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FACOLTÀ DI SCIENZE MATEMATICHE, FISICHE E NATURALI
Dipartimento di Matematica e Fisica "Ennio De Giorgi"

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Ph.D. Thesis:

Search for top squark pair production and decay
in t and $\tilde{\chi}_1^0$, with two leptons in the final state, at
the ATLAS Experiment with LHC Run 2 data

Supervisors:
PROF. EDOARDO GORINI
DR. MARGHERITA PRIMAVERA

Candidate:
DR. LUIGI LONGO



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Introduction

The elementary particles, together with the strong, electromagnetic and weak interactions among them, are coherently described by the Standard Model (SM) of particle physics. The SM predictive power was tested several times and the discovery of the Higgs boson in 2012 at the Large Hadron Collider (LHC), performed by the ATLAS and CMS experiments, was a particularly fundamental verification. However, there are several aspects in nature suggesting that SM cannot be a conclusive theory; it is, in fact, not able to explain, for example, the dark matter nature, the origin of the matter-anti-matter asymmetry in the universe, the neutrino masses and the huge difference between the Planck scale and the electroweak scale.

All these issues need an extension of the Standard Model to be solved. Among all the various SM extensions (extra-dimensions, hidden sectors, extended Higgs sectors, etc.), Supersymmetry (SUSY) is one of the most promising, and it can also provide, in a R -parity conserving scenario, a natural candidate for the dark matter: the lightest neutralino. Furthermore, SUSY can lead to a possible couplings unification of the strong, electromagnetic and weak interactions. All this requires, however, the discovery of new particles, called "superpartners" of the Standard Model ones.

In the work for my Ph.D. thesis, I focused my attention on the minimal supersymmetric extension of the Standard Model, known as Minimal Supersymmetric Standard Model (MSSM), analysing a R -parity conserving model where the superpartner of the top quark ($\tilde{t}_1$) decays into a top quark (t) and the lightest neutralino ($\tilde{\chi}_1^0$), with a branching ratio of 100%. The analysis was, in particular, developed to target the mass region $m_{\tilde{t}_1} \approx m_t + m_{\tilde{\chi}_1^0}$, usually called *compressed region*, characterised by a kinematic of the top quarks from $\tilde{t}_1 \tilde{t}_1^*$ very similar to the one coming from $t\bar{t}$ process, making the distinction between the SUSY process under study and the SM process very challenging. The analysis uses the 36.1 fb^{-1} of proton-proton collision data collected by the ATLAS experiment during 2015 and 2016 at $\sqrt{s} = 13 \text{ TeV}$, looking for final states with two opposite sign leptons (electrons or muons), at least three jets and large missing transverse energy. The obtained results are part of the paper *Search for direct top squark pair production with two leptons in $\sqrt{s} = 13 \text{ TeV}$ pp collisions with the ATLAS detector* published on The European Physical Journal C on December 2017 [1]. After an introduction about the Minimal Supersymmetric Standard Model (Ch. 1), the ATLAS experiment (Ch. 2), the objects reconstruction (Ch. 3) in ATLAS and, finally, all details of the analysis (Ch. 4) are described here.

In parallel with the main subject of this work, I spent some time in the characterisation at high temperature of two resistive-strip bulk micromegas detectors, whose technology will be employed in the upgrade (Phase 1) of the Small Wheel of the ATLAS experiment.

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The results of this work were presented at the 5th *International Conference on Micro-Pattern Gas Detectors* (MPGD2017), held at Temple University in Philadelphia in May 2017 [2]. Details of this study are reported in Sect. 2.3.1.

Chapter 1.

Minimal Supersymmetric Standard Model

Even if experimental evidences have demonstrated that the Standard Model of particle physics [3–8] is a predictive theory able to describe, in a successful way, the weak, electromagnetic and strong interactions, there are still open questions that the Model is not able to address, such as the so called *hierarchy problem* [9] or the nature of the dark matter [10]. Several theories have been therefore developed to answer to the SM open questions and, among these, Supersymmetry [11–16] is for several reasons one of the most appealing SM extensions, for example since it can provide a natural candidate for the dark matter. In this chapter, after a brief description of the Standard Model and its limitations, an overview of the Minimal Supersymmetric Standard Model [17] is presented, in order to introduce the SUSY process which is the subject of the study performed in this thesis.

1.1. Standard Model

The Standard Model of particles physics describes the fundamental constituents of the matter together with the strong, electromagnetic and weak interactions. In particular, the SM is characterised by three different types of particles: *leptons*, *quarks* and *gauge bosons*.

Quarks (u, d, c, s, t, b) and leptons (e, μ, τ , neutrinos $\nu_{l=e,\mu,\tau}$) are the basic components of the ordinary matter. They are spin 1/2 fermions and both of them could be regrouped in three families, or generations, having the same electric charge¹ Q , spin S , weak-isospin T and weak-hypercharge Y . Furthermore, they can be organized as doublets or singlets

¹The electric charge is related to the weak-isospin and the weak-hypercharge by the following formula $Q = T_3 + \frac{Y}{2}$ with Q expressed in terms of the elementary charge $|e|$.

of the weak-isospin group $SU(2)$ in the following way

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L \quad (1.1)$$

$e_R \qquad \mu_R \qquad \tau_R$

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L \quad \begin{pmatrix} c \\ s' \end{pmatrix}_L \quad \begin{pmatrix} t \\ b' \end{pmatrix}_L \quad (1.2)$$

$u_R, d'_R \qquad c_R, s'_R \qquad t_R, b'_R$

where neutrinos are assumed to be purely left-handed and massless and d', s' and b' are the weak interaction eigenstates, described by the *Cabibbo-Kobayashi-Maskawa* matrix as a linear combination of the flavor eigenstates d, s and b [18, 19].

Gauge bosons are instead the mediators of the three fundamental interactions and they are characterized by spin equal to 1. The 8 gluons $g_{i=1-8}$ are the carriers of the strong force, the photon γ is the responsible of the electromagnetic interaction and finally the $Z, W^\pm$ are the mediators of the weak force.

From a theoretical point of view, the SM is a non-abelian gauge theory invariant under the symmetry group

$$SU(3)_C \times SU(2) \times U(1)_Y \quad (1.3)$$

where $SU(3)_C$, $SU(2)$ and $U(1)_Y$ are the groups related to the colour charge, the weak isospin and the hypercharge, respectively. In particular, to preserve the gauge symmetry, the Standard Model predicts massless gauge bosons, and needs to introduce a spontaneous symmetry breaking² in the electro-weak sector, better known as *Higgs mechanism* [20, 21], in order to explain the experimental results showing massive Z and $W^\pm$ bosons (Fig. 1.1 and Fig. 1.2).

1.1.1. Glashow-Weinberg-Salam model

In the Glashow-Weinberg-Salam model a renormalized theory³ of electro-weak interactions, incorporating massive gauge bosons, can be achieved by spontaneously breaking

²Spontaneous breaking of a symmetry happens in a given physical system when the Lagrangian describing it obeys to a symmetry but the lowest-energy state of the system does not exhibit the same symmetry.

³Quantum field theories can be classified as super-renormalizable, renormalizable and non-renormalizable. Super-renormalizable theories show only a finite number of divergent Feynman diagrams. Instead renormalizable theories have a finite number of divergent amplitudes and divergences occur at all orders of perturbation theory. Finally non-renormalizable theories present amplitudes that are divergent at a sufficiently high order in perturbation theory.

It is possible to understand if a theory is super-renormalizable, renormalizable or non-renormalizable on the basis of the coupling constant: a theory is super-renormalizable or non-renormalizable if the coupling constant has respectively positive or negative mass dimension; it is instead renormalizable if the coupling constant is dimensionless.

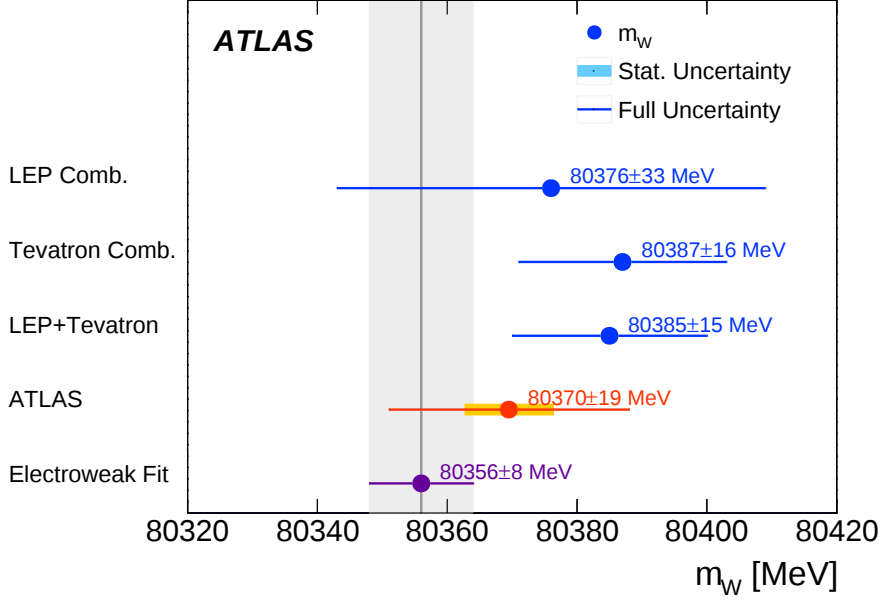


Figure 1.1.: The W mass, m_W , measured by the ATLAS [22] experiment is reported [23]. It is compared to the SM prediction from the global electroweak fit [24] updated using recent measurements of top quark and Higgs boson masses, $m_t = 172.84 \pm 0.70$ GeV and $m_H = 125.09 \pm 0.24$ [25,26], and to the combined values of m_W measured at LEP [27] and at the Tevatron collider [28].

the local gauge symmetry $SU(2) \times U(1)_Y$ [34]. Focusing the description only on the leptonic families, the corresponding Lagrangian can be expressed through the following formula

$$\begin{aligned} \mathcal{L}_{SU(2) \times U(1)_Y} = & i (\bar{\nu}_f \quad \bar{f})_L \gamma^\mu \left[\partial_\mu + ig \frac{\tau_i}{2} \cdot W_\mu^i + ig' \frac{Y}{2} B_\mu \right] \begin{pmatrix} \nu_f \\ f \end{pmatrix}_L \\ & + i \bar{f}_R \gamma^\mu (\partial_\mu + ig' \frac{Y}{2} B_\mu) f_R - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W_{\mu\nu}^i W^{\mu\nu i} \end{aligned} \quad (1.4)$$

where f is one of the leptons with $T_3 = -1/2$, g and g' are respectively the coupling constants of weak isospin and hypercharge groups, τ_i are the Pauli's matrixes while $W_\mu^{i=1,2,3}$ and B_μ are the gauge fields of $SU(2)$ and $U(1)$ with:

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu \quad (1.5)$$

$$W_{\mu\nu}^i = \partial_\mu W_\nu^i - \partial_\nu W_\mu^i - g \epsilon_{ijk} W_\mu^j W_\nu^k. \quad (1.6)$$

In order to give masses to the vector bosons $W^\pm$, Z and leave the photon massless, 4 real scalar fields ϕ_i are introduced; they are organized in a weak isospin doublet, called

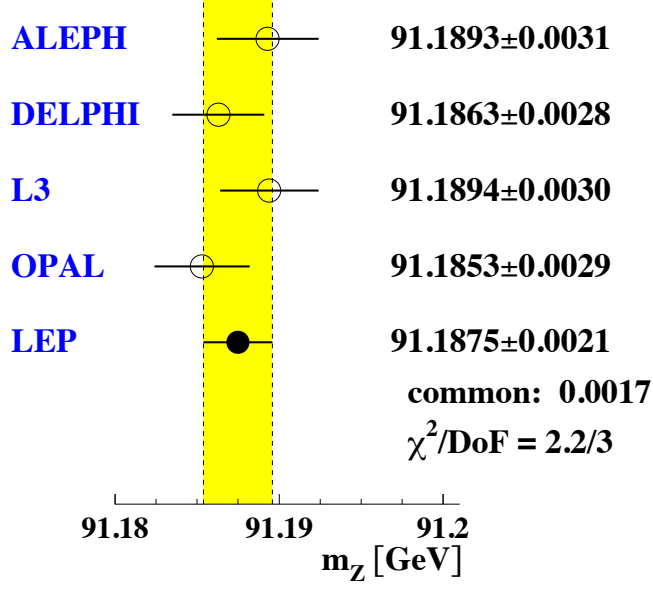


Figure 1.2.: Average of the Z mass measurements performed by ALEPH [29], DELPHI [30], L3 [31] and OPAL [32] collaboration at LEP is reported [33].

Higgs doublet,

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad \text{where} \quad \begin{aligned} \phi^+ &\equiv (\phi_1 + i\phi_2)/\sqrt{2} \\ \phi^0 &\equiv (\phi_3 + i\phi_4)/\sqrt{2} \end{aligned} \quad (1.7)$$

characterized by $Y = 1$ and whose $SU(2) \times U(1)_Y$ gauge invariant Lagrangian is:

$$\begin{aligned} \mathcal{L}_\Phi &= \left| \left(\partial_\mu + ig \frac{\tau_i}{2} \cdot W_\mu^i + ig' \frac{Y}{2} B_\mu \right) \Phi \right|^2 - V(\Phi) \\ &= \left| \left(\partial_\mu + ig \frac{\tau_i}{2} \cdot W_\mu^i + ig' \frac{Y}{2} B_\mu \right) \Phi \right|^2 - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2. \end{aligned} \quad (1.8)$$

Once it has been assumed $\mu^2 < 0$ and $\lambda > 0$, $V(\Phi)$ has its minimum when

$$\Phi^\dagger \Phi = \frac{1}{2}(\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2) = -\frac{\mu^2}{2\lambda}, \quad (1.9)$$

i.e. a set of points invariant under $SU(2)$ transformation. An appropriate choice of the corresponding vacuum expectation value is therefore

$$\Phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad \text{with} \quad v = \sqrt{-\frac{\mu^2}{\lambda}} \quad (1.10)$$

being characterized by $T = 1/2$, $T_3 = -1/2$, $Y = 1$ and consequently $Q = 0$; in this way it is in fact possible to break both $SU(2)$ and $U(1)_Y$, leaving unbroken the electric charge group $U(1)_{em}$ and massless its gauge boson, the photon.

In particular, after having parametrized the field Φ as

$$\Phi = U \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}, \quad (1.11)$$

with U generic $SU(2)$ transformation and h real scalar field reflecting the fluctuation nearby the vacuum expectation value, it can be verified, after an appropriate gauge transformation, that the Higgs doublet can be reduced to the only real field h , better known as *Higgs field*, with mass equal to

$$m_h = \sqrt{-2\mu^2} = \sqrt{2\lambda v^2} \quad (1.12)$$

and that the bosons $W^\pm$, Z and γ can be defined through the following relations

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

$$Z_\mu = -\sin\theta_W B_\mu + \cos\theta_W W_\mu^3 \quad \text{with } M_{Z_\mu} = \frac{1}{2}v\sqrt{g^2 + g'^2} \quad (1.14)$$

$$A_\mu = \cos\theta_W B_\mu + \sin\theta_W W_\mu^3 \quad \text{with } M_{A_\mu} = 0 \quad (1.15)$$

where A_μ is the massless photon and θ_W is the Weinberg angle given by

$$\tan\theta_W = \frac{g'}{g}. \quad (1.16)$$

With the same mechanism, it is also possible to generate the leptons e , μ and τ masses introducing the following Yukawa term

$$\mathcal{L}_{Yukawa} = -G_f \left[(\bar{\nu}_f \bar{f})_L \begin{pmatrix} \phi^+ \\ \phi_0 \end{pmatrix} f_R + h.c. \right], \quad (1.17)$$

with G_f coupling constant⁴. In this case the fermion mass is provided by the following expression

$$m_f = \frac{G_f}{\sqrt{2}}v. \quad (1.18)$$

In Fig. 1.3 the agreement between the measured masses of top-quark (m_t) and W-boson (m_W) with the values provided by the global electroweak fit of the Standard Model is shown.

⁴For what concern the quarks, due to the necessity to generate the mass also for the $T_3 = 1/2$ member of the doublet and to take into account the CKM matrix, a more generic Yukawa term is needed

$$\mathcal{L}_{Yukawa} = -G_d^{ij} (\bar{u}_i \bar{d}'_i)_L \Phi d_{jR} - G_u^{ij} (\bar{u}_i \bar{d}'_i)_L (-i\tau_2) \Phi^* u_{jR} + h.c.$$

width $i, j = 1, 2, 3$

where u_i is one of the $T_3 = 1/2$ quarks (u, c, t), d'_i is one of the $T_3 = -1/2$ quarks (d', s', b'), G_u^{ij} and G_d^{ij} are the coupling constant between the Higgs field and the up-type and down-type quarks.

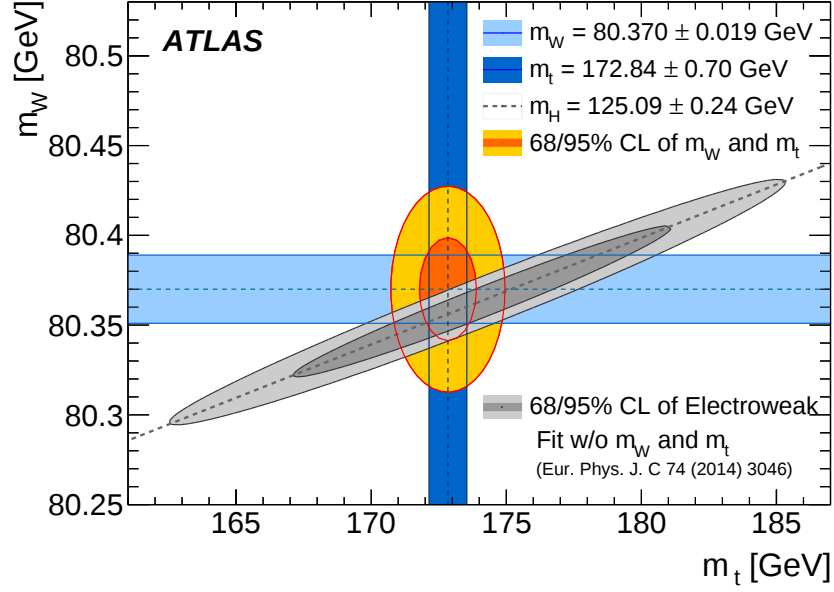


Figure 1.3.: The 68% and 95% confidence-level contours of the m_W and m_t indirect determination from the global electroweak fit are compared to the 68% and 95% confidence -level contours of the ATLAS measurements of the top-quark and the W-boson masses. The determination from the electroweak fit uses as input the LHC [35] measurement of the Higgs-boson mass, $m_H = 125.09 \pm 0.24$ GeV [23].

1.1.2. QCD and $SU(3)_C$

The strong interaction is described by the Quantum Chromodynamics (QCD) theory [7,8] which, as already mentioned, is based on a $SU(3)$ symmetry. Each quark is characterized by an additional quantum number, called *color*, that can be equal to *red* (R), *blue* (B) or *green* (G), while the gluons, which mediate the QCD force, come in eight different color combinations:

$$R\bar{G}, R\bar{B}, G\bar{R}, G\bar{B}, B\bar{R}, B\bar{G}, \sqrt{\frac{1}{2}}(R\bar{R} - G\bar{G}), \sqrt{\frac{1}{6}}(R\bar{R} + G\bar{G} - 2B\bar{B}) \quad (1.19)$$

The theory also predicts two particular phenomena, called *quark confinement* and *asymptotic freedom*. According to the first one, there is no possibility to observe colored particles in nature, and (anti-)quarks are confined in non-colored final states, mainly known as baryons (combinations of three quarks) or mesons (combinations of quark/anti-quark). Nevertheless, in particular conditions, characterized by high matter and energy density, it could be possible to reach a matter state, called *quark-gluon plasma* (QGP), where gluons and quarks behave as free particles.

1.1.3. SM limitations

Despite the large number of experimental proofs, the Standard Model cannot be considered an exhaustive theory. There are still several aspects of the nature which are not explained by it, like the neutrino masses, the dark matter and the matter-anti-matter asymmetry observed in the universe. As a consequence, SM is considered an effective field theory⁵ (EFT).

There is, therefore, the necessity to determine the energy scale Λ beyond which the first evidence of new physics could be observed. Λ can be assumed, in principle, equal to the Planck scale ($M_P = (8\pi G_{\text{Newton}})^{-1/2} = 2.4 \times 10^{18}$ GeV), since the gravitational interaction is not yet included in the model, or to the GUT⁶ scale ($\Lambda_{GUT} \approx 10^{16}$ GeV). In both cases the electroweak scale (≈ 100 GeV) is several order of magnitude smaller and this huge difference between the energy scales, is usually known as *hierarchy problem*. This discrepancy is not a real issue for the Standard Model itself [9] but it leads to an m_h^2 value receiving enormous quantum corrections from the virtual effects of every particle or other phenomenon that couples, directly or indirectly, to the Higgs field.

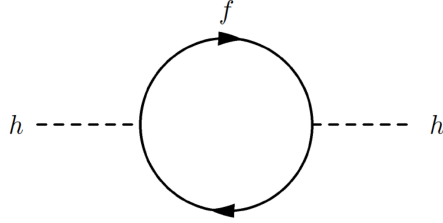


Figure 1.4.: Diagram of a fermionic contribution to the Higgs boson mass.

To better understand the problem, let's consider the one-loop contributions to the Higgs mass of a fermion f , with a repetition number N_f , and a Yukawa coupling $\lambda_f = \sqrt{2}m_f/v$ (Fig. 1.4). Assuming that the fermion is so heavy to neglect the Higgs momentum squared, the correction to m_h^2 is given by

$$\Delta m_h^2 = N_f \frac{\lambda_f^2}{8\pi^2} \left[-\Lambda^2 + 6m_f^2 \log \frac{\Lambda}{m_f} - 2m_f^2 \right] + (1/\Lambda^2) \quad (1.20)$$

which is of the order of $(10^{18})^2$ or of $(10^{16})^2$ GeV² when Λ_{GUT} or M_P are respectively considered for Λ , against a mass for the Higgs boson of 125 GeV. It is thus needed to add a term that adjusts m_h^2 with a precision of $\mathcal{O}(10^{-30})$, which seems highly unnatural. This issue is called the *naturalness* or *fine-tuning* problem.

