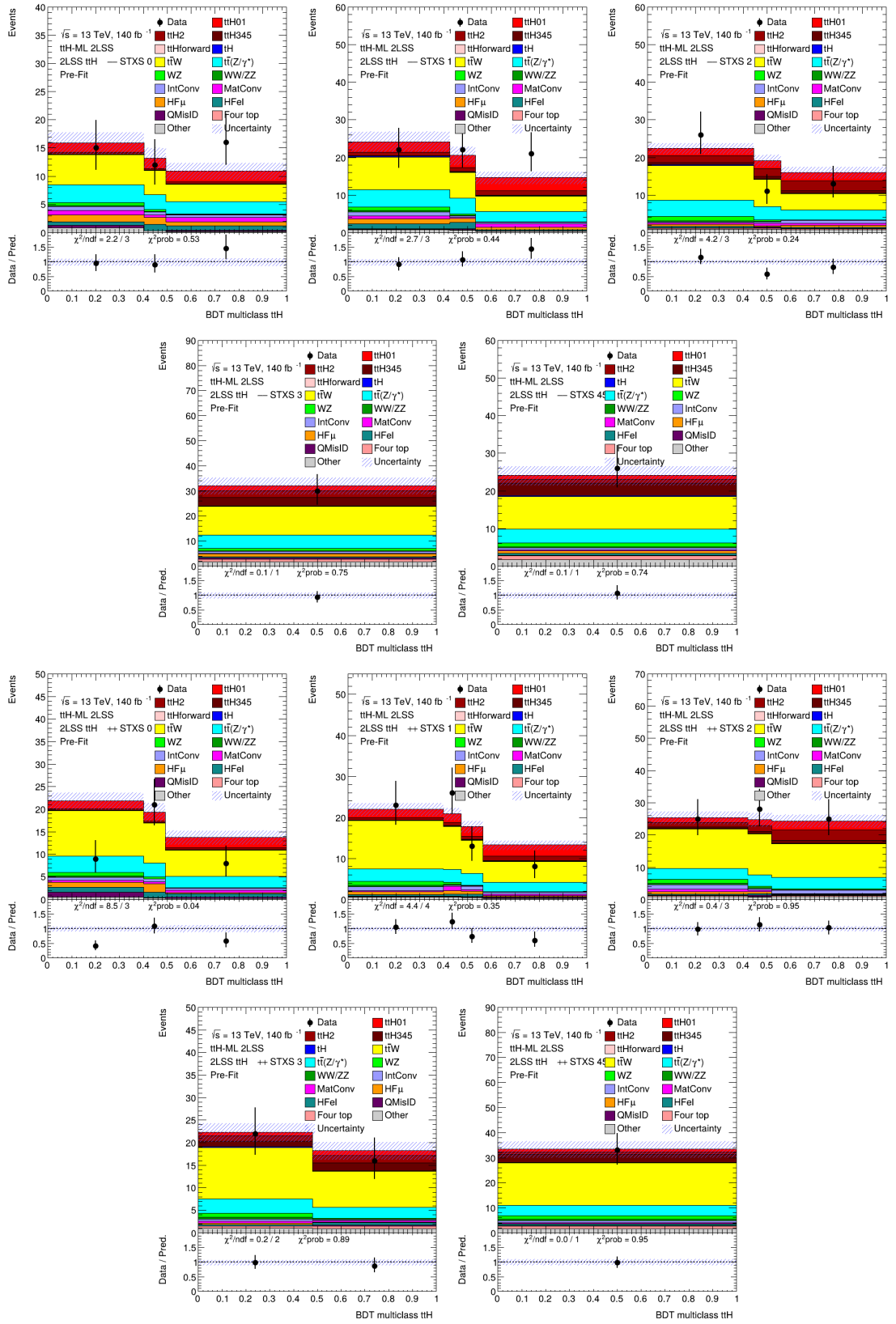


Figure 7.82: Expected distributions compared to data in the STXS SRs for the $2\ell\text{SS} + 0\tau_{\text{had}}$ channel. The uncertainty bands include statistical and systematic uncertainties.

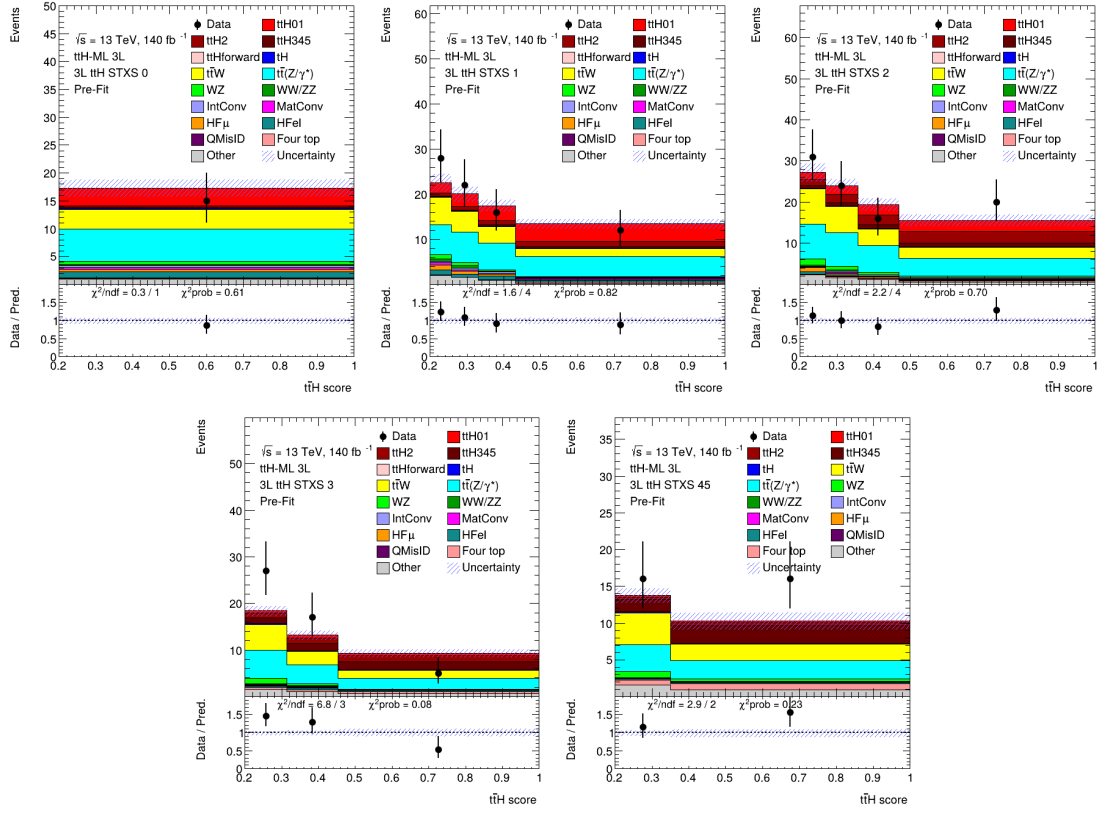


Figure 7.83: Expected distributions compared to data in the STXS SRs for the $3\ell + 0\tau_{\text{had}}$ channel. The uncertainty bands include statistical and systematic uncertainties.

