Measurement of missing transverse momentum and search for $H \rightarrow \tau\tau$ in $pp$ collisions at $\sqrt{s} = 8$ TeV with ATLAS

Supervisore: Dott. Donatella CAVALLI
Cosupervisore: Dott. Leonardo CARMINATI
Coordinatore: Prof. Marco BERSANELLI

Tesi di Dottorato di:
Rosa Simoniello

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Commission of the final examination:

External Referee:
Prof. Peter LOCH (University of Arizona)

External Member:
Dr. Marumi KADO (Université Paris-Sud et CNRS/IN2P3)

External Member:
Dr. Monica D’ONOFRIO (University of Liverpool)

Internal Member:
Prof. Emanuela MERONI (Università degli Studi di Milano)

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Università degli Studi di Milano, Dipartimento di Fisica, Milano, Italy

Cover illustration: Display of a $H \rightarrow \tau_{lep}\tau_{had}$ event selected by the ATLAS multivariate analysis in the VBF category. One $\tau$ decays to an electron indicated by the blue track matched to the green cluster, the hadronically decaying $\tau$ lepton (1 prong decay) is indicated by the green track and the yellow cluster, the two jets are marked with turquoise cones. ATLAS-CONF-2013-108.

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si sa che gli universi si fanno
e si disfanno ma è sempre lo stesso materiale che gira

everyone knows that universes
come and go, but it’s always the same stuff that goes round

_I Meteoriti_ - _Italo Calvino_
Introduction

The Large Hadron Collider (LHC) at CERN, Geneva, Switzerland, collides protons at unprecedented energies and with the highest luminosities achieved in a collider so far. The proton-proton ($pp$) collisions provide access to new and far extended kinematic regimes for the two multi-purpose experiments (ATLAS [1] and CMS [2]), and a dedicated experiment analyzing heavy quark production (LHCb [3]). In particular ATLAS and CMS are well suited to not only explore new physics beyond the Standard Model (SM), but also to test SM predictions for elementary particles and their interactions.

Understanding the origin of the mass of elementary particles has been one of the main quests for high energy physics for the last decades. The theory of the mass generating mechanism was independently hypothesized by Brout, Englert and Higgs in 1964 [4, 5]. It has been experimentally confirmed with the discovery of the particle predicted by this theory, the Higgs boson, announced by the ATLAS and CMS experiments on July 4, 2012 [6, 7]. At the time of this announcement only Higgs couplings to bosons could directly be proven. Subsequent crucial tests of the theory require to prove that the Higgs boson also couples to fermions.

The most promising channel for this search is the $H \rightarrow \tau\tau$ process that is discussed in this thesis. One of the aspects that makes the analysis of this channel challenging is the need of a proper evaluation of the missing transverse energy ($E_T^{\text{miss}}$) introduced by neutrinos in the final state. For this reason, a substantial part of this thesis is devoted to the $E_T^{\text{miss}}$ reconstruction, calibration and to techniques for pile-up suppression. More specifically, this thesis reports my work in the last three years developed in the context of the ATLAS collaboration and of the Milano University group, following the full path from low-level detector signals, through $E_T^{\text{miss}}$ reconstruction and calibration, to the $H \rightarrow \tau\tau$ physics analysis. The thesis is organized as follows.
In Chapter 1, an introduction to the theoretical framework of the Standard Model is given together with a description of the mass mechanism and its phenomenology crucial for the analysis.

In Chapter 2, the LHC, the ATLAS experiment, and the experimental conditions during the data taking in 2011 and 2012, which are characterized by a large amount of pile-up interactions introduced by the high luminosity reached with the LHC, are introduced. Particular attention is given to the ATLAS calorimeter system since its importance for the subjects dealt in this thesis.

In Chapter 3, the algorithms for the $E_T^{\text{miss}}$ reconstruction used in ATLAS are described. The $E_T^{\text{miss}}$ performance, which has been extensively studied, is presented for several final state topologies, and the crucial aspects for the $H \rightarrow \tau \tau$ analysis are discussed. This chapter represents significant input from my original studies.

In Chapter 4, the degradation of the $E_T^{\text{miss}}$ performance due to pile-up is shown and the methods to mitigate these effects are described. I have devoted large part of my activity in the development of innovative methods for pile-up suppression using either tracks or calorimeter information or a combination of both, and to their implementation in the official collaboration software package.

In Chapter 5, the cut-based analysis for the search of $H \rightarrow \tau \tau$ in the semileptonic $\tau_{\text{lep}} \tau_{\text{had}}$ final state is described in all its main aspects, from the selection and categorization of the events, the estimation of the backgrounds, the statistical analysis, to the final signal extraction, where I have been more involved. In particular, it is shown how the $E_T^{\text{miss}}$ after pile-up suppression improves the analysis sensitivity. The same pile-up suppressed $E_T^{\text{miss}}$ is also used in the ATLAS $H \rightarrow \tau \tau$ analysis employing multivariate techniques, which ultimately led to the observation of the Higgs boson decaying into two taus.
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Chapter 1

Introduction to the Standard Model and the Higgs Boson

The Standard Model (SM) is a quantum field theory that describes the matter constituents and their interactions. It provides at present our best understanding of the phenomenology of particle physics. Experiments performed in the last 70 years have successfully tested the model to an impressive level of accuracy.

Special acknowledgments were received with several Nobel prizes assigned to particle physics achievements. The Nobel prize in 1979 to Glashow, Salam and Weinberg for the electroweak unification and the prediction of the neutral currents observed for the first time by the Gargamelle collaboration [8]. The Nobel prize in 1984 to Rubbia and Van Der Meer for their decisive contributions to the large project that led to the discovery of the W and Z bosons by UA1 and UA2 experiments [9, 10]. The Nobel prize in 2008 to Kobayashi and Maskawa for the formulation of the CP (charge-parity) violation extensively studied in B-meson system by the Babar and Belle collaborations. Finally this year (2013) the Nobel prize to Englert and Higgs for the mass mechanism and the prediction of the Higgs boson recently observed by the ATLAS and CMS collaboration [6, 7].

In this chapter, the mathematical formulations of the SM are discussed in Sections 1.1 to 1.3. It includes the main ideas of modern physics: fields, quantum mechanics and special relativity. Local gauge symmetry and spontaneous
symmetry breaking are key concepts to provide dynamics and mass mechanisms for SM particles. Experimentally, the mass mechanism results in an observable massive particle, the Higgs Boson: the status of ATLAS searches and measurements of the Higgs properties are briefly summarized in Section 1.4. Despite the huge success of the SM predictions, there are hints indicating that the SM might not be consider as complete. Conceptual problems and limitations of the SM are highlighted in Section 1.5.

1.1 Basic constituents of the Standard Model

Phenomenologically, four fundamental interactions are observed in nature: electromagnetic, weak, strong and gravity. In the SM framework they are described by vector boson fields (the gauge fields) and represented as exchange of particles with spin 1, the force carriers. Gravity is not included in the theory because a consistent gravitational quantum formulation does not yet exist. However, at the energy scales currently accessible in experiments (order 1 TeV) gravity is weaker than the electromagnetic force by 40 orders of magnitude so its effects are negligible. They are expected to become relevant only at a much higher energy scale, the Planck scale ($1.22 \times 10^{19}$ GeV).

The observable vector bosons associated respectively to the strong, electromagnetic and weak interaction are the gluons, the photon and the bosons $W^\pm$ and $Z^0$. The weakness of the weak interaction is due to its massive force mediators. Despite its strength, the weak interaction gives rise to distinctive experimental signatures because it violates parity P, charge conjugation C, their combination CP, time-reversal T, and fermion generation, which are conserved by electromagnetic and strong interactions.

Matter constituents are elementary particles of spin 1/2 (fermions) divided into three families with increasing mass. They are represented by complex spinor fields $\psi(x)$ obeying the Dirac equation:

$$\left(i\gamma^\mu \partial_\mu - m\right)\psi(x) = 0 \quad (1.1)$$

where $\gamma^\mu$ are the Dirac matrices and $m$ is the fermion mass. Dirac’s equation has also a negative energy solution which is interpreted as the corresponding antiparticle of each particle, exactly matching the particle but with opposite charge.

Each fermion is associated to two chiralities, left-handed and right-handed. Chirality is conserved for massless fermions, in which case the chirality coincides
Figure 1.1: List of SM elementary and their interactions [14]. Particles are characterized by their spin, mass, and the quantum numbers (charges) determining their interactions. Moving between fermion generations quantum numbers stay the same while the particle mass increases for higher generations. The heavier generations are unstable and decay into the lightest one, which makes up most of the ordinary matter.

with the helicity. Despite the results from neutrino oscillation experiments [11, 12, 13], in the SM the neutrinos ($\nu_\ell$) are considered massless, so right-handed neutrinos are not foreseen in the theory.

The coupling with gauge fields provides the interaction between the otherwise free particles. Fermions can be classified according to the interactions experienced. All of them interact by the electroweak force. The fermions which carry also a color quantum number (red, blue, green), the charge of the strong interaction, are classified as quarks otherwise they are classified as leptons. The elementary particles in the SM with their classification and properties are summarized in Figure 1.1.

Quarks are never observed in isolation but always bound in color-singlet particles, the hadrons. Integer spin particles ($q\bar{q}$ states) are called mesons while
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Half-spin particles (qqq states) are called baryons.

As shown in the next sections the SM embodies the phenomenological structure described above in an elegant mathematical formulation where the concept of symmetry plays a key role for the construction of the theory.

1.2 Symmetries of the Standard Model

The construction of the Standard Model has been guided by covariance and local gauge symmetry principles [15, 16, 17]. The covariance (invariance under Lorentz transformation) ensures the compatibility of the theory with the special relativity, while symmetries provide information to determine the conservation laws and the dynamics of the interactions in quantum field theory:

Conservation laws are established by the Noether’s theorem stating that if an action (integral of the Langrangian over time) is invariant under some group of transformations (symmetry), then there exist conserved quantities which are associated to these transformations.

The dynamics of the SM interaction fields is realized asking for invariance of the theory under local gauge transformations $U(x)$ depending on space and time. Gauge transformations are important because they relate equivalent field configurations accounting for the redundant degrees of freedom in the Lagrangian and associate them with a unique physics observable. Moreover they imply the renormalizability of the theory ensuring the correct unitary behavior at high energy.

Applying the guidelines listed above, the first step is to apply a local gauge transformation $U(x)$ to the fermion field:

$$\psi(x) \rightarrow \psi'(x) = U(x)\psi(x)$$  \hspace{1cm} (1.2)

The gauge transformation $U(x)$ is usually expressed, for each symmetry of the theory, using the hermitian generators, $H_j$, of the Lie group:

$$U(x) = e^{-i\sum_{j=1}^{n} \theta_j(x)H_j}$$  \hspace{1cm} (1.3)

where $\theta(x)$ is an arbitrary function.

Substituting expressions 1.2 and 1.3 in the Dirac’s equation 1.1, the presence of a partial derivative leads to additional terms that break the invariance of the
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equation:

\[
\partial_\mu \psi(x) \rightarrow \partial_\mu \psi'(x) = e^{i \theta(x) \sum_{j=1}^n H_j} \left[ \partial_\mu + i \partial_\mu \theta(x) \sum_{j=1}^n H_j \right] \psi(x) \\
\nequiv e^{i \theta(x) \sum_{j=1}^n H_j} \partial_\mu \psi(x).
\] (1.4)

The invariance can be restored by introducing a spin-1 field \( A_\mu(x) \), the gauge field, with coupling constant \( g \), to the partial derivative \( \partial_\mu \) to form the covariant derivative \( D_\mu \):

\[
\partial_\mu \rightarrow D_\mu = \partial_\mu + ig \sum_{j=1}^n A_\mu(x)
\] (1.5)

In this sense one can say that the gauge field responsible for the interaction is brought into the free particle theory by imposing gauge invariance, and the complete dynamic is obtained as follow.

The expression for the transformation of the field \( A_\mu(x) \) under \( U(x) \) is determined by the invariance requirements of the theory, it must generate terms canceling the non-invariant contributions in Dirac’s equation:

\[
A_\mu(x) \rightarrow A_\mu'(x) = A_\mu^j(x) - \frac{1}{g} \partial_\mu \theta^j(x) - \Sigma_{k,l} h_{jkl} \theta^k(x) A_\mu^l(x)
\] (1.6)

where the \( h_{jkl} \) are the structure constants of the Lie algebra with generators \( H_j \).

The field strength tensor characterizing the gauge interaction is defined as:

\[
F^{i}_{\mu\nu} = \partial_\mu A^i_\nu - \partial_\nu A^i_\mu - g h_{ijl} A^j_\mu A^l_\nu
\] (1.7)

Terms proportional to \( F^{i}_{\mu\nu} F^{\mu\nu} \) in the Lagrangian are identified with the kinetic terms for the gauge fields.

Theories can be classified as Abelian groups, like \( U(1) \), that have not field self-couplings, and non-Abelian groups (also called Yang-Mills theories), like \( SU(N) \) that instead imply field self-interaction. This can be understood from the absence of the last term in Equations 1.6 and 1.7 for the Abelian case. Therefore, the Lagrangian has no trilinear or quartic terms in the fields responsible for the self-couplings in this case.

According to the general case discussed above, Quantum Electrodynamics (QED) [18, 19] can be derived from equations 1.2 to 1.6 by asking for local invariance under the \( U(1) \) group, \( U(1)_{EM} \), of the form \( U(x) = e^{i \theta(x)} \). The associated gauge field is identified with the photon and the coupling strength between the photon and a fermion is the electric charge of the fermion. Since \( U(1)_{EM} \) is an Abelian group the gauge fields does not experience self-interaction, therefore, the photon does not carry electromagnetic charge.
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The QED symmetry group is not directly included in the SM model because it can be seen as the low energy theory of a more fundamental symmetry realized at higher energy. In this regime the electromagnetic and the weak interactions are unified in the electroweak force that breaks down in the two separate forces at the electroweak scale, $O(100 \text{ GeV})$.

Therefore, in order to match the particle phenomenology described in Section 1.1, the minimal global symmetry group for the SM is:

\[ SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \] (1.8)

where the $SU(3)_C$ group determines the strong interaction sector, while the $SU(2)_L \otimes U(1)_Y$ group determines the electroweak interaction sector. The independent product of the three symmetry groups results into three independent coupling constants, one for each group. Further details are in the next sections.

1.2.1 The strong interaction sector $SU(3)_C$

The quantum chromodynamics (QCD) [20, 21] describes the strong interaction between quarks. It is based on the $SU(3)_C$ group, where $C$ stands for color. Each quark flavor corresponds to an $SU(3)_C$ quark triplet in a three-dimensional color space with base (red, blue, green).

For the $SU(3)_C$ group there are eight generators expressed by the Gell-Mann matrices and resulting in the same number of massless vector fields, the gluons, $G^a_\mu$, $a = 1, \ldots, 8$. Since $SU(3)_C$ is a non-Abelian group, gluon self-interaction occurs implying that gluons carry color charge.

The coupling strength $g_S$ is more commonly expressed in terms of the strong coupling constant $\alpha_S = g_S^2/(4\pi)$. As result of the renormalization, which cancels divergences in the theory, the coupling constant depends on the renormalization scale, $\mu^2$, and on the virtuality (momentum transfer) of the process, $Q^2$, (running coupling constant) [22]. Even though QCD does not give a prediction for the absolute value of $\alpha_S$, its form is completely determined by the renormalization group equations (RGE). At the lowest order it can be expressed by the following equation:

\[ \alpha_S(Q^2) = \frac{\alpha_S(\mu^2)}{1 + \alpha_S(\mu^2)\beta_0 \ln \frac{Q^2}{\mu^2}} \] (1.9)

where $\beta_0 = (33 - 2N_f)/(12\pi) > 0$, and $N_f$ is the number of the accessible quark flavors.
threshold matching at the heavy quark pole masses $M_c = 1.5 \text{GeV}$ and $M_b = 4.7 \text{GeV}$. Results from data in ranges of energies are only given for $Q = M_{Z^0}$. Where available, the table also contains the contributions of experimental and theoretical uncertainties to the total errors in $\alpha_s(M_{Z^0})$.

Finally, in the last two columns of table 1, the underlying theoretical calculation for each measurement and a reference to this result are given, where NLO stands for next-to-leading order, NNLO for next-next-to-leading-order of perturbation theory, "resum" stands for resummed NLO calculations which include NLO plus resummation of all leading and next-to-leading logarithms to all orders (see [39] and [32]), and "LGT" indicates lattice gauge theory.

Figure 1.2: Summary of measurements of $\alpha_s(Q)$ as a function of the respective energy scale $Q$. Open symbols indicate Next-to-Leading Order (NLO), and filled symbols Next-to-next-to-Leading Order (NNLO) QCD calculations used in the respective analysis. The curves are the QCD predictions for the combined world average value of $\alpha_s$, evaluated at mass $M_Z$ of the $Z^0$ boson [26].

The prediction of the $\alpha_s$ dependence on $Q^2$ has been successfully tested by many experiments, as showed in Figure 1.2. $\alpha_s(Q^2)$ decreases with increasing $Q^2$ of the process. This means that the higher the available energy in the process becomes, the more the quarks can be considered as free particles called partons (asymptotic freedom) [23, 24, 25]. On the contrary $\alpha_s(Q^2)$ diverges for low energy values and exceeds unity for $Q^2 < 1 \text{ GeV}$. In this region the force gets so strong that it is impossible to extract a single quark from a hadron. This is understood from the fact that if the quark receives enough energy to overcome the binding energy of the hadron, it also has sufficient energy to produce quark-antiquark pair until the color charge is neutralized and all quarks are bound into color singlets (confinement). Finally, at large $\alpha_s$, perturbative expansions in $\alpha_s$ are not meaningful so only phenomenological model and numerical computation are presently available.

The cross-section for high-energy hadron collisions can be described by a
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“hard” contribution given by the parton level interaction, $\sigma(ij \rightarrow X)$, convoluted with the Parton Distribution Functions (PDFs), $f_i(x, \mu_F^2)$, describing the probability for a parton of flavor $i$ to carry a fraction $x$ of the total momentum of the hadron:

$$\sigma(pp \rightarrow X) = \sum_{ij} \int dx_1 dx_2 f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2) \hat{\sigma}(ij \rightarrow X). \quad (1.10)$$

PDFs depend on the factorization scale of the process, $\mu_F^2$, that is needed to regularize collinear divergence for incoming partons.

This factorization is the base to describe all interesting processes (hard scatter interactions) at hadrons colliders.

1.2.2 The electroweak sector $SU(2)_L \otimes U(1)_Y$

The electroweak force is described by the symmetry group $SU(2)_L \otimes U(1)_Y$, with $U(1)_Y \neq U(1)_{EM}$ [16]. The three generators $T_i$, $i = 1, 2, 3$, (Pauli’s matrices) of the $SU(2)_L$ group are called weak-isospin generators and act differently on left-handed and right-handed components (in particular, right-handed particles are singlets under the weak isospin, hence the subscript $L$ that stands for left-handed). The generator of the $U(1)_Y$ group is called weak-hypercharge operator $Y$ and it is related to the electric charge $(Q)$ and the weak-isospin generators through the relationship:

$$Q = T_3 + \frac{1}{2}Y \quad (1.11)$$

The generators of the group result in the same number of massless gauge fields consisting of a vector boson triplet under $SU(2)_L$, $W^i_{\mu}$, $i = 1, 2, 3$, and a vector boson singlet under $SU(2)_L$, $B_{\mu}$.

The observed weak bosons, $W^\pm$ and $Z^0$, are massive. This can be generated in the theory through a system of spontaneous symmetry breaking and the Higgs mechanism, described in Section 1.3. The breaking scheme $SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{EM}$ lets three independent linear combinations of the four gauge boson fields, identified with the $W^\pm$ and $Z^0$, to acquire mass while preserving the massless of the photon as required.
The observed states are therefore a mixing of the the gauge bosons:

\[ W^\pm_\mu = \frac{W^1_\mu \mp iW^2_\mu}{\sqrt{2}} \]  \hspace{1cm} (1.12)

\[ \begin{pmatrix} A_\mu \\ Z_\mu \end{pmatrix} = \begin{pmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} B_\mu \\ W^3_\mu \end{pmatrix} \]  \hspace{1cm} (1.13)

where \( \theta_W \) is known as the Weinberg angle or electroweak mixing angle and it is related to the coupling constants by:

\[ g \sin \theta_W = g' \cos \theta_W = e \]  \hspace{1cm} (1.14)

\[ \tan \theta_W = \frac{g'}{g} \]  \hspace{1cm} (1.15)

At the time of the formulation of the electroweak interaction only charged weak currents mediated by \( W^\pm \) were observed. The prediction of an additional neutral current mediated by the \( Z^0 \) boson and its first observation in the Gargamelle neutrino experiment [8] was a huge confirmation of the validity of the theory that was extensively tested by the LEP precision measurements on the \( Z \) mass pole [27]. These measurements still provide very stringent constraints on the model and they are useful in testing and possibly excluding new theories.

1.2.3 Gauge invariance and mass terms

As discussed in Section 1.2, the gauge invariance is one of key concepts for building the SM theory. However, invariance requirements also prevent to directly introduce mass terms for fermions and vector bosons in the SM Lagrangian.

For fermions, the mass terms would have the following form:

\[ m\bar{\psi}\psi = m (\bar{\psi}_R \psi_L + \bar{\psi}_L \psi_R) \]  \hspace{1cm} (1.16)

that is not \( SU(2)_L \) invariant since left-handed and right-handed fermion fields transform in a different way under transformation.

In the same way, the mass term for vector bosons would have the form:

\[ m^2 A^\mu A_\mu \]  \hspace{1cm} (1.17)

that is not invariant under a gauge transformation of the field \( A^\mu \) (equation 1.6).

Hence, SM particles should be massless but the mass of the fermions and the vector bosons \( W^\pm \) and \( Z^0 \) are experimentally measured. The gauge symmetry
must therefore be broken in order to provide these masses. This can be done through the mechanism of spontaneous symmetry breaking. The main concept is that no explicit breaking of the symmetry is introduced: the equations of the dynamics are kept symmetric, but they can accommodate solutions that are not symmetric. Therefore, the system “spontaneously” breaks the symmetry choosing a ground state.

The explicit case of the Higgs mechanism and how the mass of the SM particles are generated is described in next session.

1.3 The mass mechanism and the Higgs boson

The Brout-Englert-Higgs mechanism [4, 5] is a way to provide mass for fermions and vector bosons without spoiling the gauge invariance of the Lagrangian. As argued in Section 1.2.3 this can be achieved with a spontaneous symmetry breaking mechanism (SSB).

In order to have a coherent theory consistent with experimental data, the minimal configuration to realize SSB in the SM Lagrangian is by introducing a complex scalar field, \( \phi \), with a Lagrangian \( L_{\text{Higgs}} \) defined as:

\[
L_{\text{Higgs}} = (\partial^\mu \phi)^\dagger (\partial_\mu \phi) - V(\phi^\dagger \phi), \quad V(\phi^\dagger \phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2
\] (1.18)

where the parameter \( \lambda \) must be not negative in order to avoid instability in the theory, while the parameter \( \mu^2 \) (despite the notation) can be either positive or negative. The shape of the potential for the two cases is shown in Figure 1.3. For \( \mu^2 > 0 \) there is a unique minimum not allowing any symmetry breaking, whereas for \( \mu^2 < 0 \) the potential has a whole family of not trivial minima. Therefore, although the Lagrangian remains invariant under \( SU(2)_L \otimes U(1)_Y \), the system choosing one of the equivalent ground states breaks the symmetry.

At this point, one can develop the theory around the chosen ground state. The Higgs doublet can be written in terms of four real fields \( \theta_1(x), \theta_2(x), \theta_3(x) \) and \( H(x) \) as:

\[
\phi(x) = \frac{1}{\sqrt{2}} e^{i \frac{\tau_a}{2} \theta_a(x)} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix} \xrightarrow{\text{gauge trans}} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}
\] (1.19)

where \( \tau_a \) are the three Pauli’s matrices and \( v \) is the vacuum expectation value of the Higgs field. The exponential enclosing the dependence on the three scalar fields \( \theta_a(x) \) can be removed with a gauge transformation, leaving only one physical
The Higgs mechanism

The contradiction pointed out in the last section left the theorists with a difficult question: should one brutally add the mass terms to the Lagrangian and abandon gauge invariance, or is there an alternative to generate masses without breaking the symmetry explicitly?

The answer is yes and came from the work of Higgs, Englert, Brout and others [28]. For the case with $\mu^2 > 0$ (a) and $\mu^2 < 0$ (b), of the left-handed and right-handed fermion fields to the Higgs field and expressing the Higgs field as in equation 1.19, have the following form

$$M_{H} = \sqrt{2} \lambda v M_{W} = M_{Z} \cos \theta_{W} = \frac{1}{2} g v$$

where $\theta_{W}$ is the Weinberg angle introduced in Section 1.2.2.

Mass terms for fermions can be introduced in the Lagrangian via Yukawa coupling, $\lambda_{f}$, of the left-handed and right-handed fermion fields to the Higgs field that, expressing the Higgs field as in equation 1.19, have the following form for each fermion:

$$\mathcal{L}_{\text{fermion}} = - \frac{(v + H)}{\sqrt{2}} \lambda_{f} \bar{\psi} \psi$$

The term proportional to $v$ has the right form of a mass term for fermions, $m_{f} \bar{\psi} \psi$,

Figure 1.1: Illustration of the Higgs potential for a scalar field $F = \text{real} + i \text{im}$ with $\mu^2 > 0$ and $\mu^2 < 0$.

Figure 1.3: Shape of the potential for a complex scalar field with $\mu^2 > 0$ (a) and $\mu^2 < 0$ (b) [28]. For the case with $\mu^2 > 0$ there is only a trivial minimum, instead for $\mu^2 < 0$ a ring of minima is found. Despite the symmetric shape of the potential, the system, choosing one of the equivalent minima (ground state), spontaneously breaks the symmetry.
1.4 STATUS OF THE HIGGS BOSON SEARCHES AND MEASUREMENTS AT LHC

with:

\[ m_f = \lambda_f \frac{v}{\sqrt{2}} \]  

(1.23)

while the term proportional to \( H \) gives the fermion-Higgs coupling. Using equation 1.23 the value of the coupling strength can be expressed as \( m_f/v \), meaning the Higgs field couples to a fermion proportionally to the fermion mass. Since the Yukawa coupling are not a priori set, fermions masses are free parameters of the theory.

1.4 Status of the Higgs boson searches and measurements at LHC

As discussed in Section 1.3, the Brout-Englert-Higgs mechanism addresses the problem of the origin of mass for elementary particles introducing the interaction with a new field, the Higgs field, and predicts the existence of an observable massive particle, the Higgs boson, associated to the field. For many years, particle experiments have searched for this particle able to confirm and complete the SM theory. The difficulty of the search, beyond the small Higgs cross-section and the compelling experimental conditions, lies in the a priori unknown mass of the Higgs boson. This means that the search must be performed across a wide range for the Higgs boson mass where the signal is predicted to manifest differently and different background compositions are expected. By consequence, in order to cover this variety of experimental signatures, several analyses have been set up and separately optimized.

The discovery of the Higgs boson on the 4th July 2012 has been a huge success for the physics community and the start of a new physics program. In the SM, all properties of the Higgs boson are defined once its mass is known, making precise measurements of those properties [29, 30, 31] crucial to provide further constraints on the theory. These measurements are also important also to test many alternative theories extending the SM that make different predictions for the properties of one or more Higgs bosons. They include measurement of the Higgs mass, width, quantum numbers (charge, spin, CP), differential cross-sections and couplings, and are pursued with high priority at the LHC.

The status of these measurements in ATLAS are reported in the next sections after a description of the main Higgs production and decay modes in high energy proton-proton collisions (\( \sqrt{s} = 7/8 \) TeV at the LHC).
Chapter 1: Introduction to the Standard Model and the Higgs Boson

1.4.1 Higgs production modes at LHC

At the LHC the Higgs boson is produced through the four main production modes shown in Figure 1.4. The cross-sections for the dominant production modes at 8 TeV are compared in Figure 1.5 as a function of the Higgs mass [29] and listed below.

Gluon fusion is the dominant production mode, mediated by a top quark loop and, to a lesser extend, a $b$-quark loop. This process receives huge contributions from higher order QCD corrections. The uncertainties on the total values varies from 10% to 40% depending on the prescription used for their calculation.

Vector boson fusion (VBF) is the sub-leading mode at the LHC, with the Higgs produced in association with two quarks. The quarks are expected to give rise to very energetic jets located in the forward regions, with a large rapidity separation between them. Since its a very distinctive experimental signature, it provides a powerful filter against other backgrounds and where possible it is explored in the analysis final state.

Associated production with $W$ or $Z$ bosons initiated by $q\bar{q}$. The decays of the vector bosons to leptons (including neutrinos) provide good trigger efficiency and help in reducing QCD backgrounds. For this reason, in the last year at the increasing of the available luminosity it became more attractive at the LHC and more and more analyses started to explore how to fully
1.4. STATUS OF THE HIGGS BOSON SEARCHES AND MEASUREMENTS AT LHC

maximize its experimental signature.

Associated production with top quarks can be initiated by a pair of gluons or quarks, the Higgs being radiated from a quark line in the latter case. The low yields restrict at the moment the experimental potential of this mode.

1.4.2 Higgs decay modes at LHC

The couplings of the Higgs boson to other SM particles are proportional to the particle mass for fermions and to the square of the mass for the $W^\pm$ and $Z$ vector bosons. Hence, the Higgs is favored to decay into the heaviest particles kinematically accessible and the corresponding Higgs decay branching fractions (BR) change as a function of the Higgs mass, as shown in Figure 1.6. Around $m_H \sim 125.5$ GeV, the mass value for the observed Higgs boson, all the decay modes are accessible, and provide a wide spectrum of final states which can be experimentally tested.

In order to select and study Higgs events an efficient trigger is necessary. According to the specific decay channel studied it requires either the presence of leptons or photons or large missing transverse momentum, $E_T^{\text{miss}}$, and high-
Figure 1.6: Decay branching ratios of the SM Higgs boson as a function of its mass [33]. Decays to massless particles (gluons and photons) proceed through a loop of either fermions or gauge bosons: the major contribution comes from top quark in the case of the gluon channel and from the W boson in the case of the photon channel.

$p_T$ jets. Furthermore, experimental conditions and a distinctive signature of the signal with respect to the backgrounds play a crucial role in the tagging of the events and in the final sensitivity of the analysis. Hence, despite the high BR, $H \rightarrow b\bar{b}$ and $H \rightarrow \tau\tau$ decay modes are not the most sensitive channels due to their complex background composition, the presence of $E_T^{miss}$ and the not fully efficient b-jet and $\tau$ identification. In the same way, despite the low BR, $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4\ell$ give the highest sensitivity, due to their peculiar signature. Moreover, since in these channels it is possible to fully reconstruct all the physics objects in the final state, high resolution mass measurement can be achieved.

Some more details about the characterizations of the varies decay channels are given in the following.

$H \rightarrow b\bar{b}$ has the highest BR at low masses, but it suffers from huge QCD multijets background, many order of magnitude larger than the signal. The absence of an efficient trigger excludes the identification of gluon fusion and vector boson fusion productions. Therefore, in order to have a signature for the events, only the associated Higgs production with a leptonically decay vector boson ($W \rightarrow \ell\nu$, $Z \rightarrow \ell\ell$ and $Z \rightarrow \nu\nu$) is considered.
1.4. STATUS OF THE HIGGS BOSON SEARCHES AND MEASUREMENTS AT LHC

H → ττ is the most sensitive channel for H decaying into fermions. A full description for the cut-based analysis is reported in Chapter 5 highlighting the complexity of the mass reconstruction of the ττ system, due to the presence of more than one neutrino and the background composition and estimation.

H → VV (V = W, Z) provides a good sensitivity in the whole Higgs mass range. In the low Higgs mass range the H → ZZ → 4ℓ and the H → WW → ℓνℓν provide important contributions. The former is the “golden channel” leading to a narrow invariant mass peak on the top of a relatively smooth and small background, the latter has a large BR but does not have a high resolution mass reconstruction due to the presence of missing transverse momentum in the final state. Searches for additional Higgs bosons at higher mass are pursued as well, in this mass region, the most important channel is given by H → WW → ℓνq̅q.

H → γγ is one of the most important channels in the low mass range because it has a very distinctive signature given by two isolated and energetic photons with a narrow invariant mass peak.

1.4.3 Discovery of the Higgs boson

The ATLAS [6] and CMS [7] experiments independently announced, on the 4th July 2012, the discovery of a new particle consistent with a SM Higgs boson with \( m_H \sim 125 \text{ GeV} \) with signal significances of 5.9 and 5.8, respectively. The results were obtained using the data collected by the two experiments in 2011 and 2012.

The discovery was driven by the high resolution mass channels H → γγ and H → ZZ → 4ℓ. In both cases the final state can be fully reconstructed: two energetic and isolated photons in the first case and two pairs of same flavor and opposite sign leptons in the latter case. Hence the signal appears in the distribution of the invariant mass as a narrow peak over a quite smooth background, as shown in Figure 1.7, which reports the ATLAS results for the two channels. The channel H → WW → ℓνℓν has a good sensitivity to the Higgs signal as well, but it has a poor mass resolution because of the presence of neutrinos.

To increase the sensitivity to a Higgs boson signal, the analyses exploit different topologies separating the events in mutually exclusive categories having different kinematics distributions and signal-to-background ratios. In particular in the H → γγ analysis an exclusive category of events containing two jets
Figure 1.7: The distribution of the invariant mass for the diphoton system in the $H \rightarrow \gamma\gamma$ search in (a) and the four leptons system in the $H \rightarrow ZZ \rightarrow 4\ell$ search in (b) in the ATLAS experiment [6].

improves the sensitivity to VBF.

A statistical analysis is performed to quantify the observed excess. Figure 1.8(a) shows the combined 95% CL exclusion limits on the signal strength of the Higgs boson as a function of $m_H$ after the combination of all channels. The mass range accessible with the data ($110 < m_H < 582$ GeV) is excluded, except for the region $122 < m_H < 131$ GeV, where an excess is observed. In order to quantify the significance of this excess the local $p_0$, i.e. the probability that the background can produce a fluctuation greater than or equal to the excess observed in data, is computed as a function of the Higgs boson mass as shown in Figure 1.8(b): the largest local significance is found for a SM Higgs boson mass hypothesis of $m_H = 126.5$ GeV, where it reaches about $6\sigma$, with an expected value in the presence of a SM Higgs boson signal at that mass of $4.9\sigma$.

1.4.4 Measurements of the Higgs boson properties

After the discovery ATLAS started the study of the properties of the new observed particle, that include mass, coupling constants and spin measurements, to test the compatibility with the SM. Any deviation from the SM predictions, for any of the decay mode, could be a signal of new physics. The study of these properties is performed in the individual channels, then all the measurements are combined
1.4. STATISTICS OF THE HIGGS BOSON SEARCHES AND MEASUREMENTS AT LHC

![Graph](image)

(a) 95% CL limits on the signal strength

Figure 1.8: Exclusion limit on the signal strength of the Higgs boson in (a) and local significance (b) as a function of the SM Higgs boson mass $m_H$ in the ATLAS experiment. The results are the combination of the $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4\ell$ and $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ searches [6].
Figure 1.9: The profile likelihood ratio -2 ln \( \Lambda(m_H) \) as a function of \( m_H \) for the \( H \rightarrow \gamma\gamma \) and \( H \rightarrow ZZ^* \rightarrow 4\ell \) channels and their combination. The dashed line shows the statistical component of the mass measurement uncertainty [34].

...to maximize the statistical power.

Primarily, the measure of the mass of the observed Higgs boson, \( m_H \), was performed combining the two high-resolution channels, \( H \rightarrow \gamma\gamma \) and \( H \rightarrow ZZ \rightarrow 4\ell \) [34]. The most updated result for \( m_H \) is obtained by the analysis of the combined full data sets from 2011 and 2012:

\[
m_H = 125.5 \pm 0.2^{+0.5}_{-0.6} \text{(syst)} \text{GeV}
\]

The individual mass measurements and their combination are shown in Figure 1.9: they are compatible within 2.4\( \sigma \).

The signal strength, \( \mu \), represents the local significance of the signal and it is defined as the ratio of the measured cross-section multiplied by the branching ratio and the SM prediction:

\[
\mu = \frac{\sigma \times BR}{\sigma_{SM} \times BR_{SM}}
\]

(1.24)

It is a convenient observable to test the compatibility of the data with the background-only hypothesis, \( \mu = 0 \), and the SM Higgs hypothesis, \( \mu = 1 \). Assuming a Higgs mass value of 125.5 GeV, as previously measured, the individual
1.4. STATUS OF THE HIGGS BOSON SEARCHES AND MEASUREMENTS AT LHC

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>$m_H = 125.5$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>$\mu = 1.55_{-0.14}^{+0.33}$</td>
</tr>
<tr>
<td>Low $R_h$</td>
<td>$\mu = 1.7_{-0.3}^{+0.5}$</td>
</tr>
<tr>
<td>High $R_h$</td>
<td>$\mu = 1.7_{-0.3}^{+0.5}$</td>
</tr>
<tr>
<td>$\gamma\gamma$ mass (VBF)</td>
<td>$\mu = 1.9_{-0.6}^{+0.8}$</td>
</tr>
<tr>
<td>VH categories</td>
<td>$\mu = 1.3_{-0.2}^{+0.3}$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4l$</td>
<td>$\mu = 1.4_{-0.1}^{+0.1}$</td>
</tr>
<tr>
<td>VH+VH-like categories</td>
<td>$\mu = 1.3_{-0.3}^{+0.2}$</td>
</tr>
<tr>
<td>Other categories</td>
<td>$\mu = 1.4_{-0.3}^{+0.2}$</td>
</tr>
<tr>
<td>$H \rightarrow WW^* \rightarrow b\bar{b}$</td>
<td>$\mu = 0.99_{-0.11}^{+0.13}$</td>
</tr>
<tr>
<td>2 jet VBF</td>
<td>$\mu = 0.92_{-0.22}^{+0.22}$</td>
</tr>
<tr>
<td>0+1 jet</td>
<td>$\mu = 1.2_{-0.5}^{+0.5}$</td>
</tr>
<tr>
<td>Comb. $H \rightarrow \gamma\gamma, ZZ^<em>, WW^</em>$</td>
<td>$\mu = 1.3_{-0.11}^{+0.21}$</td>
</tr>
</tbody>
</table>

Total uncertainty on $\sigma$:

$\sigma_{(stat)} = 0.21$ $\sigma_{(sys)} = 0.15$ $\sigma_{(theo)} = 0.16$

Figure 1.10: The measured production strengths for a Higgs boson of mass $m_H = 125.5$ GeV, for diboson final states and their combination [35].

The best-fit value for the global signal strength factor $\mu$ does not give direct information on the relative contributions from different production modes. Therefore, in addition to the signal strength in different decay modes, the signal strengths of different Higgs production processes contributing to the same final state are determined. A common signal strength scale factor $\mu_{ggF+ttH}$ has been assigned to both gluon fusion production ($ggF$) and the very low rate $ttH$ production mode, as they both scale dominantly with the $ttH$ coupling in the SM. Similarly, a common signal strength scale factor $\mu_{VBF+VH}$ has been assigned to the VBF and VH production modes, as they scale with the $WH/ZH$ gauge coupling in the SM [35]. The results are reported in Figure 1.11: no significant deviation from SM couplings is observed, all results are compatible with each other, and with the SM, within 95% CL.

Another important test for the Higgs boson is the determination of its quan-
Figure 1.11: Likelihood contours for the diboson final states in the $(\mu_{ggF+ttH}, \mu_{VBF+VH})$ plane for a Higgs boson mass hypothesis of $m_H = 125.5$ GeV [35].

thus this hypothesis is tested against others: $0^-, 1^\pm, 2^\pm$ [36, 37, 38]. The measurement is performed independently in the diboson decay channels, $H \rightarrow \gamma\gamma$, $H \rightarrow WW \rightarrow l\nu l\nu$, $H \rightarrow ZZ \rightarrow 4\ell$, and it is based on combinations of different kinematic observables like the angular distributions of decay products in the resonance rest frame. The Landau-Yang theorem forbids the direct decay of a spin-1 particle into a pair of photons [39, 40], therefore, the spin-1 hypothesis is therefore strongly disfavoured by the observation of the process $H \rightarrow \gamma\gamma$. The measurement of the Higgs boson parity is performed in the channel $H \rightarrow ZZ \rightarrow 4\ell$ and is found to be “positive”, so in agreement with the SM expectation. Finally, the $0^+$ hypothesis against a $2^+$ scenario is tested as well. In this analysis the discriminating observables are dependent on the production mechanism, therefore, multiple scenarios are studied varying the fractions of production processes initiated by $qq$ and $gg$. The combination of the results from individual channels is performed through a likelihood fit and the $2^+$ hypothesis is excluded at a confidence level $> 99%$. 

$J^P = 0^+$

31
1.5 Limits of the Standard Model theory

The SM is presently our best description of particle phenomenology, its prediction has been intensively tested leading to impressive constraints of the theory itself. Nevertheless, on the base of principles of universality, elegance of the formulation and experimental consistence, criticism of the SM is rising. The SM is not considered a complete theory because it does not include gravity, does not provide a dark matter candidate and does not accommodate for neutrinos mass terms, all aspects for which there are instead experimental confirmations. Moreover, the SM does not completely explain the baryon asymmetry in the universe and even if it provides mass to the fermions, does not predict their large mass spectrum spanning about 5 orders of magnitude (0.5 MeV - 171 GeV) or more, if neutrinos masses are considered (eV scale or less). These unknowns contribute to the 19 free parameters of the SM, which from a theoretical point of view is considered an excessive number for a fundamental theory. Finally, there is the hierarchy problem: the high energy separation between the electroweak and the Planck scale generates large radiative corrections that ask for a not natural fine-tuning cancellation. This last issue has mostly stimulated the formulation of possible theories extending the SM in the last decades. Further information about some of the conceptual and experimental limits of the SM is given in the following sections.

The gravitational force

Presently the gravitational force is the least understood of all physical forces, and very little is known about is microscopic effects. A gravity mediator, the graviton, can be introduced in the theory in analogy to the other forces but with spin 2, however so far there are no experimental confirmations for its existence. Moreover the gravity may not be a force at all, but only a geometrical effect due to the bending described by General Relativity [41, 42]. Anyway, regardless of the possibility of a quantum formulation for the gravitational force, something is expected to happen at the Planck scale (1.22⋅10^{19} \text{ GeV}) where gravity would not be negligible anymore and would directly affect particle phenomenology.

Throughout the years, theories extending the Standard Model have been formulated to include gravity in a natural way. Some examples are the “grand unification” theories [43, 44] that aim to merge all forces into a single interaction defined by a larger gauge symmetry, and Supersymmetry theories [45, 46] that provide an additional symmetry allowing to convert fermions into bosons, as
required for a gravity unification, and including a dedicated gravitational sector. All these theories predict additional particles in the model but so far none has been yet observed. In particular, in the last years LHC experiments highly constrained the parameter space of new models pushing the mass limits for new observable particles to 700-800 GeV [47].

**Dark Matter**

A proof of the incompleteness of the SM comes from the inability of the SM to provide an explanation for all the mass of the universe, and its phenomenology. In the last years astrophysics experiments studying the motion of stars in galaxies and the galaxy orbits in galaxy clusters established the presence of Dark Matter, a matter that emits minimal to no light (or other electromagnetic radiation) but has gravitational effects [48]. The Dark Matter should account for a large part of the total mass in the universe but in the SM there is no particle description for it. The total matter described by the SM is only the 4% of the total matter in the universe.

Supersymmetry theories are appealing because they provide a Dark Matter candidate, but still no experimental observation is provided, like in searches looking for a direct Dark Matter pair production [49, 50]. The ATLAS Run 2 will be crucial for these searches, that could rule out some of the models.