Assuming at this point the existence of N_s scalar particles having all the same mass m_s and trilinear and quadrilinear couplings to the Higgs boson given, respectively, by

⁵In physics, an effective field theory is an “approximation” of a general theory. It describes physical phenomena occurring at a given energy, ignoring the substructure that would be present at higher energy. Fermi's explanation of β -decay is the best known example.

⁶In the Grand Unification Theory the strong, electromagnetic and weak interactions are described by a unique gauge group. There is only one coupling constant which the SM couplings are related to.

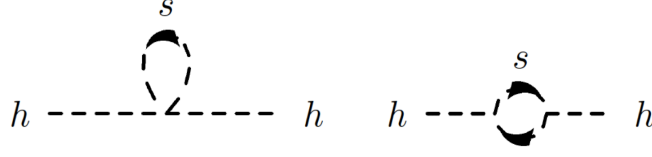


Figure 1.5.: Diagram for the contribution of scalar particles to the Higgs boson mass.

$v\lambda_s$ and λ_s , it can be demonstrated that their contribution to m_h^2 , via the two diagrams in Fig. 1.5, can be written as

$$\Delta m_h^2 = \frac{\lambda_s N_s}{16\pi^2} \left[-\Lambda^2 + 2m_s^2 \log \left(\frac{\Lambda}{m_s} \right) \right] - \frac{\lambda_s^2 N_s}{16\pi^2} v^2 \left[-1 + 2 \log \left(\frac{\Lambda}{m_s} \right) \right] + (1/\Lambda^2) \quad (1.21)$$

which leads, under these assumptions

- $\lambda_f^2 = 2m_f^2/v^2 = -\lambda_s$
- $N_s = 2N_f$,

to a total contribution to the Higgs boson mass squared equal to

$$\Delta m_h^2 = \frac{\lambda_f^2 N_f}{4\pi^2} \left[2m_f^2 \log \left(\frac{m_s}{m_f} \right) + m_f^2 \log \left(\frac{\Lambda}{m_f} \right) - m_s^2 \log \left(\frac{\Lambda}{m_s} \right) \right] + (1/\Lambda^2). \quad (1.22)$$

As it can be seen, the quadratic divergences disappeared in the final result and, even if the logarithmic divergence is still present, the contribution is very small even for $\Lambda \sim M_P$. Moreover, if the fermions and the scalar particles have the same mass, the correction to the Higgs boson mass squared completely vanishes. Therefore, a symmetry between fermion and scalar particles can protect the Higgs boson mass. One can also generalize the argument to include the contributions of other SM particles to the m_h^2 radiative correction.

However, if the symmetry is “badly” broken and the difference in mass between scalar and fermionic particles is huge, the naturalness problems is introduced again in the theory due to the logarithmic correction. Therefore, to keep the Higgs mass in the range of the electroweak symmetry breaking scale, the difference in mass between SM and new particles is needed to be rather small, thus leading to new particle masses not heavier than the TeV scale, $\mathcal{O}(1 \text{ TeV})$.

The theory that tries to find a solution to the SM issues, assuming a symmetry between fermions and bosons in a similar way of what has been described before, is *supersymmetry* [11–16].

1.2. The Minimal Supersymmetric Standard Model

The minimal supersymmetric extension of the Standard Model, known as *Minimal Supersymmetric Standard Model* [17], supposes that each chiral component of the fermions

1.2. The Minimal Supersymmetric Standard Model

($f_{L(R)}$), characterized by helicity state $\pm 1/2$, is associated with a complex scalar partner ($\tilde{f}_{L(R)}$), called generically *sfermion*⁷, while each gauge boson, having helicity equal to ± 1 , has a massless spin-1/2 Weyl fermion, known as *gaugino*, as superpartners. Moreover, differently from the SM, the MSSM requires two Higgs doublets, $H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$ and $H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$, which have two $SU(2)_L$ -doublet left-handed Weyl spinors, $\tilde{H}_u = \begin{pmatrix} \tilde{H}_u^+ \\ \tilde{H}_u^0 \end{pmatrix}$ and $\tilde{H}_d = \begin{pmatrix} \tilde{H}_d^0 \\ \tilde{H}_d^- \end{pmatrix}$ known as *Higgsinos*, as associated superparticles. In Tab. 1.1 and in Tab. 1.2 the full list of MSSM particles and their organization in *supermultiplets* is reported.

Names		Spin 0	Spin 1/2	$SU(3)_C, SU(2), U(1)_Y$
<i>squark, quark</i>	$\mathbf{Q}_i$	$\tilde{Q}_i = \begin{pmatrix} \tilde{u}_i \\ \tilde{d}_i \end{pmatrix}_L$	$Q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix}_L$	(3,2,$\frac{1}{3}$)
($\times 3$ families)	$\bar{\mathbf{u}}_i$ $\bar{\mathbf{d}}_i$	$\tilde{u}_{Ri}^*$ $\tilde{d}_{Ri}^*$	$u_{Ri}^\dagger$ $d_{Ri}^\dagger$	($\bar{3},1,-\frac{4}{3}$) ($\bar{3},1,\frac{2}{3}$)
<i>sleptons, leptons</i>	$\mathbf{L}_i$	$\tilde{L}_i = \begin{pmatrix} \tilde{\nu}_{e_i} \\ \tilde{e}_i \end{pmatrix}_L$	$L_i = \begin{pmatrix} \nu_{e_i} \\ e_i \end{pmatrix}_L$	(1,2,-1)
($\times 3$ families)	$\bar{\mathbf{e}}_i$	$\tilde{e}_{Ri}^*$	$e_{Ri}^\dagger$	(1,1,2)
<i>Higgs, Higgsinos</i>	$\mathbf{H}_u$ $\mathbf{H}_d$	H_u H_d	$\tilde{H}_u$ $\tilde{H}_d$	(1,2,+1) (1,2,-1)

Table 1.1.: *Chiral (or scalar) supermultiplets* in the Minimal Supersymmetric Standard Model. Each chiral supermultiplet is the combination of a spin-0 complex scalar field plus a spin-1/2 two component Weyl fermion. The standard convention is that all chiral supermultiplets are defined in terms of left-handed Weyl spinors, so that the conjugates of the right-handed quarks and leptons (and their superpartners) are shown in the table. For each supermultiplets, while the first column indicates its symbol, the last column shows, in bold, the number of $SU(3)_C$ and $SU(2)$ eigenstates and, in a regular format, the corresponding hypercharge value [17].

1.2.1. R-parity

In the Standard Model Lagrangian baryon number (B) and lepton number (L) are conserved by the requirements of gauge invariance and renormalizability. In the MSSM,

⁷The names for the spin-0 partners of quarks and leptons are usually constructed by prepending an *s* to the corresponding SM particle name, i.e. *squark* refers to the scalar partner of a generic quark, *stop* to the top superpartner, etc. It could be also possible to call the superpartner as *quark* – *name* squark, i.e. *top squark* instead of stop.

Names	Spin 1/2	Spin 1	$SU(3)_C, SU(2), U(1)_Y$
<i>gluino, gluon</i>	$\tilde{g}$	g	(8,1,0)
<i>winos, W bosons</i>	$\tilde{W}^\pm, \tilde{W}^3$	$W^\pm, W^0$	(1,3,0)
<i>bingo, B boson</i>	$\tilde{B}$	B	(1,1,0)

Table 1.2.: *Gauge (or vector) supermultiplets* in the Minimal Supersymmetric Standard Model. Each gauge supermultiplet contains a spin-1/2 gauginos and a spin-1 gauge boson. For each supermultiplets the last column shows, in bold, the number of $SU(3)_C$ and $SU(2)$ eigenstates and, in a regular format, the corresponding hypercharge value [17].

instead, it can be demonstrated that the most general gauge-invariant and renormalizable superpotential could also include B- and L- violating terms allowing for a proton decay, never observed experimentally.

In order to avoid this, a new multiplicative quantum number, known as R – *parity* and defined for each MSSM particle by the formula

$$P_R = (-1)^{3(B-L)+2S}, \quad (1.23)$$

is introduced. All SM particles, Higgs bosons included, have P_R equal to 1 while all SUSY particles have $P_R = -1$. If R –parity is exactly conserved, there cannot be any mixing between sparticles and particles and every interaction vertex must have an even number of SUSY particles. This brings to three extremely important phenomenological consequences:

- the lightest supersymmetric particle, LSP, must be stable. If the LSP is electrically neutral, it interacts only weakly with the ordinary matter and it could be considered a good candidate for the non-baryonic dark matter.
- Each sparticle except the LSP must decay into a state containing an odd number of LSPs.
- In collider experiments sparticles can only be pair-produced.

There are also SUSY models where R –parity is not conserved. Typically in these models only one of the R –parity violating terms is set to non-zero value, such that only the lepton or baryon number is violated⁸, while the rest remains zero according to the proton’s lifetime observation [36]. In this thesis only SUSY scenarios, where R –parity is conserved, are considered.

⁸Proton decay can be possible only if both quantum numbers are violated.

1.2.2. Soft supersymmetry breaking

If supersymmetry was exact, experimental observations should have shown SUSY particles degenerate in mass with the SM particles. Unfortunately no sparticle has been observed so far, then it is necessary to introduce terms, consistent with the $SU(3)_C \times SU(2) \times U(1)_Y$ gauge invariance and the R -parity conservation, that lead to the supersymmetry breaking but preserving the cancellation of the divergent terms in the radiative corrections (*soft breaking*) [9].

Only mass terms and coupling parameters having positive mass dimension can be included in the Lagrangian and, applying this recipe to the MSSM, it can be verified that the most general extension should include the following terms:

- mass terms for gluinos, winos and bino

$$\mathcal{L}_{\text{gaugino}} = \frac{1}{2} \left[M_1 \tilde{B} \tilde{B} + M_2 \sum_{i=1}^3 \tilde{W}_i \tilde{W}_i + M_3 \sum_{i=1}^8 \tilde{G}_i \tilde{G}_i + \text{h.c.} \right] \quad (1.24)$$

- mass terms for the scalar fermions

$$\mathcal{L}_{\text{sfermions}} = \sum_{i=1}^3 m_{\tilde{Q}_i}^2 \tilde{Q}_i^\dagger \tilde{Q}_i + m_{\tilde{L}_i}^2 \tilde{L}_i^\dagger \tilde{L}_i + m_{\tilde{u}_i}^2 |\tilde{u}_{R_i}|^2 + m_{\tilde{d}_i}^2 |\tilde{d}_{R_i}|^2 + m_{\tilde{e}_i}^2 |\tilde{e}_{R_i}|^2 \quad (1.25)$$

- mass and bilinear terms for the Higgs bosons⁹

$$\mathcal{L}_{\text{Higgs}} = m_{H_u}^2 H_u^\dagger H_u + m_{H_d}^2 H_d^\dagger H_d + b(H_u \cdot H_d + \text{h.c.}) \quad (1.26)$$

- trilinear couplings between sfermions and Higgs bosons

$$\mathcal{L}_{\text{tril.}} = \sum_{i,j=1}^3 \left[A_{ij}^u Y_{ij}^u \tilde{u}_{R_i}^* H_u \cdot \tilde{Q}_j + A_{ij}^d Y_{ij}^d \tilde{d}_{R_i}^* H_d \cdot \tilde{Q}_j + A_{ij}^l Y_{ij}^l \tilde{e}_{R_i}^* H_d \cdot \tilde{L}_j + \text{h.c.} \right] \quad (1.27)$$

The MSSM thus built is called *unconstrained* MSSM. In its most general formulation, allowing mixing among generation and complex phases, the soft susy breaking terms introduce 105 parameters in the model, in addition to the 19 parameters of the SM, thus making quite difficult any phenomenological analysis.

1.2.2.1. Phenomenological MSSM

Several parameters introduced in the unconstrained MSSM can be removed assuming minimal flavor and CP violation. A phenomenologic MSSM can be defined, for instance, with the following assumptions:

⁹The product between $SU(2)$ doublets reads $X \cdot Y \equiv \epsilon_{ab} X^a Y^b$ where a, b are $SU(2)$ indices and $\epsilon_{12} = 1 = -\epsilon_{21}$.

- all the soft SUSY-breaking parameters are real and therefore there is no new source of CP-violation in addition to the one coming from CKM matrix;
- the matrices for the sfermions masses and for the trilinear couplings are all diagonal, implying the absence of Flavor Changing Neutral Currents (FCNC) at tree-level;
- universality of the first and second sfermion generation at low energy.

These three assumptions reduce the initial 105 parameters to 22:

- the ratio of the vacuum expectation values (VEV) of the two Higgs doublet ($\tan \beta$);
- the Higgs mass parameters squared ($m_{H_u}^2, m_{H_d}^2$);
- the bino, wino and gluino mass parameters (M_1, M_2, M_3);
- the first/second generation sfermion mass parameters;
- the first/second generation trilinear couplings (A_e, A_d, A_e);
- the third generation sfermion mass parameters;
- the third generation trilinear couplings (A_t, A_b, A_τ).

This model, with a relatively moderate number of free parameters, is more predictive and much easier to investigate. One can refer to it as the *phenomenological* MSSM or pMSSM.

1.2.3. The MSSM mass spectrum

Due to the electroweak symmetry breaking the particle scheme described in the previous sections, does not match exactly the mass eigenstates; neutral higgsinos and gauginos, in fact, mix together to form 4 mass eigenstates, known as *neutralinos*, while the charged higgsinos and winos mixing brings to 2 eigenstates, called *charginos*, with charge ± 1 . Similarly, quarks and leptons superpartners, having the same quantum numbers, mix together [17].

1.2.3.1. Charginos/neutralinos sector

In the gauge-eigenstate bases $(\tilde{B}, \tilde{W}, \tilde{H}_d^0, \tilde{H}_u^0)$ and $(\tilde{W}^+, \tilde{H}_u^+, \tilde{W}^-, \tilde{H}_d^-)$, the neutralino and chargino masses in the Lagrangian are given by the following matrices

$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z \sin \theta_W \cos \beta & M_Z \sin \theta_W \sin \beta \\ 0 & M_2 & M_Z \cos \theta_W \cos \beta & -M_Z \cos \theta_W \sin \beta \\ -M_Z \sin \theta_W \cos \beta & M_Z \cos \theta_W \cos \beta & 0 & -\mu \\ M_Z \sin \theta_W \sin \beta & -M_Z \cos \theta_W \sin \beta & -\mu & 0 \end{pmatrix} \quad (1.28)$$

1.2. The Minimal Supersymmetric Standard Model

$$\mathcal{M}_{\tilde{\chi}^\pm} = \begin{pmatrix} 0 & 0 & M_2 & \sqrt{2}M_W \cos \beta \\ 0 & 0 & \sqrt{2} \sin \beta M_W & \mu \\ M_2 & \sqrt{2}M_W \sin \beta & 0 & 0 \\ \sqrt{2}M_W \cos \beta & \mu & 0 & 0 \end{pmatrix} \quad (1.29)$$

and their corresponding mass eigenstates¹⁰, $\tilde{\chi}_i^0$ ($i = 1, 2, 3, 4$) and $\tilde{\chi}_j^\pm$ ($j = 1, 2$), can be obtained after diagonalizing $\mathcal{M}_{\tilde{\chi}^0}$ and $\mathcal{M}_{\tilde{\chi}^\pm}$. However, it can be demonstrate that there is a limit for which the electroweak symmetry breaking effects can be seen as a small perturbation. In particular, if

$$M_Z \ll |\mu \pm M_1|, |\mu \pm M_2| \text{ and } M_1 < M_2 \ll |\mu| \quad (1.30)$$

is assumed, the neutralino and chargino mass eigenstates are:

- *bino-like* ($\tilde{\chi}_1^0 \approx \tilde{B}$),
- *wino-like* ($\tilde{\chi}_2^0 \approx \tilde{W}^0$; $\tilde{\chi}_1^\pm \approx \tilde{W}^\pm$),
- *higgsino-like* ($\tilde{\chi}_3^0, \tilde{\chi}_4^0 \approx (\tilde{H}_u^0 \pm \tilde{H}_d^0)/\sqrt{2}$; $\tilde{\chi}_2^{+(-)} \approx \tilde{H}_{u(d)}^{+(-)}$)

with mass eigenvalues of the order of M_1 , M_2 and $|\mu|$ respectively.

If $\tilde{\chi}_1^0$ is the lightest SUSY particle, due to the R-parity conservation it must be stable and therefore represents a natural Dark Matter candidate [17].

1.2.3.2. Sfermions sector

In the sfermionic sector it can be verified that the mixing, due to the electroweak symmetry breaking, is important only for the third generation: $(\tilde{t}_L, \tilde{t}_R)$, $(\tilde{b}_L, \tilde{b}_R)$ and $(\tilde{\tau}_L, \tilde{\tau}_R)$ pairs. This happens because their squared mass matrices have off-diagonal contributions proportional to the corresponding SM partner mass, leading to a relevant left-right mixing only for the third generation. In the stop sector, due to the large top mass value, the mixing is so strong that it could generate a large splitting between the masses of the two stop mass eigenstates, with the lightest one, $\tilde{t}_1$, much lighter than the other squarks and the top quark itself [9].

1.2.3.3. Higgs sector

The Higgs sector shows new features with respect to the Standard Model, due to the additional $SU(2)$ doublet introduced in the theory, which provides eight degrees of freedom instead of the SM four ones. When the electroweak symmetry is broken, five scalar particles, instead of one, are indeed introduced:

- two CP-even neutral scalars (H^0, h^0),

¹⁰The neutralino and chargino mass eigenstates are denoted by $\tilde{\chi}_i^0$ ($i = 1, 2, 3, 4$) and $\tilde{\chi}_i^\pm$ ($i = 1, 2$). By convention, these are labeled in ascending order, so that $m_{\tilde{\chi}_1^0} < m_{\tilde{\chi}_2^0} < m_{\tilde{\chi}_3^0} < m_{\tilde{\chi}_4^0}$ and $m_{\tilde{\chi}_1^\pm} < m_{\tilde{\chi}_2^\pm}$. The same convention is also followed for the sfermions mass eigenstates.

- one CP-odd neutral scalar (A^0),
- a charged scalar (H^+) and its charge conjugate (H^-).

It can be proven that the masses of A^0 , H^0 and $H^\pm$ can be arbitrarily large, while h^0 mass is limited from above:

$$m_{h^0} \lesssim 135 \text{ GeV}. \quad (1.31)$$

This assumes that all sparticles that can contribute to $m_{h^0}^2$ in loops have masses not exceeding 1 TeV, and the limit increases logarithmically with top squark masses [17].

In the so-called *decoupling limit* ($m_A \gg m_Z$), it can be also demonstrated that H^0 , A^0 and $H^\pm$ are mass degenerate and they do not play a significant role at low-energy experiments, while h^0 shows properties similar to the SM Higgs boson [37].

1.2.4. Hint of Grand Unification Theory

Unlike the Standard Model, where the three gauge couplings do not reach a similar value at the GUT scale, this happens in the MSSM, thus leading to a possible coupling unification (Fig. 1.6). This unification might be an accident, or it may be considered a strong hint in favour of a Grand Unification Theory. On the contrary, the failure of coupling constant unification, as it happens for SM, may cover the fact that new physics must exist between the electroweak scale and Λ_{GUT} [17].

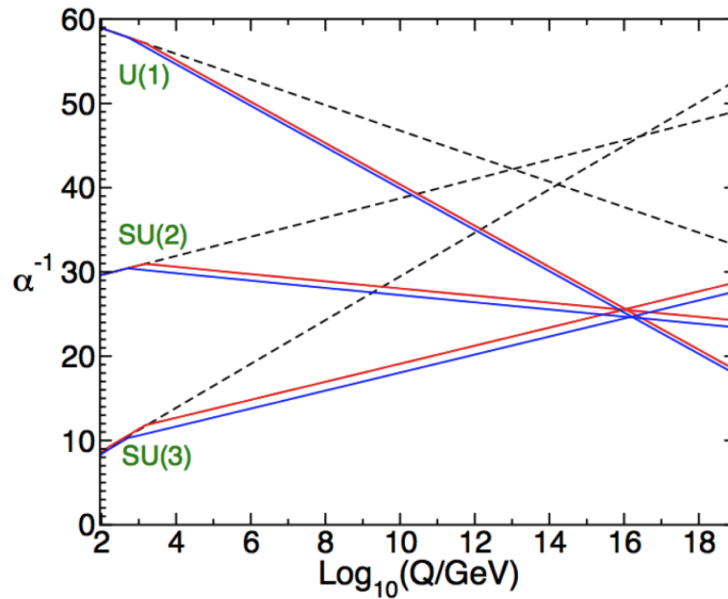


Figure 1.6.: Evolution of the inverse gauge couplings, i.e. $\alpha^{-1}(Q) \equiv \frac{4\pi}{g^2}$, in the Standard Model (dashed lines) and in the MSSM (solid lines) [17].

1.3. SUSY searches at LHC

Due to the large number of parameters characterising the MSSM, it is impossible to cover the whole phase space. Therefore the sensitivity of the SUSY searches at LHC is estimated by applying three complementary strategies:

- the *constrained SUSY model* strategy, where boundary conditions are applied at high energy in order to strongly reduce the number of MSSM parameters, thus allowing a systematic scan of the parameter space. An example of this is the *minimal SUpEr GRAvity* (mSUGRA) model, where the parameter reduction is done assuming that gravity is responsible of the soft susy breaking [38, 39];
- the *simplified model* strategy where only few SUSY particles are involved, while the masses of all other SUSY particles are supposed to assume multi-TeV values, not accessible at LHC. In this case the cascade decays of the remaining particles to the LSP, typically with zero or one intermediate step, are defined only by the particles masses hierarchy. These models are suitable for direct particles production. The advantage in using them is related also to the fact that the analyses can be used to constrain several models (SUSY or not) that predict similar final states;
- the *phenomenological MSSM* strategy where results are interpreted in the pMSSM model.

In this thesis, the simplified model strategy is applied, focusing the attention on a R -parity conserving scenario where the only light sparticles are the lightest top squark and the neutralino $\tilde{\chi}_1^0$ (bino-like) with $m_{\tilde{t}_1} \geq m_t + m_{\tilde{\chi}_1^0}$, so that the only possible decay is via $\tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0$.