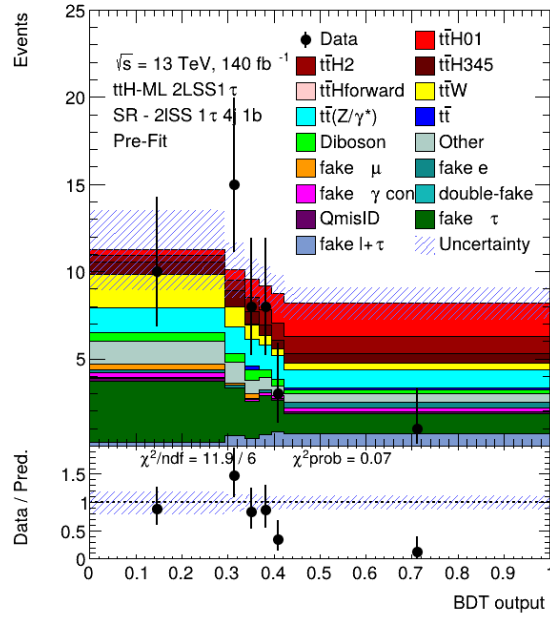


Figure 7.84: Expected distributions compared to data in the SR for the $2\ell\text{SS}+1\tau_{\text{had}}$ channel. The uncertainty bands include statistical and systematic uncertainties.

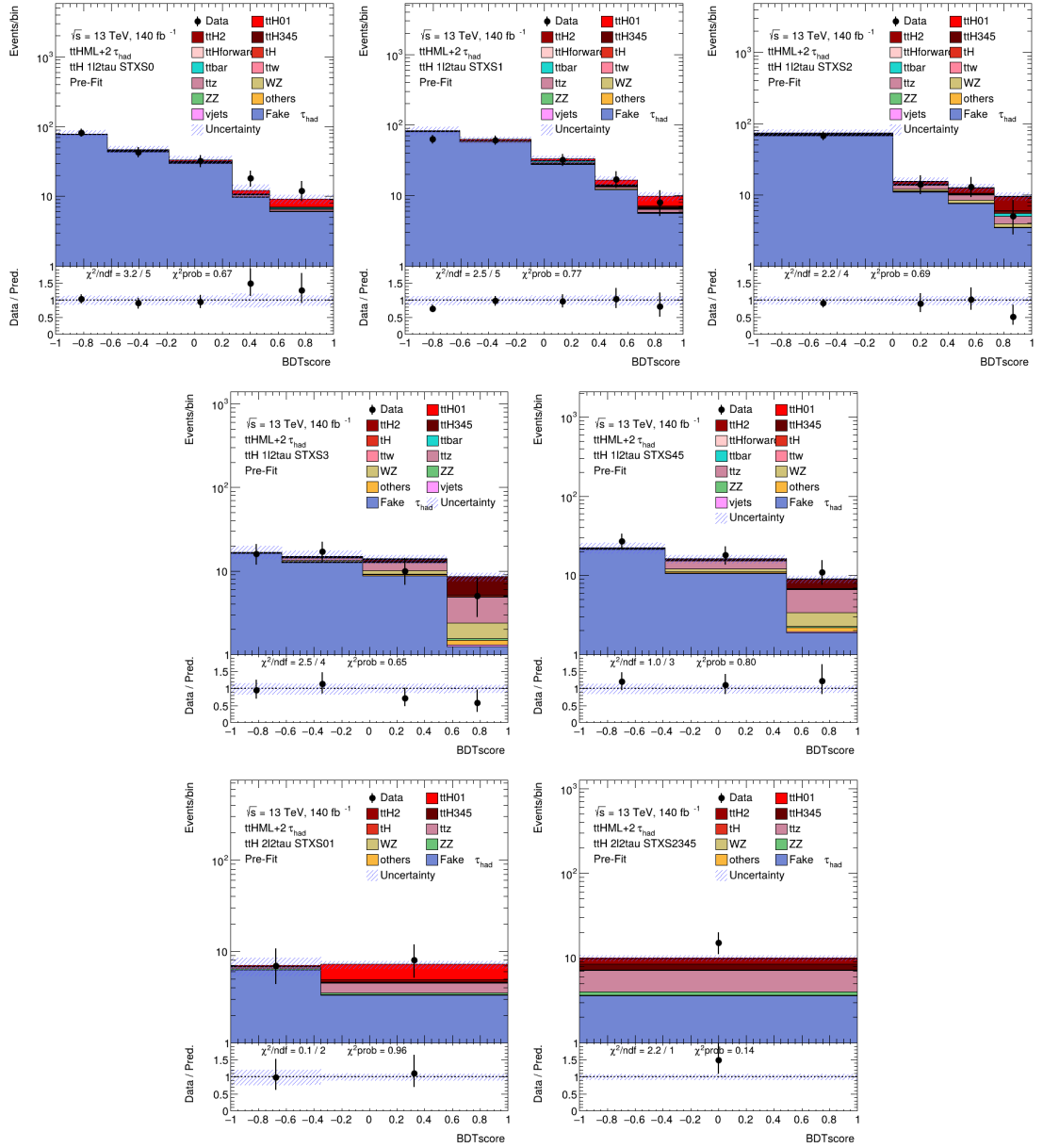


Figure 7.85: Expected distributions compared to data in the STXS SRs for the $2\tau_{had}$ channels. The uncertainty bands include statistical and systematic uncertainties.

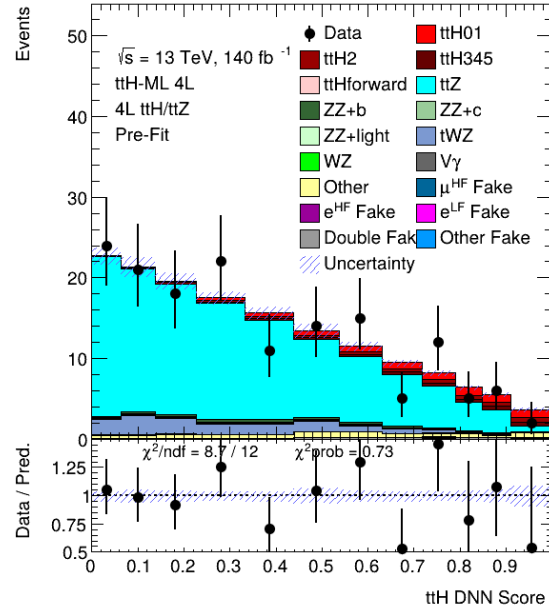


Figure 7.86: Expected distributions compared to data in the SR for the 4ℓ channel. The uncertainty bands include statistical and systematic uncertainties.