**Neutrinos masses**

In the SM Lagrangian there is not right-hand component for the neutrinos, making them massless particles. This is in contrast with the observation of the neutrinos oscillation phenomena by atmospheric, solar and accelerator-based neutrino experiments [11, 12, 13]. To induce oscillation a mixing mechanism is required: the weak eigenstates must be a mix of the mass eigenstates with different masses. Hence neutrino masses cannot be all the same and certainly not all equal to zero. Presently the upper bound on neutrinos masses is less than 1 eV.

The measurements of the mixing parameters introduced by the oscillation mechanism can provide further information about the neutrino nature. For example, one fundamental point is to determine if the neutrinos are Dirac fermions like the other fermions of the SM, or if they are Majorana fermions, for which particle and anti-particle would coincide [51].
1.6. CONCLUSION

Hierarchy problem

The SM does not explain why the electroweak scale is by far lower than the Planck scale. As an effect of these two highly-separated scales the bare value of the Higgs mass receives high corrections through loop contributions. In fact these corrections are proportional to the next higher scale in the theory ($\delta m_H^2 \propto \Lambda^2$) that, if there is no new physics in between, is the Planck scale. Hence, the Higgs mass should be very large in contrast with the direct and indirect experimental constraints. The Higgs mass is indeed now measured to be 125.5 GeV [34], but also before the Higgs boson’s experimental discovery it was known that its mass should have been below 1 TeV in order to unitarize the WW scattering amplitude.

In order to keep the Higgs mass low, a very fine cancellation between the bare value of $\mu^2$ and the radiative corrections is necessary. This fine-tuning process does not seem to be very natural, therefore new theories are developed in order to provide a more natural cancellation of the radiative corrections. There are basically two different approaches. The first is to introduce a new symmetry protecting the Higgs mass, as done in Supersymmetry theories, while the second looks at the Higgs as a composite bound state with strongly interacting dynamics at the TeV scale [52, 53]. Once again no experimental evidence has been found yet, constraining the parameter space for the models beyond the SM.

1.6 Conclusion

In the last 50 years theoretical and experimental successes led to the affirmation of the Standard Model as well-established quantum field theory describing particles and their interactions.

The start of the LHC opened an exciting time for particle physics culminating with the discovery of a new particle consistent with the predicted Higgs boson. The ATLAS and CMS experiments have already started an intense physics program to measure the properties of this particle, and so far everything is found to be compatible with the Standard Model expectations, thus providing further confirmation of the theory. However, the level of precision achieved in the coupling measurements leaves still room for new physics, thus making future LHC runs at higher center-of-mass energies very attractive.

Beyond the Higgs measurements, both ATLAS and CMS have a wide physics program for direct searches of new particles, stimulated mainly by the indirect observation of Dark Matter and by the unexplained large separation between the
electroweak and the Planck scale. Also these searches look with interest at future runs where the higher center of mass energy could increase the sensitivity to new phenomena.

The results so far achieved are just the beginning of a new exciting time during which we expect to improve our understanding of fundamental matter and find answers to the open questions of particle physics.
1.6. CONCLUSION
Chapter 2

The Large Hadron Collider and the ATLAS experiment

The Large Hadron Collider (LHC) is presently the largest and the most powerful particle accelerator in the world. During its first four years of running the data collected and analyzed by the LHC experiments have provided exciting physics results. First of all stands the observation of the Higgs boson [6, 7], followed by the investigation of the fundamental forces of nature up to the TeV scale, an energy regime never explored before, thus opening a new era for particle physics. In 2015, after the long shut-down, LHC will operate at its design conditions and will reach new frontiers of energy and luminosity, further increasing the physics analyses potential and the discovery power for new phenomena.

To completely exploit the physics potential provided by the LHC collisions, the LHC experiments have to face and find solutions for unprecedented technical challenges of complex mechanical structures, radiation tolerant electronics, fast data acquisition and high precision measurements, continuously stimulating engineering innovation and the development of new technologies.

More information about the LHC complexity and the run conditions are reported in Sections 2.1 and 2.2. A brief description of the experiments operating at LHC and their physics reach is given in Section 2.3. Finally, a more detailed discussion about the ATLAS experiments and its sub-detectors is reported in Section 2.4.
2.1. THE LHC COLLIDER

The Large Hadron Collider (LHC) \[\text{[54, 55, 56]}\] is a proton-proton (pp), ion-proton (Pb-p) and an ion-ion (Pb-Pb) collider located at CERN, near Geneva, Switzerland. It is installed in the same 27 km long underground tunnel which housed the Large Electron Positron (LEP) \[\text{[57]}\] until 2000. Since LHC collides particles of the same charge, two separate beam lines with opposite magnetic fields are needed to deflect the particles into circular trajectories. The oppositely running particle beams are finally collided in four dedicated interaction points instrumented with large experiments.

The LHC is the last stage of the acceleration chain shown in Figure 2.1 and composed of a series of particle accelerators that progressively increase the energy of the proton beams \[\text{[58]}\]. The beams are first accelerated to 50 MeV using a linear accelerator (LINAC2), then they are further accelerated up to 1.4 GeV by a circular booster (BOOSTER) and then up to 26 GeV by the Proton Synchrotron (PS). Before being transferred to the LHC, the proton beams are injected to the Super Proton Synchrotron (SPS), where protons reach the minimum energy at which the LHC can maintain a stable beam, 450 GeV. Finally, in the LHC ring the acceleration is performed by radio-frequency (RF) cavities. A 400 MHz

Figure 2.1: The LHC collider: the figure shows the acceleration chain for both proton and heavy ion beams \[\text{[54]}\].
superconducting system increases the beam energy by 485 keV at each turn until it reaches the designed energy, 3.5 TeV for 2011 runs and 4 TeV for 2012 runs. Because the LHC is a proton collider, energy losses from synchrotron radiation are small: $\sim 10^{-9}$ of the proton’s energy.

To allow the acceleration through the RF cavities and the monitoring of the beams, the colliding particles are injected in the acceleration chain in “bunches”. Bunch properties like the number, intensity, frequency and collimation have a direct impact on the collider performances. A more complete discussion about these properties and their effects can be found in the next section.

2.2 Luminosity and pile-up conditions

The main purpose of experiments at particle colliders is the search for rare processes like the production of the Higgs boson or new physics beyond the Standard Model, characterized by a small cross-section $\sigma$. In order to observe these rare processes, it is necessary to maximize the rate $dN/dt$ of the process, that is linearly related to the instantaneous luminosity:

$$\frac{dN}{dt} = \sigma L$$

(2.1)

The luminosity does not depend on the physics process but only on beam-parameters and can be expressed by:

$$L = \frac{f n N_1 N_2}{A}$$

(2.2)

where $n$ is the number of colliding bunches, $N_1$ and $N_2$ is the number of particles in each bunch, $f$ is the accelerator frequency and $A$ is the inverse of the beam cross-section. The values for the main detector parameters during 2010, 2011 and 2012 runs, compared with the design values, are reported in Table 2.1.

The peak luminosity is the maximum value of the instantaneous luminosity. Since during a fill (the period the beams are kept colliding) the instantaneous luminosity drops as the beams lose intensity, the peak luminosity is reached at the beginning of a fill. Figure 2.2 shows the peak luminosity as a function of the data taking time.

Beside holding the luminosity record, LHC is presently the accelerator that collides particles at the highest center-of-mass energy, $\sqrt{s}$ (twice the beam energy). After the first collisions at $\sqrt{s} = 900$ GeV in November 2009, LHC increased the beam energy to reach $\sqrt{s} = 2.36$ TeV in December 2009 (first world
2.2. LUMINOSITY AND PILE-UP CONDITIONS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>design</th>
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</thead>
<tbody>
<tr>
<td>Beam energy [TeV]</td>
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<td>4</td>
<td>7</td>
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<tr>
<td>$\beta^*$ in IP 1 and 5 [m]</td>
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<td>1.5/1.0</td>
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<td>Bunch spacing [ns]</td>
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<tr>
<td>Max. n. of bunches</td>
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<td>1380</td>
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<tr>
<td>Max. n. of p per bunch</td>
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<tr>
<td>Peak luminosity [cm$^{-2}$s$^{-1}$]</td>
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<td>$3.7\times10^{33}$</td>
<td>$7.7\times10^{33}$</td>
<td>$1\times10^{34}$</td>
</tr>
<tr>
<td>Max. $\langle \mu \rangle$</td>
<td>4</td>
<td>17</td>
<td>37</td>
<td>19</td>
</tr>
</tbody>
</table>

Table 2.1: Setup values of the main detector parameters for runs in 2010, 2011, 2012 and comparison with the design values [59]. IP 1 and IP 5 are the interaction points where the two LHC general purpose experiments, ATLAS and CMS, are located. $\langle \mu \rangle$ is the average number of collision per bunch crossing.

Figure 2.2: Peak luminosity as a function of the data taking time [60].
energy record) and further increased it to reach $\sqrt{s} = 7$ TeV for 2010 and 2011 runs and $\sqrt{s} = 8$ TeV for 2012 runs. Currently the machine is in a shut-down phase to be prepared to run at the design $\sqrt{s} = 14$ TeV in 2015.

By integrating the rate for a process in a certain period of time, one gets the estimate of the total number of events ($N_{tot}$) recorded in that period:

$$N_{tot} = \int dt L \times \sigma \quad (2.3)$$

The quantity $\int dt L$ is the integrated luminosity, usually it is expressed in inverse of cross-section units (i.e. fb$^{-1}$) and it is a measurement of the collected data size. The integrated luminosity recorded by ATLAS is shown in Figure 2.3 as a function of the data taking time. In this thesis all the datasets corresponding to the total integrated luminosity recorded by ATLAS, 21.3 fb$^{-1}$, are used.

According to equation 2.2 an increase in the luminosity can be achieved by squeezing the beams and reducing their transverse size$^1$, or by increasing the number of protons per bunch (up to $1.7 \times 10^{11}$ at the end of the 2012 run) or increasing the number of bunches (1380 in the 2012 run). However, there are

---

$^1$The beams are squeezed in the transverse plane by magnetic quadrupoles and are confined in an area of $O(\mu m \times \mu m)$ at the interaction points.
2.2. LUMINOSITY AND PILE-UP CONDITIONS

Figure 2.4: $\langle \mu \rangle$ distribution expressing the pile-up level for ATLAS physics runs at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV [60].

limitations on these parameters, such as the beam-beam limit, the long-range beam-beam interactions, the electron cloud effects and machine protection. Furthermore, the high luminosity introduces some experimental difficulties as well, such as the presence of pile-up generated by additional $pp$ interactions occurring in the same bunch crossing as the hard collision of interest. This pile-up is a consequence of the high overall $pp$ cross-section. The pile-up can be classified as "in-time" if the multiple $pp$ interactions arise from the same bunch crossing, or as "out-of-time" if the interaction are originated from different bunch crossing during the time taken for the detector to process the signal from a single event.

The in-time pile-up is affected by the focusing of the beams and by the number of protons in each bunch. Since the number of protons is the same for each beam ($N_1 = N_2$ in equation 2.2) this contribution is particularly important because it has a quadratic effect. As one example moving from the low luminosity runs characterized by $N \sim 8 \cdot 10^{10}$ to higher luminosity runs with $N \sim 1.45 \cdot 10^{11}$ the fraction of events with pile-up increases by more than 50%. Experimentally this is evaluated by the number of reconstructed primary vertices, $N_{PV}$.

The out-of-time pileup is a detector effect due to the integration time of the readout electronics. Its effects are highly dependent on the detector system, and the beam conditions, mainly the bunch spacing time. For example, the
bunch-spacing decreased from 150 ns in 2010 to 75 ns and then to 50 ns in 2012, which strongly increased the contribution of the out-of-time pile-up in the ATLAS Liquid Argon calorimeters. Experimentally it can be evaluated looking at the average number of interactions per bunch crossing \( \langle \mu \rangle \) as shown in Figure 2.4 for different physics runs.

2.3 The LHC experiments

The LHC beams collide in four different interaction points where the large experiments are located: ATLAS (A Toroidal LHC ApparatuS) [1], CMS (Compact Muon Solenoid) [2], ALICE (A Large Ion Collider Experiment) [61] and LHCb (LHC beauty experiment) [3]. All of them are aiming to better understand the fundamentals of nature and to answer the open questions concerning particle and astroparticle physics.

**ATLAS and CMS** are general purpose detectors with broad physics programs including both Standard Model studies and searches for new physics. B-physics and heavy-ions studies are pursued as well. After the observation of the Higgs boson, the particle responsible for the origin of mass and the particles mass spectrum, the study of its properties has become one of the main goals. All these measurements and searches address the open questions of the Standard Model, like the unification of forces (including gravitation) and the presence of the dark matter. Both experiments were designed to operate at the highest luminosity achievable at the LHC but they rely on different detection system and technologies. A more detailed description of the ATLAS detector will be given in the next chapter.

**ALICE** is specialized in heavy-ion physics and is devoted to the characterization of quark-gluon plasma, a phase present in the early universe and characterized by extremely high temperature and densities. It can help explaining why quarks and gluons are never observed as free particles but always bound together confined inside composite particles, and why only 1\% of the proton and neutron mass is given by the quark mass.

**LHCb** is devoted to b-quark physics and precise CP violation measurements, addressing the question of the asymmetry between matter and antimatter in the universe. Moreover, B-physics analyses can be sensitive as well to
new physics through loop processes. LHCb is designed to operate at a luminosity almost two orders of magnitude lower than the nominal one.

## 2.4 The ATLAS experiment

The ATLAS detector is optimised for the high-intensity and high-energy LHC collision environment, described in Section 2.2. It provides high precision measurements and the identification of rare processes of physics interest, with cross-sections many orders of magnitude below the total pp cross-section dominated by QCD. The comparison between the cross-section of Standard Model processes, Higgs production processes and the total cross-section is shown in Figure 2.5 as a function of the center-of-mass energy.

As most of the experiments at beam-beam colliders, ATLAS has been designed with a cylindrical layout, a forward-backward symmetry with respect to the interaction point and a nearly hermetic system in order to detect as much as possible all the particles generated by the LHC collisions and to fully reconstruct the physics event.

To measure the particle energy and momentum in a broad \( p_T \) spectrum (from hundreds of MeV to some TeV), and to have an efficient particle identification, ATLAS is divided into sub-detectors employing different technologies, with different granularity and radiation resistance, that surround the interaction point, as shown in Figure 2.6. The innermost detector is a precision tracking system operating in a solenoidal magnetic field. It uses the measurement of the bending radius to reconstruct the momenta of charged particles and interaction vertices. The middle layer consists of the calorimetric system, divided into an electromagnetic and hadronic calorimeters, which provide the energy measurements of both neutral and charged particles. Finally, the outermost detector is the muon spectrometer that, in combination with a dedicated toroidal magnetic field, measures the muon momenta. Weakly interacting particles as neutrinos or new particles foreseen by Standard Model extensions do not interact with the detector and their contributions can be determined from the energy balance of the event. A summary of the interaction of different particles through the ATLAS detector is sketched in Figure 2.7.

Further information about the ATLAS sub-detectors are given in Sections 2.4.2 to 2.4.4, while the particle reconstruction, identification and calibration are discussed in Section 3.2. Finally, the ATLAS trigger system is described in
Figure 2.5: Cross-sections for some interesting physics processes as a function of the center-of-mass energy. The discontinuity at $\sim 4$ TeV is from the transition from proton-anti-proton collisions at the Tevatron on the left to proton-proton collisions at the LHC on the right. The vertical lines indicate the running energy of the Tevatron (1.96 TeV), the running energy of the LHC in 2011 (7 TeV), in 2012 (8 TeV) and the possible future running energy (14 TeV) [62].
2.4. THE ATLAS EXPERIMENT

Figure 2.6: The ATLAS detector: the inner tracking detector surrounds the beam pipe and it is followed by the electromagnetic calorimeter, the hadronic calorimeter and the muon spectrometer [1].

Section 2.4.5.

2.4.1 ATLAS coordinate system

ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the $z$-axis coinciding with the axis of the beam pipe. The $x$-axis points from the IP to the centre of the LHC ring, and the $y$ axis points upward.

The $x$ and $y$ axes define the transverse plane, where cylindrical coordinates $(r, \phi)$ are used, $\phi$ being the azimuthal angle around the beam pipe.

Since the partons that give rise to the signal process of interest carry an a priori unknown fraction of the proton momentum, the overall boost of the collision is not known. For this reason, boost-invariant quantities are preferred.

Therefore, a convenient way of expressing the polar angle, $\theta$, is through the pseudorapidity, $\eta$, that transforms additively under boosts in the $z$-direction and it is defined as:

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

(2.4)
The pseudorapidity is a geometrical quantity and it is the limit case for massless particles of the rapidity, \( y \):

\[
y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right)
\] (2.5)

The difference in rapidity is as well a Lorentz-invariant but it depends not only by the polar angle but also on the mass of the particle.

Finally, boosts along the beam axis also do not affect the azimuthal angle, hence a Lorentz-invariant distance \( R \) can be defined in the \( \phi - \eta \) plan:

\[
R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2}
\] (2.6)

### 2.4.2 The tracking system

Tracking systems rely on the measure of the positions of charged particles in different radial layers of the detectors to perform the track reconstruction and on the measure of the curvature radius due to the bending of the magnetic field to compute the track momentum according to: \( p_T[GeV] = 0.3 \times B[T] \times R[m] \).

ATLAS has two separate superconducting magnet systems to provide the magnetic fields for the inner detector and the muon spectrometer. The structure is shown in Figure 2.8 and consists in:
2.4. **THE ATLAS EXPERIMENT**

![Sketch of the ATLAS magnetic system](image)

**Figure 2.8:** Sketch of the ATLAS magnetic system [64].

A **central solenoid** providing an almost uniform 2 T magnetic field for the inner detector. The field is parallel to the beam axis and bends particles in the transverse plane.

A **barrel air-core toroid** consisting of 8 independent coils and providing a peak magnetic field of 4 T for the muon spectrometer. The field is mostly perpendicular to the muon trajectories and deflects them in the $\eta$ direction. Since muon travels mainly through the air the degradation in resolution due to multiple scattering is minimized.

Two **endcaps air-core toroids** providing a peak magnetic field of 4 T for the muon spectrometer and bending charged particles in the $\eta$ direction.

**The inner detector**

The inner detector [65, 66] is the closest sub-detector to the beam pipe and to the interaction point. It is highly granular to allow reconstructing tracks from individual charged particles at high precision in a high particle flux environment. Other features of the inner detector are very precise particle momentum measurements, highly efficient vertex reconstruction and precise and highly efficient primary vertex and secondary vertex (from e.g. b-quark decays) identification.

Precise tracking is achieved by providing few but high-precision space points (track hits) at small radii close to the interaction point, and a larger number of lower precision points at larger radii by combining the measurement from three sub-detectors: the pixels, the SCT and the TRT, that are highlighted in Figure 2.9.

Each of the three sub-detectors is divided in a barrel region, where the detector modules are laid out in cylindrical layers, and an endcap region, where disks are
The Pixel Tracker [68] is the inner-most device, with the first of its three layers positioned at 5 cm from the interaction point. All the layers consist of high-precision and high-efficiency semiconductor modules with a tight bi-dimensional segmentation that provides high granularity. It results in the measurement of three high-resolution points with a spatial resolution of better than 14 µm in the r-ϕ plane.

The SCT (Semi-Conductor Tracker) [66] consists of silicon microstrip layers. It contributes with up to eight high-resolution tracking points with a spatial resolution of better than 20 μm in the r-ϕ plane.

The TRT (Transition Radiation Tracker) [69, 70] is composed by straw tubes filled with gas interleaved with polypropylene fibers and foils. A high-voltage potential is applied to collect the ionization given by the passing charged particles. It provides 36 points with lower resolution with respect to the inner layers (<0.17 mm in the r-ϕ plane). The TRT also helps in discriminating electrons over other particles, since when electrons pass through the material between the straw tubes they generate X-rays.
2.4. THE ATLAS EXPERIMENT

![Image of ATLAS physics event](image)

Figure 2.10: From the top, an ATLAS physics event with: 2 vertices, 7 vertices and 25 vertices [71].

In presence of pile-up, the number of primary reconstructed vertices ($N_{PV}$) increases with the number of additional $pp$ interaction, making the tracking environment denser and denser, as shown in Figure 2.10. Despite such compelling background the track and the vertex performance in 2012 allowed for a high efficiency for the $N_{PV}$ reconstruction, thus making $N_{PV}$ a stable and unbiased estimator for the in-time pile-up. The first primary collision vertex is chosen as the one with the hardest-scatter contribution, i.e. the maximum $\sqrt{\sum_{track}p_T^2}$. The possibility to associate, where possible, energy contributions to their specific vertex, and the insensitivity of the tracker to out-of-time pile-up, makes $N_{PV}$ a powerful variable to identify and suppress the pile-up contribution.

**The muon spectrometer**

Muons are the most penetrating particles detected by ATLAS and they are able to pass through the inner detector and the calorimeter without being absorbed.
Therefore the last layer of the detector, the muon spectrometer [1, 66], was designed for triggering the muons and for measuring their electrical charge and momenta. Different types of muon chambers are employed to achieve these tasks:

**Monitored Drift Tube chambers (MDT)** are high-precision chambers, the position of muons can be determined to 80 $\mu$m. They are employed in the central region for the measurement of the muon momenta. Since the charge drift time for these chambers is larger than the colliding bunch spacing they need to be integrated by fast trigger chambers tagging the collision event.

**Cathode-Strip Chambers (CSC)** are multiwire proportional chambers with high resolution muon position can be determined to 60 $\mu$m. Since they have high rate capability and time resolution, they are employed in the forward region. They withstand the demanding rate and background conditions, and can cope with the high particle multiplicities in the inner-most tracking layer close to the beam pipe.

**Trigger Chambers** provide a fast response within 15-25 ns, and can tag the bunch crossing of interest. They are divided into Resistive Plate Chambers (RPC) installed in the barrel region ($|\eta| < 1.05$) and Thin Gap Chambers (TGC) installed in the endcap ($1.05 < |\eta| < 2.4$). They also provide a second coordinate measurement for muons.

### 2.4.3 The calorimeter system

The calorimeter system [1] measures the energy and position of electrons, photons and hadronic particles, following their shower development and measuring the absorbed energy. For precise measurements of jets and missing transverse momentum ($E_T^{\text{miss}}$) the ATLAS calorimeter is built with a full azimuthal coverage and an almost hermetic $\eta$ coverage extending up to $|\eta| = 4.9$. An optimal performance through the whole $\eta$ range is provided using different techniques for the barrel and endcap regions, according to the demands of a wide range of physics process and the varying challenges from the radiation environment.

The system is primarily divided into an electromagnetic and a hadronic calorimeter to take into account the difference in the development of electron or photon showers with respect to hadronic ones, and then into seven sub-detectors as shown in Figure 2.11: the presampler barrel (PEMB) in $0 < |\eta| < 1.8$ and endcaps (PEMEC) in $1.5 < |\eta| < 1.8$, the electromagnetic calorimeter barrel (EMB) in $|\eta| < 1.475$ and endcaps (EMEC) in $1.375 < |\eta| < 3.2$, the hadronic
2.4. THE ATLAS EXPERIMENT

Figure 2.11: ATLAS calorimeter system. It consists of an electromagnetic calorimeter (closer to the beam pipe) and a hadronic calorimeter which use different technologies to contain the different shower development of electromagnetic and hadronic particles, respectively. Then each detector is divided into barrel, endcap and forward according to the $\eta$ coverage [72].

Calorimeter barrel (TILE) in $|\eta| < 1.7$ and endcaps (HEC) in $1.5 < |\eta| < 3.2$, the forward calorimeters (FCAL) in $3.2 < |\eta| < 4.9$. Detailed information about the pseudorapidity extensions, segmentation and granularity of each calorimeter are summarized in Table 2.2.

All of them employ a sampling technique alternating layers of absorber material, where the shower is generated, to layers of active medium, where the shower energy is detected. As active medium, Liquid Argon (LAr) [73] has been employed for all the calorimeters, apart the Tile calorimeters, for its intrinsic linear behavior, radiation-hardness and stability of response over time. On the other hand, the integration time for the electronic pulse is quite slow, about 400 ns making these systems very sensitive to pile-up. The Tile calorimeter, instead, uses a scintillating material characterized by a faster response, therefore, pile-up effects are much less significant.

ATLAS calorimeters are non compensating: the hadron response is lower than the response to electromagnetically interacting particles. Usually, the hadron contribution is corrected applying a proper calibration either before the physics
## Chapter 2: The Large Hadron Collider and the ATLAS experiment

<table>
<thead>
<tr>
<th>Calorimeter</th>
<th>Coverage</th>
<th>Granularity ($\Delta \eta \times \Delta \phi$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EM calorimeter</strong></td>
<td><strong>barrel</strong></td>
<td><strong>end-cap</strong></td>
</tr>
<tr>
<td>Presampler</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>Sampling 1</td>
<td>$</td>
<td>\eta</td>
</tr>
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<td></td>
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<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sampling 2</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td></td>
<td></td>
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<tr>
<td>Sampling 3</td>
<td>$</td>
<td>\eta</td>
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<table>
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<tr>
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<th><strong>barrel</strong></th>
<th><strong>extended barrel</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling 1</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>Sampling 2</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>Sampling 3</td>
<td>$</td>
<td>\eta</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Hadronic end-cap calorimeter</strong></th>
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<td></td>
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</table>

<table>
<thead>
<tr>
<th><strong>Forward calorimeter</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Samplings 1-3</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

$a |\eta| < 1.4$, $b 1.4 < |\eta| < 1.475$, $c 1.375 < |\eta| < 2.5$, $d 2.5 < |\eta| < 3.2$, $e 1.5 < |\eta| < 2.5$

Table 2.2: Pseudo-rapidity coverage, longitudinal segmentation and granularity of the ATLAS calorimeters [68].
object reconstruction at constituent level, or after the reconstruction including this effect in a scale factor applied to recover the correct energy of the reconstructed object.

**Electromagnetic calorimeter**

The electromagnetic (EM) calorimeters [73, 74] are optimized to detect, contain and measure electron and photon showers. An important parameter expressing the shower containment is the radiation length, $X_0$, defined as the mean distance over which a high-energy electron on average loses all but $1/e$ of its energy by bremsstrahlung. The EM barrel calorimeter has a thickness of $> 24X_0$ while the endcaps has a thickness of $> 22X_0$ for an almost full containment of the electromagnetic showers generated by electrons and photons. The region between the barrel and the endcaps (crack region), $1.375 < |\eta| < 1.52$, contains additional material to instrument and cool the inner detector, and usually it is excluded from offline analysis for a precise identification and measurement of electrons candidates.

The EM calorimeters employ a lead-LAr technology with accordion-shape absorbers and electrodes, as shown in Figure 2.12. A high-voltage potential is placed through the electrodes across the medium (ionization gap) in order to collect the charges from the ionization produced by the passage of particles through the LAr. The width of this gap varies with the pseudorapidity due to the accordion geometry, therefore, the high-voltage potential needs to vary accordingly to maintain a constant calorimeter response (defined as the measured fraction of the energy of the incident particle) as a function of the pseudorapidity.

All charged particles produced in the development of an electromagnetic (induced by electrons and photons) or hadronic (induced by neutral and charged hadrons) cascade and entering the LAr generate an ionization signal in form of an electric current across the LAr gap [75]. This current is measured. To reduce and control fluctuations between the energy invested into the ionizations and the resulting current, the LAr is kept at a stable and constantly monitored temperature of 88 K and a stable density, by a dedicated cryogenic system.

Once the ionization charge is collected, it is transformed by the ATLAS electronics in a bipolar pulse shape signal, the amplitude of which gives the energy measurement. The integral of the whole pulse shape is 0, as it is characterized by a positive component and a long negative tail as shown in Figure 2.13. This approach was chosen to have an average cancellation of in-time and out-of-time
pile-up for collisions happening at the nominal run conditions with a bunch spacing of 25 ns.

The accordion geometry is an innovative design to provide full and symmetric coverage in $\phi$ without cracks, high granularity and a segmentation in depth. Over the region devoted to precision physics, the EM calorimeter is segmented into three longitudinal sections: strips, middle and back.

The strips is the first layer, it is finely segmented along $\eta$, thus providing a high resolution, an accurate position measurement and discriminating power to distinguish photons from decaying neutral pions ($\pi^0 \rightarrow \gamma\gamma$).

The middle is the the second layer and collects the largest fraction of the energy of the electromagnetic shower.

The back is the the third layer aiming to collect the tail of the electromagnetic shower.

Finally, the electromagnetic calorimeters, both in the barrel and endcap regions, are integrated with presamplers, instrumented with finely segmented
2.4. THE ATLAS EXPERIMENT

Figure 2.13: The ATLAS bipolar pulse shape [76].

readout structures that provide a measurement of the energy lost in front of the electromagnetic calorimeters.

Hadronic calorimeter

The hadronic calorimeter is designated to measure the energy of jets, a bundle of collimated particles generated by the hadronization of quarks and gluons. Its absorption power is defined in terms of its depth in interaction length, \( \lambda \), which is defined as the mean distance traveled by a hadron before undergoing an inelastic interaction with matter. The hadronic calorimeter extends up to 9.7 \( \lambda \) in the barrel and 10 \( \lambda \) in the endcaps, thus ensuring good resolution for high-energy jets and limiting particles escaping into the muon spectrometer (punch-through). The material budget for each sub-calorimeter is reported in Figure 2.14 in terms of the interaction length and as a function of pseudorapidity.

The Tile calorimeter [77] (barrel region) is composed by scintillator tiles oriented radially to the beam pipe with steel as absorber material allowing to maximize the radial width while keeping the cost contained. The granularity is coarser with respect to the electromagnetic calorimeter but thigh enough to meet the resolution needs for proper jet reconstruction and energy measurement.
The endcap region features the HEC, a copper-LAr parallel plate hadronic calorimeter. The high radiation resistance of copper and LAr, and a high readout granularity, ensure that the calorimeter withstands the high particle fluxes and pile-up characterizing the regions closer to the beam pipe. The HEC consists of two independent wheels per endcap that cover the region $1.5 < |\eta| < 3.1$, overlapping both with the Tile and Forward calorimeters. Each wheel is divided into two longitudinal segments, for a total of four layers per end-cap.

**Forward calorimeter**

The forward calorimeters increase the calorimeter coverage towards the beam pipe, thus allowing the detection of forward physics objects and improving the resolution for the $E_T^{\text{miss}}$ measurement.

They are approximately 10 interaction lengths deep, and on each side consist of three modules along the beam axis direction. All of them employ LAr as active medium with different choices for the absorber medium. The first module employs copper and is optimized for electromagnetic shower measurements, while the other two employ tungsten and measure predominantly the energy of hadronic particles.

Since the forward calorimeters are located in the highest pseudorapidity region, they have to cope with very intense particle fluxes. Therefore, in order to deal with pile-up, a special matrix geometry was designed consisting in reg-
2.4. THE ATLAS EXPERIMENT

<table>
<thead>
<tr>
<th>Calorimeter</th>
<th>Particle</th>
<th>Energy Resolution</th>
<th>$a$ (% $\sqrt{\text{GeV}}$)</th>
<th>$c$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromagnetic</td>
<td>electrons</td>
<td>10.0 ± 0.4</td>
<td>0.4 ± 0.1</td>
<td></td>
</tr>
<tr>
<td>Hadronic End-Cap</td>
<td>pions</td>
<td>70.6 ± 1.5</td>
<td>5.8 ± 0.2</td>
<td></td>
</tr>
<tr>
<td>Forward</td>
<td>electrons</td>
<td>28.5 ± 1.0</td>
<td>3.5 ± 0.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>pions</td>
<td>94.2 ± 1.6</td>
<td>7.5 ± 0.4</td>
<td></td>
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<tr>
<td>Tile</td>
<td>pions</td>
<td>56.4 ± 0.4</td>
<td>5.5 ± 0.1</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.3: Resolution of the different calorimeters for pions and electrons evaluated with test beam data, given by the stochastic term $a$ and the constant term $c$ as in equation 2.7. The constant term for the full electromagnetic calorimeter is expected to be around 1% [1].

Calorimeter performance

The energy resolution of each sub-calorimeter is usually evaluated with the following expression:

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$ (2.7)

the stochastic term ($a$) is the contribution arising from stochastic fluctuation in the energy measurements. The noise ($b$) and the constant ($c$) term are added in quadrature to account respectively for noise due to the calorimeter electronics and pile-up, and for energy that might be lost in non-instrumented areas of the detector, in addition to effects from uncorrected channel-to-channel signal inefficiencies. The measured resolution performance for different calorimeters is summarized in Table 2.3. Figure 2.15 reports the electronic and pile-up noise for each sub-calorimeter as a function of the pseudorapidity showing an increasing of the noise moving towards forward calorimeters. In particular, at high luminosity the noise in the endcaps and forward region is dominated by the pile-up contribution.
Figure 2.15: Electronic and pile-up noise for LAr subcalorimeters for $\langle \mu \rangle = 14$ [78]. At high luminosity, the noise in the endcaps and forward region is dominated by pile-up.

2.4.4 The forward detectors

The ATLAS experiment has detectors also in the most forward regions to provide inputs about very forward particle flow, including the measurement of the instantaneous luminosity, trigger events and control the general behavior of the experiment [1, 79].

**LUCID (LUminosity Cherenkov Integrating Detector)** is composed by two symmetric arms deployed at about 17 m from the ATLAS interaction point. The main aim of this detector is to monitor the luminosity delivered by the LHC machine to the ATLAS experiment.

**ALFA (Absolute Luminosity For ATLAS)** provides a luminosity measurement looking at elastic scattering at small angles (3 $\mu$rad). In order to achieve this measurement the two detector stations have to be placed far away from the interaction point (240 m) and as close as possible to the beam.

**ZDC (Zero-Degree Calorimeters)** has the main aim to detect forward neutrons and photons with $|\eta| > 8.3$, in both proton-proton and heavy-ion collisions. It measures the luminosity recorded by ATLAS, moreover, its inputs are used to reduce backgrounds created by beam-gas and beam-halo...
2.4. THE ATLAS EXPERIMENT

effects, by requiring a tight coincidence from its two arms.

**BPTX** stations are located along the LHC on both sides of ATLAS, 175 m away from the interaction point. They are used for both L1-trigger and for the monitoring of beams and timing signals.

**MBTS (Minimum Bias Trigger Scintillators)** consist of two sets of scintillator counters installed in the inner face of the LAr endcap cryostat. They are used to trigger on minimum bias events.

2.4.5 The trigger and the data acquisition system

The high LHC luminosity gives a bunch collision rate of 40 MHz but current technology does not allow recording all detector signals for each collision. However, most of the corresponding interactions are due to soft physics and therefore not of interest for high transverse momentum SM and discovery physics analyses. Hence a three level trigger system [1] is used in ATLAS to discriminate the interesting events due to the hard scattering and to reduce the data flow rate to 200 Hz.

The first level, L1, gets inputs from the trigger muon chambers and the calorimeter to search for high $p_T$ muons, electrons, photons, jets, and $\tau$ leptons decaying into hadrons, as well as large missing transverse momentum and large total energy. In addition, it is possible to turn on and off the $p_T$ thresholds for different objects and set the $p_T$ threshold levels, through a configurable trigger menu. In each event, if interesting objects are found, L1 defines one or more Region of Interest (RoI) providing the $(\eta, \phi)$ coordinate of the object and the criteria that it has passed. The L1 trigger takes about 2.5 $\mu$s to make a decision and reduces the interaction rate from 40 MHz to about 75 kHz. Events which pass the L1 selection are sent to the Data Acquisition system (DAQ) and to the next trigger step: the high level trigger (HLT).

The HLT is divided into Level2 (L2) and Event Filter (EF). The L2 trigger looks at the RoI defined by L1, and takes into consideration signals from the Inner Detector. It takes about 40 ms to make a decision and it is designed to reduce the trigger rate to about 3.5 kHz. Then data goes through the last step of the online selection, the EF, which has a decision time of 1 s and leads to a final rate of about 200 Hz. The EF uses algorithms similar to offline algorithms, including calibrations, alignment and electromagnetic field maps, to record the raw data (RDO).
2.4.6 ATLAS computing and analysis data model

The huge amount of data collected by the ATLAS detector needs a highly efficient and distributed computing system to be recorded, processed, stored and finally analyzed.

The computing toolkit relies on two basic aspects: a degree of hierarchy with distinct roles of the different computer facilities and a high degree of decentralization and sharing of computer resources based on the GRID paradigm [80].

The Analysis Data Model provides common interfaces and data objects which are necessary to ensure easy maintenance and coherence of the experiment software platform over a long period of time for a large collaboration as ATLAS. The data objects are created by the reconstruction program starting from the recorded raw data (RDO) [81]. The software framework used in ATLAS is called ATHENA, a C++ framework based on the GAUDI project [82]. Depending on the different level of information stored, different output formats are used: ESD, DESD, AOD and D3PD.

2.5 Conclusion

LHC is a powerful machine instrumented with large experiments able to achieve an impressive level of precision. Over the first three years of activity the machine, the experiments and the computing facilities performed brilliantly by exceeding all expectations. In particular, the luminosity was continuously increased and the accelerator delivered more than $6 \cdot 10^{18}$ of $pp$ collisions, allowing the LHC experiments to obtain important results quicker than expected.

During the last few days of activity, the space between bunches has been successfully reduced to 25 ns, in preparation for Run 2. The machine is now in a shut-down phase but an intense activity is under way to upgrade and consolidate the infrastructure to prepare LHC to safely operate at higher energy and luminosity. The major upgrade for the ATLAS detector concerns the tracking system: a fourth layer, the IBL (insertable B-layer), will be added closer to the beam pipe improving the tracking precision and ensuring good performance also for the high pile-up conditions that will characterize the Run 2.

All the valuable experience gained during the Run 1 and the one that will come with Run 2 is a precious starting point to further develop technologies and stimulate the engineer innovation for the subsequent high luminosity era.
2.5. CONCLUSION
Chapter 3

Physics object reconstruction

The proton-proton collisions at LHC produce many particles of different type resulting in a complex final state. In order to resolve this complexity, accurate and efficient particle reconstruction and identification has to be performed.

This is done by exploiting the different interactions of these particles with matter in dedicated ATLAS sub-detectors. The signals generated by these interactions feed into the reconstruction of the final state of a given collision event. The output of the reconstruction are the “physics objects”, representing individual particles and particle jets with their respective kinematics, and missing transverse momentum carried by non-interacting particles. The same algorithms used to reconstruct these objects in data are used for the Monte Carlo simulations needed to test physics analysis predictions and performance results. The full ATLAS simulation chain is described in Section 3.1, then the algorithms for particle reconstruction and identification are discussed in Section 3.2. Finally, since its importance for this thesis, special attention is dedicated to the missing transverse momentum reconstruction and calibration in Section 3.3.

3.1 Monte Carlo simulation

Monte Carlo simulations (MC) are widely used in ATLAS to test and extrapolate performance for different run conditions, to derive energy correction factors and to estimate backgrounds for physics processes.
3.1. MONTE CARLO SIMULATION

The MC production chain is generally divided into three steps: generation of the event and immediate particle decays, simulation of the particle interactions in the detector and digitization of the energy deposited in the sensitive regions of the detector into electronic signals corresponding to the ones generated in the readout of the ATLAS detector. The output of the simulation chain has a format identical to the output of the ATLAS data acquisition system. Thus, both the simulated and real data from the detector can then be run through the same ATLAS trigger and reconstruction software [83].

The information about stable particles (“truth” information) produced in each physics event is also recorded and can be processed in the reconstruction to measure the performance of the reconstruction software.

3.1.1 Event generation step

Event generators are indispensable tools for the modeling of the complex physics processes that are initiated by a \( pp \) interaction at LHC, potentially leading to the production of hundreds of particles per event. The generator is responsible for any prompt decays and stores any stable particle expected to propagate through a part of the detector. At this level, filter algorithms can be provided to select only interesting event topologies, kinematic phase spaces, or interesting particles for a specific physics channel.

Many event generators are available in ATLAS, like Pythia [84], Alpgen [85], Sherpa [86] and McAtNlo [87]. Pythia has been chosen as the default generator thanks to its easy use, speed, and robustness but it can be supplemented by other generators, either to obtain some estimate of the uncertainties, or when specialized generators are expected to give a better physical description in certain final states.

The description of the proton substructure is encoded in the parton distributions functions (PDFs), which are generally used by all event generators as external inputs. Then, according to the different models used to describe the color coherence effects, fragmentation and confinement, different parton shower and hadronization generators can be employed, such as Pythia or the combination of Herwig+Jimmy [88, 89] specially tuned for the underlying event at ATLAS.

Finally, specialized generators can be run in conjunction with general purpose generators to improve the accuracy for specific decays or specific final states. For example, the Photos and Tauola generators [83, 90, 91] are employed to respectively handle modeling of higher order electromagnetic radiation and tau...
decays where particular attention is paid to the tau polarization.

3.1.2 Detector simulation and digitization steps

In the simulation process, each particle provided by the event generator is propagated through a model of the full ATLAS detector. This task performed using the Geant4 (GEometry ANd Tracking) [92, 93], toolkit for the simulation of the passage of particles through matter. In Geant4 it is possible to encode detailed information about the particle interactions and the detector structure, such as the detector geometry including misalignments and distortions, the position and the extension of dead materials, the maps of the electromagnetic fields and the detector response.

Since its complexity, large computing resources are required to accurately model the detector geometry and the detailed physics descriptions in the standard ATLAS detector simulation. This put limits on the available statistics for the Monte Carlo simulation samples, some of which cannot be large enough to meet the requirements of specific physics studies, especially with increasing of the luminosity. This led to the development of some fast simulation strategies which enable faster production of large Monte Carlo samples.

The default fast simulation in ATLAS is Atlfast-II. It reduces the simulation time by one order of magnitude by means of parameterizations of the longitudinal and lateral energy profile of the electromagnetic and hadronic showers in the calorimeters combined with the standard simulation in the Inner Detector and Muon spectrometer. A further order of magnitude in simulation time can be gained using a fast track simulation (Atlfast-IIF) in the Inner Detector and Muon System based on simplified geometry and parameterizations of physics processes [94].

Activity from multiple pile-up interactions per bunch crossing is modeled by overlaying simulated minimum bias events, generated with Pythia and specially tuned for minimum bias interactions at the LHC, over the original hard-scattering event. Recently a pile-up overlay using real zero-bias data events [95] has been also tested providing encouraging results especially for the improved agreement between data and MC simulations.

As a final step, the energies deposited in the sensitive regions of the detector are recorded as “hits” containing the total energy deposition, position, and time. At this level the digitization process [95] is applied to perform the conversion of the energy deposited by particles into electronic signals reproducing the output
3.2. PHYSICS OBJECTS RECONSTRUCTION

given by the readout of the ATLAS detectors. It employs detailed modeling of
the signal formation, including the noise, signal shaping and digitalization, in the
real detector electronics.

3.2 Physics objects reconstruction

Starting from the recorded electronic detector signals, sophisticated algorithms
reconstruct tracks and calorimeter energy clusters. These are the primary ele-
ments for physics object reconstruction, particle identification and computation
of the particle energy and direction.

The particle reconstruction performance is tested on data and then compared
with MC simulation. Since any disagreement between data and MC is prop-
gagated directly into physics analyses, where mismodelling are observed, specific
parametrized corrections called “scaling factors” are computed to reflect MC par-
ticles reconstruction efficiency, isolation, energy resolution and scale, to match
the values observed in data. This significantly improves the accuracy of the yields
predicted by the simulation in physics analyses.

Systematic uncertainties on the scaling factors are also provided. Their im-
impact on a specific physics analysis depends on the relative importance of the
reconstructed physics objects in the final state of the considered analysis.