1.3.1. Results of $\tilde{t}_1$ searches at LHC in Run1

If supersymmetry exists, the most copiously produced SUSY particles at LHC at $\sqrt{s} = 13$ TeV must be those interacting with the proton constituents via the strong force and having masses accessible to the LHC energy. In Fig. 1.7 can be noticed that, for a given mass, the first two squark generations together with gluinos are the sparticles that should be mainly produced at LHC. In fact, they can benefit from t -channel diagrams (not feasible for the scalar top production since its SM partner is not a proton constituent) and consequently have higher cross-section. However, as already discussed in Sect. 1.2.3, $\tilde{t}_1$ can be lighter than the other squarks and then its production may become dominant at LHC, thus justifying the large interest of dedicated searches for $\tilde{t}_1$ direct production¹¹. Moreover, from the naturalness point of view a light top squark is warmly hoped since it is responsible of one of the largest contributions to the Higgs mass corrections at one loop order.

¹¹Unless otherwise specified, in this thesis the term "top squark" or "stop" will always refer to the lightest top squark $\tilde{t}_1$.

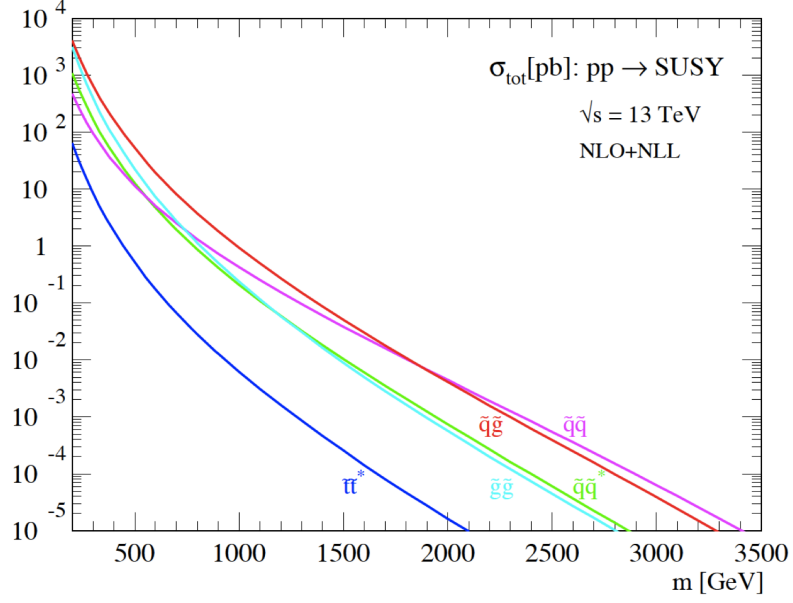


Figure 1.7.: Sparticles production cross-section, as function of their average masses, in proton-proton collision for a center-of-mass energy of 13 TeV [41].

Both ATLAS and CMS [40] experiments have devoted a huge effort in searching for the lightest top superpartner during Run1¹², examining several signal models characterized by different decay processes. Depending on the difference in mass between the top squark and the neutralino, and assuming that the lightest SUSY particles are $\tilde{t}_1$ and $\tilde{\chi}_1^0$, it is possible to have the following decay processes:

- $\tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0$ with $m_{\tilde{t}_1} \geq m_t + m_{\tilde{\chi}_1^0}$ (2-body decay);
- $\tilde{t}_1 \rightarrow b + W + \tilde{\chi}_1^0$, through an off-shell top, so that $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) < m_t$ but still greater than the W mass, m_W (3-body decay);
- $\tilde{t}_1 \rightarrow b + f + f' + \tilde{\chi}_1^0$, through an off-shell top and W , where f and f' are two fermions from the off shell W decay (4-body decay);
- $\tilde{t}_1 \rightarrow c + \tilde{\chi}_1^0$ (2-body decay) when $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) < m_W$.

Furthermore, if the lightest chargino is supposed to have mass below $m_{\tilde{t}_1}$ but greater than the neutralino one, it is also possible the two step decay $\tilde{t}_1 \rightarrow b + \tilde{\chi}_1^\pm$ (2-body decay) with $\tilde{\chi}_1^\pm$ subsequently decaying to $W + \tilde{\chi}_1^0$.

The CMS and ATLAS Run1 results, targeting the simplified models mentioned above, are shown in Fig. 1.8 and in Fig. 1.9. For all of them, even in cases where more than one branching ratio (BR) could be possible, the simplified assumption of a 100% BR has been made.

¹²The LHC data taking period going from 2010 to 2012 is referred to as Run1. More details about the LHC roadmap are reported in Ch. 2.

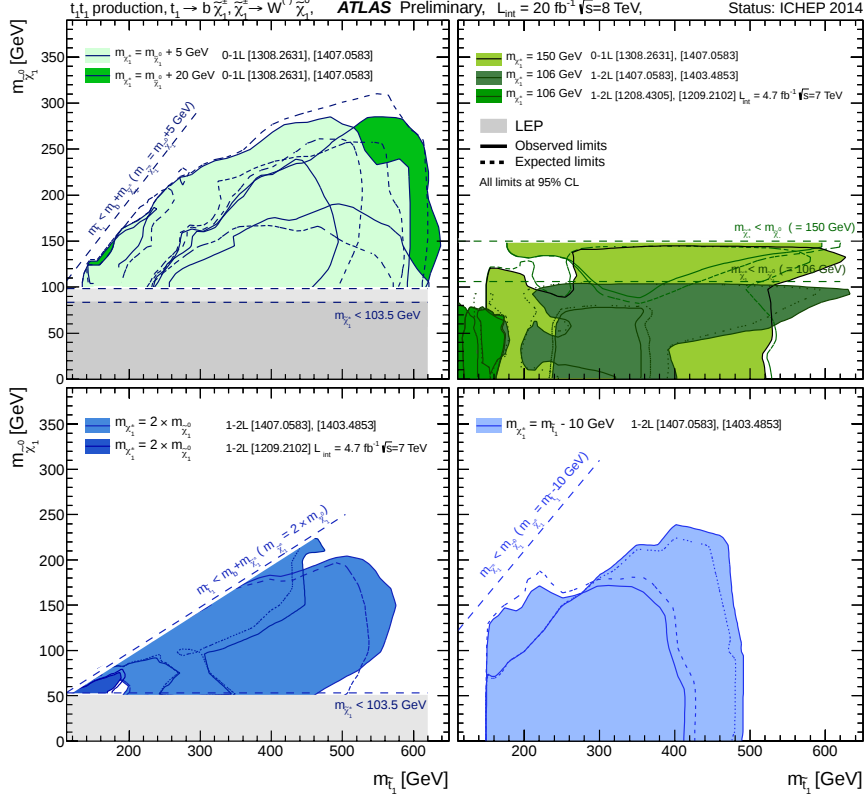
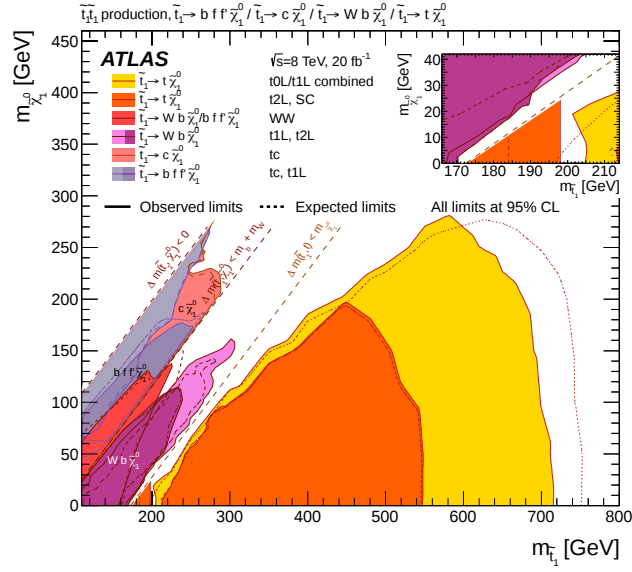
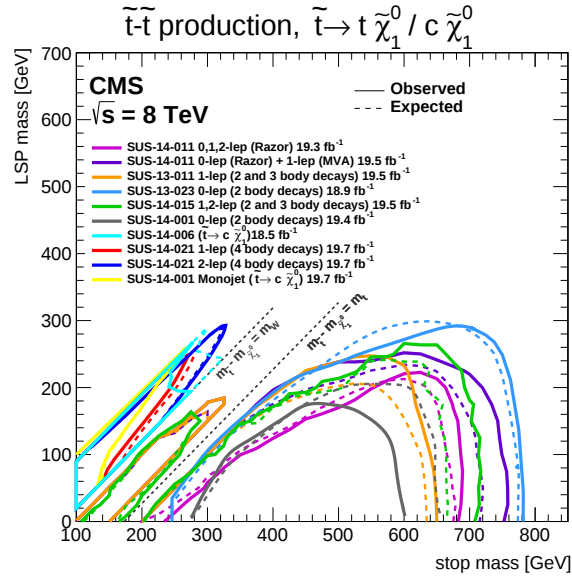


Figure 1.8.: Summary of dedicated ATLAS searches for top squark pair production based on 20 fb^{-1} of pp collision data taken at $\sqrt{s} = 8$ TeV and 4.7 fb^{-1} of pp collisions taken at $\sqrt{s} = 7$ TeV [42]. Exclusion limits at 95% CL are shown in $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$ mass plane. The dashed and solid lines show respectively the expected and observed limits. The decay mode $\tilde{t}_1 \rightarrow b + \tilde{\chi}_0^\pm$ with $\tilde{\chi}_1^\pm \rightarrow W + \tilde{\chi}_1^0$ is assumed with a BR of 100%. Various hypotheses on $\tilde{t}_1$, $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ masses hierarchy are made: fixing $m_{\tilde{\chi}_1^\pm}$ at 106 or 150 GeV (just above the LEP limit of 103.5 GeV [43]), $m_{\tilde{\chi}_1^\pm} = 2 \times m_{\tilde{\chi}_1^0}$ (under the assumption of gauge coupling unification at GUT scale), $\Delta m(\tilde{t}_1, \tilde{\chi}_1^\pm)$ equal to 10 GeV (characterised by soft b -jet), $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ at 5 or 20 GeV (characterised by soft leptons).



(a)



(b)

Figure 1.9.: Summary of the the ATLAS [42] (a) and CMS [44] (b) Run1 results in searches for direct top squark pair production in models where no supersymmetric particle other than $\tilde{t}_1$ and $\tilde{\chi}_1^0$ is involved in $\tilde{t}_1$ decay. The 95% CL exclusion limits are shown in $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$ mass plane. The dashed and solid lines show the expected and observed limits. Four decays mode are considered separately with a branching ratio of 100%: $\tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0$, $\tilde{t}_1 \rightarrow b + W + \tilde{\chi}_1^0$, $\tilde{t}_1 \rightarrow c + \tilde{\chi}_1^0$ and $\tilde{t}_1 \rightarrow b + f + f' + \tilde{\chi}_1^0$.

Chapter 2.

The Large Hadron Collider and The ATLAS experiment

The analysis described in this thesis was performed on data of proton-proton collisions collected by the ATLAS experiment at the Large Hadron Collider at CERN¹, during 2015 and 2016, at a center-of-mass energy ($\sqrt{s}$) of 13 TeV. Since all ATLAS sub-detectors play an important role in the definition of the objects used for the analysis finalisation, in this chapter, after a brief introduction about LHC [35], a general description of the ATLAS experiment and its upgrade program is reported [22].

In particular, in Sect. 2.3.1, the results obtained in the characterisation at high temperature of the micromegas detectors, technology that will be used for the ATLAS upgrade, are shown. As already mentioned in the introduction of this thesis, these temperature tests results were shown at 5th International Conference on Micro-Pattern Gas Detectors (MPGD2017), held at Temple University in Philadelphia in May 2017 [2].

2.1. The Large Hadron Collider

The Large Hadron Collider (LHC) is an hadron (proton or heavy ion) collider installed in the existing, 27 km long, tunnel initially constructed for the Large Electron-Positron (LEP) machine [27] at CERN (Fig. 2.1). The LEP tunnel has eight straight sections and eight arcs and lies between 45 m and 170 m below the earth surface on a plane inclined with a slope of 1.4% towards the Léman lake. There are two transfer tunnels, each approximately 2.5 km long, linking the LHC to the CERN accelerator complex that acts as injector (Fig. 2.2).

Being LHC a collider of particles with the same charge, two beams run in opposite directions in two separated rings, differently from what happens in particle-antiparticle colliders where both beams can share the same ring. The tunnel in the arc sections has an internal diameter of 3.7 m, which made extremely difficult to install two completely separated proton rings. The limited space led to the adoption of twin-bore magnets, where coils and beam channels are hosted within the same mechanical structure and cryostat (Fig. 2.3).

¹Conseil Européen pour la Recherche Nucléaire

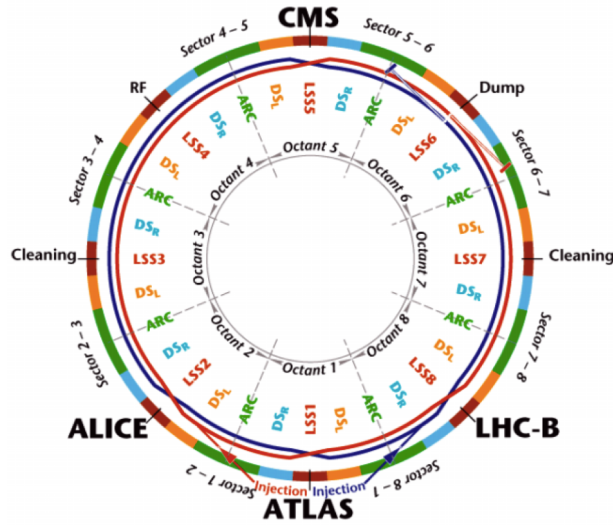


Figure 2.1.: Layout of the LHC. The eight arcs (ARC), the eight long straight sections (LSS), the four interaction points where the experiments are located (ALICE, ATLAS, LHC-B, CMS), the beam cleaning and dump systems, the radiofrequency accelerating system (RF) are reported. [45].

The main experiments located along the LHC ring are: the two multi-purpose detectors ATLAS (A Toroidal Lhc ApparatuS) and CMS (Compact Muon solenoid) [40], LHCb (LHC beauty experiment) [48], focusing on b-physics, and ALICE (A Lhc Ion Collider Experiment) [49], optimised to investigate heavy-ion collisions.

2.1.1. The LHC program

The LHC experimental program follows a well-defined schedule of data taking periods interspersed by technical stops (*long shutdown*) used to repair and upgrade the accelerator and the experiments. The roadmap is shown in Fig. 2.4.

For each operating period the LHC performance can be described by the following parameters:

- beam energy,
- number of bunches per beam,
- bunch spacing,
- bunch intensity (number of particles per bunch),
- mean number of interactions per bunch crossing (μ),
- peak (instantaneous) luminosity².

2.1. The Large Hadron Collider

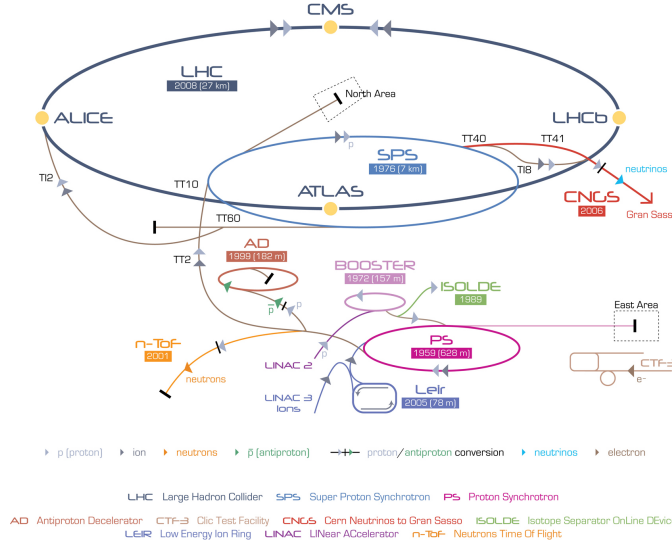


Figure 2.2.: CERN accelerator complex. An electric field is used to extract protons from hydrogen atoms. Linac 2 accelerates the protons to the energy of 50 MeV. The beam is then injected into the Proton Synchrotron Booster (PSB), which accelerates the protons to 1.4 GeV, followed by the Proton Synchrotron (PS), which pushes the beams up to 25 GeV. Protons are then sent to the Super Proton Synchrotron (SPS) where they are accelerated to 450 GeV before being transferred to the two beam pipes of the LHC [46]. In yellow the main LHC experiments are shown.

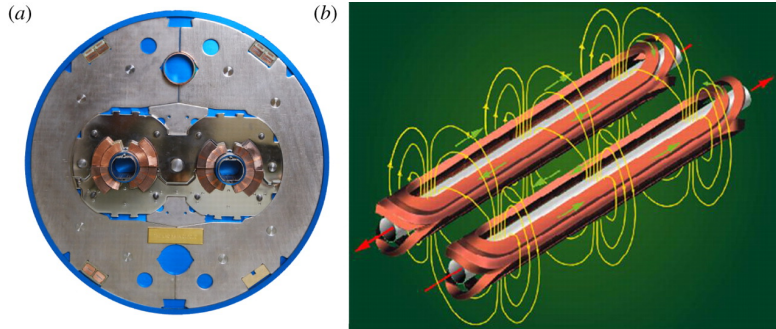


Figure 2.3.: (a) Cross-section of the LHC dipole without the cryostat. (b) Dipole magnetic field [47].

²If two bunches containing n_1 and n_2 particles collide head-on with frequency f , a basic expression for the luminosity is

$$\mathcal{L} = f \frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$

where σ_x and σ_y are related to the transverse beam dimensions in the horizontal and vertical directions. This formula assumes that the bunches have identical transverse Gaussian profiles along

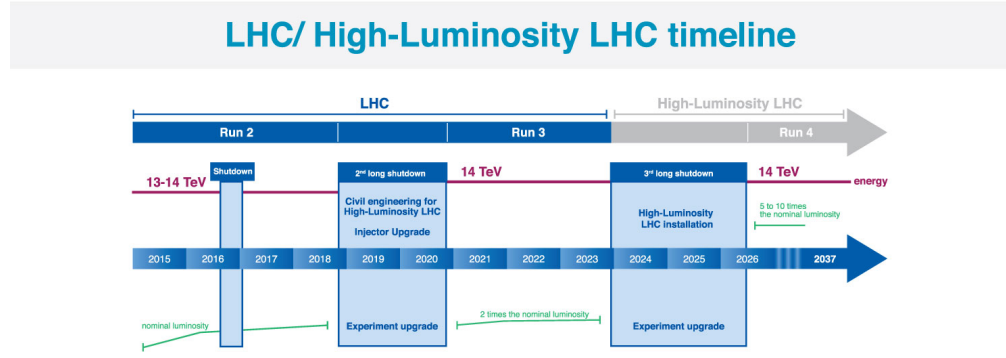


Figure 2.4.: LHC schedule up to the so-called high-luminosity LHC (HL-LHC) phase, where a peak luminosity of $5\text{--}10 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ is expected to be reached [50].

Parameters	Design values	Run1			Run2		
		2010	2011	2012	2015	2016	2017
Beam energy [TeV]	7	3.5	3.5	4	6.5	6.5	6.5
Bunch spacing [ns]	25	150	50	50	25	25	25
Maximum colliding bunches	2808	348	1854	1380	2232	2208	2544
Maximum bunch intensity [$\times 10^{11}$]	1.15	1.	1.3	1.5	1.2	1.3	1.35
Peak luminosity [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	1	0.021	0.365	0.773	0.502	1.38	2.06
Integrated luminosity [fb^{-1}]		0.048	5.46	22.8	4.2	38.5	50.4

Table 2.1.: Running conditions, provided by LHC to the ATLAS experiment, during Run1 (2010-2012) and Run2 (2015-2018) together with the corresponding design values. In red the parameters that have already overcome the design values. The integrated luminosity refers to the one delivered by LHC and not the one considered for the physics analyses, that takes also into account the quality of the data.

The values of these parameters, as recorded by the ATLAS experiment during the run periods called Run1 (2010-2012) and Run2 (2015-2018), are reported in Tab. 2.1

the bunch longitudinal dimension and that the particle distributions are not modified during bunch crossing. Non-zero beam crossing angles and long bunches reduce the luminosity [51]. Instantaneous luminosity unit is $\text{cm}^{-2}\text{s}^{-1}$ or $\text{b}^{-1}\text{s}^{-1}$ where one barn (b) is equivalent to 10^{-24} cm^2 . The number of events of a specific process, N_{exp} , is given by the product of the cross section of the process of interest, σ , and the time integral over the instantaneous luminosity (integrated luminosity):

$$N_{exp} = \sigma \times \int \mathcal{L} dt.$$

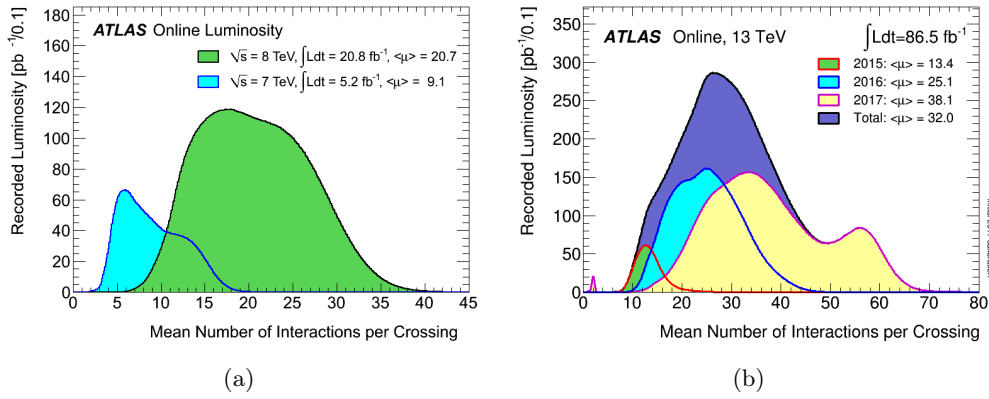


Figure 2.5.: Luminosity-weighted distribution of the mean number of interactions per crossing for the 2011-2012 (a) and 2015-2017(b) data [52, 53].

and in Fig. 2.5.

The analysis described in this thesis was performed on the LHC data collected by the ATLAS experiments in 2015 and 2016, from proton-proton collision at $\sqrt{s} = 13$ TeV and corresponding to an integrated luminosity of 36.1 fb^{-1} .

