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**Search for the associated production of
the Higgs boson with a top quark pair
in multilepton final states at $\sqrt{s} = 13 \text{ TeV}$
with the ATLAS detector**

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Introduction

During the last decades, much effort has been devoted to the search for a theoretical model able to explain the fundamental interactions among the elementary particles. Nowadays, the Standard Model represents the most complete theory and, at the same time, it is greatly supported by several experimental evidences. This theory predicts the existence of a particle responsible for giving mass to all the fundamental massive particles of the Standard Model: the Higgs boson. Finding the SM Higgs boson has been of the most topical goals of particle physics in the last 50 years.

The Large Hadron Collider, located at CERN laboratories in Geneva, is the largest particle accelerator in the world and it is designed to allow the search for new processes at TeV scale. On the 4th July 2012, the ATLAS and CMS collaborations announced the discovery of a $125\text{ GeV}/c^2$ mass resonance, with properties similar to those of the the SM Higgs boson, with a confidence level of more than 5σ .

The Higgs boson can be produced at LHC via different processes. Among them, the $t\bar{t}H$ production mode shows the lowest cross-section and the limited statistics makes this search a challenge. The measurement of the Yukawa coupling between the Higgs boson and the top quark and its comparison with the Standard Model expectation could provide a further confirmation of the validity of the theory, leading to a more complete understanding of the Higgs mechanism.

The measurement of the properties of the Higgs boson (spin, couplings, production cross-sections and decay processes), is essential for contemporary physics. The $t\bar{t}H$ process, not yet observed, would permit a direct measurement of the quark top-Higgs coupling. Moreover, the comparison of this measurement with indirect measurements, already performed via gluon-gluon fusion production mode and Higgs boson decay into photon pairs, has the potential to identify and disentangle new physics effects that can modify the $t\bar{t}H$ production cross section relative to the SM expectation. For these reasons, the $t\bar{t}H$ channel is becoming of particular interest in the study of the Higgs boson production.

In this thesis a search, performed using 13.2 fb^{-1} of data recorded by the ATLAS detector in 2015 and 2016 at a centre-of-mass energy of 13 TeV, is presented. The analysis is designed to search for the Higgs boson, produced in association to a top quark pair, through its decays into WW^* , ZZ^* and $\tau\tau$. These channels present a quite complex signature, characterized by a high jet multiplicity and a different number of light leptons in the final state, according to the decay modes of the top quark pair and Higgs boson. In particular, the analysis object of this work, requires the presence of three leptons (electrons or muons) in the final state.

This thesis is structured as follows. Chapter 1 introduces the Standard Model and the Brout-Englert-Higgs mechanism, while Chapter 2 is dedicated to the $t\bar{t}H$ production mode. Some recent results on $t\bar{t}H$, obtained by the ATLAS collaboration during the previous data-taking run, are also reported. Chapter 3 gives an overview of the ATLAS detector, the experimental apparatus used to collect data which this thesis is based on. In Chapter 4 the description of the event object reconstruction is presented.

Chapter 5 shows the structure of the $t\bar{t}H$ search in multilepton final states: the optimization of the analysis strategy, the event selection and the background estimation. In this context, my main contribution has been devoted to the final state containing three light leptons (e or μ). For this channel, I developed the estimation of the background due to non-prompt leptons, which result is shown in Chapter 6.

Moreover, due to the low sensitivity of the 3ℓ channel, I elaborated a study based on the full event kinematic reconstruction, with the goal of reducing the background from vector

bosons produced in association to a top quark pair ($t\bar{t}V$). This work is presented in Chapter 7. Finally, Chapter 8 reports the statistical analysis, performed to compare the results with the SM expectations. The results obtained for the 3ℓ channel and the combination with the other $t\bar{t}H$ multilepton searches are here presented.

Chapter 1

The Standard Model

1.1 The Standard Model: a general overview

The Standard Model (SM) is a re-normalizable quantum field theory that describes the elementary particles and their interactions accurately. It has been developed in the early 1970s. This model has been tested with several high energy physics experiments and it explains successfully a wide variety of phenomena. Three of the four forces observed in nature are currently described by the SM theory: the electromagnetism, the weak and the strong nuclear force. Only the gravitational interaction is actually out from this scheme[1][2][3][4][5].

In the SM two type of point-like particles exist: fermions, spin-1/2 particles that represent the matter content, further divided in leptons and quarks, and the bosons, spin-1 particles which are the mediators of the interaction fields. Fermions interacts by the exchange of spin-1 bosons: eight massless gluons and one massless photon for the strong and the electromagnetic interactions, respectively, and three massive bosons, $W^\pm$ and Z for the weak interaction. Fermions are arranged in a structure consisting in three "families", as shown in Fig.1.1.

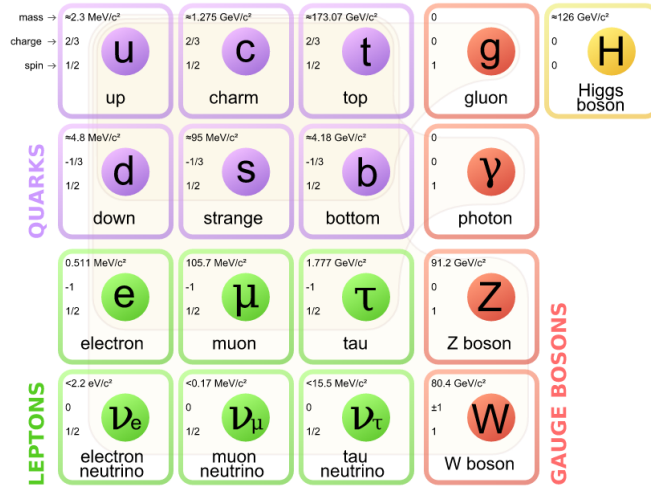


Figure 1.1: Standard Model particles

The SM is a non-Abelian Gauge theory, based on the symmetry group $SU(3)_C \times SU(2)_L \times U(1)_Y$, where $SU(3)_C$ is the non-Abelian gauge group of the Quantum Chromodynamics (QCD), the theory describing the interaction of quarks and gluons, while the $SU(2)_L \times U(1)_Y$ is the non-Abelian symmetry group of the electroweak interaction (EW).

The SM Lagrangian can then be written as the sum of QCD and EW Lagrangians, as shown in Eq.1.1, each of which will be described in the next sections.

$$\mathcal{L}_{SM} = \mathcal{L}_{QCD} + \mathcal{L}_{EW} \quad (1.1)$$

1.1.1 QCD theory

The Quantum Chromodynamics is the quantum field theory describing the strong force, the interaction between quarks and gluons which make up hadrons such as the proton, neutron and pion.

This theory is based on a non-abelian gauge group, the $SU(3)_C$. The QCD analogue of electric charge is a property called color (C): the eight massless and spin-1 gluons, g_μ^A ($A = 1, \dots, 8$), are the gauge bosons of the interaction, like photons are for the electromagnetic force in the quantum electrodynamics (QED). The matter fields are colour triplets of quarks q_i^a , where i indicates the quark flavour. There are three possible color charge values, conventionally called *red*, *blue* and *green*.

The Lagrangian of the QCD is shown in Eq.1.2.

$$\mathcal{L}_{QCD} = -\frac{1}{4} \sum_{a=1}^8 G^{a\mu\nu} G_{\mu\nu}^a + \sum_{f=1}^6 \bar{q}_f (i\not{D} - m_f) q_f \quad (1.2)$$

where q_f are the quark fields, of 6 different flavours (u, d, s, c, b, t) and mass m_f , and $\not{D} = D_\mu \gamma^\mu$. γ^μ represents the 4×4 Dirac matrices and D_μ the covariant derivative defined in Eq.1.3. $G_{\mu\nu}^a$ corresponds to the tensor of the gluon field g_μ^A .

$$D_\mu = \partial_\mu - ie_s \sum_{A=1}^8 t^A g_\mu^A. \quad (1.3)$$

e_s is the gauge coupling, related to α_s through $\alpha_s = \frac{e_s^2}{4\pi}$, and t^A are the $SU(3)$ group generator in the triple representation of quarks.

The algebra of $SU(3)_C$ is not commutative and this gives rise to the self-interactions of the gluon fields. This structure leads also two peculiar properties of the QCD theory: the confinement and the asymptotic freedom.

The confinement consists on the peculiarity that the force between quarks does not diminish as they are separated. Trying to separate two coloured particles, the energy in the gluon field is enough to create another quark pair; quarks are, thus, forever bound into hadrons. The direct consequence is the impossibility to observe a coloured isolated particles.

The asymptotic freedom related to the behaviour of the strong coupling constant α_s as a function of the transfer momentum q of the interacting particles. In particular α_s decreases with the increasing of q^2 and asymptotically vanishes for $q^2 \rightarrow \infty$. The coupling of the interaction, α_s , depends on the energy (q^2) of the interactions through the Eq.1.4.

$$\alpha_s(q^2) = \frac{12\pi}{(33 - 2n_f) \ln \left(q^2 / \Lambda_{QCD}^2 \right)} \quad (1.4)$$

where Λ_{QCD} is the typical energy scale of the strong interaction and n_f is the number of quarks with mass up to $\sqrt{q^2}$. Only at high energy scales, a perturbative treatment of the strong interaction is possible.

The proton is a bound state of quarks and gluons and its total momentum is shared among its constituents. The production cross sections for any specific processes depend on the parton distribution functions (PDF), describing the probability in a hard interaction at a scale μ^2 to find a parton of a particular flavour with a fraction "x" of the momentum of the proton[6].

In Fig.1.2, the PDF (multiplied by x) for quarks and gluons the energy scales $\mu^2 = 10 \text{ GeV}^2$ and $\mu^2 = 100 \text{ GeV}^2$ is shown.

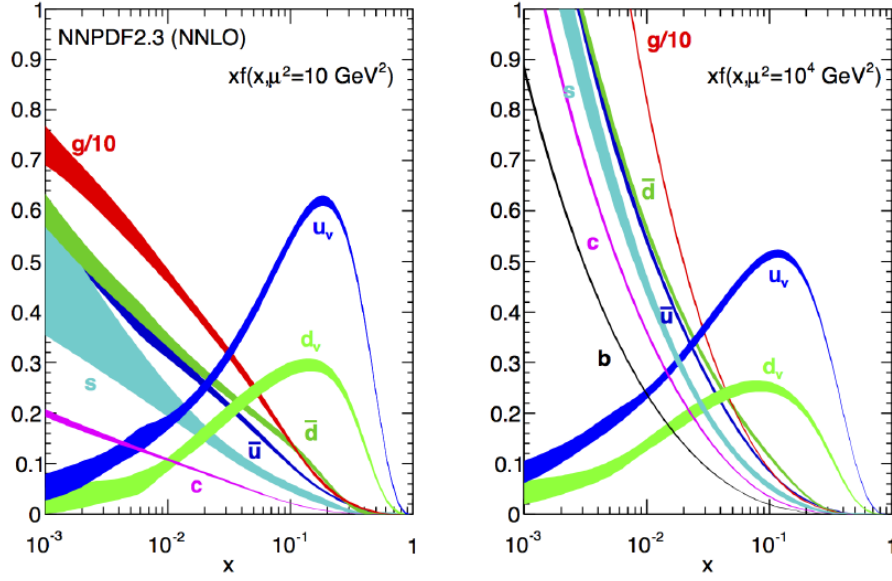


Figure 1.2: Fraction of energy x carried by the parton times the parton distribution function $f(x, \mu^2)$ for protons at energy scales $\mu^2 = 10 \text{ GeV}^2$ and $\mu^2 = 100 \text{ GeV}^2$.

1.1.2 Electroweak theory

The Electroweak theory has been proposed by S. Glashow, A. Salam and S. Weinberg in 60's and 70's. In this theory, the *Quantum Electro Dynamics* has been unified to the *Weak interaction*, using a gauge theory based on $SU(2)_L \times U(1)_Y$ group, where Y is the weak hypercharge and L refers to left-handed particles.

The relation between Y , the electric charge Q and the third component of the weak isospin I_3 is given by the Gell-Mann–Nishijima formula, shown in Eq.1.5:

$$Q = I_3 + \frac{1}{2}Y \quad (1.5)$$

The weak interaction mediates transitions between fermions. In this context, the fundamental constituents of the matter are arranged in doublets of left-handed (see Eq.1.6 and Eq.1.7) and singlets of right-handed fermions (see Eq.1.8, Eq.1.9 and Eq.1.10).

$$L_i = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L, \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L, \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L \quad \begin{matrix} I_3 = +1/2 \\ I_3 = -1/2 \end{matrix} \quad Y = -1 \quad (1.6)$$

$$Q_i = \begin{pmatrix} u \\ d \end{pmatrix}_L, \quad \begin{pmatrix} c \\ s \end{pmatrix}_L, \quad \begin{pmatrix} t \\ b \end{pmatrix}_L \quad \begin{matrix} I_3 = +1/2 \\ I_3 = -1/2 \end{matrix} \quad Y = +1/3 \quad (1.7)$$

$$l_{R,i} = e_R^-, \quad \mu_R^-, \quad \tau_R^-, \quad I_3 = 0 \quad Y = -2 \quad (1.8)$$

$$u_{R,i} = u_R, \quad c_R, \quad t_R, \quad I_3 = 0 \quad Y = +4/3 \quad (1.9)$$

$$d_{R,i} = d_R, \quad s_R, \quad b_R, \quad I_3 = 0 \quad Y = -2/3 \quad (1.10)$$

The request of the local gauge invariance leads to the introduction of four vector bosons: the W^i fields ($i=1,2,3$) for the $SU(2)_L$ group and the field B for the $U(1)_Y$ group. The physical

fields A_μ (photon field), Z_μ (neutral boson Z^0 field) and $W^\pm$ (charged bosons $W^\pm$ fields) can be obtained from a combination of the gauge fields, as shown in Eq.1.11, 1.12 and 1.13.

$$A_\mu = B_\mu \cos \theta_W + W_\mu^3 \sin \theta_W \quad (1.11)$$

$$Z_\mu = W_\mu^3 \cos \theta_W - B_\mu \sin \theta_W \quad (1.12)$$

$$W_\mu^\pm = \frac{W_\mu^1 \mp iW_\mu^2}{\sqrt{2}} \quad (1.13)$$

In the above equations the mixing angle θ_W , which specifies the mixture of Z_μ and A_μ fields in W_μ^3 and B_μ , is known as *Weinberg angle*. θ_W also relates the masses of the weak bosons, as shown in Section 1.2.1.

The analytic form of the EW Lagrangian is shown in Eq.1.14.

$$\mathcal{L}_{EW} = -\frac{1}{4} \sum_G F_G^{\mu\nu} F_{\mu\nu} + i \sum_f \bar{f} D_\mu \gamma^\mu f \quad (1.14)$$

where the index G indicates that the first sum is extended to all the vectorial fields, while the index f indicates that the second sum is extended to all the fermionic fields. The first term in Eq.1.14 describes the dynamics of the bosons, while the second term the interaction between fermions mediated by the four bosons.

The interaction between fermions and bosons can be derived by writing down the definition of the covariant derivative:

$$D_\mu = \partial_\mu - ig_G(\lambda^\alpha G_\alpha)_\mu \quad (1.15)$$

where g_G is the coupling constant to the G_μ field ($G = A, Z, W^\pm$) and λ^α are the generators of the group to which the G field refers ($SU(2)$ or $U(1)$).

The SM Lagrangian as written above is gauge invariant but it doesn't contain any mass term for fermions and bosons. This contradicts the experimental evidence that, apart for the photon, the particles that we observe have a non-zero mass. Any attempt to include ad-hoc mass terms in the Lagrangian spoils the gauge invariance and the re-normalizability of the theory.

The *spontaneous EW symmetry breaking*, described in the next section, is found to be the best solution apt to guarantee the invariance of the Lagrangian. This mechanism is shown in the next section.

1.2 The Higgs Boson and the EWSB

The basic equations of the Standard Model describe correctly the electroweak interaction and its associated force-carrying particles, except for the fact that the Z and W bosons remain without mass, conversely to what experiments show ($M_Z \sim 91 \text{ GeV}$ and $M_W \sim 80 \text{ GeV}$).

A mechanism has been introduced by physicist Robert Brout, François Englert and Peter Higgs, allowing the theory to give mass to these bosons: the so called Brout-Englert-Higgs mechanism[7][8]. The Higgs mechanism provides mass to the mediators of the weak interaction through the spontaneous symmetry breaking of the electroweak interaction (EWSB).

The main assumption for this model is that the universe is permeated with a spin-0 field, the Higgs field. In order to understand the Higgs mechanism, it is necessary to explain what is a broken symmetry. The vacuum state, in quantum field theory, is the one with the lowest energy. Applying the spontaneous symmetry breaking to the vacuum state means to consider this state as degenerate. This degeneracy must be created by a potential that, in case of Higgs mechanism, has the form shown in Eq.1.16.

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 = \mu^2 |\phi|^2 + \lambda |\phi|^4 \quad (1.16)$$

where ϕ is a complex scalar field and μ^2 and λ arbitrary real parameters. Powers higher than Φ^4 would make the theory not renormalizable. To guarantee the existence of a ground state for such a potential, $\lambda > 0$ is also requested.

The behaviour of the Higgs potential is illustrated in Fig.1.3 as a function of the scalar field ϕ for $\mu^2 > 0$ (left) and $\mu^2 < 0$ (right). The structure of the Higgs potential for $\mu^2 < 0$ is shown in detail, in a three dimensional representation, in Fig.1.4.

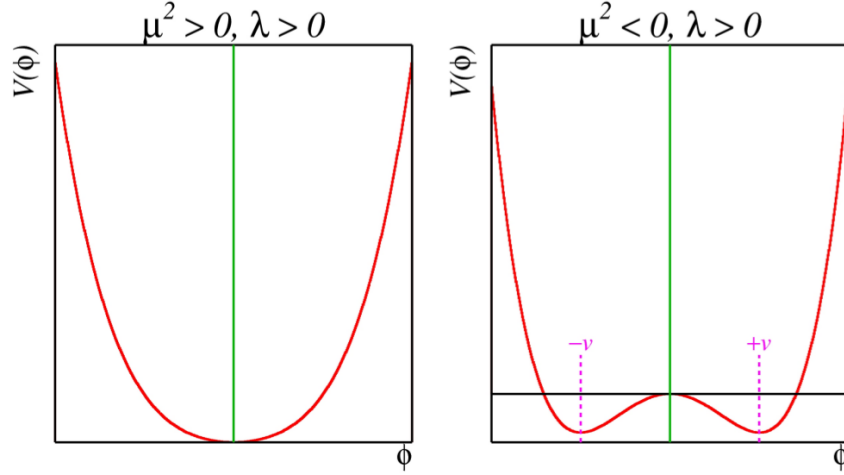


Figure 1.3: Higgs potentials $V(\Phi)$ as a function of the complex scalar field ϕ for $\mu^2 > 0$ (left) and $\mu^2 < 0$ (right).

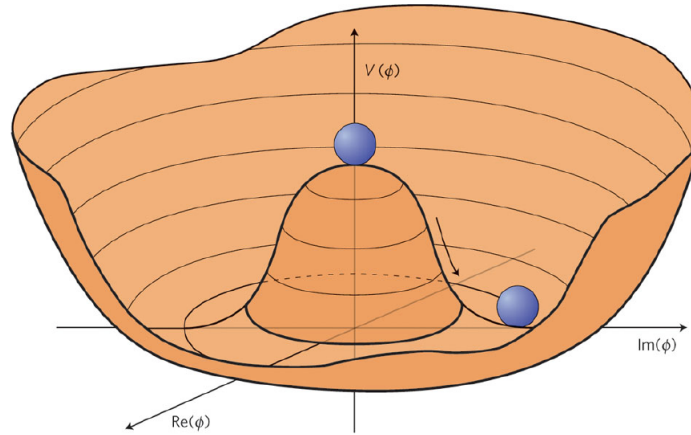


Figure 1.4: Potential of the Higgs field with its typical shape of a "mexican hat".

When $\mu^2 > 0$ the potential has only one absolute minimum in $\phi(x) = 0$. In order to have a degenerate vacuum state, it is thus necessary to consider the case in which $\mu^2 < 0$. In this case, the potential has a relative maximum in $\phi(x) = 0$ and a circumference of minima as shown in Eq.1.17:

$$\phi(x) = \phi_0 \sqrt{\frac{-\mu^2}{2\lambda}} e^{i\theta} \quad (1.17)$$

with $0 < \theta < 2\pi$ and constant ϕ_0 . Choosing a specific direction θ means to operate a spontaneous symmetry breaking for the representation of the vacuum state. It is possible to choose arbitrarily $\theta = 0$ and thus Eq.1.17 becomes:

$$\phi(x) = \phi_0 \sqrt{\frac{-\mu^2}{2\lambda}} \equiv \phi_0 \frac{v}{\sqrt{2}} \quad \text{with} \quad v \equiv \sqrt{\frac{-\mu^2}{\lambda}}. \quad (1.18)$$

It is now possible to apply the Higgs mechanism. The simplest way to introduce the spontaneous symmetry breaking in the SM Lagrangian is by adding a new $SU(2)_L$ doublet of complex scalar fields, the Higgs field:

$$\Phi \equiv \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

The Lagrangian of this scalar doublet is shown in Eq.1.19.

$$\mathcal{L}_H = (D^\mu \Phi)^\dagger (D_\mu \Phi) - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2. \quad (1.19)$$

The covariant derivative is defined in Eq.1.20.

$$D^\mu = \partial^\mu + \frac{i}{2} g \tau_j W_j^\mu + \frac{1}{2} g' Y B^\mu \quad (1.20)$$

where the sum over the index $j = 1, 2, 3$ is implied, τ_j are the Pauli matrices, g and g' are the coupling constants of fermions to the W^μ and B^μ respectively and Y is the weak hypercharge operator. The Lagrangian contains the symmetric potential in Fig.1.4. The vacuum expectation value is then different from zero:

$$\Phi_0 = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \quad (1.21)$$

where $v = \sqrt{-\mu^2/\lambda}$. The Eq.1.21 states that the ground state of the $V(\Phi)$ potential occurs for a non-vanishing value of the Φ field. The ground state is not symmetric under $SU(2)_L \times U(1)_Y$ transformations since there is a preferred direction: the symmetry is spontaneously broken.

To understand the physical content of this mechanism we expand the Φ field perturbatively around its ground state, as shown in Eq.1.22:

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + \sigma(x) \end{pmatrix} \quad (1.22)$$

The gauge in which the Higgs field has the above form is called the *unitary gauge*. In this gauge the imaginary part of the complex Φ field can be eliminated through a local transformation of the field. By substituting the expanded expression for the Higgs field in the Lagrangian in Eq.1.19, we find:

$$\mathcal{L} = \frac{1}{2} \partial_\mu \sigma \partial^\mu \sigma + 2\mu^2 \sigma^2 - 2\sqrt{-2\lambda\mu^2} \sigma^3 - \lambda \sigma^4 + \text{const.} \quad (1.23)$$

The real field $\sigma(x)$ measures the deviation of the field $\Phi(x)$ from the equilibrium ground state configuration $\Phi(x) = \Phi_0$. The Eq.1.23 can be interpreted as the Lagrangian of a scalar field $\sigma(x)$ with mass $\sqrt{2\lambda}v$. It contains a cubic term that breaks the symmetry of the Higgs potential, shown in Fig.1.4.

The Higgs field describes a scalar neutral particle, the Higgs boson, with mass given in Eq.1.24:

$$m_H = \sqrt{2}\mu = \sqrt{2\lambda}v. \quad (1.24)$$

The value of m_H depends on μ , which is a free parameter of the Standard Model. For this reason, the theory is not able to predict the Higgs boson mass.

1.2.1 Boson masses

Bosons masses originate from the interaction of the $SU(2) \times U(1)$ gauge fields (W^μ and Z^μ) with the Higgs field. This interaction takes place through the covariant derivative D^μ shown in Eq.1.20. Replacing the covariant derivative in the scalar Lagrangian, the Eq.1.25 is obtained:

$$(D_\mu \Phi)^\dagger D^\mu \Phi \rightarrow \frac{1}{2} \partial_\mu \sigma \partial^\mu \sigma + (v + \sigma)^2 \left(\frac{g^2}{4} W_\mu^\dagger W^\mu + \frac{g^2}{8 \cos^2 \theta_W} Z_\mu Z^\mu \right). \quad (1.25)$$

Both the $W^\pm$ and the Z^0 bosons have acquired mass, since they appear in the previous formula as quadratic terms. The mass of the $W^\pm$ and the Z^0 bosons are related to each other, through the Eq.1.26:

$$M_Z \cos \theta_W = M_W = \frac{1}{2} v g. \quad (1.26)$$

Since $\tan \theta = \frac{g'}{g}$, we can also write the expressions for the W and Z boson, as shown in Eq.1.27 and 1.28:

$$M_W = \frac{v g}{2}, \quad (1.27)$$

$$M_Z = \frac{v}{2} \sqrt{g^2 + g'^2}. \quad (1.28)$$

1.2.2 Fermion masses

Fermions masses are generated by coupling the Higgs doublet and the fermions. The additional Yukawa term to add to the SM lagrangian has the form shown in Eq.1.29:

$$\mathcal{L} = -g_\psi (\bar{\psi}^L \Phi \psi^R) + h.c. \quad (1.29)$$

where g_ψ is the coupling constant of the fermionic field ψ to the Higgs field and ψ^L and ψ^R are the left- and right-handed fermion fields respectively. Expanding the Eq.1.29 around the ground state of the Higgs field, it is possible to derive the fermion mass term:

$$m_\psi = g_\psi v / \sqrt{2} \quad (1.30)$$

where g_ψ is the value of the Yukawa coupling of the fermions with the Higgs boson. It is evident from Eq.1.30, that boson and fermion masses depend strongly on the value of the parameter v , as well as on the m_H . It can be shown[9] that the parameter v is related to the Fermi constant G_F through Eq.1.31:

$$v = (\sqrt{2} G_F)^{-1/2} \approx 246 \text{ GeV}. \quad (1.31)$$

1.3 Higgs boson searches before its discovery

Finding the SM Higgs boson has been one of the most topical goals of particle physics in the last decades. The first extensive search for the Higgs boson has been conducted at the Large Electron-Positron Collider (LEP) at CERN in the 1990s, with the experiments ALEPH, DELPHI, L3 and OPAL. At the end of its service in 2000, LEP had found no conclusive evidence for the Higgs. Combining their final results, the four LEP experiments set limits on the Standard Model Higgs boson mass, excluding the mass range $< 114.4 \text{ GeV}/c^2$ at the 95% confidence level [10].

The search continued at Fermilab in the United States, with the experiments CDF and D0, exploiting $p\bar{p}$ collisions, provided by the collider Tevatron at center of mass energy of 1.96 TeV. The Tevatron has been able to exclude further ranges for the Standard Model Higgs mass. The final analysis, performed with about 10 fb^{-1} of data, excluded, at the 95% C.L., the possibility of a Higgs boson with a mass between $100 \text{ GeV}/c^2$ and $103 \text{ GeV}/c^2$ and between $147 \text{ GeV}/c^2$ and $180 \text{ GeV}/c^2$. Higgs boson masses below $100 \text{ GeV}/c^2$ were not studied.

In addition, an excess of events was found, possibly indicating a Higgs boson with a mass between $115 \text{ GeV}/c^2$ and $140 \text{ GeV}/c^2$ [11]. A summary of LEP and Tevatron searches is shown in Fig. 1.5. Exclusion limits from ATLAS and CMS, preceding to the Higgs boson discovery, are also shown in the same plot.

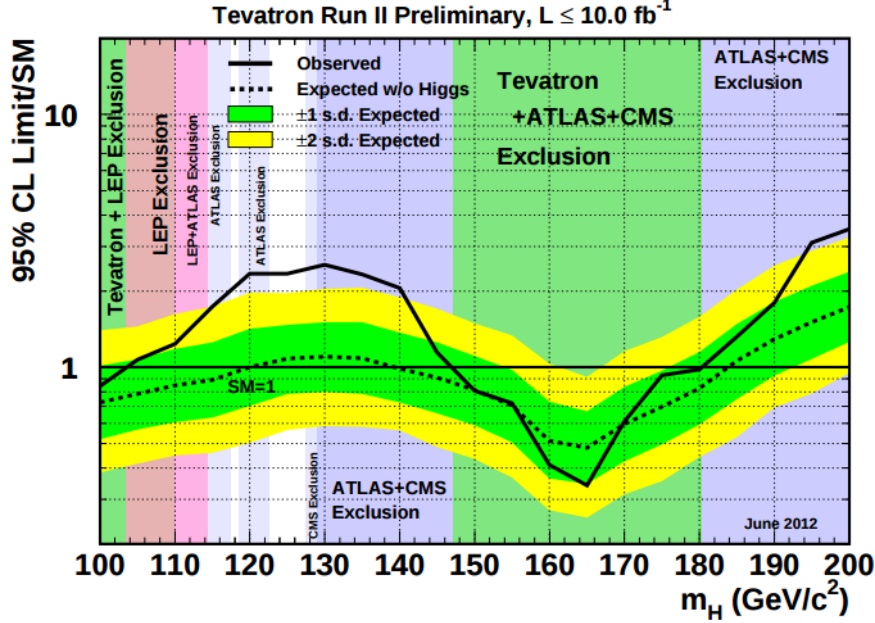


Figure 1.5: Observed and expected 95% C.L. upper limits on the ratios to the SM cross section, as functions of the Higgs boson mass for the combined CDF and D0 analyses. The green and yellow bands indicate, respectively, the 68% and 95% probability regions where the limits can fluctuate, in the absence of signal[11].

1.4 Higgs boson production at LHC

At the LHC collider (see Section 3.1) the Higgs boson can be produced through four different modes. The cross sections of these processes depend on the Higgs boson mass and on the center-of-mass energy. In Fig.1.6, the cross sections of the main Higgs boson production modes at $\sqrt{s} = 13 \text{ TeV}$ as a function of the Higgs boson mass are shown. The four main Higgs production processes are described below.

- The production mode with the higher cross section, in the whole Higgs boson mass range, is the gluon-gluon fusion (ggF). This is mainly mediated by a top quark loop, as shown in the Feynman diagram in Fig1.7(a). This production channel has no any distinctive experimental signatures; it can be detected only with a clear identification of the Higgs boson decay products.
- The second most relevant production mode is the vector boson fusion (VBF). This process has a cross section a factor 10 smaller than ggF. The relative Feynman diagram is shown in Fig1.7(b). Two vector boson (W or Z) are radiated by quarks and fusing to create the Higgs boson. VBF shows a peculiar kinematic signature: the Higgs boson production is accompanied by two light jets, directed predominantly in the forward region of the detector.
- The Higgs boson associated production with $W^\pm$ or Z^0 , also called the Higgs-strahlung, has the third larger cross-section at LHC. Both the associated production modes are useful to test the SM predictions, since they are sensitive to the direct coupling between

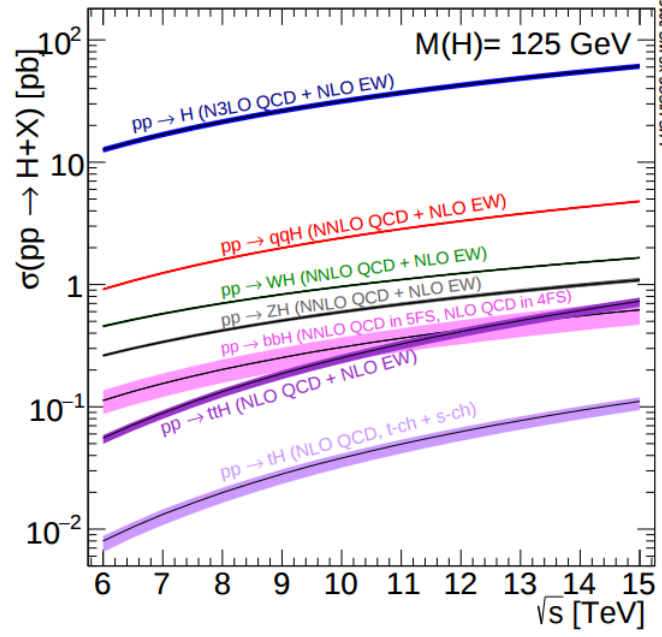


Figure 1.6: Higgs boson cross sections for the main production modes as function of the center-of-mass energy. The m_H value is fixed at 125 GeV. The bands represent the theoretical uncertainties[12].

the Higgs boson and the vector bosons. The associated Feynman diagram is shown in Fig1.7(c).

- The production mode with the smaller cross section is the ttH , reported in Fig1.7(d). This process occurs via a top-loop. For this reason, despite the small cross section, a factor 100 smaller than the ggF , this production mode is interesting to test the SM couplings and in particular the direct coupling between the Higgs boson and the Top quark.

According to the SM predictions, the Higgs boson can decay in several modes. The branching ratios for each decay mode are shown in Fig.1.8, as a function of m_H .

Since the Higgs boson couplings are proportional to masses, as m_H increases the Higgs particle becomes strongly coupled. This reflects in the sharp rise of the Higgs boson total width, shown in Fig.1.9, as a function of the Higgs mass. Fig.1.10 shows the Feynman diagrams for the Higgs decays in vector bosons and in fermions.

The largest branching ratio is the one corresponding to the decay into a $b\bar{b}$. This event topology is hard to be identified at LHC because of the high multi-jets background. This is true for all the final state with hadronic activity, including $\tau\tau$ with τ decaying to hadrons.

The Higgs decays $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ offer a very clear experimental signature. Despite the low branching ratios, they played a great role in the discovery of the Higgs boson, as shown in Section 1.5, thanks to the complete reconstruction of the event kinematic. The Higgs signal, in fact, manifests itself as a clear peak in the invariant mass distribution of the final state particles (muons and photons, respectively).

The $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay channel is the primary discovery channel for a large Higgs boson mass range, but it suffers the presence of the missing transverse momentum. Because of the presence of neutrinos, in fact, it is not possible to reconstruct the exact invariant mass of the Higgs particle.

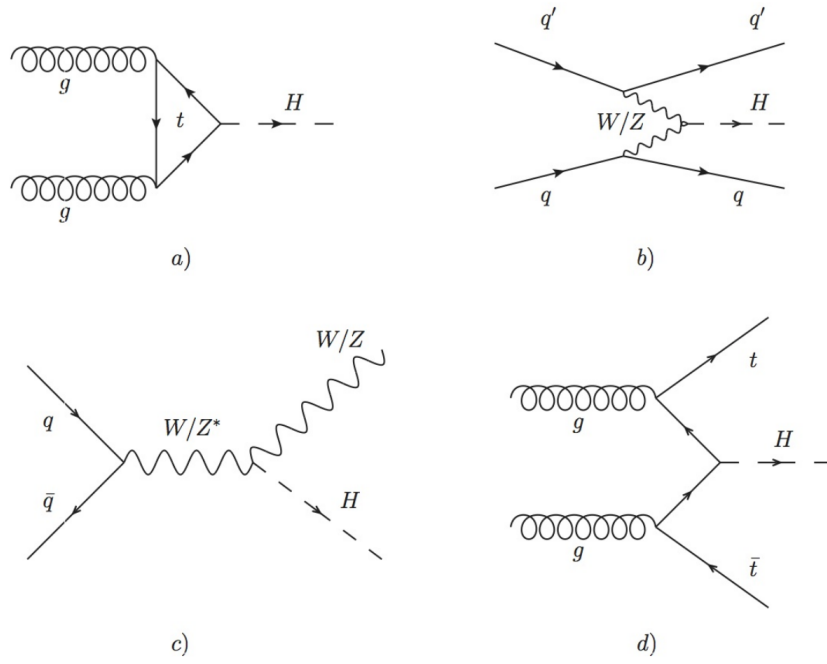


Figure 1.7: Tree-level Feynman diagrams for the Higgs boson production at LHC: the gluon-gluon fusion (a), the Vector Boson Fusion (b), the associated production with a $W^\pm$ or Z^0 boson (c), the ttH production (d).

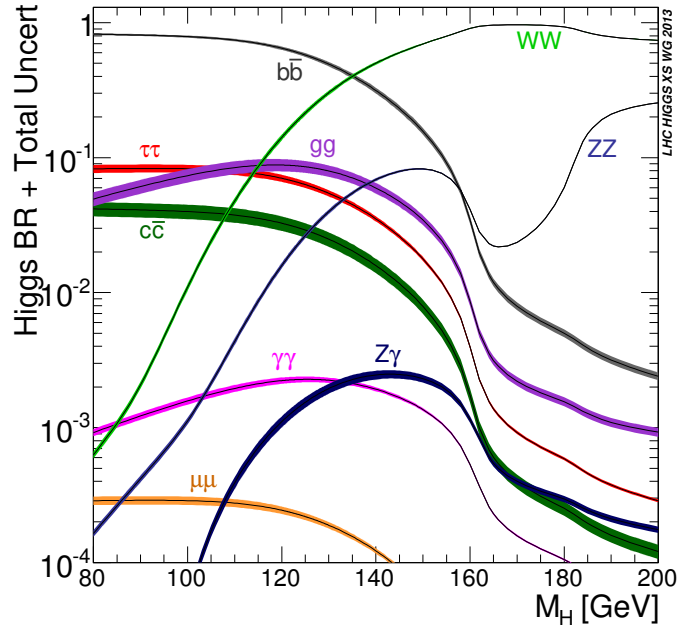


Figure 1.8: Higgs boson branching ratios as a function of its mass. The bands represent the theoretical uncertainties[12].

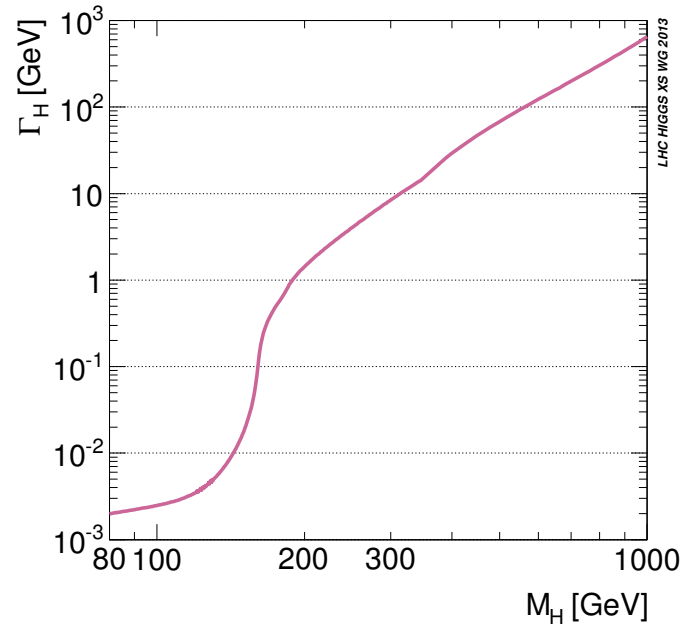


Figure 1.9: Higgs total width as a function of its mass[12].

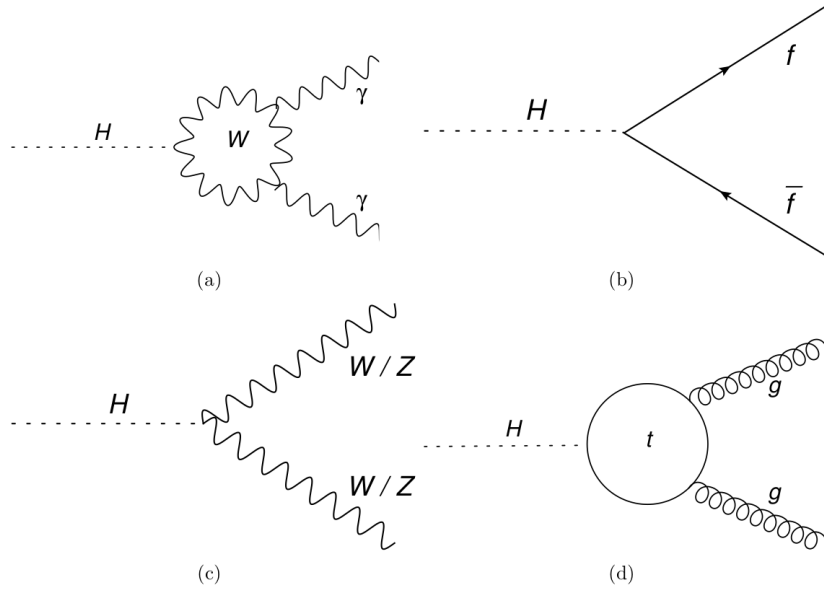


Figure 1.10: SM Higgs boson decay Feynman diagrams.

1.5 Higgs boson discovery

After more than 20 years of continuous searches, on 4th July 2012 the ATLAS and CMS collaborations announced independently the discovery of a new particle, compatible with the predicted Higgs boson [13] [14]. Both experiments exploited the proton-proton collisions delivered by the LHC accelerator at $\sqrt{s} = 7 \text{ TeV}$ during 2011 and at $\sqrt{s} = 8 \text{ TeV}$ during 2012.

The ATLAS experiment used a dataset corresponding to integrated luminosities of approximately 4.8 fb^{-1} collected at $\sqrt{s} = 7 \text{ TeV}$ and 5.8 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$. The search is performed in five decay modes: $H \rightarrow ZZ^*$, $H \rightarrow WW^*$, $H \rightarrow \gamma\gamma$, $H \rightarrow \tau\tau$ and $H \rightarrow b\bar{b}$. ATLAS observes the evidence for the production of a neutral boson with a measured mass of $126.0 \pm 0.4(\text{stat}) \pm 0.4(\text{sys}) \text{ GeV}$ with a significance of 5.9 standard deviations.

If Fig.1.11, a clear evidence for the production of a new particle, consistent with the SM Higgs boson, is shown. The plot shows the distribution of the four-lepton invariant mass, compared to the background expectation in the 80–250 GeV mass range, for the combination of the $\sqrt{s} = 7 \text{ TeV}$ and $\sqrt{s} = 8 \text{ TeV}$ data.

The CMS collaboration used data samples corresponding to integrated luminosities of 5.1 fb^{-1} at $\sqrt{s} = 7 \text{ TeV}$ and 5.3 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$. The search is performed in the same channel as ATLAS and the observed local significance is 5.0 standard deviations.

In Fig.1.12, the diphoton invariant mass distribution for the combination of the $\sqrt{s} = 7 \text{ TeV}$ and $\sqrt{s} = 8 \text{ TeV}$ data recorded by the CMS experiment is shown. The presence of the peak in the falling continuum background distribution represents the clear evidence for the production of a new particle, consistent with the SM Higgs boson.

In 2015, the ATLAS and CMS collaboration published a new paper[15] in which the combination of the Higgs boson mass measurements is presented. The datasets used for the combination include 5 fb^{-1} of integrated luminosity at $\sqrt{s} = 7 \text{ TeV}$ and 20 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$, for each experiment. The summary of the Higgs boson mass measurements from the individual analyses of ATLAS and CMS and from the combined analysis is shown in Fig.1.13.