Calorimeter clustering algorithms

Incoming particles usually deposit their energy in many calorimeter cells, both
in the lateral and longitudinal directions (with respect to the particle direction
of flight). Clustering algorithms are designed to group these cells scanning the
whole calorimeter and to collect the total deposited energy into clusters. These
cluster energies are then calibrated to account for the energy deposited outside the
cluster and in dead material. The calibration depends on the incoming particle
type.

The cell grouping can be either performed with a fixed window size as done in
the sliding window approach used for electrons and photons, or with a variable
size based on the cell signal significance, as done in the topocluster approach used
for taus, jet and $E_{T}^{\text{miss}}$ [96]. In particular the topocluster approach is efficient
at suppressing noise, and thus improving the energy resolution of the physics
objects built from the formed topological clusters.
The topological clustering algorithm usually runs in two steps: the cluster building and the cluster splitting.

The cluster building starts with the identification of a seed cell with significant energy compared to the expected electronic and pile-up noise. This threshold is optimized to be $|E_{\text{cell}}| \geq 4\sigma_{\text{noise}}$. Then the cluster develops in the three dimensions by adding all the neighbouring cells with $|E_{\text{cell}}| \geq 2\sigma_{\text{noise}}$ and finally all the neighbouring cells of the accumulated ones are added as well, as sketched in Figure 3.1. This 4-2-0 scheme has been found to be the most performant configuration also in busy pile-up environments.

The cluster splitting searches for local maxima with energies larger than 500 MeV and larger than the energy of any neighbouring cells in the clusters built as described above. If a cluster contains more than one maximum it is split.

In order to correct for non-compensating calorimeter effects and energy losses, a calibration can be applied on the clustered cells. The default calibration in ATLAS is based on the local hadronic calibration (LCW) scheme [97, 98], that uses properties of clusters to calibrate them individually. It first classifies calorimeter clusters as electromagnetic or hadronic, according to the cluster topology, and then weights each calorimeter cell signal in clusters according to the cluster energy and the cell energy density. Additional corrections are applied to the cluster energy for the average energy deposited in the non-active material before and between the calorimeters and for unclustered calorimeter energy.

### 3.2.1 Electrons and photons reconstruction

Electrons and photons reconstruction and identification algorithms are designed to ensure a good discrimination against background objects such as hadron jets and stable performance over the full detector acceptance and over a broad energy range (few GeV to few TeV) [100]. In order to achieve this task, a combination of signals from the ATLAS sub-detectors is used, including electromagnetic calorimeter, inner detector and TRT.

The first step of the procedure consists in an efficient reconstruction of the calorimeter electromagnetic showers based on a “sliding-window” algorithm. The strategy of the algorithm is to group cells moving over the calorimeter a fixed window of size $N_\eta \times N_\phi = 3 \times 5$. A seed cluster is identified if the energy sum of

---

1 $\sigma_{\text{noise}}$ is the Gaussian width of the cell energy distribution measured in randomly triggered events.

2 $N_\eta, N_\phi$ are respectively the number of cells in the middle layer in the $\eta$ and in the $\phi$
3.2. PHYSICS OBJECTS RECONSTRUCTION

Figure 3.1: Sketch of the topological cluster building [99].

the window cells is above a threshold of 2.5 GeV [96]. The window size and the seed energy threshold are optimized to obtain the best reconstruction efficiency, to collect most of the energy deposited by the particle in the calorimeter, and at the same time to limit the fake rate due to electronic and pile-up noise.

The inner detector information is included to discriminate electrons from photons. Electromagnetic clusters are matched with the tracks extrapolated to the second EM calorimeter layer. If the cluster has no associated track the object is classified as a photon candidate, otherwise as an electron candidate. Then, electrons that are actually from converted photons are tagged looking for secondary vertices. This is of particular importance since the fraction of converted photons is significant, spanning from $\sim 30\%$ in the central region to $\sim 45\%$ in the endcap region [101].

In the identification process, criteria based on shape variables computed from the lateral and longitudinal energy profiles of the shower in the electromagnetic calorimeter and a veto on the energy deposited in the hadronic calorimeter are used to reject charged and neutral hadrons. For electrons, additional criteria are required to ensure a good track quality, strict track-cluster matching and direction, respectively. Each middle layer cell has size of $0.025 \times 0.025$. 

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high-threshold hits in the TRT. The selection criteria vary as a function of the reconstructed $\eta$ of the candidate to take into account significant change in the total thickness of the upstream material and variations in the calorimeter geometry or granularity. In particular the very fine granularity of the first EM calorimeter layer allows for a discrimination between single photon shower and two overlapping showers originating from a $\pi^0$ decay.

According to the tightness of the selection different working points can be defined [102]. For electrons, there are mainly three working points: loose, medium and tight. The most commonly used working point is the medium one that ensure a high-$p_T$ electron efficiency near to 90% at a few percent fake rate. Similarly, for photons two working points are defined: loose and tight. The photon purity is around 90% for isolated high energy tight photons but it is strongly reduced for non-isolated ones, to about 50% for low energy photons [103].

After the reconstruction, the sliding window cluster energy is calibrated with specific methods based on Monte Carlo simulation [104]. For electrons the energy is computed as a weighted average between the cluster energy and the track momentum. The $\eta$ and $\phi$ directions are usually taken from the corresponding track parameters at the vertex. The track refitting is performed with the Gaussian Sum Filter (GSF) algorithm [105], in order to account for the effects of radiative energy by bremsstrahlung, which can give deviations from the original charged particles path especially for high-energy electron.

The standard calibration is individually optimized for electrons, unconverted photons and converted photons and estimates separately four sources of energy loss.

The “front” component is the energy loss due to the amount of material in front of the calorimeter.

The “sampling” or “accordion” component is the energy loss due to dead material inside the calorimeter.

The “out of cluster” component is the energy loss laterally outside of the reconstructed cluster.

The “leakage” component is the energy loss longitudinally behind the electromagnetic calorimeter.

An in-situ calibration with collision data allows to determine the absolute energy scale and inter-calibrates the different regions of the calorimeters. Electrons
3.2. PHYSICS OBJECTS RECONSTRUCTION

Figure 3.2: Invariant $Z$ mass for electron pairs compared with the Monte Carlo simulation prediction. There is a good agreement between data, MC predictions and the fit results [106].

produced in $Z$ decays are used as shown in Figure 3.2. The derived calibrations and corrections are cross-checked with electrons from $W \rightarrow e\nu$ and $J/\psi \rightarrow ee$ events.

3.2.2 Muons reconstruction

Mainly two sub-detector systems are involved in muon identification and reconstruction: the Muon Spectrometer (MS) and the Inner Detector (ID). They provide independent momentum measurements that can be combined by specific algorithms to increase the purity and performances of the reconstructed muons. In specific cases also the energy deposited by the muon in the calorimeters, which is on average of about 2-3 GeV, can be used. This allow an optimal reconstruction performance over a large $\eta$ range and over a broad $p_T$ range (from a few GeV up to a few TeV) [100, 107].

In the identification process, according to the available information from different sub-detectors, muons can be classified as follow.

**Standalone muons** are reconstructed using only the MS information. This extends the coverage up to $|\eta| = 2.7$. The direction of flight and the impact parameter of the muon at the interaction point are determined by extrapolating the spectrometer track back to the beam line taking the energy loss
Combined muons are obtained by the combination of independent MS and ID measurements. The match is performed by a $\chi^2$ quality test. The combination improves the resolution with respect to the single ID and MS measurements and it allows rejection of muons from secondary interactions and from $\pi/K$ decays in flight.

Segment-tagged muons are identified only by segments in the MS, so the momentum can be reconstructed using only the ID information. The ID track is used as a seed and it is extrapolated to the first station of the MS to be matched, using a $\chi^2$ quality test, with track segments in the precision muons chambers. They are employed to recover a small inactive Muon Spectrometer region around $|\eta| \sim 1.2$.

Calorimeter-tagged muons are identified only by a track in the ID and by calorimetric information. The ID track is used as a seed and the associated energy deposits in the calorimeter are used to check the compatibility with the minimum ionizing particle hypothesis. These muons have lower purity but can help to recover acceptance in the un-instrumented region of the MS around $\eta \sim 0$.

The capability of the ATLAS detector to reconstruct muons on a wide $p_T$ range is shown in Figure 3.3, where the di-muon spectrum is shown.

The muon efficiency reconstruction (on average above 97%) and the momentum resolution (1.5-3 GeV) are measured using data-driven techniques employing $Z \rightarrow \mu\mu$ or $J/\psi \rightarrow \mu\mu$ decays. The comparison with MC simulation allows to derive scale factor corrections as a function of the muon momentum and pseudo-rapidity.

In ATLAS two independent algorithms, Staco and MuID, are available for the muon reconstruction. A third muon chain called Muons has been recently provided combining the previous approaches and it will be the default for ATLAS Run 2. For the results reported in this thesis only Staco muons are used.

3.2.3 Taus reconstruction

Tau leptons are the heaviest known leptons, with a mass of 1.777 GeV [109]. Due to this, taus are the only leptons for which also decays into hadronic particles are allowed. They occur in 64.8% of all tau decays [110]. In this decay mode
3.2. PHYSICS OBJECTS RECONSTRUCTION

Figure 3.3: Di-muon invariant mass spectrum for data from combined opposite sign muons. Visible peaks correspond to the different resonances reported in the plot [108].

(referred to as $\tau_{\text{had}}$), the tau decays to a $\nu_\tau$ in addition to one or more hadrons (predominantly pions). The relative branching fractions are reported in table 3.1.

With a proper decay length of 87 $\mu$m, tau leptons decay before reaching the detector and can only be identified through the reconstruction of their decay products. In the case of leptonic decays ($\tau \rightarrow \ell \nu_\ell \nu_\tau$), the decay products cannot be distinguished from prompt electrons or muons, therefore here after only hadronic decays are considered.

$\tau_{\text{had}}$ candidates are reconstructed using the jet anti-$k_t$ algorithm [111] with a distance parameter $R = 0.4$. They are seeded from jets with $E_T \geq 10$ GeV and $|\eta| \leq 2.5$. The tau candidate can be associated to a different vertex from the one with the highest $\Sigma p_T^2$ (identified as the primary vertex) by a Tau Jet Vertex Association (TJVA) algorithm [112]. Consequently, calorimeter cell and cluster directions are calculated in a coordinate system having the TJVA vertex as origin, and only tracks associated to this vertex are considered. Tracks passing the following quality criteria:

- $p_T \geq 1$ GeV
- $N_{\text{PIXEL}}^{\text{hits}} \geq 2$, $N_{\text{PIXEL}}^{\text{hits}} + N_{\text{SCT}}^{\text{hits}} \geq 7$
- $|d_0| \leq 1.0$ mm, $|z_0\sin\theta| \leq 1.5$ mm
Chapter 3: Physics object reconstruction

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>decay channel</th>
<th>BR</th>
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<tbody>
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<td>Hadronic decay</td>
<td>$\pi^\pm \nu$</td>
<td>11%</td>
</tr>
<tr>
<td></td>
<td>$\pi^\pm \pi^0 \nu$</td>
<td>25%</td>
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<tr>
<td></td>
<td>$\pi^\pm \pi^0 \pi^0 \nu$</td>
<td>9%</td>
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<tr>
<td></td>
<td>$\pi^\pm \pi^\pm \pi^\pm \pi^0 \nu$</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>other</td>
<td>5%</td>
</tr>
<tr>
<td>Leptonic decay</td>
<td>$e\nu\nu$</td>
<td>17%</td>
</tr>
<tr>
<td></td>
<td>$\mu\nu\nu$</td>
<td>17%</td>
</tr>
</tbody>
</table>

Table 3.1: Branching fraction for tau decay modes [109].

are then associated to the candidate if they fall within the core region, defined as $\Delta R < 0.2$, around the jet barycentre. According to the number of associate tracks, $\tau_{\text{had}}$ candidates are defined either as 1-prong (1 associated track) or multi-prong (mostly 3 associated tracks).

Due to the background from multi-jet processes, efficient tau identification techniques with large jet rejection are essential. The narrow shower shape and the small number of tracks characteristic of hadronic tau decays are useful in discriminating them from other signatures in the detector. But, since these single variable criteria are not enough to efficiently distinguish taus from jets and electrons, multivariate techniques are employed. The two main algorithms for the tau identification in ATLAS are: a projective likelihood method (LLH) and a boosted decision trees method (BDT) that is used in the $H \rightarrow \tau\tau$ analysis reported in this thesis. The BDT is fed with tracking information and calorimeter shape variables properly corrected to mitigate the pile-up effects on the output result.

Three working points for the tau identification are established based on the signal efficiency: loose, medium, and tight. For 1-prong (multi-prong) taus, these efficiencies are 70% (65%), 60% (55%), and 40% (35%), respectively.

Additional fake taus are generated by electrons that mimic the signature of a 1-prong $\tau_{\text{had}}$, and by muons if a muon track is associated with a sufficiently energetic calorimeter cluster. In order to reject these backgrounds a further BDT and cut-based approach is used for electrons and muons respectively [113].

In tau reconstruction, calorimeter topoclusters are already used calibrated at the LCW scale to account for the not-compensating calorimeter effects and for
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the energy lost in dead materials, yielding an improvement of the $\tau_{\text{had}}$ energy resolution with respect to the use of topological clusters at the EM scale. Nevertheless, in order to restore the true visible tau energy, a proper calibration (TES) is required to correct for energy lost before the calorimeters, for underlying event and pileup contributions, and for out-of-cone effects [114].

The TES calibration is based on simulated tau decays, with its systematic uncertainty including contributions from single particle response measurements, pile-up and material modeling. The single particle uncertainties are evaluated by in-situ measurements based on the comparison between the calorimeter energy measurements and the momenta measured in the Inner Detector ($E/p$). This evaluation is then combined with test-beam measurements for $|\eta| < 0.8$ and with an uncertainty estimated comparing different simulated shower models for $0.8 < |\eta| < 2.5$. In-time pile-up effects are corrected with an offset method while out-of-time pile-up effects are found to be less than 1% and thus negligible. The results for 1- and multi-prong taus in the central region of the detector are shown in Figure 3.4: the systematic uncertainty of the TES for $p_T^\tau > 20$ GeV and $|\eta| < 2.5$ is found to be less than 3% for the hadronic decay modes with exactly one reconstructed track, and less than 4% for the hadronic decay modes with at least two reconstructed tracks.

The uncertainty on the TES is also evaluated by using in-situ measurements for cross-check. The strategy relies on the reconstruction of the visible mass peak$^3$ for $Z$ bosons decaying semileptonically into $Z \rightarrow \tau\tau \rightarrow \mu\nu_\tau \nu_\tau \tau_{\text{had}}$. The results are compatible with the systematic uncertainties determined with the formerly described method.

3.2.4 Jets reconstruction

As result of the strong interaction and hadronization discussed in Section 1.2.1, quarks and gluons materialize into collimated bunches of hadrons flying roughly in the same direction, the so-called jets. Therefore, their reconstruction and identification is crucial to resolve the partonic flow coming from the hard scatter interaction.

Jets in theory and experiment are the result of an algorithm mapping observable final state particles or signals representing them, into one kinematic object if these particles are signals are deemed to come from a common source (parton). This mapping is not deterministic, due limitations in the calculation of

\[ E_T^{\text{miss}} \]

$^3$Invariant mass of the visible products, no $E_T^{\text{miss}}$ is included.
Figure 3.4: TES uncertainty for $\tau_{1-prong}$ (top) and $\tau_{multi-prong}$ (bottom) for a central pseudo rapidity bin ($|\eta| < 0.3$). The individual contributions are shown as points and the combined uncertainty is shown as a filled band. [114].
the parton shower and fragmentation introduced by non-perturbative kinematic domains, and the limitations of the detectors in the reconstruction of all particles generated in the collision. As M. J. Tannenbaum said in [115], “Jets are legal contracts between theorists and experimentalists”. This means, that the algorithms defining a jet in the experiment and in calculations need to be completely specified, and follow a few rules to allow for comparisons of measurements with theory. The “Snowmass Agreement” [116] collects these rules:

1. Simple to implement in experimental analysis;
2. Simple to implement in theoretical calculation;
3. Defined at any order of perturbation theory;
4. Yields at a finite cross-section at any order of perturbation theory;
5. Yields to a cross-section that is relatively insensitive to hadronization;

The fourth requirement directly translates in the infrared and collinear safety (IRC) condition, i.e.: the number of reconstructed jets has to be independent on the emission of a soft (infrared) or collinear particle [117].

Sequential recombination jet algorithms are specifically designed to satisfy the IRC condition and thus to be usable for calculations at any order in perturbation theory. Typically they work by calculating a distance between particles, and then recombine them pairwise according to a given order, until some condition is met. The process terminates when no particles are left.

Different objects can be used as input of the jet finding algorithm, resulting in different jet collections. In particular, in order to suppress the calorimeter noise, the topoclusters described in Section 3.2 are used as input objects to jet finding for calorimeter jets. Then, the distance $d_{ij}$ between two objects and the distance $d_{iB}$ between an object and the beam can be defined as:

$$d_{ij} = \min\left(k_{T,i}^{2p}, k_{T,j}^{2p}\right) \frac{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}{R^2} \quad (3.1)$$

$$d_{iB} = k_{T,i}^{2p} \quad (3.2)$$

where $k_{T,i}$, $y_i$ and $\phi_i$ are respectively the transverse momentum, the rapidity and the azimuthal angle of the considered object, $R$ is the resolution parameter.

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4A four-momentum recombination scheme is used: the combination of two objects is performed via a four-momentum sum.
controlling the extension of the jet, and $p$ is a parameter defining the distance scales, as discussed later. The $R$ value is a compromise to limit the contribution from underlying event but at the same time to capture all the energy in the direction around the initial quark or gluon generated through parton shower and hadronization effects. In the results reported in this thesis all jets are reconstructed with $R = 0.4$, if not stated differently.

The recombination procedure is defined by the following steps: a list of all the distances $d_{ij}$ defined in Equation 3.1 is compiled, then the minimum distance among all objects, $d_{\text{min}} = \min (d_{ij})$ is computed and compared with the beam distance $d_{iB}$. If $d_{\text{min}} < d_{iB}$ then the $i^{th}$ and the $j^{th}$ objects are combined and the procedure is repeated from the start. Otherwise the $i^{th}$ object is identified as a jet and removed from the list. The procedure is repeated until all the objects are removed from the input list and classified as jets.

According to the value of the $p$ parameter in Equation 3.1, different algorithms with different properties are defined. For $p = 0$, the algorithm is known as Cambridge-Aachen (C/A) [118] and the object recombination is performed only on the base of the geometrical distance. Shortest distance objects are recombined first, which leads to irregularly shaped jets. The $k_t$ algorithm is obtained by setting $p = 1$. It is characterized by clustering first soft objects, resulting in rather irregular shapes for the final jets [119]. Finally for $p = -1$ the anti-$k_t$ algorithm is obtained [111]. This is the ATLAS default because by clustering the hardest contributions first it effectively removes sensitivity to the internal structure of the parton shower and results in rather regularly shaped jets. Nevertheless, $k_t$ and C/A algorithm can be useful tools for studies looking at the jet substructure and for pile-up suppression methods [120, 121, 122].

A correction factor, the jet energy scale (JES), is required to account for the lower hadron response, calorimeter non-uniformities, pile-up, energy loses and “out-of-cone” effects. The JES is derived using MC-based and in-situ methods according to the sequential procedure sketched in Figure 3.5. The procedure starts with jets at the constituents scale that can be calibrated either with the EM$^5$ or the LCW calibration. Jets used in the analysis reported in this thesis are LCW calibrated. Then, a pile-up subtraction is performed relying on the Jet Area method [120]. A residual offset correction as a function of $N_{PV}$ and $\mu$ is also applied. It is mostly relevant in the high-$\mu$ and high-$\eta$ region where the out-of-

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5The EM scale is the basic calorimeter signal scale for the ATLAS calorimeters. It provides the correct scale for energy deposited by electromagnetic showers but does not correct for energy leakage or losses in the dead material.
3.2. PHYSICS OBJECTS RECONSTRUCTION

Figure 3.5: Sketch of the JES sequential procedure [125].

time pile-up effects are more important. A MC based correction is then computed to account for all the detector non-uniformites, differences in response for neutral components and for different $p_T$ jets. Finally, in-situ methods based on the ratio between the jet $p_T$ and a well measured $p_T$ reference, are exploited to ensure good uniformity over the whole detector using di-jets events for $\eta$ intercalibration, and to ensure coherence across a broad jet $p_T$ range using $Z+$jet balance for the low $p_T^{\text{jet}}$ region, $\gamma+$jet balance for the intermediated $p_T^{\text{jet}}$ range and multi-jet balance for the high $p_T^{\text{jet}}$ region up to 1 TeV [123, 124].

In-situ methods give a large number (up to 49) contributions to the JES uncertainties grouped in four categories. In addition, systematics for pile-up, flavor, MC non-closure, $E/p$ measurements are considered.

In physics analyses using a profile likelihood approach, systematic uncertainties are treated as nuisance parameters (NP). A good splitting of the different systematic sources is therefore required to ensure a proper combination between different analysis channels or through different periods of data taking with different experimental conditions (e.g., pile-up). Nevertheless, the full systematics scheme typically has too many NPs for a general analysis. Therefore reduction schemes are provided by grouping the in-situ NPs that contain less information about correlations. At the price of loosing only a few % of the correlations a reduction scheme with a total of 24 NPs is used in the final analysis reported in this thesis. A further reduction is then applied at the analysis level in order to include only significative systematic variations in the fit for the limits extraction excluding statistics noise.

The results for the 2012 JES uncertainties split in its main components are shown in Figure in 3.6. In particular the JES uncertainties in the high-$\eta$ regions are up to 4-7% and have an important contribution in vector boson fusion topologies due the presence of forward jets (see Chapter 5).
Figure 3.6: Fractional jet energy scale systematic uncertainty components for anti-\(k_t\) jets with \(R = 0.4\) calibrated using the LCW+JES calibration scheme as a function of the jet \(p_T\) (top) and \(|\eta|\) (bottom). The total uncertainty (all components summed in quadrature) is shown as a filled blue region topped by a solid black line. Average 2012 pile-up conditions were used, and topology dependent components were taken from inclusive dijet samples [126].
3.3. $E_T^{\text{miss}}$ RECONSTRUCTION

3.3 $E_T^{\text{miss}}$ reconstruction

In a collider event the missing transverse momentum is defined as the momentum imbalance in the plane transverse to the beam axis, where momentum conservation is expected. Such an imbalance may signal the presence of unseen particles, such as neutrinos or stable, weakly-interacting supersymmetric (SUSY) particles. The vector momentum imbalance in the transverse plane is obtained from the negative vector sum of the momenta of all particles detected in a $pp$ collision and is denoted as missing transverse momentum, $E_T^{\text{miss}}$. The symbol $E_T^{\text{miss}}$ is used for its magnitude [127, 128, 129].

The precise measurement of $E_T^{\text{miss}}$ is essential for physics at LHC. A large $E_T^{\text{miss}}$ is a key signature for searches for new physics processes such as SUSY and extra dimensions. The measurement of $E_T^{\text{miss}}$ also has a direct impact on the quality of a number of measurements of Standard Model (SM) physics, such as the reconstruction of the top-quark mass in $t\bar{t}$ events. Furthermore, it is crucial in the search for the Higgs boson in the decay channels $H \rightarrow WW$ and $H \rightarrow \tau\tau$, where a good $E_T^{\text{miss}}$ measurement improves the reconstruction of the Higgs boson mass [130].

An important requirement on the measurement of $E_T^{\text{miss}}$ is the minimization of the impact of limited detector coverage, finite detector resolution, the presence of dead regions and different sources of noise that can produce fake $E_T^{\text{miss}}$. Such sources can significantly enhance the background from multi-jet events in SUSY searches with large $E_T^{\text{miss}}$ or the background from $Z \rightarrow \ell\ell$ events accompanied by jets of high transverse momentum in Higgs boson searches $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ in final states with two leptons and neutrinos.

The values of $E_T^{\text{miss}}$ and its azimuthal coordinate ($\phi^{\text{miss}}$) are calculated as:

$$E_T^{\text{miss}} = \sqrt{(E_x^{\text{miss}})^2 + (E_y^{\text{miss}})^2}$$
$$\phi^{\text{miss}} = \arctan\left(\frac{E_y^{\text{miss}}}{E_x^{\text{miss}}}\right)$$ (3.3)

where $E_x^{\text{miss}}$, $E_y^{\text{miss}}$ are the negative sum of all the momentum components ($p_x$, $p_y$) reconstructed with the detector. measured in the detector projected respectively onto the $x$ and $y$ direction. Primarily these include contributions from energy deposits in the calorimeters ($E_{x(y)}^{\text{miss,calo}}$) and muons reconstructed in the muon spectrometer ($E_{x(y)}^{\text{miss,\mu}}$):

$$E_{x(y)}^{\text{miss}} = E_{x(y)}^{\text{miss,calo}} + E_{x(y)}^{\text{miss,\mu}}$$ (3.4)
Moreover, information from the inner detector is added as well: low-$p_T$ tracks are used to recover low $p_T$ particles which do not reach in the calorimeters, and muons reconstructed from the inner detector are used to recover muons in regions poorly covered by the muon spectrometer.

In the $E_{\text{miss}}$ reconstruction algorithm, the computation of the calorimeter term uses only the energy in topoclusters (Section 3.2) in order to suppress electronic and pile-up noise and to use only the calorimeter energy deposits that generate a significant signal. Other $E_{\text{miss}}$ algorithms, based on a simple cell $\sigma_{\text{noise}}$ cut to suppress the calorimeter noise, have been studied as well [131]. Indeed, despite they have shown to be less performant specially in terms of $E_{\text{miss}}$ resolution, they can be employed for tests of the detector performance particularly in very busy environments, like heavy-ions collisions, where the topocluster approach may not be able to ensure anymore infrared safety.

In an early phase of the ATLAS data taking, $E_{\text{miss}}$ algorithms that calibrate all the calorimeter cells according to the same calibration scheme (LCW) have been firstly employed [131, 132, 133]. A significant improvement of the $E_{\text{miss}}$ performance is achieved with a more refined algorithm for the $E_{\text{miss}}$ reconstruction, tagged RefFinal [127, 128, 129, 133], where a proper calibration is applied to each physics object, thus providing a $E_{\text{miss}}$ computation coherent with the specific choices in the context of a physics analysis. A detailed description of the algorithm is given in Section 3.3.1.

### 3.3.1 The RefFinal algorithm

In this section the $E_{\text{miss}}$ reconstruction and calibration based on the RefFinal algorithm sketched in Figure 3.7 is described in detail. The $E_{\text{miss}}$ calculation
3.3. $E_T^{\text{miss}}$ RECONSTRUCTION

Figure 3.8: Data-MC comparison for the total $E_T^{\text{miss}}$ distribution in $Z \rightarrow \mu\mu$ events.

uses reconstructed and well calibrated physics objects. The overlap between the different objects in calorimeters is resolved by associating topoclusters to the reconstructed objects in a defined order: electrons, photons, taus, jets, muons. Topoclusters not associated with any such objects are also taken into account in the $E_T^{\text{miss}}$ calculation by collecting them into the soft term $E_T^{\text{miss,SoftTerm}}$. Therefore, the $E_T^{\text{miss}}$ is calculated as follows:

$$E_{x(y)}^{\text{miss}} = E_{x(y)}^{\text{miss,e}} + E_{x(y)}^{\text{miss,\gamma}} + E_{x(y)}^{\text{miss,\tau}} + E_{x(y)}^{\text{miss,jets}} + E_{x(y)}^{\text{miss,SoftTerm}} + E_{x(y)}^{\text{miss,\mu}}$$  \hspace{1cm} (3.5)$$

where each term is calculated as the negative sum of the calibrated reconstructed objects, projected onto the $x$ and $y$ directions. Particular attention is paid in avoiding energy double counting of the various physics objects that could create fake unbalance in the event and result in tails of the $E_T^{\text{miss}}$ distribution. Figures 3.8 shows that there is a good agreement between data and MC simulation prediction for the $E_T^{\text{miss}}$ total distribution.

The definition and the calibration of the physics objects entering the RefFinal algorithm are described in the following sections for the default configuration used to produce the results reported in this thesis. However, the physics object options are customizable to meet the analysis selection choices.
Electron term, $E_{\text{T}}^{\text{miss},e}$

Electrons are required to pass "medium" identification criteria (Section 3.2.1) and have $p_T$ greater than 10 GeV. They are treated by the algorithm as full four-momentum objects including the ATLAS standard electron calibration [102]. Since electrons clusters are built with the sliding-window approach (Section 3.2), topoclusters containing more than the 50% of the the sliding window cells are removed in order to avoid energy double counting. Figure 3.9 shows a good agreement for the electron term in $Z \rightarrow ee$ events.

Photon term, $E_{\text{T}}^{\text{miss},\gamma}$

Photons are required to pass the "tight" identification criteria (Section 3.2.1) and have $p_T$ greater than 10 GeV. If a photon is also reconstructed as an electron, the electron is kept. Since the photon purity is poor for non-isolated photons, photons are usually calibrated at the EM scale. For analyses selecting photons in the final state, in order to improve the $E_{\text{T}}^{\text{miss}}$ reconstruction, it is possible to customize a specific $E_{\text{T}}^{\text{miss}}$ including the proper calibration for the selected photons. As for electrons, topoclusters containing more than the 50% of the sliding window cells are removed in order to avoid energy double counting.
3.3. $E_T^{\text{MISS}}$ RECONSTRUCTION

**Tau term, $E_T^{\text{miss, } \tau}$**

Taus are required to pass the “medium” identification given by the BDT multivariate algorithm where also muon and electron veto is included (see Section 3.2.3) and have $p_T$ greater than 20 GeV. They should not overlap with either electrons or photons. Should this be the case, the electron/photon is kept and the remnant topoclusters from the tau object not overlapping the sliding window cluster of the electron/photon, are moved to the $E_T^{\text{miss,SoftTerm}}$ term. Taus are seeded by an anti-$k_t$ jet of $R = 0.4$ and the TES is applied only in the core defined by $R = 0.2$. The full four-momentum $\tau$-object, including calibration and an offset pile-up suppression, is used for the $E_T^{\text{miss}}$ calculation. To avoid energy double counting all topoclusters are associated to the $\tau$ if they are located within $\Delta R < 0.3$.

**Jet term, $E_T^{\text{miss, } \text{jet}}$**

The jet algorithm used for the $E_T^{\text{miss}}$ reconstruction is the anti-$k_t$ with a distance parameter $R = 0.4$. Jets are treated as four-momentum objects including the full JES calibration described in Section 3.2.4 and they are required to pass a $p_T$ cut of 20 GeV evaluated at the full calibrated scale. The default $E_T^{\text{miss}}$ reconstruction makes use of jets with the LCW+JES calibration scheme but if a physics analysis uses jets calibrated with a different scheme it is possible to customize $E_T^{\text{miss}}$ to include the corresponding jets.

Jets are required to not overlap with previous objects selected by the $E_T^{\text{miss}}$ algorithm (electrons, photons and taus) with more than 50% of their energy. If there is an overlap larger than 50%, the overlapping object is kept and the remnant topoclusters of the jet are moved to the $E_T^{\text{miss,SoftTerm}}$ term. If the overlap is smaller than the 50% both the overlapping object and the jet are kept and, in order to avoid energy double counting, the jet momentum is scaled down to account for the percentage of the overlap.

Figure 3.10 shows a good agreement between data and MC simulation for the $E_T^{\text{miss, } \text{jet}}$ term in $Z \rightarrow \mu\mu$ events. The peak at zero is due to events without jets with $p_T > 20$ GeV. The region below 20 GeV is populated by events with two jets balancing each other, and the peak at $E_T^{\text{miss, } \text{jet}} \sim 20$ GeV is a threshold effect introduced by the jet selection.

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6Reconstructed jets are larger than reconstructed electrons, photons and taus.
Soft term, $E_{T}^{\text{miss,SoftTerm}}$

The soft term is calculated from calorimeter topoclusters and tracks not associated to high-$p_T$ objects. Tracks are added to recover the contribution from low-$p_T$ particles which do not reach the calorimeter or do not seed a topocluster. The topoclusters are calibrated using the LCW technique. To avoid energy double counting, any overlap between topoclusters and tracks is removed.

Presently also topoclusters with negative energy are used in the soft term computation. Out-of-time pile-up can lead to an increase of the negative energy contribution due to the ATLAS calorimeter signal shape, however, including this negative contribution for the 2012 pile-up condition has a negligible effect (less than 1%) on the $E_{T}^{\text{miss}}$ resolution.

The combination of the track information from the inner detector and the topoclusters is performed by an energy flow ($eflow$) algorithm, sketched in Figure 3.11. The algorithm works in two steps, the “track selection” and the “topocluster removal”.

Track selection

Reconstructed tracks from any reconstructed vertex with $p_T > 400$ MeV and passing quality selection criteria are used for the calculation of the soft

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7Topoclusters with negative energy are taken at the EM scale.
3.3. $E_T^{\text{MISS}}$ RECONSTRUCTION

![Diagram](image)

Figure 3.11: Sketch of the $eflow$ algorithm.

term. A minimum number of hits associated to the reconstructed track in the pixel, SCT and TRT detectors is required.

- Tracks with $p_T > 0.5$ GeV are required to have:
  - $N_{\text{PIXEL}}^{\text{hit}} + N_{\text{SCT}}^{\text{hit}} > 6$
  - $N_{\text{hit}}^{\text{PIXEL}} + N_{\text{hit}}^{\text{SCT}} + N_{\text{hit}}^{\text{TRT}} > 10$.

- To increase the low-$p_T$ acceptance, tracks with $p_T < 0.5$ GeV are required to have:
  - $N_{\text{hit}}^{\text{PIXEL}} + N_{\text{hit}}^{\text{SCT}} > 8$

- For tracks with $p_T > 10$ GeV, the $\chi^2$ probability for the track fit should be:
  - $\chi^2 > 0.01$

- Only tracks with $p_T < 100$ GeV are used to ensure that contribution from high energy objects do not enter in the computation.

**Track association and topocluster removal**

All selected tracks are extrapolated to the second layer of the electromagnetic calorimeter and very conservative criteria are used for the association
to reconstructed objects or topoclusters. The association is based on the ratio $\Delta R/\sigma(\Delta R)$. The radial distance $\Delta R$ is calculated as:

$$\Delta R = \sqrt{(\eta_{clu} - \eta_{extr})^2 + (\phi_{clu} - \phi_{extr})^2}$$  \hspace{1cm} (3.6)$$

where $\eta_{clu}(\phi_{clu})$ and $\eta_{extr}(\phi_{extr})$ are the topocluster and the track directions at the calorimeter surface, respectively, and $\sigma(\Delta R)$ is the $\Delta R$ resolution parameterized as a function of the track momentum. Tracks are retained if this ratio is greater than 8. In this case, the $p_T$ resolution, given by the error from the track fit, is smaller than the expected energy resolution of the associated cluster.

To avoid energy double counting, the following tracks are vetoed:

- Tracks associated to any high-$p_T$ object used in the $E_T^{\text{miss}}$ reconstruction;
- Tracks associated to muons and inside a cone around the reconstructed jets, the dimension of the cone depending on the jet algorithm;
- Tracks connected to topoclusters entering the reconstructed objects.

Finally, the track acceptance and the topocluster removal is performed according to the following criteria:

- If a track is neither associated to a topocluster nor a reconstructed object, its transverse momentum is added to the calculation of the soft term.
- If a topocluster in the $E_T^{\text{miss},\text{SoftTerm}}$ is associated to a selected tracks, the track momentum is used instead of the topocluster energy, thus exploiting the better calibration and resolution of tracks at low momentum compared to topoclusters.
- If more than one topocluster is associated to a track, only the topocluster with the largest energy in a cone of $\Delta R/\sigma(\Delta R) < 4$ around the selected tracks is excluded from the $E_T^{\text{miss}}$ calculation. The remaining topoclusters not associated to tracks are added for the $E_T^{\text{miss}}$ calculation.

Figure 3.12 shows a good agreement between data and MC simulation for the $E_T^{\text{miss},\text{SoftTerm}}$ in $Z \rightarrow \mu\mu$ events. A degradation of the performance and of the efficiency of the algorithm were observed moving to higher pile-up conditions due
3.3. $E_{T}^{\text{miss}}$ RECONSTRUCTION

Figure 3.12: Data-MC comparison for the $E_{T}^{\text{miss,SoftTerm}}$ term in $Z \rightarrow \mu\mu$ events.

to the increasing of not-isolated tracks for which selection cuts are not optimal. Therefore, the track selection will be revisited for ATLAS Run 2.

Muon term, $E_{T}^{\text{miss,}\mu}$

The $E_{T}^{\text{miss}}$ muon term is calculated from the momenta of the reconstructed muons. In order to include in the $E_{T}^{\text{miss}}$ a very well-measured muon contribution, different muon types described in Section 3.2.2 are employed resulting in a rather complex procedure summarized in Figure 3.13.

In the region $|\eta| < 2.5$, mainly combined muons are used. The matching requirement considerably reduces contributions from fake muons that can be created from high hit multiplicities in the muon spectrometer, due to very energetic jets punching through the calorimeter into the muon system. Low-$p_T$ muons and muons lost in the small inactive Muon Spectrometer regions can be recovered by the use of tagged muons through the information from inner detector.

In order to properly deal with the energy deposited by the muon in the calorimeters, the muon term is calculated differently for isolated and non-isolated muons\textsuperscript{8}:

Isolated muons: the $p_T$ of an isolated muon is determined from the combined measurement of the inner detector and muon spectrometer. The energy

\textsuperscript{8} Muon isolation is defined on the base of the distance $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$: if $\Delta R < 0.3$ the muon is classified as non-isolated, otherwise as isolated.
lost by the muon in the calorimeter is included in the combined $p_T$ so it is not added in the $E_{T}^{\text{miss}}$ computation to avoid double counting of energy. The energy loss in the calorimeter, on average around 2-3 GeV, is not supposed to seed a topocluster, therefore, the energy in the cells contained in a cone around the muon trajectory is used for the computation. When the $E_{T}^{\text{miss}}$ reconstruction is performed from data formats containing only the topocluster information, the parametrized energy loss in calorimeters is subtracted from the $p_T$ of the isolated muons entering the $E_{T}^{\text{miss},\mu}$ term.

**Non-isolated muons:** for a non-isolated muon, the energy deposited in the calorimeter cannot be resolved from the calorimetric energy depositions of the particles in the jet, so it is presumed to be already added in the $E_{T}^{\text{miss}}$ computation. Therefore, to avoid energy double counting, the $p_T$ measured by the Muon Spectrometer only is used, unless there is a significant mismatch between the spectrometer and the combined measurement. In this case the combined measurement where a parameterized estimation of the muon energy loss in the calorimeter [134] is subtracted is used for the $E_{T}^{\text{miss}}$ calculation.

For higher values of pseudorapidity ($2.5 < |\eta| < 2.7$), outside the fiducial volume of the inner detector, there is no matched track requirement and the
3.3. $E_T^{\text{miss}}$ RECONSTRUCTION

Figure 3.14: Data-MC comparison for the $E_T^{\text{miss,}\mu}$ term in $Z \rightarrow \mu\mu$ events.

The muon spectrometer $p_T$ of standalone muons is used for both isolated and non-isolated muons.

The standard $E_T^{\text{miss}}$ configuration uses muons reconstructed starting from the Staco muon chain, but it is also possible to configure a case based on the MuID muon chain. The performances for the two cases are very similar. The validation of the third muon chain in the $E_T^{\text{miss}}$ is currently under study.

Figure 3.14 shows a good agreement between data and MC simulation for the $E_T^{\text{miss,}\mu}$ term in $Z \rightarrow \mu\mu$ events.

3.3.2 Study of the $E_T^{\text{miss}}$ performance

The $E_T^{\text{miss}}$ performance is evaluated in terms of resolution, scale and tails in spectra. In order to compare $E_T^{\text{miss}}$ performance between different event topologies or across different data taking periods, it is useful to define some key variables to test crucial aspects of the $E_T^{\text{miss}}$ computation and their impacts on physics analyses. A brief overview of the most used variables and performance plots is reported in the following sections.

Event variables

The total (scalar) transverse energy in the calorimeters, $\Sigma E_T$, which includes also the unassociated low-$p_T$ tracks used in the soft term but not the track from the
muon spectrometer, is an important quantity to parameterize and understand the $E_T^{\text{miss}}$ performance. It is defined as the scalar sum:

$$\Sigma E_T = \Sigma E_T^e + \Sigma E_T^\gamma + \Sigma E_T^{\text{jets}} + \Sigma E_T^{\text{SoftTerm}}$$  \hspace{1cm} (3.7)$$

where each contribution is obtained by sum of the transverse momentum of the objects reconstructed and calibrated according to the scheme described in Section 3.3.1.

From this quantity the total transverse energy in the event is obtained by summing also the $p_T$ of muons:

$$\Sigma E_T^{\text{event}} = \Sigma E_T + \Sigma p_T^\mu$$  \hspace{1cm} (3.8)$$

This variable is important to compare electron and muon channels at the same overall event activity.

In MC simulation samples, event-by-event comparison between the reconstructed and the “truth” $E_T^{\text{miss}}$ value and direction provide a useful test of the $E_T^{\text{miss}}$ reconstruction and calibration performance.

$E_T^{\text{miss}}$ resolution

The $E_T^{\text{miss}}$ resolution is expected to depend on the amount of energy measured in the detectors, and in particular on the $\Sigma E_T$ in the calorimeter. The resolution is estimated from the width of the distribution $F_{x,y}^{\text{miss}} - F_{x,y}^{\text{miss, truth}}$ in bins of the total transverse energy in the event, calculated from Equation 3.8. For minimum bias and $Z \to \ell\ell$ events, where no genuine $E_T^{\text{miss}}$ is expected, the $E_T^{\text{miss}}$ resolution can be estimated with data events taking the width of the $E_{x,y}^{\text{miss}}$ distributions. In each $\Sigma E_T$ bin the measure from the two $E_T^{\text{miss}}$ components is combined\(^9\) resulting in two entries for each event. The core of each distribution is fitted with a Gaussian over a range spanning twice the expected resolution, and the fitted width, $\sigma$, is examined as a function of $\Sigma E_T^{\text{event}}$ from Equation 3.8.

The $E_T^{\text{miss}}$ resolution follows an approximately stochastic behaviour as a function of $\Sigma E_T$. Deviations are expected in the low $\Sigma E_T$ region due to the electronic noise and the presence of pile-up, and in the high $\Sigma E_T$ region where

\(^9\)Both the $(E_{x,y}^{\text{miss}} - E_{x,y}^{\text{miss, truth}})$ distributions are confirmed to be well centered at zero and with a comparable width. So, no bias is introduced by their combination.
3.3. $E_T^{\text{miss}}$ RECONSTRUCTION

![Graph showing $E_T^{\text{miss}}$ resolution curve at the early phase of ATLAS data taking with very low pile-up conditions (2010). Pb-Pb collisions data and $pp$ collision data are superimposed to show the compatibility between the two measurements.](image)

Figure 3.15: $E_T^{\text{miss}}$ resolution curve at the early phase of ATLAS data taking with very low pile-up conditions (2010). Pb-Pb collisions data and $pp$ collision data are superimposed to show the compatibility between the two measurements.

the constant term dominates. In any case, the shape of the resolution curve is parametrized and fitted with a good agreement according to the simple function:

$$\sigma = k \cdot \sqrt{\Sigma E_T}$$  \hspace{1cm} (3.9)

where the parameter $k$ quantifies the $E_T^{\text{miss}}$ resolution.

In absence of pile-up, this simple model for the $E_T^{\text{miss}}$ resolution as a function of the $\Sigma E_T$ has been confirmed first with $pp$ collisions and then with Pb-Pb collisions up to the 10 TeV in 2010, as shown in Figure 3.15 for minimum bias events. This figure demonstrates the excellent performance of the ATLAS calorimeter. The effects of pile-up on the $E_T^{\text{miss}}$ resolution is discussed in detail in Chapter 4.