2.2. The ATLAS experiment

ATLAS is a general purpose experiment, i.e. designed to perform high-accuracy measurements on a wide spectrum of physics channels. It is composed by several concentric detectors, each of them sensitive to some classes of particles produced during the collisions (Fig. 2.6). The *Inner detector* (ID) is the innermost one and it measures trajectory and momentum of the charged particles coming from the interaction point, being immersed in a solenoidal magnetic field of 2 Tesla and by mean of different technologies: a *Pixel Detector*, a *Semiconductor Tracker* (SCT) and a *Transition Radiation Tracker* (TRT). The ID is surrounded by the calorimeter system, able to identify and measure the energy of electrons, positrons, photons, charged and neutral hadrons; it consists of a central *electromagnetic calorimeter*, an *hadronic end-cap calorimeter*, a *forward calorimeter* all based on the liquid argon technology and a central *tile calorimeter* using steel as absorber and scintillation plates as active material. The most external detector is the *Muon Spectrometer* (MS), located inside a toroidal magnetic field with intensity varying between 0.5 and 1 Tesla over all the volume and responsible of the muon identification, trajectory reconstruction and momentum measurement.

2.2.1. The ATLAS coordinate system

The ATLAS coordinate system assumes the interaction point as origin and the z -axis coincident with the beam direction. The $x - y$ plane, known as transverse plane, is

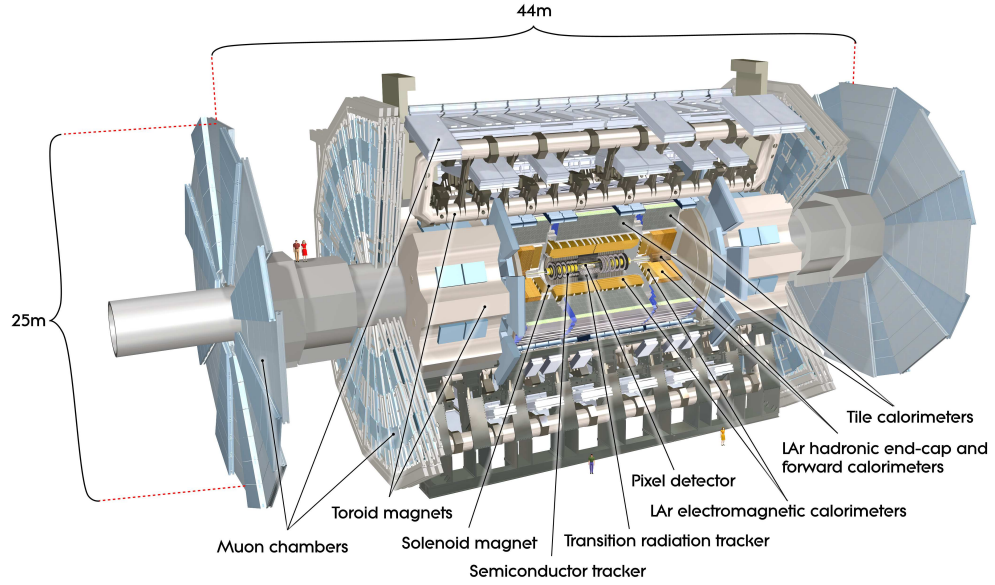


Figure 2.6.: View of the ATLAS detector. The overall dimensions are 25 m in height and 44 m in length. The total weight is approximately 7000 tonnes [22].

orthogonal to this direction. The x -axis assumes positive values moving from the interaction point to the center of LHC ring while the positive y -axis goes from the origin to the ground surface. The $x - y$ is usually described in terms of the angular variable ϕ , measured with respect to the positive x -axis, and the radial distance r . The polar angle θ is defined as the angle around the positive z -axis; however it is usually preferred to express θ in terms of the *pseudorapidity* (η) defined as

$$\eta = -\ln \tan \left(\frac{\theta}{2} \right) \quad (2.1)$$

For a particle of energy E and longitudinal momentum p_z , the pseudorapidity³ thus defined is approximately equal to the *rapidity* y given by the formula

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right), \quad (2.2)$$

when the particle mass m is negligible with respect to its momentum p ($p \gg m$) [51].

In terms of pseudorapidity it's possible to distinguish between the central volume of the detector, called *barrel* ($|\eta| < X$ with X depending of the specific part of the detector), and the *end-caps* volumes ($|\eta| > X$).

³The advantage of considering pseudorapidity is related to the fact that rapidity differences are invariant under Lorentz boost and, consequently, only the distribution in $d\eta$, and not in $d\theta$, is Lorentz invariant along the z -axis under the constraint that $p \gg m$.

2.2.2. Inner detector

The inner detector [22] surrounds the beam pipe complying with a cylindrical geometry, as shown in Fig. 2.7 and in Fig. 2.8. It was designed to finally reach an excellent resolution for charged particles momentum measurements

$$\frac{\sigma_{p_T}}{p_T} = 0.05\% \oplus 1\% \quad (2.3)$$

with p_T transverse momentum expressed in GeV, exploiting the performance of the various technologies it is made of.

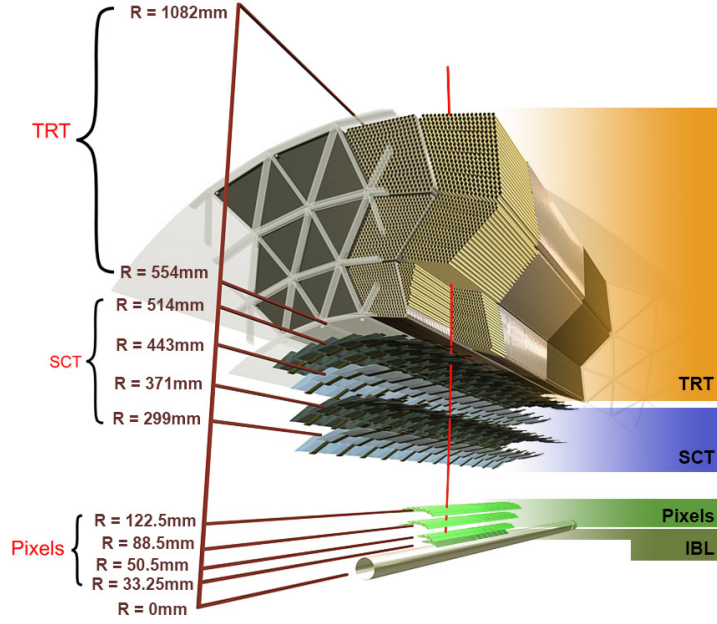


Figure 2.7.: View of the ATLAS ID: after the beam pipe, charged particles coming from the interaction vertex at small $|\eta|$ cross the Insertable (silicon-pixel made of) B-Layer (IBL), three cylindrical silicon-pixel layers, four cylindrical double layers of barrel SCT, and approximately 36 layers of 4 mm diameter straw tubes in the barrel TRT modules. [22].

Among the ID components, the silicon pixel detector is the nearest to the interaction points and it is characterized by a fine granularity, needed to cope with the high track density, and to accomplish the momentum and vertex resolution requirements for high precision measurements. During Run1 it consisted of three barrel layers (with mean radii of 50.5 mm, 88.5 mm and 122.5 mm) and six disk layers, arranged in two end-caps with three disks each, and it is able to reach a spatial resolution of $10 \mu\text{m}$ in the azimuthal plane and $115 \mu\text{m}$ along the z/r direction for $|\eta| < 2.5$. The innermost pixel layer, known as B-Layer, plays a crucial role for ATLAS tracking and vertexing capabilities but it was designed to operate efficiently up to 300 fb^{-1} and with a peak luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$,

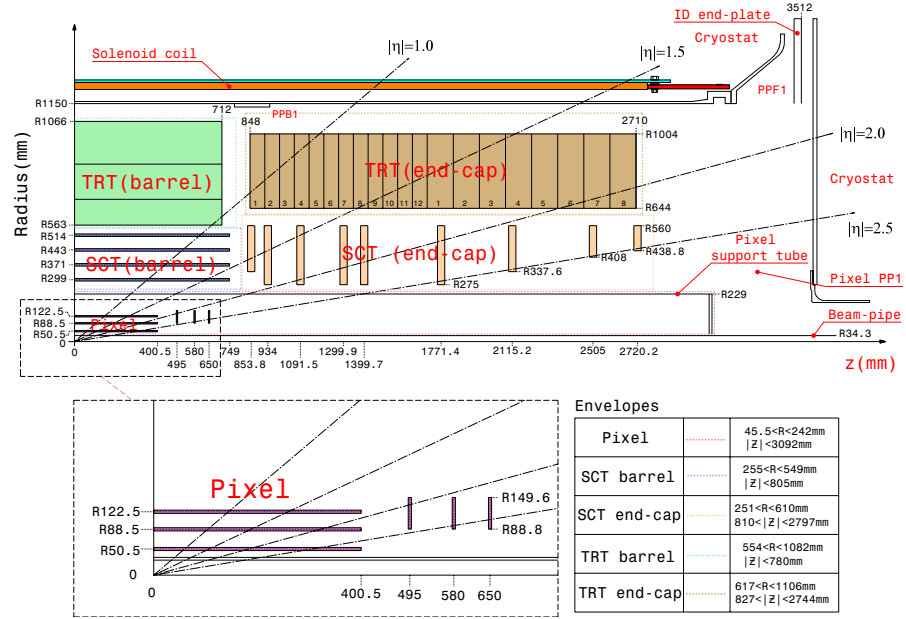


Figure 2.8.: A quarter of a side view of the ATLAS ID showing each of the major detector elements and the relative dimensions and envelopes. [22]. IBL is not shown in this schema.

already reached (and overtaken) in Run2. It was thus necessary the installation of a forth pixel layer, the Insertable B-layer⁴ (IBL) [54], during the long shutdown 2013-2014, in order to provide an additional space point and keep high the tracking performance.

The Semiconductor Tracker surrounds the pixel detector and consists of silicon microstrip detectors, arranged in four layers in the barrel and nine layers in each of the two end-caps. In the barrel region each silicon sensitive element has a surface of $64.0 \times 63.6 \text{ mm}^2$ with a strip pitch of $80 \text{ } \mu\text{m}$, instead in the end-caps the disks use wedge shaped sensors of five slightly different sizes, to accommodate the more complex geometry, with a strip pitch ranging from $56.9 \text{ } \mu\text{m}$ to $90.4 \text{ } \mu\text{m}$. Each layer is in particular made of two silicon strips structures glued together back-to-back at a stereo angle of 40 mrad between each other, in order to measure hit positions with a resolution of $17 \text{ } \mu\text{m}$ in the azimuthal direction and $580 \text{ } \mu\text{m}$ along the z/r direction. SCT is able to provide from four to nine position measurements per particle up to $|\eta| < 2.5$.

The Transition Radiation Tracker is the external ID detector layer, based on the use of straw detectors, that can operate at the very high rates required by the LHC. It consists of a barrel and two end-cap components, for a total coverage up to $|\eta| < 2$, and it is able to reconstruct at least 36 spatial points for charged track with $p_T > 0.5 \text{ GeV}$. TRT is made in total of about 300000, 4 mm in diameter, straw drift tubes, equipped with a

⁴To make the insertion of the IBL possible, the beam pipe has been replaced by a new one, with reduced radius (from 29mm to 24mm).

31 μm diameter gold-plated tungsten wire and operating with a gas mixture⁵ of 70% Xe, 27% CO₂ and 3% O₂ or 70% Ar, 27% CO₂ and 3% O₂, the latter for those modules with large gas leaks [55]. Each TRT tube provides drift-time measurements and it is able to measure hit positions with a resolution of 130 μm . Another important TRT feature is its electron identification capability, based on transition radiation⁶ (TR) photon detection and exploiting two independent signal thresholds to discriminate between tracking hits and transition-radiation hits, thus distinguishing between pions and electrons up to momentum values of ~ 100 GeV [55] (see Fig. 2.9).

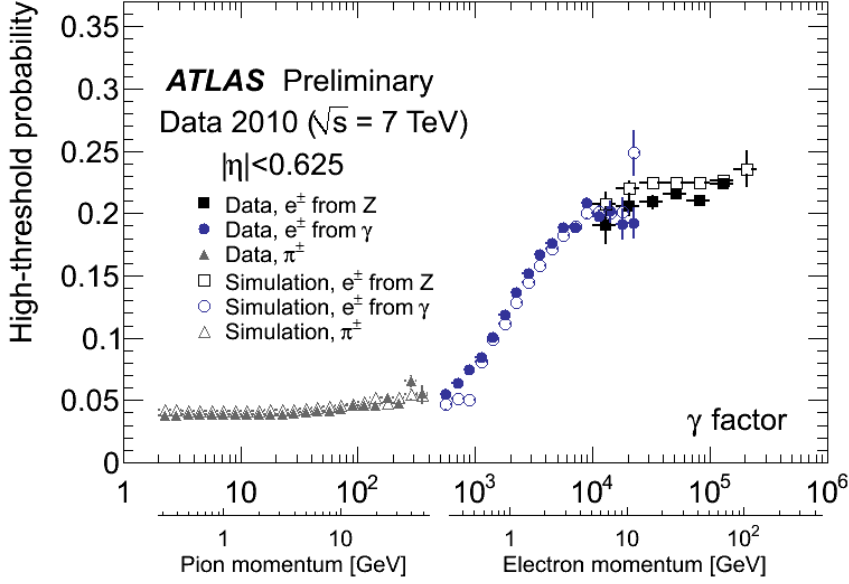


Figure 2.9.: The signal on each TRT wire is amplified, shaped and discriminated against two adjustable thresholds: low threshold (LT) and high threshold (HT). In the figure it is shown, for the xenon-based gas mixture, the probability to have a high threshold hit in the barrel TRT as a function of the Lorentz factor of the particle crossing it, considering 2010 LHC collision events [56].

2.2.3. Calorimeters

The calorimeter system [22] consists of different sampling calorimeters and it allows to measure energy and position of electrons, photons and hadrons up to η of 4.9 (Fig. 2.10)

⁵During Run 1, all the straws were filled with the xenon-based gas mixture.

⁶Transition radiation arises when ultra-relativistic charged particles cross a boundary between media with different dielectric constants. The probability of a given particle to emit transition radiation is determined solely by its Lorentz γ -factor. In the X-ray energy range of the TR photons, this probability is a step-like function which rises from about zero to its maximum when the γ -factor changes from about 500 to 2000.

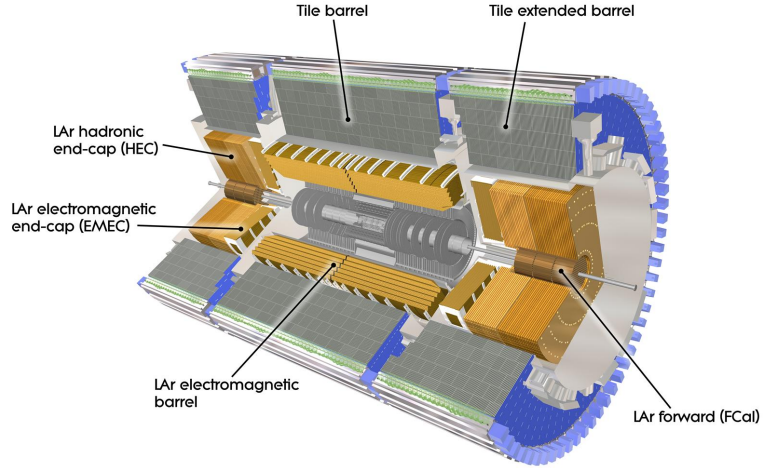


Figure 2.10.: View of the full ATLAS calorimeter [22], showing its different components.

Electrons and photons energy is measured by an electromagnetic calorimeter (EM) divided into a barrel part ($|\eta| < 1.475$) and two end-cap components ($1.375 < |\eta| < 3.2$). Each end-cap calorimeter is, in turn, divided into two coaxial wheels: an outer wheel covering the region $1.375 < |\eta| < 2.5$ and an inner wheel in $2.5 < |\eta| < 3.2$. The EM calorimeter is a lead-liquid argon detector with accordion-shaped lead absorber plates over its full coverage. The accordion geometry provides complete ϕ symmetry without azimuthal cracks (Fig. 2.11(a)). In the region devoted to precision physics ($|\eta| < 2.5$) the EM calorimeter is longitudinally segmented in three sections of different depths, as shown in Fig. 2.11(b), with the first section segmented into high-granularity strips in the η direction and acting as a pre-shower detector, in order to provide $\gamma - \pi^0$ separation and photon direction measurement. In a similar way also the end-cap inner wheel is longitudinally segmented in two sections.

The hadron energy measurement is performed with the hadronic calorimeter, whose structure is not uniform. For $|\eta| < 1.7$ a sampling calorimeter using steel as absorber and scintillating tiles as active material is used, while in the end-caps, for $|\eta| \in [1.5, 3.2]$, a liquid argon technology with copper plates is exploited.

Finally, to guarantee a coverage up to $|\eta|$ equal to 4.9, a forward calorimeter is also installed in $|\eta| \in [3.1, 4.9]$. It consists of three modules in each end-cap, all of them having liquid argon as active material: the first, using copper as passive material, is optimised for electromagnetic measurements, while the other two, having tungsten as absorber, measure the energy of the hadronic particles.

The energy resolutions of the electromagnetic calorimeter, hadronic calorimeter and

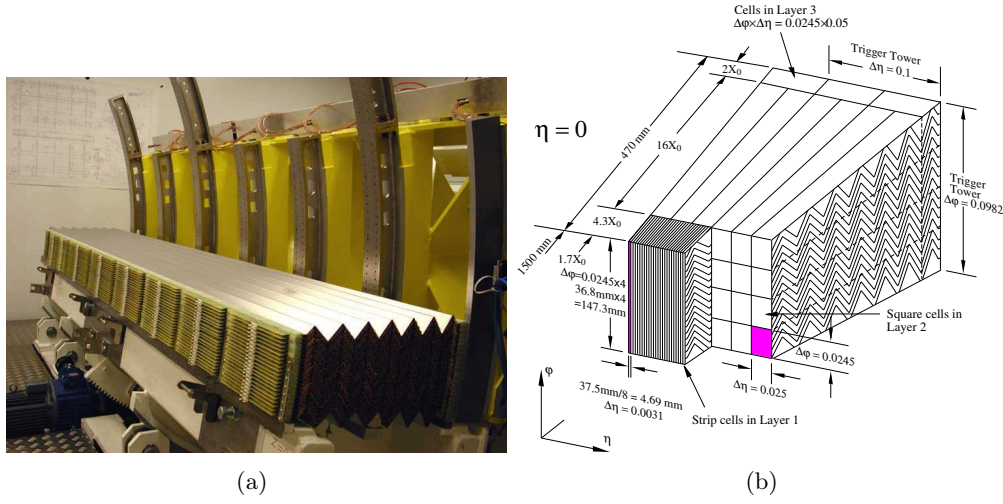


Figure 2.11.: (a) Accordion structure of the electromagnetic calorimeter. (b) Longitudinal segmentation scheme in the barrel EM [22].

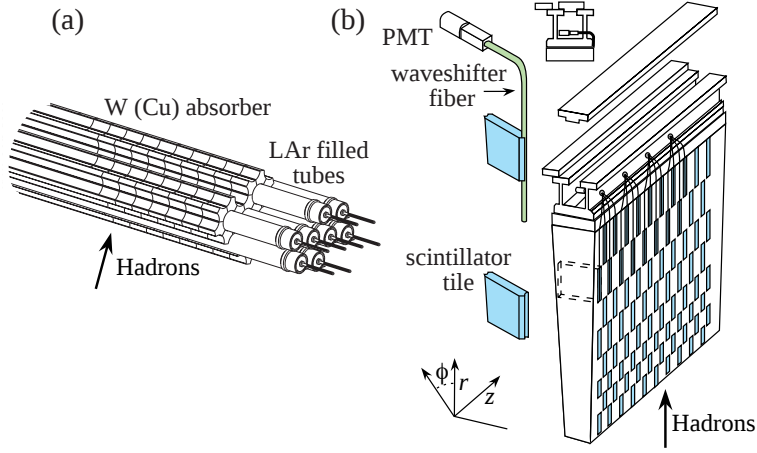


Figure 2.12.: (a) ATLAS forward calorimeter structure: tubes containing liquid argon are embedded in a copper or tungsten matrix. (b) ATLAS central hadronic calorimeter wedge: iron with plastic scintillator tile with wavelength-shifting fiber readout [51].

forward calorimeter are respectively:

$$\frac{\Delta E}{E} = \frac{10\%}{\sqrt{E}} \oplus 0.7\%, \quad (2.4)$$

$$\frac{\Delta E}{E} = \frac{50\%}{\sqrt{E}} \oplus 3\%, \quad (2.5)$$

$$\frac{\Delta E}{E} = \frac{100\%}{\sqrt{E}} \oplus 10\%. \quad (2.6)$$

2.2.4. Muon Spectrometer

The muon spectrometer [22] forms the outer part of the ATLAS detector and it is designed to detect muons and measure their momentum in the pseudorapidity range $|\eta| < 2.7$. Furthermore, the muon system provides trigger capabilities in the region $|\eta| < 2.4$. The driving criterion to design it was to reach a stand-alone transverse momentum resolution of approximately 10% for 1 TeV tracks, which means to measure a sagitta along the z -axis of about $500 \mu\text{m}$ with a resolution $\leq 50 \mu\text{m}$ in the magnetic field provided by the large superconducting toroid magnets. Muon momenta down to a few GeV and up to few TeV can be measured. The chambers in the barrel are arranged in three concentric cylindrical shells around the beam axis at radii of approximately 5 m, 7.5 m and 10 m (Fig. 2.13(a)). In the two end-cap regions, muon chambers form large wheels, perpendicular to the z -axis and located at distances of $|z| \approx 7.4 \text{ m}$, 10.8 m, 14 m and 21.5 m from the interaction point (Fig. 2.13(b)).