Combining the individual mass measurements from $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ channels from both the experiments, a value for the Higgs boson mass of $125.09 \pm 0.24 \text{ GeV}$ (corresponding to a precision of about 0.2%) is obtained.

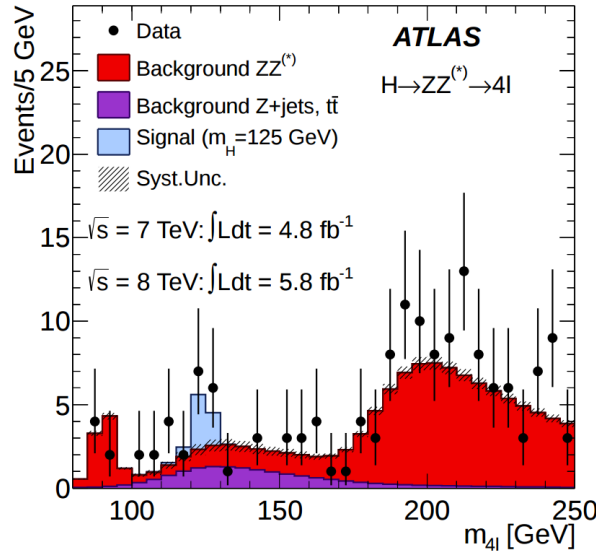


Figure 1.11: The distribution of the four-lepton invariant mass, compared to the background expectation in the 80–250 GeV mass range, for the combination of the $\sqrt{s} = 7 \text{ TeV}$ and $\sqrt{s} = 8 \text{ TeV}$ data. The signal expectation for a SM Higgs with $m_H = 125 \text{ GeV}$ is also shown[13].

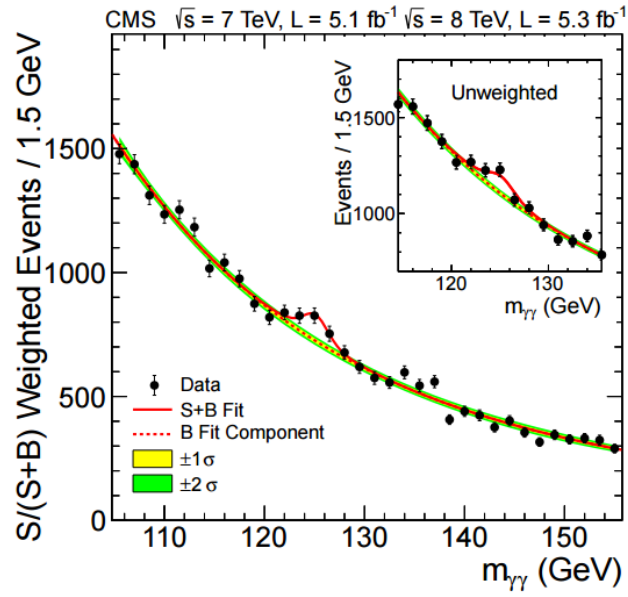


Figure 1.12: The diphoton invariant mass distribution with each event weighted by the $S/(S+B)$ value of its category. The lines represent the fitted background and signal, and the coloured bands represent the ± 1 and ± 2 standard deviation uncertainties in the background estimate[14].

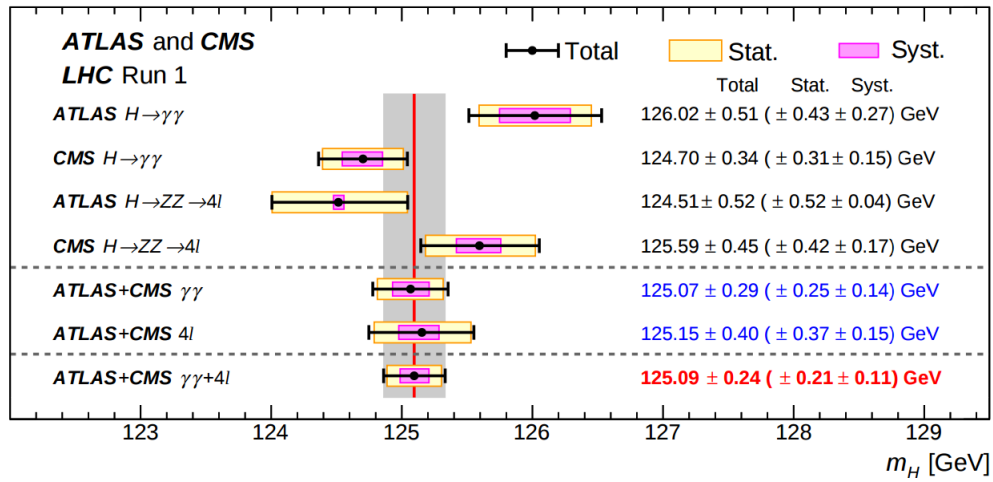


Figure 1.13: Summary of Higgs boson mass measurements from the individual analyses of ATLAS and CMS and from the combined analysis[15].

1.6 Standard Model: an incomplete theory?

The discovery of the Higgs boson has been certainly one of the latest great success of the Standard Model. Although its robustness, the Standard Model is still an "incomplete theory". In fact, there are some physical phenomena in nature not adequately explained by the theory. Some of them are listed below:

- the SM does not contain any interpretation of gravitational field;
- the existence of the dark matter: cosmological observations tell us that dark matter exists but the theory does not supply any fundamental particles that are good dark matter candidates. Are the dark matter particles connected to the Standard Model particles, or are they part of an entirely new dark sector of particles?
- matter–antimatter asymmetry. The universe is made out of mostly matter. However, the theory predicts that matter and antimatter should have been created in equal amounts. Which mechanism produced the excess of matter over anti-matter that we see in the Universe?
- neutrino masses: why are neutrinos so light compared to other matter particles? Moreover, are neutrinos their own antiparticles?
- the SM does not provide any explanation to the existence of the dark energy, which should include about 69% of the energy present in the universe.
- is there one only Higgs particle or many? Is the Higgs particle elementary or composite?

Chapter 2

ttH production mode

2.1 ttH production mode

The Higgs boson production in association with a top quark pair (ttH) represents the Higgs production mode with the smallest cross-section with respect to all other Higgs production mechanism. This makes the observation of ttH very difficult with limited statistics. Nevertheless, the search for ttH is very challenging in the LHC physics program.

The leading-order Feynman diagrams for the Higgs boson production in association to a top quark pair are shown in Fig.2.1. A comparison among the cross section values for the main five Higgs production modes at LHC at a centre-of-mass energy $\sqrt{s} = 13 \text{ TeV}$ for $m_H = 125 \text{ GeV}$ is shown in Table 2.1.

Process	Cross section [pb]	Calculation
ggF	$43.92^{+7.4\%}_{-7.9\%}(\text{QCD Scale})^{+7.1\%}_{-6.0\%}(\text{PDF} + \alpha_S)$	NNLO+NNLL QCD, NLO EW
VBF	$3.748^{+0.7\%}_{-0.7\%}(\text{QCD Scale})^{+3.2\%}_{-3.2\%}(\text{PDF} + \alpha_S)$	NNLO QCD, NLO EW
WH	$1.380^{+0.7\%}_{-1.5\%}(\text{QCD Scale})^{+2.2\%}_{-2.2\%}(\text{PDF} + \alpha_S)$	NNLO QCD, NLO EW
ZH	$0.8696^{+3.8\%}_{-3.8\%}(\text{QCD Scale})^{+2.2\%}_{-2.2\%}(\text{PDF} + \alpha_S)$	NNLO+NNLL QCD, NLO EW
ttH	$0.5085^{+5.7\%}_{-9.3\%}(\text{QCD Scale})^{+8.8\%}_{-8.8\%}(\text{PDF} + \alpha_S)$	NNLO QCD

Table 2.1: Cross section values for the main five Higgs production modes at LHC at a centre-of-mass energy $\sqrt{s} = 13 \text{ TeV}$. The Higgs boson mass is fixed to 125 GeV [12]. Uncertainties on the cross section values derive mainly from the QCD scale, PDF set and α_S .

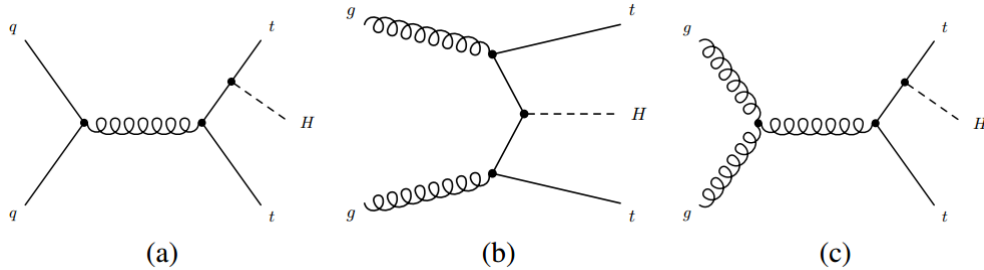


Figure 2.1: Leading-order Feynman diagrams for the Higgs boson production in association to a top quark pair.

The SM predicts that the Yukawa coupling of the Higgs boson to the top quark, g_t , is proportional to the top quark mass, as described in Section 1.2.2. Due to its large mass ($m_t \sim 173 \text{ GeV}$), the top quark Yukawa coupling is expected to be of order one: $g_t = \sqrt{2}m_t/v \sim 0.99$.

Since the top quark is heavier than the Higgs boson, this latter cannot decay into a top quark pair. Hence the top-Higgs coupling cannot be measured using this decay channel. The Higgs boson produced in association with a pair of top quarks represent the only process for a direct measurement of the top quark-Higgs boson Yukawa coupling.

Indirect constraints on the top Yukawa coupling can be also inferred from gluon-gluon fusion production of the Higgs boson (ggF), as well as from $H \rightarrow \gamma\gamma$ decays, since the quark top is the heaviest SM particles and its contribution in the loop is expected to be the dominant one, in both production (ggF) and decay ($H \rightarrow \gamma\gamma$). ggF and $H \rightarrow \gamma\gamma$ leading-order Feynman diagrams are shown in Fig.2.2.

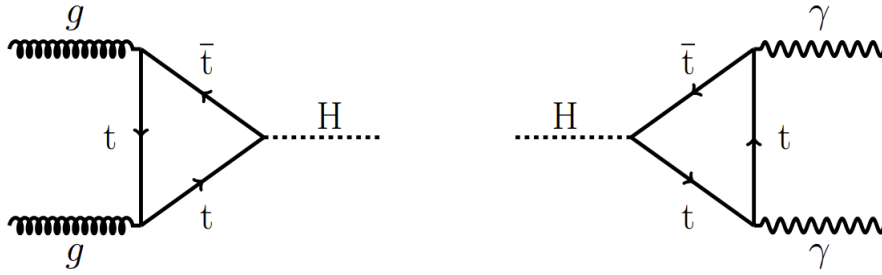


Figure 2.2: Higgs production via gluon-gluon fusion (left) and Higgs decay in two photons (right).

In the ggF diagram for the Higgs production the loop could involve also bottom quarks. Nevertheless, since the bottom quark is about 40 times lighter than the top quark and the Yukawa coupling is proportional to the fermion masses, its contribution in the loop is negligible.

The top quark is not the only particle involved in the $H \rightarrow \gamma\gamma$ decay loop. The W boson can also be present, since it couples both to the Higgs boson and photons, as shown in Fig.2.3. The Higgs-W coupling can be again inferred from the measurement of the WH production mode or through the decay $H \rightarrow WW^*$.

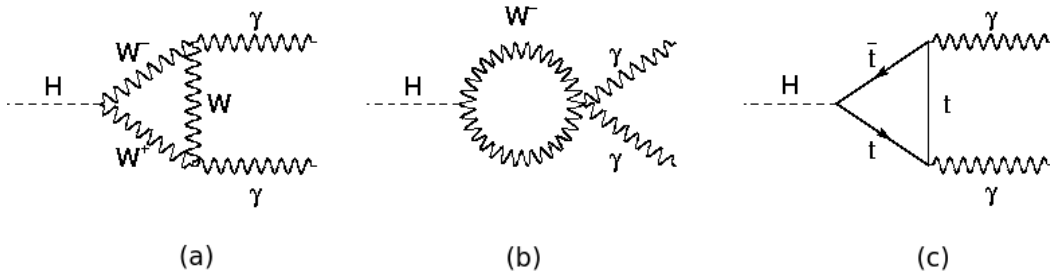


Figure 2.3: Feynman diagrams for the Higgs decay in two photons.

The measurement of the $t\bar{t}H$ production rate provides a direct test of the coupling between the top quark and the Higgs boson. Moreover, many new physics scenarios predict the existence of heavy top quark partners that would decay into a top quark and a Higgs boson.

Having both the tree- and loop-level measurements would allow disambiguation of new physics effects[16]. Any significant deviations in the $t\bar{t}H$ production rate with respect to the SM prediction would be an indirect indication of Beyond Standard Model (BSM) physics.

2.2 ttH search results from ATLAS Run-1

Due to its small production cross section, shown in Table 2.1, and to the abundance and topology of the backgrounds, this mechanism has not been directly observed yet. The $pp \rightarrow ttH$ process can be studied in a large variety of complex final states, depending on the top quark pair decay topology (all-hadronic, semileptonic or dileptonic decays) and the Higgs decay mode.

The branching ratios for the SM Higgs boson with mass $m_H = 125 \text{ GeV}$ are reported in Table 2.2. The Higgs decays in a bottom quark pair and in W boson pair represent almost the 80% of the total Higgs boson decay width.

Decay channel	Branching Ratio [%]
$H \rightarrow b\bar{b}$	57.5 ± 1.9
$H \rightarrow W\bar{W}$	21.6 ± 0.9
$H \rightarrow g\bar{g}$	8.56 ± 0.86
$H \rightarrow \tau\bar{\tau}$	6.30 ± 0.36
$H \rightarrow c\bar{c}$	2.90 ± 0.35
$H \rightarrow Z\bar{Z}$	2.67 ± 0.11
$H \rightarrow \gamma\gamma$	0.228 ± 0.011
$H \rightarrow Z\gamma$	0.155 ± 0.014
$H \rightarrow \mu\bar{\mu}$	0.022 ± 0.001

Table 2.2: Standard Model prediction for the decay branching ratios of the Higgs boson. m_H is set to 125 GeV[17].

An analysis using the full Run-1 data set, corresponding to 20.3 fb^{-1} , has been already published by the ATLAS collaboration in 2015 [18]. The analysis has been performed exploiting several final states, sensitive to the different Higgs decays mode: $H \rightarrow b\bar{b}$, $H \rightarrow W\bar{W}^*$, $H \rightarrow Z\bar{Z}^*$, $H \rightarrow \tau\bar{\tau}$, and $H \rightarrow \gamma\gamma$.

The ttH searches that are combined are:

- ttH ($H \rightarrow b\bar{b}$) in the single-lepton, opposite-charge dilepton and full-hadronic $t\bar{t}$ decay channels, using data at $\sqrt{s} = 8 \text{ TeV}$;
- ttH ($H \rightarrow (W\bar{W}^*, Z\bar{Z}^*, \tau\bar{\tau})$) in the final states with: two same-charge leptons, three leptons, four leptons, two hadronically decaying τ leptons plus one light lepton and two same-charge leptons plus one hadronically decaying τ , using data at $\sqrt{s} = 8 \text{ TeV}$;
- ttH ($H \rightarrow \gamma\gamma$) in the single-lepton, opposite-charge dilepton and full-hadronic $t\bar{t}$ pair decay channels, using data at $\sqrt{s} = 7 \text{ TeV}$ and $\sqrt{s} = 8 \text{ TeV}$;

The best-fit value of the signal strength $\mu = \sigma_{obs}^{ttH} / \sigma_{SM}^{ttH}$ is determined using a maximum likelihood fit to the data yields of the different categories. The details on the statistical procedure will be shown in Chapter 8. The observed cross section is defined as follows:

$$\sigma_{obs} = \frac{N_{obs} - N_{bkg}}{\mathcal{L} \cdot BR \cdot \epsilon} \quad (2.1)$$

where $N_{obs} - N_{bkg}$ is the difference between the number of events observed in data and the estimated background, $\mathcal{L}$ is the integrated luminosity of the dataset, BR is the branching ratio referred to the particular final state expressed in percentage and ϵ is a correction factor that accounts for detector inefficiency and acceptance.

The measured values of μ in the combined fit for the different signal categories are shown in Fig.2.4. The $\mu = 1$ hypothesis assumes Standard Model Higgs boson production and decay with $m_H = 125 \text{ GeV}$. The processes tHqb and tHW, sensitive to the Higgs-Top coupling, are considered as backgrounds and set to the Standard Model expectation.

The combined μ is found to be $1.7_{-0.8}^{+0.8}$, fully compatible with the SM predictions.

The 95% confidence level (CL) upper limits on the signal strength μ are shown in Fig.2.5.

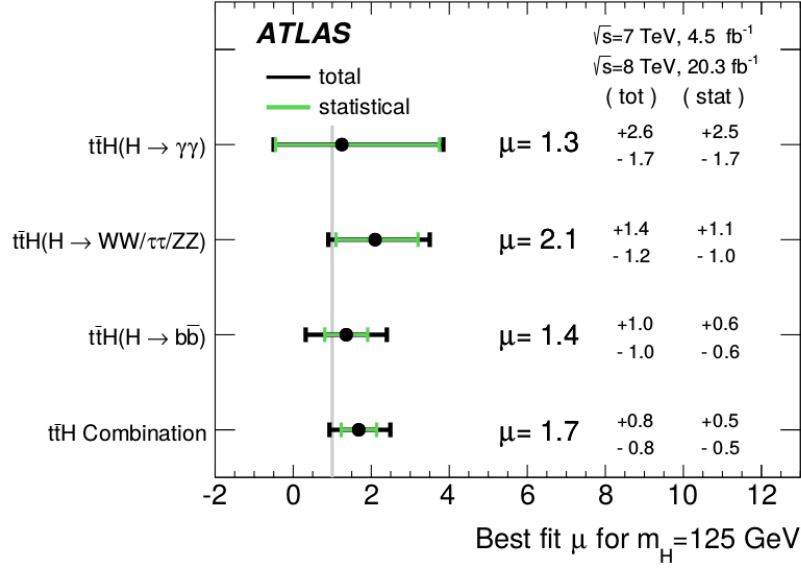


Figure 2.4: Summary of the measurements of the signal strength μ for the individual channels and for their combination, assuming $m_H = 125 \text{ GeV}$. The total (tot) and statistical (stat) uncertainties of μ are shown. The SM $\mu = 1$ expectation is shown as the grey line[17].

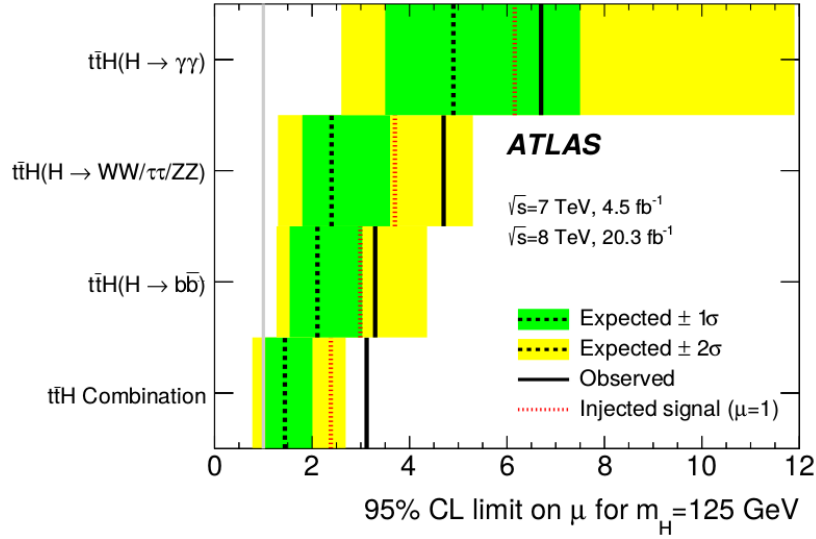


Figure 2.5: Upper limits on the signal strength μ for the individual channels as well as for their combination, at 95%CL. The observed limits (solid lines) are compared to the expected median limits under the background-only hypothesis (black dashed lines) and under the signal-plus-background hypothesis assuming the SM prediction for $\sigma_{t\bar{t}H}$ (red dotted lines). The surrounding green and yellow bands correspond to the $\pm 1\sigma$ and $\pm 2\sigma$, around the expected limits under the background-only hypothesis[17].

The observed (expected) upper limit, obtained from the combination of all channels, is 3.1 (1.4).

The study of multi-leptonic final states performed by ATLAS categorizes events according to the number of leptons (electron or muons) and hadronically decaying τ leptons. The result arising from the combination of all multilepton final states has been already shown in Fig.2.4.

The results in terms of the signal strength μ for the individual multilepton final states are shown in Fig.2.6. The value of the strength parameter μ obtained from the best-fit to data is $\mu = 2.1^{+1.4}_{-1.2}$, compatible with the SM predictions[16].

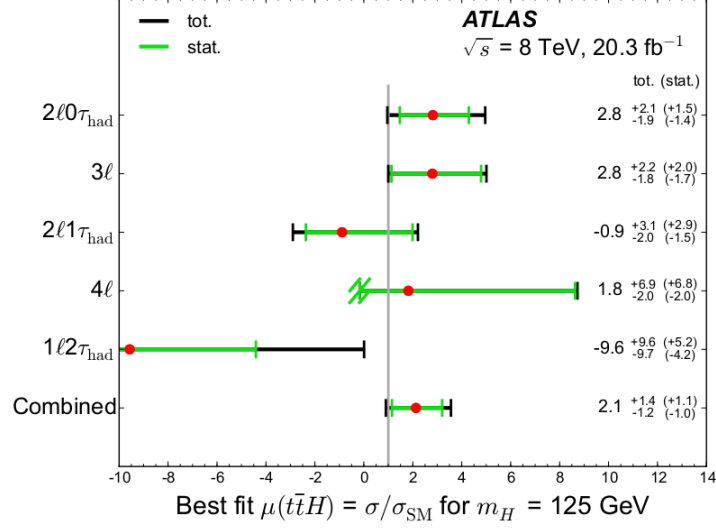


Figure 2.6: Results of the ATLAS search of $t\bar{t}H$ in multilepton final states in terms of the best fit values of the signal strength parameter[16].

The subject of this thesis work consists in the study of the $t\bar{t}H$ production mode in multilepton final states channel, using the ATLAS dataset at $\sqrt{s} = 13 \text{ TeV}$. In particular, more emphasis will be given to the 3ℓ final state. The aim is improving the currents results thanks to the increasing of the $t\bar{t}H$ production cross section at the new centre-of-mass energy (see Chapter 5) and thanks to the application of new techniques, described in Chapter 7.

Chapter 3

The ATLAS experiment

The data analysis shown in this thesis has been performed exploiting the data collected during 2015 and 2016 by the ATLAS (A Toroidal LHC ApparatuS) experiment[19] at the Large Hadron Collider (LHC), the most powerful particle accelerator at CERN (European Organization for Nuclear Research). ATLAS is one of the four main detectors being built to study the particle collisions delivered by LHC. In this chapter the description of the LHC as well as the full detector apparatus will be described. The accelerator mechanism is similar for protons as well for ions. Since this study is based on proton-proton collision analysis, from this point forward, only protons will be discussed.

3.1 The LHC accelerator

The LHC is a particle accelerator located between Switzerland and France, close to the city of Geneva. It is actually the most powerful particle accelerator in the world and it is able to accelerate protons as well as heavy ions (lead ions), providing collisions at center of mass energy on the TeV scale. It is 27 Km long about and it lies in a tunnel 175 metres deep underground.

In order to accelerate particles up to these very high energies, one only accelerator is not enough. CERN, during several years, developed a very complex accelerator system that is shown in Fig.3.1. Before to be injected into the LHC ring, particles go through several acceleration stages. Protons are firstly generated stripping the valence electrons from hydrogen atoms and accelerated by a linear accelerator, the LINAC2, up to 50 MeV energy and then injected in a circular accelerator, the Proton Synchrotron Booster (PSB), where the particles reach an energy of about 1.4 GeV.

Protons are, then, injected in a larger accelerator, the Proton Synchrotron (PS), 628 meters long, where the beam energy rises to 26 GeV and later into the Super Proton Synchrotron (SPS) which increases their energy up to 450 GeV. SPS is 7 Km long about and before to be the injector for LHC, it was, from 1981 to 1984, a proton-antiproton collider providing data for the UA1 and UA2 experiments, allowing the discovery of the W and Z bosons.

The particles enter the LHC into two parallel rings and, after ramping up to the desired energy, the beams are squeezed and direct towards the dedicated LHC experiments, ATLAS, ALICE[20], CMS[21] and LHCb[22], for the collisions. At the nominal conditions, the maximum number of protons per each bunch and the number of bunches per each beam are $\sim 10^{11}$ about and 2808, respectively. At full operation, the interactions between two beams take place every 25 ns, corresponding to a collision rate of 40 MHz.

Beam focusing and acceleration are obtained using magnets (quadrupoles) and six radio-frequency (RF) cavities, respectively. LHC is equipped with 1232 superconducting dipole magnets, providing a magnetic field of 8.3 T and needed to bend the particles along the circumference. In order to reach and keep the superconductivity conditions in LHC, a complex cooling system provides fluid helium, guaranteeing a temperature of about 1.9 K. Some of the main LHC parameters are shown in Table 3.1.

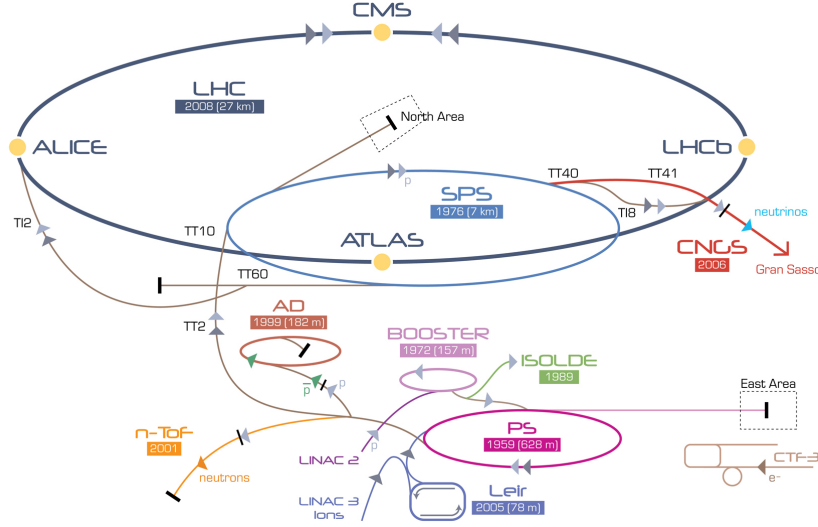


Figure 3.1: The CERN accelerator system.

Parameter	Value
N_p	1.6×10^{11}
n	2200
f	40 MHz
β^*	0.6 m
σ_z	9.4 cm
$\sigma_{x,y}$	19 μ m

Table 3.1: LHC machine parameters. N_p is the number of protons per bunch, n is the number of bunches per beam, f is the frequency of the proton collisions, β^* is the β function, σ_z is the RMS bunch length and $\sigma_{x,y}$ is the transverse RMS beam size at the Interaction Point (IP).

One of the main parameters for a collider machine is its instantaneous luminosity. It represents the link between the rate for a given process and its cross-section, as shown in Eq.3.1.

$$R(t) = \mathcal{L}(t) \times \sigma \quad (3.1)$$

The instantaneous luminosity is a parameter of the machine, i.e. it depends only from the technical parameters of the collider, as described in the Eq.3.2:

$$\mathcal{L} = \frac{f N_b^2 n}{4\pi \sigma_x \sigma_y} \quad (3.2)$$

where σ_x and σ_y are the Gaussian beam profiles in the transverse plane with respect to the beam direction. The nominal value for LHC instantaneous luminosity is $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, making LHC the particle collider with the higher luminosity ever. From Eq.3.1, by integrating in time-domain, it is possible to derive the Eq.3.3:

$$N = L \times \sigma. \quad (3.3)$$

Now L is the integrated luminosity and N is the total number of expected events for a given process. The knowledge of the integrated luminosity with the best precision possible is one of the fundamental requirements for every high-energy physics experiment. In fact, it is necessary for the cross-section measurement, computed using the Eq.3.3, as well as for the normalization of the number of signal and background events from Monte Carlo simulations. In this thesis, the data analysis has been performed using an integrated luminosity of 13.2 fb^{-1} . It has been measured by ATLAS with an uncertainty of 4%.

To reduce the uncertainty on the luminosity and, hence, on the measured cross-section, the instantaneous luminosity is monitored regularly during the data-taking period, for example with the Van Der Meer scans method[23]. In ATLAS, specific detectors are in operation to monitor the instantaneous luminosity delivered by LHC, such as LUCID and ALFA. A brief overview on these detectors is given in Section 3.2.5.

3.1.1 LHC operations during ATLAS Run-2

LHC started to deliver proton-proton collisions at 7 TeV center of mass energy in 2011. During this period ATLAS collected an integrated luminosity of 5 fb^{-1} about. Then, the energy has been increased up to 8 TeV, allowing ATLAS to collect 20 fb^{-1} approximately during 2012. This data-taking period is called *Run-1*. Fig 3.2 show the integrated luminosities collected by the ATLAS detector during Run-1.

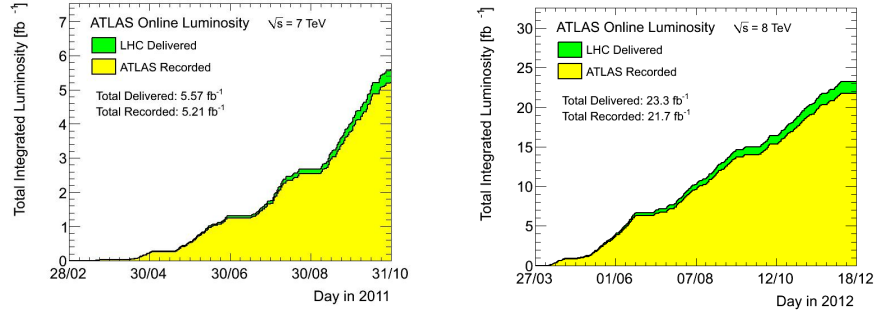


Figure 3.2: Integrated luminosity recorded by the ATLAS detector during Run-I at $\sqrt{s} = 7 \text{ TeV}$ (left) and at $\sqrt{s} = 8 \text{ TeV}$ (right).

The ATLAS Run-2 started in Spring 2015 when LHC delivered for the first time proton-proton collisions at 13 TeV (6.5 TeV per beam). Collisions occurred at 40 MHz frequency, corresponding to a bunch to bunch distance of 25 ns.

During the 2015 data taking, ATLAS collected an integrated luminosity of 3.9 fb^{-1} . In 2016 the instantaneous luminosity grow-up, reaching in the 2016 summer the nominal value of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The integrated luminosities collected during Run-2 is shown in Fig.3.3.

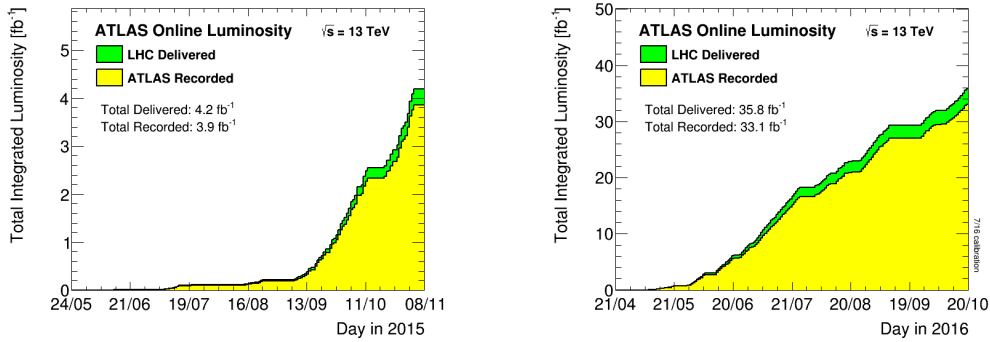


Figure 3.3: Integrated luminosity recorded by the ATLAS during Run-2 at $\sqrt{s} = 13 \text{ TeV}$ during 2015 (left) and 2016 (right). The data-taking during 2016 is still ongoing.

The amount of data, used in this analysis, corresponds to 3.2 fb^{-1} recorded in 2015 and 10.0 fb^{-1} recorded during 2016. This represents a sub-sample of the total luminosity collected by ATLAS. In fact, only data satisfying certain quality criteria are used for physics analysis. Each ATLAS run is divided in several *luminosity blocks*, called simply lumi-blocks, defined as the period of time, corresponding to 60 s, during which the data-taking is considered "good". The

list of lumi-blocks used for the analysis is called *Good Run List* (GRL). Lumi-blocks can be excluded from the GRL, reducing the total amount of data, for one of the following reasons:

- LHC not in stable beam mode;
- magnets are off or ramping;
- some sub-detectors switched off;
- many noisy calorimetric cells are present.

3.2 The ATLAS detector

ATLAS is one of the two general-purpose detectors at the Large Hadron Collider (LHC). It investigates a wide range of physics, from the search for the Higgs boson to extra dimensions and particles that could make up the dark matter. ATLAS is the largest particle detector ever built. It is 46 m long, 25 m high and 25 m wide, with a total weight of 7000 tons. It sits in a cavern 100 m underground, near the main CERN site in Switzerland. Nowadays, ATLAS is an international collaboration that counts more than 3000 scientists from 174 institutes in 38 countries.

ATLAS, shown in Fig.3.4, is a *general-purpose detector*, designed to maximize the physics discovery potential offered by the LHC accelerator. It has a cylindrical shape centred at the interaction point of LHC beams, with its axis along the beam line. It is composed of several concentric sub-detectors which measure different features of the particles generated in the pp collisions. From the innermost to the outermost layer, the ATLAS experiment is composed of an Inner Detector, a Calorimeter System and a Muon Spectrometer. Each ATLAS component will be described in the next sections.

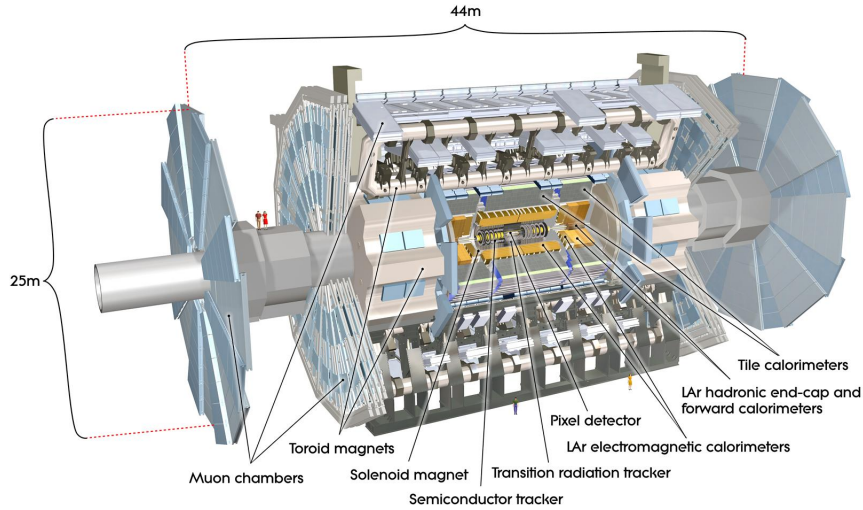


Figure 3.4: The ATLAS detector

3.2.1 The ATLAS coordinate system

ATLAS experiment uses a right-handed coordinate system, shown in Fig.3.5. The origin of the system is in the nominal proton-proton interaction point, set in the center of the ATLAS detector. The z axis is along the beam line, while the xy plane is the plane perpendicular with respect to the beam line. The positive x -axis is defined as pointing from the interaction point to the centre of the LHC ring and the positive y -axis is defined as pointing upwards.

The azimuthal angle φ is defined as the angle around the beam axis, while the polar angle θ is the angle that a particle forms with respect to the z axis. Since the angular variable θ is not invariant under boosts along the z -axis, the rapidity y , defined in Eq.3.4, is used.

$$y = \frac{1}{2} \ln \frac{E + p \cos \theta}{E - p \cos \theta}, \quad (3.4)$$

where E and p are respectively the energy and the momentum of the particle.

In the ultra-relativistic limit, the pseudo-rapidity η , defined in Eq.3.5, is a good approximation of y and it is commonly used.

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

The radial distance between two objects is defined as $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. The transverse energy is computed as $E_T = E \cdot \sin\theta$.

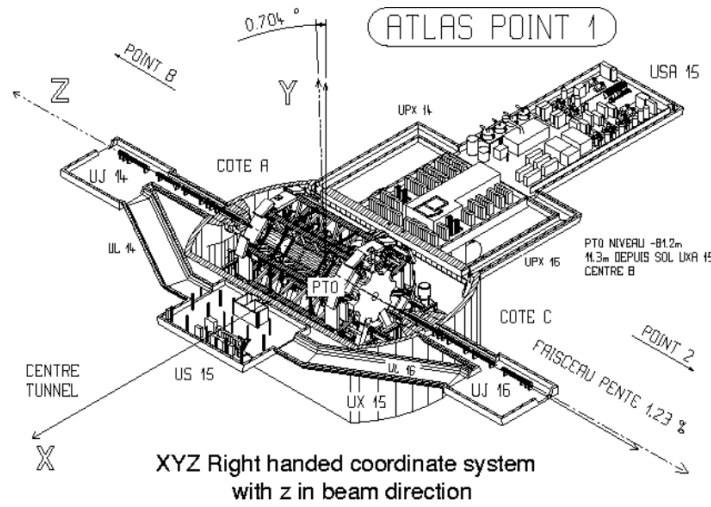


Figure 3.5: The ATLAS reference frame

3.2.2 The Inner Detector

The ATLAS Inner Detector (ID) acts as the tracking system for charged particles. It was designed to produce a robust and efficient track reconstruction. It consists of three sub-detectors: the inner one uses silicon planar technology (pixels and microstrip) while the outer one employs a drift chamber using straw tubes filled with gas. These sub-detectors are called: Pixel, Semiconductor Tracker (SCT) and Transition Radiation Tracker (TRT), respectively[24]. They are divided in three parts: one barrel and two end-caps, as shown in Fig.3.6 and Fig.3.7.

The ID provides a precision tracking of charged particles for $|\eta| < 2.5$. A superconducting solenoid surrounds the entire tracking system and it produces a 2 T axial magnetic field along the beam axis direction. This field bends the trajectory of the charged particles and allows to measure their momentum. A significant upgrade for the ATLAS Run-2 concerns the installation of the Insertable B-Layer[25], an additional pixel layer close to the interaction point, which provides high-resolution hits at small radius and an improvement on the tracking performances. It helps, in particular, to reconstruct the secondary vertices with a better precision and then it contributes to improve the ATLAS b-tagging performances.

The Pixel Tracker

The Pixel tracker is composed by four concentric cylindrical layers in the barrel and 3 disks for each end-cap. From the collision point the radii of the cylindrical layers are about 5.05 cm,

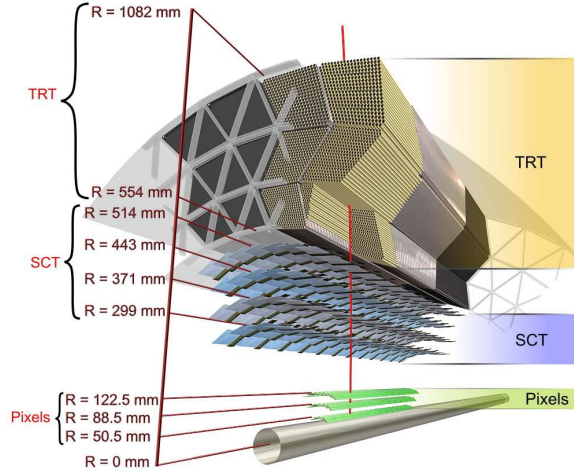


Figure 3.6: The ATLAS Barrel Inner Tracker (the IBL is not shown in this picture).

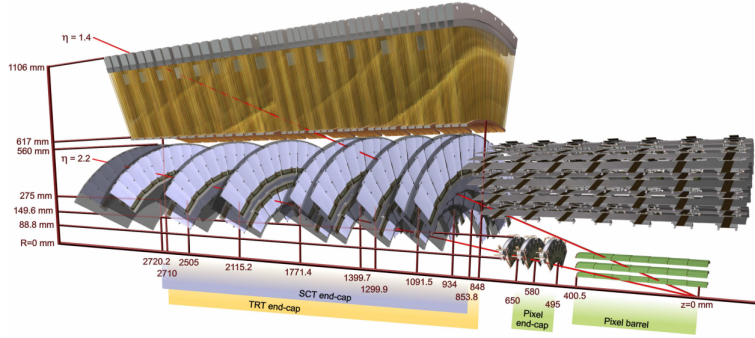


Figure 3.7: The ATLAS End-cap Inner Tracker.

8.85 cm and 12.25 cm while the 6 disks of the end-caps are located, in the z direction, between 11 cm and 20 cm on each side of the interaction point.

This is the sub-detector with the highest granularity. The pixel size is $50 \times 400 \mu\text{m}^2$; this allows to achieve a position resolutions of $10 \mu\text{m}$ in the $R - \varphi$ plane and $115 \mu\text{m}$ in z for the barrel. In the end-cap, spatial resolution are $10 \mu\text{m}$ in the $R - \varphi$ plane and $115 \mu\text{m}$ in R for the end-cap.

The Semiconductor Tracker

The barrel SCT uses four cylindrical layers of silicon microstrip detectors to provide precision points in the $R - \varphi$ and z coordinates, using small angle stereo to obtain the z measurement. Nine disks are present in each end-cap part. From the collision point, the radii of the layers are about 30.0 cm, 37.3 cm, 44.7 cm and 52.0 cm while the disks of the end-cap parts are located, in the z direction, between 85 cm and 272 cm for each side[26].

Each silicon detector is $6.36 \times 6.40 \text{ cm}^2$ with 768 readout strips, each with $80 \mu\text{m}$ pitch. The full SCT detector contains 61 m^2 of silicon detectors, with 6.2 million readout channels. The SCT guarantees a spatial resolution of $16 \mu\text{m}$ in the $R - \varphi$ plane and $580 \mu\text{m}$ in z direction.

The Transition Radiation Tracker

The TRT is composed by drift tubes, aligned in parallel to the beam line in the barrel region and perpendicular to it in the end-cap. Each tube has a diameter of 4 mm and a maximum length of 150 cm. The TRT barrel detector contains overall about 50000 straws tubes, each

divided in two at the the centre with the read-out at each end. The TRT end-caps consist of about 320000, with the read-out at the outer radius. The total number of electronic channels is 420000. Each channel provides a drift-time measurement, giving a spatial resolution of $170 \mu\text{m}$ per straw and two independent thresholds. These allow the detector to discriminate between tracking hits, which pass the lower threshold, and transition-radiation hits, which pass the higher[27].