$E_T^{\text{miss}}$ scale: diagnostic plot

A test for the $E_T^{\text{miss}}$ scale and bias can be provided for $Z \rightarrow \ell \ell$ events exploiting the balance between the leptons from the decaying $Z$ and the hadronic recoil (either jets or soft hadronic contribution), as sketched in Figure 3.16. The importance of this test is that it allows checking the $E_T^{\text{miss}}$ scale performance also in data events and not only in MC simulation as is required by comparisons with the MC “truth” information.
Figure 3.16: Sketch of a $Z \rightarrow \ell\ell$ event. The direction of the $Z$ boson in the transverse plane is defined by the momentum of the two leptons. If the system ($Z$-hadronic recoil) is well-balanced no $E_T^{\text{miss}}$ is expected along the $Z$ direction.

The direction of the $Z$ boson in the transverse plane, $A_Z$, can be defined using the momenta of the reconstructed leptons:

$$A_Z = \left( p_T^{\ell^+} + p_T^{\ell^-} \right) / |p_T^{\ell^+} + p_T^{\ell^-}|,$$  

(3.10)

where $p_T^{\ell}$ are the vector transverse momenta of the lepton and anti-lepton.

The measurement of the mean value of the projection of $E_T^{\text{miss}}$ onto the $Z$ direction, $\langle E_T^{\text{miss}} \cdot A_Z \rangle$, as a function of $p_T^Z$ is used as a diagnostic plot to validate the $E_T^{\text{miss}}$ algorithms. The expectation for this projection is 0, if the leptons perfectly balance the hadronic recoil, regardless of the energy of the lepton system. If instead a negative bias is observed, it suggests either that the lepton system energy is overestimated or the magnitude of the hadronic recoil is underestimated. Since leptons are demonstrated to be well calibrated from the respective in-situ validations, a negative bias can safely be interpreted as an underestimation of the hadronic recoil.

The effect of the limited calorimeter coverage up to $|\eta| < 4.9$ introduces a small negative bias, as shown in Figure 3.17. Similarly, the increase of the topocluster noise thresholds for the 2012 run tends to increase the observed bias in this distribution.

**Data and Monte Carlo simulation samples for the study of the $E_T^{\text{miss}}$ performance**

In order to fully exploit the detector capability in the reconstruction and calibration of different physics objects, several event topologies are explored to test the $E_T^{\text{miss}}$ reconstruction algorithm and its performance.
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Figure 3.17: $E_T^{\text{miss}}$ projected onto the $Z$ boson direction in MC $Z \to ee$ events. The distribution obtained using the “truth” information from not interacting particles is a straight line as zero as expected, while the one obtained using the “truth” information from all interacting particles inside the ATLAS calorimeter coverage shows a slight negative bias. The effect is considered negligible.

The minimum bias sample is the basic sample useful to test the $E_T^{\text{miss}}$ performance. It is a generic mixture of soft and hard collisions and, apart from a small contribution from prompt decays that could be triggered together with the more common QCD events, no genuine $E_T^{\text{miss}}$ is expected in these events. Thus the $E_T^{\text{miss}}$ reconstructed in these events is a direct result of imperfections in the reconstruction process or in the detector response.

The $Z \to \ell\ell$ channel is well-suited to the study of $E_T^{\text{miss}}$ performance because of its clean event signature and the relatively large cross-section. In general, apart from a small contribution from the semi-leptonic decay of heavy-flavour hadrons in jets, no genuine $E_T^{\text{miss}}$ is expected in these events. Thus, similarly to the minimum bias sample, it can be used to test the detector response. Moreover, compared to minimum bias events, the $Z \to \ell\ell$ events provide an important test for the lepton reconstruction in the $E_T^{\text{miss}}$.

Once the impact of the detector is well understood, it is useful to study the performance of the $E_T^{\text{miss}}$ measurement also in events containing genuine $E_T^{\text{miss}}$ originating from neutrinos, like in $W \to \ell\nu$ events, where more precise tests on the $E_T^{\text{miss}}$ scale and direction are possible.
Finally, final states with a dominant presence of jets, taus and photons are also studied in order to have a complete evaluation of the $E_T^{\text{miss}}$ performance.

For all the results reported in this thesis, cleaning criteria are applied to each sample to reduce the impact of instrumental noise and out-of-time energy deposits in the calorimeter from cosmic-rays or beam-induced background. Then, the specific selection criteria required to select the desired topology are also applied on both data and MC simulation samples. They are summarized in Appendix A for the different topologies.

### 3.3.3 $E_T^{\text{miss}}$ systematic uncertainties

The $E_T^{\text{miss}}$ is the sum of several terms corresponding to different types of reconstructed objects. The uncertainty on each individual term is evaluated given the knowledge from the reconstructed objects that are used to build it. The overall systematic uncertainty on the $E_T^{\text{miss}}$ measurement is then calculated by combining the uncertainties on each term corresponding to a reconstructed physics object and the uncertainties on the soft term which are discussed in this section.

The relative impact of the uncertainty of the constituent terms on $E_T^{\text{miss}}$ depends on the event topology, i.e. presence of leptons, jet activity, etc. In particular the contribution of the $E_T^{\text{miss,SoftTerm}}$ is important in $Z$ and $W$ events, while it becomes less important in events with higher jet activity where the $E_T^{\text{miss,jet}}$ term is the dominant contribution.

Different methods for the evaluation of the systematic uncertainties on the $E_T^{\text{miss,SoftTerm}}$ are developed. In the early phase of the ATLAS data taking (2010 and 2011 data) a method based on the evaluation and propagation of the cluster energy uncertainties has been employed [127]. Since this method leads to largely conservative estimates, for analyses on 2012 data it is replaced with an evaluation of the systematic uncertainties based on in-situ methods that also include MC modeling and pile-up effects [128, 129]. In particular two methods based on studies of $Z$ events are developed and explained in the following. A brief explanation of the method used for 2010 and 2011 data is as well reported, with some emphasis on the discussion of its limitations.

### $E_T^{\text{miss,SoftTerm}}$ systematic uncertainty based on the energy cluster uncertainty (2010 and 2011)

In an early phase of ATLAS data taking the systematic uncertainties of the $E_T^{\text{miss,SoftTerm}}$ have been derived combining uncertainties from the detector ge-
3.3. $E_{\text{T}}^{\text{MISS}}$ RECONSTRUCTION

ometry and MC generator effects, found to be around 3%, with the systematic uncertainties of the topocluster energy reconstruction derived with an $E/p$ method, dominating to the order of 10%.

This procedure led to very conservative systematic uncertainties for the soft term due to the difficulty to determine the $E/p$ ratio in a busy environment and the overestimation of the cluster energy uncertainty in the forward region where no track information is available.

When moving to the 2011 data, an additional systematic uncertainty accounting for pile-up effects is needed. The average of the relative discrepancies\(^{10}\) between the $\Sigma E_{\text{T}}$ distribution in data and MC simulation\(^{11}\) as a function of the number of primary vertices in the different calorimeter regions is used for evaluation of this uncertainty contribution, and propagated to the $E_{\text{T}}^{\text{miss}}$ and $E_{y}^{\text{miss}}$ components. The resulting pile-up uncertainty estimated for the 2011 data is at most 5.6%, reduced to 2.3% after a reoptimization of the procedure.

\(^{10}\)In this way the effect of the simulation mismodelling is excluded.

\(^{11}\)Effects on MC uncertainties like the $\mu$-scaling is also taken into account.

$E_{\text{T}}^{\text{miss,SoftTerm}}$ \textbf{systematic uncertainties from the in-situ method based on evaluation from data/MC ratio in $Z \rightarrow \mu\mu$ events without jets (2011 and 2012)}

The systematic uncertainties on both the scale and the resolution of the $E_{\text{T}}^{\text{miss}}$ soft term are evaluated from the comparison of observables in data with the Monte Carlo prediction for events without jets. In order to isolate the soft term contribution, the subset of $Z \rightarrow \mu\mu$ events that do not contain jets with $p_{\text{T}} > 20 \text{ GeV}$ is selected because in these events only the leptons and the soft term contribute to $E_{\text{T}}^{\text{miss}}$. The muon channel is preferred over the electron channel since on average the muons leave just a small contribution (around 2-3 GeV) in the calorimeter. Nevertheless, the results are cross-checked with $Z \rightarrow ee$ events indicating comparable values for the systematic uncertainties.

As discussed in Section 3.3.2, the projection of the $E_{\text{T}}^{\text{miss}}$ onto the $Z$ boson transverse direction provides a test of the bias on the $E_{\text{T}}^{\text{miss}}$ scale. As shown in Figure 3.18, the data-MC ratio of this observable for events without jets can then be used as a measure of the systematic uncertainty on the scale of the soft term, which is calculated as the average deviation from unity. A parametrization as a function of $\Sigma E_{\text{T}}$ is chosen to allow a straightforward extrapolation of the systematic uncertainties also for events that do not contain a $Z$ decay.
Figure 3.18: Projection of the $E_T^{\text{miss}}$ onto the $Z$ boson transverse direction as a function of $\Sigma E_T$, for data and MC simulation $Z \rightarrow \mu\mu$ events without jets with $p_T > 20$ GeV. The data-MC ratio used to evaluate the systematic uncertainties is shown in the bottom part of the plot.

The systematic uncertainty on the soft term resolution is determined in a similar manner, using the $E_x^{\text{miss}}$ and $E_y^{\text{miss}}$ resolution as a function of $\Sigma E_T$, to quantify the level of data-MC agreement as shown in Figure 3.19.

The $N_{PV}$ and $\mu$ dependences of the data-MC ratio for both $E_T^{\text{miss,SoftTerm}}$ scale and resolution uncertainties are checked looking at the evolution of the ratio in regions characterized by different pile-up conditions. In order to deal with the limited statistics and to ensure a solid fit procedure, the distributions inclusive in $\mu$ are studied to determine the dependence on $N_{PV}$, and similarly the distributions inclusive in $N_{PV}$ are studied to determine the dependence on $\mu$. The effect of increasing either $N_{PV}$ or $\mu$ was determined to be significantly below the percent level and so negligible. The small observed dependence is attributed to the almost linear correlation between $\Sigma E_T$ and $N_{PV}$ and $\mu$.

Effects given by possible jet reconstruction inefficiencies, or the accidental promotion of soft contribution into the $E_T^{\text{miss,Jet}}$ term due to the increasing pile-up energy are not examined individually by isolating their specific contribution. Rather, their effect is included in the total value of the uncertainty provided by the data-MC ratio.

The values of the systematic uncertainties evaluated with this method depend
3.3. $E_T^{\text{miss}}$ RECONSTRUCTION

Figure 3.19: $E_{\text{miss}}^{x(y)}$ resolution as a function of $\Sigma E_T$, for data and MC simulation $Z \rightarrow \mu\mu$ events without jets with $p_T > 20$ GeV. The data-MC ratio used to evaluate the systematic uncertainties is shown in the bottom part of the plot.

on the MC simulation used. Events simulated with Powheg+Pythia are used to determine the systematic uncertainties on the soft term with this method. Then, it is also checked that these uncertainties cover the data-MC discrepancies when using $Z \rightarrow \mu\mu$ events generated with either Alpgen or Sherpa, and found to be compatible at the 0.5% level. The systematic uncertainties for Atlfast-II (Section 3.1.2) are also evaluated. The results are found to be compatible with the general case because the large pile-up contribution entering the soft term is simulated in the same way in both the Atlfast-II and the full simulation samples resulting in very similar distributions for the $E_T^{\text{miss}}$ and $\Sigma E_T$ quantities shown in figure 3.20. A large discrepancy up to 20% is only observed in the high $\Sigma E_T$ region that, for the purposes of the systematic uncertainties evaluation, just enters as a small binning effect.

$E_T^{\text{miss,SoftTerm}}$ systematic uncertainties from the in-situ method based on evaluation from the balance between the soft term and the hard objects (2011 and 2012)

The method uses inclusive $Z \rightarrow \mu\mu$ events and exploits the balance between the $E_T^{\text{miss,SoftTerm}}$ and the total transverse momentum of the hard objects in the
Chapter 3: Physics object reconstruction

Figure 3.20: Comparison between the full and Atlfast-II simulation for the $E_{\text{miss}}^T$ and $\Sigma E_T$ distributions for $Z \rightarrow \mu \mu$ events without jets with $p_T > 20$ GeV.

Events, defined as:

$$p_{\text{hard}}^x(y) = \Sigma_\mu p_\mu^x(y) + \Sigma_\nu p_\nu^x(y) + \Sigma_{\text{jets}} p_{\text{jets}}^x(y) + \Sigma_\gamma p_\gamma^x(y) + \Sigma_\nu p_\nu^x(y),$$

$$p_{\text{hard}}^T = \sqrt{(p_{\text{hard}}^x)^2 + (p_{\text{hard}}^y)^2}.$$  (3.11)

$p_{\text{hard}}^x(y)$ is in general calculable only for MC events, since it includes invisible particle momenta which are not known in data. While not a direct and universal observable, it is nevertheless a useful quantity to characterize events since transverse momentum balance dictates that it ought to be equal to $E_{\text{miss},\text{SoftTerm}}^T$.

The mean and the resolution of the $E_{\text{miss},\text{SoftTerm}}^T$ components are studied both with respect to $p_{\text{hard}}^T$ and to $N_{\text{PV}}$ to study the effect of pile-up. In these events $p_{\text{hard}}^x(y)$ is close to zero and it is assumed to be zero in data. Since the magnitude and direction of the $E_{\text{miss},\text{SoftTerm}}^T$ depends on the number of jets, leptons and neutrinos in the event, the systematic uncertainties have been derived in bins of $p_{\text{hard}}^x(y)$. Then, the parametrization determined from $Z \rightarrow \mu \mu$ events can be used to evaluate the systematic uncertainties on the $E_{\text{miss},\text{SoftTerm}}^T$ in other samples as well.

To evaluate the $E_{\text{miss},\text{SoftTerm}}^T$ mean and resolution, the $E_{\text{miss},\text{SoftTerm}}^T$ is decomposed along and perpendicular to the $p_{\text{hard}}^T$ direction. The mean longitudinal component is a measure of the $E_{\text{miss},\text{SoftTerm}}^T$ scale, as the longitudinal direction is sensitive to the balance between the high-$p_T$ objects and the $E_{\text{miss},\text{SoftTerm}}^T$.
3.3. $E^\text{MISS}_T$ RECONSTRUCTION

<table>
<thead>
<tr>
<th>$E^\text{miss,SoftTerm}_T$ uncertainty</th>
<th>data/MC method</th>
<th>balance method</th>
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Table 3.2: Systematic uncertainties on the scale and on the resolution of the $E^\text{miss,SoftTerm}_T$, calculated with the two different in-situ methods: based on the data/MC ratio and on the balance between the soft term and the hard objects. The large percentage error quoted for the $E^\text{miss}_T$ scale for the balance method has to be referred to the small bias of the $E^\text{miss,SoftTerm}_T$ of $\sim 3$ GeV, therefore its net effect is less then 1 GeV and less important with respect to the resolution uncertainty.

Results and combination of the scale and resolution uncertainties on the $E^\text{miss,SoftTerm}_T$ and closure test

The results for the systematic uncertainties on the scale and resolution of the $E^\text{miss,SoftTerm}_T$, obtained with the two in-situ methods previously described, are summarized in Table 3.2. Both the methods are validated performing a closure test in $Z \rightarrow \mu\mu$ events without jets with $p_T > 20$ GeV. The results are shown in Figure 3.21(a) for the Powheg+Pythia MC generator using the data-MC ratio method and in Figure 3.21(b) for the Alpgen generator using the balance method. The variation distribution are obtained scaling the soft term up and down according to its scale uncertainty and smearing it according to its resolution uncertainty.

For the first method the scale and resolution uncertainties are assumed uncorrelated and are both scaled up and down simultaneously, and then added in quadrature. For the second method both longitudinal and perpendicular components of the resolution uncertainties are varied and the fully correlated and fully anticorrelated cases uncertainties are added in quadrature.

The first thing to notice is that while for the Powheg+Pythia generator the nominal $E^\text{miss}_T$ value is quite centered around the unity, for the Alpgen generator the ratio distribution shows a systematic trend suggesting that the MC $E^\text{miss}_T$ distribution has a larger RMS than the one observed in data. This observation is also confirmed by the fact that the down variation for the resolution gives a data-MC ratio around unity. In any case, both methods are able to cover the
Figure 3.21: Comparison between data, nominal and variated MC simulation for the $E_T^{\text{miss}}$ distribution in $Z \rightarrow \mu\mu$ events without jets with $p_T > 20$ GeV for the Powheg+Pythia MC generator for the first method in (a) and for the second method in (b). In the bottom part of the plots are shown the respective ratio between data and the nominal and the variated MC.

deviation of data-MC ratio from unity in the full range.

Prospects for the $E_T^{\text{miss,SoftTerm}}$ systematic uncertainties evaluation

In order to further improve the evaluation of the $E_T^{\text{miss,SoftTerm}}$ systematic uncertainties, a lot of work is currently on-going on different fronts.

A more precise evaluation can be achieved with a split of the resolution and scale $E_T^{\text{miss}}$ uncertainties into components originated by different physics sources. This would allow each physics analysis to constrain more the specific components of the systematic uncertainties to which the analysis is more sensitive, and it would also give more flexibility in the combination of different physics analyses. In order to perform a complete splitting of the systematic uncertainties a common metric scale not depending on pile-up effects and on the specific topology examined would be very useful, hence there is a large activity in this direction.

The splitting of the systematic uncertainties in physics sources could also help in the evaluation of the correlation between the different terms contributing to
3.4. CONCLUSION AND PROSPECTS

$E_T^{\text{miss}}$. In particular, a correlation between the jets and the soft term is expected, since only a $p_T$ threshold establishes the separation between a jet and a soft term contribution. Using a splitting scheme for the soft term uncertainties might give the opportunity to identify a relation between the components of the systematic uncertainties of different physics objects. These studies should also include possible migration effects between the different $E_T^{\text{miss}}$ terms and the evaluation of “close-by” effects between objects of different type, like electrons and jets, that could have non-negligible effects on boosted topologies\textsuperscript{12}.

Finally, the systematic uncertainty on the $E_T^{\text{miss}}$ scale might benefit from the use of an in-situ evaluation of the $E_T^{\text{miss}}$ scale using $W \to \ell \nu$ events [127] and $Z \to \tau \tau$ events. This has so far not been explored due to the limited statistics after the hard selection required to efficiently reject background in this analysis.

3.4 Conclusion and prospects

Since the beginning of the data taking significant effort has been invested into a good understanding of the detector system and the development of high precision reconstruction algorithms exploiting information from the full detector. Highly efficient and performant physics object reconstruction, identification and calibration and an accurate evaluation of the systematic uncertainties have a direct impact on physics analyses allowing to achieve high precision measurements and searches for rare events.

In particular, the $E_T^{\text{miss}}$ reconstruction is a complex and refined procedure that relies on the reconstruction and calibration performance of all the other physics objects. A careful investigation has been executed to improve the treatment of each contribution and to guarantee sufficient configuration flexibility to establish coherence between the $E_T^{\text{miss}}$ and the analysis selection choices.

The use of more sophisticated and refined techniques is required to cope with the increasing of pile-up condition resulting in a very busy environment. The case of the $E_T^{\text{miss}}$ algorithm is extensively discussed in the next chapter.

\textsuperscript{12}In these final states the decay products are close to each other.
Chapter 4

Pile-up suppression methods for the $E_T^{\text{miss}}$ reconstruction

As discussed in Section 2.2, the high luminosity provided by LHC in 2012 (with an instantaneous luminosity peak close to $8 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$) combined with a bunch crossings time of 50 ns, lead to unprecedented backgrounds from additional proton-proton collisions.

The $E_T^{\text{miss}}$ reconstruction is affected not only by the multiple interactions in the same bunch crossing (in-time pile-up), but also by the bunch crossing signal history in the ATLAS calorimeters (out-of-time pile-up). Several approaches to suppress the pile-up signals, especially for the soft term contribution, have been developed and evaluated, making use of reconstructed tracks, calorimeter signals, or a combination of both.

The impact of pile-up in the $E_T^{\text{miss}}$ reconstruction is discussed in Section 4.1. The pile-up suppression methods are described in Sections 4.2-4.4. The performance improvements for various final states are evaluated and compared in Section 4.5. Finally, the evaluation of the systematic uncertainties after applying the corrections are presented in Section 4.6.

4.1 Pile-up effects in $E_T^{\text{miss}}$ performance

The large pile-up in the 2012 data taking has significant effects on the detector signals relevant for $E_T^{\text{miss}}$ reconstruction, in particular on the calorimeter energy
4.2. PILE-UP SUPPRESSION METHODS

clusters: energy fluctuations in these observables directly translate in fluctuation in the $E_T^{\text{miss}}$ measurement, and thus can not only worsen the resolution but also affect the $E_T^{\text{miss}}$ scale.

In order to mitigate the effects of residual pile-up contributions in the clustering formation or in creating additional clusters, an appropriate optimization of the LAr optimal filtering, and a re-evaluation of the noise thresholds and of the LCW weights used in the topological clustering, are provided for 2012 data. Nevertheless, a large pile-up contribution is still included in the $E_T^{\text{miss}}$ reconstruction.

The degradation in performance is quantified studying the stability of the basic $E_T^{\text{miss}}$ reconstruction observables as a function of the number of the reconstructed primary vertices, $N_{\text{PV}}$, which is a good estimator for in-time pile-up, and as a function of the average number of collisions in a given time window around the recorded event, $\mu$, which is a good scale for the effects of out-of-time pile-up. The evolution of the pile-up conditions described by the $N_{\text{PV}}$ and $\mu$ observables during the 2012 data taking is shown in Figure 4.1. The effects of pile-up for the various $\Sigma E_T$ terms and for the total $\Sigma E_T$ in different pseudorapidity calorimeter regions are shown in Figure 4.2(a) and 4.2(b), respectively, as a function of $N_{\text{PV}}$. Figure 4.2(a) shows that the soft term is largely dominated by pile-up, indicating the need for a dedicated correction. This is specifically the case in low multiplicity final states, such as $Z$, $W$ and Higgs production, where the importance of the soft term contribution to the $E_T^{\text{miss}}$ is enhanced. A simple omission of this term is not appropriate, because the true soft event associated with the triggered hard scattering signal gives an important contribution to $E_T^{\text{miss}}$ reconstruction performance especially with respect to the $E_T^{\text{miss}}$ resolution, and depending on the final state topology, also to $E_T^{\text{miss}}$ scale. In the following sections, techniques for the pile-up suppression in the soft term are described in detail. It is important to notice that a correction for the soft term is not straight forward because the $E_T^{\text{miss,SoftTerm}}$ is reconstructed from tracks and calorimeter clusters not associated with the hard objects, and thus lacking a universal and stable calibration reference especially for the individually calorimeter cluster signals.

4.2 Pile-up suppression methods

As discussed in the previous section, the $E_T^{\text{miss}}$ reconstruction is challenged by the presence of pile-up, especially the soft term that receives a huge additional
energy contribution. This pile-up contribution needs to be removed from the true signals as much as possible in order to restore comparable reconstruction performances to the ones achieved in the low luminosity running periods of the ATLAS data taking. It is important to notice that, in order to not create a fake non-balance in the $E_{\text{miss}}$ computation, the pile-up contribution must be removed from all the $E_{\text{miss}}$ terms in Equation 3.5. Therefore, the pile-up corrections for each physics object, described in the previous chapter, are automatically included in the $E_{\text{miss}}$ reconstruction.

Concerning jets, since the pile-up not only affects the jet energy reconstruction but can also create additional jets and since the jet area correction described in Section 3.2.4 only captures event-by-event fluctuations and not local fluctuations in the same event, an additional track based filter (JVF) is applied in order to enhance the likelihood for a particular jet to be generated by the hard scattering vertex. A description of the JVF filter is given in Section 4.3.1.

In this section methods for the pile-up suppression for the $E_{\text{miss}}$ soft term are presented. They are mainly divided into two categories: track based methods and jet area based methods. The main concepts on which these methods are based are described in the following, while a full description of each method is given in Sections 4.3 and 4.4.

**Tracking based pile-up correction (STVF, TST)**. These methods exploit the tracks association with the primary vertex to exclude pile-up contributions from the $E_{\text{miss}}$ reconstruction. Moreover, the tracking detector, having a faster response than the calorimeter, is not sensitive to the out-of-
4.2. PILE-UP SUPPRESSION METHODS

Figure 4.2: The dependence on pile-up of the $\Sigma E_T$ terms and of the $\Sigma E_T$ distribution in different pseudorapidity regions as a function of $N_{PV}$ are shown respectively in (a) and (b).

time pile-up contribution. This makes reconstructed tracks a powerful tool for pile-up suppression. Two methods are explored in this thesis and are described in details in Section 4.3:

**STVF** The Soft Term Vertex Fraction (STVF) method makes use of both tracks and clusters entering the $E_{Tmiss,SoftTerm}$, and employs the ratio of the scalar sum of the soft event track $p_T$ associated with the hard scatter vertex to the sum of all the soft event track $p_T$ from all reconstructed vertices in the event. This ratio is used to scale all soft event contributions to $E_{Tmiss}$ and $\Sigma E_T$ in the given event.

**TST** The Track-based Soft Term (TST) method uses only tracks not included in high-$p_T$ physics objects and associated to the primary vertex. No cluster information is used, thus neglecting the contribution of neutral and forward particles to the soft term.

**Jet area based pile-up suppression (EJA, EJAF, JAF).** The common aspect of these methods is the use of an event-by-event estimator for the transverse momentum density, $\rho$, of the soft event, which is then used to compute the pile-up contribution in each jet, $\rho \times A_{jet}$, where $A_{jet}$ is the jet area. The procedure involves the decomposition of the soft event into soft jets, down to $p_T = 0$, with typically two different definitions for these jets: one for the measurement of the transverse momentum density (“$\rho$-jets”),
and another one as a basis for applying the $p_T$ threshold (“filter-jets”).

Three implementations are studied in this thesis:

**EJA** The Extrapolated Jet Area (EJA) method measures the $\rho$ using the soft event in the central part of ATLAS ($|\eta| < 2$, approximately) only. It is then extrapolated to the forward region using transverse momentum flow profiles measured with minimum bias data.

**EJAF** The Extrapolated Jet Area with Filter method (EJAF) uses a similar configuration as EJA to measure the $\rho$, including the extrapolation. It then applies a JVF based selection on filter-jets in addition.

**JAF** The Jet Area with Filter (JAF) method uses a $\rho$ calculated from the soft event over the full acceptance of ATLAS ($|\eta| < 5$), without extrapolation. It also applies a JVF based selection on the filter-jets.

### 4.3 Track-based methods

As discussed in the previous section, the tracking based pile-up correction exploits the $p_T$ activity from charged tracks not associated with physics objects but linked to a given hard scatter primary vertex, hereafter indicated with the symbol $V_{\text{primary}}$. The track reconstruction is as well challenged by the increasing of pile-up conditions, in particular the effects of splitting and merging between vertices has a large impact on the vertex reconstruction efficiency.

In this section the computation of the JVF filter and the two track based methods for the pile-up suppression in the soft term, STVF and TST, are described in detail.

#### 4.3.1 Jet Vertex Fraction (JVF) filter

Jets entering the $E^{\text{miss}}_T$ computation still have pile-up contamination. Further improvements in the performance are achieved by requesting an association of jets contributing to $E^{\text{miss,jet}}_T$ term to the hard scatter vertex. For $E^{\text{miss}}_T$ reconstruction, central jets not even weakly associated with the primary event vertex can be safely interpreted as originating from one of the additional pile-up interactions and should therefore be omitted from $E^{\text{miss}}_T$.

The filter applied to the accepted jets is based on the jet vertex fraction JVF, which measures the amount of $p_T$ carried by reconstructed tracks associated\(^1\)

---

\(^1\)Tracks are associated to calorimeter jets following the ghost association procedure [135].
4.3. TRACK-BASED METHODS

with the jet and coming from the primary vertex $V_{\text{primary}}$ relative to the $p_T$ carried by all tracks associated with the jet:

$$JVF = \frac{\sum_{i=1}^{N_{\text{jet}}^{V_{\text{primary}}}} p_{T,\text{trk},i}^{\text{jet}}(V_{\text{primary}})}{\sum_{k=1}^{N_{\text{vtx}}} \sum_{i=1}^{N_{\text{jet}}^{V_k}} p_{T,\text{trk},i}^{\text{jet}}(V_k)}$$

(4.1)

where $N_{\text{trk}}^{V_k}(V_k)$ is the number of tracks at vertex $V_k$ pointing to the jet, and $N_{\text{vtx}}$ is the total number of collision vertices in the event. $p_{T,\text{trk},i}^{\text{jet}}(V_k)$ is the $p_T$ of track $i$ associated with vertex $V_k$ and pointing to the jet.

$JVF$ is a quantity assigned jet-by-jet. It can only be calculated for jets within the ID acceptance ($|\eta_{\text{jet}}| < 2.4$), and for jets with tracks associated at all:

$$JVF = \begin{cases} 
-1 & \text{no tracks associated with jet} \\
0 \ldots 1 & \text{all central jets with tracks}
\end{cases}$$

In particular, $JVF = 0$ corresponds to the case in which the jet has no tracks associated to the $V_{\text{primary}}$.

Jets within $|\eta_{\text{jet}}| < 2.4$ and with $p_T < 50$ GeV are accepted for $E_T^{\text{miss}}$ only if $JVF \neq 0$ (weak association with $V_{\text{primary}}$). The selection applied is efficient for letting hard scattering jets survive, with a significant rejection of pile-up jets, see Ref. [136] for details.

The $JVF$ distribution, shown in Figure 4.3(a), is not well modelled specially for low values, therefore, by cutting on this variable, a discrepancy in the jet selection efficiency for $E_T^{\text{miss}}$ can be introduced. This effect can be observed in the comparison between data and MC simulation for the $E_T^{\text{miss,jet}}$ term distribution before applying the $JVF$ cut and after the cut, shown in Figure 4.3(b). The region below 20 GeV is dominated by jets balancing each other and a clear disagreement is introduced after applying the $JVF$ cut since for the MC simulation is more likely to filter out one of the jets reducing the number of the entries in this region with respect to the ones observed in data. Instead, in the region defined by $E_T^{\text{miss,jet}} > 20$ GeV, a better agreement is observed after the application of the $JVF$ cut. This is probably due to an overestimation in the number of jets in the MC simulation before the $JVF$ pileup suppression. This hypothesis is also confirmed by the improvement in the data-MC agreement for the jet multiplicity studied before and after the $JVF$ filter [136].

\footnotetext{2From the $JVF$ plot one can observe that MC simulation has more jets with $JVF=0$ with respect to the data.}
4.3.2 Soft Term Vertex Fraction (STVF)

The STVF method provides an event-by-event average correction to be applied to both the tracks and the topoclusters contributing to the soft term as described in Section 3.3.1. In particular, it relies on the evaluation of the pile-up activity within an event via the Soft Term Vertex Fraction (STVF), defined as the ratio of the scalar $p_T$ sum of tracks from the primary (hard scatter) event vertex $V_{primary}$ to the total summed reconstructed track $p_T$ from all $k = 1 \ldots N_{vtx}$ event vertices $V_k$:

$$STVF = \frac{\sum_{i=1}^{N_{trk}(V_{primary})} p_{trk}^{(i)}(V_{primary})}{\sum_{k=1}^{N_{vtx}} \sum_{i=1}^{N_{trk}(V_k)} p_{trk}^{(i)}(V_k)}$$  (4.2)

where $p_{trk}^{(i)}(V_k)$ is the $p_T$ of soft event track $i$ coming from vertex $V_k$, $N_{trk}(V_k)$ is the total number of reconstructed tracks not associated with any hard object from this vertex, and $N_{vtx}$ is the total number of the collision vertices in the event. The tracks used are all the reconstructed tracks in the soft event and the track selection is the same used by the $eflow$ algorithm introduced in Section 3.3.1.

The pile-up suppression is then applied by scaling the $E_{T,\text{SoftTerm}}^{\text{miss}}$ compo-
4.3. TRACK-BASED METHODS

ten and the $\Sigma E_T^{\text{SoftTerm}}$ by the STVF factor, with $0 \leq \text{STVF} \leq 1$:

$$
E_{x(y),\text{corr}}^{\text{miss},\text{SoftTerm}} = \text{STVF} \cdot E_{x(y)}^{\text{miss},\text{SoftTerm}}
$$

$$
E_{T,\text{corr}}^{\text{miss},\text{SoftTerm}} = \text{STVF} \cdot E_T^{\text{miss},\text{SoftTerm}}
$$

$$
\Sigma E_T^{\text{SoftTerm},\text{corr}} = \text{STVF} \cdot \Sigma E_T^{\text{SoftTerm}}
$$

Applying the STVF factor on the total $E_T^{\text{miss}}$ and $\Sigma E_T$ implicitly relies on two strong assumptions. The first is that the fraction of the charged pile-up component is the same as the fraction of the neutral pile-up component and the second is that the pile-up estimation in the central region is also valid in the forward region. Attempts applying the STVF factor only in the central region where the track information is available lead to discouraging results, since the pile-up contributions in the forward region are then included in the $E_T^{\text{miss}}$ computation without any correction.

The corrected $E_T^{\text{miss}}$ components, $E_{x(y),\text{corr}}^{\text{miss},\text{SoftTerm}}$, are then combined following Equation 3.5, together with a $E_{x(y)}^{\text{miss},\text{jet}}$ term using JVF filtered jets, to finally calculate the total corrected $E_T^{\text{miss}}$.

Figure 4.4 shows the STVF distribution in $Z \rightarrow \mu\mu$ events without and with hard jets ($p_T > 20$ GeV). The agreement between data and MC is good in the regions of low STVF, but deteriorates at larger STVF. This is due to more significant effects from mis-modeling of the track activity in MC for small $N_{PV}$ values (large STVF). While for large $N_{PV}$ (small STVF) the overall track distribution in space and the overall track $p_T$ spectrum agrees more with data (due to mixing of many individually simulated interactions), the basic differences between simulated and measured track distributions are more enhanced for individual vertices (p-p interactions).

4.3.3 Track-based Soft Term (TST)

This method completely neglects the cluster contribution and computes the soft term using only tracks associated with the hard scatter vertex. The soft term built this way is expected to be resilient to pile-up effects, with other limitation arising from the omission of the soft neutral and forward particle contributions. It is then combined with the contribution from the high-$p_T$ physics objects properly calibrated according to Equation 3.5.

Former studies [128], show a worse performance for the $E_T^{\text{miss}}$ reconstructed with a soft term calculated from tracks associated to the primary vertex and selected as for the *eflow* algorithm (see Section 3.3.1). The TST method is now
Chapter 4: Pile-up suppression methods for the $E_T^{\text{miss}}$ reconstruction

Figure 4.4: Comparison of the Soft Term Vertex Fraction, STVF, as defined in Equation 4.2, for a $Z \to \mu\mu$ sample without any jets with $p_T > 20$ GeV in (a), and for the inclusive sample from the same final state in (b).

optimized to use the same track selection employed for the track based $E_T^{\text{miss}}$ estimation [137].

- The tracks are required to have:
  - $p_T > 500$ MeV, $|\eta| < 2.5$
  - $N_{\text{PIXEL}}^{\text{hits}} \geq 1$, $N_{\text{SCT}}^{\text{hits}} \geq 6$

- The association with the primary vertex is obtained asking for:
  - transverse impact parameter with respect to the primary vertex
    $|d_0| < 1.5$ mm
  - longitudinal impact parameters with respect to the primary vertex
    $|z_0 \sin(\theta)| < 1.5$ mm.

- Finally, in order to reduce the number of mis-reconstructed tracks$^3$, isolated tracks, excluding muon tracks, with $p_T > 200$ GeV and $|\eta| < 1.5$, and with $p_T > 120$ GeV and $|\eta| > 1.5$ are used if:
  - the relative uncertainty on the charge to track-momentum ratio ($q/p$) is
    $\sigma(q/p)/(q/p) < 0.4$

$^3$Tracks can have their momentum badly mis-reconstructed due to low $p_T$ tracks interacting with the ID material and thus producing a large number of secondary particles, all of which can leave enough hits in the pixel/SCT subdetectors to be reconstructed with a much higher momentum.
4.4 Jet Area based methods

The track based pile-up suppression methods discussed in the previous Section 4.3 have the advantage of using well reconstructed tracks from the central detector region to correct $E_{\text{miss}}^{\text{SoftTerm}}$, $T$. They potentially rely on the correlation between the central and forward transverse momentum flow, and the identification of the actual hard scattering vertex in a given event. To use more direct measures of the $p_T$ flow across the full ATLAS detector acceptance ($|\eta| < 5$), an alternative approach largely exploiting calorimeter signals from the soft event has been developed. It is based on the $p_T$ density of the soft event, in a variation of the originally suggested pile-up suppression strategy in Ref. [135], and its application to jets in ATLAS discussed in Ref. [136].

The common procedure for the jet area techniques described in the following sections is based on three steps:

1. The determination event-by-event of the event transverse momentum density, $\rho_{\text{evt}}^\text{med}$, described in Section 4.4.1.

2. The computation jet-by-jet of the jet’s susceptibility to pile-up, $A_{\text{jet}}$, and the subtraction of pile-up contribution $\rho_{\text{evt}}^\text{med} \times A_{\text{jet}}$, described in Section 4.4.2.

3. An additional and optional JVF filter on the previously corrected soft term jets.

4.4.1 Determination of the transverse momentum density

The transverse momentum density, $\rho_{\text{evt}}^\text{med}$, is designed to capture the event-by-event fluctuations in pile-up.

In the original suggestion, all particles within the full detector acceptance are clustered into jets using a recursive recombination algorithm like the original $k_T$ [119, 138] or the Cambridge-Aachen [118, 139] flavoured version, both with small ($R = 0.4$) distance parameters. All jets with $p_T^\text{jet} \geq 0$ are formed and
their catchment (active) area $A_{\text{jet}}$ [140] is calculated. This allows measuring a transverse momentum density $\rho_{\text{jet},i}$ for any soft event jet $i$ with $p_{T,i}^{\text{jet}}$ and $A_{\text{jet},i}$, and to determine a median $p_T$ density from the soft event ($\rho_{\text{evt}}^{\text{med}}$) from all $N_{\text{jets}}$ soft event jets within a given range $\eta_{\text{min}} < \eta_{\text{jet}} < \eta_{\text{max}}$:

$$\rho_{\text{jet},i} = \frac{p_{T,i}^{\text{jet}}}{A_{\text{jet},i}} \quad \text{and} \quad \rho_{\text{evt}}^{\text{med}} = \text{median}\{\rho_{\text{jet},i}\}$$  \hspace{1cm} (4.3)

The evaluation range $[\eta_{\text{min}}, \eta_{\text{max}}]$ for $\rho_{\text{evt}}^{\text{med}}$ can be the full detector acceptance or, as for the correction discussed below, any restricted region of sufficient size.

The specific use of the median $5\rho_{\text{evt}}^{\text{med}}$ of all $\rho_{\text{jet}}$ in any given $\eta$ region emphasizes the contribution of the soft event signals to the event $p_T$ density, which is most sensitive to pile-up.

Studies of pile-up suppression for jets in ATLAS found that $\rho_{\text{evt}}^{\text{med}}$ is an appropriate estimator of the in-time pile-up activity, especially if determined in the central detector region only (about $|\eta| < 2$) [136], but it also has some sensitivity to the out-of-time pile-up contribution. According to this finding, two of the methods studied in this thesis evaluate the $\rho_{\text{evt}}^{\text{med}}$ in the central detector region and then extrapolate it to the forward region using transverse momentum flow profiles measured with minimum bias data, as described in the following section, while a third method employs a $\rho_{\text{evt}}^{\text{med}}$ estimated in the whole detector acceptance ($|\eta| < 4.9$). Including the whole event plane in $(\eta, \phi)$ into the $\rho_{\text{evt}}^{\text{med}}$ reconstruction yields a smaller estimate of the pile-up activity than the one obtained from the central detectors. This is due to the particularities of the ATLAS calorimeter and to the reconstruction of its (cluster) signal. The readout granularity in the more forward regions of the calorimeter system is significantly reduced, leading to a more sparsely populated event plane even at the level of calorimeter cells. Applying the topological cell clustering and its implicit noise suppression, which is necessary to reduce local signal fluctuations to acceptable levels, leads to even more sparser spatial occupancy, as cell signals are typically collected into only a few $(\eta, \phi)$ barycenters. Analyzing the event plane with e.g. $k_t$ jets with $p_T^{\text{jet}} \geq 0$.

\footnote{Note that jets with $p_T = 0$ are not actually clustered, rather they reflect the unclustered area in the rapidity/azimuth plane ($\Delta y \times \Delta \phi \approx 10 \cdot 2\pi$ for an approximate $y$-range of $|y| < 5$ in ATLAS) after all jets with $p_T > 0$ are removed. The number of $p_T = 0$ jets is then this unclustered area divided by the most probable expected active jet area $A_{\text{jet}}(p_T = 0) \approx \pi R^2/2$ for the $k_t$ algorithm, if no particles are present (active ghost area, see Ref. [140]).}

\footnote{A median evaluation is indeed less biased than an average evaluation by the few hard scatter contributions entering the $\rho_{\text{evt}}$ computation.}
leads to a larger number of $p_T^{\text{jet}} = 0$ jets, thus reducing the median transverse momentum density of the event significantly. While some drop of the transverse momentum density is expected with increasing $\eta$ [141], the observed drop of the local density is much steeper due to the instrumental effects discussed above. This can be partly mitigated by e.g. increasing the jet distance parameter to $R = 0.8$, and thus decreasing the number of $p_T = 0$ jets.

**Extrapolation of the transverse momentum density into the forward regions**

The jet area based pile-up corrections implemented for $E_{\text{miss,SoftTerm}}^T$ using $\rho_{\text{evt}}^{\text{med}}$ employ filter-jets with $R = 0.4$, built from the soft event tracks and calorimeter clusters with the $k_t$ algorithm implemented in FASTJET [141]. The contribution $p_{T,\text{SoftJet}}^{\text{SoftJet}}$ of these soft event jets (with transverse momentum $p_T^{\text{jet}}$, area $A_{\text{jet}}$, and at direction $\eta_{\text{jet}}$) is defined by the following filter:

$$E_{x(y)}^{\text{miss,SoftTerm}} = - \sum_{i=1}^{N_{\text{jets}}} p_{x(y),i}^{\text{SoftJet}}, \text{with}$$

$$p_{T,i}^{\text{SoftJet}} = \begin{cases} 0, & p_{T,i}^{\text{SoftJet}} < f_{\text{scale}} \cdot \rho_{\text{evt}}^{\text{med}}(\eta_{\text{jet},i}) \cdot A_{\text{jet},i} \\ \rho_{T,i}^{\text{SoftJet}} - \rho_{\text{evt}}^{\text{med}}(\eta_{\text{jet},i}) \cdot A_{\text{jet},i}, & p_{T,i}^{\text{SoftJet}} \geq f_{\text{scale}} \cdot \rho_{\text{evt}}^{\text{med}}(\eta_{\text{jet},i}) \cdot A_{\text{jet},i} \end{cases}$$

The scale factor $f_{\text{scale}}$ can be optimized, but it has been found that $f_{\text{scale}} = 1$ delivers good performance. The median transverse momentum density $\rho_{\text{evt}}^{\text{med}}(\eta_{\text{jet}})$ in this case is determined from $\rho$-jets, with various configurations as described in Section 4.4.2. To avoid the already discussed occupancy issues, it is determined event by event in the central detector region only (typically $|\eta| < 1.8 - 2.0$), and then extrapolated to higher $\eta$. The extrapolation function is measured with minimum bias events using a sliding window of total width $\Delta \eta = 1.6$ such that the mean $\langle p_T(\eta) \rangle$ at any direction $\eta \in [-5, 5]$ is the average of the event by event summed $p_T$ from calorimeter signal clusters reconstructed using the local hadronic calibration, and located within this window $(\eta - \Delta \eta/2, \eta + \Delta \eta/2)$.