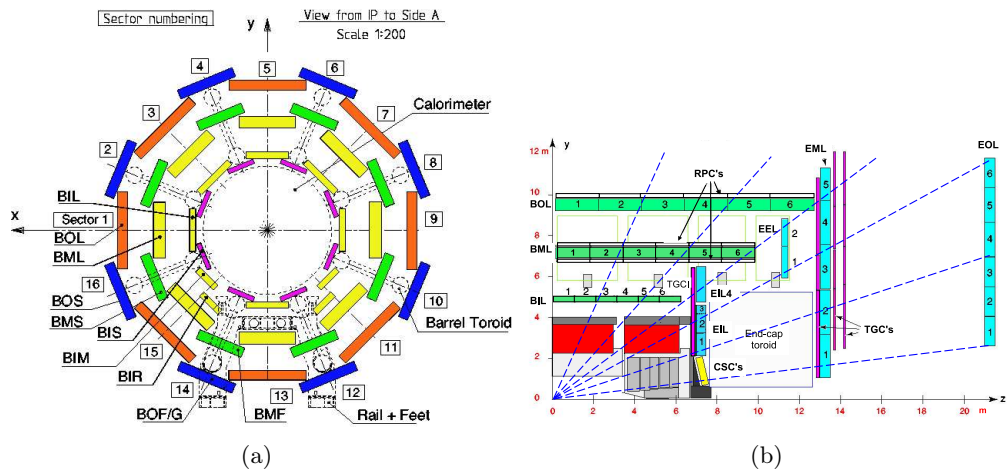


Figure 2.13.: (a) Section of the barrel muon system in the transverse plane, showing three concentric cylindrical layers of eight large and eight small chambers; a schematic view of the eight coils of the superconducting barrel toroid magnet is also shown. (b) quarter of a side view of the muon system: Monitored Drift Tube (MDT) detectors are shown by the green and azure boxes while Cathode-Strip Chambers (CSC), Thin Gap Chambers (TGC) and Resistive Plate Chambers (RPC) are indicated [22].

The precision momentum measurement is performed by the *Monitored Drift Tube* (MDT) chambers. They cover the pseudorapidity range $|\eta| < 2.7$ with the exception of the innermost end-cap layers, where their coverage is limited to $|\eta| < 2.0$. These chambers consist of two multi-layer (3-4) of aluminium drift tubes, filled with a mixture of 93%Ar and 7%CO₂ at an absolute pressure of 3 bar, which achieve an average resolution of $80 \mu\text{m}$ per tube, and about $35 \mu\text{m}$ per chamber. The MDT operating conditions also allow a small Lorentz angle and excellent ageing properties. In the forward region ($2 < |\eta| < 2.7$), *Cathode-Strip Chambers* (CSC) are used in the innermost tracking layer

due to their higher rate capability and time resolution, needed in the harsh conditions at high pseudorapidities. The CSCs are multiwire proportional chambers with cathode strip readout and with a symmetric cell in which the anode-cathode spacing is equal to the anode wire pitch. Both coordinates are measured from the induced-charge distribution on the segmented cathode by the avalanche reaching the anode wire. CSCs operate with a gas admixture containing 80%Ar and 20%CO₂ with no hydrogen to reduce the neutron background. The resolution of a chamber is $\sim 40 \mu\text{m}$ in the bending plane and about 5 mm in the transverse plane.

The precision-tracking chambers are complemented by fast trigger chambers capable of delivering track information within a few tens of nanoseconds after the passage of the particle. In the barrel region ($|\eta| < 1.05$), *Resistive Plate Chambers* (RPC) were selected to this purpose while in the end-cap ($1.05 < |\eta| < 2.4$) *Thin Gap Chambers* (TGC) were chosen. The basic RPC unit is a narrow gas gap into two parallel resistive Bakelite plates, separated by insulating spacers. The primary ionization electrons generate avalanche by a high electric field of about 4.9kV/mm in a gas mixture based on tetrafluoroethane (C₂H₂F₄) with some small admixture isobutane and SF₆. TGCs are very thin Multiwire Proportional Chambers, with an anode wire pitch larger than the cathode-anode distance. Signals, from the anode wires (parallel to the MDT ones), provide the trigger information together with read-out strips orthogonal to the wires. This allows a very short drift time and a fast response. TGCs are operated in saturated mode with a gas mixture of 55%CO₂ and 45%n-C₅H₁₂ (n-pentane) at a tension of about 3 kV. Both chamber types have excellent time resolution, thus providing beam-crossing identification and assignment. The trigger chambers also measure both coordinates of the track, z/r and ϕ , the latter one known as "second coordinate", which helps the track reconstruction performed by the MDTs (Tab. 2.2).

Type	Function	Chamber resolution (RMS) in		
		z/r	ϕ	time
MDT	tracking	$35\mu\text{m}$ (z)	-	-
CSC	tracking	$40\mu\text{m}$ (r)	5mm	7ns
RPC	trigger	10mm (z)	10mm	1.5ns
TGC	trigger	2-6mm(r)	3-7mm	4ns

Table 2.2.: Parameters of the four sub-system in the muon spectrometer. The quoted spatial resolution does not include chamber-alignment uncertainties. The time resolution is relative to the intrinsic time resolution of each chamber type, to which contributions from signal-propagation and electronics contributions need to be added [22].

However the system final performance in momentum resolution strictly depends on the chamber relative alignment and on the alignment with respect to the full detector, which is obtained with a precision of about $30 \mu\text{m}$ by mean of a sophisticated alignment system. The purpose of the precision-tracking chambers is to determine the coordinate of

the track in the bending direction (η). After matching of the MDT and trigger chamber hits in the bending direction, the trigger chamber coordinate in the non-bending direction (ϕ) is adopted as the second coordinate of the MDT measurement. This method assumes that in any MDT/trigger chamber pair a maximum of one track per event is present, since with two or more tracks the η and ϕ hit cannot be combined in an unambiguous way. Simulations show that the probability of a track in the muon spectrometer with transverse momentum $p_T > 6$ GeV is about 6×10^{-3} per beam-crossing, corresponding to about 1.5×10^{-5} per chamber. Assuming uncorrelated tracks, this leads to a negligible probability to find more than one track in any MDT/trigger chamber pair. When correlated muon tracks do occur, caused for example by two-body-decays, the ambiguity in η and ϕ assignment is resolved by matching the muon track candidates with tracks from the inner detector.

2.2.5. Trigger system

An important role in the data acquisition is played by the ATLAS trigger system, given its responsibility in the events selection. Differently from Run1, where three trigger levels, referred to as *Level-1* (L1), *Level-2* (L2) and *Event Filter* (EF) were implemented, in Run2 the ATLAS trigger system consists of the only Level-1 trigger with the addition of a software-based *High Level Trigger* (HLT) (Fig. 2.14) [57].

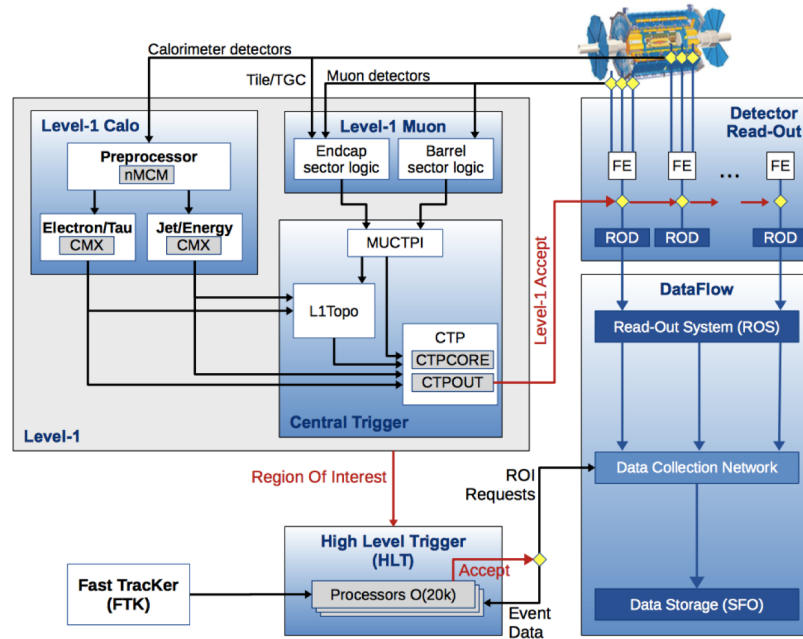


Figure 2.14.: Schematic layout of the ATLAS trigger and data acquisition system in Run2 [58].

Level-1 trigger, implemented through a hardware-based system, uses a subset of de-

tector information, from the calorimeters and the muon spectrometer, to take a decision within an average time of 25 ns about chambers areas, which are identified as interesting and are labelled as Regions-of-Interest (RoIs), and it is able to reduce the rate from 40 MHz to ~ 100 kHz.

HLT is instead a software based trigger, where the events are processed considering the finer-granularity calorimeter information, the precision measurements coming from the muon spectrometer and the tracking information from the inner detector. Depending on the necessity, the HLT reconstruction can be performed within the L1 RoIs or considering the full detector. A two-stage approach is applied for the event selection; initially a fast first-step reconstruction is done to reject the majority of events, later a second selection is performed after a slower precision reconstruction. Between the two steps there is no fixed rate limitations and the HLT aim is to reduce the rate to less than 1 kHz.

2.2.6. Forward detectors

In addition to the main ATLAS systems, described previously, in the forward region there are other smaller detectors used for luminosity measurements, detection of neutral particles and beam monitoring. In the following a short description of these detectors is reported.

2.2.6.1. LUCID

LUCID (LUMinosity measurement using Cherenkov Integrating Detector) is the main luminosity monitor and it is located at a distance of ± 17 m from the interaction point. In Run2, to cope with the new and more demanding LHC conditions, an upgrade of LUCID detector, called LUCID-2, has been necessary. The basic principle of the detector is that the number of interactions in a bunch crossing is proportional to the number of the particles detected. In particular the detection is performed by collecting the Cherenkov light emitted by the charged particles passing through the detector; since there is no Landau tail in the measurement of Cherenkov light, it is possible to determine the number of the particles by simply using pulse height measurements [22, 59].

2.2.6.2. ZDC

ZDC (Zero Degree Calorimeter) consists of two sampling calorimeters symmetrically located at 140 m from the interaction point. It covers a pseudorapidity range of $|\eta| > 8.3$ and uses tungsten plates, as absorber material, and quartz rods, as active media. It can provides energy information of the incident particles and, being segmented longitudinally and transversely, also their position. Its primary purpose is to detect neutrons in heavy ions collisions given that they are expected in the forward region. In this way a coincidence between the two ZDC calorimeters can be use as heavy ions triggers in ATLAS [22, 60].

2.2.6.3. ALPHA

ALFA (Absolute Luminosity For ATLAS) is used to determine the absolute luminosity via elastic scattering at small angles. The optical theorem in fact connects the elastic-scattering in the forward direction to the total cross-section and can be used to extract the luminosity. ALFA detector consists of scintillating-fibre trackers located, on both side of ATLAS, at a distance of approximately 240 m from the interaction point [22].

2.2.6.4. BCM, BLM and DBM

During LHC operation, it might happen that several proton bunches hit the collimators in front of the detectors. In this situation, while the accumulated radiation dose corresponds to that one acquired during a few days of normal operation, the enormous instantaneous rate might cause detector damages. It has been thus necessary to build a set of detectors designed to detect these events and trigger an abort in time to prevent serious damages to the detectors. Three types of diamond detectors are used; they are called Diamond Beam Monitor (DBM), Beam Condition Monitor (BCM) and Beam Loss Monitor (BLM) and they are symmetrically located at 0.93 m, 1.84 m and 3.45 m from the interaction point respectively. BCM can also be used to determine the luminosity but it saturates when the instantaneous luminosity reaches $\sim 10^{34}\text{cm}^{-2}\text{s}^{-1}$. DBM can instead overcome this limitation thanks to its better segmentation [22, 61, 62].

2.3. Future ATLAS upgrade

As already shown in Fig. 2.4, LHC has scheduled a series of upgrades leading to an increase of the instantaneous luminosity, up to $5\text{-}10 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$, in the high-luminosity LHC (HL-LHC) phase. Consequently, a harsher radiation environment and higher detector occupancies are expected and changes to the subsystems are needed to deal with higher particle flux and radiation damage. The detectors affected by these new experimental conditions are the inner detector, the forward calorimeters and the innermost wheels of the muon spectrometer, usually called *Small Wheels*. For this reason, their upgrade is planned and it will be done in two phases, that will take place in the remaining two LHC long technical shutdowns: *Phase-I* from 2019 to 2020 and *Phase-II* from 2024 to 2026. In particular, during Phase-I, it is planned an upgrade of the Small Wheel, called *New Small Wheel* (NSW), that will be based on the use of micromegas (MM) detectors and of small-strip Thin Gap Chambers (sTGC). NSW will be able to provide trigger information that will be matched with the TGC ones in order to reject muons not coming from the interaction point, thus reducing the muon trigger rates in the MS end-caps and allowing to run with lower trigger thresholds. In Phase-II, instead, ATLAS has decided to replace the entire inner detector with a new, all-silicon *Inner Tracker* (ITk) and to substitute all on-detector readout electronics for all calorimeters. The forward calorimeters upgrade is also planned in Phase-II and at the moment two possible solutions are under study: its complete replacement or the installation of a small warm calorimeter in front of it to reduce the ionization and heat load to acceptable levels.

In both phases an upgrade of the trigger systems is also planned [63].

2.3.1. Characterisation of Micromegas detectors at high temperature

Performance and long-term ageing studies on the detector technologies candidates for the upgrades are needed to fully understand the detector behaviour. In particular, for the micromegas technology considered for the NSW construction, these ageing studies have been performed on small resistive-strip bulk micromegas detectors, called T-chambers, at the CERN Gamma Irradiation Facility (GIF++) [65,66], where high energy charged particle beams⁷ (mainly muons), combined with a flux of photons from 13.9 TBq ^{137}Cs source, can be used for the detectors irradiation studies. During these studies, changes in the resistive strips current, not related to the irradiation exposure itself, were noticed and found to be related to environmental temperature changes. For this reason, the behaviour of the detectors was studied in varying temperature conditions, and a *dark current* (i.e. measured in absence of irradiation sources) increasing with the temperature, but not affecting the detector performance, was detected.

In the next paragraphs, after an introduction on the micromegas technology, the obtained temperature tests results are reported.

2.3.1.1. Micromegas technology and characteristics

Micromegas, i.e. Micro Mesh Gaseous Structures (MM), relies on a gaseous technology which was developed in the middle of 1990 and provides the possibility to construct thin wireless gaseous particle detector [64,67,68]. A schematic view of a micromegas detector is reported in Fig. 2.15: it consists of a planar drift electrode, a gas gap few millimeters large acting as conversion and drift region, and a thin metallic mesh 100-150 μm far away from a readout electrode, which is made by micro-strips printed on an insulating support. The distance between the readout electrode and the mesh, which together define the detector amplification region, is kept uniform by small insulating pillars⁸.

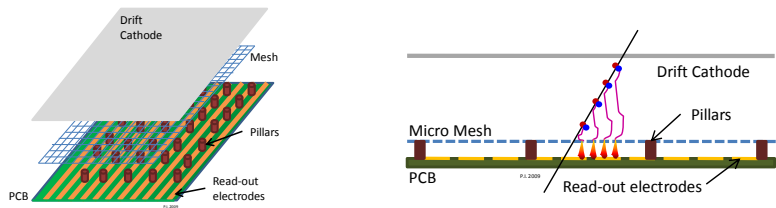


Figure 2.15.: Sketch of the layout and the operating principle of a micromegas detector [64].

⁷The momentum of the beam can range from 10 GeV up to 450 GeV.

⁸In the first detector design the distance between the mesh and the readout electrode was kept by quartz spacers [67].

In the original detector design, the drift electrode and the mesh were set to negative high voltage potential while the readout electrode was at ground potential. For the measurements described in this section, to be coherent with the micromegas HV configuration decided to be used in ATLAS, it was instead decided to set the drift electrode at negative voltage, the readout electrode at positive voltage and the mesh at ground. The HV potentials were chosen such that the electric field in the drift region was a few hundred V/cm and roughly 40-50 kV/cm in the amplification region. In this way charged particles traversing the drift space ionize the gas, and the electrons created by the ionization processes drift towards the mesh, which turns out to be transparent to more than 95% of the electrons. The electron avalanche takes place in the thin amplification region delimited by the mesh.

The drift of the electron in the conversion gap usually takes several tens of nanoseconds, depending on the gas used, the width of the drift region and the drift field. The amplification process instead happens in a fraction of a nanosecond, resulting in a fast pulse of electrons on the readout strips. The ions, produced in the avalanche, move back to the mesh in about 100 ns and this fast evacuation of the positive ions makes the MM particularly suited to operate at very high particle fluxes.

2.3.1.2. Resistive bulk Micromegas

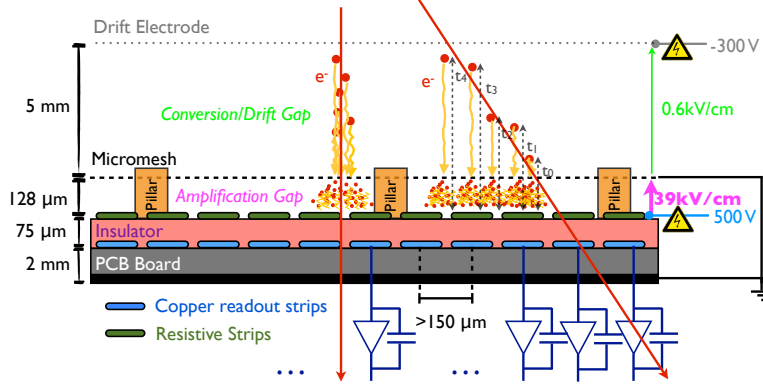
The specific design of the MM chambers, with their thin amplification region, make them particularly vulnerable to sparking, given that the total number of electrons in the avalanche can easily reach values of a few $10^7 - 10^8$, that are close to the Raether limit⁹ [69]. Micromegas detectors usually operates at a gas gain of the order of 10^4 to have a high detection efficiency for minimum ionising muons, but a sparking risk is present for those particles producing more than 1000 electrons over distances of a few 100 μm , such as slowly-moving charged particles produced by the interaction of the primary hadrons with ATLAS calorimeters or other materials [64].

To overcome the problem of sparking, that can damage both the detector and the readout electronics and/or lead to large dead times as a result of HV breakdown, a resistive protection scheme has been introduced in the MM design to be used in ATLAS. The principle of the detector design is illustrated in Fig. 2.16 and the detector is referred to as *resistive bulk micromegas* [68]. An insulator layer is used to cover and protect the copper readout strips and, on top of it, strips of resistive paste (with a resistivity of a few $\text{M}\Omega/\text{cm}$) are deposited in a geometrical way that matches the pattern of the readout

⁹Multiplication in gas detectors occurs when the primary ionization electrons gain sufficient energy from the accelerating electric field to also ionize gas molecules. Assuming α , better known as *Townsend coefficient*, as the inverse of the mean free path of the electron for a secondary ionizing collision, the additional electrons produced in a path dx are given by $dn = n_0\alpha dx$ with n_0 original number of electrons. Consequently, the total number of electron produced in a path x are given by

$$n = n_0 e^{\alpha x}$$

where it has been assumed α independent from x . The multiplication factor $e^{\alpha x}$ is known as *gas gain* or gas amplification factor (G). It has been demonstrated that G should be lower than 10^8 or $\alpha x < 20$ (Raether limit) to avoid electrical breakdown.



Resistive MM

Figure 2.16.: Sketch of a bulk micromegas layout.

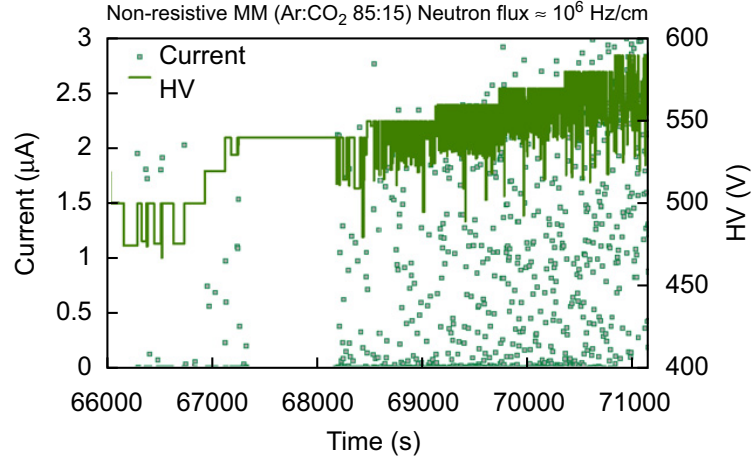
strips. Resistive and readout strips form therefore a capacitor and the signal produced in the avalanche is read capacitively from the readout strips. To define the amplification region, a woven stainless steel mesh (*amplification mesh*) is held by small pillars (400 μm of diameter), made of the photoimageable coverlay DuPoint™ Pyralux® PC 1025 [70], at a distance of 128 μm from the resistive strips. Finally, above the amplification region, at a distance of 5 mm, another stainless steel mesh (*drift mesh*) is put as drift electrode. A summary of the technical features of the two bulk micromegas prototypes referred to as T1 and T2 and used for the performed temperature tests, are reported in Tab. 2.3.

Fig. 2.17 shows the benefits coming from the application of the coverlay. Under neutron beams¹⁰ of 5.5 MeV, bulk micromegas does not show any evident voltage drop due to spark production [68].

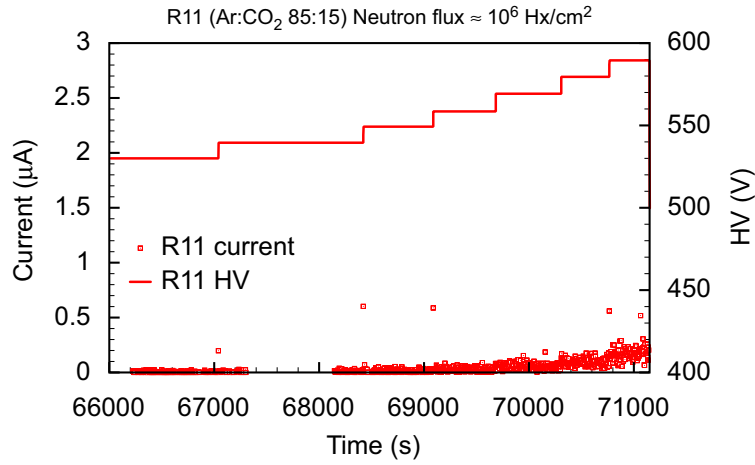
¹⁰The test was performed at the Demokritos National Laboratory in Athens.