The tubes are filled with a gas mixture of $Xe : CO_2 : O_2 = 70:27:3$ that is ionized when a charged particle cross it. Since the transition radiation (TR) is connected to the speed of a particle, TRT offers a good discrimination between electrons and hadrons.

3.2.3 The Calorimeter System

The ATLAS calorimeter system, shown in Fig.3.8, is divided into an electromagnetic (EM) part and an hadronic part. The main goal of the EM calorimeter is to measure the energy of the photons and electrons with high precision. The goal of the hadronic calorimeter is focused on the jet energy measurement. Both the systems use sampling calorimeters, detectors in which particles cross alternatively inert and active materials. The active material used is liquid argon (LAr) for most of the calorimeter, while the absorber material depends on the region in which the detector is located.

The choice of LAr is connected to its performance and in particular to the linearity of the signal, the fast response and the radiation hardness[28]. The EM calorimeters are divided in barrel (EMB) and end-cap (EMEC). The EMB uses LAr as active material and lead as absorber and the full system covers a pseudorapidity of $|\eta| < 1.475$. The first layer has the best granularity in η while the second provides a better resolution in φ . The number of radiation lengths in the EMB is $24 X_0$. The EMEC calorimeters are made with the same material of the EMB but the number of radiation lengths in the end-cap is larger ($26 X_0$). In the end-cap the EM is composed of two concentric wheels covering the range $1.375 < |\eta| < 3.2$.

The hadronic calorimeter system is located after the EM calorimeters. As the EM, it is divided in a barrel (TileCal) and two end-caps (HEC). The TileCal is composed by steel, as absorber, and plastic scintillators, as active material[29]. The number of interaction lengths in the TileCal is about 9λ . The HEC is composed of LAr and copper and it covers up to $|\eta| < 3.2$. It is divided in two wheels for each end-cap. In the end-cap regions the total number of interactions lengths (including the EMEC) is 12λ .

To cover pseudorapidity larger than $|\eta| > 3.2$ another calorimetric is used: the forward calorimeter (FCAL). FCAL is composed by one EM and two hadronic calorimeters and covers between $3.1 < |\eta| < 4.9$. The number of interaction lengths is about 10λ .

3.2.4 The Muon Spectrometer

The ATLAS Muon Spectrometer (MS), shown in Fig.3.9, is the outermost component of the ATLAS detector. It is designed to reconstruct the muon trajectories, measuring the muon momentum independently from the ID, and to provide muon trigger signals. Muons are, in fact, the only particles able to escape from the calorimeter system. The MS is instrumented with precision tracking and trigger detectors. It also includes three large superconducting toroids which bend the particles along the η coordinate.

The MS measures the muon momentum in a pseudorapidity range $|\eta| < 2.7$. Within the range $|\eta| < 1.4$, the magnetic bending is provided by the large air core toroid. In the range $1.6 < |\eta| < 2.7$, muon tracks are bent by two smaller air core toroid end-cap magnets inserted into both ends of the barrel toroid. Over $1.4 < |\eta| < 1.6$, usually referred to as the *transition region*, magnetic deflection is provided by a combination of barrel and end-cap fields.

The MS consists of four different technologies, two connected mainly to the trigger and two mainly connected to the precise tracking. The precision tracking consists of the Monitored Drift Tubes (MDT) and the Cathode Strip Chambers (CSC), while for the trigger measurement the Resistive Plate Chambers (RPC) and the Thin Gap Chambers (TGC) are used[30].

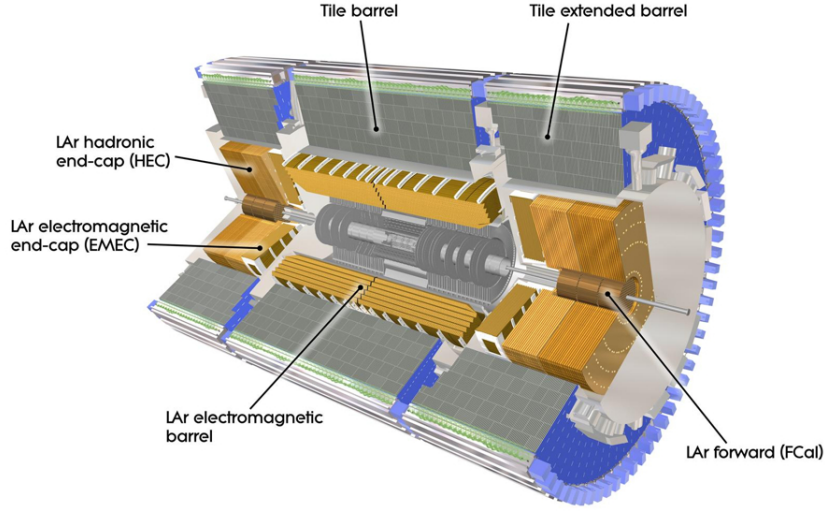


Figure 3.8: The ATLAS Calorimeter System

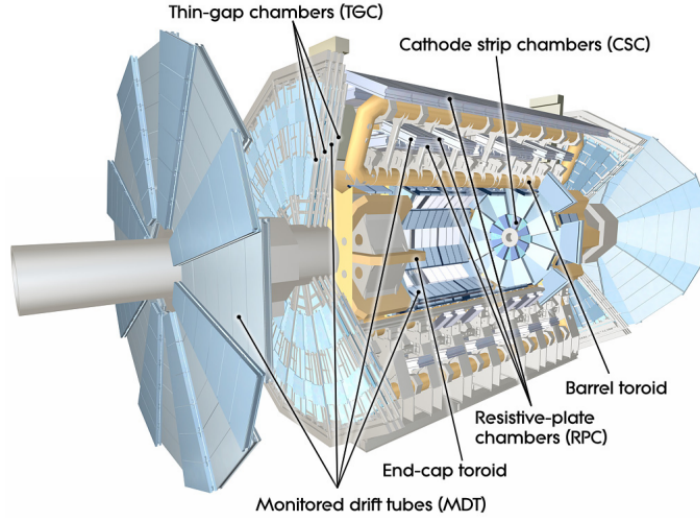


Figure 3.9: The ATLAS Muon Spectrometer

Muon Drift Chamber

The MDT system is composed by 1088 chambers: each chamber is made by two multi-layers of three or four (only in the innermost chambers) layers of tubes with 3 cm diameter and $400\ \mu\text{m}$ thick aluminium walls.

The gas mixture is $93\% \text{ Ar} + 7\% \text{ CO}_2 + 10^3 \text{ ppm } \text{H}_2\text{O}$ operating at 3 bar pressure and at 3040 V. The MDT are located in both the barrel and end-cap regions. In the barrel region, $|\eta| < 1.3$, the chambers are divided in 16 sectors along φ . In each sector there are large and small chambers. This allows a full coverage and an overlap between chambers that ensure a robust muon momentum measurement. In the end-cap the MDTs cover the region $1.3 < |\eta| < 2.4$.

Resistive Plate Chamber

The RPCs are used in the barrel in the range $|\eta| < 1.05$, to produce the trigger signal. They are also able to measure the transverse coordinate and are therefore complementary to the MDTs.

The RPC system consists of 544 chambers, located in three concentric layers connected to the MDT. Each chamber has 2 layers of gas gap, filled with a gas mixture of 94.74% C₂H₂F₄ + 5% isoC₄H₁₀ + 0.3% SF₆, where the last one is added to limit the charge avalanches in the chamber. The RPC chambers are made with bakelite plates of 2 mm and readout strips with pitches of about 3 cm. The RPC works at 9.8 kV and provide a time resolution of 1.5 ns.

Cathode Strip Chamber

The Cathode Strip Chambers (CSCs) are multi-wire proportional chambers located between $2.0 < |\eta| < 2.7$. They are designed to provide high precision tracking in the detector region near to the beam pipe. The CSCs are divided in 16 sectors for each of the two wheels, 8 small and 8 large. The chambers, composed by four layers, are in overlap to ensure no loss of information. The chambers are mounted in the $R - \varphi$ plane such that the muon track position will be measured by the interpolation of the induced charges in different strips of the layers.

The gas mixture is $Ar + CO_2$ and the typical spatial resolution is $40 \mu m$ in the magnet field direction and $5 mm$ in the azimuthal direction. The time resolution is about 7 ns.

Thin Gap Chamber

The Thin Gap Chambers (TGCs) are multi-wire proportional chambers dedicated to the trigger system on the end-cap part of the ATLAS detector. They cover the forward region in the pseudorapidity range $1.05 < |\eta| < 2.7$.

The TGCs, like the RPCs, provide also a measurement of the muon track coordinate orthogonal to the one provided by the precision tracking chambers. The nominal spatial resolution for the TGCs it is 3.7 mm in the $R - \varphi$ plane. The TGC system is divided in 4 layers, one innermost (TGI) and three in the end-cap (TGC1, TGC2 and TGC3). The TGC1 covers $1.05 < |\eta| < 1.92$ while the others TGC layers cover up to $|\eta| = 2.7$. TGC1 is composed by three chambers while TGC2 and TGC3 are composed by two chambers. The gas mixture used for these chambers is 55 % CO_2 and 45% C₅H₁₂. TGC chambers work at 2.9 kV and their time resolution is about 4 ns.

3.2.5 The forward detectors

The ATLAS detector is also equipped with four detectors which partially cover the forward rapidity region. They are LUCID, ZDC, ALFA and AFP[31].

They are located at various distances from the interaction point and close to the beam pipe. They are mainly used for the luminosity and proton-proton cross-section measurements. A general overview is reported below.

- LUCID (*Luminosity measurements Using Cherenkov Integrating Detector*) is composed of two modules located at $\pm 17 m$ from the interaction point which provide a coverage for charged particles in the range $5.5 < |\eta| < 5.9$. LUCID is a Cerenkov detector and it is mainly used to detect inelastic proton-proton scattering for instantaneous luminosity measurements.
- ZDC (*Zero Degree Calorimeter*) is positioned at a distance of $\pm 140 m$ and provides a coverage of the region $|\eta| > 8.3$. It provides trigger and energy measurements of the spectator neutrons dissociated from the colliding nuclei, during the Pb-Pb physics program. Moreover, the ZDC rate gives directly the absolute luminosity, for heavy-ion collisions, with an accuracy of better than 5%.
- ALFA (*Absolute Luminosity For ATLAS*) is located approximately at $\pm 240 m$ from the IP. Its purpose is the measurement of the absolute luminosity via elastic proton-proton scattering at small angles in the Coulomb-Nuclear Interference (CNI) region. This goal can be achieved by using a special optic configuration: LHC running at high β^* , low luminosity and parallel-to-point focusing.

- AFP (*ATLAS Forward Proton*) is located at 210 *m* away from the ATLAS interaction point. It identifies events in which one or two protons emerge intact from the proton-proton collisions at the LHC. The core of the AFP physics program is the study of soft and hard diffractive events at low luminosities.

3.2.6 Magnetic system

High magnetic fields are a crucial elements for detectors such as ATLAS[32]. In fact, the measurement of the charged particles momentum is allowed thank to the bending of the particles in the magnetic field. The ATLAS detector has a very complex magnetic system, shown in Fig.3.10. It consists of:

- a Barrel Solenoid;
- a Barrel Toroid;
- 2 End-cap Toroids.

The superconducting solenoid provides a 2 T axial magnetic field. It is located in the barrel region, outside the ID and in front of the calorimeter system and it works at a temperature of 4.5 K. It is needed for the momentum measurement of the particles tracked in the ID and it was designed to minimize the materials in order to reduce the multiple scattering and the energy loss, which can affect the momentum and the energy measurements.

The Barrel Toroid magnet, located after the calorimeter system, is formed by eight superconducting coils. It provides the magnetic field of about 0.5 T and allows the bending of muons, needed for muon momentum measurement.

Finally, in the End-Cap region, the magnetic field is provided by small toroids, one for each side, producing a 1 T magnetic field.

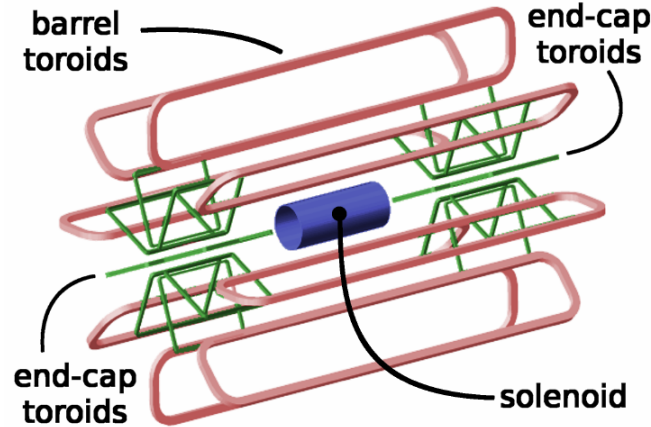


Figure 3.10: The ATLAS Magnet System

3.3 The ATLAS Trigger system

The trigger system is one of the fundamental component for high-luminosity experiments in High Energy field, such as ATLAS. In these experiments the rate of data is so high that the recording in a disk storage is unbelievable (~ 1.7 MB of data per each event in ATLAS). The ATLAS Trigger system filters out events, produced by proton-proton collisions in LHC, without physics interest, lowering the average output rate to a level of few hundreds Hz.

The ATLAS trigger during Run-2 is based on two stages, described in the next sections. A schematic view of the ATLAS trigger system is shown in Fig.3.11.

3.3.1 The Level-1 Trigger

The Level-1 (L1) trigger system is the first stage of event selection for the ATLAS experiment. It consists of three sub-systems: The Level-1 Calo Trigger (L1Calo), the Level-1 Muon Trigger (L1Muon) and the Central Trigger Processor (CTP). In the CTP the trigger decision is made, based on thresholds received from L1Calo and L1Muon. The L1 trigger is completely hardware-based, being implemented directly with custom-built electronics boards (FPGA and ASIC boards).

L1 is designed to identify the interesting collision events to be passed on to the next selection stage, reaching a decision within a latency of less than $2.5 \mu s$. By Level-1 the output data rate is lowered from $40 MHz$ up to $100 KHz$ about. During this step, the signals from the Calorimeter and the Muon Trigger Systems are combined in the CTP which processes the overall "L1 Accept" decision.

The CTP implements a trigger menu made up of combinations of trigger selections. Pre-scaling of trigger menu items is also available, allowing optimal use of the bandwidth as luminosity changes during the run. In each event, the L1 trigger also defines one or more *Regions-of-Interest* (RoI), i.e. the geographical coordinates in η and ϕ , of those regions within the detector where its selection process has identified interesting features. The RoI data include the informations on the type of identified feature and the passed criteria (e.g. a threshold). This informations are subsequently used by the High Level Trigger (HLT).

For the ATLAS Run-II, a new approach for the trigger is also used. It consists of L1 topological triggers (L1Topo) which allows the combination of L1 objects from the Calorimeter and Muon systems to reconstruct interesting kinematic signatures. This is achieved using FPGAs, which return topological decisions in near real time, exploiting particular criteria to accept or reject events, such as isolation requirements, overlap removals, angular relations, invariant mass and global quantities such as the missing transverse momentum (see Section 4.8). A representation of the topological criteria, exploited by L1Topo, are shown in Fig.3.12. However, topological triggers have been not employed in the analysis presented in this thesis.

3.3.2 The High Level Trigger

The final stage of the event selection is carried out by the HLT. Its selections are implemented using offline analysis procedures, within an average event processing time of $0.2 s$. HLT reduces the event rate from $100 KHz$ at L1 to an average of about $1 KHz$.

For the HLT, fast off-line algorithms run on a unique PC farm and access data from an RoI. Algorithms can reconstruct trigger objects in RoIs, but also unseeded reconstruction algorithms can be run for specific detectors such as the calorimeters and the muon spectrometer.

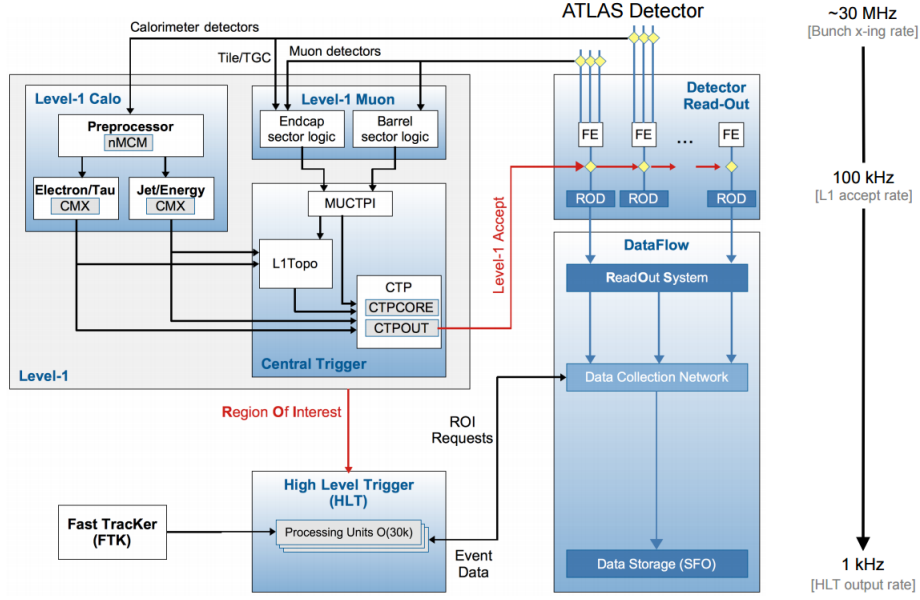
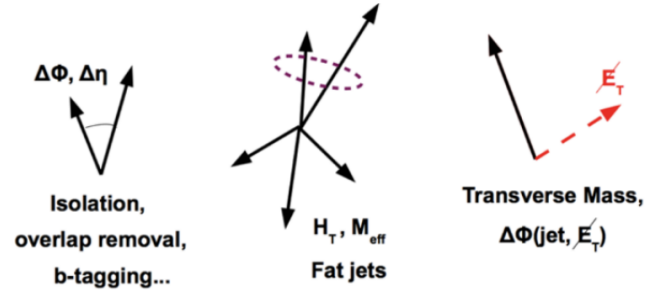


Figure 3.11: Trigger scheme

Figure 3.12: Examples of topologies used for topological trigger decisions: angular distributions (left), sum of energies or momenta (center), E_{miss}^T (right).

Chapter 4

Physics objects definition and reconstruction

4.1 Introduction

In proton-proton collisions at the centre-of-mass energy of TeV order, leptons, photons and jets are produced within a large range of energy from few GeV to several TeV. A large variety of processes involve these particles, such as Standard Model processes (J/Ψ , Z, W decays), Higgs decays, Beyond Standard Model (BSM) scenarios (Z' , W' , SUSY, extra dimensions) and so on. The large variety of these processes requires an excellent object reconstruction and identification, in a wide range of the energy spectrum. Good performances are needed to separate prompt leptons and photons from the respective objects coming from hadron jets, allowing ATLAS analyses to have a good background rejection.

Goal of this chapter is to give a general overview of the reconstruction and identification of all the physics objects used in the ATLAS physics analyses.

4.2 Track and vertex reconstruction

Charged particles travelling in the ATLAS apparatus leave several hits in the different sub-detectors of the ID. The hits of Pixel, SCT and TRT are reconstructed into tracks. The tracks are used to reconstruct vertices and to identify the primary vertex (PV). At Run-2 LHC luminosity, the average number of proton-proton hard interactions per bunch-crossing is about 40. The PV is defined as the vertex with the largest $\sum_i^N (p_T^i)^2$, where N is the number of tracks associated to each vertex and p_T^i is the module of the transverse momentum of the i-th track. In Fig.4.1, the picture of an event recorded by ATLAS with 25 reconstructed primary vertices is shown.

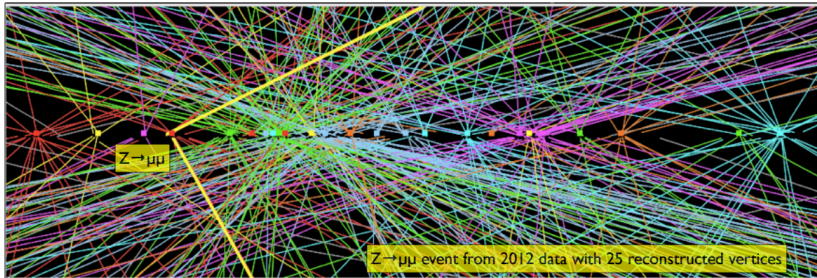


Figure 4.1: Picture of a $Z \rightarrow \mu\mu$ event recorded by ATLAS with 25 reconstructed primary vertices.

Events are required to have at least one PV with at least two associated tracks, each with $p_T > 400 \text{ MeV}$. If there is more than one reconstructed, only the PV is used in the reconstruction

of the main physics objects in the analysis: electrons, muons, taus, jets and missing transverse momentum.

In the ATLAS ID, the track reconstruction is split into several steps, taking into account information from different detectors. In the first step, seed tracks are reconstructed using the Pixel and, partially, the SCT informations. These tracks are then extended through all the SCT to collect additional hits.

To remove fake tracks and solve the ambiguities between clusters shared by many tracks, at this stage, a score is computed for each track. Tracks with few hits and not passing quality criteria are rejected. The remaining tracks are extended to the TRT to collect new hits and refit with the full information from all the ID detectors. Once tracks are reconstructed using all the information of the ID, they can be used for the vertex reconstruction, which is performed associating the tracks to a particular vertex candidate and performing a fit to determine the exact vertex position. The profile of the ATLAS ID, obtained through the reconstruction of the secondary vertices from hadron decays, is shown in Fig.4.2.

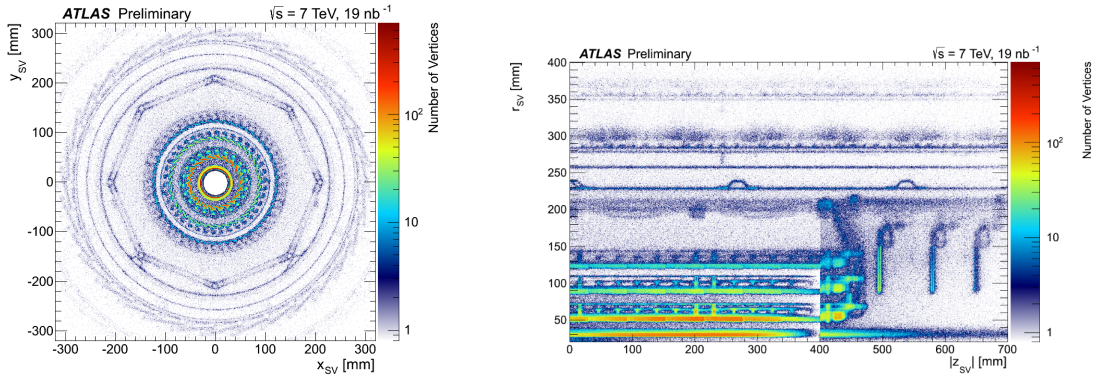


Figure 4.2: Number of selected secondary vertices in data in the x-y plane (left) and r-z (right) of the ID, showing the high performances of the ATLAS tracker system. Secondary vertices come mainly from hadron decays in the detector material so that the plots show the profile of the ATLAS ID tracker.

Particle trajectories in a solenoidal magnetic field can be parametrized with a five parameter vector, as shown in Equation 4.1:

$$\tau = \tau(d_0, z_0, \phi, \theta, q/p). \quad (4.1)$$

d_0 is the transverse impact parameter, defined as the distance of closest approach in the transverse plane ($r-\phi$ plane) of the track to the PV. z_0 is the longitudinal impact parameter, that is the difference between the z coordinates of the primary vertex position and of the track at this point of closest approach in $r-\phi$ plane. ϕ and θ are the azimuthal and polar angles respectively and, q/p is the ratio between the particle momentum and its charge. Since tracks originating from secondary hadronic interactions generally have large impact parameters with respect to the PV, these parameters are useful in the analyses to select prompt leptons against secondary leptons. The experimental resolution for impact parameters d_0 and z_0 is shown in Fig.4.4.

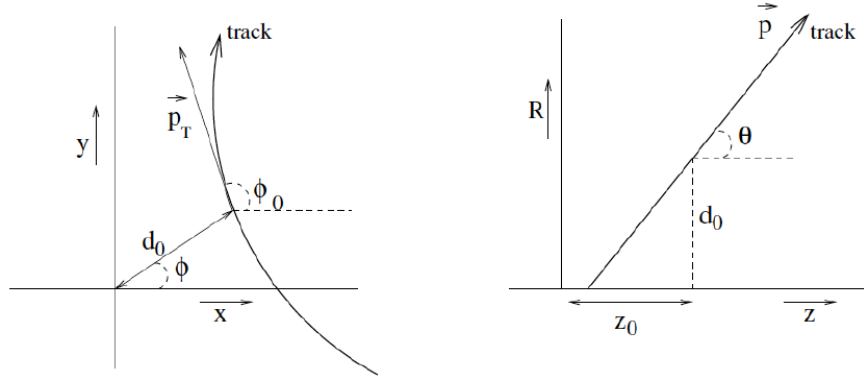


Figure 4.3: Illustration of the track parameters in the transverse plane (left) and RZ-plane (right), as defined in the ATLAS tracking frame.

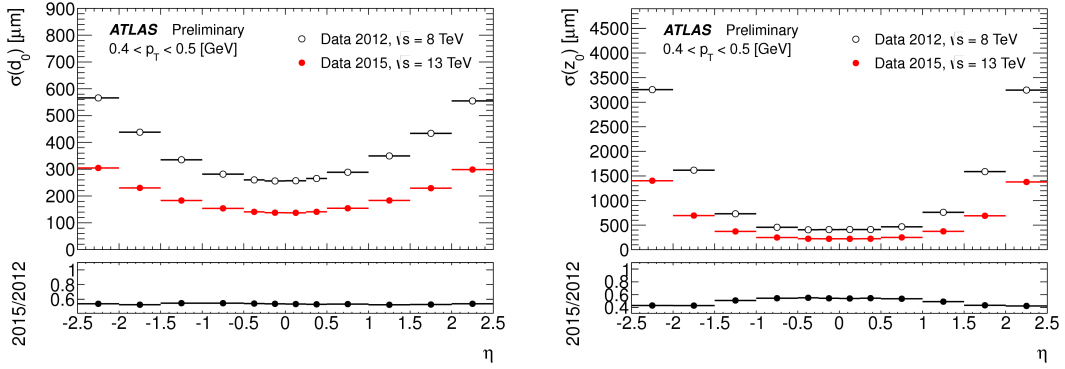


Figure 4.4: Measured resolution for the impact parameters d_0 (left) and z_0 (right) using data in 2015 (including the IBL), as a function of η for tracks with $0.4 < p_T < 0.5$ compared to that measured from data in 2012.

4.3 Electron reconstruction

Information from both the calorimeter and tracking systems are used for the electron identification. Electrons are identified through the matching of an ID track to a calorimeter cluster, whose shower profile is consistent with an electromagnetic shower. The tracks are required to have a minimum number of hits in the tracking detectors (pixel, SCT and TRT).

They are identified within the region $|\eta| < 2.47$, that represents the limit in η for the ID. The region $1.37 < |\eta| < 1.52$ corresponds to the so called *crack region*, situated between barrel and end-cap calorimeters. Here, a precise simulation of the material is difficult, due to the presence of infrastructures for cooling, support and services. Electrons in this region are therefore excluded from the analyses.

Electrons are distinguished from the other particle types using several sets of identification criteria with different levels of background rejection and signal efficiency. These identification criteria rely on the shapes of electromagnetic showers in the calorimeter as well as on tracking and track-to-cluster matching quantities. A likelihood-based electron identification tool has been developed and adopted in the analysis to improve upon the cut based method of particle identification by exploiting the advantages of Multivariate Analysis (MVA)¹. Different operating points with different levels of electron efficiency and background rejection are provided. The identification levels are categorised in *LooseLH*, *MediumLH* and *TightLH*, which correspond to approximately 95%, 90% and 80% identification efficiency for an electron with transverse energy

¹MVA techniques are used extensively in physics analyses to separate signal from background, since they allow, in contrast to cut-based methods, the simultaneous evaluation of several properties when making a selection decision.

(E_T) of 40 GeV, where E_T is defined as the energy projected into the transverse plane[34].

Each operating point cut on the likelihood discriminant takes into account a different set of variables. The most largely used variables are:

- the lateral width of the shower;
- the total shower width;
- the ratio of E_T in the hadronic calorimeter to E_T of the EM cluster;
- the number of total hits in the pixel and SCT detectors;
- the transverse impact parameter;
- the total number of hits in the TRT;
- the number of hits in the b-layer (2° innermost pixel layer).

The Loose likelihood regime uses variables useful for discrimination against light-flavour jets and electron conversions. In the Medium and Tight regimes, additional variables (d_0 , number of hits in the first pixel layers) are added for further rejection of conversions and heavy-flavour jets. Although different variables are used for the different operating points, electrons passing tighter operating points are almost entirely contained within looser ones. The level of non-overlap has been found to be no larger than 0.05% between the two menus.

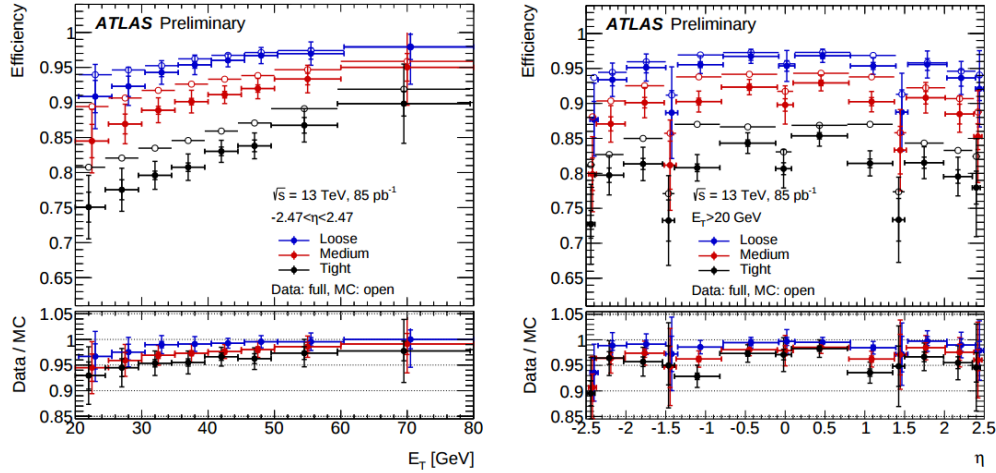


Figure 4.5: Electron reconstruction efficiency as a function of η (left) and E_T (right), measured in $Z \rightarrow ee$ events for electrons with $p_T > 15 \text{ GeV}$ shown for Loose, Medium and Tight selections, both for MC and DATA. The efficiencies have been measured in 85 pb^{-1} of data, recorded by the ATLAS experiment in 2015 at a centre-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$, and are compared to MC simulation.

Electrons are also required to be isolated. This allows to select, as much as possible, prompt electrons, removing those coming from hadron decays and contained within jets. For the isolation requirement, both tracking and calorimeter information are used. p_T -dependent cuts are applied to the scalar sum of the transverse momenta of other tracks from the primary vertex within a cone around the electron track (**Pt-Cone**) and to the scalar sum of the transverse energies, measured in calorimeter cells within a cone (**Et-Cone**), excluding the energy associated to the particle itself. Three different isolation working points with increasing of purity, Loose, Medium and Tight, have been defined for electrons.

4.4 Photon reconstruction

Photon candidates are reconstructed from clusters of energy, deposited in the electromagnetic calorimeter. Before going into the details about the photon classification, a short introduction is needed. At photon energies above 1 GeV, the interaction of the photons with the tracker will be completely dominated by e^+e^- pair production, through the process $\gamma \rightarrow e^+e^-N$, also known as "photon conversion". All other interactions between the photons and the tracker material, such as Compton or Rayleigh scattering, have cross-sections which are orders of magnitude below with respect to the photon conversion, and can thus be ignored.

Candidates without a matching track or reconstructed conversion vertex in the inner detector are classified as *unconverted photons*. Those matching a reconstructed conversion vertex or a track, consistent with originating from a photon conversion, are classified as *converted photons*. Those matched to a track consistent with a track originating from an electron from the primary vertex are kept as electron[35].

As it is the case for electrons, also photon identification criteria are based primarily on shower shapes in the calorimeter system. A loose selection is derived using only the information from the hadronic calorimeter and the lateral shower shape in the second layer of the electromagnetic calorimeter, which contains most of the photon energy. The final tight selection applies tighter criteria to these variables, different for converted and unconverted photon candidates. It also places requirements on the shower shape in the finely segmented first calorimeter layer to ensure the compatibility of the measured shower profile with that originating from a single photon impacting the calorimeter. To further reject the background from jets misidentified as photons, the photon candidates are required to be isolated using both calorimeter and tracking detector information.

The photon efficiency is shown in Fig.4.6 for data and MC simulations for two different pseudorapidity intervals. For the photon efficiency measurement, a data sample enriched in $Z \rightarrow \ell\ell\gamma$ events has been exploited.

Since the ATLAS simulation does not model the distribution of the photon shower accurately (see Fig.4.6), the identification efficiency in MC is corrected using scale factors obtained from data.

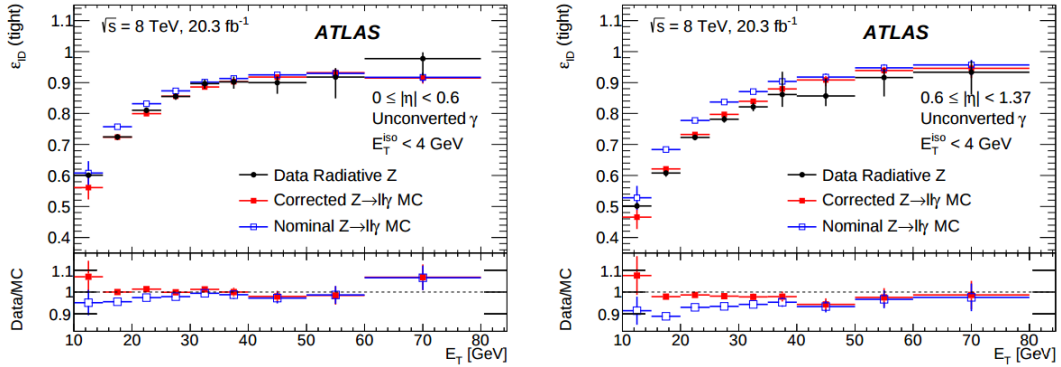


Figure 4.6: Comparison of the radiative Z boson data-driven efficiency measurements of unconverted photons to the nominal $Z \rightarrow \ell\ell\gamma$ MC predictions as a function of photon E_T for two pseudorapidity intervals: $|\eta| < 0.6$ (left) and $0.6 \leq |\eta| < 1.37$. The bottom panels show the ratio of the data-driven results to the MC predictions.

4.5 Muon reconstruction

In the ATLAS experiment, muon reconstruction is performed exploiting the informations from ID and Muon Spectrometer.

Until they reach the MS, muons traverse typically 100 radiation lengths (X_0) of material, most part instrumented by the electromagnetic and hadronic calorimeters. Muons produced

in the hard interactions in LHC have energies between 10 GeV and 1 TeV, typically. At these energies muons can be treated as Minimum Ionizing Particles (MIP). They deposit a small amount of energy in the calorimeter system of 3-4 GeV about[36].

Thus, the information from individual sub-detectors can be combined to form the muon tracks that are used in most physics analyses[37].

In the ID, muons are reconstructed like any other charged particles. A Hough transform [38] is used to search for hits aligned on a trajectory in the bending plane of the detector. Muon track candidates are then built by fitting together hits from segments in different layers. The segments are selected using criteria based on hit multiplicity and fit quality and are matched using their relative positions and angles. The information on energy deposit in the calorimeter system is also used and corrections are applied to take into account the energy loss in the material.

Four different types of muons are defined in ATLAS, depending on which sub-detectors are used in reconstruction. They are listed below:

- **Combined (CB) muons:** track reconstruction is performed independently in the ID and MS, and a combined track is formed with a global fit that uses the hits from both the ID and MS sub-detectors. Muons are firstly reconstructed in the MS, where the track density is much smaller, and then extrapolated inward and matched to an ID track. They are the most commonly used muons in physics analyses since they have the highest purity and the best resolution on the kinematic properties.
- **Segment-tagged (ST) muons:** a muon is classified like ST muon if a track in the ID, once extrapolated to the MS, is associated with at least one local track segment in the MDT or CSC chambers. ST muons are used when muons cross only one layer of MS chambers, either because of their low p_T or because they pass through in regions with reduced MS acceptance.
- **Calorimeter-tagged (CT) muons:** a track in the ID is identified as a muon if it can be matched to an energy deposit in the calorimeter compatible with a minimum-ionizing particle. This kind of muons have the lowest purity with respect to all the other muon types but they allow to recover the acceptance in regions where the ATLAS Muon Spectrometer is partially instrumented (to host cabling and services), close to $|\eta| = 0$.
- **Extrapolated (ME) muons:** the muon trajectory is reconstructed based only on the MS track and a loose requirement on compatibility with originating from the IP. ME muons are mainly used to extend the acceptance for muon reconstruction into the region $2.5 < |\eta| < 2.7$, which is not covered by the ID.

In the same way as for electrons, muon candidates are defined as "Loose", "Medium" and "Tight", with increasing purity, according to the quality of the reconstruction and identification.

- **Loose muons** The Loose identification criteria are designed to maximise the reconstruction efficiency, providing, however, good-quality muon tracks. All muon types are used in the loose definition. All CB and ME muons satisfying the Medium requirements are included in the Loose selection. CT and ST muons are restricted to the $|\eta| < 0.1$ region. In the region $|\eta| < 2.5$, about 97.5% of the Loose muons are CM, approximately 1.5% are CT and the remaining 1% are reconstructed as ST muons.
- **Medium muons:** The Medium identification criteria provide the default selection for muons in ATLAS. This selection minimises the systematic uncertainties associated with muon reconstruction and calibration. Only CB and ME tracks are used. The former are required to have ≥ 3 hits in at least two MDT layers, except for tracks in the $|\eta| < 0.1$ region, where tracks with at least one MDT layer but no more than one MDT hole layer are allowed. The latter are required to have at least three MDT/CSC layers, and are employed only in the $2.5 < |\eta| < 2.7$ region to extend the acceptance outside the ID geometrical coverage. A loose selection on the compatibility between ID and MS momentum measurements is applied to suppress the contamination due to hadrons misidentified as

muons. Specifically, the q/p significance is required to be less than seven. In the pseudorapidity region $|\eta| < 2.5$, about 0.5% of the muons classified as Medium originate from the inside-out combined reconstruction strategy.

- Tight muons** Tight muons are selected to maximise the purity of muons at the expense of an higher inefficiency. Only CB muons with hits in at least two stations of the MS and satisfying the Medium selection criteria are considered. In order to remove pathological tracks, the normalised χ^2 of the combined track fit is required to be < 8 . A two-dimensional cut in the ρ and q/p significance variables is performed as a function of the muon p_T to ensure stronger background rejection for momenta below 20 GeV, where the misidentification probability is higher.
- High-pT muons:** The High-pT selection aims to maximise the momentum resolution for tracks with transverse momentum above 100 GeV. The selection is optimised for searches for high-mass Z' and W resonances. CB muons passing the Medium selection and having at least three hits in three MS stations are selected. Specific regions of the MS where the alignment is suboptimal are vetoed as a precaution. Requiring three MS stations, while reducing the reconstruction efficiency by about 20%, improves the p_T resolution of muons above 1.5 TeV by approximately 30%.

Muon reconstruction efficiency as a function of η is shown in Fig. 4.7 for Loose, Medium and Tight muons. In the analysis presented in this work, the muons are required to be at least Loose. The muon reconstruction efficiency in simulated events is corrected with data-to-simulation scale factors obtained from tag-and-probe studies of J/Ψ meson and Z boson decays in a muon pair. The ATLAS muon reconstruction efficiency is very high, being close to 100 %.

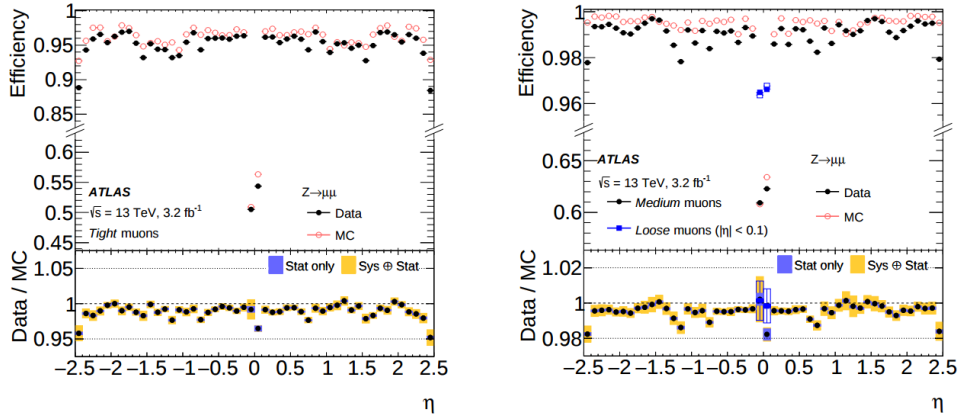


Figure 4.7: Muon reconstruction efficiency as a function of η , measured in $Z \rightarrow \mu\mu$ events for muons with $p_T > 10\text{ GeV}$ shown for Loose ($|\eta| < 0.1$), Medium and Tight muon selections. In the region $|\eta| < 0.1$, the Loose and Medium selections differ significantly. The error bars on the efficiencies indicate the statistical uncertainty. Panels at the bottom show the ratio of the measured to predicted efficiencies, with statistical and systematic uncertainties.

Concerning the isolation requirements, similar considerations, as for electrons, can be made for muons. Also in this case, three different working points, corresponding to Loose, Medium and Tight, have been defined for muons.

4.6 Jet reconstruction

Jets are produced in pp collisions from the hadronization of quarks and gluons. In ATLAS, they are reconstructed in the calorimeter using the *anti* - k_T algorithm with a radius parameter $R = 0.4$ or $R = 0.6$ and using calibrated topological clusters as input. The *anti* - k_T algorithm

is a cluster algorithm that builds jets by clustering them in an iterative procedure. More details can be found in [39]. In this work jets are reconstructed using $R = 0.4$.

Topological clusters are the main input for the *anti* - k_T algorithm. They are three-dimensional groups of calorimeter cells designed to follow the shower development exploiting the fine segmentation of the calorimeter. The cluster is seeded by a calorimeter cell with a total energy above the noise, $|E_{cell}| > 4\sigma_{cell}$, where σ_{cell} corresponds to the RMS of the energy distribution measured in events with a random trigger. Cells neighbouring with $|E_{cell}| > 2\sigma_{cell}$ are then added to the cluster, increasing its size. The reconstructed topo-cluster has an energy equal to the energy sum of all the included calorimeter cells, zero mass and a direction calculated by averaging η and ϕ of all the constituent cells. A second input to the algorithm comes from *Noise-suppressed towers* and *Ghost-towers*, not described here. More details can be found in [40]. Once clusters and towers have been built, the jet reconstruction takes place.