The average amount of energy scattered into any $\Delta \eta$ window at a given direction $\eta$ by these minimum bias events depends on the in-time and out-of-time pile-up. Thus the reconstructed $\langle p_T(\eta) \rangle$, which is exposed to these influences, depends on the experimental observables measuring the in-time pile-up activity ($N_{\text{PV}}$) and the out-of-time pile-up effect ($\mu$), and needs to be determined as $\langle p_T(\eta, N_{\text{PV}}, \mu) \rangle$ for all run conditions ($N_{\text{PV}}, \mu$) occurring in 2012 ATLAS data taking. This is done by collecting $\langle p_T(\eta, N_{\text{PV}}, \mu) \rangle$ profiles in bins of $N_{\text{PV}}(\Delta N_{\text{PV}} = 1)$ and $\mu$.
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$(\Delta \mu = 2)$ and converting them to average density profiles $\langle \rho \rangle(\eta, N_{\text{PV}}, \mu)$, using the effective width of the $\eta$ windows in the area calculation by taking into account detector boundaries.

As the central $\rho_{\text{evt}}^\text{med}$ determined in the central region is a sensitive event by event estimator of the pile-up signal activity, the $\langle \rho \rangle(\eta, N_{\text{PV}}, \mu)$ profiles have been normalized such that:

$$P^\rho(\eta, N_{\text{PV}}, \mu) = \frac{\langle \rho \rangle(\eta, N_{\text{PV}}, \mu)}{\langle \rho \rangle_{\text{central}}(N_{\text{PV}}, \mu)}.$$  (4.5)

$\eta_{\text{plateau}}$ defines the boundary of the central profile region within which $\langle \rho \rangle(\eta, N_{\text{PV}}, \mu)$ can be approximated by its average:

$$\langle \rho \rangle_{\text{central}}(N_{\text{PV}}, \mu) = \frac{1}{2\eta_{\text{plateau}}} \int_{-\eta_{\text{plateau}}}^{+\eta_{\text{plateau}}} \langle \rho \rangle(\eta, N_{\text{PV}}, \mu) \, d\eta$$

therefore the normalization scale $1/\langle \rho \rangle_{\text{central}}(N_{\text{PV}}, \mu)$ in Equation 4.5 only depends on $N_{\text{PV}}$ and $\mu$. For the normalized profiles this means that $P^\rho(\eta, N_{\text{PV}}, \mu) = 1$ for $|\eta| < \eta_{\text{plateau}}$ for all pile-up conditions $(N_{\text{PV}}, \mu)$. For simplicity of the extrapolation function and supported by the experimental observations, $P^\rho(\eta, N_{\text{PV}}, \mu)$ can safely be assumed as symmetric around $\eta = 0$. $P^\rho(\eta, N_{\text{PV}}, \mu)$ drops from its plateau value starting at $|\eta| \approx \eta_{\text{plateau}}$. The shape of these drops are well described by Gaussian shaped shoulders with width $\sigma_{\text{center}}$, and mean $\eta_{\text{plateau}}$ for the $\eta > 0$ hemisphere, and $-\eta_{\text{plateau}}$ for the $\eta < 0$ hemisphere. A wide baseline underlines the plateau and the Gaussian slopes, it follows a Gaussian form with a mean of $\eta = 0$, a width $\sigma_{\text{base}}$, and a peak amplitude $A_{\text{base}}$ and it is constraint by the measured averaged densities at high $|\eta|$. The sum of the central ($G_{\text{center}}$) and base ($G_{\text{base}}$) shapes is normalized such that the total amplitude peaks at 1 at $\eta = \pm \eta_{\text{plateau}}$, to smoothly connect to the normalized plateau value described above. The overall functional form describing the complete shape is then

$$P^\rho_{\text{fct}}(\eta, N_{\text{PV}}, \mu) = \begin{cases} 1 & |\eta| < \eta_{\text{plateau}} \\ (1 - G_{\text{base}}(\eta_{\text{plateau}})) \cdot G_{\text{center}}(\eta) + G_{\text{base}}(\eta) & |\eta| \geq \eta_{\text{plateau}} \end{cases}. \quad (4.6)$$

The Gaussian shapes in $P^\rho_{\text{fct}}$ are defined as

$$G_{\text{center}}(\eta) = \begin{cases} \exp \left[ -\frac{(\eta - \eta_{\text{plateau}})^2}{2\sigma_{\text{center}}^2} \right] & \eta \geq \eta_{\text{plateau}} \\ \exp \left[ -\frac{(\eta + \eta_{\text{plateau}})^2}{2\sigma_{\text{center}}^2} \right] & \eta \leq -\eta_{\text{plateau}} \end{cases} \quad (4.7)$$

$$G_{\text{base}}(\eta) = A_{\text{base}} \cdot \exp \left[ -\eta^2/(2\sigma_{\text{base}}^2) \right] \quad (4.8)$$
The measured $P^\rho(\eta, N_{PV}, \mu)$ shapes have been carefully studied in all the available $(N_{PV}, \mu)$ bins. The dependence on $N_{PV}$ and $\mu$ of the shape parameters, $\eta_{\text{plateau}}, \sigma_{\text{center}}, A_{\text{base}}, \sigma_{\text{base}}$, in Equations 4.7 and 4.8 are shown in Figures 4.5 and 4.6. An iterative fitting procedure of the functional form $P^\rho_{\text{fct}}(\eta, N_{PV}, \mu)$ from Equation 4.6 with a basic polynomial ansatz for the $N_{PV}$ and $\mu$ dependence of the parameters in $G_{\text{base}}$ and $G_{\text{center}}$, and thus capturing a possible dependence of these parameters on the pile-up environment, yields:

$$
\eta_{\text{plateau}}(N_{PV}, \mu) = \eta_{\text{plateau}} = \text{const}
$$

$$
\sigma_{\text{center}}(N_{PV}, \mu) = \sigma_{\text{center}}(N_{PV}) = \alpha_0 + \alpha_1 N_{PV} + \alpha_2 N_{PV}^2
$$

$$
A_{\text{base}}(N_{PV}, \mu) = A_{\text{base}}(N_{PV}) = \beta_0 + \beta_1 N_{PV} + \beta_2 N_{PV}^2
$$

$$
\sigma_{\text{base}}(N_{PV}, \mu) = \gamma_0(N_{PV}) + \gamma_1(N_{PV}) \mu + \gamma_2(N_{PV}) \mu^2
$$

As shown in figure 4.6, all $\mu$ dependence of $P^\rho_{\text{fct}}(\eta, N_{PV}, \mu)$ can be collected in $\sigma_{\text{base}}(N_{PV}, \mu)$, reflecting that in general the $\mu$ dependence of the calorimeter signal is largest in the ATLAS forward calorimeters, the region which constraints $\sigma_{\text{base}}$ most.

The final set of 16 parameters $\{\eta_{\text{plateau}}, \alpha_i, \beta_i, \gamma_{i,k}\}$ is universal and valid for the whole 2012 data taking period. It has been exclusively derived from data, and the resulting $P^\rho(\eta, N_{PV}, \mu)$ shapes are used for both data and MC. The $\eta$, $N_{PV}$ and $\mu$ dependent transverse momentum density from minimum bias events is then

$$
\rho_{\text{med}}^{\text{med}}(\eta) = \rho_{\text{med}}^{\text{med}} \cdot P^\rho_{\text{fct}}(\eta, N_{PV}, \mu),
$$

where $\rho_{\text{med}}^{\text{med}}$ is determined within $\eta_{\text{min}} = -\eta_{\text{plateau}}$ and $\eta_{\text{max}} = \eta_{\text{plateau}}$ from the already discussed soft event $k_t$ jets with $R = 0.4$, see Equation 4.3. This is expected to be a good representation of the pile-up activity and effect on the soft event calorimeter signals for any pile-up condition in ATLAS running in 2012. The normalized shapes $P^\rho_{\text{fct}}(\eta, N_{PV}, \mu)$ for selected pile-up conditions expressed by combinations of $N_{PV}$ and $\mu$ are shown in Figure 4.7.

4.4.2 Applying a jet area based pile-up suppression

To apply pile-up suppression to the soft term, the $E^{\text{miss,SoftTerm}}_T$ components are re-summed using only the soft event jets passing the filter using the transverse
Figure 4.5: The dependence on $N_{PV}$ and $\mu$ and the relative fit function of the $\eta_{\text{plateau}}$ parameter are shown in (a) and (b) respectively. The same dependencies are shown for the $\sigma_{\text{center}}$ parameter in (c) and (d), and for the $A_{\text{base}}$ parameter in (e) and (f).
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Figure 4.6: The dependence on $N_{PV}$ and $\mu$ of the shape parameter $\sigma_{base}$ is shown in (a). The fit of the $\mu$ dependence according to a three-parameter function is shown in (b). The $N_{PV}$ dependence of the three parameters $\gamma_0$, $\gamma_1$, $\gamma_2$ is shown respectively in (c), (d) and (e).
Figure 4.7: The average transverse momentum density shape $P^\rho(\eta, N_{\text{PV}}, \mu)$ for $N_{\text{PV}} = 3$ and $7.5 < \mu < 9.5$, determined from 2012 ATLAS minimum bias data, as a function of $\eta$ (a). The relative increase of the forward activity due to increasing of in-time pile-up ($N_{\text{PV}} = 8$) for the same level of out-of-time pile-up can seen in (b). The signal modulation in the forward region by the out-of-time pile-up effects, as introduced by the particularities of the signal shaping functions in this calorimeter region, can be seen by comparing plot (c) at lower $\mu$ with the plot in (d), which shows $P^\rho(\eta, N_{\text{PV}}, \mu)$ at higher $\mu$ but the same in-time pile-up ($N_{\text{PV}} = 6$). The solid curves show the results for the fully parameterized extrapolation shape $P^\rho_{\text{fct}}(\eta, N_{\text{PV}}, \mu)$ given in Equation 4.6, while the dashed curves indicate the shapes of the underlying $G_{\text{base}}(\eta)$ model given in Equation 4.8.
4.4. JET AREA BASED METHODS

momentum densities, computed coherently for each method, according to Equation 4.4 with $f_{\text{scale}} = 1$. The various configurations considered are:

**Extrapolated Jet Area (EJA)** $\rho_{\text{evt}}^{\text{med}}(\eta_{\text{jet}})$ is measured and extrapolated as explained in Section 4.4.1. The $\rho$-jets and filter-jets are identical, and formed with the $k_t$ algorithm with $R = 0.4$.

**Extrapolated Jet Area Filtered (EJAF)** $\rho_{\text{evt}}^{\text{med}}(\eta_{\text{jet}})$ is measured and extrapolated as explained in Section 4.4.1. The $\rho$-jets and the filter-jets are $k_t$ jets with $R = 0.6$. After being selected according to Equation 4.4, an additional filter is applied by requiring $|JVF| > 0.25$ on these jets.

**Jet Area Filtered (JAF)** $\rho_{\text{evt}}^{\text{med}}$ is determined within the whole pseudo rapidity range $|\eta| < 5$ with $k_t$ jets with $R = 0.8$. The filter-jets are clustered with $k_t$ with $R = 0.4$, and corrected according to Equation 4.4. They are then further filtered by requiring $|JVF| > 0.25$.

Note that the filter-jets used for defining the pile-up corrected signal contribution to $E_T^{\text{miss,SoftTerm}}$ do not need to be constructed by the same jet definition (algorithm and algorithm parameters) as the $\rho$-jets used to measure $\rho_{\text{evt}}^{\text{med}}$. Any jet definition using the soft event signals as input and providing a consistent jet area measurement can be used. The details of the JVF filter are given in Section 4.3.1, with a different jet definition and a requirement for a stronger association ($|JVF| > 0.25$) to the primary event vertex.

4.4.3 Transverse momentum density in data and MC

As discussed in the previous sections, the median transverse momentum density $\rho_{\text{evt}}^{\text{med}}$ is the basic observable for the jet area based pile-up corrections of the soft event contribution to $E_T^{\text{miss}}$. It has been measured for the three $\rho$-jet sizes under considerations, $R = \{0.4, 0.6, 0.8\}$ and the corresponding $\eta$ ranges. The resulting densities are shown in Figure 4.8 as a function of $N_{\text{PV}}$ and $\mu$, respectively for data and MC simulation. Note that the differences in the $\rho_{\text{evt}}^{\text{med}}$ value ranges are primarily not introduced by the $\rho$-jet size, but rather by the $\eta$ range used to determine $\rho_{\text{evt}}^{\text{med}}$.

A reasonable agreement is found between data and MC simulations for all three considered configurations with some discrepancies that can be due to pile-up modeling. Also, using different $\rho_{\text{evt}}^{\text{med}}$ for the same pile-up conditions in data and MC is in principal not a problem because $\rho_{\text{evt}}^{\text{med}}$ is determined event by event.
and therefore automatically consistent with the real or modeled pile-up activity. The $\rho_{\text{med}}^{\text{evt}}$ extrapolation shapes displayed in Figure 4.7 and used by the EJA and EJAF methods, are found to be universal as well, so that common data derived extrapolation functions $P^\rho(\eta,N_{\text{PV}},\mu)$ are used in both data and MC.

### 4.5 Performance results and comparison

The $E_{\text{T}}^{\text{miss}}$ reconstruction performance are extensively tested and evaluated separately in many final states with different event topologies.

In this section the effects of the various pile-up correction methods on the $E_{\text{T}}^{\text{miss}}$ resolution, scale and direction are estimated and compared as a function of a reference $p_T$ or the global event activity measured by $\Sigma E_{\text{T}}$. The stability of these performance as a function of the pile-up activity (parametrized by $N_{\text{PV}}$ and $\mu$) is also studied. Since this thesis is focused on the methods for the pile-up suppression in the soft term, the $E_{\text{T}}^{\text{miss}}$ performance are firstly studied in events without jets in order to see the direct impact of the various corrections, then the performance are also studied in inclusive events to understand the effects of the pile-up and of the pile-up suppression methods in the presence of a hard scattering interaction.

These large variety of studies is not fully available for the TST case, since the method was recently developed and only tests on $Z \rightarrow \ell\ell$ simulated samples are performed so far.

#### 4.5.1 Effects of pile-up corrections in $Z \rightarrow \mu\mu$ events

$E_{\text{T}}^{\text{miss}}$ distribution in $Z \rightarrow \mu\mu$ inclusive events

The principal validation of the pile-up suppression methods is based on the data-MC comparisons of the reconstructed $E_{\text{T}}^{\text{miss}}$ and its components. The effect of the various corrections on the distribution of the $E_{\text{T}}^{\text{miss,SoftTerm}}$ in inclusive $Z \rightarrow \mu\mu$ events is shown in Figure 4.9. The observed increased disagreement in the $E_{\text{T}}^{\text{miss}}$ soft term spectra after pile-up corrections using tracks, as can be seen for the STVF based correction in Figure 4.9(b), and the two corrections applying JVF based filters (EJA in Figure 4.9(d) and JAF in Figure 4.9(e)), indicates the already mentioned mis-modeling of reconstructed tracks in Pythia (see discussion of Figure 4.4 in Section 4.3.2).

The overall $E_{\text{T}}^{\text{miss}}$ distributions for this sample are presented in Figure 4.10.
4.5. PERFORMANCE RESULTS AND COMPARISON

Figure 4.8: Data-MC comparisons of the mean $\langle \rho \rangle = \langle \rho_{\text{evt}}^{\text{med}} \rangle$, as used in the $\rho$ configurations for the jet area based pile-up correction methods. The central $\rho_{\text{evt}}^{\text{med}}$ used in the $\rho$ extrapolation for EJA is shown as a function of $N_{\text{PV}}$ in (a) and as a function of $\mu$ in (b). Similarly, the central $\rho_{\text{evt}}^{\text{med}}$ used in the extrapolation and filter method EJAF is shown as a function of $N_{\text{PV}}$ in (c) and as a function of $\mu$ in (d). The $\rho_{\text{evt}}^{\text{med}}$ within the full ATLAS calorimeter coverage, as used by the JAF method, is shown as a function of $N_{\text{PV}}$ in (e) and as a function of $\mu$ in (f).
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Figure 4.9: Data-MC comparisons of the $E_T^{\text{miss,SoftTerm}}$ distribution in inclusive $Z \rightarrow \mu\mu$ events: the uncorrected spectrum in (a), after the STVF based pile-up suppression in (b), after the EJA in (c), after the EJAF in (d) and after the JAF in (e).
4.5. PERFORMANCE RESULTS AND COMPARISON

The improved data-MC agreement with respect to the soft term comparisons can
be understood because the relative contribution of the soft term to the total $E_T^{\text{miss}}$
is strongly reduced after pile-up suppression, moreover, the total $E_T^{\text{miss}}$ includes
also jets and leptons that are the same for all the soft term corrections.

$E_T^{\text{miss}}$ and $\Sigma E_T$ dependence on $N_{\text{PV}}$ in exclusive $Z \rightarrow \mu \mu$ events without
jets with $p_T > 20$ GeV

A very good test of the pile-up suppression methods is the study of the stability
of some observables as a function of $N_{\text{PV}}$.

The dependence of $\Sigma E_T$ and $E_T^{\text{miss}}$ on $N_{\text{PV}}$ is shown in Figure 4.11 for a
$Z \rightarrow \mu \mu$ sample without jets with $p_T^{\text{jet}} > 20$ GeV. Before applying any pile-up
suppression the mean value of both the $\Sigma E_T$ and the $E_T^{\text{miss}}$ in each $N_{\text{PV}}$ bin is
largely affected by pile-up and linearly increases with $N_{\text{PV}}$. Large improvements
are observed for all the pile-up suppression methods in particular for the STVF
method that has very stable performance as a function of $N_{\text{PV}}$. Examining
the Jet Area techniques, a residual pile-up dependence is observed in the $\Sigma E_T$
distribution for the $E_{\text{JAF}}$ method but not for $E_{\text{JAF}}$ and $\text{JAF}$ indicating that the
track-based JVJ filter actually helps to identify the contributions associated to
the hard scatter signal. Both definitions largely mitigate the pile-up dependence
also for the $E_T^{\text{miss}}$ distribution even though they are not completely stable as a
function of $N_{\text{PV}}$.

It can be noticed that the $E_{\text{JAF}}$ methods performs better for $N_{\text{PV}} < 15$ while
the JAF method performs better for $N_{\text{PV}} > 15$. This is due to the limited phase
space coverage in $(N_{\text{PV}}, \mu)$ available for the determination of the extrapolation
functions described in Section 4.4.1. In particular, Figure 4.2(b) shows a faster
rise of the $\Sigma E_T$ in the forward calorimeter region beyond $N_{\text{PV}} \approx 15$ than the one
reflected by the extrapolation.

$E_T^{\text{miss}}$ resolution in $Z \rightarrow \mu \mu$ events

Details about the resolution evaluation are given in Section 3.3.2. The $E_T^{\text{miss}}$
resolution in events without genuine missing transverse momentum is measured
by the fluctuations in the $E_T^{\text{miss}}$ components $E_x^{\text{miss}}$ and $E_y^{\text{miss}}$, which are expected
to have a gaussian distribution centered at zero. These fluctuations are increased
by the presence of the in-time and out-of time pile-up. One of the aims of the
pile-up corrections is to reduce any dependence of the reconstructed $E_T^{\text{miss}}$ on
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Figure 4.10: Data-MC comparisons of the total $E_T^{\text{miss}}$ distribution in inclusive $Z \rightarrow \mu\mu$ events: the uncorrected spectrum in (a), after the STVF based pile-up suppression in (b), after the EJA in (c), after the EJAF in (d) and after the JAF in (e).
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Figure 4.11: Mean of the $\Sigma E_T$ in (a) and of the $E_T^{\text{miss}}$ in (b) as a function of $N_{\text{PV}}$ in exclusive $Z \rightarrow \mu\mu$ data events without jets with $p_T > 20$ GeV. The performance before and after the various pile-up suppression methods are compared.

Figure 4.12 shows the $E_T^{\text{miss}}$ resolution as a function of $N_{\text{PV}}$. The same trends discussed for the $E_T^{\text{miss}}$ and $\Sigma E_T$ distribution in the previous section are observed: the corrections using track based information (STVF based, and EJAF and JAF) have a better performance. In particular, the STVF method looks very stable at the increasing of the pile-up activity. Nevertheless, no strong conclusion can be drawn at this level: the $E_T^{\text{miss}}$ performance needs to be evaluated in all its aspects, including the study of the $E_T^{\text{miss}}$ scale, direction and tails. Since the STVF method relies on an overall reduction of the soft term signal in general, the effect on the $E_T^{\text{miss}}$ scale, discussed in detail in Section 4.5.3, can be particularly crucial.

4.5.2 Effects of pile-up corrections in inclusive hard scattering events

In this section the $E_T^{\text{miss}}$ performance are studied in presence of a hard scattering final states with and without genuine $E_T^{\text{miss}}$. The inclusive $Z \rightarrow \mu\mu$ sample provides a reference for a sample lacking genuine $E_T^{\text{miss}}$, while the evaluation of the performance for the soft term pile-up corrections in final states with genuine $E_T^{\text{miss}}$ is mainly based on an inclusive $W \rightarrow e\nu$ sample, where the $E_T^{\text{miss}}$ is generated by the neutrino ($p_T^\nu$). For both the $Z$ and $W$ samples employed for these studies,
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Figure 4.12: $E_T^{\text{miss}}$ resolution as a function of $N_{PV}$ in exclusive $Z \rightarrow \mu\mu$ data events without jets with $p_T > 20$ GeV. The performance before and after the various pile-up suppression methods are compared.

about 40% of the events are reconstructed with at least one jet with $p_T^{\text{jet}} > 20$ GeV. Simulated Higgs samples with the Higgs decaying to a $\tau$-pair are also used to test the $E_T^{\text{miss}}$ performance since their importance for this thesis, the $E_T^{\text{miss}}$ is given by the neutrinos produced in the $\tau$ decays. In all these samples the soft term gives an important contribution to the total $E_T^{\text{miss}}$, therefore, the effects of applying a pile-up suppression on this term can be appreciably observed. Topologies with a larger jet activity such as $t\bar{t}$ and simulated SUSY events, are also investigated in Ref. [129] and show no clear benefit by applying any soft term pile-up suppression in these final states.

$E_T^{\text{miss}}$ and $\Sigma E_T$ dependence on $N_{PV}$ in inclusive $Z/W$ events

The mean value of the reconstructed $E_T^{\text{miss}}$ as a function of $N_{PV}$ is shown in Figure 4.13 for the $Z \rightarrow \mu\mu$ and $W \rightarrow e\nu$ inclusive samples before and after the different pile-up suppression corrections. In the comparison between $Z$ and $W$ events it can be noticed that also before applying a pile-up suppression for the soft term the reconstructed $E_T^{\text{miss}}$ in $W$ events is more stable as a function of $N_{PV}$ due to the presence of genuine $E_T^{\text{miss}}$ than the one reconstructed in $Z$ events. Indeed, in events without a genuine $E_T^{\text{miss}}$ the measured mean value of the $E_T^{\text{miss}}$ (different from 0) is given by the finite $E_T^{\text{miss}}$ and $E_y^{\text{miss}}$ resolution.

Comparing Figure 4.13(a) and 4.13(b), a good data-MC agreement is observed in $Z$ events, whereas, comparing Figure 4.13(c) and 4.13(d), a disagreement of about 3 GeV is observed in $W$ events for the whole $N_{PV}$ spectrum. This is due to the QCD and electroweak background that are contained in data but that are
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Figure 4.13: Mean of the $E_T^{\text{miss}}$ as a function of $N_{\text{PV}}$ in inclusive $Z \rightarrow \mu\mu$ data events in (a), in MC events in (b), in inclusive $W \rightarrow e\nu$ data events in (c) and MC events in (d). The performance before and after the various pile-up suppression methods are compared.
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Figure 4.14: Mean of the $\Sigma E_T$ as a function of $N_{\text{PV}}$ in inclusive $Z \rightarrow \mu\mu$ data events in (a), in MC events in (b), in inclusive $W \rightarrow e\nu$ data events in (c) and MC events in (d). The performance before and after the various pile-up suppression methods are compared.

not considered in the MC simulation. Indeed all these backgrounds, expect for $t\bar{t}$, contribute mostly to the low $E_T^{\text{miss}}$ region, and thus lower the mean value of the $E_T^{\text{miss}}$.

The dependence of the uncorrected $\Sigma E_T$ and the $\Sigma E_T$ after the different pile-up corrections on $N_{\text{PV}}$ can be seen in Figure 4.14. In general the corrections have the same effect in the $Z$ and the $W$ final states, as expected. The soft term pile-up corrections yield slightly worse pile-up suppression in inclusive events with respect to the events without jets shown in Figure 4.11(a) and Figure 4.11(b). This indicates a residual pile-up dependence in the jet reconstruction and a small incoherence between the pile-up corrections applied to jets and to the soft term, which is stronger corrected.
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Figure 4.15: \( E_{\text{miss}}^{x(y)} \) resolution as a function of \( N_{\text{PV}} \) evaluated in inclusive \( Z \rightarrow \mu\mu \) data events in (a) and in inclusive \( W \rightarrow e\nu \) MC events in (b). The performance before and after the various pile-up suppression methods are compared.

\( E_{\text{miss}} \) resolution as a function of \( N_{\text{PV}} \) for inclusive \( Z/W \) events

The \( E_{\text{miss}} \) resolution is calculated as described in Section 3.3.2. It can be measured only in MC sample for \( W \rightarrow e\nu \) because the \( E_{\text{miss},\text{True}}^{x(y)} \) is needed, while it can be measured in both data and MC for \( Z \rightarrow \mu\mu \) events because \( E_{x(y)}^{\text{miss},\text{True}} \) is expected to be zero. The \( E_{\text{miss}} \) resolution as a function of \( N_{\text{PV}} \) is shown in Figure 4.15(a) for the inclusive final state with a \( Z \) boson in data, and in Figure 4.15(b) for the inclusive \( W \) boson in MC. All the pile-up suppression methods improve the \( E_{\text{miss}} \) resolution with respect to the uncorrected case. As already observed in Figure 4.11 and Figure 4.12, the figures indicate that the efficiency of the pile-up correction methods using the extrapolation of the transverse momentum density into the forward region drops for \( N_{\text{PV}} > 15 \), approximately. This is due to the limitations in the fitting of the extrapolation function, which are already discussed for the the exclusive \( Z \rightarrow \mu\mu \) sample in Section 4.5.1.

In the comparison with the exclusive case in Figure 4.12, it can be noticed that also for the resolution, slightly worse performance are achieved in the inclusive case due to residual pile-up contamination in the jet reconstruction.

\( E_{\text{T}}^{\text{miss}} \) resolution as a function of \( \Sigma E_{T} \) for inclusive hard scattering events

As discussed in Section 3.3.2, the \( E_{\text{T}}^{\text{miss}} \) resolution performance can be studied as a function of the total event \( \Sigma E_{T} \). In this representation an increase of the resolution proportional to \( \sqrt{\Sigma E_{T}} \) is expected. The results, before and after ap-
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[Graphs showing $E_T^{\text{miss}}$ resolution as a function of uncorrected total event $\Sigma E_T$ for different processes.]

Figure 4.16: $E_T^{\text{miss}}$ resolution as a function of the uncorrected total event $\Sigma E_T$ evaluated in inclusive $Z \rightarrow \mu\mu$ data events in (a), in inclusive $W \rightarrow e\nu$ MC events in (b) and in inclusive MC $H \rightarrow \tau\tau$ events produced via a $g-g$ fusion mechanism in (c) and via a VBF mechanism in (d). The performance before and after the various pile-up suppression methods are compared.

Applying a pile-up suppression, are shown in Figure 4.16 for data $Z \rightarrow \mu\mu$ events, and simulated $W \rightarrow e\nu$ and $H \rightarrow \tau\tau$ events. For the Higgs events the two main production modes, gluon fusion and vector boson fusion (VBF), are considered.

Particular attention needs to be paid in the definition of the $x$-axis: the choice of employing the uncorrected $\Sigma E_T$ as a common axis provides a direct comparison between the various pile-up suppression methods. Similar conclusions as before can be drawn: all the pile-up suppression methods improve the resolution with respect to the uncorrected case, in particular the STVF method performs best. The improvement in the resolution after pile-up suppression is smaller in Higgs events because of the higher jet activity in these topologies that makes
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the correction on the soft term less significant. It also important to notice that the $E_T^{\text{miss}}$ resolution is estimated according to the width of a Gaussian fit performed on the core of the $E_T^{\text{miss}}(x,y)$ distributions, thus tails given by the presence of backgrounds events in data or by possible inefficiency of the pile-up suppression methods, are basically removed from the resolution measurements.

4.5.3 Effects of pile-up corrections on the $E_T^{\text{miss}}$ scale

The $E_T^{\text{miss}}$ scale is given by the residual $p_T$ mis-balance between all objects contributing to the $E_T^{\text{miss}}$ signal in final states without genuine missing transverse momentum. The evaluation of the $E_T^{\text{miss}}$ scale in events with $E_T^{\text{miss},\text{True}} > 0$ requires MC, as only here the expectation value for $E_T^{\text{miss}}$ is available (e.g., $E_T^{\text{miss},\text{True}} = p_T^{\nu}$). In both cases it is expected that the $E_T^{\text{miss}}$ scale is independent of any other hard scale in the event, such as $p_T^Z$ or $p_T^{\nu}$. Any absolute systematic and constant deviation from the expectation value for the examined final state is not very important, in particular when this deviation can be well modeled in MC.

For low reference $p_T$ scales, a non-linear deviation from signal linearity is expected for $E_T^{\text{miss}}$, as by construct this observable suffers from an observation bias introduced by the $E_T^{\text{miss}}$ resolution. This is discussed further in the following section.

The $E_T^{\text{miss}}$ scale from the diagnostic plot in $Z \rightarrow \ell\ell$ events

As discussed in Section 3.3.2, for collision events without genuine $p_T$, the projection of the $E_T^{\text{miss}}$ components onto the $Z$ transverse momentum direction is indicative of the features of the $E_T^{\text{miss}}$ scale as function of a (stable) hard scale in the event, like $p_T^Z$. This reference is particularly attractive as it is very little to not at all affected by pile-up. In addition, the particular deviation from a linear $E_T^{\text{miss}}$ response, which depends on the composition of the final state and therefore on the inter-calibration between all contributions to $E_T^{\text{miss}}$, is very visible in this diagnostic observable. The effects of pile-up and the applied corrections in the soft term can be seen in the diagnostic plot for the exclusive $Z \rightarrow ee$ sample presented in Figure 4.17(a) for data, and in Figure 4.17(b) for MC. The indications from these figures are that the STVF suppresses pile-up but it also removes a larger part of the momentum recoil to the $Z$ boson in the transverse plane and thus leads to a worse $E_T^{\text{miss}}$ response than the jet area based methods, in particular the EJA and JAF methods. These two methods lead to about the
Figure 4.17: Projection of the $E_T^{\text{miss}}$ onto the $Z$ direction as a function of $p_T^Z$ in exclusive $Z \rightarrow ee$ events without jets with $p_T > 20$ GeV for data in (a) and of MC in (b), and in inclusive $Z \rightarrow ee$ events for data in (c) and for MC in (d). The performance before and after the various pile-up suppression methods are compared.
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same (accidental) loss of recoil signal, and the additional application of JVF in JAF, does not remove any more signals than EJA. Using EJAF, which uses larger jets ($R = 0.6$ instead of $R = 0.4$) for the determination of the central transverse momentum density $\rho_{\text{evt}}^{\text{med}}$ and applies a JVF based selection, removes slightly more recoil than EJA and JAF, mainly due to the fact that the larger soft jet size more likely collects recoil signals and pile-up signals into the same jet. These jets then have lower overall transverse momentum density and are more likely removed from $E_T^{\text{miss,SoftTerm}}$ due to the $\rho_{\text{evt}}^{\text{med}}$ based selection in Equation 4.4.

Both data and MC show very similar effects with respect to the uncorrected and the various pile-up corrected projections for the two $Z \rightarrow ee$ event selections. This is revisited in the discussion of the systematic uncertainties related to the pile-up correction methods in Section 4.6.

For the inclusive $Z \rightarrow ee$ sample, the $E_T^{\text{miss}}$ response is already partly recovered by the (corrected) hard jet response, especially at higher $p_T^Z$. As can be seen in Figure 4.17(c) and (d), the STVF method does not fully restore the scale of the not pile-up corrected case for high $p_T^Z$, while the jet area based methods are performing better with this respect. This is yet another indication of the already mentioned observation that STVF suppresses too much recoil signal. Instead, applying the JVF based filters on the soft term jets in addition to the jet area based selections enhances the recoil signal in the inclusive sample by removing a sufficient amount of pile-up everywhere, while not affecting the now harder signals in the non-jet recoil of the event.

The $E_T^{\text{miss}}$ scale as a function of $N_{\text{PV}}$ in $Z \rightarrow ee$ events

The deviation from linearity of the $E_T^{\text{miss}}$ scale as function of $N_{\text{PV}}$ is displayed in Figure 4.18 for both inclusive and exclusive $Z \rightarrow ee$ samples. As expected, the pile-up affects less the scale of $E_T^{\text{miss}}$ than its resolution, resulting in a less pronounced dependence of the $E_T^{\text{miss}}$ scale on $N_{\text{PV}}$ also before any pile-up suppression.

For the inclusive final state, two transverse momentum regimes have been selected by asking for $p_T^Z < 80$ GeV and $p_T^Z \geq 80$ GeV, respectively. This is motivated by the features visible in the diagnostic projection shown in Figure 4.17. The performance of the pile-up suppression methods affects the scale very differently at low $p_T^Z$ when compared to the higher $p_T^Z$ regime. For low $p_T^Z$ all the physics objects in the recoil are less boosted. This makes a clean separation be-
Figure 4.18: Projection of the $E_T^{\text{miss}}$ onto the $Z$ direction as a function of $N_{PV}$ in $Z \to ee$ data events with $p_T^{Z} < 80$ GeV in (a), with $p_T^{Z} \geq 80$ GeV in (b), in events without jets with $p_T > 20$ GeV in (c) and in events with at least one jet with $p_T > 20$ GeV (d). The performance before and after the various pile-up suppression methods are compared.
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tween true low energy signals arising from this recoil and pile-up energy deposits much harder. For the high $p_T^Z$ regime the pile-up suppression methods seem to work better, in particular jet area based methods are able to slightly improve the performance of the $E_T^{\text{miss}}$ scale of the not pile-up corrected case.

The exclusive plots show that most of the worsening in the scale of the $E_T^{\text{miss}}$ is observed in events with no jets, that are indeed less boosted. For events with at least one jet with $p_{\text{jet}}^T > 20$ GeV, since the $E_T^{\text{miss}}$ scale is driven now by the hard objects, also the STVF case approaches the performance given by other methods.

The $E_T^{\text{miss}}$ scale in events with genuine $E_T^{\text{miss}}$

The effect of the pile-up corrections on the $E_T^{\text{miss}}$ scale in events with genuine missing transverse momentum can only be evaluated in MC, as already discussed before. The signal linearity here is then evaluated for the uncorrected and the various corrected $E_T^{\text{miss}}$ by the relative deviation of the reconstructed $E_T^{\text{miss}}$ from the true missing transverse momentum taken from the neutrino,

$$\frac{E_T^{\text{miss}} - E_T^{\text{miss, True}}}{E_T^{\text{miss, True}}}, \text{ with } E_T^{\text{miss, True}} = p_T^\nu.$$  

The results are shown in Figure 4.19 as a function of $N_{PV}$ for events that have no jet with $p_{\text{jet}}^T > 20$ GeV. The vast majority of the events are around $E_T^{\text{miss, True}} = p_T^\nu \approx 40$ GeV. The low $E_T^{\text{miss}}$ region, defined as $E_T^{\text{miss, True}} < 40$ GeV, is dominated by the bias introduced by the finite $E_T^{\text{miss}}$ resolution. Hence, for these events the reconstructed $E_T^{\text{miss}}$ is probably larger than the true $E_T^{\text{miss}}$ value. Therefore, in each $N_{PV}$ bin the distribution of the difference of the reconstructed $E_T^{\text{miss}}$ and its true value, $E_T^{\text{miss}} - E_T^{\text{miss, True}}$, is not symmetric around zero, but shows a positive tail biasing the overall result towards higher values. Moreover, this also introduces the large $E_T^{\text{miss}}$ resolution dependence on $N_{PV}$, as shown in Figure 4.19(a). In order to decouple the resolution effects from the $E_T^{\text{miss}}$ scale in Figure 4.19(b) only the peak value of the linearity distribution is fitted. The points in these plots show larger error bars since they reflect the quality of the fit. The results show a reduced dependence of the $E_T^{\text{miss}}$ scale on $N_{PV}$. It is also now visible that the STVF method gives slightly negative values, again indicating an overcorrection of the $E_T^{\text{miss}}$ soft term by this method. The jet area methods show a better behavior for the scale and slightly improve the performance of the uncorrected case.
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Figure 4.19: $E_T^{\text{miss}}$ linearity as a function of $N_{PV}$ in exclusive MC $W \to e\nu$ events without jets with $p_T > 20$ GeV: the mean value in (a), the position of the fitted peak in (b). The performance before and after the various pile-up suppression methods are compared.

The $E_T^{\text{miss}}$ linearity can be studied as a function of the $E_{T}^{\text{miss, True}}$, as shown in Figure 4.20(a), for an inclusive MC $W \to e\nu$ sample. In this plot the positive bias for $E_{T}^{\text{miss, True}} < 40$ GeV described previously is directly visible. This plot confirms the conclusions drawn so far: despite the STVF method is more stable with increasing pile-up, it also tends to overcorrect the soft term with the consequence of the $E_T^{\text{miss}}$ measurement being in general lower than the true value. This is mostly driven by events without jets with $p_T^{\text{jet}} > 20$ GeV. All the jet area techniques perform better with this respect.

The same study is also performed on MC simulated VBF Higgs events decaying to a $\tau$-pair and shown in Figure 4.20(b). The linearity is good (within 1%) for all the $E_T^{\text{miss}}$ definitions. The STVF method, thanks to its better resolution, manages to better restrict the positive bias observed at low $E_{T}^{\text{miss, True}}$ values and achieves a better linearity mainly in the region $E_{T}^{\text{miss, True}} < 100$ GeV.

Effect of pile-up corrections on the $E_T^{\text{miss}}$ azimuth measurement

The $E_T^{\text{miss}}$ direction in the transverse plane ($\phi^{\text{miss}}$) which is calculated from the components of $E_T^{\text{miss}}$, has no specific truth expectation value in events without genuine missing transverse momentum. It is subject to rather large fluctuations and is very sensitive to small signal and intercalibration features, misalignment of the detector with respect to the interaction vertex, and any uncorrected misalignment between detector subsystems. In events with $E_{T}^{\text{miss, True}} > 0$, though,
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Figure 4.20: $E_{\text{T}}^{\text{miss,True}}$ linearity as a function of $E_{\text{T}}^{\text{miss,True}}$ in inclusive MC $W \rightarrow e\nu$ events in (a), and MC VBF $H \rightarrow \tau\tau$ events in (b). The performance before and after the various pile-up suppression methods are compared.

this angle represents the neutrino scattering azimuth, and the performance of its reconstruction can be evaluated using MC simulations.

Figure 4.21(a) shows the average angular deviation $\Delta \phi(E_{\text{T}}^{\text{miss}}, E_{\text{T}}^{\text{miss,True}})$ between the neutrino azimuth and the reconstructed $E_{\text{T}}^{\text{miss}}$ azimuth, in the inclusive $W \rightarrow e\nu$ sample, as function of $N_{\text{PV}}$. The central value is very close to zero, which indicates a good reconstruction of the neutrino direction in the transverse event plane. Neither pile-up itself, nor the methods applied to correct for it affect the angular reconstruction in a significant way. A slight pull can be observed, in particular for the uncorrected and, to a lesser extent for the $E_{\text{JAF}}$ corrected $\Delta \phi(E_{\text{T}}^{\text{miss}}, E_{\text{T}}^{\text{miss,True}})$ at higher $N_{\text{PV}}$. All corrections using tracking and jet area can re-establish the expected performance on average.

The azimuthal resolution, shown in Figure 4.21(b) , is measured by the fluctuations of $\Delta \phi(E_{\text{T}}^{\text{miss}}, E_{\text{T}}^{\text{miss,True}})$ around its central value in each bin of $N_{\text{PV}}$. It shows sensitivity to pile-up for the uncorrected $E_{\text{T}}^{\text{miss}}$ reconstruction, which can be reduced by applying the pile-up corrections. The methods combining tracking and calorimetry (EJAF and JAF) perform better than the calorimeter only based EJA method, yet the tracking only based STVF performs best with respect to the azimuthal resolution.
4.5.4 Effects of pile-up corrections in calorimeter regions

The effect of pile-up on the calorimeter signal formation is different in the various calorimeter regions defined by the pseudorapdity $\eta_{\text{det}}$ with respect to the nominal vertex in ATLAS. It depends on the sensitivity in these regions to smaller energy deposits, mostly limited by signal fluctuations introduced by electronic and pile-up noise, and by reconstruction thresholds (in terms of smallest safely measurable energy) in the topological cluster formation in the calorimeter. Additional limitations in sensitivity to small energies in the $E_{\text{T}}^\text{miss, SoftTerm}$ are introduced by the changing of the calorimeter readout granularity, which may sparsify the signal in the event plane in ($\eta_{\text{det}}, \phi$) space, as already seen in the discussion of the $\rho_{\text{evt}}^\text{med}$ measurement and extrapolation in Section 4.4.1. As for the $E_{\text{T}}^\text{miss}$ scale, the signal modulations by out-of-time pile-up are also changing with calorimeter regions in ATLAS, which is demonstrated in Ref. [142]. These region dependencies are addressed differently in the correction methods, with STVF and JAF using no particular regional information, while EJA and EJAF use an $\eta_{\text{det}}$-dependent transverse momentum density.

It is possible to define a truth expectation for $E_{\text{T}}^\text{miss}$ for a given calorimeter region using MC simulations. Contrary to the usual $E_{\text{T}}^\text{miss}$ truth, which is given by the transverse momentum of the final state neutrino in interactions with genuine missing transverse momentum ($E_{\text{T}}^\text{miss, True} = p_{\nu}^\text{T}$), the regional truth reference
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Figure 4.22: Comparison of the reconstructed $\Sigma E_T$ in (a) and $E_T^{\text{miss}}$ in (b) with the corresponding expectations from the particle level truth event in inclusive $Z \rightarrow ee$ events. The effects of the various pile-up corrections on these two quantities are shown in two regions, $|\eta_{\text{det}}| < 3.2$ and $3.2 < |\eta_{\text{det}}| < 4.9$.

has to be calculated using the generated flow of interacting particles in MC. It is therefore a pure detector performance related reference, rather than one for physics analysis, with the advantage of providing a truth reference also for samples without neutrinos.

The pile-up correction methods are expected to at least reinstate the interacting particle truth on average, overall and in given regions of the detector. Figure 4.22 shows the average ratio of reconstructed over particle level $\Sigma E_T$ and $E_T^{\text{miss}}$ in two larger regions of the ATLAS calorimeters ($|\eta_{\text{det}}| < 3.2$ and $3.2 < |\eta_{\text{det}}| < 4.9$), for an inclusive $Z \rightarrow ee$ MC sample. The results are presented inclusive in $N_{PV}$, with an average $\langle N_{PV} \rangle \approx 11$ in the sample. The already indicated overcorrection by the STVF approach is confirmed, especially for $\Sigma E_T$ in the more forward calorimeter region. The methods using an extrapolated transverse momentum density into this region, EJA and EJAF, produce the same corrected $\Sigma E_T$ and $E_T^{\text{miss}}$ in the forward region, as the JVF based selection is not applied to soft term jets beyond $|\eta_{\text{det}}| > 2.4$. They reconstruct the true $\Sigma E_T$ very well in the forward region, and also perform best for the $E_T^{\text{miss}}$ reconstruction.