T1 and T2 technical features	
active area	10x10 cm ²
readout strip width	300 μm
readout strip pitch	400 μm
resistive strip resistivity	20 M Ω /cm
amplification region height	128 μm
amplification mesh wire diameter	18 μm
amplification mesh pitch	63.5 μm
drift region height	5 mm
drift mesh wire diameter	30 μm
drift mesh pitch	80 μm

Table 2.3.: Technical features of the bulk micromegas detectors T1 and T2 [71].



(a)



(b)

Figure 2.17.: Monitored HV and currents as a function of the time under neutron irradiation for non-resistive micromegas (a) and resistive bulk micromegas (b). The continuous line shows the HV, the points the current [68].

2.3.1.3. Temperature measurements

Three different studies were performed for the characterisation of the micromegas behaviour as a function of the temperature. First of all the two resistive bulk micromegas detectors, T1 and T2, were warmed up inside a wooden insulated box (Fig. 2.18(a)) to temperature higher than 45°C , without applying any voltage to the drift electrode and without any radiation source that could generate any signal on the resistive strips. In these conditions, the dark current flowing from the resistive strips to the amplification mesh was monitored (Sect. 2.3.1.3.1). As a second step, taking into account that only the Pyralux material is interposed between the resistive strips and the mesh, this material was studied, using the test board shown in Fig. 2.18(b), to understand if changes in temperature could affect its resistivity and, consequently, justify the dark current increase (Sect. 2.3.1.3.2). Finally, using a ^{55}Fe source¹¹, the detector response of T1 as a function of the temperature was investigated to understand if the dark current could affect the detector performance (Sect. 2.3.1.3.3). In the initial and last tests the detectors were operated with an Ar:CO₂ 93:7 premixed gas at atmospheric pressure.

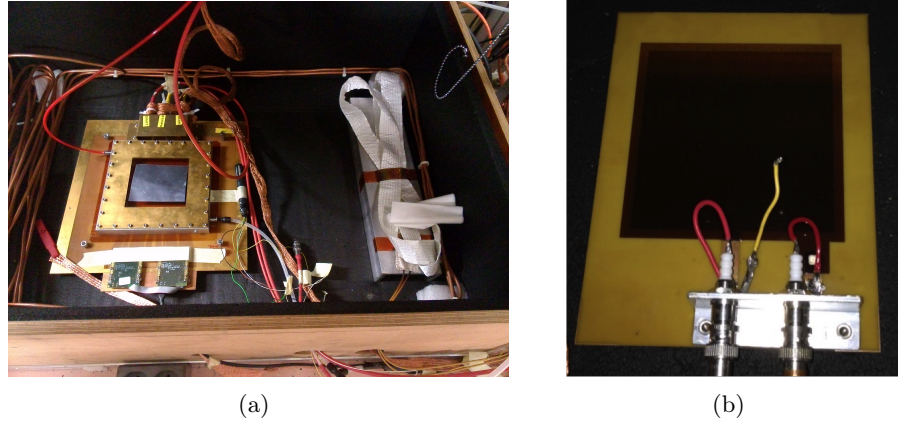


Figure 2.18.: (a) The wooden insulated box used for the temperature tests. Inside the box: on the left the chamber T1 and on the right the thermoelectric strip-device used to increase the temperature. (b) The test board used for the characterisation of the pillars material: a $10 \times 10 \text{ cm}^2$ copper area is covered with $128 \text{ }\mu\text{m}$ of DuPont™ Pyralux® PC 1025 material (brown area in the picture); a mesh has been applied on top of the Pyralux material to make possible the HV application.

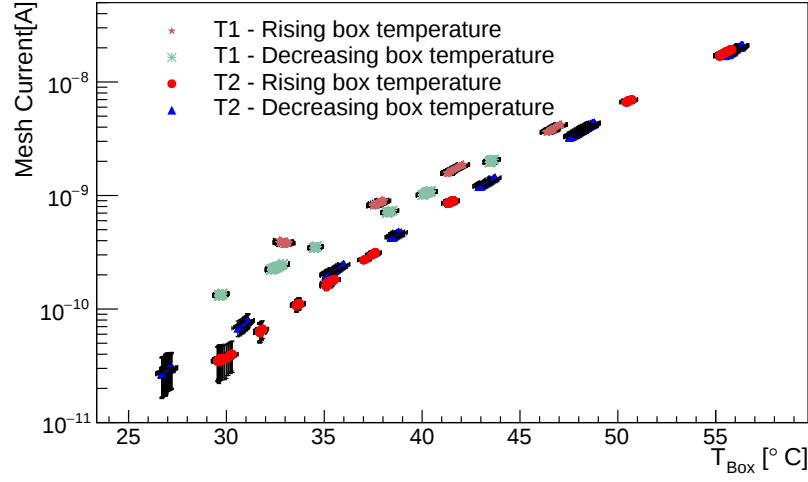
¹¹ ^{55}Fe decays to ^{55}Mn with a half-life of ~ 2.7 years by capturing a K-shell electron. The vacancy created is filled by an electron from a higher shell. The difference in energy is mainly released by emitting:

- Auger electrons of mean energy $\sim 5.2 \text{ KeV}$ ($\sim 60\%$ of the cases),
- K-alpha-1, K-alpha-2 X-rays with energy close to $\sim 5.9 \text{ KeV}$ ($\sim 25\%$ of the cases),
- K-beta X-rays with energy of $\sim 6.5 \text{ KeV}$ ($\sim 3\%$ of the cases).

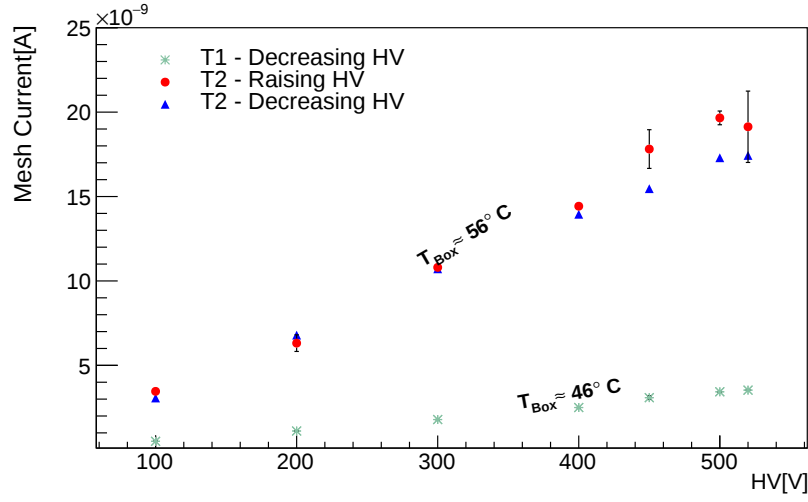
2.3.1.3.1. Dark current measurements

The dark current measurements were performed putting one of the T-chambers at a time inside the wooden insulated box, which was slowly warmed up by a thermoelectric strip-device connected to a potentiometer. In order to avoid gas thermalisation, a gas flow of 10 l/h was used, so that only the chambers material could be heated. The high voltage (HV) was applied only to the resistive strips and was set to +520 V. The micro-mesh instead was grounded through a pico-amperometer, needed to monitor the current coming from the micro-mesh itself. The temperature of the box (T_{Box}) and of the gas (T_{Gas}), at the gas outlet of the chamber, were monitored together with the atmospheric pressure (P).

As shown in Fig. 2.19(a) for both chambers, a dark current growing exponentially as a function of T_{Box} , was observed. No hysteresis effect was noticed: approximately the same current behavior was observed increasing and, successively, decreasing the box temperature, for both T1 and T2. Figure 2.19(b) suggests that the material responsible for the dark current must be ohmic. The HV scans, at $T_{Box} \approx 46^\circ\text{C}$ and 56°C , show in fact a linear correlation between the HV applied to the resistive strips and the measured current. Therefore a possible responsible for this behaviour is the Pyralux material.



(a)



(b)

Figure 2.19.: (a) The dark current observed for T1 and T2 while the box temperature was increased or decreased: for both chambers the linear trend on the log scale indicates an exponential growth of the current; no hysteresis effect seems to be present. (b) Mesh current as function of the HV at 46°C and 56°C.

2.3.1.3.2. Temperature test of the Pyralux material

Using the test board shown in Fig. 2.18(b), the resistivity (ρ) of the Pyralux material was measured in different conditions of temperature and, as shown in Tab. 2.4, it was observed that ρ decreases with increasing temperature. In particular, the tempera-

ture dependence shows an exponential behaviour that can easily explain the exponential growth of the dark current.

$T_{Box} [^{\circ}\text{C}]$	$\rho \text{ (}\Omega\text{cm)}$
≈ 20	$\approx 5 \times 10^{14}$
≈ 29	$\approx 1.2 \times 10^{14}$
≈ 38.3	$\approx 3 \times 10^{13}$
≈ 48.5	$\approx 6.8 \times 10^{12}$

Table 2.4.: Test board resistivity as function of the temperature.

Moreover, it was noticed that the nominal resistivity value provided by the Pylux material datasheet ($3.4 \times 10^{16} \Omega\text{cm}$) [70] could roughly be reached, for a temperature of about 20°C , only in an almost completely dry atmosphere as shown in Fig. 2.20.

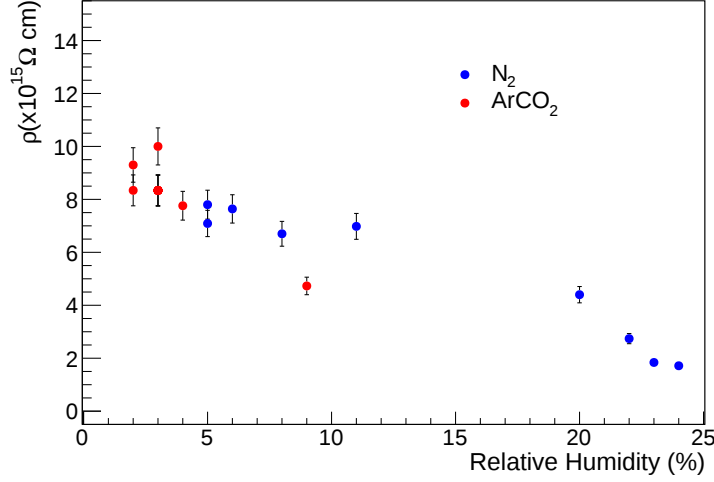


Figure 2.20.: Test board resistivity as a function of the environmental relative humidity: drying the test board with an Ar-CO₂ 93%-7% mixture or with N₂ gives the possibility to reach one order of magnitude higher resistivity values.

2.3.1.3.3. Detector performance

The chamber T1 was used to check the detector performance at high temperature. As for the dark current measurement, the chamber was warmed up inside the wooden insulated box but, in this case, applying HV also to the drift electrode (-300 V) and using a gas flow of 0.3 l/h to ensure the gas thermalisation. A ^{55}Fe source was used and its energy spectrum¹² was acquired several times, in different temperature conditions,

¹²The ^{55}Fe source was located on top of the chamber, where a window made of Kapton® was present.

via a multi-channel analyzer (MCA). The atmospheric pressure P , and the temperatures T_{Gas} , T_{Box} were constantly monitored, and for each MCA acquisition their average was computed.

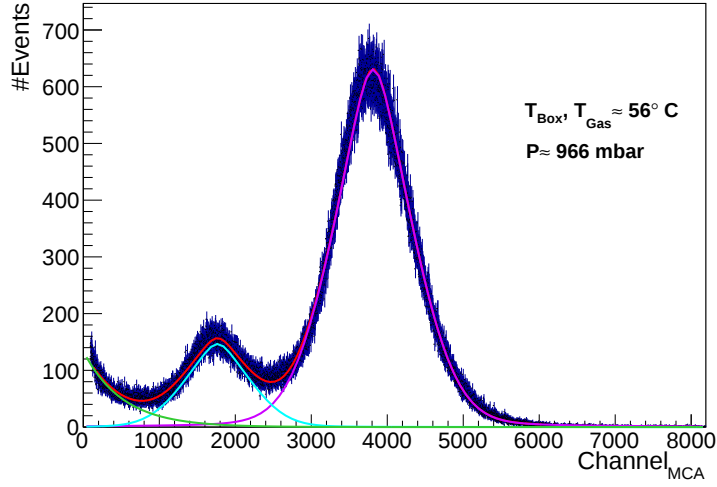
No issue was observed in the chamber operation up to a temperature of $\sim 56^\circ \text{C}$. For each collected ^{55}Fe spectrum, a fit was performed to evaluate the main peak position, x_{peak} , and the Full Width at Half Maximum (FWHM), as described in the caption of Fig. 2.21(a). Fig. 2.21(b) shows that x_{peak} increases linearly with the gas temperature for T_{Gas} up to the Pyralux glass-transition temperature (T_g), equal to 45°C as reported in [70], once the effect of the atmospheric pressure was taken into account. The corresponding effect on the gain can be seen in Fig. 2.22(a), where an increase of about 55% is observed varying the temperature from 20°C to 45°C . For the same temperature variation, an improvement in the energy resolution of the 8% was also visible, as shown in Fig. 2.22(b).

Given that the Kapton® ensures only the X-rays passage, the spectrum observed by the micromegas detector is only due to X-rays. A main peak corresponding to the K-alpha-1, K-alpha-2 X-rays is present together with the so-called *escape peak*, coming from the ionisation of a K-shell electron of an argon atom. Since the binding energy for a K-shell electron is 3.2 KeV, the energy of the ejected electron is roughly equal to 2.7 KeV.

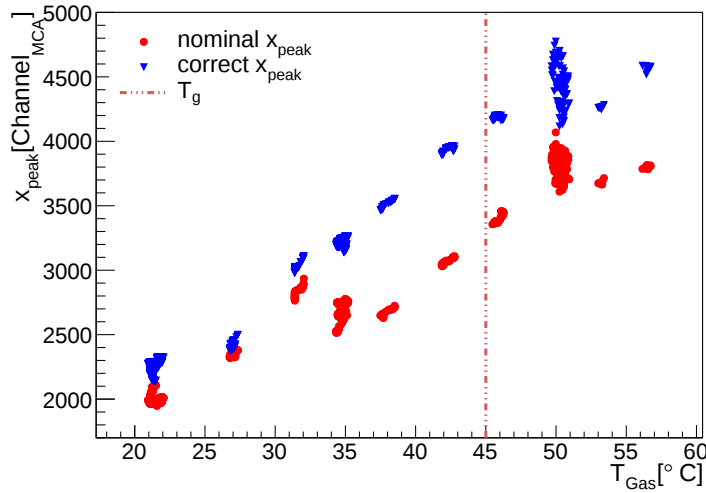
¹³In the Korff approximation the Townsend coefficient (α) is provided by

$$\frac{\alpha}{P} = Ae^{-\frac{BP}{E}}$$

where A and B are constants depending on the gas, P is the pressure and E is the electric field. For Ar and CO₂ the constants are respectively given by A=14 cm⁻¹ torr and B=180 V cm⁻¹ torr⁻¹, A=20 cm⁻¹ torr and B=466 V cm⁻¹ torr⁻¹.



(a)



(b)

Figure 2.21.: (a) A ^{55}Fe source spectrum, fitted with an exponential function (green curve) to take into account the background component and two Gaussian plus Cauchy distributions for the escape and main peak description (cyan and violet curves respectively); the final curve, describing all the different contributions, is shown in red. (b) The main peak position in the spectrum as a function of the gas temperature; the red points are obtained directly from the fit, the blue points are the same data after correcting the gas gain for the atmospheric pressure change, using the Korff approximation¹³ and assuming an initial value for the pressure of 950 mbar.

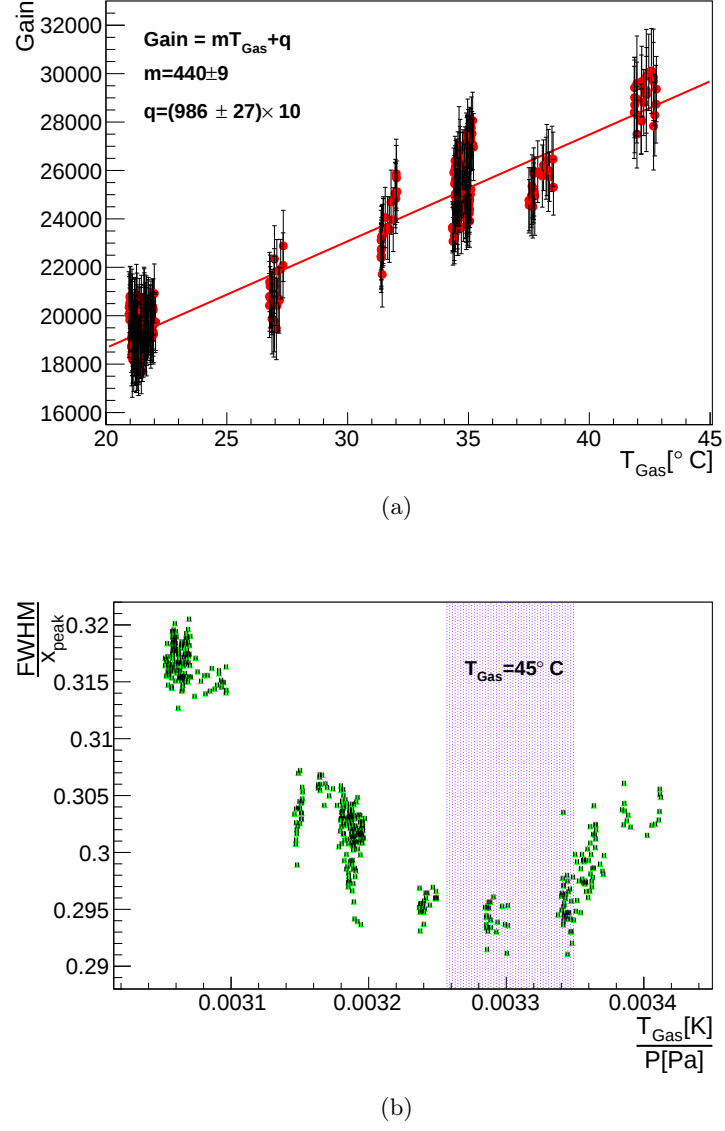


Figure 2.22.: (a) Gas gain as a function of the gas temperature. (b) Energy resolution as a function of T_{Gas}/P ; the shaded area represents the region where T_{Gas} is approximately $45^{\circ}C$.

2.3.1.3.4. Conclusion

The temperature behaviour of two small resistive micromegas detectors was studied. For both chambers the test, performed at fixed gas temperature, showed a dark current growing exponentially with the detector temperature, without any hysteresis effect. This behaviour is explained by the properties of the pillar material inside the MM chambers. It was, in fact, verified that its resistivity strongly decreases with growing temperature and increasing humidity. However, the detector performance was not affected; chamber T1 was able to operate at temperatures higher than 40°C, with a peak temperature of about 56°C. A linear growth of the gain was observed varying the temperature from 20°C to 45°C: in this temperature range the detector gain increased by about 55% while for the energy resolution an improvement of 8% was observed.

All the results, described in this section, were presented at 5th *International Conference on Micro-Pattern Gas Detectors* (MPGD2017), held at Temple University in Philadelphia in May 2017 [2].

Acknowledgments All the measurements were done at CERN RD51 GDD laboratory and I would like to thank the CERN RD51 GDD community for their continuous support.

Chapter 3.

Event reconstruction

The particles directly produced in the collisions or their decay products are reconstructed and identified through specific algorithms that take into account the informations provided by the various ATLAS sub-detectors. Depending on the analysis, the algorithms may be different and, for this reason, in this chapter it is described how the "objects" (electrons, muons, photons, the results of hadronisation processes called *jets* and missing transverse energy), which were used in this analysis, are defined in ATLAS.

3.1. Electrons

Electrons and positrons, collectively referred to as electrons in the ATLAS nomenclature, give rise to tracks in the inner detector and to energy deposits (clusters) in the electromagnetic calorimeter. Consequently, their reconstruction must involve both ID and EM [72] and, in the central region $|\eta| < 2.47$, it can be described through the following steps:

Seed-cluster reconstruction: a sliding window with a size 3×5 in units of 0.025×0.025 in $\eta \times \phi$ space, corresponding to the EM granularity of the middle layer (Fig. 2.11(b)), is used to identify calorimeter regions, called *seed*, with a total transverse energy¹ (E_T) above 2.5 GeV. Calorimeter clusters are then built around the seed using a clustering algorithm. The efficiency of this cluster search ranges from 95% at $E_T = 7$ GeV to more than 99% above $E_T = 15$ GeV.

Track reconstruction: pattern recognition and track fit algorithms are employed. The standard ATLAS pattern recognition [73] uses the pion hypothesis for energy loss at materials surfaces. This has been complemented with a modified pattern recognition algorithm (based on a Kalman filter-smoother formalism) [74] which assumes the electron hypothesis to allow energy loss at each material surface, accounting for possible bremsstrahlung. If a track seed (consisting of three hits in different layers of the silicon detectors) with a transverse momentum larger than 1 GeV cannot

¹It is common in collider physics to define a vector energy $\vec{E}$ by combining the energy deposited in the calorimeter with the deposit direction. For relativistic particles $\vec{E}$ is a good approximation of their momentum.

be extended to a full track of at least seven hits but it falls within one of the EM cluster region, a second attempt is performed with the new pattern recognition algorithm. Track candidates are then fit with the pion or electron hypothesis (in agreement with the hypothesis used in the pattern recognition), using the ATLAS Global χ^2 Track Fitter [75]. Moreover tracks, having at least four silicon hits and being loosely associated to electron clusters, are refit using an optimised Gaussian Sum Filter (GSF) [76] algorithm in order to take into account the bremsstrahlung effects.

Track-cluster matching: the electron candidates are obtained matching the EM cluster center of gravity with the position of the track extrapolated in the calorimeter middle layer and, in case more than one track points to the same cluster, priority is given to the track with silicon hits and with the smallest angular distance from the EM cluster² $\Delta R(\text{track}, \text{cluster})$. Electron candidates with no silicon hit associated to the track are discarded, in order to remove photon conversions.

Finally, the four-momentum of the electron is computed from the final calibrated cluster energy and the track variables η and ϕ associated to the electron.