The theoretical and experimental requirements for a good jet reconstruction algorithm are listed below:

- infrared safety: sensitivity of an algorithm to the presence of an additional soft particles not related to the hadronization of the primary particles. If there is a low energy cluster between two high energy clusters, the algorithm must be able to define them as two separated objects (see Fig.4.8);
- collinear safety: the number of reconstructed jets can be altered due to the splitting of hard and collinear particles (see Fig.4.8);
- stability with the instantaneous luminosity (control of underlying events and pile-up effects);
- high reconstruction efficiency;
- reconstruct jets "easy" to calibrate;
- easy to compare with the QCD theory predictions.

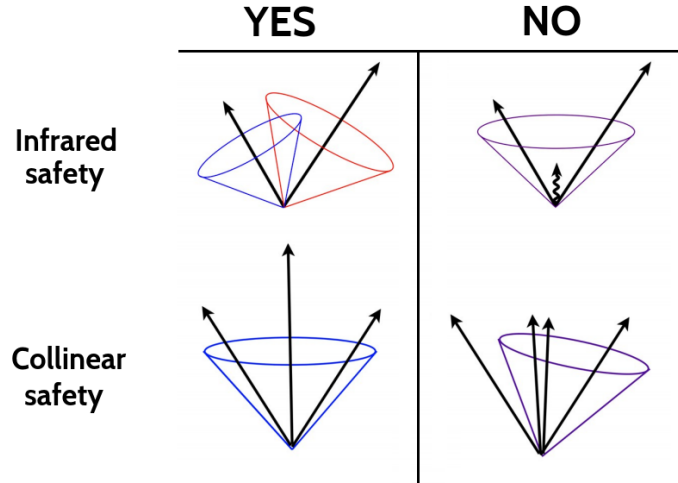


Figure 4.8: Infrared and collinear safety principles.

The *anti* - k_T algorithm addresses such requests; it consists of the following steps:

1. the first step is to compute the distance d , defined as $d = \min(d_{ij}, d_{iB})$, where i and j are the topological clusters, d_{ij} is the distance ΔR between them and d_{iB} is the distance between the entity i and the beam axis;
2. if $d = d_{ij}$ then merge i and j and go to step 1;

3. if $d = d_{iB}$ then i is a single complete jet.

This procedure is repeated until no elements are left in the list. The quantities d_{ij} and d_{iB} are defined as follows:

$$d_{ij} = \min \left(\frac{1}{p_{Ti}^2}, \frac{1}{p_{Tj}^2} \right) \frac{\Delta R_{ij}^2}{R^2} \quad (4.2)$$

$$d_{iB} = \frac{1}{p_{Ti}^2} \quad (4.3)$$

where R is the reference radius parameter (0.4). In the *anti* - k_T algorithm, the recombination starts from hardest objects. The soft particles tend to cluster with hard particles long before they cluster among themselves and the shape of the jet is unaffected by soft radiation. Reconstructed jets have a regular boundary shape (cone like jets without using stable cones), so that they are unaffected by soft radiation. These features distinguish the *anti* - k_T algorithm from the k_T algorithm[39].

As for electrons and muons, in order of increasing purity, different quality selections for the jet reconstruction exist: Loose, Medium, Tight, with an increasing of purity. The Looser selection has been designed to provide an efficiency above 99.8% with an high fake jet rejection (fake jets deriving principally from calorimeter electronics noise, cosmic rays and no-collision backgrounds). The Tighter selection has designed to provide a much higher fake jet rejection, above 99%, with an inefficiency not larger than a few percent[41].

The energy of the jets reconstructed in ATLAS needs to be calibrated to the true energy of the corresponding jet of stable hadronic particles. The calibration takes into account several different effects, discussed below:

- calorimeter non-compensation;
- dead material: energy lost in inactive areas of the detector;
- leakage: showers reaching the outer edge of the calorimeters;
- out-of-cone effects: fraction of energy lost through low energy particles deflected at large angle by the magnetic field and not reconstructed in the jet cone;
- energy deposits below noise thresholds;
- pile-up.

This calibration is usually called "*Jet Energy Scale*" (JES) and its uncertainty represents one of the major systematic uncertainties in many ATLAS analyses[42].

4.6.1 b-tagging

The identification of jets initiated in the hadronization of b-quarks ("b-tagging") at the end of the parton shower, called *b-jets*, is an important task for a general purpose experiment such as ATLAS. b-jets are a key ingredient for many physics analyses, ranging from precise top-quark measurements to Higgs and BSM searches. b-tagging is widely used in this work, since the ttH production mode contains two top quarks, which decay exclusively into bottom quarks ($t \rightarrow bW$).

Several algorithms exist to identify jets containing b-hadrons. Some of them are based on the reconstruction of secondary vertices or on the presence of tracks with large impact parameters. These features are shown in Fig.4.9. The lifetime-based tagging algorithms take advantage of the relatively long lifetime of hadrons containing a b quark, of the order of 1.5 ps ($c\tau \approx 450\mu m$). For example, a b-hadron with $p_T = 50 GeV$ will have a significant mean flight path length $l = \beta\gamma c\tau$, travelling on average about 3 mm in the transverse direction before

decaying and generating at least one vertex displaced from the point where the hard-scatter collision occurred.

The vertex-based algorithms show a higher light-jet rejection with respect to the impact parameter-based algorithms, but their efficiency is limited by the secondary vertex finding efficiency (15% - 30%, depending on the b-jet p_T).

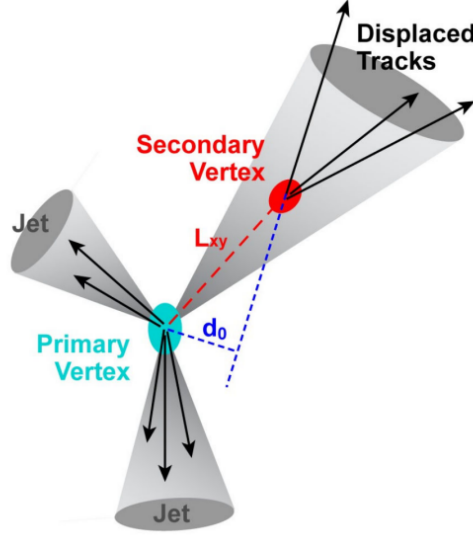


Figure 4.9: Schema of an event with two light jets, originating from the primary vertex, and a b-jet, originating from a secondary vertex. The impact parameter d_0 of one of the tracks and the displaced vertex (in red) are also shown.

In ATLAS both approaches are combined together to define a new discriminating variable, making use of Multi-Variate Analysis (MVA)[43] techniques. The goal is to improve the rejection of jets coming from light flavour quarks (u, d, s, c) and gluons and to increase the b-jet tagging efficiency as much as possible. The input variables are combined using a Boosted Decision Tree[45] (BDT) algorithm. The most important are:

- the jet transverse momentum;
- the invariant mass of tracks at the secondary vertex;
- the fraction of the charged jet energy in the secondary vertex;
- the number of tracks from the secondary vertex;
- the distance between the primary and secondary vertices;
- the distance between the primary and secondary vertices divided by its uncertainty.

The MV2 algorithm is defined as the output of such a BDT, with the training performed on a sample of $t\bar{t}$ events, in which b-jets are used as signal and a mixture of light-flavour jets and c-jets as background. Three different output variables are provided $MV2c0$, $MV2c10$ and $MV2c20$, each of them containing different fractions of c-jet are in the training, 0%, 10%, 20%, respectively. A comparison between the three different MV2 BDT output is shown in Fig.4.10.

Several working points are provided for each MV2 algorithm. In this work, b-jets are selected via $MV2c10$, using a working point which corresponds to an efficiency $\epsilon_b = 0.7$ and a light flavour rejection $\epsilon_{LF} = 0.97$. The $MV2c10$ BDT output for b-jets, c-jets and light-flavour jets is shown in Fig.4.11.

The light rejection versus b-jet efficiency for the $MV2c20$ b-tagging algorithm and the comparison with respect to $MV1$ b-tagging algorithm, used for the ATLAS Run-1 analyses, is shown in Fig.4.12. The large improvement of $MV2c20$ with respect to $MV1$ is due especially to the new pixel layer, the IBL, which enhance the ID tracking performance.

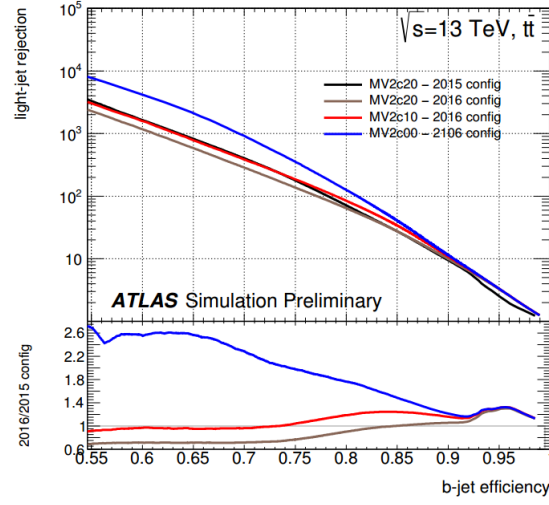


Figure 4.10: Light-flavour jet rejection versus b-jet efficiency for the MV2 b-tagging algorithm evaluated in $t\bar{t}$ events with three different fractions of c-jet present in the training (0%, 10%, 20%).

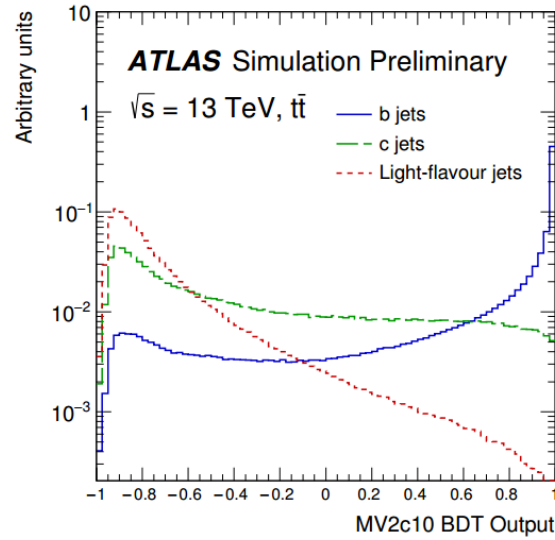


Figure 4.11: MV2c10 BDT output for b- (blue line), c- (green line) and light-flavour (red line) jets evaluated in $t\bar{t}$ events.

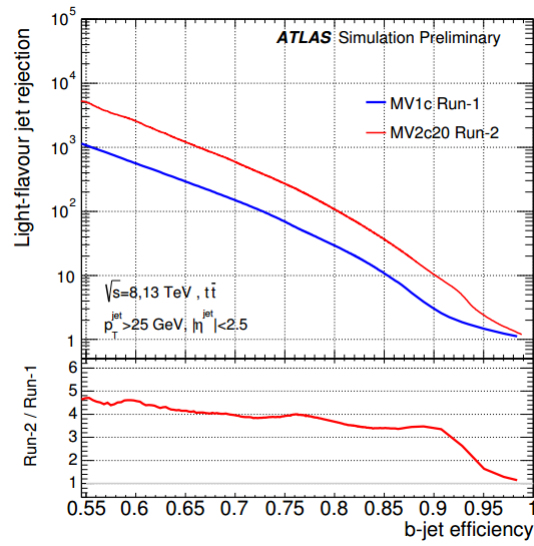


Figure 4.12: The light rejection versus b-jet efficiency for the MV1 b-tagging algorithm using the Run-1 detector and reconstruction software (blue) compared to the MV2 b-tagging algorithm using the Run-2 setup (red).

4.7 Hadronic decaying τ lepton reconstruction

Due to their mass ($1.78 \text{ GeV}/c^2$), τ leptons are the only leptons that can also decay to hadrons. Figure 4.13 summarizes all the possible final states in tau decays. Moreover, electrons and muons originated in τ lepton decays cannot be distinguished from prompt electrons and muons, since τ leptons decay before interacting with the sensitive detectors of ATLAS ($\tau_\tau = 290 \pm 10^{-15} \text{ s}$ [46]). Therefore, only hadronically decaying τ leptons will be reconstructed.

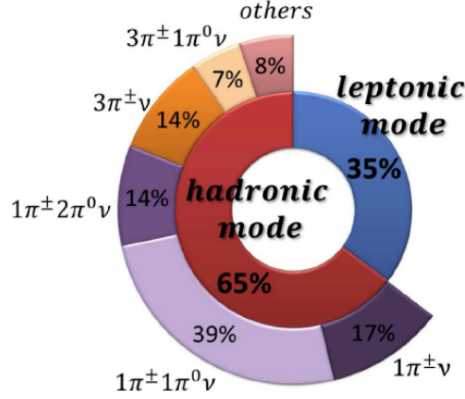


Figure 4.13: Tau lepton branching ratio.

Tau signature consists of a narrow jet, if compared to quark- and gluon-initiated jets, and in a characteristic number of charged tracks: one (1-prong τ) or three (3-prongs τ), as shown in Fig.4.14. Taus decaying hadronically are reconstructed using clusters in both the electromagnetic and the hadronic calorimeters. To correctly discriminate taus from jets, due to the similarity of their signature, the combined informations from other sub-detectors are used.

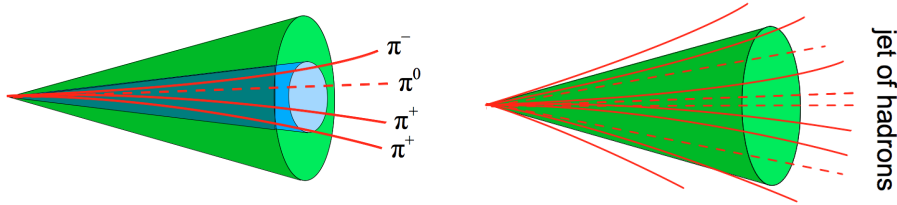


Figure 4.14: Comparison between tau- (left) and quark- or gluon- (right) initiated jet.

Jets formed using the *anti* - k_T algorithm are used as seeds of the τ reconstruction algorithm if they satisfy $p_T > 10 \text{ GeV}$ and $|\eta| < 2.5$ [47]. The τ p_T is set to the total energy of topo-clusters within $\Delta R < 0.2$. The τ vertex (TV) association algorithm uses as input all tau candidate tracks in the region $\Delta R < 0.2$ around the jet seed direction. The p_T of these tracks is summed and the primary vertex candidate, for which the largest fraction of the p_T sum is matched, is chosen as the TV. Tracks associated to the τ candidate are required to be in the core region $\Delta R < 0.2$ around the τ direction and to satisfy the following criteria: $p_T > 1 \text{ GeV}$.

After the τ lepton has been reconstructed, a multivariate technique (BDT) is used for its discrimination against jets, which give rise to a similar signature. A similar approach is also used to distinguish τ leptons from electrons. The combined informations from other sub-detectors are used as input in the multivariate analysis.

Hadronically decaying τ leptons are grouped into categories ordered by purity: Loose, Medium and Tight. The identification and reconstruction efficiencies are shown in Fig.4.15 for 1-prong τ leptons.

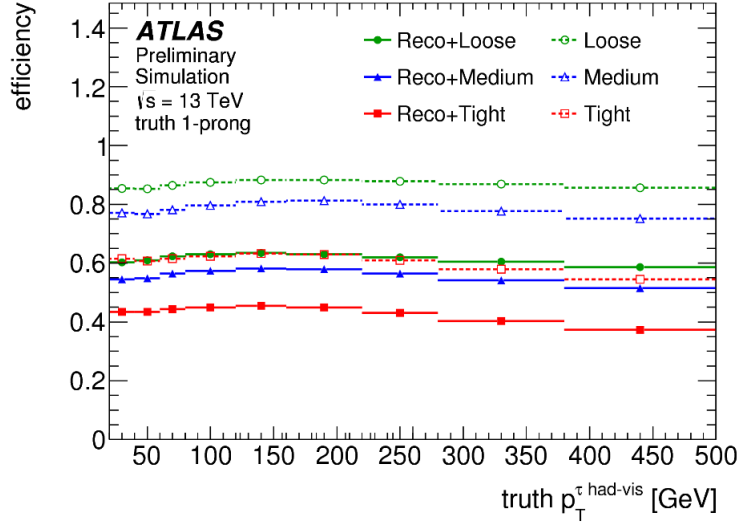


Figure 4.15: MC efficiency for τ leptons identification (open dots) and combined reconstruction and identification efficiency (full dots) as a function of the τ transverse momentum for 1-track τ candidates.

4.8 Missing Transverse Momentum

In hadron collider experiments, the four-momentum component orthogonal to the beam axis (z-axis) is equal to 0 before and after the collision. This implies that the total transverse momentum of the collision products should sum to zero. Then, any imbalance is known as “*Missing Transverse Momentum*”, usually called E_T^{miss} [48].

The missing transverse momentum, with magnitude E_T^{miss} , is calculated as the negative vectorial sum of the transverse momentum of all calibrated selected objects, such as electrons, muons, taus and jets, as shown in Eq.4.8.

$$E_{x,y}^{miss} = - \left(\sum_e P_{x,y}^e + \sum_\mu P_{x,y}^\mu + \sum_\tau P_{x,y}^\tau + \sum_\gamma P_{x,y}^\gamma + \sum_{jets} P_{x,y}^{jets} + \sum_{soft} P_{x,y}^{soft} \right) \quad (4.4)$$

The soft term is reconstructed from detector signal objects not associated with any hard object passing the selection cuts. These can be ID tracks (track-based soft term, TST) or calorimeter cells (calorimeter-based soft term, CST). Contributions to the soft term arise from underlying event activity and soft radiation from the hard event. Two different algorithms have been developed to measure the E_T^{miss} soft term. They are reported below.

- Calorimeter-based soft term (CST) is constructed from the energy deposits in the calorimeter not associated with any hard objects. CST is sensitive to additional proton-proton interactions overlapping with the hard-scatter process (pile-up interactions). These interactions, which can happen in the same bunch crossing (in-time pile-up) or in preceding bunch crossings, occurred 25 ns before (out-of-time pile-up), give an additional contribution to the calorimeter-based soft term, which spoils the correlation between the E_T^{miss} value and the real energy imbalance in the physical event.
- The soft term (TST) definition is based on the momentum of ID tracks, making this term robust against pileup effects. Tracks, in fact, are required to come from the PV, but the same requirement cannot be applied to the energy deposits in the calorimeter cells. A purely track-based quantity is, however, insensitive to neutral particles (which do not leave signals in the ID) and has an acceptance limited by the tracking volume of the ATLAS tracker. Only tracks associated to the identified hard scatter vertex are used for the track-based soft term. TST represents the standard soft term in the E_T^{miss} computation generally adopted in the ATLAS analyses.

E_T^{miss} is a quantity indicating the presence of weakly-interacting stable particles in the final state. In the Standard Model, the E_T^{miss} contribution arises from neutrinos only. Several BSM theories predict the existence of other weakly-interacting particles, making E_T^{miss} an important variable in searches for exotic signatures. Fake E_T^{miss} , however, can result from interacting Standard Model particles which escape from the acceptance of the detector or particles badly reconstructed.

E_T^{miss} performances are studied exploiting a particular event topology, without genuine E_T^{miss} : $Z \rightarrow \mu\mu$. These events provide an ideal final state for the evaluation of E_T^{miss} performance, due to the limited backgrounds and precise measurement of the kinematics of the two muons. The resolution, indicative of the E_T^{miss} reconstruction quality, is measured by the width of the $E_{x(y)}^{miss}$ distribution.

It is found that the experimental resolution on the E_T^{miss} is strongly dependent on the sum of all the visible transverse energy in the event, $\sum E_T$. In Fig.4.16 and Fig.4.17 the resolutions of the E_X^{miss} and E_Y^{miss} terms, as function of $\sum E_T$ and the number of primary vertices (NPV), are shown.

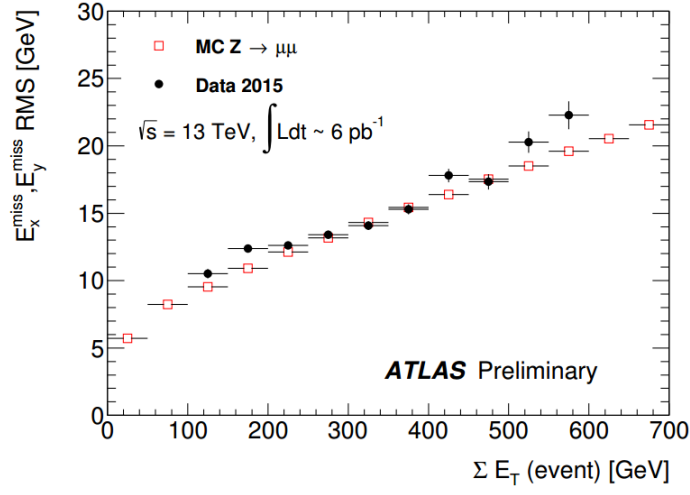


Figure 4.16: Resolution obtained from the combined distribution of E_X^{miss} and E_Y^{miss} as a function of the ΣE_T in the event.

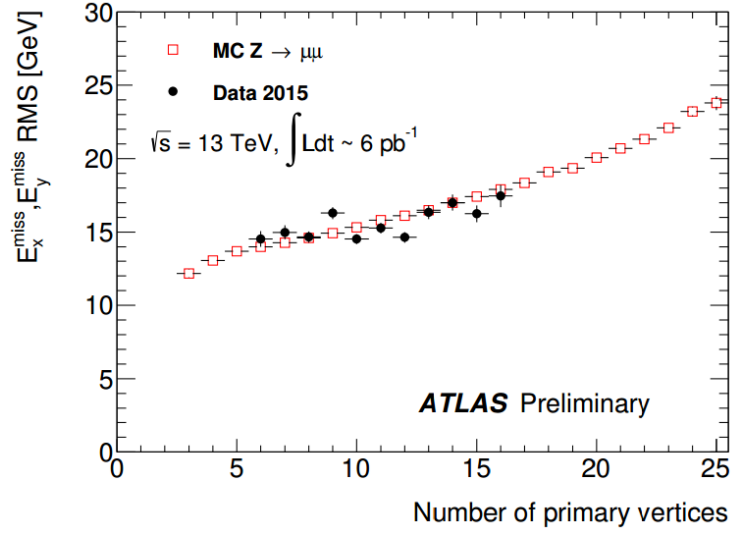


Figure 4.17: Resolution obtained from the combined distribution of E_X^{miss} and E_Y^{miss} as a function of NPV.

Chapter 5

ttH in multilepton final state

5.1 Introduction

The ATLAS and CMS collaborations have already searched for the ttH production in pp collisions at LHC, using the dataset collected at $\sqrt{s} = 7 \text{ TeV}$ and $\sqrt{s} = 8 \text{ TeV}$ center of mass energies. The Run-1 results have been shown in Section 2.2.

This work uses the Run-2 dataset at $\sqrt{s} = 13 \text{ TeV}$ for the ttH search in multilepton final states. An improvement on the analysis comes from the increase of the SM cross section for ttH production by a factor of 3.9, as the center of mass energy is changed from 8 TeV to 13 TeV. For the main backgrounds, the ratio $\sigma_{13\text{TeV}}/\sigma_{8\text{TeV}}$ is lower. In the Table 5.1, the SM cross-section values at $\sqrt{s} = 13 \text{ TeV}$ and $\sqrt{s} = 8 \text{ TeV}$ for the ttH signal and the main backgrounds is reported, as well as the ratio at the two center-of-mass energies. Moreover, optimizations in the analysis have been performed in order to suit the updates of the ATLAS experiment from Run-1 to Run-2.

Process	$\sigma_{8 \text{ TeV}}$	$\sigma_{13 \text{ TeV}}$	$\sigma_{13 \text{ TeV}}/\sigma_{8 \text{ TeV}}$
$t\bar{t}H$	129 fb (NLO) [18]	507 fb (NLO)[49]	3.9
$t\bar{t} + ll$	215 fb (NLO)[50]	840 fb (NLO)[51]	3.9
$t\bar{t}W$	232 fb (NLO)[50]	600 fb (NLO)[51]	2.6
$t\bar{t}$	253 pb (NNLO + NNLL)[52]	832 pb (NNLO + NNLL)[53]	3.3

Table 5.1: Ratio between the SM cross-sections for signal and background processes between $\sqrt{s} = 13 \text{ TeV}$ and $\sqrt{s} = 8 \text{ TeV}$ center-of-mass energy.

This chapter is organized as follows. In Section 5.2, the different signal signatures exploited in the analysis are shown. Backgrounds, estimated with a combination of MC simulations and data-driven techniques, are described in Section 5.3. The object selections and the overlap removal procedure, common to all the multilepton channels, are given in Section 5.4 and Section 5.4.1, respectively. Section 5.5 shows the signal region definitions for each specific channel. The Monte Carlo (MC) samples, as well as the recorded data-set used to perform this analysis, are given in Section 5.6. Several validation regions are used to test the agreement between data and MC backgrounds. They are shown in Section 5.7.

A global fit to the yields in all final states is used to extract the best estimate for the ttH production rate. The expected yields for signal and background, as well as the results from the global fit in terms of the signal strength will be shown later in Chapter 8.

In this chapter, more attention will be dedicated to the 3ℓ ttH multilepton analysis, being this the channel on which I focused my work during the PhD.

5.2 Signal signatures

The ttH production mode with multilepton final states can be observed through different topologies according the Higgs boson and the top quark decays. Top and anti-top quarks decay es-

entially in $W^\pm b$. Each W boson can decay either leptonically ($\ell=e^\pm, \mu^\pm, \tau^\pm$) or hadronically, leading to many possible different topologies.

Four different multilepton final states, distinguished by the multiplicity and the flavour of the leptons and sensitive to the Higgs boson decays into WW^* , $\tau\tau$ and ZZ^* , where the WW^* is the dominant one, are considered in this ATLAS analysis:

- exactly two light leptons with same-sign charges and with hadronic tau veto, denoted as $2\ell 0\tau_{had}$ (see Fig.5.1), further split into three categories according to the lepton flavour pair (ee , $e\mu$ and $\mu\mu$);

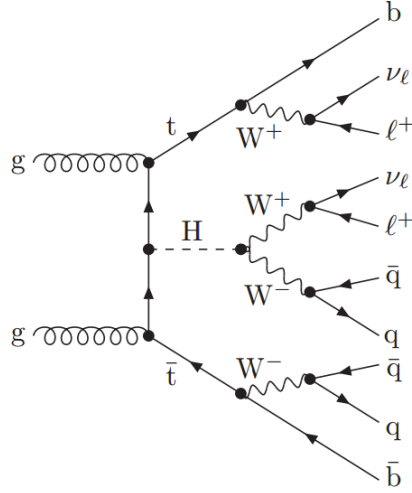


Figure 5.1: Example of a Feynman diagram for ttH with 2 same sign leptons in the final state.

- exactly two light leptons with same-sign charges and only one hadronically decaying tau lepton, $2\ell 1\tau_{had}$ (see Fig.5.2);

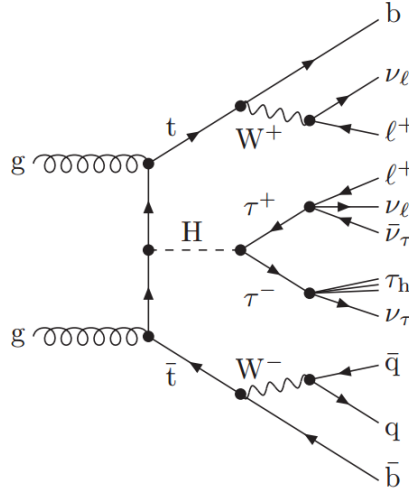


Figure 5.2: Example of a Feynman diagram for ttH with 2 same sign leptons in the final state and one hadronically decaying tau lepton.

- exactly three light leptons, denoted as 3ℓ (see Fig.5.3);

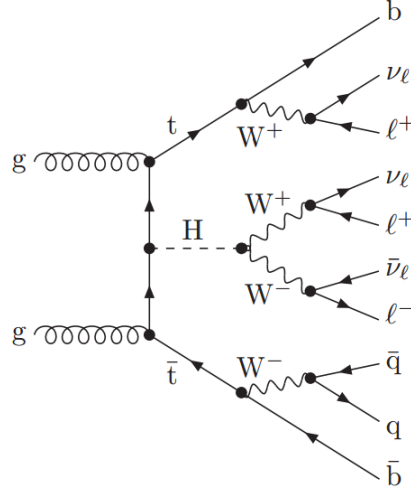


Figure 5.3: Example of a Feynman diagram for $t\bar{t}H$ with 2 same sign leptons in the final state.

- exactly four light leptons, denoted as 4ℓ (see Fig.5.4).

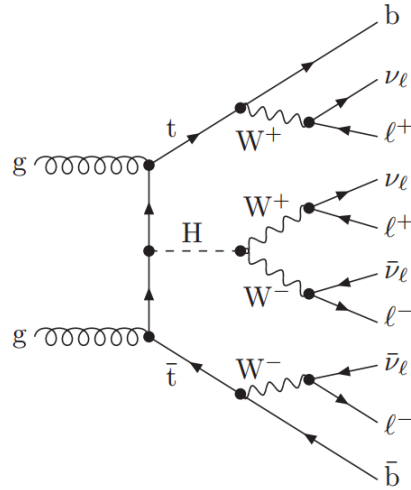


Figure 5.4: Example of a Feynman diagram for $t\bar{t}H$ with 4 leptons in the final state.

These four channels are statistical independent by construction, being sorted by light leptons and hadronic tau multiplicity.

In spite of their low branching ratio, the multilepton final states guarantee a very clear event signature, helping to distinguish the $t\bar{t}H$ signal from the QCD processes, extremely abundant in hadronic colliders, such as LHC. At the same time, hadronically decays, deriving mainly from $W^\pm \rightarrow q\bar{q}'$, thanks to the higher branching ratio, guarantee a significant signal rate and make this analysis a good compromise in terms of efficiency and purity.

The fraction of the expected $t\bar{t}H$ signal for each signal region, arising from different Higgs boson decay modes, is shown in Table 5.2. The Higgs decay in WW^* bosons represents the dominant contribution for the channels without hadronically decaying τ leptons.

Category	Higgs boson decay mode			
	WW^*	$\tau\tau$	ZZ^*	Other
$2\ell 0\tau_{had}$	77%	17%	3%	3%
$2\ell 1\tau_{had}$	46%	51%	2%	1%
3ℓ	74%	20%	4%	2%
4ℓ	72%	18%	9%	2%

Table 5.2: Fraction of the expected ttH signal arising from different Higgs boson decay modes in each Signal Region category. The decays contributing to the "other" column are dominantly $H \rightarrow \mu\mu$ and $H \rightarrow b\bar{b}$. Rows may not add to 100% due to rounding.

5.3 Backgrounds

Two kinds of background processes are considered in the ttH multilepton analysis:

1. events, originated from processes with the same final state as signal, are called *irreducible backgrounds*. They are estimated directly from MC simulations and validated in apposite regions, called *Validation Regions* (VR), enriched in these backgrounds. VRs will be described in Section 5.7;
2. events containing a real non-prompt lepton or a fake lepton (originated from instrumental backgrounds), selected as prompt and leading to a final state compatible with the signal signature, and events in which the charge of the prompt lepton is mis-reconstructed (*charge mis-ID*) are called *reducible backgrounds*.

Channels $2\ell 0\tau_{had}$ and $2\ell 1\tau_{had}$, described in Section 5.5, are mostly affected by charge mis-ID. $t\bar{t}$ processes, contributing with two opposite-sign leptons, represents the main source of this kind of background.

The reducible backgrounds are estimated exploiting different data-driven techniques, according to the channel. For the 3ℓ channel, the reducible background estimate will be described in the Chapter 6. For the other multilepton channels, more details can be found in Ref.[49].

Backgrounds from *Double Parton Interactions* ($t\bar{t}$ and Higgs signatures in the same interaction between two protons) are considered negligible in the analysis presented in this work, since the typical cross-sections of these processes are of the order of 10^{-9} pb[54].

5.4 Object Preselections

All analysis channels share common jet and lepton pre-selections, as well as a common overlap removal procedure, for the categorisation of the events. In this way the statistical independence among all the channels is guaranteed without any overlaps. Once the statistical independence is established, each channel can be further optimized, in order to enhance the statistical significance. This step will be described in Section 5.5.

The selections, applied to define the physical objects used in the analysis, are reported below.

Electron selections

- $p_T > 10$ GeV: this selection is performed to remove most of the non-prompt leptons, coming from hadron semileptonic decays, which, generally, have low transverse momentum;
- $|\eta| < 1.37$ & $1.52 < |\eta| < 2.47$. The region $|\eta| < 2.47$ corresponds to the fiducial acceptance of the EM calorimeter. Electrons with η falling in the crack region, $1.37 < |\eta| < 1.52$, are removed, as explained in Section 4.3;

- looseLH ID: looser requirement on the identification quality, described in Section 4.3;
- $\frac{d_0}{\sigma_{d_0}} < 10$: this variable represents the significance on the impact parameter d_0 , defined in Section 4.2. Only electrons whose tracks are reconstructed in accurate way are used in the analysis;
- $z_0 \cdot \sin\theta < 2mm$. This selection allows to select, mainly, electrons coming from the primary vertex, whose impact parameter, calculated with respect to the reconstructed primary vertex, is small;
- isolation Loose: this working point corresponds to the looser isolation requirement and exploits minimal selections at level of calorimeter and tracking isolation. Leptons are required to be isolated to suppress the background from secondary leptons. Most of the non prompt electrons, originated by hadronic jets, are then removed.

Similarly, for muons, taus and jets the following requirements are used:

Muon selections

- $p_T > 10 \text{ GeV}$;
- $|\eta| < 2.5$;
- loose ID;
- $\frac{d_0}{\sigma_{d_0}} < 10$;
- $z_0 \cdot \sin\theta < 2mm$;
- isolation Loose.

Hadronically decaying τ selections

- $p_T > 10 \text{ GeV}$;
- $|\eta| < 1.37 \text{ \& } 1.52 < |\eta| < 2.5$;
- charge = ± 1 ;
- medium ID;
- number of tracks: 1 or 3;
- isolation Loose.

Jet selections

- $p_T > 25 \text{ GeV}$;
- $|\eta| < 2.5$;
- loose ID;
- provenance from the PV to suppress jets from pileup (Jet Vertex Tagger).

5.4.1 Overlap Removal

When a reconstructed object is close, within a cone of a given ΔR , to another reconstructed object or when two objects share a common track, they are considered as generated by the same object. One of the two objects is then removed. This is the case, for example, of the electrons and hadronic jets, since both objects are reconstructed exploiting the deposits of energy in the calorimeter system of the detector. A different case concerns the overlap removal procedure between jets and muons, in which the muon is removed in order to reject leptons coming from semi-leptonic decays of hadrons inside the jet (non-prompt leptons). The size of the cone opening and the overlap removal criteria are described in Table 5.3.

Keep	Remove	ΔR overlap or shared track
e	τ_{had}	$\Delta R < 0.2$
μ	τ_{had}	$\Delta R < 0.2$
e	CT μ	Shared Tracks
μ	τ_{had}	Shared Tracks
Electron	Jet	$\Delta R < 0.2$
Jet	Electron	$\Delta R < 0.4$
Muon	Jet	$\Delta R < 0.2$
Jet	Muon	$\Delta R < 0.4$
Tau	Jet	$\Delta R < 0.4$

Table 5.3: Overlap Removal algorithm.

5.4.2 Trigger requirements

Leptons in the final state are distinctive signatures of many physics studies performed with the collisions of high energy protons. Being these ttH channels enriched in leptons in the final state, lepton triggers are used to select the events of interest in this work. The analysis data set has been collected using unprescaled single lepton triggers. The triggers used involve both electron and muon triggers. Each selected event must satisfy at least one of the following trigger requirements.

For the 2015 data set, the ttH multilepton analysis employed three electron high-level triggers with different thresholds on p_T (24, 60 and 120 GeV) and on electron identification qualities (medium, medium and loose respectively). For the trigger with the lowest p_T threshold, isolation from hadronic activity in the calorimeter is also required. Two triggers with p_T thresholds at 20 GeV and 50 GeV have been used for muons. For the muon trigger with p_T cut at 20 GeV, a loose isolation cut is also required.

For the 2016 data set, the trigger menu used in the analysis has been changed, to take into account the increase of the LHC instantaneous luminosity. Higher p_T thresholds for electrons and muons are, then, required. For electrons, the thresholds on p_T has been increased to 24, 60 and 140 GeV, respectively. For muons, 24 and 50 GeV thresholds have been used. Tighter identification and isolation requirements are also required both for electrons and muons.

5.5 Signal Region definition

Once leptons have been pre-selected using the requirements shown in Section 5.4, events are divided according to the number of light leptons (e or μ) and sub-divided based on the τ_{had} content. The main signal region selections for the four channels are summarized in the Table 5.4.

Moreover, for each Signal Region, at least one of the selected off-line leptons has to be matched with the object generated by the trigger algorithms, L1 and HLT. For the trigger-matched leptons, their p_T is required to be greater than 25 GeV (21 GeV for muons in data events collected during 2015), about 1 GeV higher with respect the minimum trigger p_T threshold. This is done to ensure that the trigger-matched lepton used in the analysis have a p_T falling in plateau of the trigger efficiency turn-on curve. An example of a trigger efficiency turn-on curve is shown in Fig.5.5.

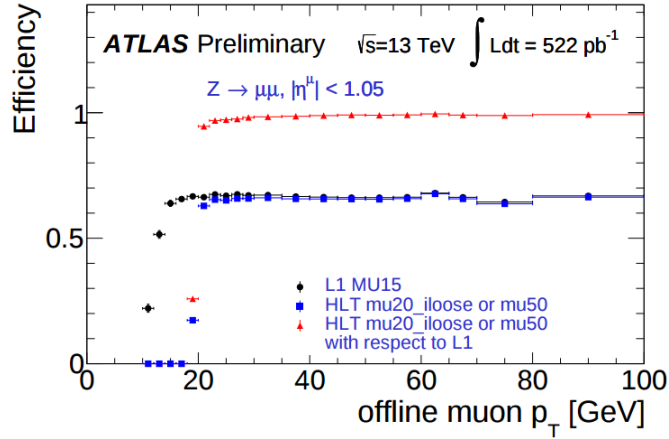


Figure 5.5: Turn-on curves for trigger efficiencies in MC $Z \rightarrow \mu^+\mu^-$ events.

Channel	Selection criteria
$2\ell 0\tau_{had}$	Two tight light leptons with $pt > 25 \text{ GeV}$ Sum of light lepton charges: ± 2 At least one trigger-matched lepton Any electrons must have $ \eta_e < 1.37$ No τ_{had} candidates $N_{jets} \geq 5$ and $N_{b-jets} \geq 1$
$2\ell 1\tau_{had}$	Two tight light leptons, with $pt > 25, 15 \text{ GeV}$ Sum of light lepton charges: ± 2 At least one trigger-matched lepton Exactly one τ_{had} candidate, of opposite charge to the light leptons $ m(ee) - 91.2 \text{ GeV} > 10 \text{ GeV}$ for ee events only $N_{jets} \geq 4$ and $N_{b-jets} \geq 1$
3ℓ	Three light leptons Sum of light lepton charges: ± 1 At least one trigger-matched lepton Two same-charge leptons must be tight and have $p_T > 20 \text{ GeV}$ $m(\ell^+\ell^-) > 12 \text{ GeV}$ and $ m(\ell^+\ell^-) - 91.2 \text{ GeV} > 10 \text{ GeV}$ for all SFOS pairs $ m(3\ell) - 91.2 \text{ GeV} > 10 \text{ GeV}$ $N_{jets} \geq 4$ and $N_{b-jets} \geq 1$, or $N_{jets} = 3$ and $N_{b-jets} \geq 2$
4ℓ	Four light leptons Sum of light lepton charges: 0 At least one trigger-matched lepton All leptons pass "gradient" isolation selection $m(\ell^+\ell^-) > 12 \text{ GeV}$ and $ m(\ell^+\ell^-) - 91.2 \text{ GeV} > 10 \text{ GeV}$ for all SFOS pairs $100 \text{ GeV} < m(4\ell) < 350 \text{ GeV}$ and $ m(4\ell) - 125 \text{ GeV} > 5 \text{ GeV}$ $N_{jets} \geq 2$ and $N_{b-jets} \geq 1$

Table 5.4: Selections for the $t\bar{t}H$ multilepton signal regions (SR).

5.5.1 $2\ell 0\tau_{had}$

In this channel, whose Feynman diagram is shown in Fig.5.1, two light leptons with same charge are required. The charge requirement allows to reject background from $t\bar{t}$ dilepton processes, in which the leptons present opposite charges. To reduce the backgrounds from non-prompt leptons, tighter criteria are applied to the leptons than in the object preselection, as specified in Table 5.4. Electrons are additionally required to satisfy $|\eta_e| < 1.37$ to reduce the impact of the electron charge mis-reconstruction as a result of the process $e^\pm \rightarrow \gamma^{(*)}e^\pm \rightarrow e^\mp e^\pm e^\pm$ occurring

in the detector material. Moreover, both leptons are required to have transverse momentum $p_T > 25 \text{ GeV}$. Events with hadronically decaying tau leptons are vetoed. Events are required to have at least 5 jets, of which at least 1 must be b-tagged. After these selections, the events are sorted into three subcategories based on the flavour of the leptons (ee , $e\mu$, and $\mu\mu$).

Backgrounds from charge mis-ID and fake leptons are estimated by data driven techniques. The rate for the charge mis-reconstruction is determined from data using di-electron events with m_{ee} consistent with the Z boson mass, comparing the yields of opposite-charge and same-charge events.

Backgrounds from secondary leptons are estimated by extrapolating from a Control Region (CR), enriched by such backgrounds, into the Signal Region, using a *transfer factor*, θ . The CR is defined reversing one or more kinematic selections for one of the two leptons (for example the isolation requirement), such that it is statistical independent with respect to the SR. The θ factor is defined as the fraction of non-prompt leptons passing tight and anti-tight selections. More details can be found in [49].

The MC yields for signal and background for this channel will be shown later in Chapter 8.

5.5.2 $2\ell 1\tau_{had}$

In $2\ell 1\tau_{had}$ channel, two light leptons with the same charge are required to pass the tight selections, shown in Table 5.4. Moreover, one τ_{had} candidate, with opposite charge to the light leptons, is required. This channel is, then, sensitive mainly sensitive to the Higgs decay in $\tau^+\tau^-$, as shown in Table 5.2. The Feynman diagram for ttH $2\ell 1\tau_{had}$ process is shown in Fig.5.2.