In the central region all corrections reconstruct $\Sigma E_T$ well, with a slight under-correction for EJA and a slight over-correction for the STVF method, both expected. The combined jet area/tracking based corrections EJAF and JAF perform best for $\Sigma E_T$. On the other, $E_T^{\text{miss}}$ in both central and forward directions is not reconstructed as well on average, which is related to the already mentioned
observation bias introduced by $E_T^{\text{miss}}$ resolution for this quantity. As most of the events populate phase space with low $p_T^Z$, $E_T^{\text{miss}}$ is typically too large compared to the truth expectation, with STVF introducing the smallest ratio to truth due to the fact that it shows the best performance in $E_T^{\text{miss}}$ resolution for this sample, compare Figure 4.12 in Section 4.5.1.

4.5.5 Effects of pile-up corrections with respect to $\mu$

The out-of-time activity in ATLAS relates to the average number of interactions $\mu$ measured in a given time window around the triggered collision event, see e.g. Ref. [142] for more details. Unfortunately $\mu$ is only slowly changing and the overall accessible range of $\mu$ values allowing a statistically meaningful evaluation of the pile-up correction features is limited. Nevertheless, Figure 4.23 shows the dependence on $\mu$ of $\Sigma E_T$ in (a), of $E_T^{\text{miss}}$ in (b), of the $E_T^{\text{miss}}$ resolution in 4.23(c), and of the $E_T^{\text{miss}}$ projection in (d), for the inclusive $Z \rightarrow \mu\mu$ sample. The pile-up corrections work very well also with respect to $\mu$. In particular the EJAF method does not show the particular performance degradation seen in the $N_{PV}$ dependence of some different observables (see e.g. Figures 4.12 and 4.15). This indicates a sufficiently good description of the out-of-time pile-up signal features by the extrapolation functions, which are mostly functions of $N_{PV}$ in the regions closest to $\eta\text{plateau}$ (see Equation 4.9). The $\mu$-dependence is explicitly included only in the width of the Gaussian baseline that mostly contributes in the forward region. In particular at an increasing of $\mu$ corresponds an effective decreasing of the transverse energy, partially compensating\footnote{Due to the particularities of the signal shaping function in the ATLAS forward calorimeters, a large $\mu$ can even lead to overcompensation of the in-time pile-up signal contribution and therefore increasing true signal loss in the region $3.2 < |\eta_{\text{det}}| < 4.9$} the overall increasing given by the in-time pile-up [142].

4.5.6 Effects of pile-up corrections on $E_T^{\text{miss}}$ tails

Instrumental effects and badly measured contributions can create fake high momentum unbalance in the evaluation of the $E_T^{\text{miss}}$. These tails of the $E_T^{\text{miss}}$ distribution lead to an additional background in searches for new undetected particles. It is, therefore, important that the methods used to narrow the bulk of the resolution function do not increase the size of those tails. Figure 4.24 compares the number of events which have $E_T^{\text{miss}}$ above a fixed threshold before and after the pile-up suppression with the various pile-up suppression methods considered in
Figure 4.23: $\mu$-dependence in inclusive $Z \rightarrow \mu\mu$ data events of the mean $\Sigma E_T$ in (a), of the mean $E_T^{\text{miss}}$ in (b), of the $E_{x(y)}^{\text{miss}}$ resolution in (c) and of the projection of the $E_T^{\text{miss}}$ onto the $Z$ direction, averaged over the full $p_T^Z$ spectrum, in (d). The performance before and after the various pile-up suppression methods are compared.
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this note for MC events in different samples. It can be seen that the pile-up mitigation techniques do not significantly increase the tails of the MET distributions. Few additional tails are created in events with jets filtered by the JVF cut and are currently under study. Since all the methods presented here share the same treatment for the jet term, the size of the additional tails is similar across all methods, while no tails are observed in events with no jets.

Figure 4.24: Percentage of events with $E_T^{\text{miss}}$ above a varying threshold in inclusive MC $Z \to \mu\mu$ events in (a), $W \to e\nu$ events in (b), VBF $H \to \tau\tau$ events in (c), $t\bar{t}$ events in (d). The performance before and after the various pile-up suppression methods are compared. The $E_T^{\text{miss, True}}$ is also shown for comparison. The lower parts of the figures show the ratio of each case (pile-up suppression method or Truth) over the default (before pile-up suppression).
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Figure 4.25: The soft track term calculated with the two track selections employed by the STVF and TST methods is compared in (a) for inclusive $Z \rightarrow ee$ MC events, the $E_T^{miss}$ spectrum before the pile-up suppression and after the STVF and TST methods is compared in (b) for exclusive $Z \rightarrow ee$ MC events without jets with $p_T > 20$ GeV.

4.5.7 Study of the performance of the TST method

The TST method, described in Section 4.3.3, was recently developed and it is currently under validation. In this section first preliminary studies based on MC simulation samples are discussed and the TST method is compared with the other track-based method, STVF, and with the $E_T^{miss}$ before applying a pile-up correction for the soft term.

The first observation is that the different track quality criteria employed by the STVF and TST methods have a large impact on the soft term computation from tracks from primary vertex only. This effect can be quantified from Figure 4.25(a), where the track soft term is shown for $Z \rightarrow ee$ inclusive events for the two methods. In particular the tighter quality criteria used by the STVF result in a lower estimation of the track soft term. On the other hand the TST track selection, even after applying the set of cuts to reject mis-reconstructed tracks listed in Section 4.3.3, still creates some tails in the $E_T^{miss}$ distribution in comparison with the STVF method as shown in Figure 4.25(b).

The $E_T^{miss}$ resolution and the diagnostic plot for the TST method are respectively shown in Figures 4.26 and 4.27 for inclusive and exclusive $Z \rightarrow ee$ events. The resolution as a function of $N_{PV}$ demonstrates the good stability of both TST and STVF methods with comparable performance. The diagnostic plot clearly
Figure 4.26: $E_{\text{miss}}^{x(y)}$ resolution as a function of $N_{\text{PV}}$ for inclusive MC $Z \rightarrow ee$ events in (a) and exclusive MC $Z \rightarrow ee$ events without jets with $p_T > 20$ GeV in (b). The performance before pile-up suppression and after the STVF and TST methods are compared.

indicates that the TST method performs better, restoring the performance of the uncorrected case at high-$p_T^Z$ and strongly reducing the negative bias for events with low $p_T^Z$.

4.6 Systematic uncertainties

In the following sections, the total systematic uncertainties on the soft term scale and resolution are presented for all pile-up suppression methods previously discussed in Section 4.2. A specific evaluation of the contribution on the uncertainties introduced by applying a pile-up suppression method is discussed in Section 4.6.2.

4.6.1 Total systematic uncertainties for the pile-up corrected $E_{\text{T}}^{\text{miss}}$ cases

To evaluate the systematic uncertainties on the soft term for each of the pile-up suppressed version of the $E_{\text{T}}^{\text{miss}}$, the same in-situ methods explained in Section 3.3.3 are employed. The results are summarized in Table 4.1. For comparisons, the systematic uncertainties on the $E_{\text{T}}^{\text{miss}}$ scale and resolution before applying any pile-up suppression are reported as well. It should be noticed that even if the fractional uncertainties are larger for the pile-up suppressed $E_{\text{T}}^{\text{miss}}$ in some
4.6. SYSTEMATIC UNCERTAINTIES

Figure 4.27: Projection of the $E_T^{\text{miss}}$ onto the $Z$ direction as a function of $p_T^Z$ for inclusive MC $Z \rightarrow ee$ events in (a) and exclusive MC $Z \rightarrow ee$ events without jets with $p_T > 20$ GeV in (b). The performance before pile-up suppression and after the STVF and TST methods are compared.

cases, they have a smaller impact on the $E_T^{\text{miss}}$ global uncertainty because the soft term is much smaller after pile-up suppression.

The systematic uncertainties for the TST $E_T^{\text{miss}}$ case are not discussed here since they are currently under derivation using a variation of the balance method (see Section 3.3.3).

4.6.2 Systematic uncertainties introduced by pile-up suppression methods

The evaluation of the systematic uncertainties, both on the $E_T^{\text{miss}}$ scale and resolution, introduced by any of the studied pile-up correction methods for the soft term is based on the quality of the modeling in MC for the relative variations between uncorrected and corrected observables, $O$, as a function of a hard scale in the collision event. This relative effect $\mathcal{R}$ of any of the corrections is measured using the ratio of a specific observable $O$ after and before a given correction is applied:

$$\mathcal{R}(\Sigma E_T) = \frac{O_{\text{corrected}}(\Sigma E_T)}{O_{\text{uncorrected}}(\Sigma E_T)}.$$  (4.11)

The hard scale at which $\mathcal{R}$ is measured is given by the (uncorrected) $\Sigma E_T$ of the event. The event sample used is the exclusive $Z \rightarrow \mu\mu$ sample without jets with $p_T^{\text{jet}} > 20$ GeV, because the events in this sample are dominated by the soft
The observables $O$ are the same variables employed for the determination of the total uncertainties described in Section 4.6.1, meaning the $E_T^{\text{miss}, \text{SoftTerm}}$ projected onto the $Z$ boson direction $< E_T^{\text{miss}} \cdot A_Z >$ for the $E_T^{\text{miss}}$ scale evaluation and the gaussian width of the $E_x^{\text{miss}}$ and $E_y^{\text{miss}}$ components for the resolution evaluation.

The scoring variable used to measure the systematic uncertainty is the ratio of the relative correction effect in MC ($R^\text{MC}$) to the one in data ($R^\text{data}$), both calculated for each pile-up correction as given in Equation 4.11,

$$F_{\text{scale}}(\Sigma E_T) = \frac{R^\text{MC}(\Sigma E_T)}{R^\text{data}(\Sigma E_T)} = \frac{O^\text{corrected}(\Sigma E_T)/O^\text{uncorrected}(\Sigma E_T)}{O^\text{corrected}(\Sigma E_T)/O^\text{uncorrected}(\Sigma E_T)}$$

(4.12)

The systematic uncertainties for each pile-up suppression method are then given by the weighted standard deviation of $F_{\text{scale}}(\Sigma E_T)$,

$$\Delta F_{\text{syst}} = \sqrt{\frac{1}{N} \sum_i F_{\text{scale},i}^2 \Delta F_{\text{scale},i}^2 - \langle F \rangle_{\text{scale}}^2}$$

with $N = \sum_i 1/\Delta F_{\text{scale},i}^2$ and $\langle F \rangle_{\text{scale}} = \frac{1}{N} \sum_i F_{\text{scale},i}/\Delta F_{\text{scale},i}$

(4.13)

from their central value $\langle F \rangle_{\text{scale}}$ averaged over the full accessible $\Sigma E_T$ range. The
4.6. SYSTEMATIC UNCERTAINTIES

<table>
<thead>
<tr>
<th>Pile-up correction method</th>
<th>Fractional systematic uncertainties</th>
<th>$E_T^{\text{miss ; scale}}$ [%]</th>
<th>$E_T^{\text{miss ; resolution}}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>STVF</td>
<td>1.4</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>EJA</td>
<td>1.0</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>EJAF</td>
<td>1.6</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>JAF</td>
<td>1.1</td>
<td>0.7</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2: Summary of the fractional systematic uncertainty contribution from applying the pile-up correction methods to the exclusive $Z \rightarrow \mu \mu$ sample.

sums run over $\Sigma E_T$ bins such that

$$F_{\text{scale},i} = \langle F_{\text{scale}} \rangle (\Sigma E_T) \quad \text{for} \quad \Sigma E_T \in [(\Sigma E_T)_i, (\Sigma E_T)_{i+1}]$$

and the corresponding (bin-by-bin) uncertainty $\Delta F_{\text{scale},i}$ determined by the uncertainty associated with this bin average. The definition decouples the estimated systematic uncertainty of the $E_T^{\text{miss}}$ measurement after corrections in data from the absolute agreement with MC simulations reflected by $\langle F \rangle_{\text{scale}}$, as this average value can be otherwise constraint in the context of a full systematic uncertainty determination, reported in Section 4.6.1.

The scoring variable, discussed in Equation 4.13, for the evaluation of the $E_T^{\text{miss \; scale}}$ and resolution uncertainties is shown respectively in Figure 4.28 and 4.29 for the four soft term pile-up correction methods, STVF, EJA, EJAF, JAF.

The systematic scale and resolution uncertainties introduced by the various pile-up correction methods and determined as described in Equation 4.13 are summarized in Table 4.2. These uncertainties have a fractional contribution to the overall uncertainties presented in Section 4.6.1, which, due to other constraints on the overall $E_T^{\text{miss}}$ reconstruction, can be reduced compared to the uncertainties quoted here.

**Systematic uncertainties from instabilities in the jet area method**

The determination of the median transverse momentum density $\rho_{\text{med \; evt}}$ in FASTJET uses an “active ghost area” approach, which allows the consistent measurement of the jet area for irregular shaped jets as well as regular (cone shaped) jets. The approach uses random seeds to cluster “ghost particles” with tiny but finite $p_T$.
Figure 4.28: Projection of the $E_{\text{miss}}^T$ onto the $Z$ direction as a function of the uncorrected $\Sigma E_T$ in exclusive $Z \rightarrow \mu\mu$ events without jets with $p_T > 20$ GeV for data and MC simulation before and after applying the STVF method in (a), the EJA method in (b), the EJAF method in (c), and the JAF method in (d). The double ratios $F_{\text{scale}}(\Sigma E_T)$, as described in Equation 4.13, are shown under the curves, respectively.
4.6. SYSTEMATIC UNCERTAINITIES

Figure 4.29: $E_{\text{miss}}^{\tau(y)}$ resolution as a function of the uncorrected $\Sigma E_T$ in exclusive $Z \rightarrow \mu\mu$ events without jets with $p_T$ 20 GeV for data and MC simulation before and after applying the STVF method in (a), the EJA method in (b), the EJAF method in (c), and the JAF method in (d). The double ratios $F_{\text{scale}}(\Sigma E_T)$, as described in Equation 4.13, are shown under the curves, respectively.
into the jets formed by real particles or detector signals. The jet area determination shows a small instability of at most 10% for very low $p_T$ soft term jets in this jet area measurement approach. While the ability to reproduce the $\rho_{\text{evt}}^{\text{med}}$ measurement is improved in ATLAS by controlling the random seeding in sequences of multiple jet area calculations, the effect of a residual Gaussian fluctuation of $\rho_{\text{evt}}^{\text{med}}$ with $\sigma = 10\%\rho_{\text{evt}}^{\text{med}}$ is evaluated for the $\Sigma E_T$ and $E_T^{\text{miss}}$ distributions for a $Z \rightarrow ee$ MC sample. The results are shown in Figure 4.30.

4.7 Conclusion and prospects

The high level of pile-up reached during 2012 introduced a large amount of additional energy in the ATLAS detector, in particular in the calorimeter system. This increases the fluctuation in the energy measurements with a direct and negative impact to the $E_T^{\text{miss}}$ reconstruction, largely worsening the resolution and scale performance. The degradation in performance is mostly driven by the soft energy contributions entering the $E_T^{\text{miss}}$ computation. Therefore, several dedicated methods are developed to suppress the pile-up contribution and to restore the good $E_T^{\text{miss}}$ performance achieved for the low-luminosity data taking.

The most performant methods are the track based methods, STVF and TST, that, exploiting the track association with the identified primary vertex, result in very stable computation. Presently, the STVF method suffers the inefficiency of the used tight track quality selection that causes an underestimation of the soft term scale, while the TST method mostly suffers the inclusion of mismeasured tracks that can create large tails. These results point out the need of a more careful optimization for the track selection.

The jet area techniques show impressive improvements in the $E_T^{\text{miss}}$ performance but are not completely able to remove the pile-up contamination. These methods can be promising in combination with track based corrections in order to re-integrate the calorimeter information from soft neutral and forward particles. One of the current limits found by these studies is the employment of the same topocluster noise thresholds for both the central and the forward calorimeter regardless to the different geometries and technologies employed in these regions. In particular, it can be shown that the use of the current values for the noise thresholds in the forward region suppresses not only pile-up but also relevant parts of the signal. A re-optimization of the noise thresholds in the forward region is currently on-going.
4.7. CONCLUSION AND PROSPECTS

Figure 4.30: The effect of $\rho_{\text{evt}}^{\text{med}}$ fluctuations on the $\Sigma E_T$ and $E_T^{\text{miss}}$ distributions in $Z \rightarrow ee$ MC events for EJA respectively in (a) and (b), for EJAF respectively in (c) and (d) and for JAF respectively in (e) and (f). The variated spectra are obtained with a 10% $\rho_{\text{evt}}^{\text{med}}$ Gaussian smearing. The ratio between the nominal and the variated spectrum is reported in the lower part of the figures.
In general, all performed studies on calorimeter-based and track-based pile-up suppression methods increased our understanding about pile-up effects on primary inputs, on the response of different subdetectors and on clustering algorithms. This is a fundamental starting point to further achieve improvements in performance exploiting the best and most complete information from each subdetector.
4.7. CONCLUSION AND PROSPECTS
Chapter 5

$H \rightarrow \tau \tau$ search in the semileptonic channel: cut-based analysis

The search for a SM Higgs boson decaying into a pair of taus, $H \rightarrow \tau \tau$, is one of the most relevant in the SM Higgs low-mass region: because of the high branching ratio and the experimental ability to suppress fake tau leptons, it is the channel with the highest sensitivity for a SM Higgs decaying to fermions. Therefore, after the recent discovery of the Higgs boson in the diboson channels $\gamma \gamma$, $ZZ$ and $WW$, this search is particularly interesting as it can provide the first direct evidence and measurement of the Higgs couplings to fermions.

According to the decay mode of the two $\tau$ leptons, the final state can be classified in three different topologies: lepton-lepton ($\tau_{\text{lep}}\tau_{\text{lep}}$) if both taus decay into either an electron or a muon, lepton-hadron ($\tau_{\text{lep}}\tau_{\text{had}}$) if one of the two taus decays leptonically and the other one hadronically, hadron-hadron ($\tau_{\text{had}}\tau_{\text{had}}$) if both taus decay into hadrons. Due to the different signal sensitivity and background composition, analyses are optimized for each channel. In this chapter, only the $\tau_{\text{lep}}\tau_{\text{had}}$ final state, which contributes for the 46% of the total branching ratio, is considered. Two independent analyses are developed for this search. The first makes use of multivariate techniques (MVA) [143], while the second is based on a cut-based approach [144, 145]. The refined MVA analysis provides a better sensitivity, while the cut-based analysis is more robust. Since the cut-based anal-
5.1. ANALYSIS STRATEGY

The search for the $H \rightarrow \tau \tau$ is a rather complex analysis, due to the variety of background sources. Therefore, to maximize the analysis sensitivity a precise selection and categorization procedure is needed to maximize the sensitivity of this analysis.

For the event selection, general cleaning criteria are applied to ensure high quality detector data and to reject non-collision events such as cosmic-rays and beam-induced backgrounds. In addition, only events with a good reconstructed vertex with at least four tracks with $p_T > 500$ MeV are considered. For the selected events, the object reconstruction and identifications (see Section 3.2) are performed according the following criteria, to ensure an efficient event reconstruction: combined muons, medium electrons, medium taus, pile-up corrected $E_T^{\text{miss}}$ with the STVF variant (see Section 4.3.2), anti-$k_t$ ($R = 0.4$) jets calibrated LCW+JES and passing the $|JVF| > 0.5$ requirement to remove residual dependences in the jet multiplicity due to pile-up. In order to resolve possible overlap between selected objects within $\Delta R < 0.2$, only the object with highest priority is kept, according to the following order: $\mu$, $e$, $\tau_{\text{had}}$, jet. For this procedure, the lepton acceptance requirement considered for overlap removal with $\tau_{\text{had}}$ candidates is lowered to loose in order to reduce the misidentification rate of leptons as $\tau_{\text{had}}$.

After this initial event selection and event definition, a first set of criteria is required to increase the purity of the data sample by specifically selecting the $\tau_{\text{lep}}\tau_{\text{had}}$ topology and thus partially rejecting background processes. After that, exclusive analysis categories are defined to fully exploit the specific experimental signatures of the different Higgs production modes, and additional selection
Chapter 5: \( H \rightarrow \tau \tau \) search in the semileptonic channel: cut-based analysis

<table>
<thead>
<tr>
<th>( \sigma \times BR [\text{pb}] )</th>
<th>( gg \rightarrow H \rightarrow \tau \tau )</th>
<th>VBF ( H \rightarrow \tau \tau )</th>
<th>( W H \rightarrow \tau \tau )</th>
<th>( Z H \rightarrow \tau \tau )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.55552503</td>
<td>0.04549584</td>
<td>0.02031456</td>
<td>0.01197365</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.1: Summary of the \( \sigma \times BR \) of a SM Higgs boson with \( m_H = 125 \text{ GeV} \) decaying in the \( \tau_{\text{lep}}\tau_{\text{had}} \) final state for the main Higgs production modes.

criteria are applied to each category to further suppress specific background processes.

5.1.1 Signal and background processes

The \( \tau_{\text{lep}}\tau_{\text{had}} \) final state is defined as follows. The hadronic \( \tau \) decay produces a \( \tau \)-jet and a neutrino in the final states, while the leptonic \( \tau \) decay produces a lepton (either an electron or a muon) and two neutrinos. The in total three neutrinos result in an \( E_T^{\text{miss}} \) signature for the final state, with the \( E_T^{\text{miss}} \) vector mainly expected to lay between the directions of the visible \( \tau \) decay products, and in general more aligned with the lepton since in the leptonic \( \tau \) decay two neutrinos are produced. Jets can be also present in the final state.

In this section the peculiar jet topologies associated with the Higgs signal for the main production modes are described together with the main background processes that can mimic these topologies.

**Higgs signal**

As discussed in Section 1.4.1, in the SM the Higgs boson is produced mainly via gluon-gluon fusion (\( gg \rightarrow H \)), vector-boson fusion (VBF) or in association with a vector boson \( V = Z, W \) (VH). For the different production modes, a brief description of the expected topology (sketched in Figure 5.1) is given in the following. The production cross-section at \( \sqrt{s} = 8 \text{ TeV} \) multiplied by the branching ratio \( (\sigma \times BR) \) for a SM Higgs boson with \( m_H = 125 \text{ GeV} \) decaying in the \( \tau_{\text{lep}}\tau_{\text{had}} \) final state are summarized in Table 5.1.

\( gg \rightarrow H \rightarrow \tau \tau \). At leading order, taus are approximately back-to-back, resulting in a low \( E_T^{\text{miss}} \) measurements. At the next-to-leading order, through initial state radiation (ISR), the Higgs boson can be produced in association with jets and receive a boost in the transverse plane. This allows a better separation of the signal from the background processes for two main reasons:
5.1. ANALYSIS STRATEGY

Figure 5.1: The expected topology for the $gg \rightarrow H \rightarrow \tau\tau$ with associated jet production is sketched in (a), for the VBF $H \rightarrow \tau\tau$ in (b) and for the $V H \rightarrow \tau\tau$ in (c).
Chapter 5: $H \rightarrow \tau\tau$ search in the semileptonic channel: cut-based analysis

- the on average enhanced $E_T^{\text{miss}}$;
- the larger jet multiplicity for $gg$ initiated processes, such as $gg \rightarrow H$, compared to the $qq$ initiated process such as the main $qq \rightarrow Z$ background.

**VBF $H \rightarrow \tau\tau$.** As already stated, the VBF production provides a very distinct experimental signature of two “high-$p_T$” jets (already from processes at leading order) with a large separation in pseudorapidity and large dijet invariant mass. The Higgs boson decay products in such events are expected to be found mainly in the central region between the tagging jets, with little additional jet activity.

**V $H \rightarrow \tau\tau$.** In the VH production mode, the Higgs boson tends to be boosted in the transverse plane with either one or two additional leptons or two jets from the $W/Z$ vector boson decay. In the analysis reported in this thesis the additional production of leptons is not exploited, but a parallel analysis is under optimization to take full advantage of this particular topology.

**Background processes**

There is a large variety of background processes which can mimic the signal events:

**$Z/\gamma^* \rightarrow \tau\tau + \text{jets}$ production:** these events are the major irreducible background since they have the same final state and a similar kinematics as the $H \rightarrow \tau\tau$.

**$Z/\gamma^* \rightarrow \ell\ell + \text{jets}$ production ($\ell = e, \mu$):** these events can contribute to the background if either one of the leptons or the jets is misidentified as a $\tau$-jet ($\ell \rightarrow \tau_{\text{had}}, \text{jet} \rightarrow \tau_{\text{had}}$). This is not a large contribution, but especially the $\ell \rightarrow \tau_{\text{had}}$ case needs a precise estimate because it tends to peak where a signal for a Higgs boson with a mass of 120-125 GeV is expected.

**$W \rightarrow \ell\nu + \text{jets}$ production:** these events give a significant background because of the large cross-section and the similar event topology to the signal final state with a lepton, genuine $E_T^{\text{miss}}$ and a jet that can fake the $\tau$-jet.

**$WW, ZW, ZZ$ production:** these events contribute as irreducible background if both the vector bosons decay leptonically in the $\tau\tau, e\tau, \mu\tau$ final states. In case of a vector boson decaying hadronically these events can still contribute as background if one jet is misidentified as a $\tau$-jet.
5.1. ANALYSIS STRATEGY

<table>
<thead>
<tr>
<th></th>
<th>SLT</th>
<th>LTT</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron</td>
<td>24</td>
<td>20</td>
</tr>
<tr>
<td>muon</td>
<td>24</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 5.2: Lepton $p_T$ thresholds for single lepton trigger and lepton+tau trigger.

**QCD multi-jets process:** these events are an important source of background because of the large cross-section. One of the jet can be misidentified as a $\tau$-jet and at the same time another jet can be misidentified as an electron or a muon. Genuine leptons can also be produced in semileptonic decays of a $B$ or $D$ hadrons.

**$t\bar{t}$ production:** these events contain decays like $tt \rightarrow WbWb$, which can produce genuine $E_T^{miss}$ and leptons ($e, \mu, \tau$) if at least one of the $W$ decays leptonically. One of the b-jet or a jet from a hadronic decay of the $W$ can be misidentified as a $\tau$-jet.

**Single top production (via $t$- or $s$-channel or in association with a $W$):** these events contain decays of $t \rightarrow Wb$, which contribute as background if the $W$ decays leptonically and the $\tau$-jet is either due to a misidentified jet or, for $Wt$ production, comes from the decay of the second $W$ boson.

5.1.2 Data and simulated samples

**Data samples**

The analysis reported in this thesis is performed on the full 2012 available statistics at $\sqrt{s} = 8$ TeV collected with the ATLAS detector, corresponding to a total integrated luminosity of $\mathcal{L} = 20.3$ fb$^{-1}$. A combination of the single lepton trigger (SLT) and the lepton+tau trigger (LTT) is used in order to increase the signal yield, since the $p_T$ lepton threshold of the LTT is consistently lower than the equivalent threshold for the SLT, as summarized in Table 5.2. For this reason, different ATLAS data streams are employed according to the trigger fired by the event: the $Egamma$ and the $Muon$ streams include events triggered by the electron and muon SLT respectively, while the $JetTauEtmiss$ includes events triggered by the LTT.


MC simulation samples

The Higgs signal samples are generated for 11 mass points from $m_H = 100$ GeV to $m_H = 150$ GeV, in steps of 5 GeV. The signal simulations are based on the NLO perturbative calculation provided by the Powheg [87, 146, 147] event generator for the gluon fusion [148] and the VBF production modes [149]. The Powheg gluon fusion samples are generated with the parameter $hfact$ set to $m_H/1.2$ in order to better match the Higgs transverse momentum spectrum predicted by the NNLO+NNLL calculations from the HqT program [150, 151]. The parton shower, hadronization and underlying event modeling is provided by Pythia [152]. The samples describing the Higgs production in association with a vector boson are based on the lowest order and simulated using Pythia.

Concerning the background samples, the MC samples for $W/Z + jets$ events are generated with Alpgen [153]. This generator employs the MLM matching scheme [154] between the hard process, employing LO multi-leg calculations with up to five jets, and the parton shower. The $tt$ and diboson ($WW, WZ, ZZ$) samples are produced with McAtNlo [87] with NLO accuracy. Single-top ($t/s$-channel, $Wt$) events are generated at LO with AcerMC [154]. In all the background MC samples the parton shower and the hadronization are generated with Herwig [155], with the underlying event from Jimmy [156]. The loop-induced $gg \rightarrow WW$ processes are generated using gg2WW [157]. Tauola [90] and Photos [91] are used to generate the $\tau$ decay and additional photon radiation from charged leptons to fit the data, respectively.

The CT10 NLO parton distribution functions (PDF) [158] are used for the Powheg and McAtNlo samples, while the CTEQ6L1 [159] set (LO) is used for the Pythia and Alpgen samples. The detector simulation in all the MC samples is performed with Geant4 [160].

5.1.3 Mass reconstruction

In the process:

$$H \rightarrow \tau\tau \rightarrow \ell\nu\ell\nu_{\tau\text{had}}\nu_{\tau}$$

the presence of multiple neutrinos increases the complexity of the $\tau\tau$ mass reconstruction because the resulting $E_T^{\text{miss}}$ is the sum of their contributions and, in order to compute the invariant mass, the energy and the direction of each neutrino are required. The kinematics can be related in a system of equations, assuming that the total $E_T^{\text{miss}}$ comes from the neutrinos only. In this system, the
number of unknowns exceeds the number of constraints:

\[
\begin{align*}
E_{x}^{\text{miss}} &= p_{\text{mis}1} \sin \theta_{\text{mis}1} \cos \phi_{\text{mis}1} + p_{\text{mis}2} \sin \theta_{\text{mis}2} \cos \phi_{\text{mis}2} \\
E_{y}^{\text{miss}} &= p_{\text{mis}1} \sin \theta_{\text{mis}1} \sin \phi_{\text{mis}1} + p_{\text{mis}2} \sin \theta_{\text{mis}2} \sin \phi_{\text{mis}2} \\
m_{\tau_{1}}^{2} &= m_{\text{vis}1}^{2} + m_{\text{vis}1}^{2} + 2 \sqrt{p_{\text{vis}1}^{2} + m_{\text{vis}1}^{2}} \sqrt{p_{\text{mis}1}^{2} + m_{\text{mis}1}^{2}} \\
m_{\tau_{2}}^{2} &= m_{\text{vis}2}^{2} + 2 \sqrt{p_{\text{vis}2}^{2} + m_{\text{vis}2}^{2}} \sqrt{p_{\text{vis}2}^{2} + m_{\text{vis}2}^{2}} - 2p_{\text{vis}2}p_{\text{mis}2} \cos \Delta \theta_{\text{vm1}} \\
m_{\tau_{1}}^{2} &= m_{\text{vis}1}^{2} + m_{\text{vis}1}^{2} + 2 \sqrt{p_{\text{vis}1}^{2} + m_{\text{vis}1}^{2}} \sqrt{p_{\text{vis}2}^{2} + m_{\text{vis}2}^{2}} - 2p_{\text{vis}2}p_{\text{mis}2} \cos \Delta \theta_{\text{vm2}}
\end{align*}
\]

(5.2)

where \( m_{\text{mis}1}, p_{\text{mis}1}, \theta_{\text{mis}1}, \phi_{\text{mis}1} \) are the invariant mass, the momentum, the polar and the azimuth angle of the \( \nu_{\tau} \nu_{\ell} \) system from the leptonic \( \tau \) decay; \( p_{\text{mis}2}, \theta_{\text{mis}2}, \phi_{\text{mis}2} \) are the momentum, the polar and the azimuth angle of the \( \nu_{\tau} \) from the hadronic \( \tau \) decay; \( p_{\text{vis}1,2}, \theta_{\text{vis}1,2}, \phi_{\text{vis}1,2} \) are the invariant mass, the polar and azimuthal angle for the visible \( \tau \) decay products (\( \ell, \tau_{\text{had}} \)). Finally, \( \Delta \theta_{\text{vm1,2}} \) is the angle between the visible and invisible decay products for each of the two \( \tau \) leptons.

Presently, there are two approaches to address this problem, the collinear approximation and the missing mass calculator (MMC).

### \( \tau \tau \) mass reconstruction with the collinear approximation

The collinear approximation works with the hypothesis that the \( \tau \)-leptons are boosted (\( m_{\tau} \ll m_{H} \)). The direction of the neutrinos produced in the \( \tau \) decays is then the same as the direction of the visible decay products. It also assumes that the mass of the \( \tau \)-leptons can be omitted. Hence the system in Equation 5.2 reduces to:

\[
\begin{align*}
E_{x}^{\text{miss}} &= p_{\text{vis}1} \sin \theta_{\text{vis}1} \cos \phi_{\text{vis}1} + p_{\text{vis}2} \sin \theta_{\text{vis}2} \cos \phi_{\text{vis}2} \\
E_{y}^{\text{miss}} &= p_{\text{vis}1} \sin \theta_{\text{vis}1} \sin \phi_{\text{vis}1} + p_{\text{vis}2} \sin \theta_{\text{vis}2} \sin \phi_{\text{vis}2}
\end{align*}
\]

(5.3)

The invariant mass \( m_{\tau\tau} \) of the \( \tau \tau \) system is then computed as:

\[
m_{\tau\tau} = \sqrt{2(p_{\text{vis}1} + p_{\text{mis}1})(p_{\text{vis}1} + p_{\text{mis}2})(1 - \cos \theta)}
\]

(5.4)

where \( \theta \) is the angle between the directions of the visible decay products of the two \( \tau \) decays.

In this approach the mass reconstruction is not possible when the two taus are back-to-back or the \( E_{T}^{\text{miss}} \) is poorly reconstructed. In VBF \( H \rightarrow \tau \tau \) (\( Z \rightarrow \tau \tau \)) events, the mass reconstruction efficiency decreases from 97(93)% when using the
$E_T^{\text{miss}, \text{True}}$ to 80(65)% when using the reconstructed $E_T^{\text{miss}}$ before pile-up suppression. It is $\sim$ 80(55)% when using the $E_T^{\text{miss}}$ after pile-up suppression with STVF, and $\sim$ 80(60)% when using the Jet Area pile-up suppression. The efficiency of the $Z \rightarrow \tau \tau$ mass reconstruction is smaller even when using $E_T^{\text{miss}, \text{True}}$, because the two $\tau$-leptons are more back-to-back (the $Z$ is less boosted than the $H$ produced through VBF) and when using the $E_T^{\text{miss}}$ before pile-up suppression because the $Z \rightarrow \tau \tau$ events have a smaller $E_T^{\text{miss}}$. It decreases after the pile-up suppression because the $E_T^{\text{miss}}$ becomes very small, mainly in the events with no jets, so the probability to have a negative solution for one or both neutrino momenta increases. These differences in the reconstruction efficiency after pile-up suppression in the two samples improve the signal significance.

The mass so reconstructed is very sensitive to the $E_T^{\text{miss}}$ measurement: the peak position depend on the $E_T^{\text{miss}}$ scale and the mass resolution is completely dominated by the $E_T^{\text{miss}}$ resolution. Hence it is an optimal variable for testing the $E_T^{\text{miss}}$ performance. Some studies are shown in Section 5.1.7.

### $\tau \tau$ mass reconstruction with MMC

The MMC approach [161] does not assume the strict collinearity of the visible and invisible $\tau$ decay products of the previous method. The tau is assumed massive with $m_\tau = 1.777$ GeV and, in order to solve the equation system in Equation 5.2, a scan in a grid of points for the $(\phi_{\text{mis}1}, \phi_{\text{mis}2})$ parameter space is performed. Then, an event weight is assigned to the mass evaluated in each point to enhance more probable solutions. This information is derived exploiting additional knowledge about the $\tau$ decay kinematics, in particular the 3-dimensional angle $\Delta \theta_{3D}$ between the directions of visible and invisible $\tau$ decay products. This distribution is fitted with a linear combination of Gaussian and Landau functions and parametrized as a function of the initial tau momentum $p_\tau$, $P(\Delta \theta, p_\tau)$. Figure 5.2 shows the $\Delta \theta_{3D}$ distribution for different $\tau$ decay modes. The event probability is thus obtain as:

$$P_{\text{event}} = P(\Delta \theta_1, p_{\tau_1}) \times P(\Delta \theta_2, p_{\tau_2}) \quad (5.5)$$

As explained in the previous section $E_T^{\text{miss}}$ resolution strongly affects the mass resolution. In order to mitigate this effect, the MMC increases the dimensionality of the scanned parameter space by including the $E_x^{\text{miss}}$ and $E_y^{\text{miss}}$ components and varying them within their experimental resolution. The event probability thus becomes:
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\[ P_{\text{event}} = P(\Delta \theta_1, p_{\tau_1}) \times P(\Delta \theta_2, p_{\tau_2}) \times P(\Delta E_{\text{miss}}^x) \times P(\Delta E_{\text{miss}}^y) \]  

(5.6)

where the probability functions \( P(\Delta E_{\text{miss}}^x) \) are defined as:

\[ P(\Delta E_{\text{miss}}^{x(y)}) = \exp \left( -\frac{(\Delta E_{\text{miss}}^{x(y)})^2}{2\sigma^2} \right) \]  

(5.7)

Here \( \sigma \) is the \( E_{\text{T}}^{\text{miss}} \) resolution, and \( \Delta E_{\text{miss}}^{x(y)} \) are the differences between the measured values for \( E_{\text{miss}}^{x(y)} \) and the values in the parameter space during the scan.

According to this procedure, a very high efficiency (\( \sim 99\% \)) is achieved for signal and \( Z \to \tau\tau \) events, while a low efficiency is observed for background samples, providing an extra handle for suppression. The reason for the 1% rejection of signal events by MMC is related to the fact that the \( \Delta \phi \) of visible and invisible \( \tau \) decay products can either be outside of the scan range, or that \( E_{\text{T}}^{\text{miss}} \) fluctuates more than 3\( \sigma \).

5.1.4 Blinding

In order to not bias the results during the optimization of the analysis, blinding is applied to the dataset in use. The data can only be looked at in the background control regions, where the signal contamination is expected to be negligible. Since the small separation between the \( Z \to \tau\tau \) background and the expected Higgs signal, the \( Z \to \tau\tau \) control region has some signal contamination but anyway with a signal efficiency below 20%. With this observation also for this control region, all distributions can be safely examined for data. As for the signal regions, all kinematics distributions except the one of the MMC mass can be safely compared between data and expectations since all these variables have a low discriminating power for the Higgs signal.

5.1.5 Preselection

In order to select the \( \tau_{\text{lep}}\tau_{\text{had}} \) topology previously discussed, the following criteria are applied:

\( \tau \)-lepton: exactly one \( \tau \)-jet is required. The values of the \( p_T \) threshold on the \( \tau \)-lepton change according to the trigger passed by the event and are summarized in Table 5.3.
However, there are only 4 equations available:

\[ \begin{align*}
\tau_1 & = \text{leptonic decay} \\
\tau_2 & = 1\text{-prong hadronic decay} \\
\tau_3 & = 3\text{-prong hadronic decay}
\end{align*} \]

The system of Eqs. (1) is solved for any point in the \((x, y, z)\) parameter space, \(v_1\) is the momentum of the initial \(\tau\) and its decay type.

![Figure 5.2: Examples of the probability distribution functions \(P(\Delta \theta, p_T)\) for \(45 < p_T \leq 50\) GeV for leptonic \(\tau\) decays in (a), for 1-prong hadronic decay in (b), and for 3-prong decay in (c) [161].](image)

Figure 5.2: Examples of the probability distribution functions \(P(\Delta \theta, p_T)\) for \(45 < p_T \leq 50\) GeV for leptonic \(\tau\) decays in (a), for 1-prong hadronic decay in (b), and for 3-prong decay in (c) [161].
5.1. ANALYSIS STRATEGY

<table>
<thead>
<tr>
<th></th>
<th>$p_T^\tau$ [GeV]</th>
<th>$p_T^\ell$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLT (e and $\mu$)</td>
<td>20</td>
<td>26</td>
</tr>
<tr>
<td>LTT (e)</td>
<td>25</td>
<td>20-26</td>
</tr>
<tr>
<td>LTT ($\mu$)</td>
<td>25</td>
<td>17-26</td>
</tr>
</tbody>
</table>

Table 5.3: Offline $p_T$ thresholds for $\tau$, $\mu$ and $e$.

e-, $\mu$-lepton: exactly one electron or muon is required. The values of the $p_T$ threshold on the light lepton change according to the trigger passed by the event and are summarized in Table 5.3. Events with more than one lepton are vetoed to reject the $Z \rightarrow \ell\ell$ and top processes.

charge correlation: the charges of the light lepton and the $\tau_{\text{had}}$ are required to have opposite sign.

Figure 5.3 shows basic kinematics distributions which will be used in the analysis. The background processes are estimated as described in Section 5.2, they are in good agreement with the observed data. The MMC mass in Figure 5.3(e) shows a discrepancy in the region $80 < m_{\text{MMC}}^{\tau\tau} < 150$ GeV, where the $Z \rightarrow \tau\tau$ contribution is dominant. This can be attributed to a shift of about 1.6% of the MC based TES employed in this analysis with respect to the in-situ measurement, resulting in a small overestimation of the $Z \rightarrow \tau\tau$ background. As shown in Figure 5.3(f), this effect is covered by the systematic uncertainties assigned to the TES. In particular for a downward variation ($-1\sigma$) good agreement is found between data and expectations.

5.1.6 Analysis categories

As discussed in Section 5.1.1 the different Higgs production modes, in particular the VBF, offer peculiar jet signatures that can be exploited to create optimize categories of final state topologies to increase the overall signal sensitivity of the analysis. Each category aims to contain a specific jet topology and it is characterized by a different background composition and signal sensitivity. Therefore, after the categorization criteria required to classify the events are applied, optimized selection criteria are employed to reject specific backgrounds. A full description after the introduction of variables useful for background rejection is given in the following.
Figure 5.3: Distributions at the preselection level: $p_T^τ$ in (a), $p_T^ℓ$ in (b), $E_T^{miss}$ in (c), $n_{jets}$ in (d), MMC mass in (e) and MMC mass with 1σ TES variation in (f).
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Common variables for non-resonant background rejection

A set of common variables can be useful across different topology categories to reject non-resonant backgrounds with a fake tau, such as QCD, diboson, $W+jets$, $t\bar{t}$ and single top processes. These variables are defined as follow:

- The transverse mass of the lepton and the $E_T^{\text{miss}}$ system defined as:

$$m_T = \sqrt{2p_T^\ell E_T^{\text{miss}}(1 - \cos\Delta\phi)}$$  \hspace{1cm} (5.8)

where $p_T^\ell$ is the lepton $p_T$ and $\Delta\phi$ is the angle between the lepton and the $E_T^{\text{miss}}$. This variable is an efficient discriminant between backgrounds with large $m_T$ like $W$ and $t\bar{t}$, and signal which tends to have low $m_T$, since in this case the $E_T^{\text{miss}}$ vector usually points between the visible $\tau$-lepton decay products.

- The $\Sigma\Delta\phi$ variable defined as:

$$\Sigma\Delta\phi = |\phi^\ell - \phi^{\text{miss}}| + |\phi^\tau - \phi^{\text{miss}}|$$  \hspace{1cm} (5.9)

where $\phi^\ell$, $\phi^\tau$, $\phi^{\text{miss}}$ are the azimuthal directions of the light lepton, the $\tau$-lepton and the $E_T^{\text{miss}}$. Like $m_T$, this variable also provides rejection against the $W$ background, since signal events usually have $E_T^{\text{miss}}$ pointing between the visible $\tau$-lepton decays products resulting in $\Sigma\Delta\phi < \pi$, which is not generally true for the $W$ background.