In Run2 analyses, the electron track is requested to be compatible with the primary interaction vertex of the hard collision. The following conditions are then applied:

$$|d_0/\sigma_{d_0}| < 5, \quad |z_0 \sin \theta| < 0.5 \text{ mm} \quad (3.1)$$

where d_0 and z_0 are the transverse and longitudinal track impact parameters, i.e. d_0 and z_0 are respectively the transverse and the longitudinal component of the track distance of closest approach to the reconstructed primary vertex³. θ is the polar angle of the track and σ_{d_0} indicates the measured d_0 resolution.

3.1.1. Electron identification

The electron candidates are further selected against backgrounds, such as hadrons or non-prompt electrons from photon conversions or heavy flavour decays, using several

²The angular distance between two points of coordinates (η_1, ϕ_1) and (η_2, ϕ_2) is defined as $\Delta R = \sqrt{(\eta_1 - \eta_2)^2 + (\phi_1 - \phi_2)^2}$.

³The reconstruction of the primary vertex is performed considering a sub-set of all reconstructed tracks, which satisfies a series of criteria that let to maintain a low rate of fake tracks (tracks which do not share a large proportion of hits with a true particle traversing the detector). Once the set of tracks is defined, vertices are reconstructed in the following steps[77]:

- a seed position for the first vertex is selected. The transverse position of the first seed is taken as the centre of the beam spot. The z -coordinate of the seed is instead the mode of the z -coordinates of the tracks at their respective points of closest approach to the reconstructed centre of the beam spot.
- The track and the seed are used to estimate the best vertex position through an iterative procedure where, for each iteration, less compatible tracks are down-weighted and the vertex position is recomputed.
- Once the vertex position is determined, the incompatible tracks are considered for the determination of other vertices.

sets of identification criteria with different levels of background rejection and signal efficiency [72]. These identification criteria rely on the shapes of the electromagnetic showers in the calorimeter, information from the transition radiation tracker, track-cluster matching related quantities, track properties and variables measuring bremsstrahlung effects. For the Run2 data analyses, likelihood-based (LH) methods have been used for the electron identification.

The likelihood method is a multivariate analysis technique that simultaneously evaluates several properties of the electron candidates when performing the selection decision. In particular it uses the signal (real electron) and background (fake electron) distributions of the discriminating variables mentioned before in order to define overall signal and background probabilities, needed for the construction of the final discriminator. Three levels of identification have been initially provided for electrons and, with respect to their tightness, they are referred to as *Loose*, *Medium* and *Tight*. In particular, the three different "working points" use the same variables but a different selection is applied so that the electrons classified as *Tight* are all selected among the *Medium* ones, which in turn are all selected among the *Loose* ones. Moreover, the working points are optimised in several bins of $|\eta|$ and E_T , since the shower shape and the track properties are expected to change significantly with the increase of the electron energy or the amount of crossed material. Figure 3.1 shows the efficiency to identify an electron as a function of the electron E_T and $|\eta|$.

Two additional working points, called *Loose+B-layer cut* and *VeryLoose*, have been defined starting from the *Loose* operating point; the most significant difference with respect to it is related to the additional request of a hit in the innermost pixel layer for *Loose+B-layer cut* and of just one hit in the pixel detector instead of two, for the *VeryLoose*.

3.1.2. Electron isolation

In addition to the identification criteria described above, isolation requirements are imposed to further discriminate signal from background [72]. The isolation variables quantify the energy of the particles produced around the electron candidate and allow to disentangle prompt electrons from other non-isolated electron candidates, such as electrons originating from converted photons or heavy flavour decays or light hadrons mis-identified as electrons. Two discriminating variables have been designed to this purpose:

- a calorimetric isolation energy, $E_T^{\text{cone0.2}}$, defined as the sum of transverse energies of clusters within a cone of $\Delta R = 0.2$ around the candidate electron cluster. The E_T contained in a rectangular cluster of size $\Delta\eta \times \Delta\phi = 0.125 \times 0.175$ centered on the electron cluster center of gravity is subtracted, in order to remove from the cone the energy of the electron itself.
- a track isolation, $p_T^{\text{varcone0.2}}$, defined as the sum of transverse momenta of all tracks with $p_T > 1$ GeV and within a cone of $\Delta R = \min(0.2, 10 \text{ GeV}/E_T)$ around the candidate electron track, excluding the electron track itself and additional tracks coming from converted bremsstrahlung photons from the electron itself.

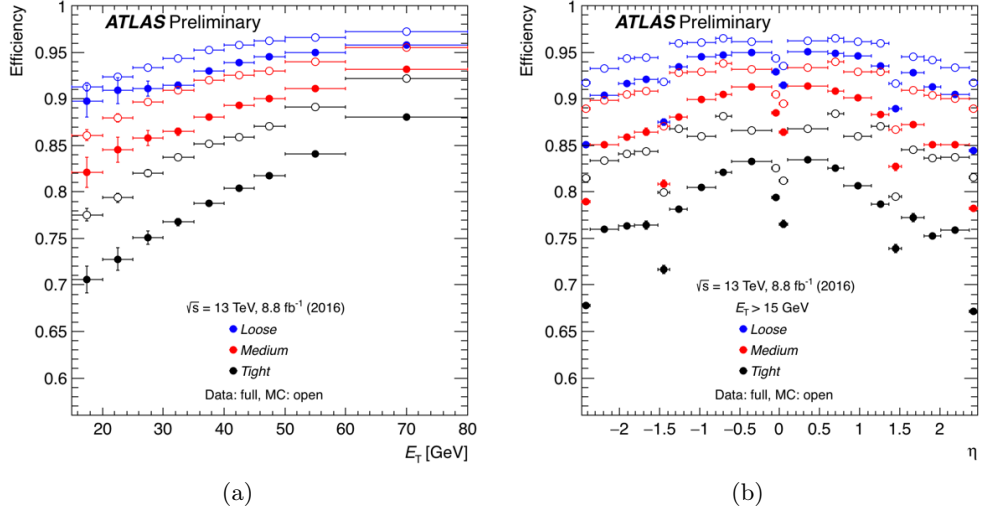


Figure 3.1.: Electron identification efficiencies in $Z \rightarrow e^+e^-$ events as function of the electron transverse energy and pseudorapidity using 8.8 fb^{-1} of data recorded at $\sqrt{s} = 13 \text{ TeV}$ and Monte Carlo (MC) simulations. The lower efficiency in data than in MC comes from a known mismodelling in TRT conditions and calorimeter shower shapes in the detector simulation, which are used in the likelihood discriminant [78]. The discrepancy between data and Monte Carlo is corrected in the various analyses by applying dedicated scale factors.

A variety of selection requirements on the quantities $E_T^{\text{cone0.2}}/p_T$ and $p_T^{\text{varcone0.2}}/p_T$ have been defined to select isolated electron candidates. The resulting working points are divided into two classes:

- efficiency targeted working points, where the requirements are chosen to obtain a given isolation efficiency ϵ_{iso} , which can be either constant or a function of p_T .
- fixed requirement working points, where the upper thresholds on the isolation variables are constant.

Table 3.1 shows the definition of the various working points used for electron isolation.

3.2. Photons

Even if photons are not considered in the analysis described in this thesis, details about their definition are reported here for completeness, given that they have very similar signatures to the electrons, in the electromagnetic calorimeter, and their reconstruction proceeds in parallel with the electrons one [79].

For photons candidates, in contrast to what happens for electrons, it is expected to observe an EM cluster either without any associated track, if there is no photon conversion, or with two tracks, if the photon converts in a positron-electron pair; while for the

(a)			
Efficiency targeted operating points			
Operating point	Calorimeter isolation	Track isolation	Total efficiency
LooseTrackOnly	-	99%	99%
Loose	99%	99%	99%
Tight	96%	99%	95%
Gradient	$0.1143\% \times p_T + 92.14\%$	$0.1143\% \times p_T + 92.14\%$	90% at $p_T = 25$ GeV 99% at $p_T = 60$ GeV
GradientLoose	$0.057\% \times p_T + 95.57\%$	$0.057\% \times p_T + 95.57\%$	95% at $p_T = 25$ GeV 99% at $p_T = 60$ GeV

(b)		
Fixed requirement operating points		
Operating point	Calorimeter isolation	Track isolation
FixedCutLoose	0.20	0.15
FixedCutTightTrackOnly	-	0.06
FixedCutTight	0.06	0.06

Table 3.1.: (a) Electron isolation efficiency targeted operating points: the number expressed in percents represent the target efficiencies used in the operating point optimisation procedure. For the Gradient and GradientLoose operating points, p_T is in GeV. (b) Electron isolation fixed requirement operating points. The calorimeter and track isolation refer to the selection based on $E_T^{\text{cone}0.2}/p_T$ and $p_T^{\text{varcone}0.2}/p_T$, respectively [72].

first case, referred as *unconverted photon*, there is no need of additional steps in the object reconstruction, for the latter one, considered as a *converted photon*, there is the necessity to reconstruct the conversion vertex in order to distinguish between electron and photon objects. Once the track-cluster matching is performed, if there are tracks associated to the electromagnetic cluster, *double-track* conversion vertex candidates are reconstructed from pairs of oppositely charged tracks that are likely to be electrons; obviously the track pairs selection is based on the assumption that converted photon tracks are close and parallel at the conversion point. Track pairs are classified into three categories, based on the fact that both tracks (Si-Si), none (TRT-TRT) or only one of them (Si-TRT) have hits in the silicon detectors and a conversion vertex fit is then performed.

The final photon energy measurement is computed using information from the calorimeter, with a cluster size that depends on the photon classification. In the barrel, a cluster of size $\Delta\eta \times \Delta\phi = 0.075 \times 0.123$ is used for unconverted photon candidates, while a cluster of size 0.075×0.172 is used for converted photon candidates to compensate for the opening between the conversion products in the ϕ direction due to the solenoid magnetic field. Instead in the end-cap a cluster size of 0.125×0.123 is used for all candidates.

3.2.1. Photon identification

To distinguish prompt photons from background photons, photon identification with high signal efficiency and high background rejection is required for transverse momenta from 10 GeV to the TeV scale. In ATLAS Photon identification [79] is based on a set of cuts on several discriminating variables, as for example the lateral and longitudinal shower development in the EM calorimeter or the shower leakage fraction in the hadronic calorimeter. Prompt photons typically produce narrower energy deposits in the EM calorimeter and have smaller leakage into the hadronic one compared to background photons from jets, due to the presence of additional hadrons near the photon candidate in the latter case. In addition, background candidates from isolated $\pi^0 \rightarrow \gamma\gamma$ decays are often characterised by two separate local energy maxima in the finely segmented first EM calorimeter layer, due to the small separation between the two photons.

In general all the selection criteria are different according to the reconstructed photon pseudorapidity, to account for the calorimeter geometry and for the different effects on the shower shapes from the material upstream of the calorimeter, which is highly non-uniform as function of $|\eta|$.

3.2.2. Photon isolation

The isolation requirements for the photons are based on the same variables used for the electrons (Sect. 3.1.2), $E_T^{\text{cone}0.2}$ and $p_T^{\text{varcone}0.2}$, with the addition of $E_T^{\text{cone}0.4}$ where a cone of $\Delta R = 0.4$ is used instead of 0.2.

3.3. Jets

Quarks and gluons produced in the interaction must go through a hadronisation process, generating a bunch of hadrons which approximately follows the direction of the original parton and can give information about their energy thanks to its energy deposits in the calorimeters, in particular in the hadronic one. The reconstruction of these bunches of hadrons is done through clustering algorithm that lead to the definition of objects called *jets*.

In particular, jets are reconstructed assuming, as constituents, calorimeter topological clusters (topo-clusters), which are neighbouring cells that show a significant amount of energy. Each topo-cluster can represent a full or a fractional response to a single particle (i.e. a full shower or a shower fragment) or the response to several particles [81]. For each cluster the relevant variables needed for the jet definition are the sum of the energies of its cells and the cluster direction with respect to the interaction point: from these variables it is possible to define a zero mass four-vector that can be used as input to the jet definition algorithm, which merges the clusters in jets.

The ATLAS collaboration has adopted the anti- k_t algorithm as jet definition algorithm [82]. It introduces the concept of distance between entities (particles or clusters) and associates those ones within a given distance R . Once the jet algorithm has defined the final jet, energies and momenta of the clusters belonging to it are added together.

However, due to the fact that ATLAS calorimeters are not compensated, the energy is calibrated according to specific corrections for the hadronic components [83].

3.3.1. Jet Vertex Tagger

Hard-scattering collision, that typically triggers the event, are accompanied by soft pp interactions, referred to as *in-time pile-up*. At the same time, when the detector and/or electronics integration time is significantly larger than the time between crossings, signals from collisions in other bunch crossings can be present and results in the so-called *out-of-time pile-up*. Concerning the jet reconstruction, both in-time and out-of-time pile-up contribute as energy deposits in the ATLAS calorimeters. This additional transverse energy is typically subtracted on average from the hard-scattering interaction of interest. However local fluctuations in the pile-up activity may comport the reconstruction of spurious jets, which are referred to as pile-up jets.

To reject these pile-up (PU) jets in favour of the hard-scattering (HS) ones [84], the following variables have been introduced:

- pile-up corrected Jet Vertex Fraction (corrJVF), defined as

$$\text{corrJVF} = \frac{\sum_k p_T^{\text{trk}_k}(\text{PV}_0)}{\sum_l p_T^{\text{trk}_l}(\text{PV}_0) + \sum_{n \geq 1} \sum_l p_T^{\text{trk}_l}(\text{PV}_n) / (k \cdot n_{\text{trk}}^{\text{PU}})} \quad (3.2)$$

where $\sum_k p_T^{\text{trk}_k}(\text{PV}_0)$ is the scalar p_T sum of tracks that are associated with the jet originated from the hard-scattering vertex (PV_0), instead the term $p_T^{\text{PU}} = \sum_{n \geq 1} \sum_l p_T^{\text{trk}_l}(\text{PV}_n)$ denotes the scalar p_T sum of the tracks coming from any of the pile-up interactions, with vertices different from V_0 . To take into account the linear increase of the average p_T^{PU} with the total number of pile-up tracks per event ($n_{\text{trk}}^{\text{PU}}$), p_T^{PU} is divided by $(k \cdot n_{\text{trk}}^{\text{PU}})$ with $k = 0.01$. corrJVF is set to -1 for those jets without any associated track. The Jet Vertex Fraction (JVF) variable is defined similarly to corrJVF but without dividing for $(k \cdot n_{\text{trk}}^{\text{PU}})$.

- R_{pT} , defined as

$$R_{pT} = \frac{\sum_k p_T^{\text{trk}_k}(\text{PV}_0)}{p_T^{\text{jet}}} \quad (3.3)$$

where p_T^{jet} is the fully calibrated jet p_T after the pile-up subtraction.

Figures 3.2(a) and 3.2(b) show respectively the corrJVF and R_{pT} distribution for pile-up and hard-scattering jets in simulated dijets events. A good discrimination power is observed for both variables. Moreover, as found after applying a selection based on corrJVF or R_{pT} , the hard-scattering jet efficiency has a stable behaviour as a function of the total number of reconstructed primary vertices in the event (Fig. 3.3).

A new discriminant variable, called jet vertex tagger (JVT), is built from R_{pT} and corrJVT as a 2-dimensional likelihood, based on a k-nearest neighbor (kNN) algorithm [85],

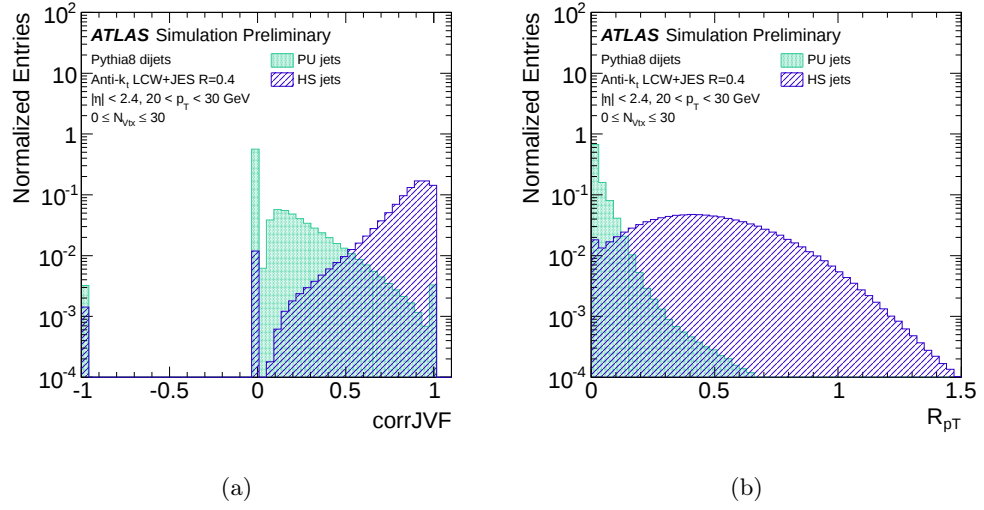


Figure 3.2.: Distribution of the variables corrJVF (a) and R_{pT} (b) for pile-up and hard-scattering jets with $20 < p_T < 30$ GeV [84].

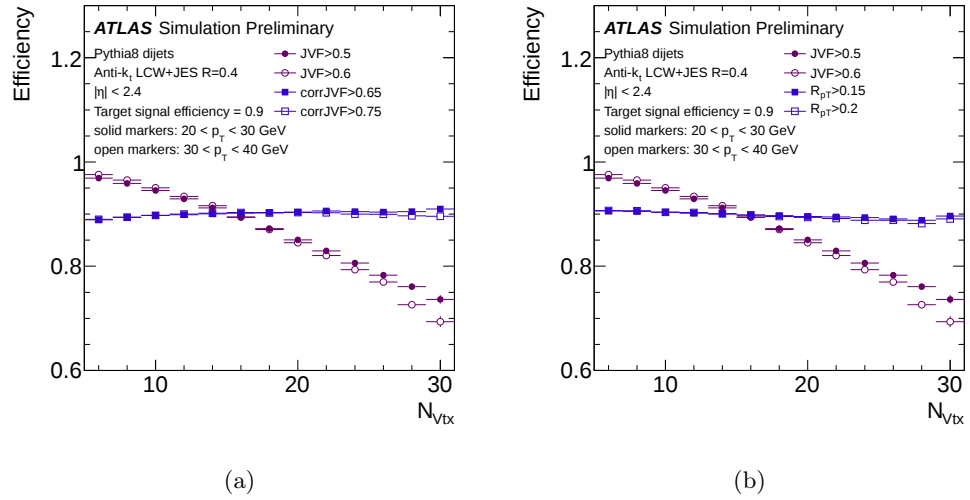


Figure 3.3.: Dependence on the total number of primary vertices in the event of the hard-scattering jet efficiency for $20 < p_T < 30$ GeV (solid markers) and $30 < p_T < 40$ GeV (open markers) jets after applying fixed cuts on corrJVF (a) and R_{pT} (b) such that the inclusive efficiency is 90%. The efficiency of JVF cut is also shown. The cut values imposed on the variables are specified in the legend [84].

to further enhance the discrimination power, as shown in Fig. 3.4. The final recommendation⁴ for the Run2 SUSY analyses is to reject all the jets with $p_T < 60$ GeV, $|\eta| < 2.4$ and $JVT < 0.59$ to avoid pile-up jet contamination.

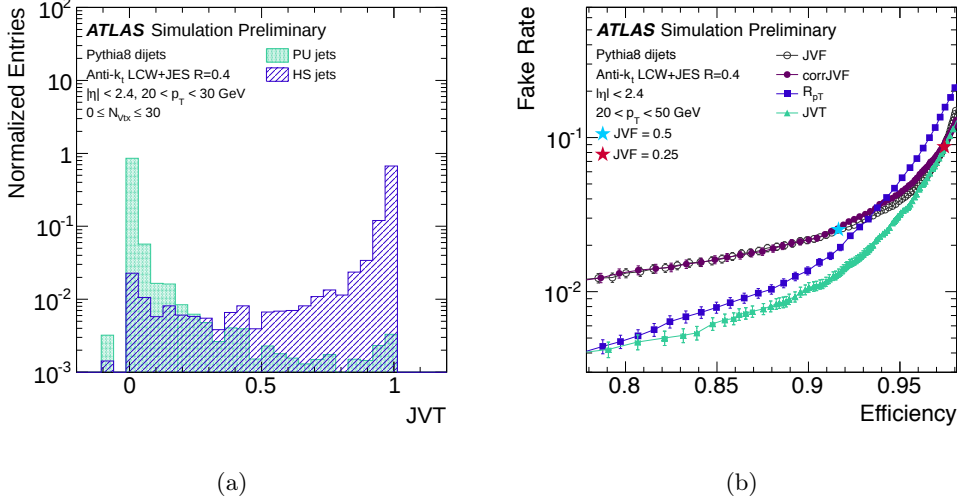


Figure 3.4.: (a) Distribution of the JVT variable for pile-up and hard-scattering jets with $20 < p_T < 30$ GeV. (b) fake rate from pile-up jets versus hard-scattering jet efficiency curves for the variables JVF, corrJVF, R_{pT} and JVT. Two JVF working points, related to the cut values 0.25 and 0.5, are indicated with red and blue stars [84].

3.3.2. Jet quality selection

In addition to pile-up, there are also the following sources of background that may simulate a jet:

- beam induced background (BIB) due to proton losses upstream of the interaction point, inducing secondary cascades that can reach the ATLAS detector;
- cosmic-ray showers produced in the atmosphere overlapping with collision events;
- calorimeter large and coherent noise or isolated pathological cells.

The selection criteria able to reject jets coming from the processes mentioned above are based on variables that use:

- the characteristic ionisation signal shape of the liquid argon calorimeters;
- the electromagnetic fraction (f_{EM}), defined as the ratio of the energy deposited in the electromagnetic calorimeter to the total energy of the jet;

⁴This prescription is applied only after the overlap removal procedure which is described in Sect. 4.5.1.

- the HEC energy fraction (f_{HEC}), defined as the ratio of the energy deposited in the hadronic electromagnetic calorimeter to the total energy of the jet;
- the maximum energy fraction (f_{max}) in any single calorimeter layer;
- the jet charged fraction (f_{ch}), defined as the ratio of the scalar sum of the p_T of the tracks coming from the primary vertex associated to the jet and the jet p_T .

Jets originating from beam-induced background or calorimeter noise tend to be more localised longitudinally in the calorimeters than jets from proton-proton collisions. Therefore, all the variables characterizing the expected direction of the shower development can be employed to discriminate between good jets and jets arising from non-collision backgrounds.