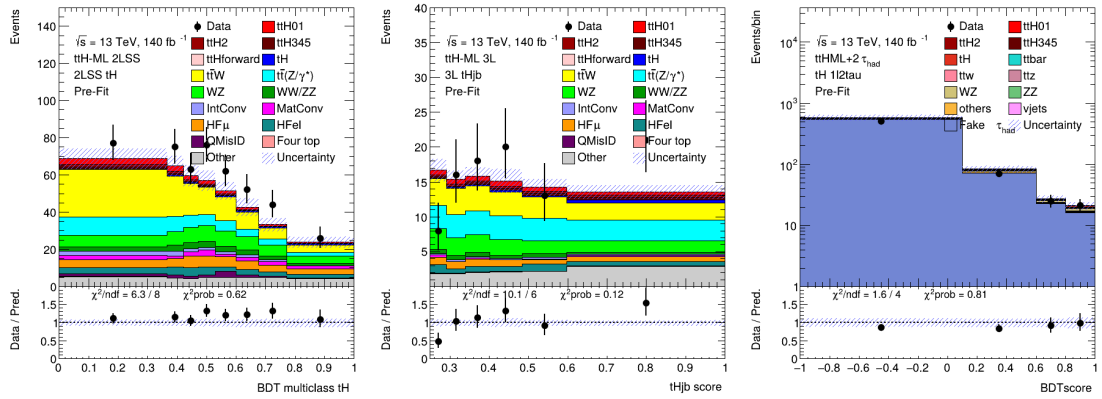


Figure 7.87: Expected distributions compared to data in the CRs for $tHjb$ for the $2\ell_{SS} + 0\tau_{had}$ (left), $3\ell + 0\tau_{had}$ (centre) and $1\ell + 2\tau_{had}$ (right) channels. The uncertainty bands include statistical and systematic uncertainties.

7.14.2 Inclusive $t\bar{t}H$ signal strength measurement

Fit free floating the $t\bar{t}H$ signal strength with fixed $tHjb$ signal strength

The fit results for the inclusive signal strength fit are shown in Figures 7.88 and 7.89. The data in the SRs are not observed to significantly modify the background NFs compared to the background only fit, presented in Section 7.12. Additionally, as shown in Figure 7.90, no significant pulls and constraints on the NPs are newly introduced. The goodness-of-fit corresponds to 86 %. A combined $t\bar{t}H$ signal strength of $\mu_{t\bar{t}H} = 0.64^{+0.22}_{-0.20}$ is measured, which corresponds to an agreement within 2σ with the SM expectation. Except for the $3\ell + 0\tau_{had}$ channel, which agrees very well with the SM prediction, all channels observe a $t\bar{t}H$ ML cross-section smaller than the prediction.

The 4ℓ and $2\tau_{\text{had}}$ channels are, however, compatible with 1 within 1σ and the $2\ell\text{SS} + 0\tau_{\text{had}}$ channel is compatible with the SM within about 2σ . As expected from the pre-fit data MC agreement, the $2\ell\text{SS} + 1\tau_{\text{had}}$ channel results in a negative signal strength for $t\bar{t}H$.

The combined result corresponds to a measurement of the $t\bar{t}H$ ML process with a significance of 3.2σ . As expected with the low fitted signal strength value, this corresponds to an important decrease in significance compared to the expected significance of 5.3σ .

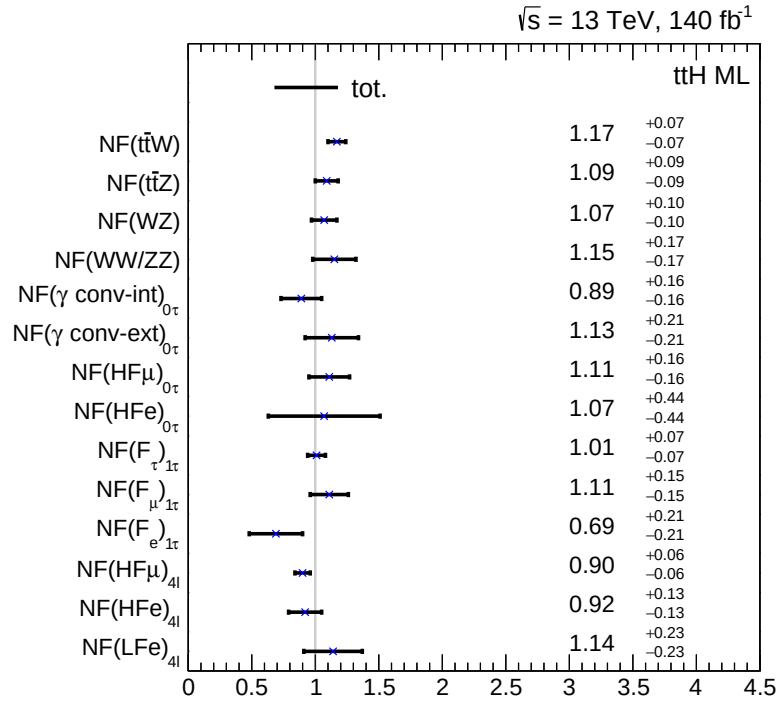


Figure 7.88: Background NF results of a combined inclusive signal strength fit to data.

The ranking of the impact of the systematic uncertainties is shown in Figure 7.91. Similar to the Asimov fit, the highest ranked uncertainties are the $t\bar{t}H$ theory cross-section scale uncertainty, as well as the $t\bar{t}W$ and $t\bar{t}Z$ NFs.

The fit results can be compared to the measurements in the partial Run 2 $t\bar{t}H$ ML analysis, presented in Section 7.3.1. The analysis presented in this thesis, shows a significant reduction of the uncertainties compared to the partial Run 2 analysis, which goes beyond the pure increase in statistics. The significance of the measurement is increased from 1.8σ to 3.2σ . Both results show a very similar behaviour, with similar signal strengths below 1. Only the result in the $2\ell\text{SS} + 1\tau_{\text{had}}$ channel shows a clear deviation from the previous measurement.

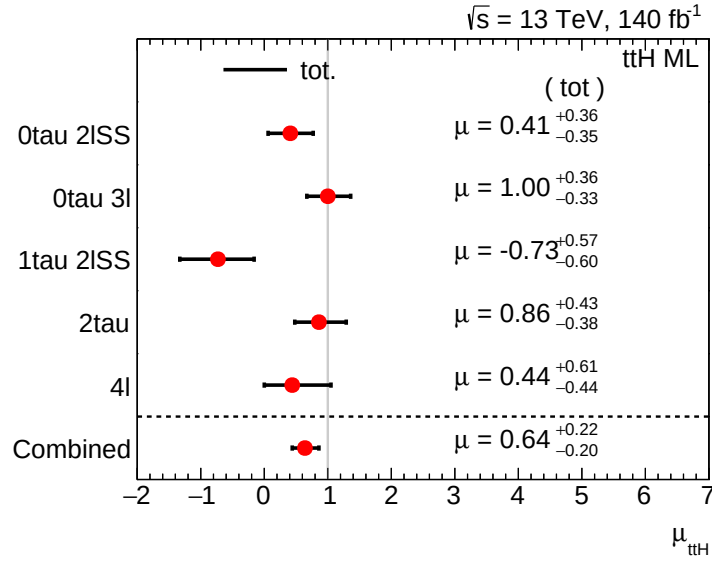


Figure 7.89: $t\bar{t}H$ signal strength results of a combined inclusive signal strength fit to data.