- The $\Delta\Delta R$ variable defined as:

$$\Delta\Delta R = |\Delta R^{\ell\tau} - \Delta R^{\ell\tau}_{\text{pred}}|$$  \hspace{1cm} (5.10)

where $\Delta R^{\ell\tau}$, $\Delta R^{\ell\tau}_{\text{pred}}$ are the measured angular separation between the lepton and the $\tau_{\text{had}}$ and its predicted value, respectively, as a function of $p_T^{\ell\tau}$ of the lepton-$\tau$ system. The predicted value is computed from the parameterization of the correlation between $\Delta R^{\ell\tau}$ and $p_T^{\ell\tau}$ with a Landau function, in simulated Higgs events.

- The $b$-veto ($70\%$ efficiency point) is applied to reject the $t\bar{t}$ background.

Figure 5.4 shows a good agreement between data and expectations for the variables described above at the preselection level.
Figure 5.4: Distributions of discriminating variables at the preselection level: $m_T$ in (a), $\Sigma \Delta \phi$ in (b) and $\Delta R_{\ell\tau}$ in (c).
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Definition of the analysis categories

Two mutually exclusive categories are defined according to the jet multiplicity and topology: the VBF category and the Boosted category. The categorization procedure first checks if a given event passes the VBF selection. If not, this event can still contribute in the Boosted category, or can be discarded completely from the analysis. Then, additional selection criteria based on the discriminating variables presented in the previous section and optimized for each category are applied to suppress background contributions specific for each category. The categorization requirements for the VBF and Boosted category are defined as follow:

**VBF category** aims to select the experimental VBF production modes, described in Section 5.1.1, by asking for:

- at least two “high-\(p_T\)” jets:
  - in opposite hemispheres of the detector and with a large pseudo rapidity separation \(\Delta \eta_{j_1,j_2}\);
  - with a large invariant mass \(m_{j_1,j_2}\);
- the tau decay products are scattered between the two tagged jets;
- a small total transverse momentum, \(p_T^{\text{tot}}\), of the full system defined as:

\[
p_T^{\text{tot}} = |p_T^{\ell} + p_T^{\tau} + p_T^{j_1} + p_T^{j_2} + E_T^{\text{miss}}|
\]

(5.11)

- only events that pass the SLT\(^1\).

All optimized values for the selections described above are summarized together with the background rejection criteria in Table 5.4 on page 174.

**Boosted category** aims to select Higgs boson candidates with a significant boost in the transverse plane and balanced by one or more jets, in particular the \(gg \rightarrow H \rightarrow \tau\tau\) with ISR described in Section 5.1.1, by asking for:

- high reconstructed Higgs transverse momentum, \(p_T^{H}\), defined as the vector sum of its expected decay products in the hypothesis that the

\(^1\)The LTT requirements on the \(\tau_{\text{had}}\) at trigger level completely deplete the corresponding region for background estimation (anti-\(\tau\) region), explained and defined in Section 5.2.3, therefore it is impossible to obtain a reliable and accurate estimate of the background shape.
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\( E^\text{miss}_T \) comes from the neutrinos contribution only:

\[
p^H_T = |p_T^\ell + p_T^\tau + E^\text{miss}_T|
\] (5.12)

This variable is particularly attractive, because it allows to classify boosted events without explicitly relying on the jet multiplicity avoiding a direct dependence on the jet energy scale, resolution and modeling. Moreover it helps to suppress \( t\bar{t} \) and QCD multi-jets non-resonant backgrounds.

- requirements on the energy fraction of the visible \( \tau \) decay products defined as:

\[
x_\ell = \frac{p^\tau_{\text{had}} \cdot p^\ell_y - p^\tau_{\text{had}} \cdot p^\ell_x}{p^\tau_{\text{had}} \cdot E^\text{miss}_y - p^\tau_{\text{had}} \cdot E^\text{miss}_x + p^\tau_{\text{had}} \cdot p^\ell_y - p^\tau_{\text{had}} \cdot p^\ell_x}
\] (5.13)

\[
x_{\tau \text{had}} = \frac{p^\tau_{\text{had}} \cdot p^\ell_y - p^\tau_{\text{had}} \cdot p^\ell_x}{p^\tau_{\text{had}} \cdot E^\text{miss}_y - p^\tau_{\text{had}} \cdot E^\text{miss}_x + p^\tau_{\text{had}} \cdot p^\ell_y - p^\tau_{\text{had}} \cdot p^\ell_x}
\] (5.14)

computed under the hypothesis of the collinear approximation that assumes collinear direction for visible and invisible (neutrinos) \( \tau \) decay products and that \( E^\text{miss}_T \) comes from neutrinos only. This variable is particularly efficient to enhance the signal contribution over non-resonant backgrounds.

All the optimal values for the selections described above are summarized together with the background rejection criteria in Table 5.4 on page 174.

Figures 5.5 and 5.6 show an acceptable agreement between data and expectations for kinematics distribution at the level of the Boosted and VBF categorization, respectively. For the MMC mass distribution data are not shown due to the blinding of the analysis described in Section 5.1.4.

In the analysis presented in Ref. [144] additional 1-jet and 0-jet categories are included by asking for no or one jet with \( p_T > 30 \) GeV, respectively, in the final state. It is observed that these categories add only a small contribution to the total expected sensitivity. Their main benefit is the provision of constraints of some nuisance parameters contributing to the systematic uncertainties. Studies are on-going to either convert these jet topological based categories into more proper control regions or to re-optimize them.

\(^1\)The optimal value was found to be at \( p^H_T > 150 \) GeV, but the theoretical uncertainties on signal production cross-section cannot be reliably estimated at such value of \( p^H_T \), so the the cut is lowered to 100 GeV.
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Figure 5.5: Kinematics variables distribution at the Boosted categorization level: 
\( p_T^\tau \) in (a), \( p_T^\ell \) in (b), \( E_{\text{miss}}^\tau \) in (c), MMC mass in (d).
Figure 5.6: Kinematics variables distribution at the VBF categorization level: $p_T$ in (a), $p_T$ in (b), $E_T^{\text{miss}}$ in (c), MMC mass in (d).
5.1. **ANALYSIS STRATEGY**

<table>
<thead>
<tr>
<th>Categorization criteria</th>
<th>VBF</th>
<th>Boosted</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>$E_T^{\text{miss}} &gt; 20$ GeV</td>
<td>$E_T^{\text{miss}} &gt; 20$ GeV</td>
</tr>
<tr>
<td></td>
<td>$p_T^\tau &gt; 30$ GeV</td>
<td>$p_T^\tau &gt; 30$ GeV</td>
</tr>
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<td></td>
<td>$p_T^{\text{tot}} &lt; 30$ GeV</td>
<td>$p_T^H &gt; 100$ GeV</td>
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<tr>
<td></td>
<td>$m_{\text{vis}} &gt; 40$ GeV</td>
<td>$0 &lt; x_\ell &lt; 1$</td>
</tr>
<tr>
<td></td>
<td>$p_T^{j_1} &gt; 40$ GeV</td>
<td>$0.2 &lt; x_{r\text{had}} &lt; 1.2$</td>
</tr>
<tr>
<td></td>
<td>$p_T^{j_2} &gt; 30$ GeV</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\eta_{j_1} \times \eta_{j_2} &lt; 0$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\Delta \eta_{j_1,j_2} &gt; 3.0$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$m_{j_1,j_2} &gt; 500$ GeV</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\min(\eta_{j_1}, \eta_{j_2}) &lt; \eta_\ell$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\max(\eta_{j_1}, \eta_{j_2}) &gt; \eta_\tau$</td>
<td></td>
</tr>
<tr>
<td>Selection criteria</td>
<td>$m_T &lt; 50$ GeV</td>
<td>$m_T &lt; 50$ GeV</td>
</tr>
<tr>
<td></td>
<td>$\Delta \Delta R &lt; 0.8$</td>
<td>$\Delta \Delta R &lt; 0.8$</td>
</tr>
<tr>
<td></td>
<td>b-jet veto</td>
<td>b-jet veto</td>
</tr>
<tr>
<td></td>
<td>$\Sigma \Delta \phi &lt; 2.8$</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.4: Categorization and selection criteria to define the VBF and the Boosted categories.
Figure 5.7: Comparison at the preselection level of the invariant mass computed with the MC truth $E_T^{\text{miss}}$ and with the reconstructed $E_T^{\text{miss}}$ in the low pile-up conditions ($N_{\text{PV}} < 6$) and high pile-up conditions ($N_{\text{PV}} > 9$) for the signal vector boson fusion events in (a), gluon fusion events in (b), and for the main background $Z \to \tau\tau$ events in (c).

5.1.7 $E_T^{\text{miss}}$ studies in the $H \to \tau\tau$ analysis

As explained in Section 5.1.1, the $Z \to \tau\tau$ process is the main background for this analysis because it has an event kinematics very similar to the signal Higgs events, and a mass peak close to an expected light Higgs mass around 125 GeV. A good mass resolution is crucial to distinguish signal events from background events and thus increasing the sensitivity of the analysis. Figure 5.7 shows the effect of the $E_T^{\text{miss}}$ resolution on the $\tau\tau$ invariant mass reconstructed with the collinear approximation (see Section 5.1.3): as it is clearly visible, the $E_T^{\text{miss}}$ resolution completely dominates the mass reconstruction. Hence, providing the best $E_T^{\text{miss}}$ measurement as possible, especially in terms of resolution performance, is essential for this analysis.

As shown in Chapter 4 in detail, the pile-up worsens the $E_T^{\text{miss}}$ resolution, with the subsequent effect on the mass resolution, shown in Figure 5.7. This figure compares the reconstruction in low pile-up conditions ($N_{\text{PV}} < 6$) with the reconstruction in high pile-up conditions ($N_{\text{PV}} > 9$). Improvements in the $E_T^{\text{miss}}$ resolution are expected for $Z$ and Higgs events by the use of the pile-up suppression methods described in details in Section 4.2 and shown in Figure 4.16. In the following, the pile-up suppression methods for the $E_T^{\text{miss}}$ are tested in the specific context of the $H \to \tau\tau$ analysis at the preselection and categorization level. For this purpose, the figures of merit considered are:
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$E_T^{\text{miss}}$ resolution: estimated from the distribution of $E_{x(y)}^{\text{miss}} - E_{x(y)}^{\text{miss, True}}$. Beyond being crucial for the mass reconstruction, the resolution performance is also important for the background rejection. Indeed the rejection efficiency of an $E_T^{\text{miss}}$ based selection and on variables computed using $E_T^{\text{miss}}$ (like the transverse mass), depends on the $E_T^{\text{miss}}$ resolution.

$E_T^{\text{miss}}$ linearity: estimated from the distribution of $E_T^{\text{miss}} - E_T^{\text{miss, True}}$. A good $E_T^{\text{miss}}$ measurement ensures the proper reconstruction also of more complex quantities, in particular of the invariant mass. Though the MMC reconstruction partially compensates for $E_T^{\text{miss}}$ effects, providing a good $E_T^{\text{miss}}$ measurement is still essential because it improves the final mass evaluation.

$E_T^{\text{miss}}$ direction: estimated from the distribution of $\phi^{\text{miss}} - \phi^{\text{miss, True}}$. The $E_T^{\text{miss}}$ direction enters in the invariant and transverse mass computation. Moreover, it can also affect categorization variables like $p_T^{\text{tot}}$, where a vector sum is involved, or $x_\ell$, $x_{\tau_{\text{had}}}$ variables, where the $E_T^{\text{miss}}$ is projected onto visible $\tau$ decay products.

$m_{\tau\tau}$ reconstruction: computed as described in Section 5.1.3. The MMC mass is the final discriminant for this analysis. However, since the complexity of the MMC procedure$^2$, the studies in this section are performed on the invariant mass reconstructed with the collinear approximation. The effect of the $E_T^{\text{miss}}$ on this variable is direct and well visible, thus it provides an optimal quantity for the performance studies.

Figures 5.8 to 5.10 show the comparison at the preselection level before and after applying $E_T^{\text{miss}}$ pile-up suppression for the scoring variables described above, for the vector boson fusion and the gluon fusion Higgs events, and for $Z \rightarrow \tau\tau$ events. For all distributions a clear improvement is observed for the pile-up corrected quantities, in particular when STVF is applied.

Figures 5.11 to 5.15 show the same comparison for the Boosted and VBF categorizations but dropping the requirements involving $E_T^{\text{miss}}$ in order to not bias the distributions for the methods under test. The same conclusion as for Figures 5.8 to 5.10 can be drawn. After applying all the selection criteria of the VBF category, the gluon fusion signal and the $Z \rightarrow \tau\tau$ samples suffer from low statistics. To be able to use higher statistics for the performance studies the requirement

$^2$In order to have a clean comparison, the MMC scanning and weighting procedure should be reoptimized for each of the $E_T^{\text{miss}}$ pile-up suppression method.
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on the invariant mass of the jet system, $m_{jj}$, is released (denoted as “VBF category loose” in the figures). Since these distributions provide less significant results due to the limited statistics, only the $E_T^{\text{miss}}$ resolution distribution and the invariant mass distribution are shown in Figure 5.15.

In Section 4.5.3, an underestimation of the true soft term contribution is observed for the STVF method. This can have an effect on the reconstructed mass. The MMC mass is evaluated as a function of the expected truth Higgs mass, as shown in Figure 5.16 for the VBF and Boosted categories. A good match between the reconstructed and the expected values is found for both categories except for a constant small underestimation of about 1.5 GeV observed for the gluon fusion Higgs events in the Boosted category. A future optimization of the pile-up suppression methods likely can correct for this effect. For the purpose of a first observation of the Higgs boson in the $\tau\tau$ channel this small effect is not crucial. For this reason, the STVF method that provides the best resolution is preferred and employed. The STVF method also provides a better stability of the reconstruction performance as a function of $N_{PV}$ and for all data taking periods in 2012, as visible in Figure 5.17. This figure shows the invariant mass reconstructed with the collinear approximation as a function of $N_{PV}$ before and after applying the STVF pile-up suppression method. The stability requirement is important since the analysis selection and optimization is performed on the whole datasets without dividing for periods.
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![Graphs showing the analysis strategy](image)

(a) $E_T^{\text{miss}}$ resolution
(b) $E_T^{\text{miss}}$ linearity
(c) $E_T^{\text{miss}}$ direction
(d) $m_{\tau\tau}$

Figure 5.8: Comparison at the preselection level before and after applying the $E_T^{\text{miss}}$ pile-up suppression methods in MC vector boson fusion Higgs events at $m_H = 125$ GeV: $E_T^{\text{miss}}$ resolution in (a), $E_T^{\text{miss}}$ linearity in (b), $E_T^{\text{miss}}$ direction in (c), and reconstructed invariant mass in (d).
Figure 5.9: Comparison at the preselection level before and after applying the $E_T^{\text{miss}}$ pile-up suppression methods in MC gluon fusion Higgs events at $m_H = 125$ GeV: $E_T^{\text{miss}}$ resolution in (a), $E_T^{\text{miss}}$ linearity in (b), $E_T^{\text{miss}}$ direction in (c), and reconstructed invariant mass in (d).
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![Graphs showing comparison at the preselection level before and after applying the $E_T^{\text{miss}}$ pile-up suppression methods in MC $Z \to \tau\tau$ events: $E_T^{\text{miss}}$ resolution in (a), $E_T^{\text{miss}}$ linearity in (b), $E_T^{\text{miss}}$ direction in (c), and reconstructed invariant mass in (d).]
Figure 5.11: Comparison at the Boosted categorization level before and after applying the $E_T^{\text{miss}}$ pile-up suppression methods in MC vector boson fusion Higgs events at $m_H = 125$ GeV: $E_T^{\text{miss}}$ resolution in (a), $E_T^{\text{miss}}$ linearity in (b), $E_T^{\text{miss}}$ direction in (c), and reconstructed invariant mass in (d).
Figure 5.12: Comparison at the Boosted categorization level before and after applying the $E_T^{\text{miss}}$ pile-up suppression methods in MC gluon fusion Higgs events at $m_H = 125$ GeV: $E_T^{\text{miss}}$ resolution in (a), $E_T^{\text{miss}}$ linearity in (b), $E_T^{\text{miss}}$ direction in (c), and reconstructed invariant mass in (d).
Figure 5.13: Comparison at the Boosted categorization level before and after applying the $E_T^{\text{miss}}$ pile-up suppression methods in MC $Z \rightarrow \tau\tau$ events: $E_T^{\text{miss}}$ resolution in (a), $E_T^{\text{miss}}$ linearity in (b), $E_T^{\text{miss}}$ direction in (c), and reconstructed invariant mass in (d).
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Figure 5.14: Comparison at the VBF categorization level before and after applying the $E_T^{\text{miss}}$ pile-up suppression methods in MC vector boson fusion Higgs events at $m_H = 125$ GeV: $E_T^{\text{miss}}$ resolution in (a), $E_T^{\text{miss}}$ linearity in (b), $E_T^{\text{miss}}$ direction in (c), and reconstructed invariant mass in (d).
Figure 5.15: Comparison at the VBF categorization level before and after applying the $E_T^{\text{miss}}$ pile-up suppression methods in MC gluon fusion Higgs events at $m_H = 125$ GeV: $E_T^{\text{miss}}$ resolution in (a) and reconstructed invariant mass in (b). The same comparison is shown in MC $Z \to \tau\tau$ events: $E_T^{\text{miss}}$ resolution in (c) and reconstructed mass in (d).
Figure 5.16: The reconstructed value of the MMC mass is plotted as a function of the true $m_H$ value for MC vector boson fusion Higgs events in the VBF category in (a) and in the Boosted category in (b), for MC gluon fusion Higgs events in the VBF category in (c) and in the Boosted category in (d).
Figure 5.17: The invariant mass reconstructed with the collinear approximation is plotted at the preselection level as a function of $N_{\text{PV}}$ before and after applying the STVF pile-up suppression method. MC vector boson fusion Higgs events with $m_H = 125$ GeV are shown in (a) and MC gluon fusion Higgs events with $m_H = 125$ GeV are shown in (b).

5.2 Background estimation

The selection criteria described in Section 5.1.6 are aimed to select signal events and to suppress backgrounds. Anyway procedures to estimate the residual backgrounds are needed. They are described in detail in this section. The main backgrounds are evaluated as much as possible with data driven techniques or or else with MC normalized to data in dedicated control regions. In particular for the main $Z \rightarrow \tau\tau$ background, a hybrid semi-data driven technique is employed and described in Section 5.2.1. Only for the small diboson background a full MC based estimation is performed.

5.2.1 $Z \rightarrow \tau\tau$ estimation with embedded sample

The $Z \rightarrow \tau\tau$ process is the dominant irreducible background for the $H \rightarrow \tau\tau$ analysis. A full data driven estimation for this background is not possible for two main reasons:

- the $\tau$ identification cannot ensure the selection of a sufficiently pure high statistics $Z \rightarrow \tau\tau$ data sample;

\[ ^3 \text{After preselection it contributes only about 0.5\%.} \]
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- the presence of signal contamination from $H \rightarrow \tau\tau$ events that cannot be completely separated from $Z \rightarrow \tau\tau$ events;

However, in order to not have a full MC based estimation for this important background, a hybrid sample, obtained embedding simulated $\tau$ leptons in $Z \rightarrow \mu\mu$ data, is employed [162]. This technique allows to exploit the main event kinematics, such as the underlying event, the pile-up and the jet activity, from data and to rely on MC only for the $\tau$ decay process that is well modeled in simulation, including the $\tau$ polarization and spin correlation.

The $Z \rightarrow \mu\mu$ data sample has been chosen as starting point for the embedding procedure for the following reasons:

- the good purity and the available high statistics for the $Z \rightarrow \mu\mu$ sample;
- the small Higgs signal contamination due to the small muon mass leading to a small coupling to the Higgs boson;
- an event kinematics similar to $Z \rightarrow \tau\tau$ events except for the mass difference between muons and taus. This difference is taken into account and corrected by rescaling the muon four momentum.

Before adding the simulated $\tau$-leptons to the considered data event, the tracks associated to the muons are removed from this event, and the corresponding estimated muon energy deposit in the calorimeter is subtracted at cell level to avoid energy double counting.

Since this procedure is complex, the embedded samples are extensively tested and a few additional corrections are applied to produce a kinematic spectrum in good agreement with the expected $Z \rightarrow \tau\tau$ spectrum. These correction includes:

- a weight to account separately for the muon trigger and reconstruction efficiencies affecting the starting $Z \rightarrow \mu\mu$ data sample;
- a $p_T$ and $\eta$ dependent weight to account for a non-operational pixel detector module that is not been included in simulation. This correction is derived separately for electrons and muons;
- a weight to account for trigger efficiency effects that are not applied during the embedding procedure.

The obtained embedded sample is normalized to data (with the non $Z \rightarrow \tau\tau$ backgrounds subtracted) in the visible mass region: $40 < m_{\text{vis}} < 70$ GeV.

\footnote{The visible mass is defined as the invariant mass computed using only the visible $\tau$ decay products. Therefore the neutrinos contribution is excluded.}
Embedded validation

Inside the analysis the embedded $Z \to \tau\tau$ sample, described in the previous section, is validated comparing the background expectation with data in dedicated control regions for the VBF and Boosted categories defined by:

- category requirements listed in Section 5.1.6;
- $m_T < 40$ GeV;
- $m_{\tau\tau}^{MMC} < 110$ GeV.

The $E_T^{miss}$ and the MMC mass distributions are shown in Figures 5.18 and 5.19, respectively, for the Boosted and the VBF category control region. The agreement between data and the expectation is good.

5.2.2 Boosted category: OS-rSS method

At the event preselection, one of the requirements to identify $H \to \tau\tau$ signal events is the opposite charge correlation for the visible $\tau$ decay products, since they are expected to come from the decay of a neutral particle into two taus of opposite charge. This condition is not present in all backgrounds, so it can be
5.2. BACKGROUND ESTIMATION

Figure 5.19: Distribution of kinematic variables in the $Z \rightarrow \tau\tau$ VBF control region: $E_T^{\text{miss}}$ in (a) and MMC mass in (b).

used for the background estimation. For the Boosted category, the number of background events in the opposite sign signal region (OS events) is estimated making use of data where the lepton and the $\tau_{\text{had}}$ have the same charge sign (SS events). The main backgrounds show the following charge correlations:

**Irreducible background with a true $\ell\tau_{\text{had}}$ signature:** dominated by $Z/\gamma^* \rightarrow \tau\tau$ events and with some contributions from diboson and top events. This sample is characterized by a strong charge correlation $N_{\text{OS}} \gg N_{\text{SS}}$, where $N_{\text{OS}}$ and $N_{\text{SS}}$ are the number of opposite and same sign events, respectively.

**Background with a jet misidentified as $\tau_{\text{had}}$:** dominated by QCD multi-jets, $W+$jets and top events. They are characterized by a moderate charge correlation with $N_{\text{OS}} > N_{\text{SS}}$. For $Z \rightarrow \ell\ell+$jets events $N_{\text{OS}} \sim N_{\text{SS}}$

**Background with a lepton misidentified as $\tau_{\text{had}}$:** dominated by $Z \rightarrow \ell\ell$ events. They are characterized by a strong charge correlation $N_{\text{OS}} \gg N_{\text{SS}}$.

The total background prediction is given by the number of same sign data events $N_{\text{SS}}^{\text{data}}$, dominated by QCD multi-jet events, and with additional contributions, the add-on terms $N_{\text{add}}^{\text{X}}$, from other backgrounds, which are estimated

---

\[ ^5 \text{The top background includes both } t\bar{t} \text{ and single top processes} \]
CHAPTER 5: \( H \rightarrow \tau\tau \) search in the semileptonic channel: cut-based analysis

<table>
<thead>
<tr>
<th>( k_{\text{OS}} )</th>
<th>( k_{\text{SS}} )</th>
<th>( Z \rightarrow \tau\tau )</th>
<th>( Z \rightarrow \ell\ell ) ((\rightarrow \tau_{\text{had}}))</th>
<th>( Z \rightarrow \ell\ell + \text{jets}(\rightarrow \tau_{\text{had}}))</th>
<th>( W + \text{jets}(\rightarrow \tau_{\text{had}}))</th>
<th>( W + \text{jets}(\rightarrow \mu_{\text{had}}))</th>
<th>( \text{top} )</th>
<th>( VV )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0.783±0.005</td>
<td>0.828±0.004</td>
<td>0.69±0.003</td>
<td>0.86±0.01</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0.783±0.005</td>
<td>1.07±0.09</td>
<td>0.89±0.07</td>
<td>0.99±0.03</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.5: Summary of the \( k \)-factors for each background in the Boosted category.

from MC or embedded samples:

\[
N_{\text{bkg}}^{\text{OS}} = r_{\text{QCD}} \cdot N_{\text{data}}^{\text{SS}} + N_{\text{add}-\text{on}}^{Z\rightarrow\tau\tau} + N_{\text{add}-\text{on}}^{Z\rightarrow\ell\ell(\rightarrow\tau\tau)} + N_{\text{add}-\text{on}}^{Z\rightarrow\ell\ell+\text{jets}(\rightarrow\tau\tau)} + N_{\text{add}-\text{on}}^{W+\text{jets}} + N_{\text{add}-\text{on}}^{\text{top}} + N_{\text{add}-\text{on}}^{VV} \tag{5.15}
\]

Here \( r_{\text{QCD}} \) is a factor that accounts for potential differences in flavor composition of final state jets. The underlying assumption of this method is that the shape of the discriminant MMC mass distribution, in the signal region is the same for OS and SS events otherwise passing all kinematic selection cuts for a given analysis category. In order to address possible mismodeling of the \( \ell \rightarrow \tau_{\text{had}} \) and \( \text{jet} \rightarrow \tau_{\text{had}} \) fake rate in MC simulation, the \( \text{add-on} \) terms are normalized to data in dedicated control regions, so \( k \)-factors are defined as \( k = N(\text{data})/N(\text{MC}) \) for each background. The \( k \)-factor for a given background \( X \) can be different for OS and SS events, to account for differences in the tau misidentification rate for jets from quark and gluon hadronization, but it is assumed to be the same between a signal region and the corresponding control region.

Each \( \text{add-on} \) term can be expressed as:

\[
N_{\text{add}-\text{on}}^{X} = k_{X}^{\text{OS}} N_{\text{OS}}^{X} - r_{\text{QCD}} k_{X}^{\text{SS}} N_{\text{SS}}^{X} \tag{5.16}
\]

where the \( k_{X}^{\text{OS}} \) and \( k_{X}^{\text{SS}} \) are the \( k \)-factors for OS and SS events, respectively, and the \( r_{\text{QCD}} k_{X}^{\text{SS}} N_{\text{SS}}^{X} \) term accounts for the contribution of each non-QCD background already included in \( N_{\text{data}}^{\text{SS}} \) in Equation 5.15. The values for the different \( k \)-factors are summarized in Table 5.5: when the \( k \)-factor is assumed equal to unity, as for the \( Z \rightarrow \tau\tau \), \( Z \rightarrow \ell\ell(\rightarrow \tau_{\text{had}}) \) and diboson backgrounds, no error is quoted. Since the diboson \( (VV) \) background is fully estimated from MC, the \( N_{\text{OS}} \) and the \( N_{\text{SS}} \) are taken from MC. For the \( Z \rightarrow \ell\ell + \text{jets}(\rightarrow \tau_{\text{had}}) \) background, no statistically significant difference between OS and SS events is expected, hence only \( N_{\text{OS}} \) is used:

\[
N_{\text{add}-\text{on}}^{Z\rightarrow\ell\ell+\text{jets}(\rightarrow\tau\tau)} = k_{Z\rightarrow\ell\ell+\text{jets}(\rightarrow\tau\tau)} N_{\text{OS}}^{Z\rightarrow\ell\ell+\text{jets}(\rightarrow\tau\tau)} (1 - r_{\text{QCD}}) \tag{5.17}
\]
5.2. BACKGROUND ESTIMATION

<table>
<thead>
<tr>
<th></th>
<th>$r_{\text{QCD}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e\tau_{\text{had}}$</td>
<td>$1.00\pm0.05(\text{stat})\pm0.12(\text{sys})$</td>
</tr>
<tr>
<td>$\mu\tau_{\text{had}}$</td>
<td>$1.10\pm0.06(\text{stat})\pm0.13(\text{sys})$</td>
</tr>
</tbody>
</table>

Table 5.6: Value of $r_{\text{QCD}}$ for $e\tau_{\text{had}}$ and $\mu\tau_{\text{had}}$ events.

$r_{\text{QCD}}$ determination

As explained in the previous section, the QCD multi-jets contribution, with one of the jets misidentified as a prompt lepton and second jet misidentified as a $\tau_{\text{had}}$, is estimate according to Equations 5.15 and 5.16:

$$N_{\text{QCD}} = r_{\text{QCD}} \cdot \left( N_{\text{data}}^{SS} \cdot \sum_{X} k_{X}^{SS} N_{X}^{SS} \right)$$  \hspace{1cm} (5.18)

At LO order, QCD dijets events include $qq$, $qq'$, $qg$ and $gg$ pairs in the final state. No charge correlation between a fake lepton and a fake $\tau_{\text{had}}$ is expected in events with jets from $gg$ and $gg$ parton pairs. However, significant charge correlation is expected in events with jets from $qq$ and $qq'$ pairs. Therefore, the charge correlation requirement can alter the flavor composition of partons in the final state and lead to differences in $N_{\text{QCD}}^{OS}$ and $N_{\text{QCD}}^{SS}$ and in kinematic distributions. This effect is corrected introducing the $r_{\text{QCD}}$ factor in Equations 5.15 and 5.18, defined as the ratio $N_{\text{QCD}}^{OS}/N_{\text{QCD}}^{SS}$ measured in an enriched QCD data control region. The QCD control region is defined as:

- $E_{T}^{\text{miss}} < 15 \text{ GeV}$;
- $m_{T} < 30 \text{ GeV}$;
- no lepton isolation requirement;
- loose tau identification.

The results for the $r_{\text{QCD}}$ determination are shown in Table 5.6 separately for $e\tau_{\text{had}}$ and $\mu\tau_{\text{had}}$ events.

Systematic uncertainties are computed varying the lepton isolation requirement, the tau identification working point, the $m_{T}$ range. These systematics are finally summed in quadrature and symmetrized to obtain a total uncertainty of 11.9% and 11.6% for the $e\tau_{\text{had}}$ and $\mu\tau_{\text{had}}$ channels, respectively.
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**k-factor determination**

In the Boosted category, the \( W+\text{jets}, t\bar{t}, Z \rightarrow \ell \ell + \text{jets}(\rightarrow \tau_{\text{had}}) \) backgrounds are evaluated from MC samples and normalized to data in dedicated individual control regions to correct for the possible MC mismodeling of the \( \text{jet} \rightarrow \tau_{\text{had}} \) fake rate. Each control region is enriched with a specific background and the small contamination from other backgrounds is subtracted from data before performing the normalization. The requirements used to select the control regions are the following.

**\( W+\text{jets} \) control region:**

- category requirements (see Section 5.1.6);
- \( m_T > 70 \text{ GeV} \);
- \( \Sigma \Delta \phi, \Delta \Delta R, x_\ell \) and \( x_{\tau_{\text{had}}} \) requirements are not applied.

Separate \( k \)-factor for OS and SS events are determined. Further corrections need to be applied on the shape of the \( W \) contribution, to account for observed shape differences between MC and data in the \( W \) control region. Two shape-dependent correction functions are applied: the first depends on the ratio between the lepton and the tau momentum \( p_\ell^T/p_\tau^T \), while the second depends on the pseudorapidity separation between the lepton and the tau \( \Delta \eta(\tau, \ell) \). After this procedure a good data-MC agreement is found, as shown for the \( E_T^{\text{miss}} \) and MMC mass distributions in Figure 5.20.

**top control region:**

- at least two jets with \( p_T > 30 \text{ GeV} \);
- at least a b-tagged jet;
- \( E_T^{\text{miss}} > 20 \text{ GeV} \);
- \( m_T > 70 \text{ GeV} \).

Separate \( k \)-factor for OS and SS events are determined. A good data-MC agreement is found after normalization, as shown for the \( E_T^{\text{miss}} \) and MMC mass distributions in Figure 5.21.

**\( Z \rightarrow \ell \ell \) control region:**

- two leptons with opposite sign and same flavor;
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Figure 5.20: Kinematics variables distribution in the $W$ Boosted control region: $E_T^{\text{miss}}$ in (a) and MMC mass in (b).

- standard isolation requirements on the leading lepton;
- no lepton associated with the $\tau_{\text{had}}$ at truth level for the $Z \rightarrow \mu\mu$ MC sample;
- $61 < m_{\ell\ell} < 121$ GeV.

A unique $k$-factor is derived for OS and SS events.

Possible mismodeling in the $\ell \to \tau_{\text{had}}$ fake rate, important for the $Z \rightarrow \ell\ell(\rightarrow \tau_{\text{had}})$, is also considered. Scale factors, computed with a tag-and-probe technique using $Z \rightarrow ee$ events, are applied to the MC simulation to correct for the electron misidentification rate. No correction is applied on the $Z \rightarrow \mu\mu$ background, since it is a small contribution. Rather, a conservative systematic uncertainty of 15% is propagated through the analysis.

5.2.3 VBF category: fake factor method

In the VBF category, the $Z \to \tau\tau$ and the MC based backgrounds are estimated and normalized to data as described in the previous section. Since the low available statistics in this category for SS events, different background estimates for the QCD multi-jets and $W$+jets contributions are provided through the Fake Factor method [163, 164].

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The method uses a control sample defined by applying the same event selection used for the VBF category described in Section 5.1.6, with the exception that the $\tau_{\text{had}}$ candidates are required to fail the $\tau_{\text{had}}$ identification (referred to as anti-\(\tau\) in the following). Fake backgrounds, $N_{\text{bkg}}^{\text{est}}$, can be estimated from anti-\(\tau\) events, $N_{\text{anti-}\tau}$, and fake factors ($FF$) according to the following formula:

$$
N_{\text{bkg}}^{\text{est}} = N_{\text{anti-}\tau} \times FF 
$$

(5.19)

$$
FF = \frac{N_{\text{identified-}\tau}}{N_{\text{anti-}\tau}} 
$$

(5.20)

where $N_{\text{identified-}\tau}$ is the number of events passing the tau identification criteria.

The fake factor is split into two separate components, $FF_{\text{QCD}}$ and $FF_{W^{+}jets}$, for samples dominated by gluon and quark jets, respectively. Thus, Equations 5.19 and 5.20 yield:

$$
N_{\text{bkg}}^{\text{est}} = (N_{\text{data}}^{\text{anti-}\tau} - N_{\text{anti-}\tau} - N_{\text{others}}^{\text{anti-}\tau}) \times FF_{\text{MIX}} 
$$

(5.21)

$$
FF_{\text{MIX}} = R_{W^{+}jets} \cdot FF_{W^{+}jets} + (1 - R_{W^{+}jets}) \cdot FF_{\text{QCD}} 
$$

(5.22)

where $N_{\text{others}}^{\text{anti-}\tau}$ is the number of other electroweak components predicted with MC simulation, and $R_{W^{+}jets}$ is the fraction of $W^{+}jets$ events in anti-\(\tau\) events.

The $R_{W^{+}jets}$ is computed according to the quark and gluon fractions in the
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Events passing the selection criteria:

$$R_{W+jets} = \frac{N_{W+jets}^{est}}{N_{W+jets}^{est} + N_{QCD}^{est}}$$  \hspace{1cm} (5.23)

where the estimated number of $W+jets$ events $N_{W+jets}^{est}$ is obtained from the number of data events in the $W+jets$ control region (as described in the previous section, with $m_T > 70$ GeV) and by the MC acceptance:

$$N_{W+jets}^{est} = N_{data}^{anti-\tau,WCR} \times \frac{N_{W+jets,MC}^{anti-\tau}}{N_{anti-\tau,WCR}^{anti-\tau}}$$  \hspace{1cm} (5.24)

while the estimated number of QCD multi-jets events is obtained from the number of data events with all the other backgrounds subtracted:

$$N_{QCD}^{est} = N_{data}^{anti-\tau} - (N_{W+jets}^{est} + N_{Z\rightarrow\tau\tau}^{anti-\tau} + N_{others}^{anti-\tau})$$  \hspace{1cm} (5.25)

$FF_{W+jets}$ and $FF_{QCD}$ are measured in separate control regions. The $m_T > 70$ GeV region is used for $FF_{W+jets}$, while the loose lepton region is used for measuring $FF_{QCD}$. Here, loose leptons are non-isolated muons for the muon channel, or non-tight identified and non-isolated electrons for the electron channel.

After applying this procedure, a residual mismodeling is observed between the background estimate and the data, due to $\tau_{had}$ candidates entering the $E_T^{miss}$ reconstruction as $\tau$, while the anti-$\tau$ mainly enter as jets, with a different calibration. In order to correct for this effect, the fake background estimate is reweighted with weights derived in the $W$ control region, where all signal selections are applied, except for the $m_T > 70$ GeV. These weights are binned in the variable $\Xi$, defined as:

$$\Xi = E_T^{miss} \cos \left( \Delta \phi(\tau_{had}, E_T^{miss})/p_T^{\tau} \right)$$  \hspace{1cm} (5.26)

A recomputation of $E_T^{miss}$ using the $\tau$ calibration for the anti-$\tau$ (coherently with the analysis choice in this particular control region), has shows an improvement of the agreement between the background estimate and the data, with no need for reweighting. A fully coherent $E_T^{miss}$ recomputation is under development and it will be integrated in the next analysis for this search.

5.3 **Systematic uncertainties**

In this section the several sources of systematic uncertainties for this analysis are described and quantified. The description of the ATLAS detector responses
and the modeling of various physics processes like pile-up, trigger efficiencies andphysics objects reconstruction and identification lead to separate systematic uncertainties that are propagated through the whole analysis. Theory uncertainties on the Higgs production cross-section and on the modeling of the underlying event are considered as well. Finally, systematic uncertainties arising from the employment of data driven methods for the background estimation and background modeling are also determined and propagated. All these systematic uncertainties are then included as nuisance parameters in the global likelihood fit discussed in Section 5.4. These systematics effect both the normalization and the shape of the MMC distribution. More details for each source of systematic uncertainties are given in the following.

5.3.1 Detector and physics object uncertainties

The following systematic uncertainties on detector performance and physics object reconstruction are considered:

**Luminosity:** the uncertainty on the integrated luminosity is $\pm 2.8\%$. It is derived following the same methodology as detailed in Ref. [165].

**Tau identification:** the correction is obtained using a tag-and-probe measurement with $Z \rightarrow \tau \tau$ events. The correction factors, to be applied in MC to ensure agreement with data, and the upward and downward corresponding variation are applied only on truth-matched hadronic taus. Furthermore, the correction factors on the rate of misidentification of electrons as $\tau_{\text{had}}$ candidates (applied on $\tau$ candidates matched with a true electron) are also varied within their uncertainties.

**Tau energy scale:** the upward and downward variations are applied to the tau according to the recommendations in Ref. [166]. The TES uncertainty is decorrelated for true and fake $\tau$ candidates, but not split into further sources of uncertainty, and also considered as a shape systematic.

**Lepton reconstruction/identification/isolation/trigger efficiency:** the corrections are obtained for each of these types of efficiencies using tag-and-probe measurements. These are then applied to MC samples to ensure agreement with data. The uncertainties are propagated to the final result by varying the corrections by one standard deviation.
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Lepton energy/momentum resolution: the electron energy and the muon momentum are smeared according to the resolutions measured in data. This systematic uncertainty plays a minor role on the final result.

Jet energy resolution (JER) and scale (JES): concerning the JER, an upwards variation of 1σ is obtained by smearing each jet with a factor accounting for the uncertainty in the resolution in-situ measurement. The final effect of the variation is symmetrized in order to have a two-sided uncertainty in the fit. This uncertainty is also included as shape systematic in the fit. As discussed in Section 3.2.4, the total JES systematic is split into several contributions according to different physics sources. However, due to the limited MC statistics, a reduction scheme is derived to not introduce statistical noise in the global fit. From the reduced scheme with 24 nuisance parameters contributing to the JES systematic uncertainty, the 11 most relevant for this analysis are extracted (see Appendix B for details). Among those are flavor response uncertainty components, modeling components, and pile-up components.

$E_{\text{T}}^{\text{miss}}$ energy scale and resolution: for each of the physics object systematic uncertainty listed above the corresponding variation is also propagated to $E_{\text{T}}^{\text{miss}}$, which is then recomputed accordingly. Independent systematics on the scale and resolution of the soft term, derived as described in Sections 3.3.3 and 4.6, are also considered and propagated through the analysis. For the soft term $E_{\text{T}}^{\text{miss}}$ resolution, the final effect of the variation is symmetrized in order to have a two-sided uncertainty in the fit.

5.3.2 Theory uncertainties

The Higgs cross-section is used to normalize the signal MC samples, therefore, uncertainties on the computation like neglecting high-order perturbative corrections or including the mass of the quarks or choosing a specific PDF set, need to be taken into account. These theory uncertainties must be applied only on the signal samples and more specifically include:

QCD scale uncertainty: it provides a realistic estimate of higher order contributions to analyses which classify events by the number of jets. An exclusive requirement on the number of jets introduces complexity in the QCD perturbative computation and in systematic uncertainties on the scale of QCD processes. The prescription considers the QCD scale uncertainties
on inclusive multi-jet cross-sections \((\sigma_{\geq 0\text{jets}}, \sigma_{\geq 1\text{jets}}, \sigma_{\geq 2\text{jets}})\) and assumes that they are uncorrelated and propagated to the exclusive jet bins. The scale uncertainties for the inclusive multi-jet cross-sections are computed with the MCFM 6.3 [167] program and the jet bin fractions are determined by subtracting the appropriate inclusive cross-section. The uncertainties are estimated using MCFM by varying the renormalization scale \(\mu_R\) and the factorization scale \(\mu_F\) between \(m_H/2\) and \(2m_H\). While the inclusive cross-section uncertainty for the gluon fusion process is only 8\%, the uncertainty in the exclusive bins used in this analysis ranges from 22\% to 26\% and can be as high as 74\% for boosted events with at least two jets.

**Modeling of the differential cross-section** \(d\sigma/dp_{H}\): the default \(gg \to H\) simulation in ATLAS is performed with the Powheg generator. The McAtNlo generator implements the same matrix element but quark mass effects on \(d\sigma/dp_{H}\) are known to be quite different for the two generators. This difference is taken into account as an additional systematic uncertainty. A variation of 29\% is observed for the Boosted category and a variation of 18\% is observed for the VBF category.

**Modeling of the underlying event**: underlying event effects are computed comparing the Perugia 2011C underlying event tuning with the AUET2B tune [168]. Observed discrepancies between the signal yields of about 6\% in vector boson fusion production, and about 30\% in gluon fusion are found.

**Parton Distribution Functions**: MCFM was also used to verify that the variation of the differential cross-sections associated with each analysis category due to different PDF sets (comparing MSTW [169], NNPDF [170] and CT10 [158]) are smaller than or equal to the inclusive variation. A PDF uncertainty of 7.5\% is assigned in all categories for gluon fusion production, and 2.8\% is assigned for VBF and VH production.

The small diboson background is evaluated completely from MC. It is normalized using its predicted cross-section, thus theory uncertainties on the cross-section evaluation and on the use of a specific PDF set are provided as well. They are 1\% and 4\%, respectively.
5.3.3 Background estimation uncertainties

The background estimation described is Section 5.2 makes use of data driven and semi data driven techniques generating additional sources of systematic uncertainties.

**Embedding technique:** two separate systematic uncertainties are considered. The first concerns the muon isolation criteria in the selection of the \(Z \rightarrow \mu\mu\) data sample. To address this uncertainty, the embedded events with the nominal selection are compared with events selected using no isolation for muons or with a tighter isolation. The second source of systematic uncertainty comes from the replacement of the muons with the simulated taus, in particular in the muon energy subtraction in the calorimeter. To evaluate this systematic uncertainty, the energy of each cell is conservatively scaled upward and downward by 20\% before the subtraction. It is also considered as a shape systematic uncertainty.