To suppress the background from non-prompt leptons, the leading lepton must have a $p_T > 25 \text{ GeV}$, while for the sub-leading a cut on $p_T > 15 \text{ GeV}$ is required. Moreover, events are required to have at least 4 jets, of which at least 1 must be b-tagged.

The background from electron charge mis-identification events is reduced by applying a Z-mass veto. Events containing two same-sign electrons with invariant mass $|m(e^\pm e^\pm) - 91.2 \text{ GeV}| > 10 \text{ GeV}$ are then removed.

Data-driven techniques are used to estimate the backgrounds from non-prompt leptons, both light leptons and τ_{had} . Backgrounds from charge mis-ID are estimated by data, using the same technique as in $2\ell 0\tau_{had}$ channel. More details on background estimation methods can be found in Ref.[49].

The MC yields for signal and background for this channel will be shown later in Chapter 8.

5.5.3 4ℓ

In the 4ℓ , whose Feynman diagram is shown in Fig.5.4, 4 light pre-selected leptons are required. The sum of the charges of the leptons in these events must be zero and all leptons must pass the isolation requirements. To reject the ttZ and ZZ backgrounds, all same-flavour $\ell^+\ell^-$ pairs in the event must satisfy $|m(\ell^+\ell^-) - 91.2 \text{ GeV}| > 10 \text{ GeV}$. To remove leptons from quarkonium (J/Ψ , Υ) decays, as in the 3ℓ channel, the cut $m(\ell^+\ell^-) > 12 \text{ GeV}$ is required for all same-flavour $\ell^+\ell^-$ pairs.

The four-lepton invariant mass must satisfy $100 \text{ GeV} < m(4\ell) < 350 \text{ GeV}$ to reduce the background coming from $ZZ \rightarrow 4\ell$ at low mass and ttZ at high mass. To reduce the contamination from other Higgs boson production processes and to ensure statistical independence from dedicated $H \rightarrow ZZ^* \rightarrow 4\ell$ measurements, a Higgs boson veto $|m(4\ell) - 125 \text{ GeV}| > 5 \text{ GeV}$ is applied.

Finally, at least two jets, of which at least one be b-tagged, are required in the event. No requirements on τ_{had} candidates are made and any jets, reconstructed as τ_{had} candidates, are treated only as jets. Other details on this channel can be found in [49].

The MC yields for signal and background for this channel will be shown later in Chapter 8.

5.5.4 3ℓ

The signature of this channel consists of three leptons with total charge $Q_{tot} = \pm 1$. The Feynman diagram for the ttH 3ℓ process is shown in Fig.5.3. The following nomenclature is used for the three selected leptons: the lepton with opposite charge with respect the other two is called ℓ_0 . The lepton closest in ΔR to ℓ_0 is called ℓ_1 . The remaining one is ℓ_2 .

In the context of ttH in multilepton final states, the 3ℓ channel has the second higher sensitivity, after the $2\ell 0\tau_{had}$ channel. The main backgrounds with three real isolated leptons (prompt leptons) are due to the ttZ and ttW processes, as well as diboson production ($W^\pm Z$ mainly). Since the final state signatures are the same of the signal, these processes represent the main irreducible backgrounds for this channel.

$t\bar{t}$, tW and Z +jets processes can contribute as background if the primary leptons are accompanied by a third lepton, produced by a semi-leptonic hadron decay inside a jet. Details on the background from non-prompt leptons and its estimate will be given in Chapter 6. Since the probability for the ℓ_0 to be the secondary lepton is small (see Section 6.1), tighter selections on transverse momentum, lepton identification (ID) and isolation are then applied to the Same Sign lepton pair. The requirements for ℓ_1 and ℓ_2 are reported below:

- $p_T > 20 \text{ GeV}$;
- Tight ID (only for electrons);
- $p_{Tcone}/p_T > 0.06$;
- $E_{Tcone}/p_T > 0.06$;

Moreover, the selections on impact parameters are tightened for all ℓ_0 , ℓ_1 and ℓ_2 .

- $\frac{d_0}{\sigma_{d_0}} < 5.0(3.0)$ for electrons (muons);
- $z_0 \cdot \sin\theta < 0.5 \text{ mm}$;

Since this channel is characterized by the presence of a pair of opposite sign leptons, in order to suppress background from ttZ processes, events with a pair of SFOS¹ leptons and an invariant mass in the range $[91.2 \text{ GeV} \pm 10 \text{ GeV}]$ are vetoed. To suppress, as well, the background from low mass resonances, such as J/Ψ or Υ mesons, events with a pair of SFOS leptons with an invariant mass smaller than 12 GeV are vetoed.

In order to remove the contribution from $Z\gamma$ events, in which the Z boson decays leptonically, the photon converts $\gamma \rightarrow e^+e^-$ and one of these four leptons is lost by some kinematic cuts, Z veto has been required also for events with $M_{\ell\ell\ell_{012}}$ within $[81.2 \text{ GeV}, 101.2 \text{ GeV}]$.

Finally, a number of jets equal to three, of which at least one is a b-tagged jet, or equal or greater than four, of which at least two are b-tagged jets, is required. No requirements on τ_{had} candidates is made and any jets, also reconstructed as τ_{had} candidates, are treated only as jets.

All the selections reported in this section have been optimized on MC simulations according to a figure of merit. The statistical significance, defined as $S/\sqrt{B}$, where S and B represents the expected yields for signal and background respectively, has been used in order to evaluate the optimal cut value on the isolation requirements. An example is shown in Fig.5.6 where the optimization for p_{Tcone}/p_T and E_{Tcone}/p_T working points is shown. The chosen values for for these cuts correspond to those reported in the text.

The signal and background yields for the 3ℓ SR are shown in Table 5.5. The estimated number of background events from non-prompt leptons is derived following the procedure reported in the next chapter.

¹Same Flavour and Opposite Sign

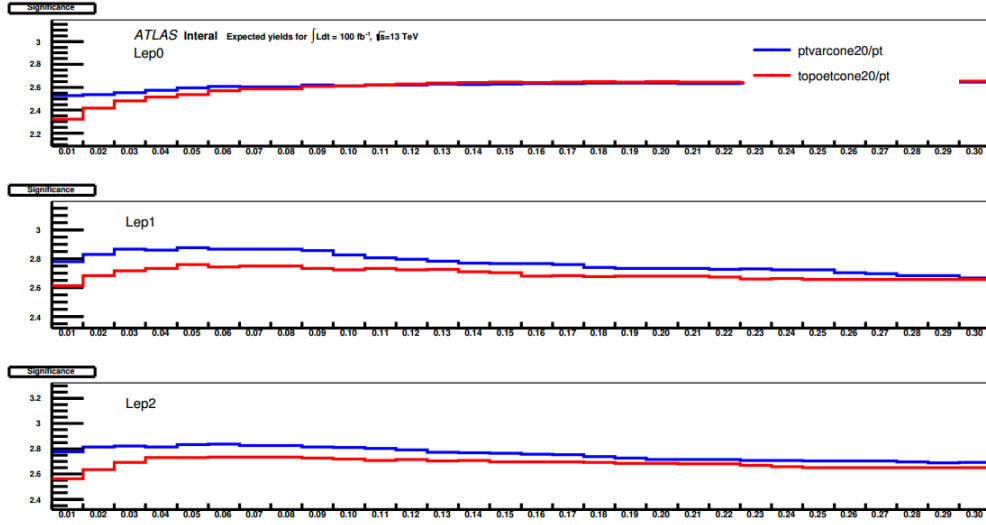


Figure 5.6: Significance vs Isolation working points used for the optimization of the cuts on p_{Tcone}/p_T and E_{Tcone}/p_T for ℓ_0 , ℓ_1 and ℓ_2 .

Process	3ℓ channel yields
ttW	6.38 ± 0.13
ttZ	11.89 ± 0.20
Diboson	1.93 ± 0.41
Non-prompt lepton	8.7 ± 2.4
Charge mis-ID	—
Other	3.38 ± 0.14
Total background	32.2 ± 3.1
ttH	6.19 ± 0.13
$S/\sqrt{B}$	1.1

Table 5.5: Expected event yields in the 3ℓ signal region normalized to 13.2 fb^{-1} . Uncertainties on the background and signal expectations is due to MC statistics. Only for the background from non-prompt leptons, also the systematic uncertainty is reported. "Other" backgrounds include tZ , tWZ , $tHqb$, tHW , $4Tops$, $ttWW$, and triboson production.

5.6 MC samples

Since MC events are generated before the end of the data-taking period, the pileup distribution is simulated according to the estimated number of interactions per bunch crossing. Simulated events are then reweighed to reflect the real mean number of additional interactions observed in data.

Event generator programs and configurations used for the simulation of the signal and background processes are shown in Table 5.6.

A summary of the Standard Model total production cross section measurements, corrected for leptonic branching fractions, and the corresponding theoretical expectations are shown in Fig.5.7.

Process	ME Generator	Parton Shower	PDF
ttH	MG5_AMC	PYTHIA 8	NNPDF 3.0 NLO/ NNPDF 2.3 LO
tHqb	MG5_AMC	PYTHIA 8	CT10/NNPDF 2.3 LO
tHW	MG5_AMC	HERWIG++	CT10/CTEQ6L1
ttW	MG5_AMC	PYTHIA 8	NNPDF 3.0 NLO/2.3 LO
tt(Z/ γ^*)	MG5_AMC	PYTHIA 8	NNPDF 3.0 NLO/2.3 LO
t(Z/ γ^*)	MG5_AMC	PYTHIA 6	CTEQ6L1
tW(Z/ γ^*)	MG5_AMC	PYTHIA 8	NNPDF 2.3 LO
$t\bar{t}t\bar{t}$	MG5_AMC	PYTHIA 8	NNPDF 2.3 LO
ttW ⁺ W ⁻	MG5_AMC	PYTHIA 8	NNPDF 2.3 LO
$t\bar{t}$	POWHEG-BOX	PYTHIA 6	CT10/CTEQ6L1
Wt,Zt,	POWHEG-BOX	PYTHIA 6	CT10/CTEQ6L1
VV, qqVV, VVV	SHERPA 2.1.1	SHERPA	CT10
Z+jets	SHERPA 2.2	SHERPA	CT10
W+jets	SHERPA 2.2	SHERPA	CT10

Table 5.6: List of the MC samples used in the analysis. MG5_aMC refers to MadGraph5_aMC@NLO. Alternative Z+jets background samples, generated with either Madgraph+Pythia8 and Powheg+Pythia8, are used as backup for background modelling validations. If only one PDF is shown, the same one is used for both the matrix element (ME) and parton shower generators. If two are shown, the first is used for the matrix element calculation and the second for the parton shower. For the signal, a Higgs boson mass of 125 GeV is assumed.

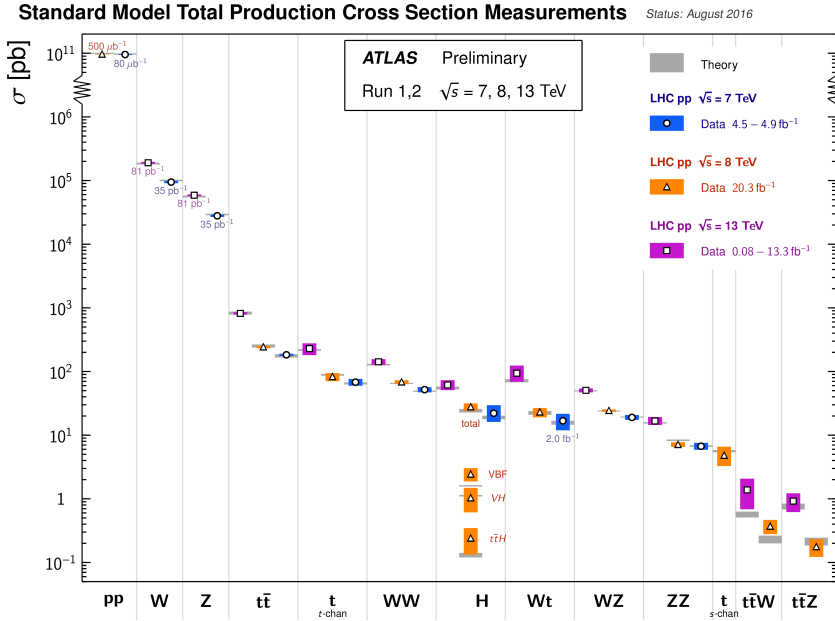


Figure 5.7: Summary of several Standard Model total production cross section measurements, corrected for leptonic branching fractions, compared to the corresponding theoretical expectations. All theoretical expectations were calculated at NLO or higher. The luminosity used for each measurement is indicated close to the data point.

5.7 Validation Regions

The yields of the irreducible backgrounds are estimated from the MC simulations. These processes, ttZ and ttW in particular, have cross sections of the same order of magnitude of the ttH signal one. Hence, because of the rarity of these processes, there is not enough statistics to perform an estimation from data.

Specific Validation Regions (VR) are defined to obtain events that are disjoint from the signal region events, trying at the same time of enriching such regions of the specific background process. These regions are used to validate the overall normalization and the distribution profiles of the various backgrounds.

All backgrounds are modelled using the MC simulations. For non-prompt and electron charge mis-ID events, mainly derived from $t\bar{t}$ processes, normalization factors are derived from the data-driven estimates in the Signal Region[49].

Several Validation Regions have been employed to test the agreement between DATA and MC simulations. The selections applied for their definition are listed in the Table 5.7. For the ttZ VRs, the invariant mass distribution of the SFOS lepton pair is shown in Fig.5.8. The distributions in terms of lepton flavour composition and jet multiplicity are shown in Fig.5.9 and Fig.5.10 for ttW and WZ VRs, respectively.

Channel	Selection criteria
Tight ttZ	3 ℓ lepton selection At least one $\ell^+\ell^-$ pair with $ m(\ell^+\ell^-) - 91.2 \text{ GeV} < 10 \text{ GeV}$ $N_{jets} \geq 4$ and $N_{b-jets} \geq 2$
Loose ttZ	3 ℓ lepton selection At least one $\ell^+\ell^-$ pair with $ m(\ell^+\ell^-) - 91.2 \text{ GeV} < 10 \text{ GeV}$ $N_{jets} \geq 4$ and $N_{b-jets} \geq 1$, or $N_{jets} = 3$ and $N_{b-jets} \geq 2$
ttW	2 $\ell 0\tau_{had}$ lepton selection $2 \leq N_{jets} \leq 4$ and $N_{b-jets} \geq 2$ $E_T^{miss} > 50 \text{ GeV}$ and $m(ee) < 75 \text{ GeV}$ or $m(ee) > 105 \text{ GeV}$ for ee events
WZ	3 ℓ lepton selection At least one $\ell^+\ell^-$ pair with $ m(\ell^+\ell^-) - 91.2 \text{ GeV} < 10 \text{ GeV}$ $N_{jets} \geq 1$ and $N_{b-jets} = 1$

Table 5.7: Selections for the ttH multilepton Validation Regions.

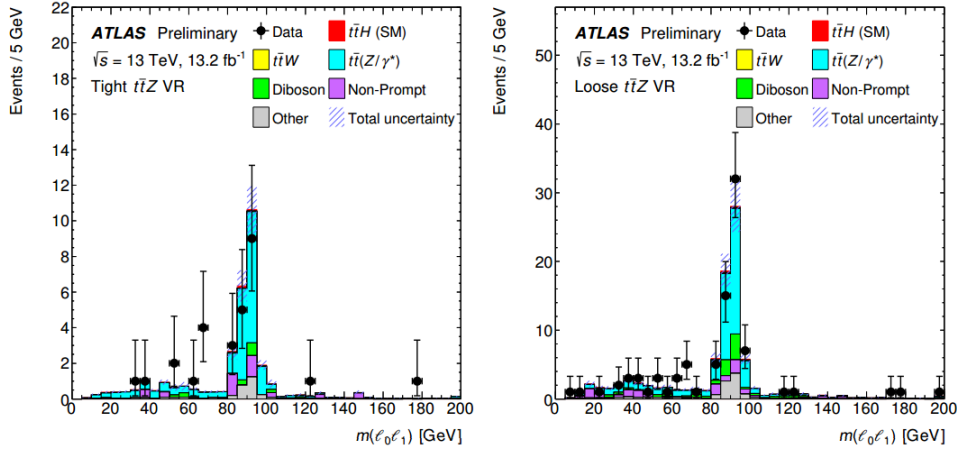
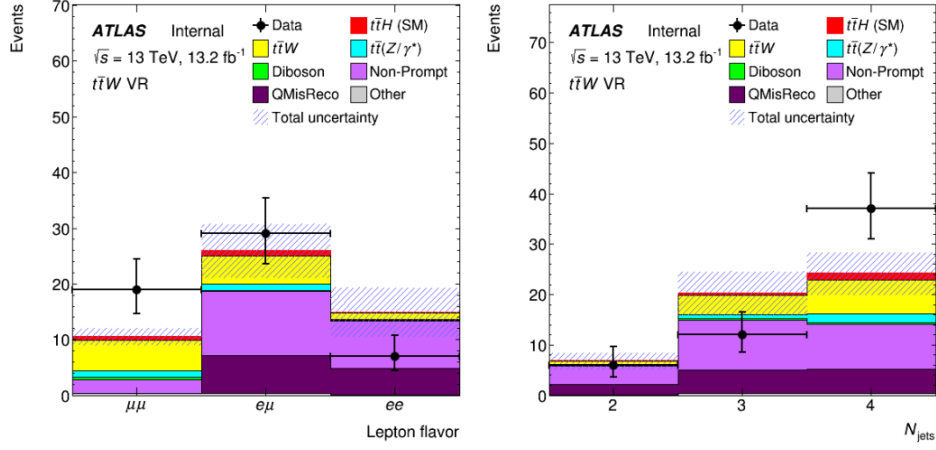
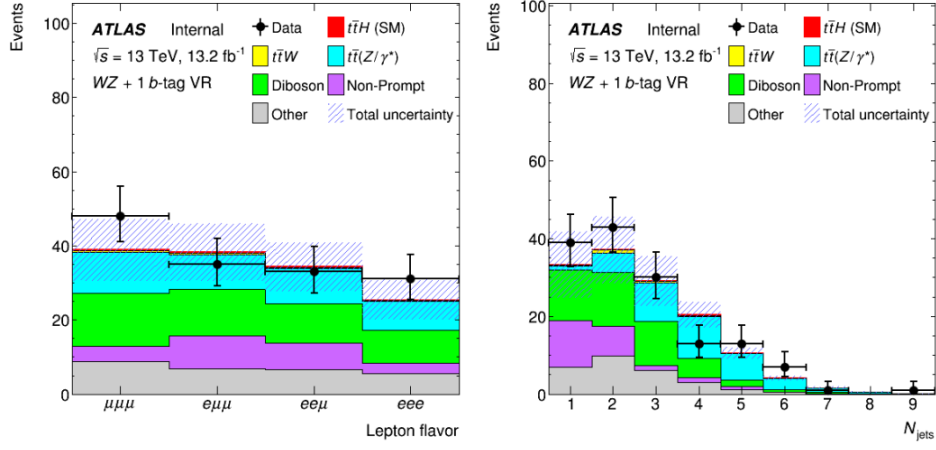


Figure 5.8: Loose and tight ttZ Validation Regions.

Figure 5.9: ttW Validation Region.Figure 5.10: WZ Validation Region.

VR	Purity	Expected	Data
Tight ttZ	68%	32 ± 4	28
Loose ttZ	58%	91 ± 12	89
WZ	33%	137 ± 27	147
ttW	22%	51 ± 10	55

Table 5.8: Expected and observed event yields in validation regions (VR). The quoted uncertainties in the expectations include all systematic uncertainties.

The expected and observed event yields in the Validation Regions (VR) are shown in Table 5.8. The overall MC normalization results to be in good agreement with the observed data. The quoted uncertainties in the expectations include also the systematic uncertainties on the acceptance for the background processes, which are derived using MC simulations. Variations of the hard process renormalization scale and PDF uncertainties are also considered. The purity of each VR indicates the fraction of events, computed from MC simulations, expected to arise from the targeted process.

Chapter 6

Estimation of background from non-prompt leptons in the 3ℓ channel

6.1 Introduction

Processes producing two prompt leptons in association with one or more jets can be accepted into the signal region when one of the following circumstances is verified:

- a secondary lepton from the semi-leptonic decay of a hadron is produced inside a jet;
- a charged lepton, referred to as fake lepton, is generated by instrumental backgrounds (e.g. "punch-through", that is to say jets directed towards a region of the calorimeter not fully instrumented) or it is reconstructed by random association of electronic noise hits.

MC simulations suggest that essentially all the background leptons selected in this analysis belong to the first category. While the background estimation developed in this work aims at evaluating specifically the contribution from secondary leptons in the SR, given the common hadronic origin, also leptons originated from the instrumental backgrounds get naturally included in the estimate.

The probability of mis-identifying a non-prompt lepton is small ($10^{-3} \div 10^{-2}$), but some processes, such as $t\bar{t}$, have cross-section large enough (832 pb at N^3LO [56]) to represent a significant background. The Feynman diagram for $t\bar{t}$ process, in which each top quark decays leptonically, is shown in Fig.6.1.

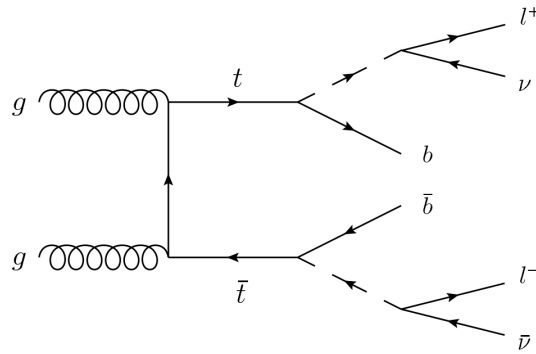


Figure 6.1: Feynman diagram for $t\bar{t}$ process with two leptons in the final state. This is the main source of background events with non-prompt leptons in the 3ℓ channel.

Smaller contributions to this kind of background come also from the associated production of a single Top quark and a W boson (tW), characterized by a cross-section of 70 pb at NNLO[57], and the production of a Z/γ^* boson together with hadronic jets ($Z/\gamma^* + \text{jets}$), that is mainly suppressed by the invariant mass veto around the Z peak. γ^* refers to a virtual photon. The Z/γ^* production cross section times the BR in $\ell^+\ell^-$ final state, calculated at NNLO, is 1890 pb[58]. tW and Z/γ^* Feynman diagrams are shown in Fig.6.2.

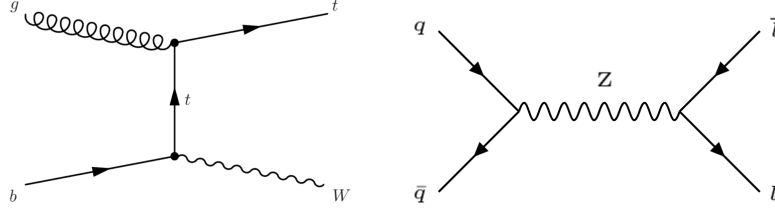


Figure 6.2: Feynman diagrams at tree level for tW (left) and Z (right) processes. They represent a smaller source of background from non prompt leptons when the two prompt ones are accompanied by a third electron or muon produced inside a jet.

As seen from the diagrams shown in Fig.6.1 and Fig.6.2, the lepton with an electric charge opposite in sign to the other two has to come from one of the two W decays, by construction. In fact, the secondary lepton can be tagged as ℓ_0 (see Section 5.5.4) only if, at the same time, the charge of ℓ_1 is mis-identified. Since the probability to identify the lepton charge incorrectly is as small as the non-prompt lepton mis-identification one, it is safe to assume that only the reconstructed ℓ_1 and ℓ_2 can originate from a semileptonic hadron decay.

For this reason, a higher p_T cut is adopted for these leptons (20 GeV in place of 10 GeV for the opposite-sign lepton). The probability to identify the lepton charge incorrectly has been estimated from MC simulation looking at events in which the invariant mass of two electrons is consistent with the Z boson mass and computing the ration between the event yields with 3 leptons with the same charge and the number of events with charge ± 1 .

A method to estimate the contribution of events from non prompt leptons in the 3ℓ channel is developed and described in this chapter. The background contribution is estimated *in-situ*: the shapes of the distributions are taken from MC simulations and validated with data in a different region, the *Auxiliary Region* (AR), described later in section 6.5, while the overall normalization of the event yield with secondary leptons is taken from data in a *Control Region* (CR) which, thanks to the large statistics in data of $t\bar{t}$ and Z+jets processes, is largely populated by this kind of backgrounds. The strategy makes use of the MC samples $t\bar{t}$, tW and $Z + \text{jets}$ to extract a correction factor, θ_{MC} , to apply to data.

In general, if the statistics allows it, the estimation of the backgrounds from data is preferable because the MC simulations are not guaranteed to model the instrumental backgrounds, either in rate or in shape, accurately. This could lead to have a different number of non prompt leptons in data and MC.

6.2 Estimation strategy

A starting number of $t\bar{t}$, tW and Z+jets events is taken from data in a CR enriched of non-prompt leptons. It contains two "prompt" leptons (i.e. leptons passing all the signal region selections listed in Chapter 5), plus a third "fake" lepton. This is defined as a lepton passing most of the object selections of the analysis, but explicitly failing some specific cuts: this ensures that the CR is statistical independent with respect to the SR. This lepton will be referred to as "CR-lepton".

The reversed lepton selections, used to to define the CR electron and muon, are chosen to be different. This reflects the different sources of the non-prompt leptons:

- heavy-flavour hadron decays for both electrons and muons;
- photon-conversions for electrons ($\sim 10\%$ of the total).

The event selections in the CR are the same as for the SR, in order to have an as-small-as-possible extrapolation from the CR to the SR, which minimize the effect of the assumptions on the associated systematic uncertainties. Hence, a transfer factor, θ_{MC} , for the events in the CR ending up in the SR, is evaluated as the ratio of the number of $t\bar{t}$, tW and Z +jets events with 3 prompt leptons over the number of 2 prompt leptons + 1 CR lepton, as shown in Eq.6.1.

$$\theta_{MC} = \frac{N_{\ell\ell\ell}}{N_{\ell\ell\bar{\ell}}} \quad (6.1)$$

This represents the relative amount of $t\bar{t}$, tW and Z + jets events in the SR over those in the CR. θ_{MC} is a single number, computed inclusively applying the same event selection for both the SR (numerator) and CR (denominator). Note that the order of the 3 leptons in Eq.6.1 corresponds to ℓ_0 , ℓ_1 and ℓ_2 , defined in Section 5.5.4.

In principle, the transfer factor θ can be estimated in two different ways. The first option, adopted in this analysis, consists on the extraction of θ from MC simulations and its validation with data in an appropriate region (Auxiliary Region).

The second option consists on the extraction of θ from data, exploiting an alternative SR, defined in such way to be statistical independent with respect to the 3ℓ SR. In fact, in order not to bias the process of designing the analysis strategy, I have decided to not look at data in the SR, until all the background estimation was completed and the analysis deemed "mature" (*SR blinding*). An alternative SR could be designed requiring orthogonal selections with respect to the SR, for example looking at events with different jet multiplicity or with an invariant mass of two same-flavour opposite-sign leptons consistent with Z boson mass. However, since in these alternative SR definitions the relative ratio between the dominant $t\bar{t}$ background and the other irreducible processes is different with respect to the SR one, I choose to estimate the transfer factor θ from MC simulation.

Finally, the estimated number of events with non prompt leptons in SR is computed using the following expression:

$$N_{fakes, SR} = [N_{data, CR} - N_{prompt, CR}^{MC}] \cdot \theta^{MC} \quad (6.2)$$

where $N_{prompt, CR}^{MC}$ represents all the processes corresponding to the "irreducible background" category, where 3 prompt leptons are present. These have much lower yields than the non-prompt in the CR and are thus taken from MC.

The θ extrapolation factor is purely object-level and depends on the modelling of few key variables of the non-prompt leptons, such as the isolation and the lepton-ID. Starting from Eq.6.1 it is possible to derive the two specific expression for the transfer factors for muons, as shown in Eq.6.3.

$$\theta_{MC}^{\mu} = \frac{N_{x\mu\mu}}{N_{x\mu p}} \quad (6.3)$$

In the above equations, "x" indicates both electrons and muons inclusively, while "p" the CR-muon. The above definition of θ , in which the second and third lepton must be a muon, guarantees that events with a CR-muon are not included in the estimation from the numerator, although reducing the sample size available for the determination of θ_{MC} . Because the CR-muon "p" can be either the second or the third lepton, this definition correctly account for all permutations of prompt+non-prompt muon events. When applied to the inclusive "x x p" population of CR, it returns the estimate of all and only the events with a non-prompt muon in the SR ($x\mu\mu + x\mu x$).

Similarly, for the estimation of non-prompt electrons, the expression for the transfer factor is shown in Eq.6.4, where "d" indicates the CR-electron.

$$\theta_{MC}^e = \frac{N_{xee}}{N_{xed}} \quad (6.4)$$

6.3 Transfer factor for non-prompt muons

The definition of the CR-muons in the CR is provided in the Table 6.1. The goal is to define a CR enriched in secondary muons coming from hadronic jets, mainly b-tagged jets. For this reason, for one of the two same-sign leptons, let's say ℓ_2 , the isolation requirement is reversed and the overlap removal algorithm between muons and jets is not applied. The variables used for the lepton isolation and the OR are defined in Sections 5.4.1 and 5.5.4, respectively.

Variable	Selection
p_T	$> 20 \text{ GeV}$
lepID	Loose
p_{Tcone}/p_T	< 0.06
OR with jets	Not applied

Table 6.1: Selections used to define the CR-muons in the muon CR. η , $\frac{d_0}{\sigma(d_0)}$ and $z_0 \cdot \sin \theta$ requirements are the same as for SR and they are not reported in the table.

Once objects have been pre-selected, the presence of 2 "tight" leptons, satisfying the selections reported in Section 5.4, and of 1 CR-muon, satisfying the cuts reported in Table 6.1, is required for the events in the muon-CR.

The expected number of events for data and MC processes in the CR is shown in Table 6.2. The comparisons of the kinematic and topological variables in the muon-CR, between data and MC simulations, are shown in Fig.6.3 for CR-muon quantities and in Fig.6.4 for global event quantities.

Sample	N.events
Data	998
$t\bar{t}$	869.0 ± 9.3
tW	35.6 ± 2.5
$Z + jets$	25.7 ± 8.3
$t\bar{t}H$	5.0 ± 0.1
prompt lepton processes	24.8 ± 1.5
data - prompt lepton processes ("dt")	973 ± 1.5
$t\bar{t} + tW + Z+jets$ ("mc")	930 ± 12
dt/mc	1.05 ± 0.01

Table 6.2: Number of observed events in data and expected number of $t\bar{t}$, tW , $Z+jets$ and other MC events in the muon-CR. The "prompt lepton processes" category includes also the $t\bar{t}H$ signal.

The resulting transfer factor θ_μ is given in Eq.6.5, where, at this point, only the statistical error is reported.

$$\theta_\mu = \frac{N(x\mu\mu)}{N(x\mu p)} = 0.00306 \pm 0.00073 \text{ (24\% stat.)} \quad (6.5)$$

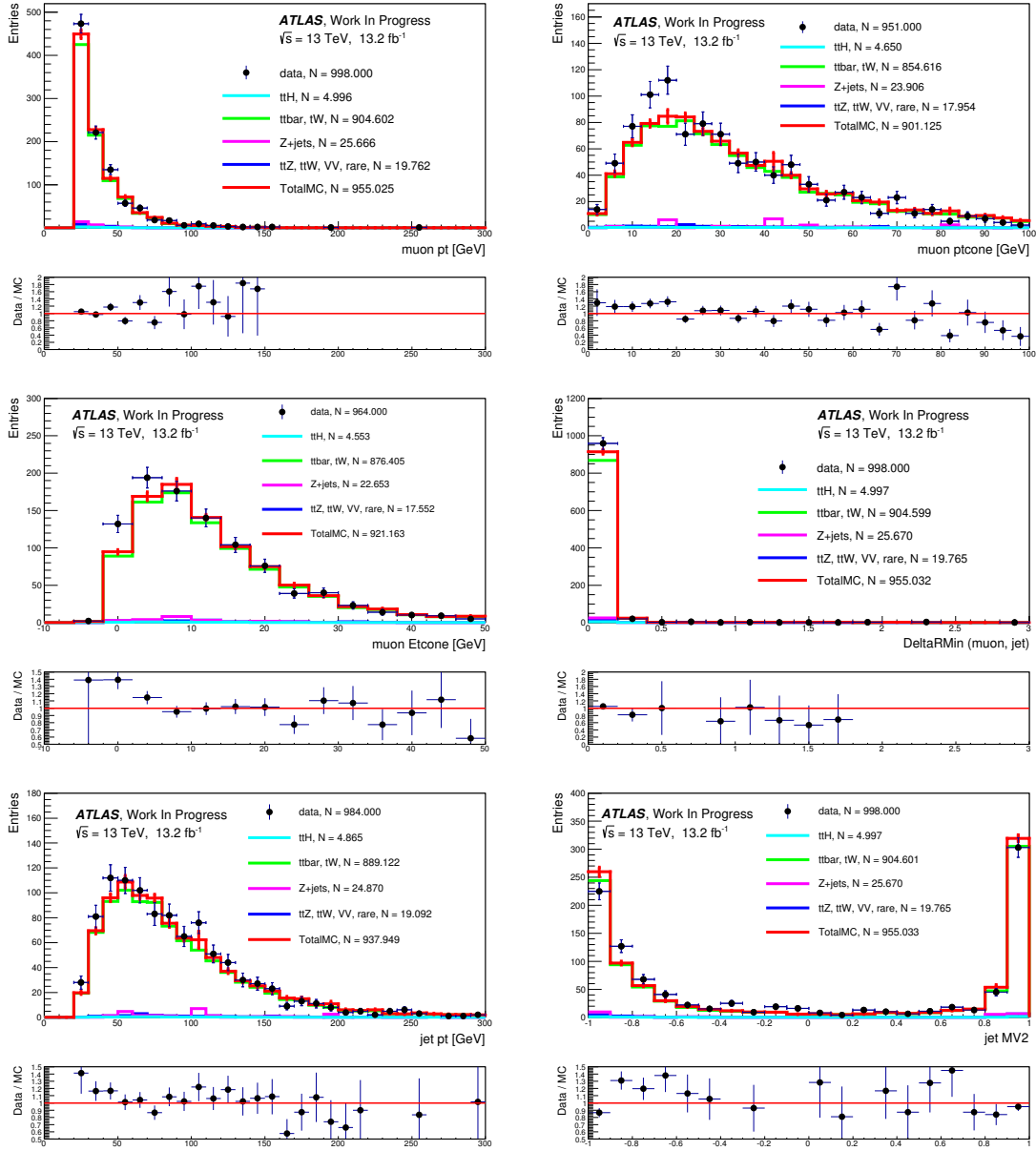


Figure 6.3: **Muon Control Region.** Distributions of the CR-muon kinematic variables more sensitive to the lepton origin and, particularly, used in the back-extrapolation from CR to SR. Data (dots) are compared with the total simulation (red line). The variables probed are: p_T and p_{Tcone} of the muon (top), E_{Tcone} and $\Delta R(\mu, \text{closest selected jet})$ (center), p_T of the jet closest to the CR-muon and its MV2 b-tagger (bottom). A ratio plot in the bottom pad is also displayed for each distribution.

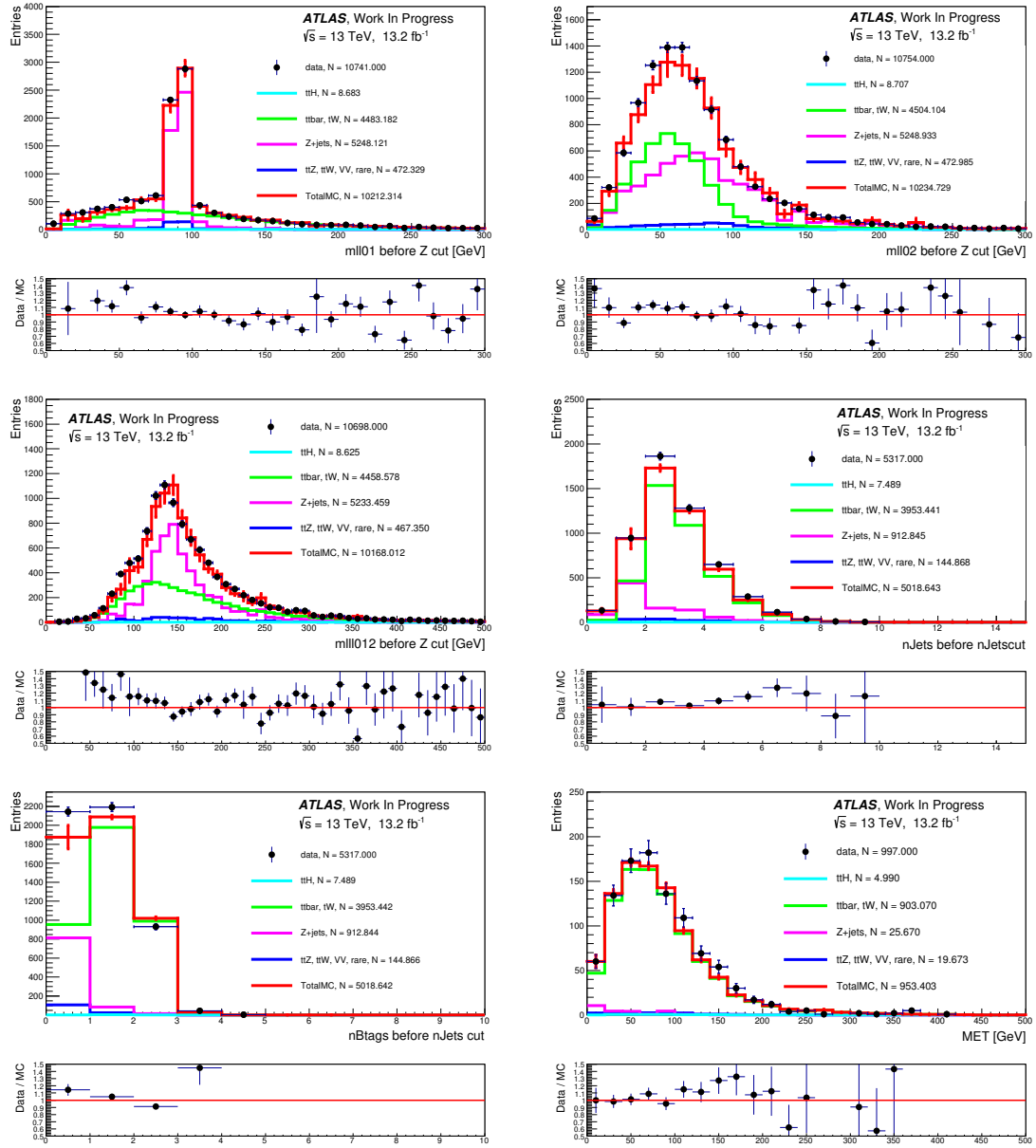


Figure 6.4: **Muon Control Region.** Distributions of invariant masses mll_{01} and mll_{02} before to apply the Z veto (top), mll_{012} before to apply the Z veto and jet multiplicity before the requirement on the number of jets (center), b-tagged jet multiplicity before the requirement on the number of jets and E_{miss}^T (bottom). A ratio plot in the bottom pad is also displayed for each distribution. MET corresponds to $E_{\text{T}}^{\text{miss}}$.

6.4 Transfer factor for non-prompt electrons

The same approach is used for the non-prompt electron background estimate. The definition of the CR-electrons in the electron-CR is provided in the Table 6.3. Unlike non-prompt muons, a second source of background for non-prompt leptons exists. Non-prompt electrons can be generated from photon conversions, through the process $\gamma \rightarrow e^+e^-N$, in which the electron or the positron is lost by the minimal kinematic requirements used in the object pre-selections. Since electrons from photon conversions are mainly removed applying tight requirements on the lepton identification (lepID), in order to define a CR enriched in non-prompt electrons only Loose and Medium ID selections are required. Moreover, in order to be sensitive also to non-prompt electrons from hadron decays, as for the muon-CR, the isolation requirements and the OR between electrons and jets are not applied.

Variable	Selection
p_T	$> 20 \text{ GeV}$
lepID	Loose or Medium
Isolation	Not applied
OR with jets	Not applied

Table 6.3: Selections used to define the CR-electrons in the electron-CR. η , $\frac{d_0}{\sigma(d_0)}$ and $z_0 \cdot \sin \theta$ requirements are the same as for SR and they are not reported in the table.

The expected number of events for the most important background processes in the CR are shown in Table 6.4.

Sample	N.events
Data	216
$t\bar{t}$	176.2 ± 4.2
tW	5.9 ± 1.0
$Z + jets$	4.3 ± 1.1
$t\bar{t}H$	0.88 ± 0.04
prompt lepton processes	5 ± 1
data - prompt lepton processes ("dt")	211 ± 1
$t\bar{t} + tW + Z+jets$ ("mc")	186.5 ± 4.5
dt/mc	1.13 ± 0.03

Table 6.4: Number of observed events in data and expected number of $t\bar{t}$, tW , $Z+jets$ and other MC events in the electron CR. The "prompt lepton processes" category includes also the $t\bar{t}H$ signal.

As for the non-prompt muon estimate, the θ_e transfer factor is extracted from MC, from the ratio of events in the SR and CR. In order to ensure that we are evaluating the transfer factor for electrons only, events with the flavour structure shown in Eq.6.6 are used. "d" refers to the CR-electrons and "x" refers to either a prompt-like electron or muon. The resulting value for the transfer factor θ_e is reported below, where only the statistical error is reported so far.

$$\theta_e = \frac{N(xee)}{N(xed)} = 0.0269 \pm 0.0057 \text{ (21\% stat.)} \quad (6.6)$$

Also in the case of electrons, even though not used in the normalization, it is interesting to compare the degree of accuracy of the simulation against the data in the CR, comparing the kinematic and topological variables more sensitive to the lepton origin and, particularly, those used in the back-extrapolation from CR to SR. Such plots are shown in Fig.6.5 for CR-electron quantities and in Fig.6.6 for global event quantities.