As the $2\ell\text{SS}+1\tau_{\text{had}}$ channel is in tension with all the other channels and the previous partial Run 2 results, a combined fit is performed where the $2\ell\text{SS}+1\tau_{\text{had}}$ channel is excluded. The main sensitivity to the backgrounds being in the [CRs](#), the background [NFs](#) are not significantly impacted. The signal strength results are shown in [7.92](#). The $t\bar{t}H$ signal strength is increased to $\mu_{t\bar{t}H} = 0.78^{+0.23}_{-0.21}$, decreasing the tension to the [SM](#) prediction to about 1σ .

The measurements can also be compared to a similar analysis performed by [CMS \[157\]](#). The results are shown in [Figure 7.93](#), where an overall $t\bar{t}H$ signal strength of $\mu_{t\bar{t}H} = 0.91^{+0.26}_{-0.23}$ is measured. Having similar uncertainties as in the analysis presented here, the result is in better agreement with the [SM](#) expectation. Both results are in agreement within 1σ .

Fit free floating the $t\bar{t}H$ and $tHjb$ signal strengths

Another fit is performed, where μ_{tHjb} is kept free floating in addition to $\mu_{t\bar{t}H}$. The background [NFs](#) do not deviate significantly to the previous fit setup. The results for the $t\bar{t}H$ and $tHjb$ signal strengths are shown in [Figure 7.94](#). While for μ_{tHjb} , a value above 1 is measured, with $\mu_{tHjb} = 8.16^{+5.07}_{-4.47}$, the signal strength for $t\bar{t}H$ is decreased further compared to the fit, where the $tHjb$ normalisation is fixed to [SM](#). Both results for $\mu_{t\bar{t}H}$ are, however, compatible within the uncertainties. As shown in [Section 7.11](#), only the $0\tau_{\text{had}}$ and $2\tau_{\text{had}}$ channels include dedicated $tHjb$ [CRs](#). The $2\ell\text{SS}+1\tau_{\text{had}}$ and 4ℓ channels are therefore not expected to have a significant sensitivity to this process. This effect is seen for 4ℓ , where a result fully compatible with 1 with very

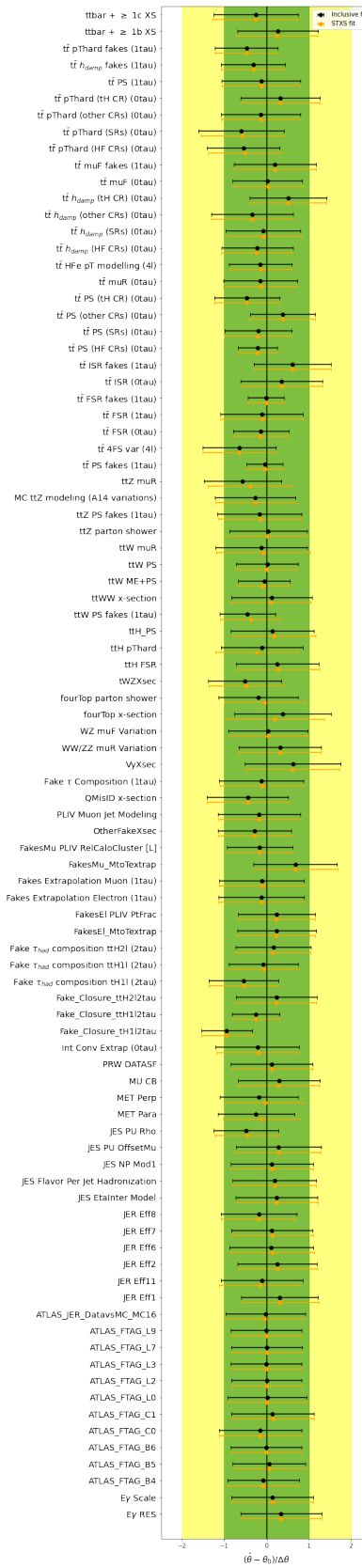


Figure 7.90: Comparison of the constraints and pulls of the NPs in a combined inclusive and STXS fit to data. Only NPs which are either pulled or over/under-constrained by more than 0.1 are shown.

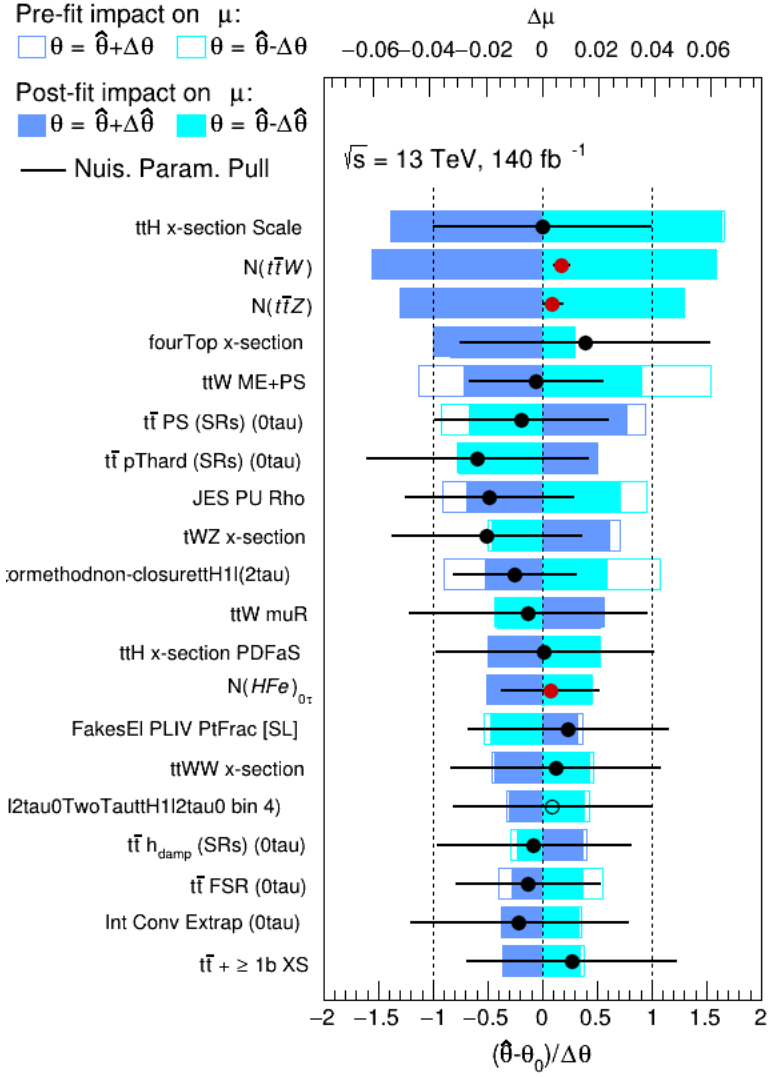


Figure 7.91: Ranking of the impact of the systematic uncertainties on the $t\bar{t}H$ signal strength in a combined inclusive signal strength fit to data.