**W+jets MC reweighting:** the two separate shape corrections as a function of \(\Delta \eta(\tau, \ell)\) and of the ratio \(p_T^\ell/p_T^\tau\), as described in Section 5.2.2, and applied after the W+jet background estimation, are obtained by a fitting procedure. The systematic uncertainty on this method reflects the statistical uncertainty of the fit and is considered a shape systematic.

**OS-rSS technique:** several sources of systematic uncertainties are associated with this method. One systematic uncertainty is derived for the \(r_{QCD}\) correction, as described in Section 5.2.2. Then, each of the \(k\)-factors, introduced for the non resonant backgrounds to normalize MC to data, has a statistical uncertainty depending on the control region requirements. It is assigned as systematic uncertainty and propagated to the analysis.

**Fake factor:** a conservative 50\% uncertainty is assigned on W+jet and QCD multi-jets background processes because of limited knowledge of the quark and gluon jet flavor composition in the signal region.

5.4 Statistical analysis and signal extraction

In the search for the Higgs boson, testing statistical hypothesis plays an important role. In particular, the sensitivity of an analysis is given in terms of the expected
significance, and the final results for either the exclusion or the discovery of a new process are quoted in terms of probability [145, 171].

Given a hypothesis $H$, the $p$-value is defined as the probability, under assumption of $H$, of finding data of equal or greater incompatibility with the predictions of $H$. The hypothesis is excluded if its $p$-value is observed below a specified threshold. The $p$-value can be converted into an equivalent significance:

$$Z = \Phi^{-1}(1 - p)$$

where $\Phi^{-1}$ is the quantile of the normal Gaussian, representing the number of standard deviations for a normal Gaussian function above which the area of the Gaussian function itself is equal to $p$.

Both the limit and the discovery procedures involve the rejection of a null hypothesis, $H_0$, in the comparison with an alternative hypothesis, $H_1$. For purposes of discovering a new signal process, $H_0$ is defined as describing only the known background processes, and it is tested against the alternative $H_1$, which includes both background and signal. The discovery is claimed when the background only hypothesis is rejected with a significance of at least $5\sigma$ ($p = 2.87 \cdot 10^{-7}$). For purposes of setting the exclusion limits for a process, the model with signal plus background plays the role of $H_0$, which is tested against the background only hypothesis, $H_1$. The exclusion is set when the signal hypothesis is rejected at the 95% confidence level (CL). It has become customary to express results of the SM Higgs searches according to a signal strength modifier $\mu$, defined in Equation 1.24, that is taken to change the SM Higgs boson cross-sections of all production mechanisms by exactly the same scale $\mu$. In the absence of a Higgs boson (background only hypothesis), $\mu = 0$, and for the Standard Model expectation, $\mu = 1$.

For the $H \rightarrow \tau\tau$ search the statistical analysis of the data employs the profile likelihood method [172] with the MMC mass as the discriminating observable. The binned likelihood function is constructed as the product of Poisson probability terms as an estimator for $\mu$. In addition to parameters of interest such as the rate (cross-section) of the signal process, the signal and background models will contain nuisance parameters whose values are not taken as known a priori but must be fitted from the data. The flexibility of the fit for each of these additional terms can be used to model associated systematic uncertainties, or to provide additional constraints on the background estimate. In particular in this analysis, the $Z \rightarrow \tau\tau$ background rate is allowed to float freely in the global fit and the impact of systematic uncertainties on the signal and background expectations is
described by nuisance parameters, $\vec{\theta}$, which are parametrized by a Gaussian or log-normal constraint.

$$\mathcal{L}(\mu, \vec{\beta}_{\text{samp}}, \vec{\theta}_s, \vec{\theta}_b, \vec{\theta}_{\text{global}}) = \text{Pois}(n|\mu_T) \text{Pois}(n_{\text{samp}}|\beta_{\text{samp}}) \mathcal{L}(\vec{\theta}_s, \vec{\theta}_b, \vec{\theta}_{\text{global}})$$

(5.28)

where:

- $n$ is the number of events in the signal region
- $\vec{\beta}_{\text{samp}}$ are the statistical uncertainties of the MC or data driven control sample events, using the initial event numbers ($n_{\text{samp}}$), before scaling to the cross-section
- $\vec{\theta}_{s,b}$ are the specific nuisance parameters related to the signal and the background, such as the efficiency and the cross-section uncertainties
- $\vec{\theta}_{\text{global}}$ represent the common nuisance parameters which are correlated between channels, such as the luminosity uncertainty
- $\mu_T$ is the total number of expected events given by

$$\mu_T = \sum_{l=1}^{4} \mu L \sigma_l(m_H) f_s(\vec{\theta}_s) f_g(\vec{\theta}_{\text{global}}) + \sum_j L \beta_j f_b(\vec{\theta}_b) f_g(\vec{\theta}_{\text{global}})$$

(5.29)

where:

- $L$ is the nominal integrated luminosity
- $\mu$ is the one parameter of interest, the scaling factor for the expected signal rate (signal strength)
- $\sigma_l(m_H)$ is the effective cross-section (in pb) for signal events in channel $l$ ($gg \rightarrow H$, VBFH, WH, ZH)
- $\beta_j$ is the nominal effective cross-section (in pb) for background $j$ (including $\beta_{\text{samp}}$)
- $f_{s,b,\text{global}}$ represent the dependence of the expected number of events on the various nuisance parameters.
The likelihood is used to construct a statistical test based on the profile likelihood ratio and asymptotic formulae [171] are used when appropriate. The statistical test is given by:

$$
\tilde{q}_\mu = \begin{cases} 
-2\ln \frac{L(\mu, \hat{\theta}(\mu))}{L(0, \hat{\theta}(0))} & \hat{\mu} < 0 \\
-2\ln \frac{L(\mu, \hat{\theta}(\mu))}{L(\hat{\mu}, \hat{\theta})} & 0 \leq \hat{\mu} \leq \mu \\
0 & \hat{\mu} \geq \mu 
\end{cases}
$$

(5.30)

where:

- $\hat{\theta}$ represent the nuisance parameters evaluated at $\mu$

- $\hat{\theta}(\mu)$ are the Maximum Likelihood Estimators (MLE) of $\mu$, $\hat{\theta}$

Toy MC experiments are generated to construct the probability density function $f(\tilde{q}_\mu|\mu, \hat{\theta}(\mu))$ under an assumed signal strength $\mu$. From this, the $p$-value for $\mu$ is calculated using:

$$
p_\mu = \int_{\tilde{q}_\mu^{\text{obs}}}^{\infty} f(\tilde{q}_\mu|\mu, \hat{\theta}(\mu)) d\tilde{q}_\mu
$$

(5.31)

The procedure to compute exclusion limits is based on the modified frequentist method, often referred to as $CL_s$ [173]. In this case the exclusion is not quoted simply as $p$-value under the $s + b$ (signal plus background) hypothesis:

$$
p_\mu = CL_{s+b} = P(\tilde{q}_\mu \geq \tilde{q}_\mu^{\text{obs}} | \mu s + b)
$$

(5.32)

but it is quoted in terms of $CL_s$:

$$
CL_s = \frac{p_\mu}{1 - p_b}
$$

(5.33)

where

$$
p_b = CL_b = P(\tilde{q}_\mu \leq \tilde{q}_\mu^{\text{obs}} | \mu = 0) = \int_{-\infty}^{\tilde{q}_\mu^{\text{obs}}} f(\tilde{q}_\mu|\mu = 0, \hat{\theta}(0)) d\tilde{q}_\mu
$$

(5.34)

The $CL_s$ method is introduced to reduce the exclusion of regions where the sensitivity is very small. In particular the $CL_{s+b}$ method in Equation 5.32 excludes regions where $p_\mu < 0.05$ also when the expected number of signal events
is much less than that of background. In the more conservative modified approach using $CL_s$, the $p$-value is effectively penalized by dividing by $1 - p_b$. If the two distributions $f(\bar{q}_\mu|\mu = 0, \hat{\theta}(0))$ and $f(\bar{q}_\mu|\mu, \hat{\theta}(\mu))$ are widely separated, then $1 - p_b$ is only slightly less than unity, the penalty is small, and thus exclusion based on $CL_s$ is similar to that obtained by using $CL_{s+b}$. However, if there is little sensitivity to the signal model, then the two distributions are close together, $1 - p_b$ becomes small, and thus the $p$-value is penalized more. This prevents from excluding signal models in cases of low sensitivity.

### 5.4.1 Settings of the fit model

In this section the main settings for the optimized fit model are summarized.

**Choice of binning for the MMC mass discriminant**: since the limit extraction uses a binned likelihood, the binning giving the highest sensitivity is chosen separately for each category as summarized in Table 5.7.

**$Z \to \tau\tau$ normalization**: this normalization is kept as an additional free parameter in the fit because of the mismodeling observed in Figure 5.3(e). In this way the the normalization can be extracted directly from data during the profile likelihood procedure.

**Treatment of the systemics uncertainties**: this is an important point for the fit model and the minimization procedure. A full description is given in the next section.

With these optimizations the limit results are obtained using a histogram-based fitting machinery (HistFactory in the RooStat package [174]). The shape of the nominal distributions of the MMC mass in each category and the corresponding systematic variations optimized as previously described are given as input.
5.4.2 Treatment of systematic uncertainties

The systematic uncertainties are an important aspect of the analysis. It must be noticed that for some samples, after all the selections are applied, small upward and downward systematic variations can be dominated by the statistical error without providing useful information. In order to avoid the possible introduction of statistical noise in the global fit and in the limit extraction, only systematic uncertainties on the normalization with an effect larger than 0.5% are kept. Moreover, for each shape systematic considered, the following smoothing and pruning criteria are applied to test the level of significance and thus decide if the systematic can enter in the global fit:

**Pruning 1:** the Kolmogorov-Smirnov test between the upward and the downward fluctuated shapes with respect to the nominal, is performed for each potential shape systematic NP and for each sample. In this calculation the statistical uncertainty that enters is only the largest of the nominal or varied one. The shape systematic is retained if the result of the Kolmogorov-Smirnov test is less than 95%, for either of the upwards or downwards fluctuated shape. If neither the upward nor the downward variation’s probability is lower than that threshold, the shape variation is considered to not be significant for the given background sample, and the shape NP is not used in the fit (the corresponding normalization uncertainty is still kept however).

**Smoothing:** the ratio of variation to nominal (separately for upward and downward variations) is smoothed, using the TH1::Smooth(1) method [175] of ROOT. The smoothed varied shape is then obtained by multiplying the nominal with the smoothed ratio. The reason for smoothing the ratio, rather than the varied shape directly, is that the ratio is expected to be a relatively smooth and non-rapidly changing function in the absence of noise. Possible overly excessive smoothing of the ratio with loss of information, which can be introduced by smoothing the shapes first,

**Pruning 2:** for each systematic and for each background sample, the maximum bin-by-bin variation significance of the MMC discriminating variable, $S_i$, has to be $S_i \geq 0.1$, in a given bin $i$. The variation significance $S_i$ is defined as $S_i = |u_i - d_i| / \sigma_{i}^{\text{tot}}$, with $u_i$, $d_i$ being the upward and downward variation in bin $i$ for a given background sample, respectively, and
with \( \sigma^\text{tot}_i \) being the statistical uncertainty for the total background estimation (i.e. for all samples) in this bin \( i \). If this condition is not satisfied, the shape variation is considered non significant and not considered further.

The effect of \( \pm 1\sigma \) variation is shown in Figures 5.22, 5.23, 5.24 and 5.25 for the main shape systematics on the MMC mass distribution (binned as reported in Table 5.7) in the Boosted and VBF categories for the background and signal samples with \( m_H = 125 \) GeV. Only the distributions for the dominant signal contribution (vector boson fusion in the VBF category and gluon fusion in the Boosted category) are included in the figures, but all significant systematic uncertainties for each signal sample are considered in the fit. Systematic uncertainties on the TES are important for all the samples and, as expected, for the backgrounds the “true” component is more important for the central mass region where the \( Z \to \tau\tau \) (with genuine \( \tau \)-leptons) is the dominant background, while the “fake” component contributes most in the low mass and high mass bins where the contribution of QCD multi-jets and of the \( W+\)jets backgrounds (where a jet is misidentified as a \( \tau \)-hadron) is dominant. In general, uncertainties on the JES give significant shape variations, while other shape uncertainties like the ones on the data driven background estimation techniques can be less significant and are occasionally pruned away.

### 5.4.3 Tests of the fit model

Since the large number of degrees of freedom introduced in the fit and the complexity of the fit procedure itself, it is useful to test the stability and the sanity of the fit, before proceeding with the limit extraction. This is done by examining possible over-constrained or ill-behaved nuisance parameters. A full list of all the nuisance parameters entering in the fit together with a brief explanation is given in Appendix B.

Figure 5.26(a) shows the correlation matrix between the nuisance parameters. When building the likelihood the distinct nuisance parameters are treated as uncorrelated. Possible correlation introduced by the fit could lead to undesired behavior, but this is not observed in the figure, indicating an overall good behavior of the fitting approach.

Another test consists of checking if some of the nuisance parameters are significantly different after the fit, compared to their nominal value before the fit. This can be symptomatic of an important mismodeling which is artificially absorbed by the fit, and must be carefully scrutinized. Figure 5.26(b) shows the difference
Figure 5.22: Effect of ±1σ systematic shape variation on the MMC mass distribution for the total background in the VBF category: the TES components are shown in (a) and (b), the JER is shown in (c), the JES components are shown in (d), (e) and (f). The bottom part of each figure shows the relative variation in percent. Here “data” refers to Asimov data [171, 176] and coincides with the nominal distribution.
5.4. STATISTICAL ANALYSIS AND SIGNAL EXTRACTION

Figure 5.23: Effect of ±1σ systematic shape variation on the MMC mass distribution for the vector boson fusion signal in the VBF category: the TES true component is shown in (a), the JES components are shown in (b), (c), (d), and (e). The bottom part of each figure shows the relative variation in percent.
Figure 5.24: Effect of ±1σ systematic shape variation on the MMC mass distribution for the total background in the Boosted category: the TES true component is shown in (a), the JER is shown in (b), the JES components are shown in (c), (d) and (e), the muon subtraction systematic on the embedded procedure is shown in (f). The bottom part of each figure shows the relative variation in percent. Here “data” refers to Asimov data [171, 176] and coincides with the nominal distribution.
5.4. STATISTICAL ANALYSIS AND SIGNAL EXTRACTION

Figure 5.25: Effect of ±1σ systematic shape variation on the MMC mass distribution for the gluon fusion signal in the Boosted category: the TES true component is shown in (a), the JER is shown in (b), the JES components are shown in (c), (d), (e), and (f). The bottom part of each figure shows the relative variation in percent.
Figure 5.26: Test of the nuisance parameters in the global fit: the correlation between the nuisance parameters is shown in (a) and the pull and the constraints after the fit are shown for each nuisance parameter in (b). The zoom for the TES uncertainty is shown in (c), for the uncertainty of the background from fakes in the VBF category in (d), and for the uncertainty on the muon subtraction in the embedded procedure in (e).
### 5.4. STATISTICAL ANALYSIS AND SIGNAL EXTRACTION

<table>
<thead>
<tr>
<th>Component</th>
<th>Boosted region yield</th>
<th>VBF region yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \tau\tau$</td>
<td>3412 ± 36</td>
<td>56 ± 4</td>
</tr>
<tr>
<td>SS/fakes</td>
<td>270 ± 17</td>
<td>11 ± 1</td>
</tr>
<tr>
<td>$W$+jets</td>
<td>148 ± 18</td>
<td>12 ± 2</td>
</tr>
<tr>
<td>Rest</td>
<td>191 ± 11</td>
<td></td>
</tr>
<tr>
<td>Total background</td>
<td>4022 ± 364</td>
<td>79 ± 16</td>
</tr>
<tr>
<td>VBFH(125)</td>
<td>10.78 ± 0.09</td>
<td>6.55 ± 0.07</td>
</tr>
<tr>
<td>$gg \rightarrow H(125)$</td>
<td>34.2 ± 0.5</td>
<td>1.5 ± 0.1</td>
</tr>
<tr>
<td>WH(125)</td>
<td>3.85 ± 0.07</td>
<td>0.05 ± 0.004</td>
</tr>
<tr>
<td>ZH(125)</td>
<td>1.91 ± 0.04</td>
<td>0.04 ± 0.002</td>
</tr>
<tr>
<td>Total signal</td>
<td>50.7 ± 0.5</td>
<td>8.1 ± 0.2</td>
</tr>
</tbody>
</table>

Table 5.8: Expected yields in the signal regions for $H \rightarrow \tau_{lep}\tau_{had}$. The quoted error is statistical only. The “Rest” contribution includes all small backgrounds summed together.

between the Maximum Likelihood estimator for the nuisance parameters and their nominal values normalized to the uncertainty of the nuisance parameters themselves, $(\theta_{\text{fit}} - \theta_0)/\Delta \theta$. No suspicious behavior is observed, as no nuisance parameter is pulled in a significant way.

Also the errors on nuisance parameter are carefully examined. Before the fit they are set to the systematic error itself. After the likelihood fit, the error on the nuisance parameter is obtained from $\partial \log L/\partial \theta$. If the error after the minimization is much smaller than the systematic uncertainty assigned to the initial parameter, it may indicate undesired behavior of the fit. The uncertainties on the TES, on the fake factor method and on the muon subtraction in the embedding procedure, displayed in Figures 5.26(c), 5.26(d) and 5.26(e), are slightly constraint but in no pathological way.

### 5.4.4 Results

In this section the expected results for the $H \rightarrow \tau_{lep}\tau_{had}$ search are quoted and discussed. The expected yields in the signal region are quoted in Table 5.8.

Figure 5.27 shows the exclusion limit on the SM Higgs cross-section times $H \rightarrow \tau_{lep}\tau_{had}$ BR normalised to the theory cross-section for the Boosted and VBF categories separately, in order to estimate their relative contribution to
The sensitivity of the measurement, and their combination. The expected 95% confidence level limit is shown as a dashed line, then, the green and yellow bands correspond to the 1σ and 2σ error bands. No observed limit is quoted, since the cut-based analysis presented in this thesis is still blinded. The combined expected limit vary between 1.25 and 3.47 times the SM Higgs cross-section in the Higgs mass range between 100 and 150 GeV, and is 1.30 at $m_H = 125$ GeV. As expected this limit is mostly driven by the VBF category that by itself gives a limit of 1.82 times the SM Higgs cross-section at $m_H = 125$ GeV. All the expected values are quoted in Table 5.9.

The expected local $p_0$ is also computed and shown in Figure 5.28, separately for the Boosted and the VBF categories and their combination. The corresponding expected significance at $m_H = 125$ GeV is 1.76, see Table 5.10 for all other considered Higgs masses.

This analysis has to be combined with the other $\tau$ decay channels $\tau_{\text{lep}}\tau_{\text{lep}}$ and $\tau_{\text{had}}\tau_{\text{had}}$, but even after this combination the expected sensitivity to the Higgs boson does not reach the needed $3\sigma$ level to claim an observation. For this reason, an analysis based on multivariate techniques (MVA) is also developed for this search, and it led to the evidence for the $H \to \tau\tau$ in ATLAS. For completeness, a brief description is given in Section 5.5, while a full description can be found in Ref. [143].

<table>
<thead>
<tr>
<th>Exp. Lim.</th>
<th>$m_H$ [GeV]</th>
<th>100</th>
<th>105</th>
<th>110</th>
<th>115</th>
<th>120</th>
<th>125</th>
<th>130</th>
<th>135</th>
<th>140</th>
<th>145</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF</td>
<td></td>
<td>3.34</td>
<td>2.49</td>
<td>2.11</td>
<td>1.80</td>
<td>1.70</td>
<td>1.82</td>
<td>1.99</td>
<td>1.94</td>
<td>2.63</td>
<td>3.12</td>
<td>4.77</td>
</tr>
<tr>
<td>Boosted</td>
<td></td>
<td>6.27</td>
<td>4.13</td>
<td>3.12</td>
<td>2.61</td>
<td>2.21</td>
<td>2.15</td>
<td>2.21</td>
<td>2.35</td>
<td>3.17</td>
<td>4.05</td>
<td>5.66</td>
</tr>
<tr>
<td>Combined</td>
<td></td>
<td>1.98</td>
<td>1.73</td>
<td>1.48</td>
<td>1.33</td>
<td>1.25</td>
<td>1.30</td>
<td>1.40</td>
<td>1.42</td>
<td>1.92</td>
<td>2.35</td>
<td>3.47</td>
</tr>
</tbody>
</table>

Table 5.9: Expected exclusion limits separately for the VBF and Boosted categories and their combination for the cut-based $H \to \tau_{\text{lep}}\tau_{\text{had}}$ analysis.
Figure 5.27: Expected exclusion limits for Standard Model Higgs boson production cross-section normalised to the theoretical SM prediction as a function of $m_H$ for the VBF category in (a) and for the Boosted categories in (b) and their combination in (c), for the cut-based $H \to \tau_\text{lep}\tau_\text{had}$ analysis.
Figure 5.28: Expected local signal probability as a function of $m_H$ obtained from the combined fit in all categories for the cut-based $H \to \tau^+\tau^-$ analysis. The breakdown of the sensitivities from VBF and Boosted categories is also shown.

<table>
<thead>
<tr>
<th>$m_H$ [GeV]</th>
<th>100</th>
<th>105</th>
<th>110</th>
<th>115</th>
<th>120</th>
<th>125</th>
<th>130</th>
<th>135</th>
<th>140</th>
<th>145</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF</td>
<td>0.63</td>
<td>0.82</td>
<td>0.99</td>
<td>1.23</td>
<td>1.37</td>
<td>1.29</td>
<td>1.20</td>
<td>1.24</td>
<td>0.90</td>
<td>0.76</td>
<td>0.50</td>
</tr>
<tr>
<td>Boosted</td>
<td>0.35</td>
<td>0.57</td>
<td>0.74</td>
<td>0.96</td>
<td>1.06</td>
<td>1.11</td>
<td>1.09</td>
<td>1.03</td>
<td>0.80</td>
<td>0.62</td>
<td>0.45</td>
</tr>
<tr>
<td>Combined</td>
<td>1.18</td>
<td>1.32</td>
<td>1.52</td>
<td>1.74</td>
<td>1.86</td>
<td>1.76</td>
<td>1.63</td>
<td>1.61</td>
<td>1.19</td>
<td>0.97</td>
<td>0.67</td>
</tr>
</tbody>
</table>

Table 5.10: Expected significance separately for the VBF and Boosted categories and their combination for the cut-based $H \to \tau^+\tau^-_{\text{had}}$ analysis.
5.5. MULTIVARIATE ANALYSIS AND RESULTS

As for the cut-based approach, separate analyses for the three channels \( \tau_{\text{lep}} \tau_{\text{lep}}, \tau_{\text{lep}} \tau_{\text{had}} \) and \( \tau_{\text{had}} \tau_{\text{had}} \) are optimized due to the different background compositions and sensitivity to the Higgs boson signal. Whenever possible, common criteria and techniques are employed in order to harmonize the analyses for the final combination. Common procedures with the cut-based analysis are also used where applicable.

Each channel is split into two mutually exclusive categories, Boosted and VBF, that are defined with less stringent criteria than the ones used in the cut-based analysis (see Section 5.1.6), see Table 5.11 for an overview. Boosted Decision Trees (BDT) are used in each category to extract the Higgs boson signal from the large number of background events. These decision trees [177] recursively partition the parameter space into multiple regions where signal or background purities are enhanced. Boosting is a method which improves the performance and stability of decision trees and involves the combination of many trees into a single final discriminant [178, 179].

The input discriminating variables for the BDT are the same employed for the category selections in Section 5.1.6, including the MMC mass. A few additional variables are also defined:

- \( E_T^{\text{miss}} \phi \) centrality quantifies the relative angular position of the \( E_T^{\text{miss}} \) with respect to the \( \tau \) decay products in the transverse plane;

<table>
<thead>
<tr>
<th>Category</th>
<th>Selection</th>
<th>( \tau_{\text{lep}} \tau_{\text{lep}} )</th>
<th>( \tau_{\text{lep}} \tau_{\text{had}} )</th>
<th>( \tau_{\text{lep}} \tau_{\text{had}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF</td>
<td>( p_T^{j1} ) [GeV]</td>
<td>40</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>( p_T^{j2} ) [GeV]</td>
<td>30</td>
<td>50</td>
<td>30/35</td>
</tr>
<tr>
<td></td>
<td>( \Delta \eta_{j1,j2} )</td>
<td>2.2</td>
<td>3.0</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>( p_H^{T} ) [GeV]</td>
<td>–</td>
<td>–</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>b-jet veto for jet ( p_T^{\text{jet}} ) [GeV]</td>
<td>25</td>
<td>30</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>( m_{\text{vis}} ) [GeV]</td>
<td>–</td>
<td>40</td>
<td>–</td>
</tr>
<tr>
<td>Boosted</td>
<td>( p_T^{j1} ) [GeV]</td>
<td>40</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>( p_H^{T} ) [GeV]</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>b-jet veto for jet ( p_T^{\text{jet}} ) [GeV]</td>
<td>25</td>
<td>30</td>
<td>–</td>
</tr>
</tbody>
</table>

Table 5.11: Selection criteria applied in each analysis category for each channel.
sphericity describes the isotropy of energy flow;

− \( \tau_{\text{had}}/\ell \eta \) centrality quantifies the \( \eta \) position of either a \( \tau_{\text{had}} \) or an isolated lepton with respect to the two leading jets in the event.

A special technique, that trains a first BDT on one half of the data sample and then evaluates it on the second half of the events, is employed. At the same time a second separate BDT on the second half of the events is trained and the evaluated using the first half of the event sample. This strategy ensures that all the available statistics is used while avoiding employment of the same BDT for both training and testing.

As for the background estimate, the same techniques described in Section 5.2 are employed also for this analysis, with the exception that the \( W+\text{jets} \) and QCD multi-jets backgrounds are evaluated also in the Boosted category using the fake factor method.

Finally, the same signal extraction procedure described in Section 5.4, with a profile likelihood ratio using the BDT as a discriminating variable, and the same smoothing and pruning procedure for shape systematics, as described in Section 5.4.2, are employed to obtain the final results. The fitted value of the signal strength parameter from the likelihood fit is \( \mu = 1.43^{+0.31}_{-0.29} \) (stat.) \( +0.44_{-0.30} \) (syst.) for \( m_H = 125 \text{ GeV} \). The observed \( p_0 \) value at \( m_H = 125 \text{ GeV} \) is \( 2.0 \cdot 10^{-5} \), which corresponds to a deviation from the background-only hypothesis of \( 4.1\sigma \), compared to an expected \( p_0 \) value of \( 6.6 \cdot 10^{-4} \) (3.2\( \sigma \)). This is direct evidence for the existence of the \( H \to \tau\tau \) decay.

Figure 5.29 shows the expected and observed data, in bins of log\((S/B)\), for all signal region bins. Here, \( S/B \) is the signal-to-background ratio calculated assuming \( \mu = 1 \) for each BDT bin in the signal regions. The expectation is shown for signal yields for both \( \mu = 1 \) and the best-fit value \( \mu = 1.4 \) for \( m_H = 125 \text{ GeV} \) on top of the background prediction also taken from the best-fit value. The background expectation with the signal strength parameter is fixed to \( \mu = 0 \) is also shown for comparison. A clear excess of events is observed in the most sensitive bins optimized for a VBF Higgs signal. An event containing a Higgs candidate produced via vector boson fusion is shown in Figure 5.30.

Figure 5.31 shows the two-dimensional contours in the plane of \( \mu_{ggF} \times B/B_{SM} \) and \( \mu_{VBF+VH} \times B/B_{SM} \) for \( m_H = 125 \text{ GeV} \), where \( B \) and \( B_{SM} \) are the hypothesised and the SM branching ratios for \( H \to \tau\tau \). The best-fit values are \( \mu_{ggF} \times B/B_{SM} = 1.1^{+1.3}_{-1.0} \) and \( \mu_{VBF+VH} \times B/B_{SM} = 1.6^{+0.8}_{-0.7} \).
5.5. MULTIVARIATE ANALYSIS AND RESULTS

Figure 5.29: Event yields as a function of \( \log(S/B) \) for the ATLAS MVA \( H \to \tau\tau \). The predicted background is obtained from the global fit (with \( \mu = 1.4 \)), and signal yields are shown for \( m_H = 125 \) GeV, at \( \mu = 1 \) and \( \mu = 1.4 \) (the best-fit value). The background only distribution (dashed line), is obtained from the global fit, but fixing \( \mu = 0 \) [143].

Figure 5.30: Display of an event selected by the ATLAS MVA \( H \to \tau_\text{lep}\tau_\text{had} \) channel in the VBF category, where one \( \tau \) decays to an electron (the blue track matched to the green cluster). The hadronically decaying \( \tau \) lepton (1 prong decay) is indicated by a green track and the yellow cluster. The two jets are marked with turquoise cones. The kinematic parameters are \( p_T^\ell = 56 \text{ GeV}, p_T^\tau = 27 \text{ GeV}, E_T^\text{miss} = 113 \text{ GeV}, m_{j_1j_2} = 1.53 \text{ TeV}, m_{\tau\tau}^{\text{MMC}} = 129 \text{ GeV}, \) and the BDT score is 0.99. The \( S/B \) ratio at this BDT score is 1.0 for this event [143].
5.6 Conclusions and prospects

Separate cut-based and multivariate analyses are executed for the search for a Higgs boson of mass 125 GeV decaying into a $\tau\tau$ final state. Both are using the full ATLAS 2012 dataset, corresponding to an integrated luminosity of $L = 20.3$ fb$^{-1}$ of $pp$ collisions at a center of mass energy of 8 TeV.

In this chapter the cut-based analysis is described in full details for the semileptonic decay channel. A brief overview of the multivariate analysis is also given.

The multivariate analysis measured a signal with a significance of 4.1 standard deviations, compared to an expected significance of 3.2 standard deviations. This constitutes direct evidence of the decay of the Higgs boson to fermions: the observed signal strength $\mu = 1.4^{+0.5}_{-0.4}$ is compatible with the Standard Model expectation. The next important step consists in the measurement of the Higgs properties in this channel, foremost the mass measurement.

The cut-based analysis presently has a lower sensitivity but has the potential to be an important confirmation for the observation of the Higgs boson in
this channel. In order to correctly interpret the cut-based result a detailed study about the correlation between the MVA and cut-based analysis can be performed. Moreover, the current cut-based analysis could be further optimized by redesigning the categorization procedure with more subdivisions, in order to isolate each Higgs production mode and the associated peculiar properties more efficiently. This can considerably increase the sensitivity of the analysis. Improvements in the background estimation techniques are as well under investigation.
Conclusion

The observation of the decay of the Higgs to a $\tau$-pair in ATLAS, with a significance of $4.1\sigma$, gives the first direct evidence of the Higgs coupling to fermions. It therefore provides an important confirmation of the Standard Model and of the mass generating mechanism for fermionic particles.

The result achieved has been made possible by the excellent performance during the whole data taking period in 2011 and 2012 (Run 1), of the ATLAS detector and of the LHC which has provided $pp$ collisions at energies and luminosities never reached before. In these high-luminosity conditions the biggest experimental challenge is the control of the effects introduced by pile-up on the detector signals. In particular, $E_T^{\text{miss}}$ reconstruction includes soft energy contributions that need to be extracted from pile-up. The pile-up suppression techniques studied and implemented in ATLAS and described in this thesis allowed to restore the $E_T^{\text{miss}}$ resolution to values close to the ones observed in the absence of pile-up.

These $E_T^{\text{miss}}$ pile-up suppression techniques can be used in the $H \to \tau\tau$ search, with the benefit of a better $\tau\tau$ mass resolution and of a stronger rejection of the main $Z \to \tau\tau$ background, thus increasing the analysis sensitivity. The ATLAS final results are obtained with the employment of a $H \to \tau\tau$ analysis based on multivariate techniques, which provides the optimal sensitivity. However, the cut-based analysis discussed in this thesis, which has the advantage to be simpler and robust, can provide not only an important confirmation for the observation of the Higgs boson in this channel, but can also be useful in the future for a mass measurement. In particular, it is shown that an expected significance of $1.76\sigma$ can be reached by the $\tau_{\text{lep}}\tau_{\text{had}}$ channel at $m_H = 125$ GeV.

The obvious extension of this analysis is the measurement of the Higgs properties in the $\tau\tau$ channel, because any deviation from the Standard Model predictions, especially in the coupling measurement, can hint to the presence of new
5.6. CONCLUSIONS AND PROSPECTS

physics. In the measurement of the Higgs mass, improvements in the $E_T^{\text{miss}}$ scale can be important to achieve more precise results. Therefore, ongoing activity is devoted to the optimization of the pile-up suppression methods for the re-analysis of the whole 2011 and 2012 dataset (including collisions at $\sqrt{s} = 7$ TeV). These optimization efforts are even more important for the preparation for LHC Run 2, where higher energy and luminosities will make the reconstruction more challenging. In the expected more hostile environments, pile-up suppression methods will be essential to fully exploit the physics potential of ATLAS.
Appendix A

Data selection and MC simulation samples for $E_{T}^{\text{miss}}$ studies

The $E_{T}^{\text{miss}}$ performance are studies in a large variety of topologies in order to fully test the reconstruction capability for different physics objects. The selection criteria and the MC simulation samples used for the different topologies are listed in the following.

Minimum bias

Minimum bias events were selected both by a random trigger and by the minimum bias trigger scintillators (MBTS), which are mounted at each end of the detector in front of the LAr end-cap calorimeter cryostats 2.4.4. For each event, at least one good primary vertex is required with a $z$ displacement from the nominal $pp$ interaction point of less than 200 mm and with at least five associated tracks.

$Z \rightarrow \ell\ell$ selection

Candidate $Z \rightarrow \ell\ell$ events, where $\ell$ is an electron or a muon, are required to pass an electron, photon or muon trigger with a transverse momentum, $p_T$, threshold between 15 and 20 GeV, where the exact trigger selection varies depending on the data period analysed. For each event, at least one good primary vertex is
required with a z displacement from the nominal pp interaction point of less than 200 mm and with at least three associated tracks.

The selection of $Z \rightarrow \mu\mu$ events requires the presence of exactly two good muons. A good muon is defined to be a muon reconstructed in the muon spectrometer with a matched track in the inner detector with transverse momentum above 25 GeV and $|\eta| < 2.5$. Additional requirements on the number of hits used to reconstruct the tracks in the inner detector are applied. The z displacement of the muon tracks from the primary vertex is required to be less than 10 mm. Isolation criteria are applied around the muon track.

The selection of $Z \rightarrow ee$ events requires the presence of exactly two identified electrons with $|\eta| < 2.47$, which pass the “medium” identification criteria (section 3.2.1), optimized for 2012 data, and have transverse momenta above 25 GeV. Electron candidates in the electromagnetic calorimeter transition region, $1.37 < |\eta| < 1.52$, are not considered for this study.

In both the $Z \rightarrow ee$ and the $Z \rightarrow \mu\mu$ selections, the two leptons are required to have opposite charge and the reconstructed invariant mass of the dilepton system, $m_{\ell\ell}$, is required to be consistent with the Z mass, $66 < m_{\ell\ell} < 116$ GeV.

$W \rightarrow \ell\nu$ selection

Lepton candidates are selected with lepton identification criteria similar to those used for the Z selection. An isolation cut is applied around the electron energy deposits in the calorimeter to reduce contamination from jets. The event is required to contain exactly one reconstructed lepton (electron or muon). The $E_T^{\text{miss}}$, is required to be greater than 25 GeV. The reconstructed mass of the transverse momentum of the lepton, $p_T^\ell$, and $E_T^{\text{miss}}$:

$$m_T = 2p_T^\ell E_T^{\text{miss}} (1 - \cos \phi)$$  \hspace{1cm} (A.1)

where $\phi$ is the azimuthal angle between the lepton momentum and $E_T^{\text{miss}}$ directions, must satisfy $m_T > 50$ GeV.

Monte Carlo simulation samples

Monte Carlo (MC) samples of $Z \rightarrow \ell\ell$ and $W \rightarrow \ell\nu$ production are generated with the next-to-leading (NLO) order Powheg \cite{87} model, with the final state partons showered by the Pythia8 program \cite{152, 180}, using the CT10 next-to-leading order (NLO) parton distribution function (PDF) \cite{158} and the ATLAS
Appendix A: Data selection and MC simulation samples for $E_T^{\text{miss}}$ studies

AU2 tune [89]. Samples of $Z \rightarrow \ell\ell$ generated with Alpgen [153] are also used for some additional data-MC comparison.

Additional inelastic pp interactions are generated using the Pythia8 program with the ATLAS MC12 A2M tune [89] and the MSTW08 leading order (LO) PDF [169]. The proton-proton bunches are organized in trains, with 50 ns spacing between bunches, closely matching the bunch structure of the LHC. The MC simulation samples are weighted such that the distribution of the average number of interactions per bunch crossing matches that observed in the 2012 data sample, to ensure that the pile-up interactions are accurately described. When the pile-up conditions are not specified for a given figure, they should be assumed to be matched to those observed in the 2012 data sample used.
Appendix B

Summary of the systematics uncertainties used in the fit

In the following tables the systematics uncertainties used in the fit model are summarized. A brief description is provided for each uncertainty.

<table>
<thead>
<tr>
<th>Workspace name</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANA_LH12_Fake</td>
<td>uncertainty on Fake Factor method in VBF category</td>
</tr>
<tr>
<td>BTag_BEFF</td>
<td>uncertainty on b-tagging efficiency (b-jets)</td>
</tr>
<tr>
<td>BTag_CEFF</td>
<td>uncertainty on b-tagging efficiency (c-jets)</td>
</tr>
<tr>
<td>BTag_LEFF</td>
<td>uncertainty on b-tagging efficiency (light-jets)</td>
</tr>
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<td>EL_EFF</td>
<td>electron identification efficiency uncertainty</td>
</tr>
<tr>
<td>EL_EFF_Emb</td>
<td>uncertainty on difference in embedding normalization for SLT and LTT events</td>
</tr>
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<td>EL_RES</td>
<td>electron energy resolution uncertainty</td>
</tr>
<tr>
<td>EL_SCALE</td>
<td>electron energy scale uncertainty</td>
</tr>
<tr>
<td>JVF</td>
<td>systematics on jet-vertex-fraction cut</td>
</tr>
<tr>
<td>LUMI_2012</td>
<td>systematics on measured integrated luminosity in 2012</td>
</tr>
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<td>TAU_EFAKE</td>
<td>uncertainty on $e \rightarrow \tau$ misidentification probability</td>
</tr>
<tr>
<td>TAU_ID</td>
<td>uncertainty for tau identification efficiency</td>
</tr>
<tr>
<td>TAU_MFAKE</td>
<td>uncertainty on $\mu \rightarrow \tau$ misidentification probability</td>
</tr>
<tr>
<td>TES_FAKE</td>
<td>uncertainty on tau energy scale for fake candidates</td>
</tr>
<tr>
<td>TES_TRUE</td>
<td>uncertainty on tau energy scale for true candidates</td>
</tr>
<tr>
<td>TRIGGER_LH_2012</td>
<td>uncertainty on the lep-had trigger efficiencies</td>
</tr>
<tr>
<td>TRIGGER_LH_2012_Emb</td>
<td>uncertainty on the lep-had trigger efficiencies for embedding</td>
</tr>
<tr>
<td>TRIGGER_LH_2012_Fake</td>
<td>uncertainty on the lep-had trigger efficiencies on fake sample</td>
</tr>
</tbody>
</table>

Table B.1: Summary of systematic uncertainties used in the $\tau_{\text{lep}}\tau_{\text{had}}$ channel.
<table>
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<th>Workspace name</th>
<th>description</th>
</tr>
</thead>
<tbody>
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<td>JER</td>
<td>uncertainty on jet energy resolution</td>
</tr>
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<td>JES_Detector1</td>
<td>JES uncertainty component</td>
</tr>
<tr>
<td>JES_Eta_StatMethod</td>
<td>JES uncertainty component</td>
</tr>
<tr>
<td>JES_Modelling1</td>
<td>JES uncertainty component</td>
</tr>
<tr>
<td>JES_PileRho_TAU_GG</td>
<td>JES uncertainty component, applies to Top and $gg \rightarrow H$</td>
</tr>
<tr>
<td>JES_PileRho_TAU_QG</td>
<td>JES uncertainty component, applies to $W \rightarrow l\nu$ and Z+jets</td>
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<td>MET_SCALESOFT</td>
<td>MET scale uncertainty on the soft term</td>
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<tr>
<td>MU_EFF</td>
<td>muon identification efficiency uncertainty</td>
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<tr>
<td>MU_EFF_Emb</td>
<td>uncertainty on difference in embedding normalization for SLT and LTT events</td>
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<td>MU_SCALE</td>
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<td>PU_RESCALE</td>
<td>pileup reweighting uncertainty</td>
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<td>uncertainty on $H \rightarrow \tau\tau$ BR</td>
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<td>Gen_Qmass_ggH</td>
<td>b- and top quark mass effect on $p_T(H)$ spectrum in $gg \rightarrow H$</td>
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<td>QCDscale_V</td>
<td>uncertainty for W/Z+jets acceptance from QCD scale</td>
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<tr>
<td>QCDscale_VH</td>
<td>uncertainty for VH acceptance from QCD scale</td>
</tr>
<tr>
<td>QCDscale_ggH</td>
<td>uncertainty for $gg \rightarrow H$ ($\geq 0$ jet) acceptance from QCD scale</td>
</tr>
<tr>
<td>QCDscale_ggH1m</td>
<td>uncertainty for $gg \rightarrow H$ ($\geq 1$ jet) acceptance from QCD scale</td>
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<td>QCDscale_ggH2m</td>
<td>uncertainty for $gg \rightarrow H$ ($\geq 2$ jet) acceptance from QCD scale</td>
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<tr>
<td>QCDscale_ggH3m</td>
<td>uncertainty for $gg \rightarrow H$ ($\geq 3$ jet) acceptance from QCD scale</td>
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<tr>
<td>QCDscale_qqH</td>
<td>uncertainty for VBF acceptance from QCD scale</td>
</tr>
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<td>pdf_Higgs_gg</td>
<td>PDF uncertainty on ggF production</td>
</tr>
<tr>
<td>pdf_Higgs_qq</td>
<td>PDF uncertainty on VBF/VH production</td>
</tr>
<tr>
<td>pdf_qq</td>
<td>PDF uncertainty on MC-based background samples</td>
</tr>
<tr>
<td>UE_gg</td>
<td>Underlying event uncertainty on ggF</td>
</tr>
<tr>
<td>UE_qq</td>
<td>Underlying event uncertainty on VBF</td>
</tr>
</tbody>
</table>

Table B.2: Summary of systematic uncertainties used in the $\tau_{lep}\tau_{had}$ channel.
In particular, the JES systematic uncertainties relevant for this analysis are: JESFlavResp, JESFlavComp, JESModelling1, JESEtaModelling, JESEtaInter-calibrationModelling, JESEtaIntercalibrationStatMethod, JESSStatistical1, JESDetector1, JESBJet, JESPUNPV, JESPURho. The first four are also considered as shape systematics. Since it is known that background and signal components can be dominated more by quark (VBFH, VH, top, diboson) or by gluon ($gg \rightarrow H$, V+jets), two different nuisance parameters are considered for the flavor composition systematic. The uncertainty components are fully correlated between categories and analysis channels, except for the JESPURho that is still considered correlated across channels but only correlated by process within three groups differing by initial state: $qq$ initiated (VH, VBF, diboson), $qg$ initiated (V+jets) and $gg$ initiated ($gg \rightarrow H$, top).
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