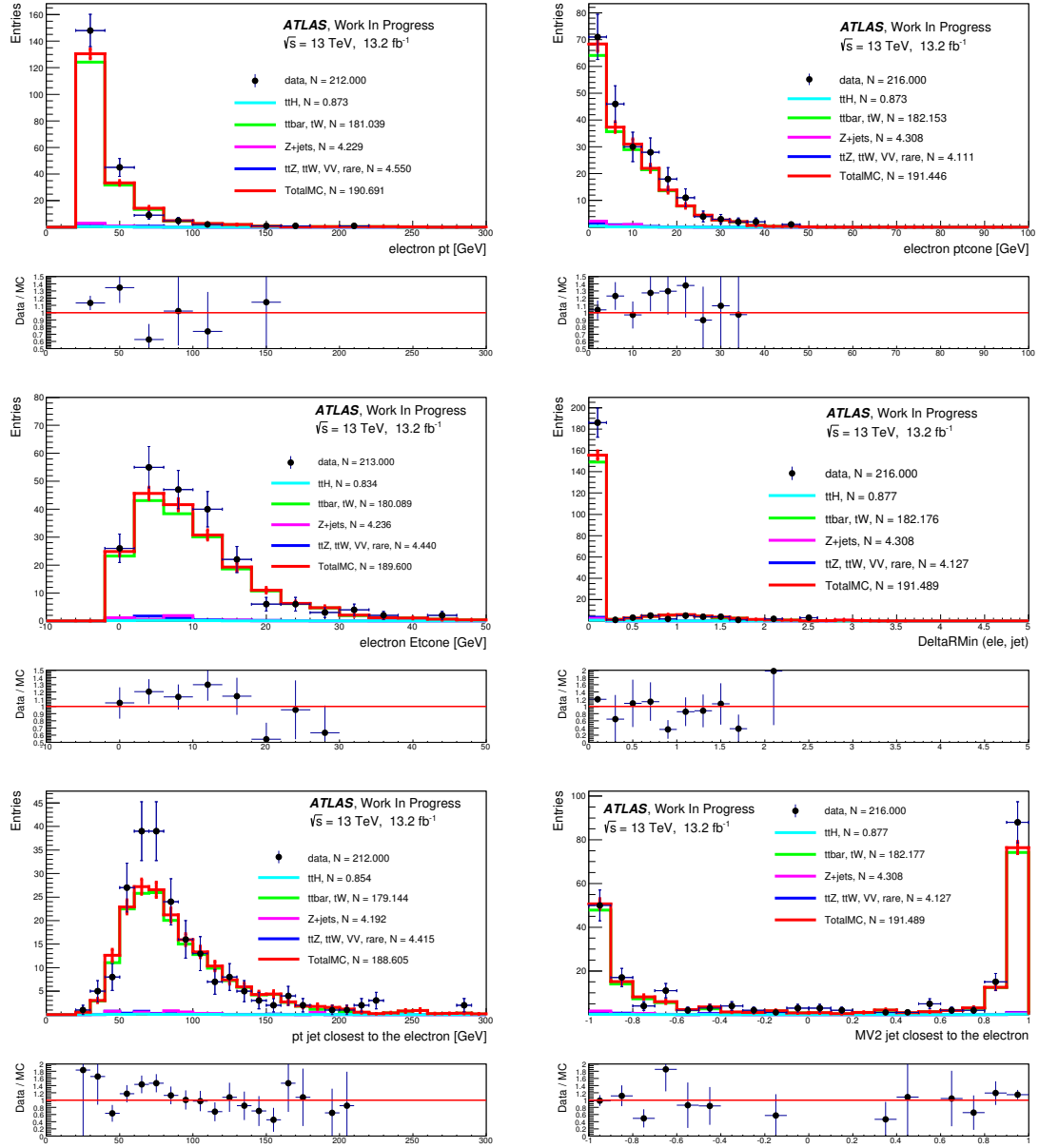


Figure 6.5: **Electron Control Region.** Distributions of the CR-electron kinematic variables more sensitive to the lepton origin and, particularly, used in the back-extrapolation from CR to SR. Data (dots) are compared with the total simulation (red line). The variables probed are: p_T and p_{Tcone} of the electron (top), E_{Tcone} and $\Delta R(\mu, \text{closest selected jet})$ (center), p_T of the jet closest to the CR-electron and its MV2 b-tagger (bottom). A ratio plot in the bottom pad is also displayed for each distribution.

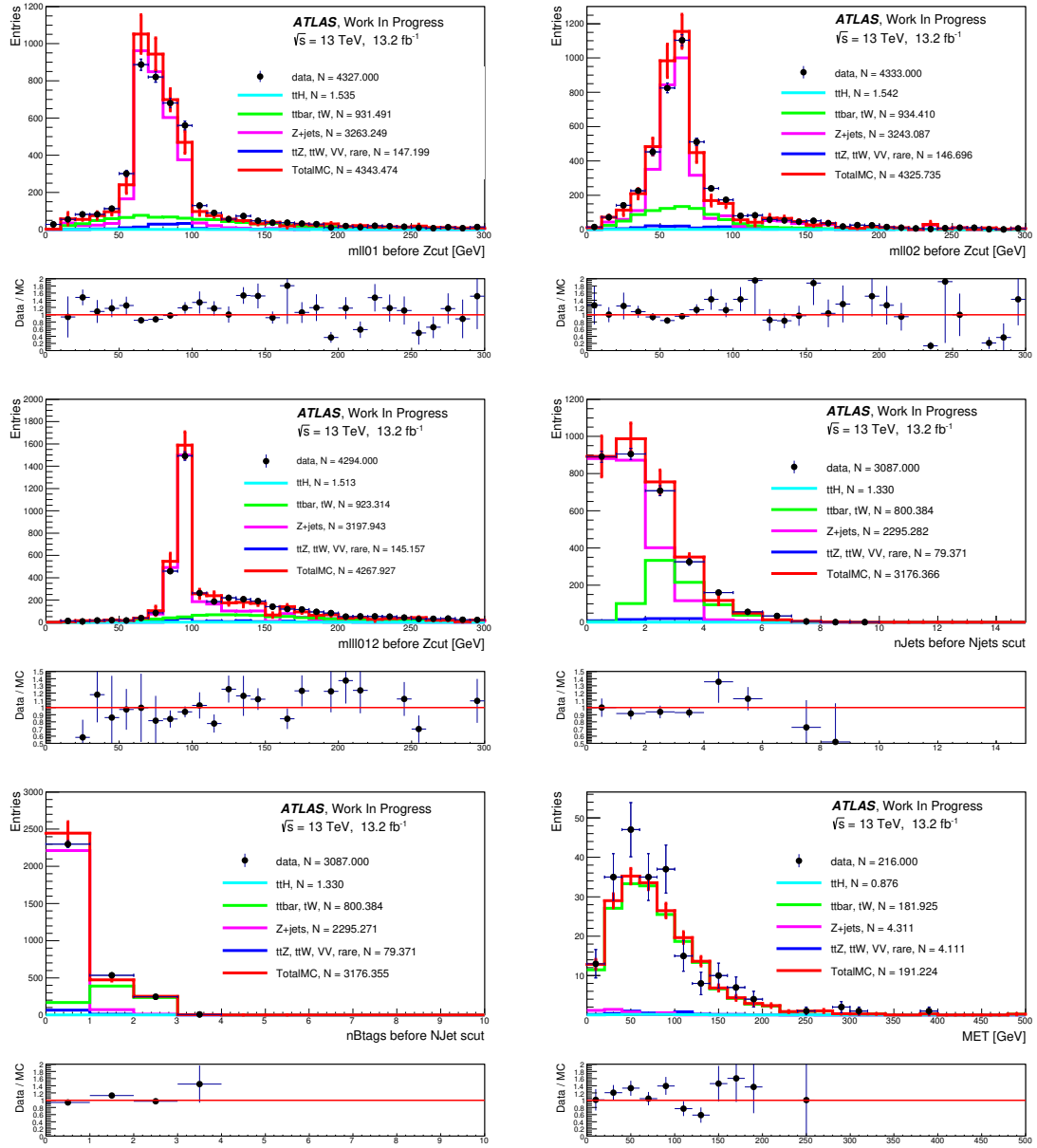


Figure 6.6: **Electron Control Region.** Distributions of invariant masses m_{ll01} and m_{ll02} before to apply the Z veto (top), m_{ll012} before to apply the Z veto and jet multiplicity before the requirement on the number of jets (center), b-tagged jet multiplicity before the requirement on the number of jets and E_{miss}^T (bottom). A ratio plot in the bottom pad is also displayed for each distribution. MET corresponds to E_T^{miss} .

6.5 Systematic uncertainty on the background estimate

The level of accuracy of the MC prediction in terms of the profiles of the variables used in the CR $\rightarrow$ SR extrapolation, hence on θ_{MC} , is assessed in a third region: the AR. It is still enriched in $t\bar{t}$ events, but with looser selections on leptons and events. The relevant variables (those in which a selection is inverted to define the CR-lepton) are separately compared in shape between data and MC in the AR.

Any difference in distribution is interpreted as a deviation from the actual data model. The maximum discrepancy across the full range on any of the variables used in the extrapolation is therefore taken as a systematic uncertainty on θ_{MC} . This region must have enough statistics to allow a meaningful comparison and be sensitive to systematic differences between the model and the data.

To this aim, two AR regions are defined both for muons and electrons, respectively. They contain events with 2 "tight" leptons and 1 satisfying looser selections. The loose lepton selections are defined as in Table 6.5 and Table 6.6. This lepton will be referred to as "AR-lepton".

Variable	Selection
p_T	$> 10 \text{ GeV}$
lepID	Loose
Isolation	Not applied
OR with jets	Not applied

Table 6.5: Selections used to define the muons in the muon-AR. η , $\frac{d_0}{\sigma(d_0)}$ and $z_0 \cdot \sin \theta$ requirements are the same as for SR and they are not reported in the table.

Variable	Selection
p_T	$> 10 \text{ GeV}$
lepID	Loose
Isolation	Not applied
OR with jets	Not applied

Table 6.6: Selections used to define the electrons in the electron-AR. η , $\frac{d_0}{\sigma(d_0)}$ and $z_0 \cdot \sin \theta$ requirements are the same as for SR and they are not reported in the table.

Once objects have been pre-selected, the presence of 2 leptons satisfying the selections reported in Section 5.4 and of 1 lepton, satisfying the cuts reported in Tables 6.5 and Table 6.6, are required for the events in the muon-AR and electron-AR, respectively. Concerning the event selections, one main difference has been introduced with respect to the SR: 2 or 3 jets of which at least 1 b-tagged jet are required for both Auxiliary Regions, in order to be statistical independent with respect to the SR.

The yields in the AR are summarized in Table 6.7 and Table 6.8 for muons and electrons, respectively. The distributions of the main variables used for the CR-to-SR extrapolation are shown in Fig.6.7 and Fig.6.8. Numbers provided in the tables are only indicative; they don't affect the derivation of the systematic uncertainty on the transfer factors through the comparison of the modelling.

It is found from Fig.6.7 and Fig.6.8 that 30% relative uncertainties cover the full extent of the mis-modelling in both the muon and electron distribution profiles. These are, hence, the systematic uncertainties associated to θ_μ and θ_e .

Sample	Muon-AR Yields
Data	1151
$t\bar{t}$	652.5 ± 7.9
tW	31.5 ± 2.2
Z+jets	417 ± 49
ttH	0.36 ± 0.02
Prompt lepton processes	46.2 ± 8.1
Total MC	1148 ± 50

Table 6.7: Observed data and expected number of $t\bar{t}$, tW, Z+jets and other processes in the muon-AR. The contamination from processes other than $t\bar{t}$, tW and Z+jets is expected to be about 4%.

Sample	Electron-AR Yields
Data	686
$t\bar{t}$	337.1 ± 5.8
tW	20.0 ± 1.8
Z+jets	396 ± 46
ttH	0.13 ± 0.01
Prompt lepton processes	41.8 ± 7.5
Total MC	795 ± 47

Table 6.8: Observed data and expected number of $t\bar{t}$, tW, Z+jets and other processes in the electron-AR. The contamination from processes other than $t\bar{t}$, tW and Z+jets is expected to be about 5%.

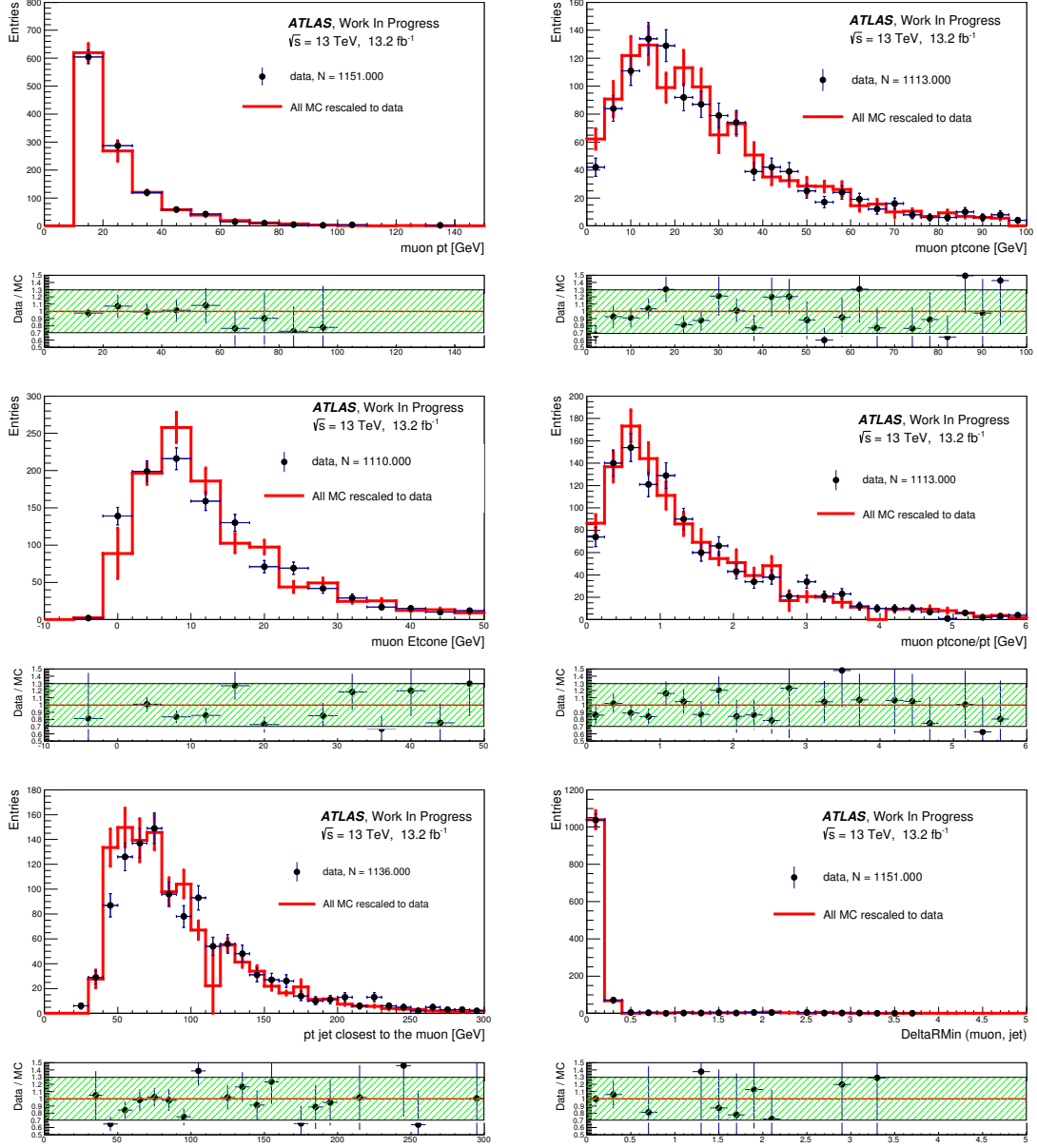


Figure 6.7: **Muon Auxiliary Region.** Distributions of the properties of the AR-muon in the AR. Data (dots) are compared with the total simulation (red line), rescaled to the integral of the data for a shape comparison. The variables probed are: p_T and p_{Tcone} of the muon (top), muon e_{Tcone} and muon p_{Tcone}/p_T (center), p_T of the jet closest to the AR-muon and $\Delta R(\mu, \text{closest jet})$ (bottom). A ratio plot in the bottom pad is also displayed for each distribution, with a box around 1 with an area up to 30% containing most of the points.

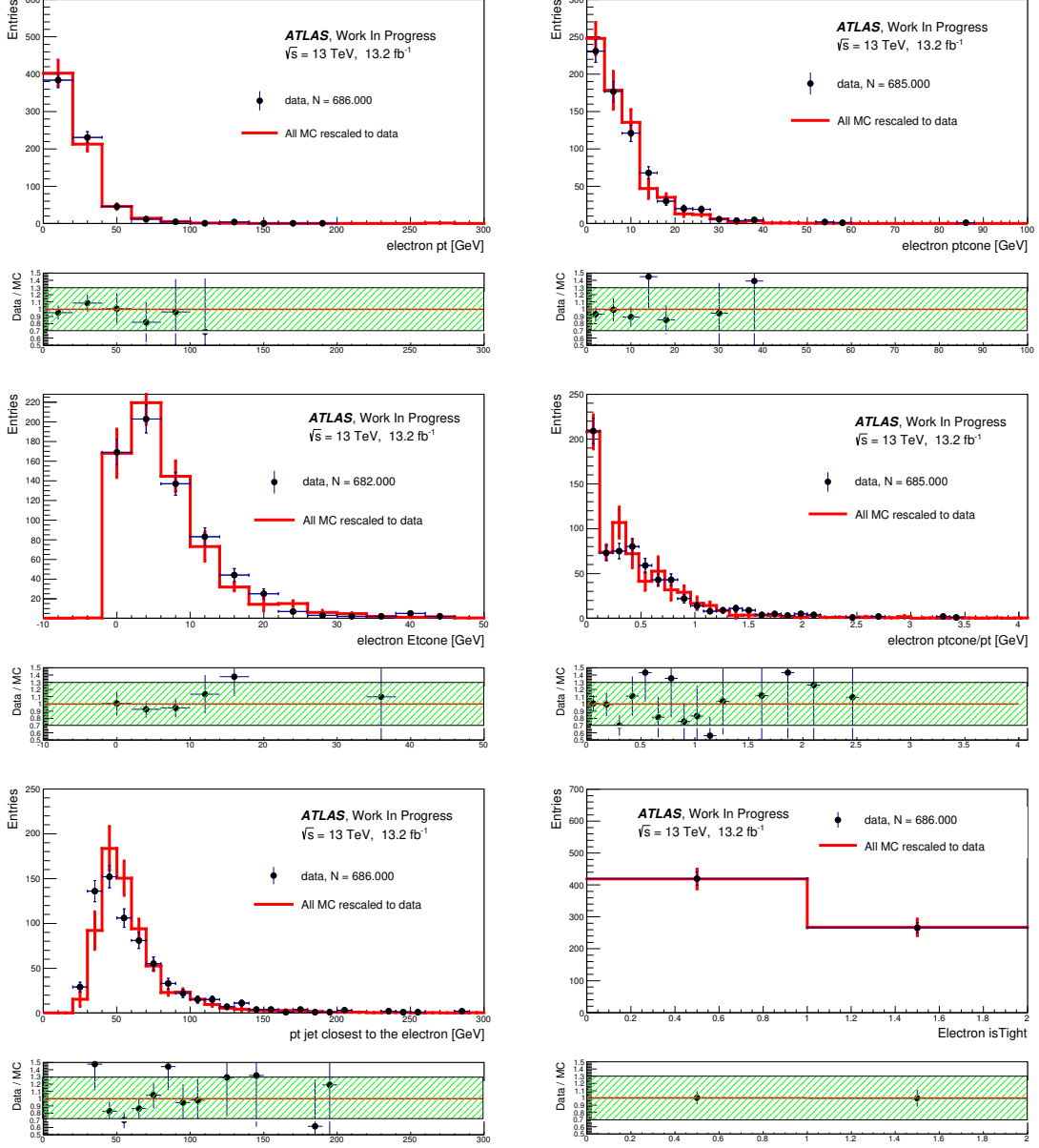


Figure 6.8: **Electron Auxiliary Region.** Distributions of the properties of the AR-electron in the AR. Data (dots) are compared with the total simulation (red line), rescaled to the integral of the data for a shape comparison. The variables probed are: p_T and p_{Tcone} of the electron (top), muon E_{Tcone} and electron p_{Tcone}/p_T (center), p_T of the jet closest to the AR-electron and ID quality (anti-tight/tight) (bottom). A ratio plot in the bottom pad is also displayed for each distribution, with a box around 1 with an area up to 30% containing most of the points.

6.6 Results

Table 6.9 summarizes all the inputs for the final estimation of the number of events with a non-prompt muon in the SR.

Stage	Value
Overall starting normalization (CR)	973.2 ± 1.5 (<i>stat</i> , 0.2%)
Transfer factor θ_μ	0.00306 ± 0.00073 (<i>stat</i> , 24%) ± 0.00092 (<i>syst</i> , 30%)

Table 6.9: Summary of the inputs for the extraction of the number of events with a non-prompt muon in the SR.

The number of estimated events containing one non-prompt muon is found to be:

$$N_{non-prompt\ \mu} = 2.98 \pm 0.72$$
 (*stat*, 24%) ± 0.90 (*syst*, 30%) = 3.0 ± 1.2 (*tot*, 39%). (6.7)

Similarly, for electrons the results are shown in Table 6.10.

Stage	Value
Overall starting normalization (CR)	211 ± 1 (<i>stat</i> , 0.5%)
Transfer factor θ_e	0.0269 ± 0.0057 (<i>stat</i> , 21%) ± 0.0081 (<i>syst</i> , 30%)

Table 6.10: Summary of the inputs for the extraction of the number of events with a non-prompt electron in the SR.

The number of estimated events containing one non-prompt electron is found to be:

$$N_{non-prompt\ e} = 5.7 \pm 1.2$$
 (*stat*, 21%) ± 1.7 (*syst*, 30%) = 5.7 ± 2.1 (*tot*, 37%). (6.8)

Summing the two estimates and assuming they are uncorrelated, the following total number of events with non-prompt leptons in the SR is estimated to be:

$$N_{non-prompt,SR} = 8.7 \pm 1.4$$
 (*stat*, 16%) ± 1.9 (*syst*, 22%) = 8.7 ± 2.4 (*tot*, 27%). (6.9)

The assumption that the two non-prompt lepton rates are uncorrelated, and thus can simply be added in quadrature, is motivated by the fact that the θ_{MC} definition separates muon and electron results by construction. This estimate can be compared with the MC only estimate of 6.18 ± 0.75 (*stat*, 12%). The two numbers are compatible at the 1.0 sigma level.

6.7 Cross-check in the Validation Region

To test the goodness of the method and the presence of possible biases, a validation on data is performed: the estimate of the number of events containing a non-prompt lepton is compared with the data yield in a Validation Region (VR). To this end, a VR with the same selections that define the Signal Region, but with exactly 2 or 3 jets and exactly 1 b-tagged, is used. With these requirements the VR is statistical independent with respect to the SR. In the VR, the contamination from irreducible backgrounds with 3 prompt leptons (e.g. ttV processes) is estimated from simulation and subtracted from the overall data yield. The difference is taken to be all originated from single and pair Top production and Z bosons and it is compared with the estimate.

For the estimation of non-prompt lepton backgrounds, I use the same procedure applied for the main analysis, defining two new CR, CR-muon and CR-ele with a low jet multiplicity requirement.

The yields from where the estimates are drawn are reported in Table 6.11. The number of data events and prompt backgrounds to be subtracted in the VR are reported in Table 6.12. A relative systematic uncertainty of 30% and 50% is associated respectively to the MC yield of ttV and VV events for the subtraction in the VR. For the rare processes, $tt+WW$, 4-Tops, VVV , tH , VH , tWZ a relative systematic uncertainty of 100% has been used. These uncertainties have been derived from previous ATLAS analyses focused on the ttH search[16].

Sample	CR-muon (low jets)	CR-electron (low jets)
Data	1272	273
ttZ	2.00 ± 0.12	0.461 ± 0.094
ttW	1.57 ± 0.057	0.317 ± 0.029
VV	5.0 ± 1.3	0.41 ± 0.22
rare	0.06 ± 0.45	0.53 ± 0.40
Total prompt bkg	8.69 ± 1.4	1.73 ± 0.47
Signal	0.61 ± 0.03	0.112 ± 0.011
Total prompt	9.30 ± 1.4	1.84 ± 0.47

Table 6.11: Number of events with a CR-lepton in the CRs at low N.jets for muons and electrons respectively.

Sample	Yields
Data	66
ttZ	4.7 ± 1.4
ttW	7.0 ± 2.1
VV	5.2 ± 2.9
rare	2.6 ± 2.6
Total prompt bkg	19.4 ± 4.4
ttH	2.443 ± 0.073
Total prompt	21.9 ± 4.4
Data – Total prompt	44.1 ± 4.4

Table 6.12: Number of observed events and expected MC yields in the VR.

The obtained values of θ , extracted using simulated $t\bar{t}$, tW and Z +jets events, are:

- $\theta_\mu = 0.0099 \pm 0.0015$ (*stat*, 15%) ± 0.0030 (*syst*, 30%)
- $\theta_e = 0.0615 \pm 0.0087$ (*stat*, 14%) ± 0.0184 (*syst*, 30%)

The relative systematic uncertainties assigned are the same as in the estimate for the main analysis: 30% both for muons and electrons, respectively. As a result, the estimates for non-prompt lepton background are:

- $N_{non-prompt\ \mu} = 12.5 \pm 1.9\ (stat, 15\%) \pm 3.8\ (syst, 30\%) = 12.5 \pm 4.2\ (tot, 39\%)$
- $N_{non-prompt\ e} = 16.7 \pm 2.3\ (stat, 14\%) \pm 5.0\ (syst, 30\%) = 16.7 \pm 5.6\ (tot, 34\%)$

Thus, the total estimated number of non-prompt lepton events is:

$$29.2 \pm 3.0\ (stat, 10\%) \pm 6.3\ (syst, 22\%) = 29.2 \pm 7.0\ (tot, 24\%). \quad (6.10)$$

This estimate has to be compared with the background-subtracted data occurrence in the VR of $44.1 \pm 4.4\ (tot, 10\%)$. The two numbers are compatible within 1.8 standard deviations.

Chapter 7

Event kinematic reconstruction for ttV background suppression

7.1 Introduction

The final stage of this work consists of a full kinematic reconstruction of the events with the goal to suppress as more as possible $tt + \ell\ell$ background. This is found to be the dominant background both in Run-1 and Run-2 ATLAS ttH multilepton analysis, since the final signature is very similar to the ttH one, as shown in Fig.7.1.

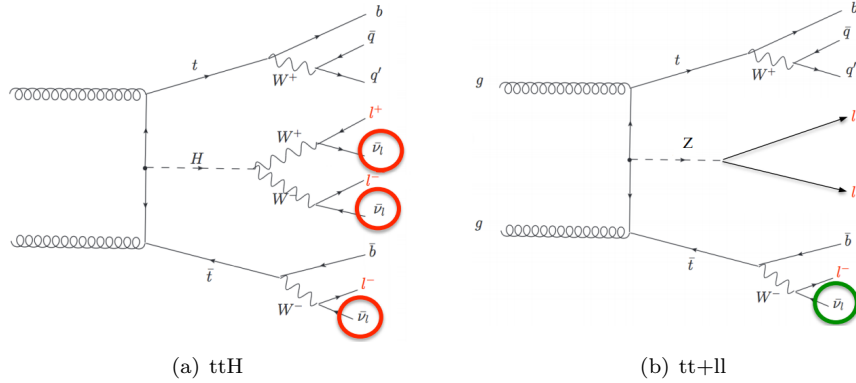


Figure 7.1: Feynman diagrams at Leading Order for the signal ttH (left) and the $tt + \ell\ell$ background (right). The picture shows also the number of prompt neutrinos in both processes. This feature of the event topologies will be used to attempt to separate $tt + \ell\ell$ background from ttH signal.

Most of the events (75% about) with one OS lepton pair, coming from on-shell Z boson, are already removed by the invariant mass veto around Z peak, $[81.2 \text{ GeV}, 101.2 \text{ GeV}]$. The residual background comes from off-shell γ photon and it is shown in Fig.7.3. A kinematic likelihood fit of the selected objects (leptons, jets and E_T^{miss}) is applied to the residual 25% of events in the Signal Region, in order to separate them into ttH -like and $tt + \ell\ell$ -like.

The idea that lays behind this study is clear looking at the tree-level Feynman diagrams of the ttH signal and $tt + \ell\ell$ background events: ttH events have three neutrinos in the final state, while $tt + \ell\ell$ events have only one neutrino, as shown in Fig. 7.1.

Since E_T^{miss} , as described in Sec.4.8, is the parameter indicating the presence of neutrinos in the final state, in an ideal case in which the experimental resolution on the E_T^{miss} was "infinite" and the contribution from other secondary neutrinos was negligible, in $tt + \ell\ell$ processes, at tree level, the E_T^{miss} would correspond to the neutrino's transverse momentum.

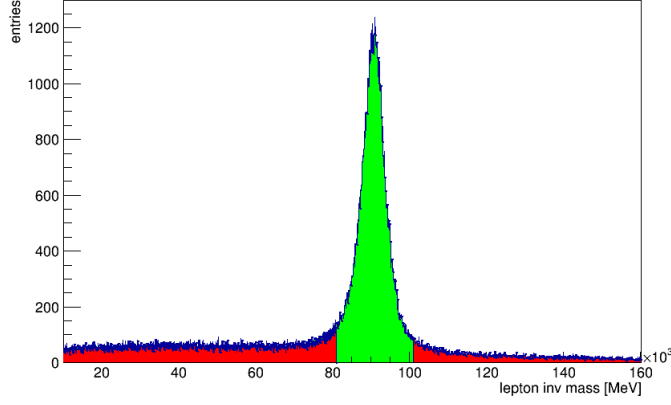


Figure 7.2: Invariant mass of two same-flavour opposite-sign leptons in an inclusive MC $tt + \ell\ell$ sample, shown only for illustrative purposes. This plot show the $tt + \ell\ell$ background composition. The green sector corresponds to the part of the background removed by the cut on the $m\ell\ell_{01}$ and $m\ell\ell_{02}$ invariant mass. The red one corresponds to the residual background ascribed to the non-resonant process.

This is not the case for the ttH events, where the E_T^{miss} is the composition of the transverse momenta of three neutrinos.

Moreover, the reconstruction of hadronically decaying top quark mass help to distinguish between ttH and ttW signatures, since in the latter both top quarks decay leptonically (assuming negligible the contribution from non-prompt leptons in the ttH events).

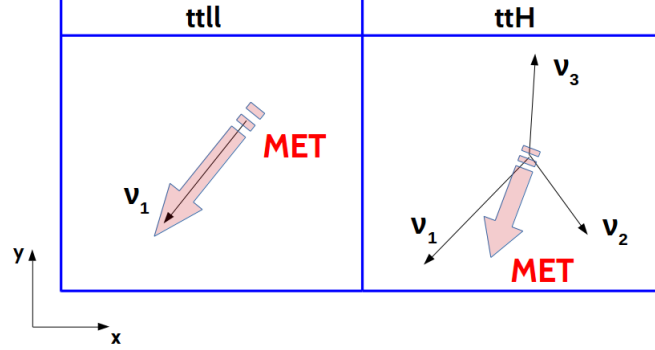


Figure 7.3: Sketch of how the missing transverse momentum is arranged, in an ideal case (tree level Feynman diagram, contribution from other neutrinos considered negligible and with infinite E_T^{miss} resolution), in $tt + \ell\ell$ and ttH processes with 3 leptons in the final state. MET corresponds to E_T^{miss} .

7.2 Potential of the method in simulation

As a starting point, the full potential of the above idea is explored looking at the physics process in MC simulation at the so-called "truth level": that is to say before folding in the effect of the detector resolution and biases of the kinematic properties of the elements involved in the final state. It's important to understand the extent of the difference of signal and background in terms of the total neutrino kinematics.

As expected, the 2D-distribution in Fig.7.4 shows clearly the presence of a strong correlation in $t\bar{t} + \ell\bar{\ell}$ events between the neutrino from Top quark (the unique prompt neutrino in event topologies such those shown in Fig.7.1) and the E_T^{miss} . The corresponding distribution for $t\bar{t}H$ events, in which the $t\bar{t}$ pair decays semi-leptonically ($t\bar{t}H$ semi-leptonic), is shown in Fig.7.5. In this case, the correlation is not present since the E_T^{miss} is arranged among three neutrinos.

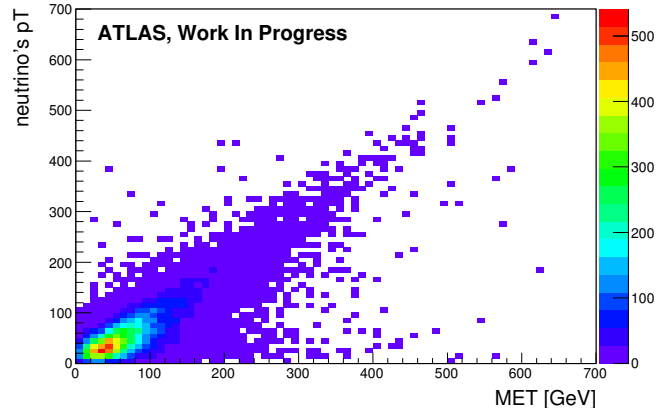


Figure 7.4: Correlation plot between the transverse momentum of the neutrino from Top quark and the E_T^{miss} in events $t\bar{t} + \ell\bar{\ell}$. Since the $t\bar{t} + \ell\bar{\ell}$ sample is inclusive in the $t\bar{t}$ pair decays, only events with only one neutrino from Top quark have been selected to produce this plot. MET corresponds to E_T^{miss} .

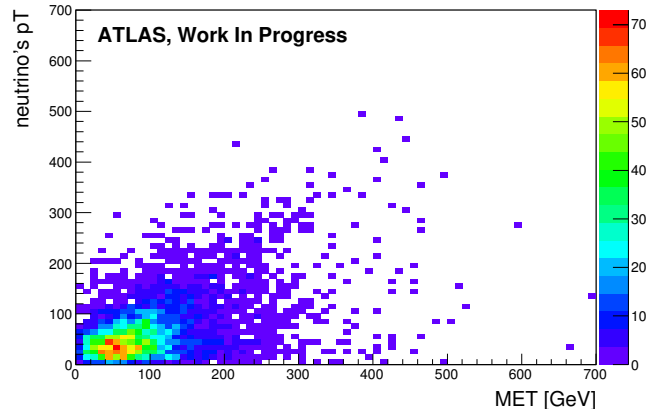


Figure 7.5: Correlation plot between the transverse momentum of the neutrino from Top quark and the E_T^{miss} in $t\bar{t}H$ with $t\bar{t}$ pair decaying semileptonically. MET corresponds to E_T^{miss} .

Fig.7.6 shows the three-momentum distribution of the two neutrino system from the Higgs boson decay, in $t\bar{t}H$ semileptonic events. The plot proves that the two neutrinos are emitted in such a way that their total momentum is different from zero. Conversely, if this happened, $t\bar{t}H$ topology would appear similar to the $t\bar{t} + \ell\bar{\ell}$ one.

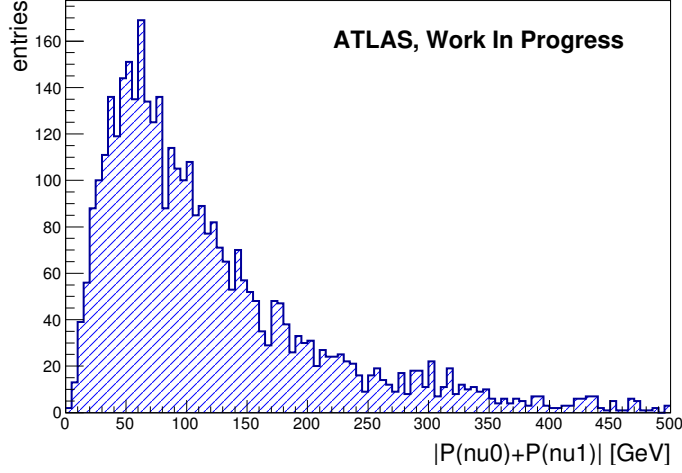


Figure 7.6: Magnitude of the vectorial sum of the three-momentum of the "prompt" neutrinos from the Higgs boson decay. The MC sample is the $t\bar{t}H$ with semileptonic top quark decays. Neutrinos are selected using truth-level selections.

A similar test has been performed, still in $t\bar{t}H$ semileptonic events, measuring the angular distance, ΔR , between the two neutrinos coming from the Higgs boson decay. The distribution shows that in the majority of the events the two neutrinos are emitted very close to each other. This means that neutrinos from the Higgs boson give a net contribution to the total E_T^{miss} .

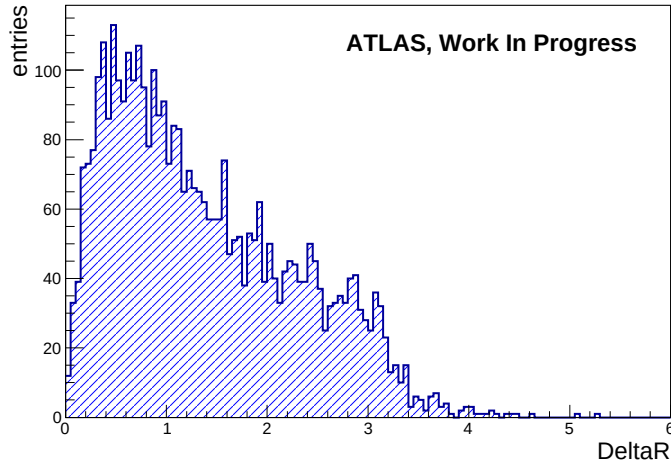


Figure 7.7: ΔR between the "prompt" neutrinos from the Higgs boson decay. The MC sample is the $t\bar{t}H$ with semileptonic top quark decays. Neutrinos are selected using truth-level selections.

The plots in Fig.7.8 and Fig.7.9, produced using the $t\bar{t} + \ell\bar{\ell}$ MC sample, demonstrate that in the E_T^{miss} the contribution from all the other secondary neutrinos is negligible. In both cases it is clear that the transverse momentum of the neutrino from top quark represents the largely dominant momentum component.

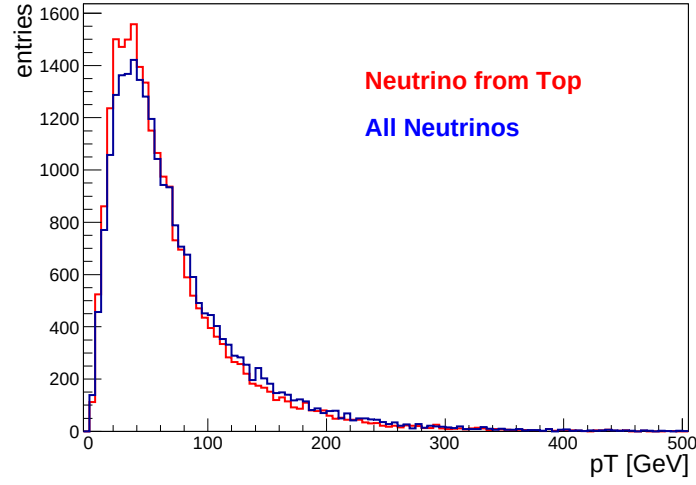


Figure 7.8: Comparison between the transverse momentum of the neutrino from Top quark and the composition of the transverse momentum of all neutrinos, including the neutrino from Top quark, in $tt + \ell\ell$ events.

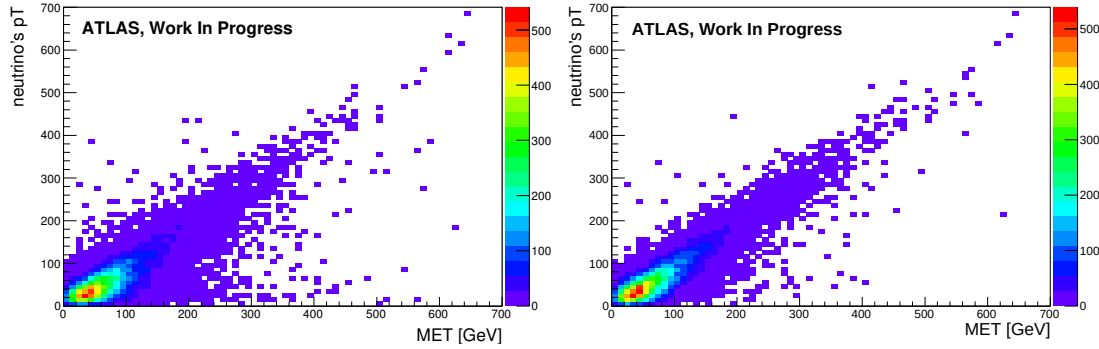


Figure 7.9: Correlation of the transverse momentum of the neutrino from Top quark and the E_T^{miss} (left) and the correlation of the transverse momentum composition of all neutrinos, including the neutrino from Top quark, and the E_T^{miss} (right). MET corresponds to E_T^{miss} .

Finally, Fig.7.10 shows the number of neutrinos coming from top quark decay in $tt + \ell\ell$ events. The plot takes into account only the neutrinos coming from the leptonic W decay, through the decay chain $t \rightarrow Wb \rightarrow \ell^\pm \nu b$. As expected, in the 3ℓ SR, most of the events contain only one neutrino from top quark. This reflects the LO $tt + \ell\ell$ diagram shown in Fig.7.1. About 30% of the events, however, contain two neutrinos from top quark decay. These are events in which both top quarks decay leptonically, providing 4 leptons in the final state. If one lepton is lost because of kinematic selections on the reconstructed object, the event falls anyway within the 3ℓ SR. In such $tt + \ell\ell$ events, the idea to approximate the neutrino's momentum with the E_T^{miss} is no longer valid.

The distributions shown in Fig.7.4, Fig.7.9 and Fig.7.8 have been realized using a $tt + \ell\ell$ MC sample, requiring only one neutrino from the $t\bar{t}$ pair.

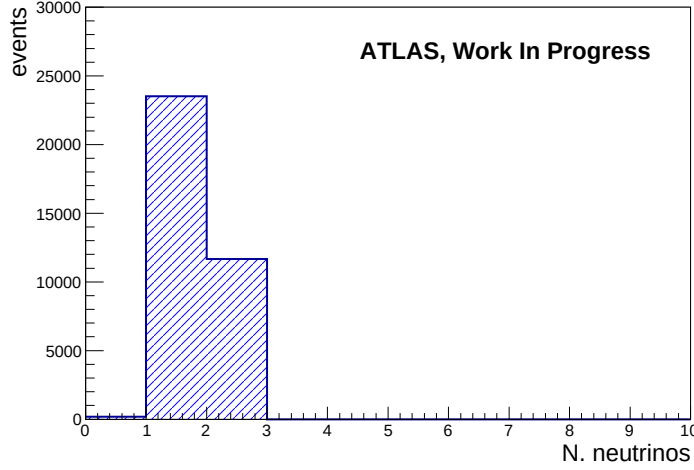


Figure 7.10: Number of neutrinos from top quark decay in $t\bar{t} + \ell\ell$ sample.

7.3 KLFitter

The Kinematic Likelihood Fitter (KLFitter) is a general tool for kinematic fits[59]. KLFitter is used as reconstruction method for top quark mass[60] and asymmetry[61] measurements. In this work, it has been employed to implement the full event kinematic reconstruction described in the previous paragraphs.

KLFitter makes use of a maximum likelihood approach and provides a discriminating variable, the likelihood itself, allowing to deplete the $t\bar{t}H$ 3ℓ SR from its most abundant background, $t\bar{t} + \ell\ell$. The likelihood function is maximised with respect to a set of parameters and constraints, described later in the text.