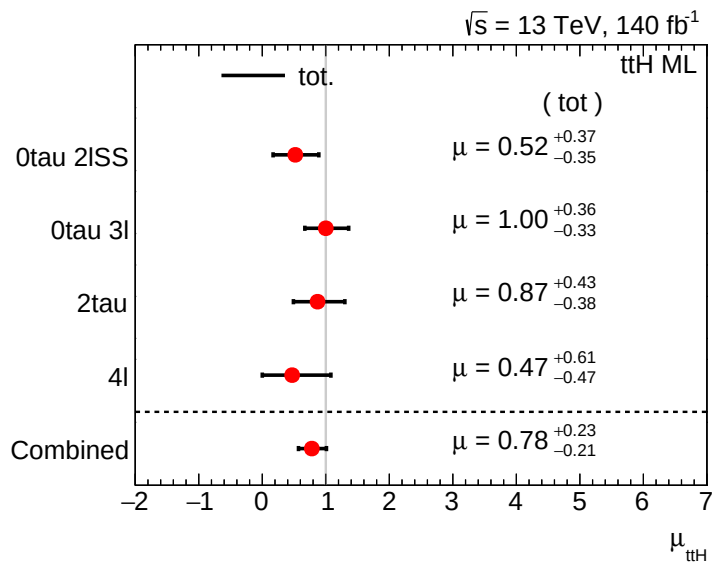


Figure 7.92: $t\bar{t}H$ signal strength results of a combined inclusive signal strength fit to data, excluding the $2\ell\text{SS}+1\tau_{\text{had}}$ channel.

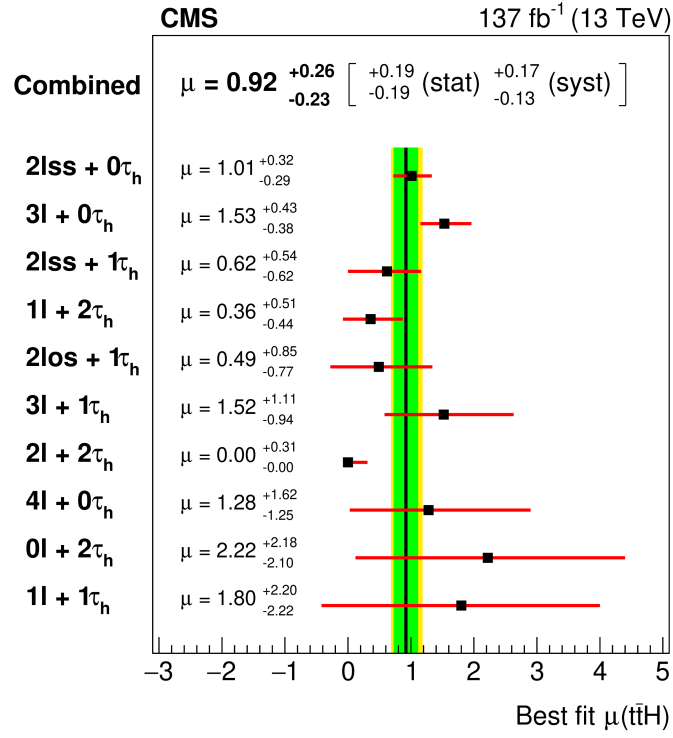


Figure 7.93: Results on the $t\bar{t}H$ signal strength in the CMS Run 2 $t\bar{t}H$ and tH ML analysis [157]

large uncertainties is observed. For $2\ell\text{SS}+1\tau_{\text{had}}$, a very high signal strength for $tHjb$ is observed, which is compatible within 2σ with the SM.

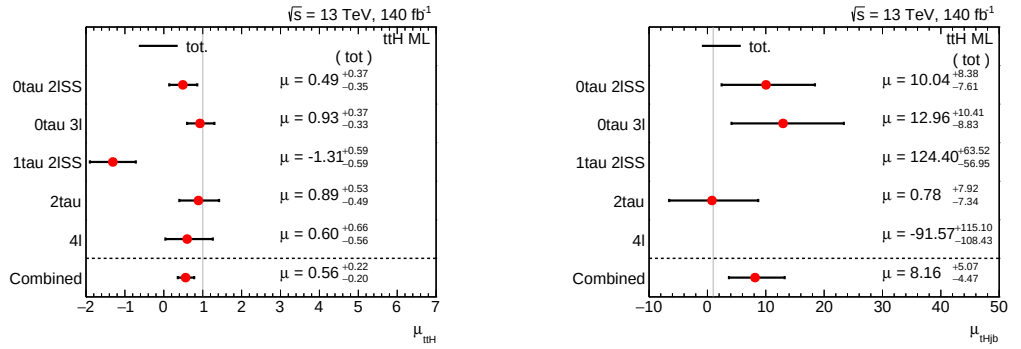


Figure 7.94: $t\bar{t}H$ and $tHjb$ signal strength results of a combined inclusive signal strength fit to data with μ_{tHjb} free floating.

Again, the same fit is performed, but excluding the $2\ell\text{SS}+1\tau_{\text{had}}$ channel. The $tHjb$ normalisation is reduced to $\mu_{tHjb} = 7.12^{+4.96}_{-4.43}$, but still more than 1σ above the SM prediction.

The CMS analysis, mentioned previously, also includes a measurement of the $tHjb$ process. Instead of the $2\tau_{\text{had}}$ channels, the $2\ell\text{SS}+1\tau_{\text{had}}$ channel is included. The results are shown in Figure 7.96. A global $tHjb$ signal strength of $\mu_{tHjb} = 5.7^{+4.04}_{-4.04}$ is obtained. Similar to the meas-

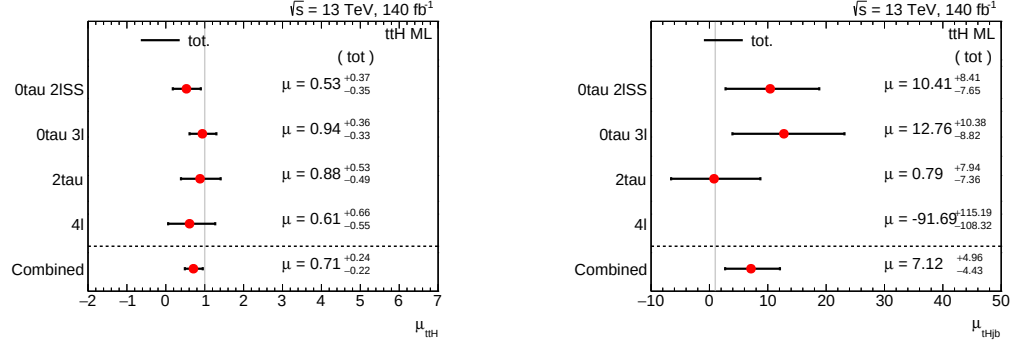


Figure 7.95: $t\bar{t}H$ and $tHj\bar{b}$ signal strength results of a combined inclusive signal strength fit to data with $\mu_{tHj\bar{b}}$ free floating, excluding the $2\ell SS + 1\tau_{had}$ channel.

urement presented in this thesis, a signal strength above 1 is measured. Again, the results are closer to the SM prediction, however, both results are compatible within 1σ .