The kinematic fit is performed for a given event topology. The topology fitted in this study is the $t\bar{t}$ in lepton+jets final state, shown in Fig.7.11. I choose to adopt the $t\bar{t}$ likelihood model since the $t\bar{t} + \ell\ell$ topology would not add any kinematic constraints. In fact, events with two opposite-sign and same-flavour leptons are vetoed if they originate from a Z boson or they derive from the off-shell γ^* .

Jets are assigned to the final state partons of the $t\bar{t}$ semileptonic decay. This final state results in four quarks, one high- p_T lepton and missing transverse energy, corresponding to the neutrino transverse momentum. In the adopted model, 4 partons, 2 b-quarks from top quark decays and 2 light-quarks from hadronic W decays are needed to perform the fit.

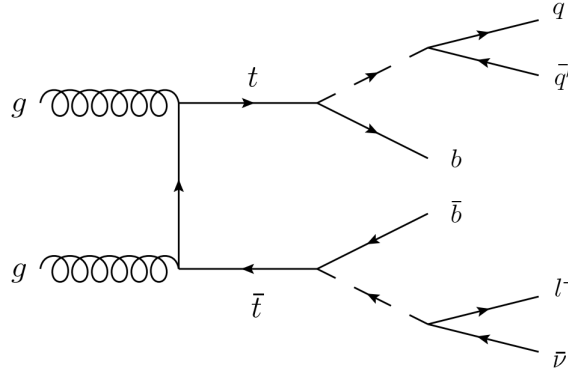


Figure 7.11: Feynman diagram at LO for the $t\bar{t} l + \text{jets}$ process.

Since the minimum number of partons required for the full event reconstruction is four, events

with exactly three jets will be not processed by KLFitter. Moreover, only events flavour-compatible with $t\bar{t} + \ell\ell$ signature are processed: events in which the ℓ_0 , defined in Section 5.5.4, has different flavour with respect to both ℓ_1 and to ℓ_2 are kept out from the kinematic reconstruction.

Since ℓ_0 is not expected to be the lepton from leptonically decaying top quark, the choice of the right lepton to be assigned to KLFitter is between ℓ_1 and ℓ_2 . The assignment for the right lepton is subject to the following reasoning:

- if ℓ_0 and ℓ_1 are SF while ℓ_0 and ℓ_2 are OF, ℓ_2 will be assigned to the leptonically decaying top quark;
- if ℓ_0 and ℓ_1 are OF while ℓ_0 and ℓ_2 are SF, ℓ_1 will be assigned to the leptonically decaying top quark;
- in events in which all three leptons have the same flavour, the ambiguity ℓ_1 or ℓ_2 cannot be resolved. In this case, both SS leptons are given as input to KLFitter, that will select the permutation with the maximum likelihood.

The parameters used in the fit are the energies of jets and the energy of the charged lepton, which are allowed to be varied in the fit within "n-times" their resolution width. The ranges in which the fit parameters can be varied will be described later. The angular variables of each reconstructed object, η and φ , are assumed to be measured with a negligible uncertainty. Constraints on the fit parameters are given by Breit-Wigner distributions around the invariant mass of the decaying W bosons and Top quarks.

In an ideal case, if no jet is lost (e.g. jets outside the acceptance detector region or jets removed by the minimum selection criteria) and if no additional jets from Initial State Radiation (ISR) or from Final State Radiation (FSR) are present, exactly 4 jets are expected to be observed from the $t\bar{t}$ semi-leptonic signature. In this case, and if the choice of lepton assignment is unique, there are 24 possible jet permutations for which jets can be associated with quarks from the final state.

Then, in general, if the total number of jets in the event is "n", the number of possible permutations is given by the formula in Eq.7.1:

$$P_{n,k} = \frac{n!}{(n-k)!}. \quad (7.1)$$

$P_{n,k}$ corresponds the number of arrangements of a k-element subset of an n-set. k is always equal to 4, corresponding to the number of partons in the final state to which to assign the jets. Since the two quarks from the decay of one of the W boson are indistinguishable ($W_{j_1,j_2} = W_{j_2,j_1}$), the number of permutations is reduced by half.

For technical issues related to available computing resources, events with a number of jets equal or greater than 8, in which the number of permutations is too large, will be not given as input to KLFitter. Finally, if both ℓ_1 and ℓ_2 are assigned to KLFitter, the number of permutations is larger by a factor 2.

Table7.1 shows the number of permutations according to the jet and lepton multiplicity. All but the correct permutation are referred to as "combinatorial background". This definition also includes permutations in which not all jets come from one of the four final state quarks, but from ISR or FSR. In section 7.3.2 different ways to use the b-tagging information will be described. These criteria will reduce the number of permutations, depending on the choice.

As anticipated previously, KLFitter makes use of a maximum likelihood approach: this means that among all the possible assignments of jets and leptons and among all sets of parameters, varied in the fit procedure, the chosen configuration per each event is the one with the largest value of the likelihood function.

Since neutrinos do not interact with the detector, their momentum cannot be measured directly. However, in processes with only one neutrino from the primary vertex, like $t\bar{t} + \ell\ell$ with 3 leptons in the final state, the neutrino transverse momentum can be estimated from the E_T^{miss} in the event. The x and y components of the neutrino momentum are identified with the transverse components of the E_T^{miss} , as shown in Eq.7.2.

Number of jets	Number of leptons	Number of permutations
4	1	12
5	1	60
6	1	180
7	1	420
8	1	840
4	2	24
5	2	120
6	2	360
7	2	840
8	2	1680

Table 7.1: Number of permutations for events with different jet and lepton multiplicity.

$$\begin{aligned} E_X^{miss} &= E_T^{miss} \cdot \cos(\varphi_{MET}) \\ E_Y^{miss} &= E_T^{miss} \cdot \sin(\varphi_{MET}) \end{aligned} \quad (7.2)$$

Finally, the z-direction of the neutrino momentum, p_ν^z , is calculated using a constraint on the W-boson mass, exploiting the equation 7.3:

$$m_W^2 = (p_\nu + p_\ell)^2 \quad (7.3)$$

where p_ν and p_ℓ are the four-momenta of the neutrino and of the charged lepton, respectively. If two solutions exist, the one which gives the maximum likelihood is chosen. If no solution exists, the longitudinal momentum is set to 0 GeV. In this last case, the p_ν^z is considered as an additional free parameter in the fit.

7.3.1 Likelihood function

The likelihood function used in the KLFFitter tool is composed of two parts: the transfer functions (TFs) and the kinematic constraints, as shown in Eq. 7.4:

$$\mathcal{L} = \mathcal{L}_{TF} \times \mathcal{L}_{Constraints}. \quad (7.4)$$

Each single term can be factorized into the product of several likelihood terms, describing the kinematics of the $t\bar{t}$ signature and containing constraints from the masses of the two W bosons and the two top quarks, as described in Eq. 7.5. The TFs are the part of the likelihood that takes into account the experimental resolutions on the measured object properties. They represent the likelihood to measure a certain value of an observable, given the true value of the associated model parameter. The kinematic constraints are given by the invariant masses of the decaying W bosons and Top quarks. With these assumptions the likelihood function takes the form:

$$\begin{aligned} \mathcal{L} = & W(\tilde{E}_{jet1}|E_{had}) \cdot W(\tilde{E}_{jet2}|E_{lep}) \cdot W(\tilde{E}_{jet3}|E_{q1}) \cdot W(\tilde{E}_{jet4}|E_{q2}) \cdot \\ & W(\tilde{E}_x^{miss}|p_{x,\nu}) \cdot W(\tilde{E}_y^{miss}|p_{y,\nu}) \cdot W(\tilde{E}_\ell|E_\ell) \cdot BW\{m(q_1q_2)|m_W, \Gamma_W\} \cdot \\ & BW\{m(l\nu)|m_W, \Gamma_W\} \cdot BW\{m(q_1q_2b_{had})|m_{top}, \Gamma_{top}\} \cdot BW\{m(l\nu b_{lep})|m_{top}, \Gamma_{top}\} \end{aligned} \quad (7.5)$$

The TFs, consisting in the first seven terms of the Eq. 7.5, are detailed in Section 7.3.3. The second term of the Eq. 7.4 corresponds to the last four terms of the Eq. 7.5. The mass terms of the hadronically and leptonically decaying W boson, m_{jj} and $m_{e\nu}$, respectively, follow a Breit-Wigner (BW) distribution, shown in Eq. 7.6, around a pole mass of $M_W = 80.4 \text{ GeV}/c^2$. The mass likelihood terms of the two top quarks, m_{jjj} and $m_{e\nu j}$, are distributed according to a Breit-Wigner distribution around the top pole mass. This has been fixed to the value of $M_t = 172.5 \text{ GeV}/c^2$. The widths of the Top quark and W resonances are shown in Table 7.2.

$$BW = \frac{1}{(M_x^2 - M_0^2) + M_0^2 \Gamma^2} \quad (7.6)$$

with M_0 being the pole mass of the resonance, Γ its width and M_x is the mass of the resonance reconstructed by KLFitter. The permutation with the largest value of the global likelihood $\mathcal{L}$ is used in the following steps of the analysis.

	m [GeV]	Γ [GeV]
top	172.5	1.5
W	80.4	2.1

Table 7.2: Pole mass and width parameters used in the BW likelihood terms for the Top and W resonances.

7.3.2 b-tagging

b-tagging, described in Sec.4.6.1, can be used to improve the reconstruction efficiency and performances of KLFitter. In particular, it helps to reduce the combinatorial background, given the high jet multiplicity in $t\bar{t} + \ell\ell$ and $t\bar{t}H$ final states. Different options are available in the KLFitter package to use b-tagging informations. Three options have been considered in this study. They are listed below:

- permutations with a light jet associated to a bottom quark of the $t\bar{t}$ 1+jets likelihood topology are removed before the fitting procedure (*kVetoNoFitLight*);
- permutations with a light jet associated to a bottom quark or with a b-tagged jet associated to a light quark are removed before the fitting procedure (*kVetoNoFitBoth*);
- permutations are weighted according to the b-tagging information, where the weights are extracted from the efficiency and mis-tag rate distributions of the b-tagger variable (*kWorkingPoint*). Using this option, light jets and b-tagged jets can be associated both to light and bottom quarks of the $t\bar{t}$ 1+jets likelihood topology.

Since the $t\bar{t}$ 1+jets likelihood model contains 2 light quarks and 2 bottom quarks, for the *kVetoNoFitLight* option, events having only 1 b-tagged jet will not enter the kinematic reconstruction. Similarly, for the *kVetoNoFitBoth* option, events having only 1 light jet or with only 1 b-tagged jet will not take part to the reconstruction algorithm.

These two configurations, especially *kVetoNoFitBoth*, enhance the probability to pick the correct jet permutation, requiring the jet flavour composition closest to the real model. On the other hand, this introduces an inefficiency in the algorithm. Considering that events with exactly 3 jets or more than 8 jets are also discarded from the kinematic reconstruction, a global inefficiency with respect to all the candidate events is found to be $(60 \pm 1)\%$ about in both $t\bar{t} + \ell\ell$ and $t\bar{t}H$ samples for both *kVetoNoFitLight* and *kVetoNoFitBoth* configurations.

In the *kVetoNoFitBoth* working point, the algorithm inefficiency comes mainly from events with less than 2 b-tagged jets, $(83 \pm 1)\%$ and $(77 \pm 1)\%$ in the $t\bar{t} + \ell\ell$ and $t\bar{t}H$ samples, respectively. The lack of at least 2 b-tagged jets in these events is due to two main reasons: the b-tagging efficiency of the MV2 tagger (having an absolute efficiency of 70%), and the kinematical selections applied to the reconstructed jets, such as $p_T > 25 \text{ GeV}$.

The *kWorkingPoint* configuration benefits from a higher efficiency, since both light and b-tagged jets can be used in place of light and bottom partons. The only inefficiency comes from the discarded events with exactly 3 or more than 8 jets. Its inefficiency has been evaluated to be about $(12.0 \pm 0.2)\%$ for $t\bar{t} + \ell\ell$ and $t\bar{t}H$ samples.

The *kVetoNoFitBoth* option is chosen as the baseline for this study, because it provides only the permutations with a flavour jet configuration compatible with the $t\bar{t}$ 1+jets model. A comparison among the results, obtained using all the three configurations, will be shown later in Section 7.4.

It should be noted that when b-tagging information is exploited in KLFitter, the number of permutations is reduced with respect to what has been shown in Table 7.1, since only b-jets can be assigned to b-partons in kVetoNoFitBoth and kVetoNoFitLight working points and only light-jets can be assigned to light-partons if the kVetoNoFitBoth option is used.

7.3.3 Transfer functions

Detector resolutions for the energy measurements are described in terms of transfer functions, $W(\tilde{E}_i|E_i)$, that map the measured energies $\tilde{E}_i$ of the reconstructed objects to the true energies of the final state particles E_i . The transfer functions are derived for electrons, muons, light (u, d, s, c) jets, b-tagged jets and E_T^{miss} , using a simulated $t\bar{t}$ MC sample, in which the association of the reconstructed objects to the underlying partons is done by a matching in $\Delta R = 0.3$ between the parton and the reconstructed object.

TFs are parametrised in terms of energy or p_T (only for muons) and in several η and φ regions of the detector to reflect better its performances, which are not uniform in the whole ATLAS apparatus. This has been done separately for light-quark jets, b-quark jets, electrons and muons using a double Gaussian resolution function and for E_T^{miss} using a single Gaussian resolution function. An example of parametrization with a double Gaussian function is shown in Eq.7.7.

$$p(E_{meas}|E_{true}) = \frac{1}{\sqrt{2\pi}(p_2 + p_3 p_5)} \cdot \left(e^{-\frac{(x-p_1)^2}{2p_2^2}} + p_3 \cdot e^{-\frac{(x-p_4)^2}{2p_5^2}} \right) \quad (7.7)$$

where $x = (E_{true} - E_{meas})/E_{true}$ and $[p_1, p_2, p_3, p_4, p_5]$ are parameters depending on the true energy. As an example, the TF for the b-quark energy is shown in Fig.7.12.

The transfer functions for E_X^{miss} and E_Y^{miss} are described by a Gauss function with mean value $\mu = 0$ GeV and width given by the sigmoid curve, function of $\sum E_T$, shown in Eq.7.8. The values of the four parameters are shown in Fig.7.13.

$$\sigma(x) = p_0 + \frac{p_1}{1 + e^{-p_2 \cdot (x - p_3)}} \quad (7.8)$$

Transfer functions used in this study are extracted from ATLAS Run-1 data at a center-of-mass energy of 8 TeV. Anyway, the impact of the new transfer functions on KLFitter performances is considered to be negligible, since no significant improvements have been performed on the ATLAS sub-detectors when passing from Run-1 ($\sqrt{s} = 8$ TeV) to Run-2 ($\sqrt{s} = 13$ TeV). The only new sub-detector in Run-2 is the IBL, already described in Chapter 3, which improve the b-tagging performances, but doesn't affect the jet energy resolution, measured at the calorimeter level. Preliminary ATLAS results, not yet published, on the resolution of the jet energy measurement, based on data collected at 13 TeV, look compatible with the Run-1 ones for different event topologies used in the final states (such as Z+jets and γ +jets).

7.3.4 Fit parameters

Taking into account the transfer functions of the measured objects and the kinematical constraints for W boson and Top quark decay vertices, 8 parameters are used in the fitting procedure. These are:

- energies of the four quarks E_{jet}^i (4 parameters);
- energy of the charged lepton E_ℓ , e or μ (1 parameter);
- momentum components of the neutrino, p_x^ν p_y^ν p_z^ν (3 parameters).

Each parameter is allowed to be varied in the kinematic fit within a certain range. The ranges of the jet energies, lepton energy and the neutrino momentum components are set individually around the measured values:

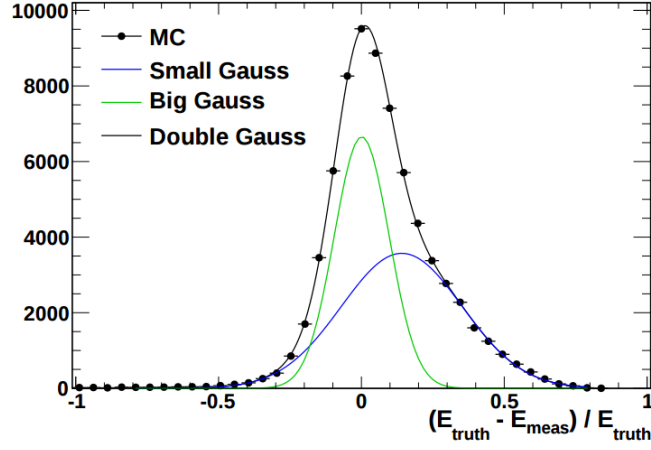


Figure 7.12: Transfer function for the b-quark energy for $0.0 < |\eta| < 0.8$. The green and the blue line show the composition of the full double-Gaussian from two individual Gaussians.[62]

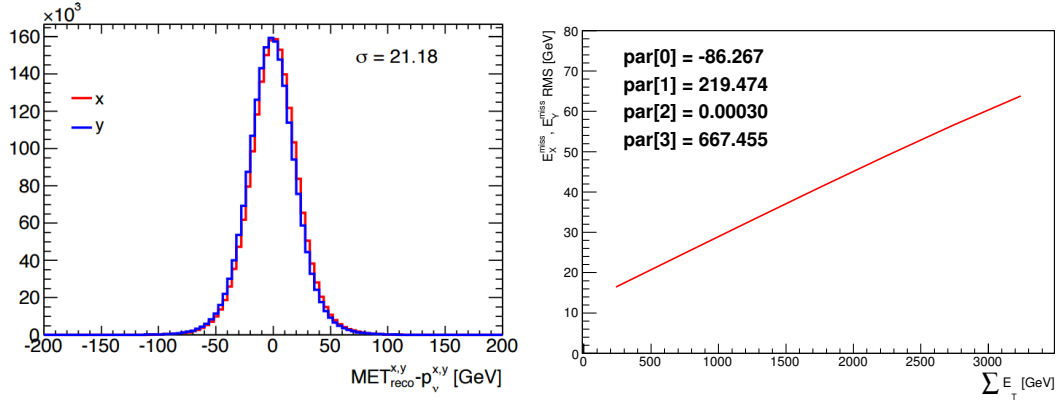


Figure 7.13: Transfer function for E_X^{miss} and E_Y^{miss} for a standard deviation on E_T^{miss} $\sigma = 21.18 \text{ GeV}$ (left) and σ dependence on $\sum E_T$ (right). MET corresponds to E_T^{miss} .

- $E_{jet}^i \in [\tilde{E}_{jet}^i - 3 \cdot \sigma, \tilde{E}_{jet}^i + 3 \cdot \sigma]$
- $E_\ell \in [\tilde{E}_\ell - 3 \cdot \sigma, \tilde{E}_\ell + 3 \cdot \sigma]$
- $p_{x,y}^\nu \in [\tilde{E}_T^{miss} - 3 \cdot \sigma, \tilde{E}_T^{miss} + 3 \cdot \sigma]$
- $p_z^\nu \in [-1000.0, 1000.0]$

where σ is the standard deviations of the measured value.

In order to take advantage from KLFitter for the $ttH/tt + \ell\ell$ discrimination, different ranges for the parameter variations have been tested: $\pm 1\sigma$, $\pm 3\sigma$ and $\pm 5\sigma$. The 3σ interval is taken as baseline.

7.4 Results

In this section the results obtained using KLFitter tool are shown. The configuration used for the b-tagging is kVetoNoFitBoth. For a clearer and simpler illustration, only ttH, $tt + \ell\ell$ and ttW processes are displayed in the following plots.

The distributions of the single likelihood terms taking into account the experimental resolutions on the reconstructed objects are shown in Fig.7.14.

In Fig.7.15 the Likelihood terms for the hadronically decaying (top) and leptonic (bottom) W boson and top quark mass constraints are shown. These four distributions show a peak in correspondence of the values $\ln(BW_W) = -10$ and $\ln(BW_{Top}) = -11$ about for W and top, respectively. These values correspond to the cases in which the fitted W and top quark masses are very close to the nominal values, 80.4 GeV and 172.5 GeV, respectively, shown in Table7.2. The ttH signal distribution has been split according to the decay of the top quark pair (semileptonic decay or dileptonic decay), in order to appreciate the different profiles for the hadronic likelihood terms. It should be noted that, in each likelihood distribution plot, the value of the likelihood corresponds to the maximum over all the possible permutations of jets and leptons and over all sets of fit parameters (see Section 7.3).

It is expected that the masses of the hadronically decaying W bosons and top quarks are reconstructed less accurately in ttW and ttH dileptonic sample than in $tt + \ell\ell$ and ttH dileptonic ones, since no hadronic top quarks are present in the final states of the former samples. However, 50% of ttW and ttH dileptonic events lies under the peak of the likelihood distribution. In these events jets from ISR or FSR have been used for the hadronic W boson and top quark mass reconstruction and their energy is changed within the experimental resolutions during the fit. This is shown in plots (A) and (B) of Fig.7.15.

Concerning the leptonic decaying W and top quark, no difference in the profile of the distributions is evident in the (C) and (D) likelihood terms.

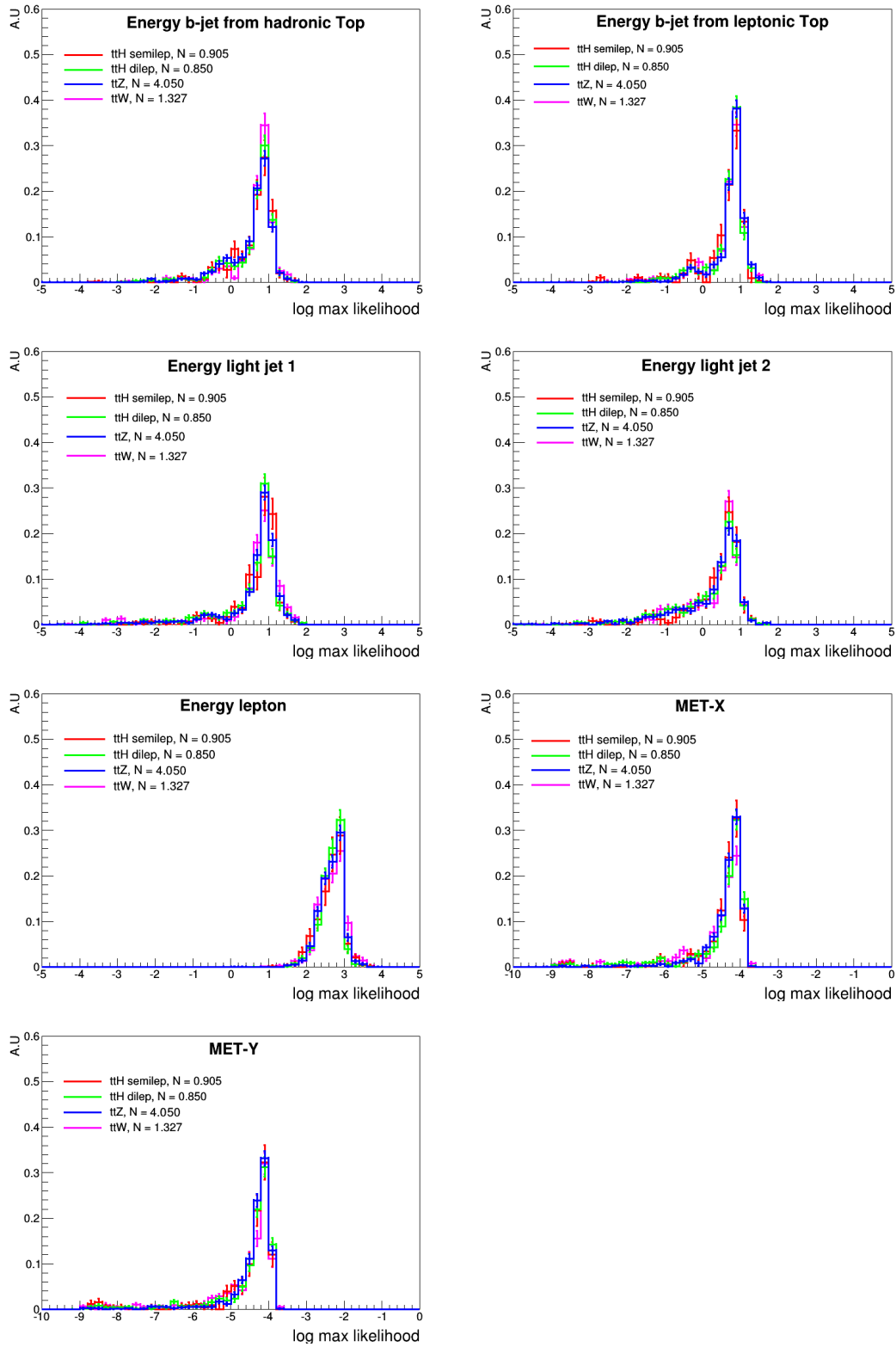


Figure 7.14: Likelihood terms for jet energies, lepton energy and E_T^{miss} resolutions in ttH , ttW and $tt + \ell\ell$ samples. Distributions are normalized to unity. The ttH signal is split according to the $t\bar{t}$ pair decay in ttH semileptonic and ttH dileptonic. The uncertainty on such distributions is only statistical. The legend shows the expected MC yields for the different processes.

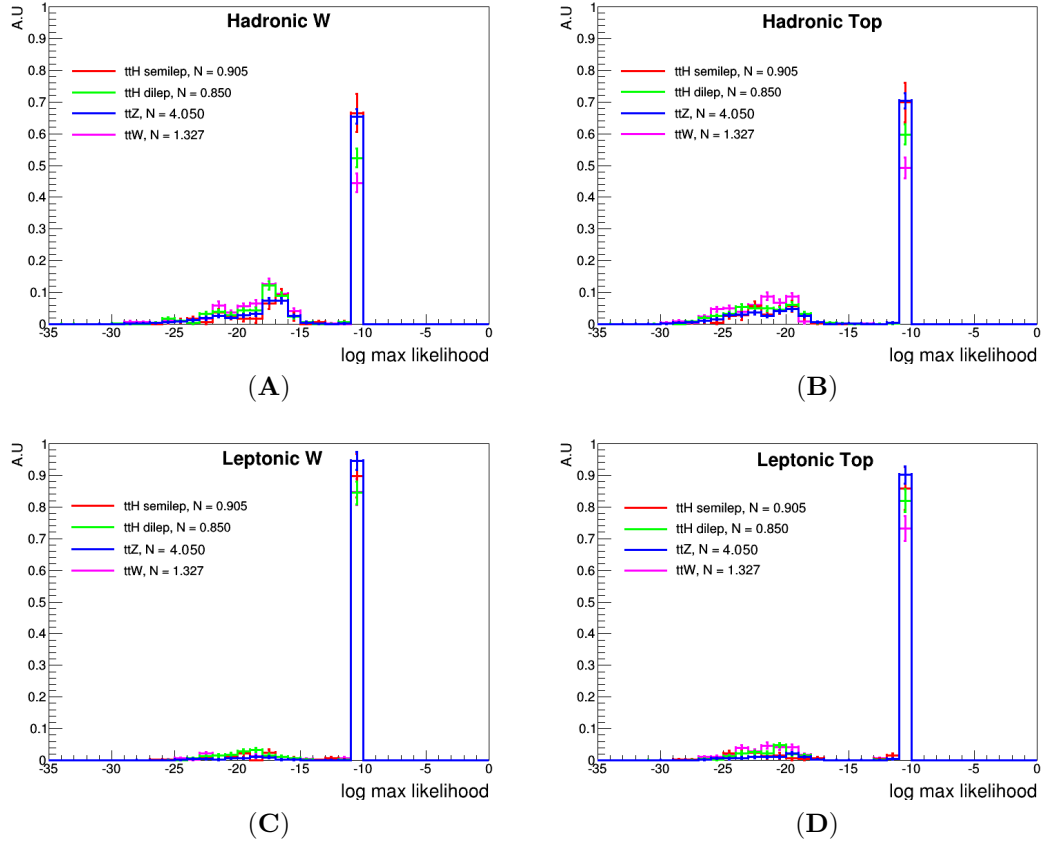


Figure 7.15: Distributions of the four likelihood terms for the W boson and top quark mass constraints in ttH , ttW and $tt + \ell\ell$ samples. Distributions are normalized to unity. The ttH signal is split according to the $t\bar{t}$ pair decay in ttH semileptonic and ttH dileptonic. The uncertainty on such distributions is only statistical. The legend shows the expected MC yields for the different processes.

In Fig.7.16 the distribution of the logarithm of the likelihood, containing only the transfer functions for the resolution terms of the jets, leptons and E_T^{miss} , is shown. This corresponds to the sum of the logarithms of the single likelihood terms, shown in Fig.7.14. It is clear from the profile of such distribution that this part of the likelihood does not offer any separation power to discriminate among the different processes.

In Fig.7.17 the distribution of the logarithm of the likelihood containing only the Breit-Wigner terms for the W bosons and top quarks is shown. This corresponds to the sum of the single likelihood terms, containing the real kinematic constraints, shown in Fig.7.15.

The distribution of the logarithm of the total Likelihood $\mathcal{L}$ is shown in Fig.7.18. In this plot, the contribution from other background processes have been added. It includes: $t\bar{t}$, VV , tW , Z +jets, tZ and other background with minor contribution. For this study, the normalization of the background from non-prompt leptons, corresponding to $t\bar{t}$, tW and Z +jets, is taken from MC simulations, since the goal is only the comparison among the profiles of the distributions.

The distribution of the total Likelihood shows a peak at -45, approximately, corresponding to the cumulative sum of the values of the four peaks for the distributions shown in Fig.7.17. Then, events falling within the peak of such distribution are those in which the W boson and top quark masses are reconstructed close to their nominal values.

The significance, defined as $S/\sqrt{B}$ has been chosen as a good figure of merit in order to evaluate the optimal value of the likelihood that enhances the discrimination between signal and

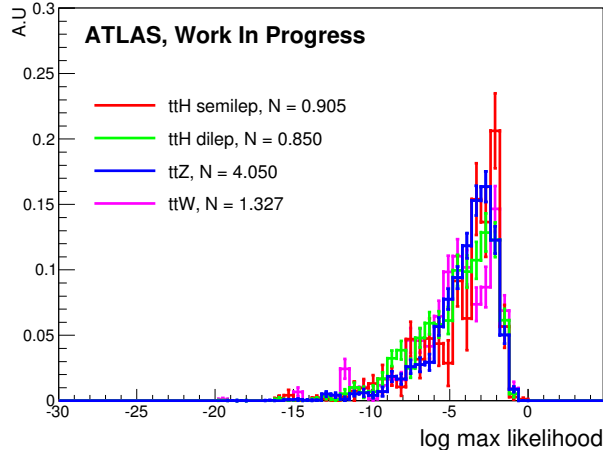


Figure 7.16: Distribution of the logarithm of the likelihood containing only the resolution terms. Distributions are normalized to unity. The $t\bar{t}H$ signal is split according to the $t\bar{t}$ pair decay in $t\bar{t}H$ semileptonic and $t\bar{t}H$ dileptonic. The uncertainty on such distributions is only statistical. The legend shows the expected MC yields for the different processes.

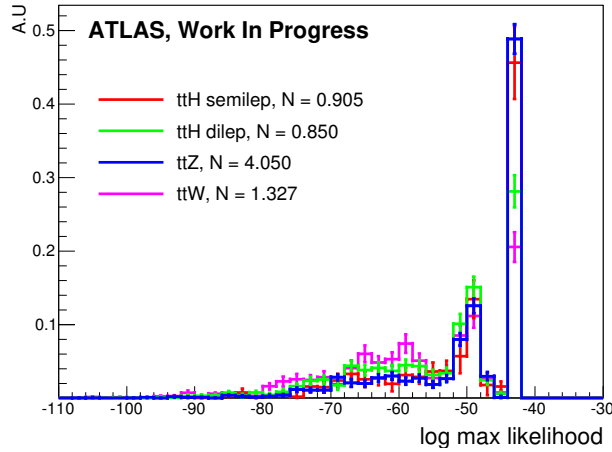


Figure 7.17: Distribution of the logarithm of the likelihood containing only the Breit-Wigner terms. Distributions are normalized to unity. The $t\bar{t}H$ signal is split according to the $t\bar{t}$ pair decay in $t\bar{t}H$ semileptonic and $t\bar{t}H$ dileptonic. The uncertainty on such distributions is only statistical. The legend shows the expected MC yields for the different processes.

background. To account for systematic uncertainty on the background yield, the background "b" is replaced with "b+ Δ b".

Two main features can be observed in the plot shown in Fig.7.18.

Firstly, no differences in the profile of the distributions are found the $t\bar{t}H$ semileptonic signal and $t\bar{t} + \ell\ell$ background. Events in both samples contain one hadronic-top and one leptonic-top in the final state and the masses of the W bosons and top quarks are reconstructed with the same quality.

It is worth to understand the origin of this peculiarity. It has been verified and shown in Section 7.2 that the contribution from secondary neutrinos in the E_T^{miss} is negligible. Since the only difference between the $t\bar{t} + \ell\ell$ and $t\bar{t}H$ semileptonic Feynman diagrams is the number of prompt neutrinos, one additional test has been performed to check if a larger separation between the two samples is obtained replacing the E_T^{miss} ("reco case") with the actual kinematic

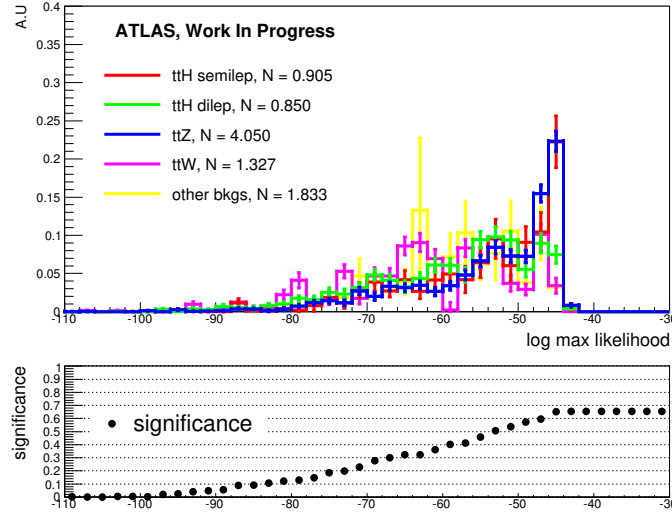


Figure 7.18: Distribution of the logarithm of the total Likelihood. The $t\bar{t}H$ signal is split according to the $t\bar{t}$ pair decay in $t\bar{t}H$ semileptonic and $t\bar{t}H$ dileptonic. The uncertainty on such distributions is only statistical. The legend shows the expected MC yields for the different processes. Distributions are normalized to unity. The bottom plot shows the statistical significance, $S/\sqrt{B}$, chosen as figure of merit: S corresponds to the integral, from left to right, of the expected $t\bar{t}H$ signal yield, while B represents the integral, from left to right, of the total expected background.

properties of the prompt neutrinos ("truth case").

The following neutrino configurations are used for the different samples:

- 1 ν from top quark for $t\bar{t}+\ell\ell$ sample;
- 1 ν from top quark + 2 ν s from Higgs boson for $t\bar{t}H$ semileptonic sample;
- 2 ν s from top quark + 1 ν from Higgs boson for $t\bar{t}H$ dileptonic sample;
- 2 ν s from top quark + 1 ν s from W boson for $t\bar{t}W$ sample;

The results is shown in Fig.7.19. The plots show the comparison between the likelihood distribution, containing only the Breit-Wigner terms, for the truth and reco cases. A larger separation between $t\bar{t}+\ell\ell$ and $t\bar{t}H$ is visible when the neutrinos transverse momenta are used in place of E_T^{miss} .

This is an indication that the experimental resolution on E_T^{miss} plays an important role in the separation power of this method. The fraction of $t\bar{t}H$ semileptonic events under the peak of the likelihood distribution goes from 45% in the reco case to 20% in the truth one. It can be noticed, however, that a fraction of $t\bar{t}H$ semileptonic still remains under the peak, corresponding to a correctly reconstructed semi-leptonic top quark decay. The absence of correlation between the momentum of the neutrino from top quark and the E_T^{miss} has been already verified (see Fig.7.5). These events are the result of the adjustment of the kinematic parameters that push the likelihood towards the peak.

Secondly, the $t\bar{t}H$ dileptonic and $t\bar{t}W$ profiles are different with respect to the $t\bar{t}H$ semileptonic and $t\bar{t}+\ell\ell$ ones. For $t\bar{t}H$ dileptonic and $t\bar{t}W$, infact, KLFFitter tries to reconstruct the mass of the W boson and top quark decaying hadronically, but there are no any hadronic top quarks in the final states of these processes. The algorithm uses the light jets coming from the parton shower to reconstruct the masses and this results in a low quality reconstruction of the W boson and top quark masses.

As anticipated in Section 7.2, the $t\bar{t}+\ell\ell$ sample contains about 30% of events with the $t\bar{t}$ pair decaying leptonically. This means that two neutrinos are present in the final state in these

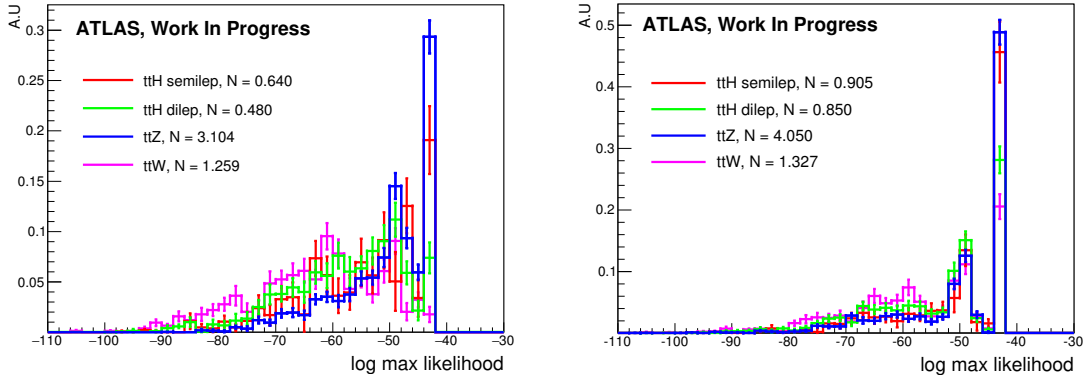


Figure 7.19: Comparison between the distributions of the logarithm of the likelihood containing only the Breit-Wigner terms for the truth (left) and reco (right) cases. Distributions are normalized to unity.

events. The plot in Fig.7.20 show the comparison of the maximum likelihood distribution for the two event topologies in the $t\bar{t} + \ell\bar{\ell}$ sample. The difference between the two distributions derives from the absence of hadronically decaying top quarks in the final state in the events with 2 prompt neutrinos.

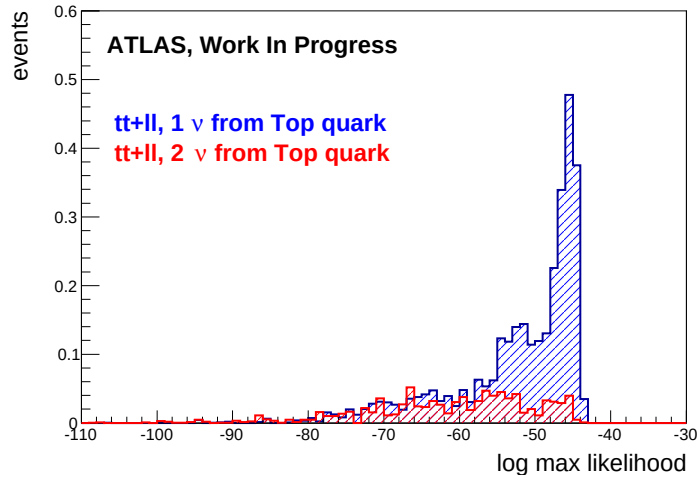


Figure 7.20: Distribution of the logarithm of the total Likelihood for $t\bar{t} + \ell\bar{\ell}$ events. The plot show the comparison between events with 1 neutrino from top quark and events in which the $t\bar{t}$ pair decay leptonically.

Two additional tests have been performed in order to study the KLFitter fit response.

A first test consists on the comparison between the likelihood distributions exploiting three different ranges of variation of the kinematical parameters. The results are shown in Fig.7.21. The parameters are allowed to vary within 1, 3 and 5 standard deviations. It is clear that larger ranges of variation for the kinematic parameters allow KLFitter to reconstruct W boson and top quark masses closest to their nominal values. This is demonstrated by the migration of events towards the peak of the likelihood distribution when the variation ranges are raised from 1 to 5 standard deviations. For this comparison the `kVetoNoFitBoth` configuration has been used for the b-tagging.

Now, a second test consists in fixing the parameter variation range to 3σ and changing only the b-tagging configurations, in order to test if `kVetoNoFitLight` and `kWorkingPoint` options

allow a larger separation between $t\bar{t}H$ semileptonic and $t\bar{t} + \ell\bar{\ell}$ distributions. A migration of events towards the peak of the likelihood distribution is visible when the `kWorkingPoint` configuration is used. In this case, in fact, any jets can be associated to both light and bottom partons, enhancing the probability to reconstruct W boson and top quark masses closest to their real values. The results are shown in Fig.7.22.

No evident differences in the profile of the distributions are visible. The conclusion of the previous tests is that changing the variation ranges of the kinematic parameters and the b-tagging option do not help in the discrimination between signal and background.

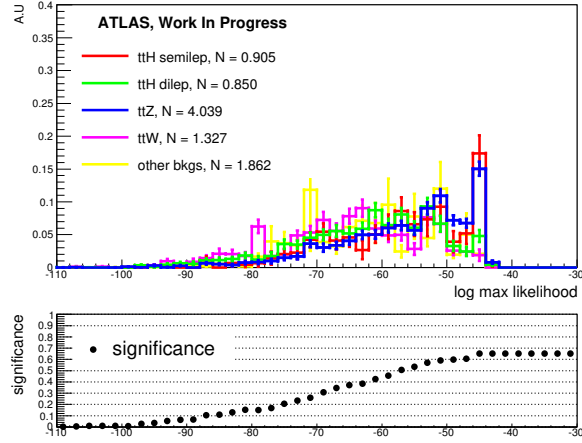
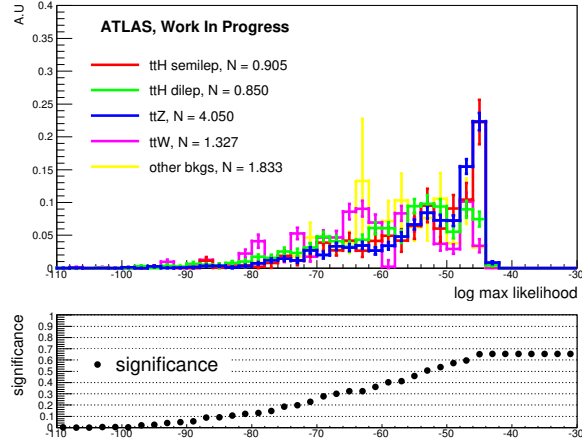
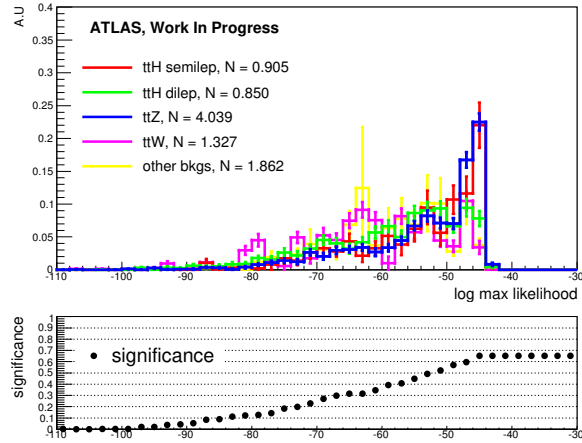
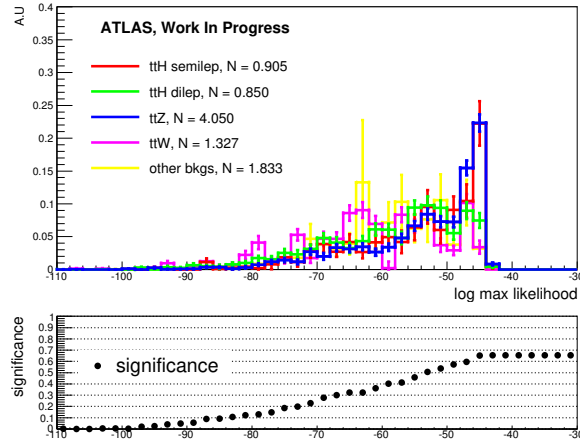
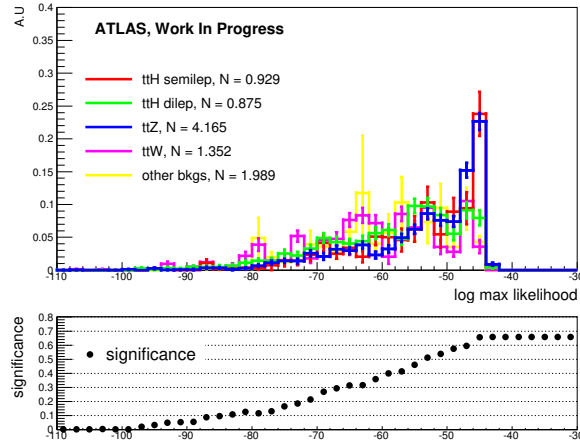
(a) 1σ (b) 3σ (c) 5σ

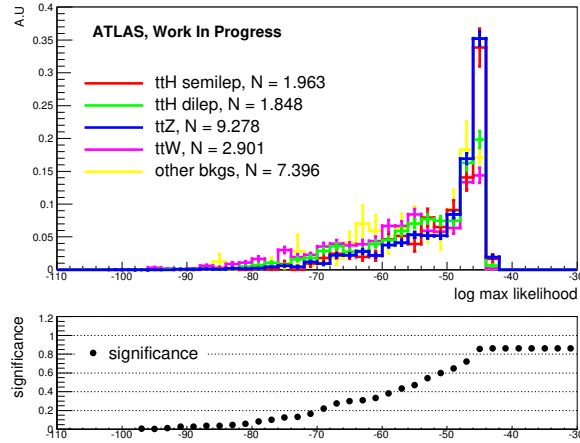
Figure 7.21: Comparison among the distributions of the logarithm of the total Likelihood for three different ranges of variation of the kinematical parameters. The configuration used for the b-tagging is the kVetoNoFitBoth option. Distributions are normalized to unity. The bottom plot shows the statistical significance, $S/\sqrt{B}$, chosen as figure of merit: S corresponds to the integral, from left to right, of the expected ttH signal yield, while B represents the integral, from left to right, of the total expected background.



(a) b-tagging configuration: kVetoNoFitBoth



(b) b-tagging configuration: kVetoNoFitLight



(c) b-tagging configuration: kWorkingPoint

Figure 7.22: Comparison among the distributions of the logarithm of the total likelihood for three different b-tagging configurations. Fit parameters are allowed to be varied within 3 standard deviations. Distributions are normalized to unity. The bottom plot shows the statistical significance, $S/\sqrt{B}$, chosen as figure of merit: S corresponds to the integral, from left to right, of the expected $t\bar{t}H$ signal yield, while B represents the integral, from left to right, of the total expected background.

7.5 Conclusions and prospects

As shown in Fig.7.18 there are no any significant improvements visible to attempt to discriminate between $t\bar{t} + \ell\bar{\ell}$ and $t\bar{t}H$ processes, applying a cut on such distribution. The profiles of the total likelihood distribution, in fact, look very similar for both signal and $t\bar{t} + \ell\bar{\ell}$ background. This is also demonstrated by the profile of the statistical significance, shown in the bottom plot of Fig.7.18. The significance, in fact, shows a monotonically increasing trend. This means that the highest significance of the analysis is reached when all the background is included.

It is also evident that changing the ranges of variation of the kinematic parameters or the b-tagging configuration do not help in the discrimination, as shown in Fig.7.21 and Fig.7.22, respectively.

The kinematic reconstruction performed by KLFitter helps when the final states of the processes differ substantially. This is the case of the $t\bar{t}W$ background, which likelihood distribution results to be very different with respect to the $t\bar{t} + \ell\bar{\ell}$ one, due to the lack of hadronic top quarks in the final state.

Given the results offered by this study, an alternative technique, that will be investigated in the future, consists in a multivariate analysis approach. In the last years, multivariate classification methods, based on machine learning techniques, have become a fundamental ingredient in many high-energy physics analyses.

The multivariate analysis could, in fact, increase the separation power between signal and background, exploiting as inputs the likelihood distributions, provided by KLFitter, jointly to other advantageous variables, e.g. the light jet multiplicity for the $t\bar{t}W$ rejection or the invariant mass of SFOS lepton pairs for the $t\bar{t} + \ell\bar{\ell}$ suppression.

This means that cutting on the MVA output, for example a Boosted Decision Tree (BDT), could give the possibility to reject more background, minimizing at the same time the loss of signal events, than applying a cut on the likelihood variables itself, with a significant gain in sensitivity of the analysis.

Chapter 8

Results

In this chapter the observed number of events is shown in Section 8.1 and Section 8.2 for the 3ℓ channel and the other ttH multilepton final states, respectively. An introduction to the statistical interpretation of the analysis results, commonly used in high energy physics experiments, is presented in Section 8.3. The goal is to estimate whether the observed number of events found in the different SRs is compatible with what expected from the SM hypothesis.

The results in terms of the signal strength μ for the 3ℓ channel are shown. In order to increase the statistical significance of the analysis, this channel is combined with the other ttH multilepton final states: $2\ell SS + 0\tau$, $2\ell SS + 1\tau$ and 4ℓ .

Finally, the systematic uncertainties associated to the measurement of μ , originated from both theoretical and experimental effects, are evaluated; and their evaluation procedure is described in Section 8.4.

The results presented in this chapter have been obtained using the RooStats framework[63], which is a C++ class library based in the ROOT and RooFit packages [64].

8.1 Observed number of events in the 3ℓ SR

The selections used to define the 3ℓ SR have been already shown in Chapter 5, while the estimates of the background from non prompt leptons have been presented in Chapter 6. Given these premises, the signal and background yields, as well as the observed number of events, in the 3ℓ SR are shown in Table 8.1.

Each MC prediction is scaled by a normalisation factor, taking into account the cross-section of the given process, the integrated luminosity recorded by ATLAS and the number of events initially simulated by the ATLAS MC production system. Scale factors are also used to correct the MC efficiencies of the reconstructed objects to the data ones (see Chapter 4). The distributions of some relevant variables in the 3ℓ SR are shown in Fig.8.1 and 8.2.

Process	3ℓ
$t\bar{t}W$	6.4 ± 1.4
$t\bar{t}+\ell\ell$	11.9 ± 2.0
Diboson	1.9 ± 1.1
Non-prompt lepton	8.7 ± 2.4
Other	3.38 ± 0.81
Total background	32.2 ± 4.5
$t\bar{t}H$	6.19 ± 0.78
$S/\sqrt{B}$	1.1
Data	46

Table 8.1: Expected event yields in the 3ℓ signal region normalized to 13.2 fb^{-1} . The integrated luminosity corresponds to the amount of data recorded by the ATLAS experiment during 2015 and 2016 at $\sqrt{s} = 13 \text{ TeV}$. The $t\bar{t}H$ yield assumes the SM production cross-section. The total uncertainty on the MC expectations is computed as the sum in quadrature of the systematic uncertainties and MC statistical error (this latter has a negligible effect). The systematic uncertainty corresponds to the sum in quadrature of all the systematics sources, described in Section 8.4, whose impact is obtained varying of one standard deviation the nominal prediction. "Other" backgrounds include tZ , tWZ , $tHqb$, tHW , $t\bar{t} + t\bar{t}$, $t\bar{t}WW$ and VVV production.

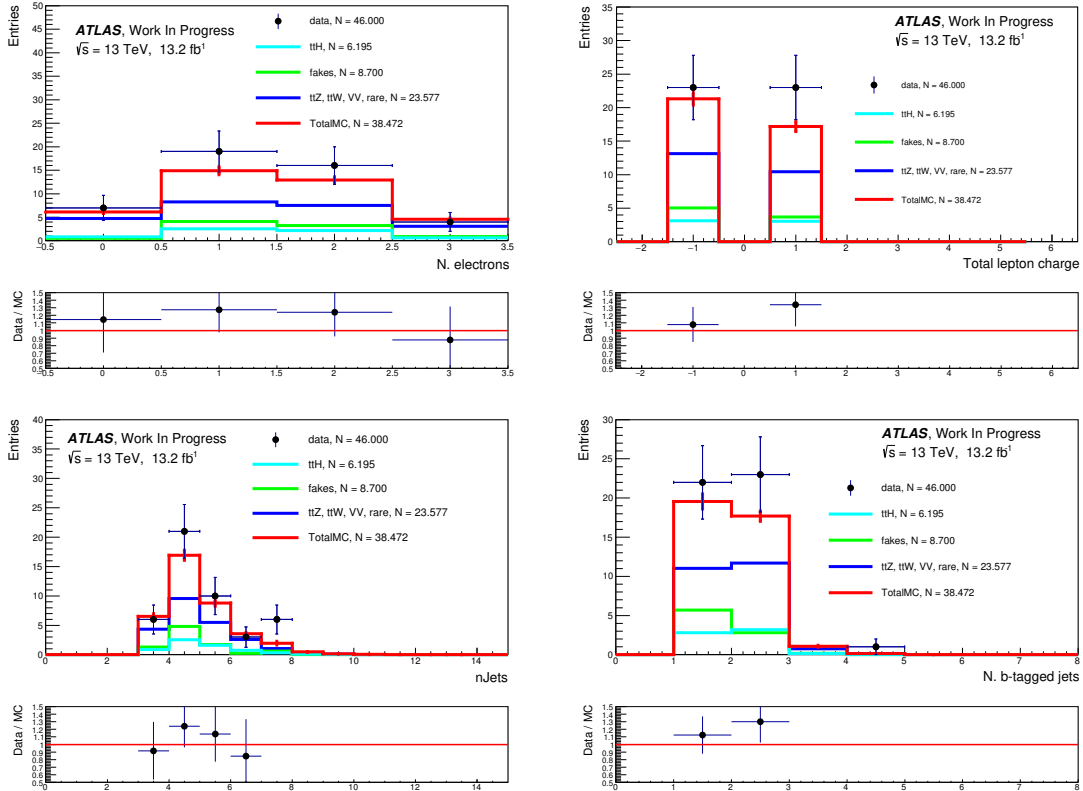


Figure 8.1: 3ℓ **Signal Region**: distributions of the electron multiplicity and total lepton charge (top), jet and b-tagged jet multiplicity (bottom). A ratio plot in the bottom pad is also displayed for each distribution. Black dots not displayed in the ratio plots are out of the y-axis range.

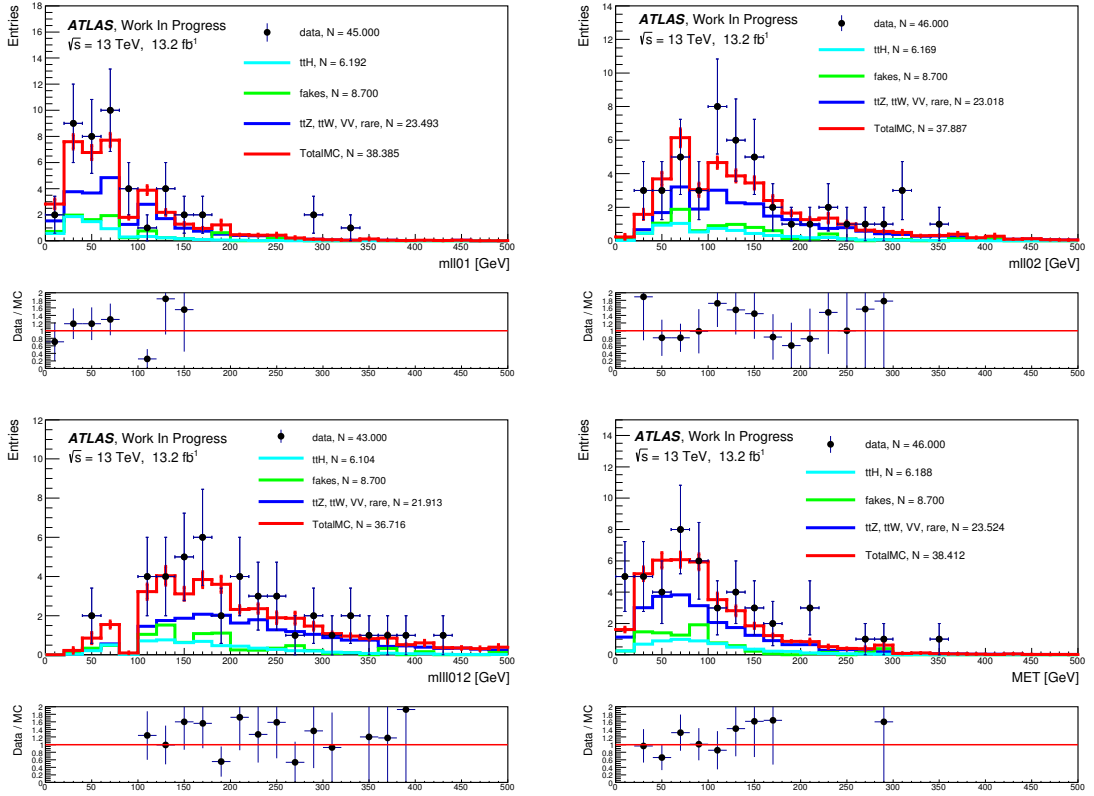


Figure 8.2: **3 l Signal Region**: distributions of invariant masses m_{ll01} and m_{ll02} (top), invariant mass m_{ll012} and E_T^{miss} (bottom). A ratio plot in the bottom pad is also displayed for each distribution. Black dots not displayed in the ratio plots are out of the y-axis range. "MET" in the bottom right plot corresponds to E_T^{miss} .

8.2 Observed number of events in the other ttH multilepton final states

The signal and background yields, as well as the observed number of events, in the other ttH multilepton SRs are shown in Table 8.2. The event selections used to define these SRs are described in Section 5.5.

Process	$2\ell 0\tau_{had} ee$	$2\ell 0\tau_{had} e\mu$	$2\ell 0\tau_{had} \mu\mu$	$2\ell 1\tau_{had}$	4ℓ
ttW	2.9 ± 0.7	9.1 ± 2.5	6.6 ± 1.6	0.8 ± 0.4	—
tt+ $\ell\ell$	1.55 ± 0.29	4.3 ± 0.9	2.6 ± 0.6	1.6 ± 0.4	1.12 ± 0.20
Diboson	0.38 ± 0.25	2.5 ± 1.4	0.8 ± 0.5	0.20 ± 0.15	0.04 ± 0.04
Non-prompt lepton	12 ± 6	12 ± 5	8.7 ± 3.4	1.3 ± 1.2	0.18 ± 0.10
Charge mis-ID	6.9 ± 1.3	7.1 ± 1.7	—	0.24 ± 0.03	—
Other	0.81 ± 0.22	2.2 ± 0.6	1.4 ± 0.4	0.63 ± 0.15	0.12 ± 0.05
Total background	25 ± 6	38 ± 6	20 ± 4	4.8 ± 1.4	1.46 ± 0.25
ttH	2.0 ± 0.5	4.8 ± 1.0	2.9 ± 0.6	1.43 ± 0.31	0.59 ± 0.10
$S/\sqrt{B}$	0.4	0.78	0.65	0.65	0.49
Data	26	59	31	14	0

Table 8.2: Expected event yields in the other five signal region categories normalized to 13.2 fb^{-1} . The integrated luminosity corresponds to the amount of data recorded by the ATLAS experiment during 2015 and 2016 at $\sqrt{s} = 13 \text{ TeV}$. The ttH yield assumes the SM production cross-section. The total uncertainty on the MC expectations is computed as the sum in quadrature of the systematic uncertainties and MC statistics error (this latter has a negligible effect). The systematic uncertainty corresponds to the sum in quadrature of all the systematics sources, described in Section 8.4, whose impact is obtained varying of one standard deviation the nominal prediction. "Other" backgrounds include tZ , tWZ , $tHqb$, tHW , $t\bar{t} + t\bar{t}$, $ttWW$ and VVV production[49].

A summary plot containing the MC event yields and the observed number of events for each ttH multilepton SR is presented in Fig.8.3. Uncertainties on the MC expectations due to systematic and statistics effects are shown.

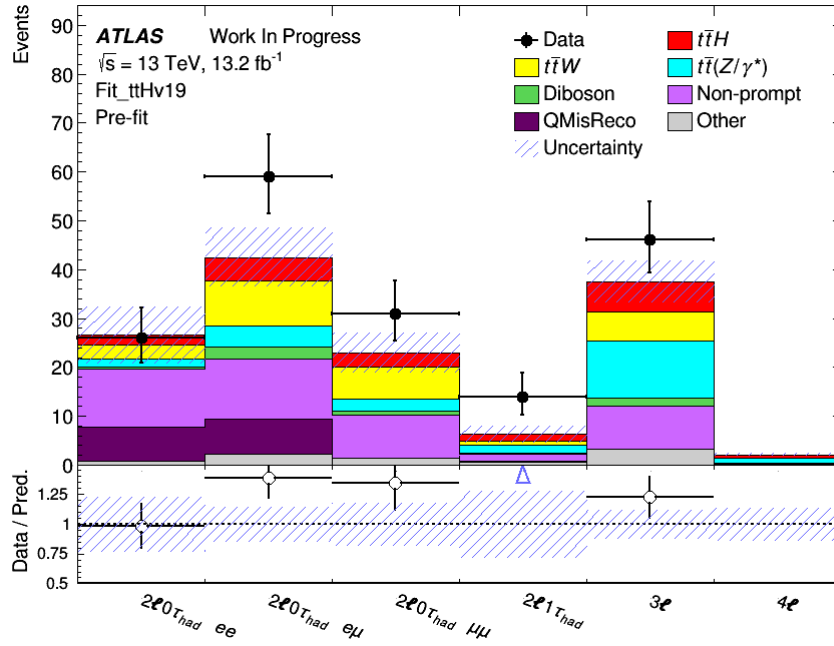


Figure 8.3: **Pre-fit** background and signal predictions and observed data yields for each signal region. The $t\bar{t}H$ prediction corresponds to the SM expectation ($\mu_{t\bar{t}H} = 1$). Charge mis-reconstruction backgrounds are indicated as "QMisReco".

8.3 Extraction of the signal strength

The statistical interpretation is based on the likelihood approach[65]. The likelihood function can be written as the product of Poisson probability terms P , computed from the number of expected signal S_i and background B_i events and from the observed N_i data events, in each i -th signal region, as shown in Eq.8.1.

$$\mathcal{L}(\mu, \theta) = \prod_i^{N_{SR}} P(N_i | \mu S_i(\vec{\theta}) + B_i(\vec{\theta})) \quad (8.1)$$

where N_{SR} corresponds to the number of signal regions considered ($N_{SR} = 6$: $2\ell 0\tau_{had} ee$, $2\ell 0\tau_{had} e\mu$, $2\ell 0\tau_{had} \mu\mu$, $2\ell 1\tau_{had}$, 3ℓ and 4ℓ).

The best-fit value of the signal strength μ , defined as the ratio between the observed cross-section σ_{obs} and the SM predicted cross-section σ_{SM} , is obtained using a maximum likelihood fit to the data yields of the different categories. The expected yields for signal and background are subject to statistical uncertainties, as well as the systematic ones. Systematic uncertainties are treated as distinct Poisson terms, known as *nuisance parameters* (NP), and constrained by Gaussian probability density functions. $\vec{\theta}$, shown in Eq.8.1, is a vector of nuisance parameter, $\vec{\theta} = \{\theta_1, \theta_2, \dots\}$ and each single term represents a different systematic source. When correlated, a single systematic source affecting more than one sample, is treated as a single NP in the fit.

The nuisance parameters θ adjust the expectations for signal and background according to the corresponding systematic uncertainties and their fitted values correspond to the amount that best matches the data. Aim of the procedure is to fit data with the SM expectations (MC yields), leaving μ as free parameter in the fit, together with the NPs. The fit result is obtained by maximizing the likelihood in Eq.8.1.

The signal strength μ is also, often, called *Parameter of Interest* (POI) since it is the most relevant information that we want to extract from the statistical procedure. The μ parameter scales the expected signal yield, with $\mu = 0$ corresponding to the background-only hypothesis (absence of signal) and $\mu = 1$ corresponding to the SM hypothesis for an Higgs boson of mass 125 GeV, produced via ttH process.

For the 3ℓ channel, the best fit value of μ , obtained using the Eq.8.1 with $i = 3\ell$ SR only, is found to be:

$$\mu_{ttH}^{3\ell} = 2.3_{-1.0}^{+1.2}(stat.) \text{ }_{-0.8}^{+1.1}(syst.) = 2.3_{-1.3}^{+1.6}, \quad (8.2)$$

corresponding, assuming the background-only hypothesis, to an observed (expected) significance of 2.0σ (0.9σ). The equivalent p-values are 0.025 and 0.19, respectively.

For the combination of the ttH multilepton channels, the best fit value is found to be:

$$\mu_{ttH}^{comb} = 2.9_{-0.7}^{+0.8}(stat.) \text{ }_{-0.8}^{+1.0}(syst.) = 2.9_{-1.1}^{+1.3}, \quad (8.3)$$

with the statistical and systematic uncertainties of the same order of magnitude. The combination of the ttH multilepton channels, each of which has been optimized separately, results in an higher significance: the observed significance is found to be 2.8σ while the expected one is 1.1σ . The equivalent p-values are 0.0023 and 0.13, respectively.

The best fit values of the signal strengths for each channel and the combination among them are shown in Fig.8.4. A small excess of data with respect to the signal+background hypothesis is observed in most of the multilepton channels, as shown in Fig.8.3. This reflects the value of the signal strength μ_{ttH} obtained from the global fit.

The plot summary in Fig.8.5 and the Table 8.3 show the post-fit MC yields for signal and background. The impact of the systematic uncertainties is evaluated after the fit and described in Section 8.4.

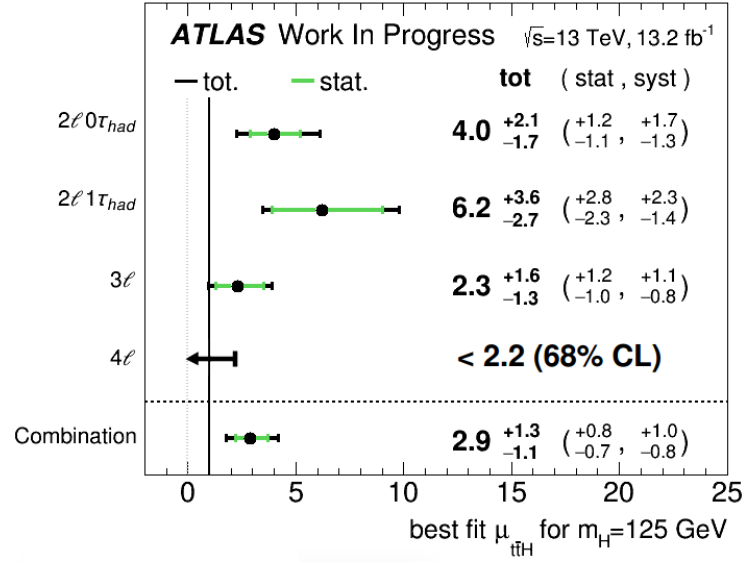


Figure 8.4: Best fit values of the $t\bar{t}H$ signal strength $\mu_{t\bar{t}H}$ for each multilepton final state and for the combination of the channels. The SM prediction is $\mu_{t\bar{t}H} = 1$. For the 4ℓ category, as zero events are observed, a 68% CL upper limit is shown.

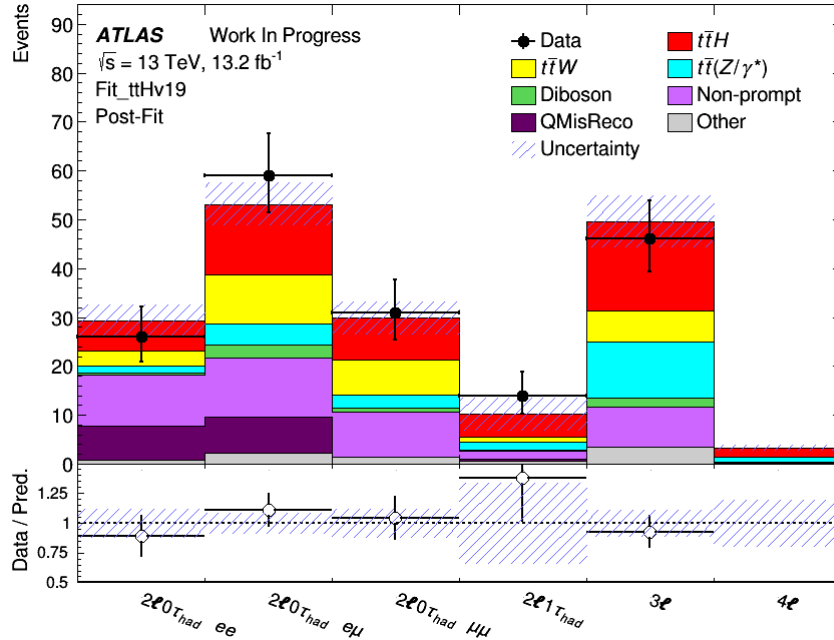


Figure 8.5: **Post-fit** background and signal predictions and observed data yields for each signal region. The prediction for $t\bar{t}H$ reflects the best-fit production rate of 2.9 times the Standard Model expectation. Charge mis-reconstruction backgrounds are indicated as "QMisReco".

Process	$2\ell 0\tau_{had} ee$	$2\ell 0\tau_{had} e\mu$	$2\ell 0\tau_{had} \mu\mu$	$2\ell 1\tau_{had}$	3ℓ	4ℓ
ttW	3.12 ± 0.83	10.0 ± 2.7	7.2 ± 1.7	0.97 ± 0.84	6.4 ± 1.4	—
tt+ $\ell\ell$	1.55 ± 0.30	4.33 ± 0.87	2.66 ± 0.59	1.67 ± 0.87	11.4 ± 2.0	1.10 ± 0.20
Diboson	0.40 ± 0.26	2.6 ± 1.4	0.83 ± 0.48	0.21 ± 0.15	1.9 ± 1.0	0.041 ± 0.036
Non-prompt lepton	10.4 ± 5.0	12.2 ± 5.3	9.1 ± 3.2	1.8 ± 1.4	8.2 ± 2.3	0.18 ± 0.10
Charge mis-ID	7.0 ± 2.7	7.2 ± 3.4	—	0.24 ± 0.06	—	—
Other	0.83 ± 0.22	2.3 ± 0.6	1.5 ± 0.4	0.65 ± 0.17	3.37 ± 0.80	0.124 ± 0.051
ttH ($\times 2.9$)	6.0 ± 1.8	14.5 ± 4.0	8.6 ± 2.4	4.6 ± 1.5	18.3 ± 4.9	1.73 ± 0.48
Total MC	29.2 ± 3.4	53.1 ± 4.5	29.8 ± 3.5	10.1 ± 3.5	49.6 ± 5.4	3.2 ± 0.6
Data	26	59	31	14	46	0

Table 8.3: Expected "post-fit" event yields in the six signal region categories normalized to $13.2 fb^{-1}$. Uncertainties on the background expectations due to systematic effects and MC statistics are shown. "Other" backgrounds include tZ , tWZ , $tHqb$, tHW , $t\bar{t} + t\bar{t}$, $ttWW$ and VVV production. Background expectations have been updated to reflect the values of systematic uncertainty nuisance parameters after the fit to data. The prediction and uncertainties for ttH reflect the best-fit production rate of $2.9^{+1.3}_{-1.1}$ times the Standard Model expectation. The uncertainty on the total background estimation is smaller than for the pre-fit values due to anti-correlations between the nuisance parameters obtained during the fit[49].

8.4 Systematic uncertainties

The impact of the main systematic uncertainties on μ_{ttH} , evaluated after the global fit, is shown in Fig.8.6 and Fig.8.7, for the 3ℓ channel and the ttH multilepton combination, respectively. The blue and cyan bars show the $\pm 1\sigma$ impact of the nuisance parameter on the signal strength (drawn conforming to the scale of the top axis). The open bars show the effect of the systematic uncertainties on μ_{ttH} before the fit, while the solid bars show the effect after the fit. The same systematic uncertainties are also reported in Table 8.4 and in Table 8.5, where the exact value for each uncertainty on the signal strength is shown.

The leading detector-related systematic uncertainty, in both the 3ℓ channel as well as in the ttH multilepton combination, arises from the efficiency of the jet-to-vertex association method of approximately 2.5% per jet with $p_T < 60 \text{ GeV}$, which becomes important in high-jet-multiplicity final states such as the ones considered in this analysis.

An important source of systematic uncertainties arises from the theoretical predictions, such as the modelling of the acceptance for ttH , $tt + \ell\ell$ and ttW events with high jet multiplicity requirements and the QCD cross-section calculations on the same processes.

ttH , $tt + \ell\ell$ and ttW processes are simulated using a NLO QCD matrix element computed by MadGraph5_aMC@NLO, matched to the Pythia8 parton shower generator. In order to study the impact of a different choice of the QCD factorization and renormalization scales, other samples have been tested having these scales varied by a factor 2 or 0.5.

The parton shower effects are studied by comparing the nominal ttH sample with different samples, having the same matrix element calculation but showered using *Herwig* ++, and by comparing the nominal ttV samples with ones with variations in the A14 Pythia8 tune.

The overall cross section for ttH production, 507 fb , is computed at NLO in QCD and electroweak couplings. It has uncertainties of $^{+5.8\%}_{-9.2\%}$ from QCD renormalization/factorization scale choice and $\pm 3.6\%$ from $PDF + \alpha_S$ uncertainties. The cross sections for ttV processes are also computed at NLO in QCD and electroweak couplings. These have QCD scale uncertainties of $\sim 12\%$ and $PDF + \alpha_S$ uncertainties of 3–4%[49].

The uncertainties in the modelling of pileup interactions and the jet energy scale also contribute significantly. Uncertainties in lepton reconstruction and trigger efficiencies have a minor impact on the signal strength uncertainty, instead.

The uncertainty on the combined 2015+2016 integrated luminosity is about 3%. It is derived from calibrations of the luminosity scale using x - y beam-separation scans performed in August 2015 and May 2016[66]. The uncertainties in the $2\ell 0\tau_{had}$, $2\ell 1\tau_{had}$ and 3ℓ non-prompt estimates have also a large effect on the global systematic error of the combined measurement.

Fig.8.6 and Fig.8.7 also report the constraints on the nuisance parameters from the fit for the 3ℓ channel and for the combined measurement, respectively. The black dots and the associated error bars, drawn according to the bottom axis, show the deviation of the fitted nuisance parameters $\hat{\theta}$ from the pre-fit value θ_0 in units of the standard deviation $\Delta\theta$ (the nuisance parameters are initially normalized to 0 ± 1).

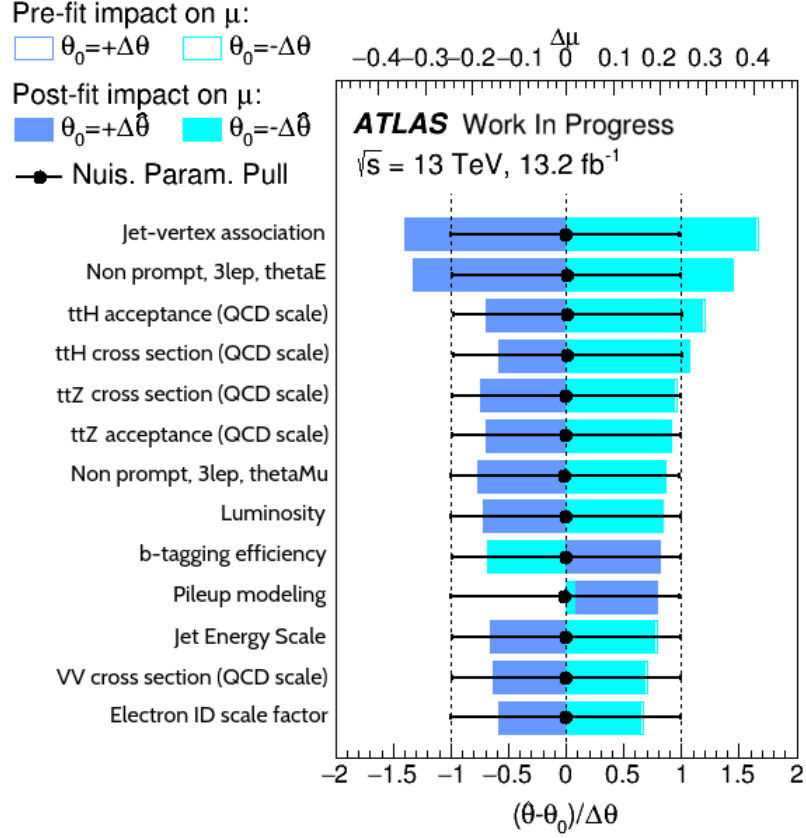


Figure 8.6: Ranking of the main systematic sources and constraints on the nuisance parameters in the 3ℓ channel analysis.

Uncertainty Source	$\Delta\mu$	
Jet-vertex association	+0.41	-0.34
Non prompt, 3lep, thetaE	+0.35	-0.32
ttH acceptance (QCD scale)	+0.29	-0.17
ttH cross section (QCD scale)	+0.26	-0.14
ttZ cross section (QCD scale)	+0.23	-0.18
ttZ acceptance (QCD scale)	+0.22	-0.17
Non prompt, 3lep, thetaMu	+0.21	-0.19
Luminosity	+0.21	-0.18
b-tagging efficiency	+0.20	-0.17
Pileup modelling	+0.19	—
Jet Energy Scale Variation	+0.19	-0.16
VV cross section (QCD scale)	+0.17	-0.15
Electron ID scale factor	+0.16	-0.14
Total systematic uncertainty	+0.9	-0.7

Table 8.4: Summary of the effects of the systematic uncertainties on μ for the 3ℓ channel analysis. Due to correlations between the different sources of uncertainties, the total systematic uncertainty can be different from the sum in quadrature of the individual sources.

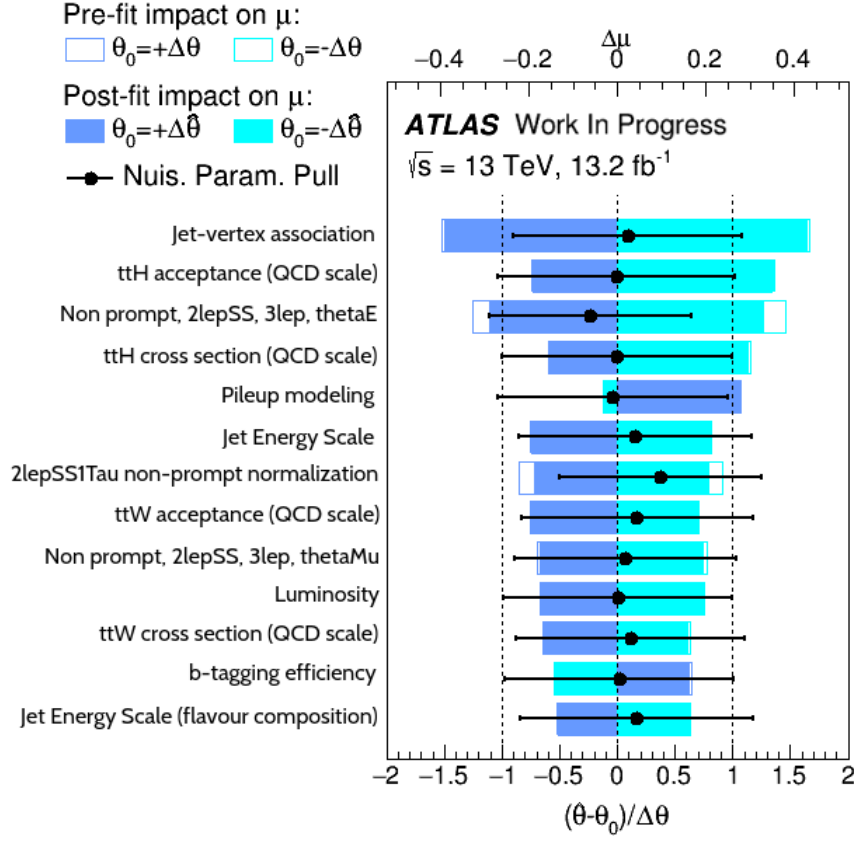


Figure 8.7: Ranking of the main systematic sources and constraints on the nuisance parameters in the ttH multilepton combined analysis.

Uncertainty Source	$\Delta\mu$	
Jet-vertex association	+0.43	-0.39
ttH acceptance (QCD scale)	+0.36	-0.19
Non prompt, 2lepSS, 3lep, thetaE	+0.33	-0.29
ttH cross section (QCD scale)	+0.30	-0.15
Pileup modelling	+0.28	-0.03
Jet Energy Scale Variation	+0.22	-0.20
2lepSS1Tau non-prompt normalization	+0.21	-0.19
ttW acceptance (QCD scale)	+0.18	-0.20
Non prompt, 2lepSS, 3lep, thetaMu	+0.20	-0.17
Luminosity	+0.20	-0.17
ttW cross section (QCD scale)	+0.16	-0.17
b-tagging efficiency	+0.17	-0.14
Jet Energy Scale (flavour composition)	+0.17	-0.14
Total systematic uncertainty	+1.0	-0.8

Table 8.5: Summary of the effects of the systematic uncertainties on μ in the ttH multilepton combined analysis. Due to correlations between the different sources of uncertainties, the total systematic uncertainty can be different from the sum in quadrature of the individual sources.

Conclusions

In this thesis, the study of the Higgs boson associated production with a top quark pair in multilepton final states has been presented. The dataset used corresponds to an integrated luminosity of 13.2 fb^{-1} from proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$, recorded by the ATLAS experiment during the LHC Run2 in 2015 and 2016.

Four different multilepton final states, distinguished by the multiplicity and the flavour of the leptons and sensitive to the Higgs boson decays into WW^* , $\tau\tau$ and ZZ^* are considered: $2\ell 0\tau_{had}$, $2\ell 1\tau_{had}$, 3ℓ and 4ℓ .

The study performed consists on a "cut-based" analysis, in which a set of kinematic and topological selections, resembling the characteristics of the signal events, has been applied to the data sample for each different final state. In particular, the analysis is focused on final states containing three light leptons (e or μ).

One of the main backgrounds for this channel comes from events with non-prompt leptons. In this scenario, the $t\bar{t}$ process is the dominant one. $t\bar{t}$ events, in which both the top quarks decay leptonically, can provide 2 light prompt leptons, whose can be accompanied by a third lepton, produced by a semi-leptonic hadron decay inside a jet. Although the probability of mis-identification of the secondary leptons is small ($10^{-3} \div 10^{-2}$), some processes, such as $t\bar{t}$, have cross-section large enough to represent a significant background. The rejection of such backgrounds can be achieved tightening the selections on the lepton identification and isolation. A strategy, focused on the estimation of the residual background from non-prompt leptons, has been developed and shown in Chapter 6.

The main irreducible background for the 3ℓ SR is the $t\bar{t}+ll$ background and a technique based on the full event kinematic reconstruction has been developed for its suppression. The idea that lays behind this study is based on the different number of prompt neutrinos in the $t\bar{t}H$ and $t\bar{t}+ll$ processes in the 3ℓ final state. In the ideal case in which the experimental resolution on the E_T^{miss} was "infinite" and the contribution from other secondary neutrinos was negligible, the E_T^{miss} would correspond to the neutrino's transverse momentum in $t\bar{t} + ll$ processes. For such reason, the top quark decays in the $t\bar{t}H$ events are expected to be reconstructed with a lower quality with respect to the $t\bar{t} + ll$ ones.

This study, shown in Chapter 7, makes use of a maximum likelihood approach: the result of the event reconstruction is presented in terms of a discriminating likelihood variable. In spite of the potential of the method, tested at the MC simulation "truth-level", it has been demonstrated that the experimental resolution on E_T^{miss} plays an important role in the separation power and, actually, applying a linear cut on the likelihood variables does not allow a powerful discrimination between signal and background. Given the results offered by this study, an alternative technique, consisting in a multivariate analysis approach, will be investigated in the future. This approach could increase the separation power of the technique, leading to a significant $t\bar{t} + ll$ background rejection.

Finally, the analysis results have been presented in Chapter 8. For the 3ℓ channel, the best fit value of μ , obtained using a maximum likelihood estimation approach, is found to be $\mu_{t\bar{t}H}^{3\ell} = 2.3_{-1.3}^{+1.6}$, corresponding to an observed (expected) significance of 2.0σ (0.9σ), assuming the background-only hypothesis.

The 3ℓ result is then combined with the other $t\bar{t}H$ multilepton channels, in order to increase the statistical significance of the analysis. The combined best fit value of the signal strength μ is found to be $\mu_{t\bar{t}H}^{comb} = 2.9_{-1.1}^{+1.3}$, corresponding to an observed (expected) significance of 2.8σ (1.1σ), assuming again the background-only hypothesis.

The further combination with the other ttH analysis, sensitive to the Higgs decays in $b\bar{b}$ and $\gamma\gamma$, as well as a larger amount of data that will be collected in the next years, will contribute significantly to reduce the uncertainty on the signal strength, leading to an increase of the significance in the ttH search analysis.

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