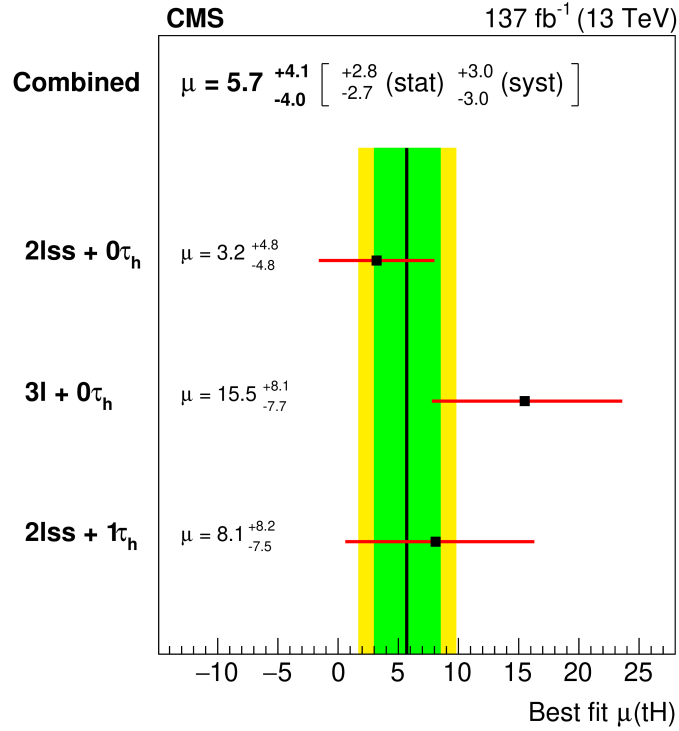


Figure 7.96: Results on the tH signal strength in the CMS Run 2 $t\bar{t}H$ and tH ML analysis [157]

7.14.3 STXS measurement

An STXS measurement is performed including all analysis channels. Similar to the Asimov fit, the background NFs and the pulls and constraints on the NPs, as shown in Figure 7.90, are mainly unchanged with respect to the inclusive fit.

The results for all three **STXS** signal strengths are shown in Figure 7.97. In the fit to data, the $2\ell\text{SS}+1\gamma_{\text{had}}$ and 4ℓ channels, which do not have a dedicated p_T^H reconstruction, do not converge properly. Therefore, the breakdown into the different channels cannot be made. As expected, due to the inclusive results, two of the **STXS** signal strengths have best-fit values below 1. Especially $\mu_{t\bar{t}H2}$ has a very small best-fit value. Similar to the Asimov fit, the **STXS** signal strengths are, however, significantly correlated. $\mu_{t\bar{t}H01}$ and $\mu_{t\bar{t}H2}$ are anti-correlated by 49 %, $\mu_{t\bar{t}H01}$ and $\mu_{t\bar{t}H345}$ correlated by 15 % and $\mu_{t\bar{t}H2}$ and $\mu_{t\bar{t}H345}$ anti-correlated by 38 %. The compatibility of the **STXS** fit with the inclusive fit is 55 %, showing a good agreement of the measured p_T^H shape with the expectation.

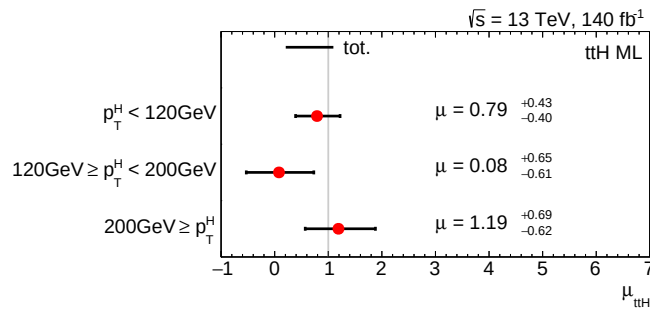


Figure 7.97: $t\bar{t}H$ **STXS** signal strength results of a combined **STXS** fit to data.

The ranking of the impact of the systematics on the different **STXS** signal strengths is shown in Figure 7.98. A very similar behaviour to the Asimov case is observed, where the normalisation of the other **STXS** bins are the dominant limitation of the measurement.

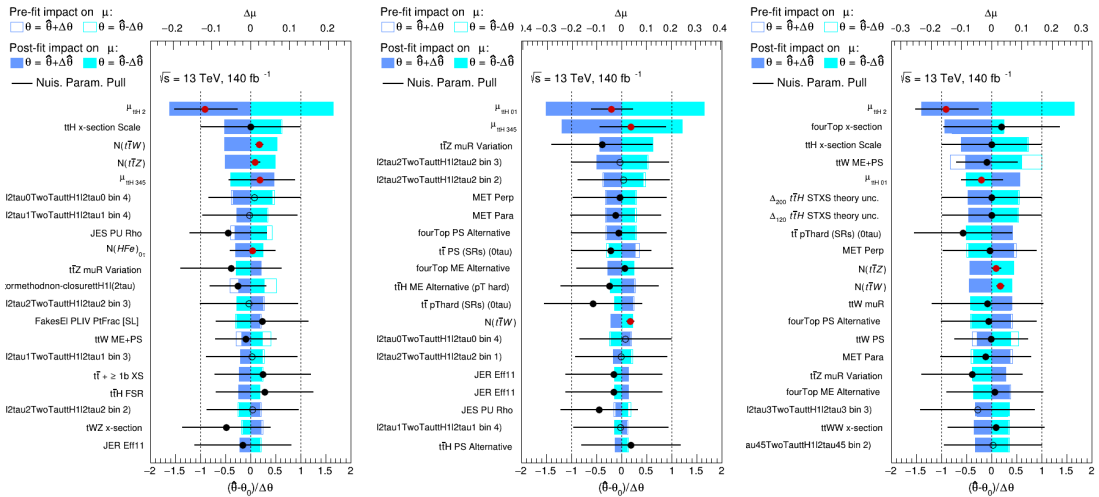


Figure 7.98: Ranking of the impact of the systematic uncertainties on the $t\bar{t}H$ **STXS** signal strengths in a combined **STXS** fit to data.

As for the inclusive setup, an **STXS** measurement, excluding the $2\ell\text{SS}+1\gamma_{\text{had}}$ channel, is performed. As expected, the agreement with the **SM** prediction increases, $\mu_{t\bar{t}H2}$ showing only a tension of slightly above 1σ to the **SM**.

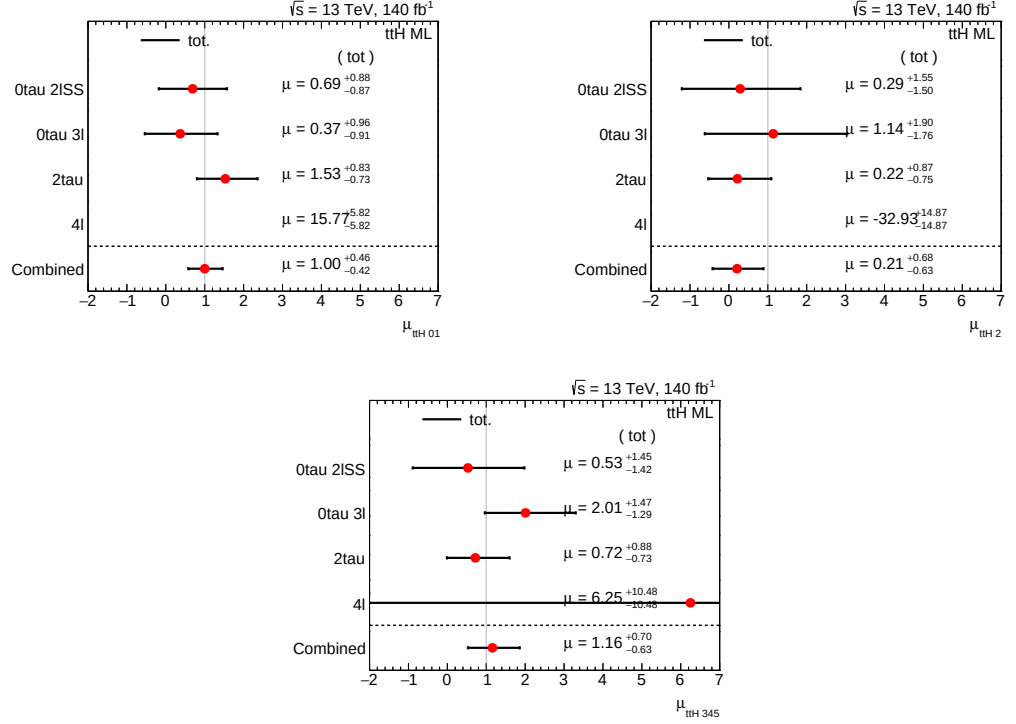


Figure 7.99: ttH STXS signal strength results of a combined STXS fit to data, excluding the $2\ell SS + 1\tau_{had}$ channel.

The STXS results can be compared to a similar measurement performed by CMS [158]. The measurement was performed in the $2\ell SS + 0\tau_{had}$ and $3\ell + 0\tau_{had}$ final state, merging the STXS bins in the same way as in the analysis presented in this thesis. The results are shown in Figure 7.100, presented in terms of cross-sections as well as in terms of signal strengths. Two of the NFs being well below the expectation and one NF being above, hints to the fact that the STXS signal strengths are strongly correlated. The results obtained in the analysis presented here significantly improve the sensitivity to the STXS signal strengths. This is likely due to the inclusion of the $2\tau_{had}$ channels in the STXS fit.

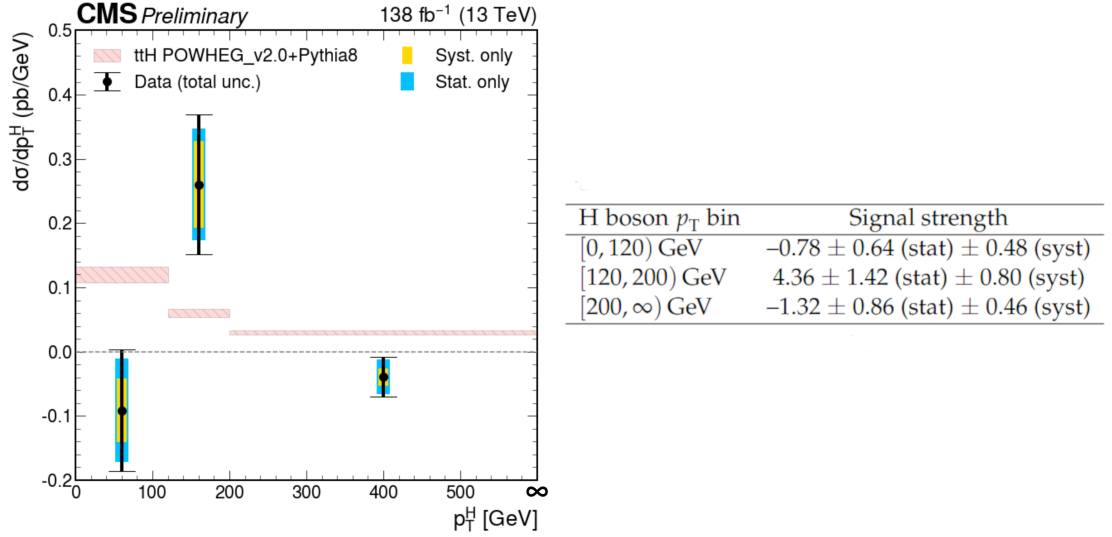


Figure 7.100: Results on the ttH cross-sections (left) and ttH signal strengths (right) in the CMS Run 2 differential ttH ML analysis [158]

7.15 Conclusion

The ttH ML analysis targets an inclusive and ttH signal strength measurement of the ttH process in a multi-lepton final state. In ATLAS, it corresponds to the first full Run 2 analysis targeting this final state and a first differential measurement of ttH ML.

The measurement is performed in six different channels with different light lepton and hadronically decaying tau multiplicities. A dedicated Higgs transverse momentum reconstruction is performed, in order to measure the ttH signal strength differentially in p_T^H inside the ttH framework. Studies were presented to understand the behaviour of the combined inclusive and ttH fit.

The analysis measures a cross-section slightly smaller than predicted by the SM. With a signal strength of $\mu_{ttH} = 0.64^{+0.22}_{-0.20}$, the observed tension is, however, not significant for the combined results, as well as for most of the channels. Additionally, the results are compatible with measurements in the partial Run 2 ATLAS and full Run 2 CMS analyses. Further studies will be performed in order to understand the deviations observed in the $2\ell SS+1\tau_{had}$ channel.

The differential measurement shows, given the overall normalisation difference in data and MC, a very good agreement with the expected p_T^H distribution. However, large correlations between the ttH signal strengths are observed.

The cross-section of ttH is proportional to the square of the top Yukawa coupling, being sensitive to the magnitude of the coupling but not the sign. In the coupling modifier framework, where the deviations of the Higgs coupling with respect to the SM couplings are considered, the

signal strength of $t\bar{t}H$ is proportional to the square of the top-Higgs coupling modifier κ_t . In a simplified approach, with the assumption that the Higgs decay follows the branching ratios predicted by the [SM](#), a reinterpretation of the inclusive signal strength in terms of κ_t can be performed. In the case where $\mu_{t\bar{t}H} = \kappa_t^2$, a value of $|\kappa_t| = 0.80^{+0.14}_{-0.13}$ is obtained when considering all channels and of $|\kappa_t| = 0.88^{+0.13}_{-0.12}$, when excluding the $2\ell\text{SS}+1\tau_{\text{had}}$ channel. The high measured signal strength of $tHjb$ lies in between the predictions with $\kappa_t = 1$ and $\kappa_t = -1$. In global Higgs process fits within the κ framework, such as in Ref [\[70\]](#), a value of $\kappa_t = 0.94^{+0.11}_{-0.11}$ was obtained. All results are compatible within uncertainties and the $t\bar{t}H$ [ML](#) channel shows a very competitive sensitivity.

CONCLUSION

The full Run 2 dataset of proton-proton collisions at a centre-of-mass energy of $\sqrt{s} = 13$ TeV collected by the [ATLAS](#) detector at the Large Hadron Collider ([LHC](#)) has given an important improvement in the sensitivity to many rare processes, such as the top pair production in association with electroweak gauge bosons or the Higgs boson. In this thesis, two measurements have been presented, targeting $t\bar{t}\ell^+\ell^-$ and $t\bar{t}H$ in multi-leptonic final states. These analyses aim at performing precision measurements of processes described by the Standard Model ([SM](#)), in order to detect potential deviations from the prediction.

The high-mass $t\bar{t}\ell^+\ell^-$ measurement, considering the four-fermion vertex with a di-lepton invariant mass above the Z peak, provides a direct constraint on new physics inside the Effective Field Theory ([EFT](#)) framework. The high m_{ll} phase-space is utilised for the first time in a dedicated measurement of four-fermion operators in the $t\bar{t}\ell^+\ell^-$ vertex. Additionally, the analysis is designed in order to be sensitive to the $t\bar{t}e^+e^-$ and $t\bar{t}\mu^+\mu^-$ vertex separately, probing potential lepton flavour universality violation. No deviations from the [SM](#) expectation are observed and limits are set on the Wilson coefficients, corresponding to the best constraints to date. The measurement is, however, heavily limited by the low statistics of $t\bar{t}\ell^+\ell^-$ in the high-mass regime. Run 3 and the high-luminosity [LHC](#) are therefore expected to considerably improve this measurement. Additionally, a significant improvement of the statistics would allow for differential measurements in the high-mass regime (such as angular distributions) which can improve the sensitivity to the [EFT](#) operators.

The $t\bar{t}H$ multi-lepton analysis provides an inclusive and differential signal strength measurement. It was preceded by an inclusive and differential $t\bar{t}W$ cross-section measurement, $t\bar{t}W$ being an important background for $t\bar{t}H$ in a multi-lepton final state, which measured a cross-section of $\sigma(t\bar{t}W) = 880 \pm 80$ fb, compatible within 1.4σ with the latest next-to-next-to-leading

order cross-section calculation. Additionally, when removing the normalisation effects, no significant deviations were found in the differential measurement. The inclusive $t\bar{t}H$ measurement is found to be slightly smaller but still compatible within 2σ with the [SM](#) expectation, with a signal strength of $\mu_{t\bar{t}H} = 0.64^{+0.22}_{-0.20}$. An interpretation of this result in terms of the top Yukawa coupling modifier results in a value of $|\kappa_t| = 0.80^{+0.14}_{-0.13}$. These simplified limits seem to be very competitive with other limits determined so far and might improve global limits on κ_t . With the increased statistics at the high-luminosity [LHC](#), the limits on κ_t are expected to improve further to less than 4 %, as shown in Figure 7.101. The differential measurement inside the Simplified Template Cross-Section framework is also found to be in good agreement with the [SM](#) expectation. The high Higgs transverse momentum spectrum is, however, still heavily limited by data statistics. The measurement is suitable for reinterpretations in order to set limits on Beyond Standard Model ([BSM](#)) physics scenarios, such as on deviations from the [SM](#) Higgs self-coupling prediction. These interpretations were, however, not considered in this thesis.

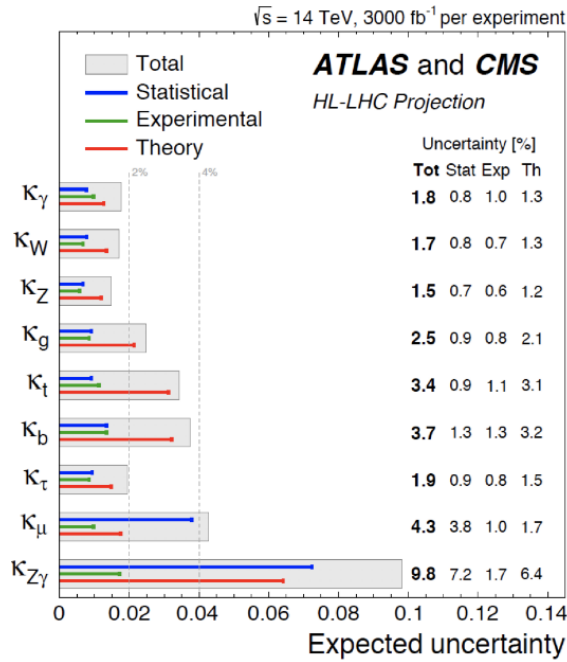


Figure 7.101: High-luminosity [LHC](#) projections for the limits on the coupling modifiers [159].

The measurements in the top and Higgs sector performed so far by the [ATLAS](#) collaboration have shown an impressive agreement with the [SM](#). Despite the new precision achieved, no evidence of new physics has been observed. New approaches are therefore utilised, in order to search for any hints of [BSM](#) physics. Differential measurements are a very powerful test of the [SM](#), as many new physics scenarios are expected to have a clear impact on the distributions in specific observables. These measurements are currently still heavily statistics dominated. The increasing amount of data collected in Run 3 and in the high luminosity [LHC](#), however, will help to provide

precise measurements over more extreme regions of phase-space, by gaining statistics in regions with very low cross-section, but also by allowing for more complex analysis approaches. These extreme parts of the phase-space, however, do not only suffer from low statistics but also from large backgrounds, as was seen in the high-mass $t\bar{t}\ell^+\ell^-$ analysis, having large contributions from other $t\bar{t}X$ ($X = Z, W, H, \gamma$) processes.

In many frameworks allowing for global searches for new physics, the effects of [BSM](#) processes on the backgrounds cannot be neglected in the case where the backgrounds have significant contributions. In the [EFT](#) formalism, for example, the [EFT](#) operators impact multiple processes. Additionally, cross-terms between the operators need to be considered. All of this highlights the importance of global precision measurements, considering several processes simultaneously.

While no new physics have been observed so far, new techniques and theoretical frameworks have been developed to systematically search for potential deviations from [SM](#) predictions through precision measurements. Moreover, the data collected during Run 3 and the high-luminosity [LHC](#) will significantly expand the accessible phase-space. Consequently, the [LHC](#) era promises to provide a broad and rigorous test of the [SM](#).

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GLOSSARY

ATLAS A Toroidal LHC ApparatuS

BDT	Boosted Decision Tree	29
BSM	Beyond Standard Model	3
CI	Confidence Interval	70
CMS	Compact Muon Solenoid	
CR	Control Region	79
DNN	Deep Neural Network	82
EFT	Effective Field Theory	1
ECal	Electromagnetic Calorimeter	19
ECIDS	Electron Chargeflip Tagger ID Selector	30
EW	Electroweak	6
FSR	Final State Radiation	49
GNN	Graph Neural Network	140
HCal	Hadronic Calorimeter	19
HF	Heavy Flavour	79
ISR	Initial State Radiation	49
LAr	Liquid Argon Calorimeter	20
LF	Light Flavour	79
LHC	Large Hadron Collider	3
LO	Leading order	48

MC	Monte Carlo	47
ME	Matrix Element	48
ML	Multi Lepton	140
MPI	Multi-Parton Interactions	53
NF	Normalisation Factor	70
NLO	Next to Leading Order	49
NN	Neural Network	103
NNLO	Next to next to Leading Order	49
NP	Nuisance Parameter	70
OSSF	Opposite-Sign Same-Flavour	80
PDF	Parton Density Function	27
PLV	Prompt Lepton Veto	30
PLIV	Prompt Lepton Improved Veto	30
PS	Parton Shower	47
QED	Quantum Electro Dynamics	54
QCD	Quantum Chromo Dynamics	7
RNN	Recurrent Neural Network	36
SM	Standard Model	1
SR	Signal Region	79
STXS	Simplified Template Cross-Section	44
VR	Validation Region	93
WC	Wilson Coefficient	13
WP	Working Point	28

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