Two different selections have been developed: the *loose* selection is designed to provide an efficiency of selecting jets from proton-proton collisions above 99.5% (99.9%) for $p_T > 20$ (100) GeV; the *tight* criterion, instead, is designed to further reject background jets with an efficiency of selecting jets from proton-proton collisions above 95% (99.5%) for $p_T > 20$ (100) GeV [86].

3.3.3. b-tagging

The identification of jets containing b -hadrons (b -tagged jet) is an important feature for several analyses [87]. Taking into account the long lifetime of b -hadrons (~ 1.5 ps, $c\tau \sim 450$ μm), the identification of b -tagged jets is based on three distinct strategies encoded in three basic algorithms that look at:

- the impact parameter,
- the secondary vertex,
- the decay chain.

However, to achieve a better discrimination, a Boosted Decisions Trees (BDT) algorithm [85] combining the output of the basic algorithms listed above is applied. In particular, three BDT variants: MV2c00, MV2c10 and MV2c20 are released varying the c -jet fraction in the training. In MV2c20 the background sample is composed of 15% (85%) c - (light-flavour) jets, in MV2c10 a mixture of 93% light-flavour jets and 7% c -jets is used as background, finally in MV2c00 no c -jet contribution is considered⁵.

Table 3.2 shows the operating points defined for MV2c10 together with performance values. Figure. 3.5 shows, as an example, the MV2c10 BDT output.

⁵In the previous version of the algorithms MV2c20, MV2c10 and MV2c00 were trained against background with a percentage of c -jets respectively equal to 20%, 10% and 0% [87].

BDT cut value	b -jet efficiency[%]	c -jet rejection	light-jet rejection	τ rejection
0.9349	60	34	1358	184
0.8244	70	12	381	55
0.6459	77	6	134	22
0.1758	85	3.1	33	8.2

Table 3.2.: Operating points for the MV2c10 b -tagging algorithm, listed together with the relative efficiencies and rejections (defined as the inverses of the corresponding efficiencies) for jets with $p_T > 20$ GeV [87].

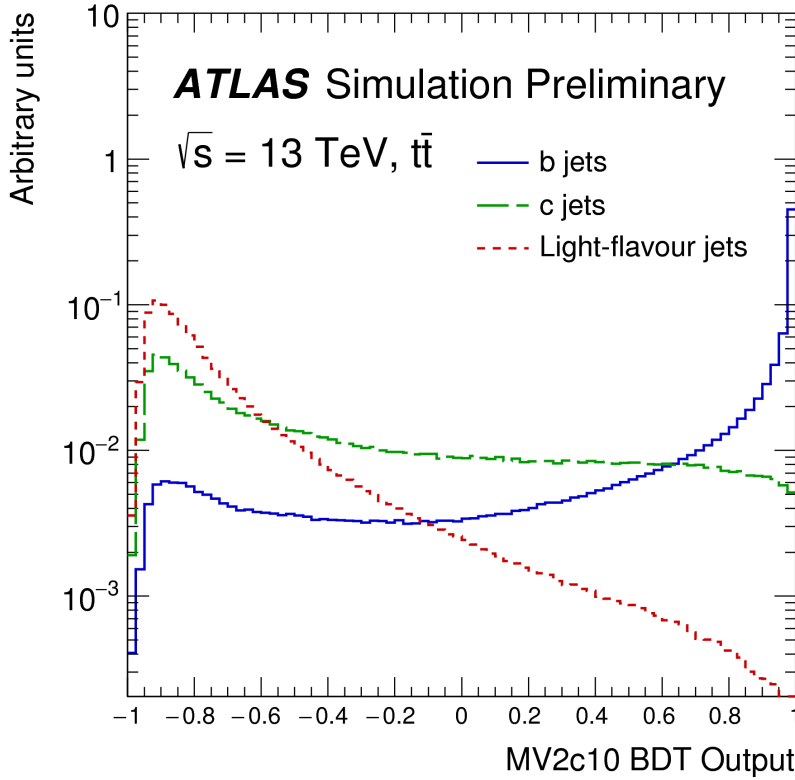


Figure 3.5.: MV2c10 BDT output for b - (solid blue), c - (dashed green) and light-flavour (dotted red) jets [87].

3.4. Muons

Muon reconstruction is initially performed in an independent way in the inner detector and in the muon spectrometer. Then the information from the various subdetectors, calorimeters included, is combined to provide the muon tracks [88].

In the ID, muons are reconstructed like any other charged particle, following the procedure described in Sect. 3.1. In the MS the reconstruction starts searching for hit patterns inside each MDT chamber to form segments. The algorithm then performs a segment-seeded combinatorial search using as seeds the segments generated in the middle layers of the MS, where more trigger hits are available, and successively the segments from the outer and inner layers. The segments are selected using criteria based on hit multiplicity and fit quality and are matched using their relative position and angles. At least two matching segments are required to build a track, except in the barrel-endcap transition region where a single high-quality segment with η and ϕ information can be used. The same segment can initially be used to build several track candidates and then an overlap removal algorithm selects the best assignment to a single track or allow the sharing of the segment between two tracks. To ensure high efficiency for close muons, all tracks with segments in the three different layers of the spectrometer are kept when they are identical in two out of three layers but share no hits in the outermost layer. As for the electrons, the hits associated with each track candidate are finally fitted using a global χ^2 fit.

Once the information from ID, MS and calorimeters are provided, four muon categories are defined depending on which subdetectors are used in their reconstruction:

- *Combined (CB) muons*: track reconstruction is performed independently in the ID and MS, then a combined track is formed with a global refit that uses the hits from both the ID and MS subdetectors. Most muons are reconstructed following an outside-in pattern recognition, in which the muons are first reconstructed in the MS and then extrapolated inward and matched to an ID track (an inside-out combined reconstruction is used as a complementary approach).
- *Segment-tagged (ST) muons*: a track in the ID is classified as muon if, once extrapolated to MS, it can be associated with at least one local track segment in the MDT or CSC chambers. ST muons are used when muons cross only one layer of MS chambers, either because of their low p_T or because they fall in regions with reduced MS acceptance.
- *Calorimeter-tagged (CT) muons*: a track in the ID is identified as muon if it can be matched to an energy deposit in the calorimeter compatible with a minimum-ionizing particle (MIP). This category has the lowest purity among all muon categories but it recovers acceptance in the region where the ATLAS muon spectrometer is only partially instrumented to allow for cabling and services of the calorimeters and the inner detector. The identification criteria for CT muons are optimised for the region $|\eta| < 0.1$ and a momentum range $15 < p_T < 100$ GeV.
- *Extrapolated (ME) muons*: the muon trajectory is reconstructed relying only on the MS track and applying a loose requirement on the compatibility of this track with the interaction point. ME muons are mainly used to extend the acceptance of muon reconstruction into the region $2.5 < |\eta| < 2.7$, which is not covered by the ID.

Overlaps between different muon categories are resolved before producing the collection of muons used in physics analysis: when two muon categories share the same ID track, preference is given to CB muons, then to ST, and finally to CT muons; the overlap with ME muons is instead resolved by analysing the track hit content and selecting the track with the better fit quality and the larger number of hits.

In Run2 muons are required to be compatible with the primary interaction vertex by applying the following constraints:

$$|d_0/\sigma_{d_0}| < 3, \quad |z_0 \sin \theta| < 0.5 \text{ mm.} \quad (3.4)$$

3.4.1. Muon identification

Muon identification is performed by applying quality requirements that suppress background, mainly from pion and kaon decays, while selecting prompt muons with high efficiency and/or guaranteeing a robust momentum measurement [88].

Muon candidates originating from in-flight decays of charged hadrons in the ID are often characterized by the presence of a distinctive *kink* topology in the reconstructed track. As consequence, it is expected that the fit quality of the resulting combined track is poor and that the momentum measured in the ID and MS may not be compatible. For CB tracks, the variables used in prompt muon identification are, for example:

- q/p significance, defined as the absolute value of the difference between the ratio of the charge and momentum of the muons measured in the ID and MS divided by the sum in quadrature of the corresponding uncertainties;
- ρ' , defined as the absolute value of the difference between the transverse momentum measurements in the ID and MS divided by the p_T of the combined track;
- normalised χ^2 of the combined track fit.

In addition, specific requirements on the number of hits in the ID and MS are also employed.

Four muon selections (*Loose*, *Medium*, *Tight* and *High- p_T*) are provided: *Loose*, *Medium* and *Tight* are inclusive categories where muons identified with tighter requirements are also included in the looser categories. Table 3.3 shows the efficiency to identify a prompt muon for the various operating points.

3.4.2. Muon isolation

For the muon isolation requirements, $p_T^{\text{varcone0.3}}$, with $\Delta R = \min(10 \text{ GeV}/p_T, 0.3)$, and $E_T^{\text{cone0.2}}$ are used in a similar way as described in Sect. 3.1.2. Table 3.4 lists the seven isolation operating points with the discriminating variables and the criteria used for their definition [88].

Operating points	4 < p _T < 20 GeV		20 < p _T < 100 GeV	
	ϵ _μ ^{MC} [%]	ϵ _{Hadrons} ^{MC} [%]	ϵ _μ ^{MC} [%]	ϵ _{Hadrons} ^{MC} [%]
Loose	96.7	0.53	98.1	0.76
Medium	95.5	0.38	96.1	0.17
Tight	89.9	0.19	91.8	0.11
High-p _T	78.1	0.26	80.4	0.13

Table 3.3.: Efficiency for prompt muons from W decays ($\epsilon_{\mu}^{\text{MC}}$) and in-flight hadron ($\epsilon_{\text{Hadrons}}^{\text{MC}}$) decays misidentified as prompt muons. The results are shown for the four selection criteria listed in the text, separating low and high momentum muons for candidates with $|\eta| < 2.5$ [88].

Isolation operating point	Discriminating variable(s)	Definition
LooseTrackOnly	$p_T^{\text{varcone0.3}}/p_T$	99% efficiency constant in η and p_T
Loose	$p_T^{\text{varcone0.3}}/p_T, E_T^{\text{cone0.2}}/p_T$	99% efficiency constant in η and p_T
Tight	$p_T^{\text{varcone0.3}}/p_T, E_T^{\text{cone0.2}}/p_T$	96% efficiency constant in η and p_T
Gradient	$p_T^{\text{varcone0.3}}/p_T, E_T^{\text{cone0.2}}/p_T$	$\geq 90(99)\%$ efficiency at 25(60) GeV
GradientLoose	$p_T^{\text{varcone0.3}}/p_T, E_T^{\text{cone0.2}}/p_T$	$\geq 95(99)\%$ efficiency at 25(60) GeV
FixedCutTrackOnly	$p_T^{\text{varcone0.3}}/p_T$	$p_T^{\text{varcone0.3}}/p_T < 0.06$
FixedCutLoose	$p_T^{\text{varcone0.3}}/p_T, E_T^{\text{cone0.2}}/p_T$	$p_T^{\text{varcone0.3}}/p_T < 0.15$
		$E_T^{\text{cone0.2}}/p_T < 0.30$

Table 3.4.: Definition of the seven isolation operating points. The discriminating variables are listed in the second column and the criteria used in the definition are reported in the third column [88].

3.5. Missing transverse energy

Momentum conservation in the transverse plane implies that the sum of the transverse momenta of all the collision products must be approximately zero. An imbalance in the sum of visible transverse momenta is referred to as *missing transverse energy*, or E_T^{miss} , and it may indicate the presence of weakly interacting stable particles in the final state. These particles are the neutrinos within the Standard Model, while in a SUSY scenario where R-parity is conserved, good candidates are the neutralinos, too.

The E_T^{miss} reconstruction process uses reconstructed, calibrated objects to estimate the transverse momentum imbalance in an event [89]. In particular it is calculated along the $x(y)$ -axis as:

$$E_{x(y)}^{\text{miss}} = E_{x(y)}^{\text{miss},e} + E_{x(y)}^{\text{miss},\gamma} + E_{x(y)}^{\text{miss},\tau} + E_{x(y)}^{\text{miss},\text{jets}} + E_{x(y)}^{\text{miss},\mu} + E_{x(y)}^{\text{miss},\text{soft}} \quad (3.5)$$

where the terms relative to jets, charged lepton and photons are the negative sum of the momenta for the respective calibrated objects. The *soft* term ($E_{x(y)}^{\text{miss},\text{soft}}$) is usually

3.5. Missing transverse energy

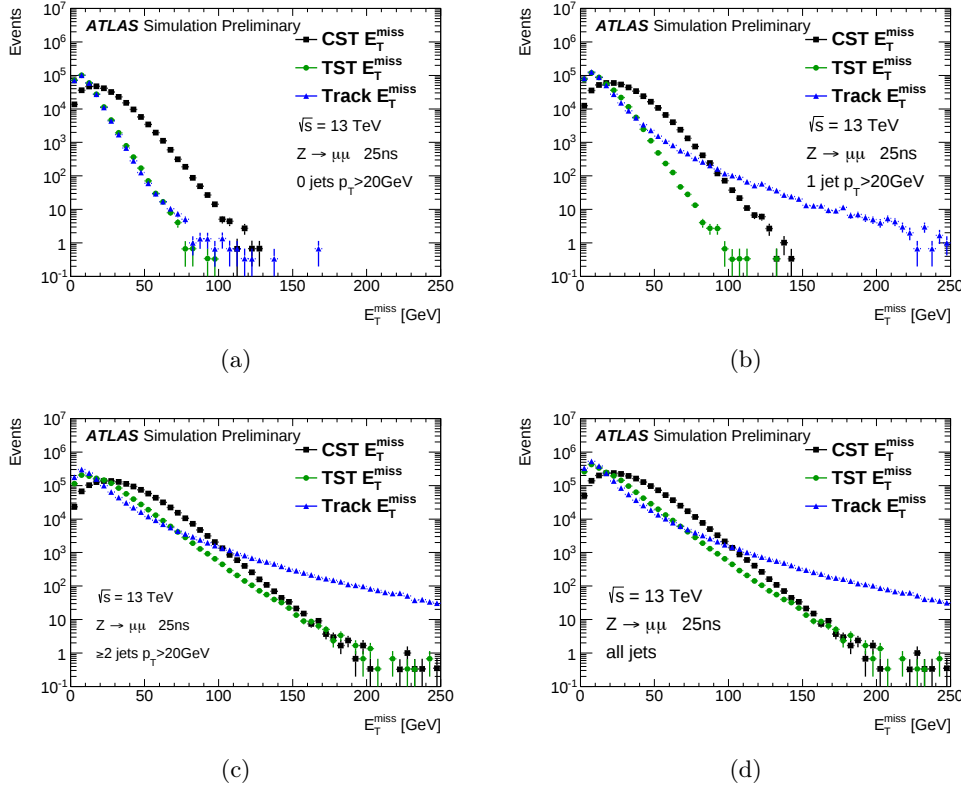


Figure 3.6.: Distribution of TST E_T^{miss} , CST E_T^{miss} and Track E_T^{miss} obtained from $Z \rightarrow \mu\mu$ simulated events. The distributions are separated on the basis of the number of calibrated jets with $p_T > 20$ GeV. The four figures show events with 0, 1, 2 or more jets [89], as described in the legends.

computed from the transverse momentum deposited in the detector but not associated with any reconstructed object; it may be obtained in two different ways:

- calorimeter-based methods, where all the energy deposits in calorimeter cells, grouped into clusters and not associated to any reconstructed hard object, are included in the Calorimeter Soft Term (CST). The corresponding E_T^{miss} is referred to as CST E_T^{miss} and it was the standard definition used in most Run1 analyses.
- Track-based methods, resulting in the Track Soft Term (TST), where all the tracks not associated to any reconstructed object but associated to a hard scattering vertex, are included. Since tracks may be accurately matched to a primary vertex, the TST is relatively insensitive to pile-up effects. However it does not include contributions from soft neutral particles and from forward regions ($|\eta| > 2.5$). The corresponding missing transverse energy is labelled as TST E_T^{miss} .

Moreover, a missing transverse energy definition, known as Track E_T^{miss} and completely

based on the momenta of the ID tracks, has been also developed. The Track E_T^{miss} is reconstructed as the negative sum of the momenta of ID tracks; only for electrons the track p_T is replaced by the calorimeter cluster measurement to take into account the energy lost in the ID. For Track E_T^{miss} the soft term is reconstructed from ID tracks not matched to either electrons or muons.

From the components $E_{x(y)}^{\text{miss}}$, the magnitude E_T^{miss} and the azimuthal angle ϕ are calculated as

$$E_T^{\text{miss}} = \sqrt{(E_x^{\text{miss}})^2 + (E_y^{\text{miss}})^2} \quad (3.6)$$

$$\phi = \arctan(E_y^{\text{miss}}/E_x^{\text{miss}}) \quad (3.7)$$

Figure 3.6 compares the distributions of total missing transverse energy as reconstructed using TST E_T^{miss} , CST E_T^{miss} and Track E_T^{miss} . Distributions for events containing 0, 1, 2 or more reconstructed jets are shown separately. In particular, to allow comparison between the different definitions, the jet multiplicity (N_{jets}) is defined without any JVT request. For events with no hard jet, TST E_T^{miss} and Track E_T^{miss} are expected to be similar, since their soft terms are defined by the same procedure. For events with few hard jets, the distribution of TST E_T^{miss} is noticeably softer than that of CST E_T^{miss} due to the robustness of the TST E_T^{miss} under pile-up. This difference vanishes for higher hard jet multiplicity given that the $E_T^{\text{miss,jet}}$ becomes dominant.

3.6. Scale factors

The choice of a specific working point can lead to a possible discrepancy between data and Monte Carlo (MC) simulation, as it is shown in Fig. 3.1. To overcome this issue, scale factors, defined as the ratio of the measured efficiency from data and from Monte Carlo, are evaluated and applied to the MC. The same assertion can be done also for a trigger choice.

Chapter 4.

Search for direct $\tilde{t}_1$ pair production and decay in $t + \tilde{\chi}_1^0$

As already mentioned in Sect. 1.3, the analysis described in this thesis targets the search for direct pair production of the lightest top squarks, $\tilde{t}_1$, in an R -parity conserving scenario. A simplified model was assumed in which $\tilde{t}_1$ decays into a top quark and a $\tilde{\chi}_1^0$, with a BR of 100% and with the lightest neutralino as LSP (Fig. 4.1). A final state with two opposite sign leptons (electrons or muons) was considered. The results were obtained analysing 36.1 fb^{-1} of proton-proton collisions data collected by the ATLAS experiment during 2015 and 2016 at $\sqrt{s} = 13 \text{ TeV}$ (Sect. 2.1.1) and are published in the article *Search for direct top squark pair production with two leptons in $\sqrt{s} = 13 \text{ TeV}$ pp collisions with the ATLAS detector* [1].

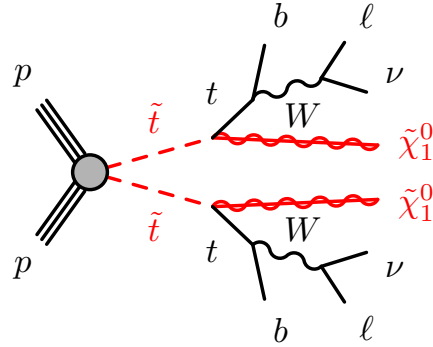


Figure 4.1.: Diagram representing a direct top squark pair production with subsequent decay of both top squarks into top and neutralino. A leptonic decay of the W boson, coming from the top quark, is considered.

4.1. Analysis motivations and strategy

Under the assumption $\tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0$ where $m_{\tilde{t}_1} \geq m_t + m_{\tilde{\chi}_1^0}$, Run1 results have already excluded large areas in the $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$ plane, extended up to $m_{\tilde{t}_1} \sim 720 \text{ GeV}$ for massless

neutralino and up to $m_{\tilde{\chi}_1^0} \sim 280$ GeV for $m_{\tilde{t}_1} \approx 580$ GeV (see Fig. 1.9(a)). Nevertheless the search for direct $\tilde{t}_1$ pair production is still a priority, given that there are areas in the plane above, also at low stop mass, not yet excluded. In particular, the region where $m_{\tilde{t}_1} \approx m_t + m_{\tilde{\chi}_1^0}$, usually called *compressed region*, is one of the most challenging. This is related to the fact that, in an R -parity conserving scenario, the discrimination power between signal and background comes mainly from the neutralinos contribution to the missing transverse energy, but in the compressed region, for kinematical reasons, this contribution becomes not relevant.

Taking into account that $\tilde{\chi}_1^0$ and t are almost at rest in the $\tilde{t}_1$ rest frame, the transverse momenta of the stop and neutralino are linked by the relation $\vec{p}_T(\tilde{\chi}_1^0) \approx (m_{\tilde{\chi}_1^0}/m_{\tilde{t}_1})\vec{p}_T(\tilde{t}_1)$. As a consequence, the contribution to the missing transverse energy in the event from both neutralinos approximately cancels out and, as a result, the kinematics of the top quarks from $\tilde{t}_1\tilde{t}_1^*$ decays is very similar to the one of SM $t\bar{t}$ background, making the distinction between signal and background very difficult. In contrast, if the top squark system is boosted by a hard jet from initial state radiation¹ (ISR) j_{ISR} , the contributions to the missing transverse energy, from both neutralinos, can be important [90,91] given that $\vec{p}_T(j_{\text{ISR}}) \approx -(\vec{p}_T(\tilde{t}_1) + \vec{p}_T(\tilde{t}_1^*))$ and consequently that

$$E_T^{\text{miss}} \approx p_T(j_{\text{ISR}}) \frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{t}_1}}. \quad (4.1)$$

It is thus clear that, having fixed stop and neutralino masses, the higher is the recoil due to the ISR jet, the larger E_T^{miss} must be expected inside the event. On the other hand, it is clear from equation 4.1 that, given the transverse momentum of the ISR jet, the missing transverse energy can be strongly attenuated by the factor $m_{\tilde{\chi}_1^0}/m_{\tilde{t}_1}$ in the massless neutralino limit.

In the analysis here described, a missing transverse energy greater than 200 GeV was requested in the event together with at least three jets, one of them being interpreted as initial state radiation jet and the other two as arising from the decay of the top quarks in the final state, in order to automatically adjust, any signal model was assumed, the cut on $p_T(j_{\text{ISR}})$ of the ISR jet. This choice does not preclude a good sensitivity in the *bulk* region where $m_{\tilde{t}_1} \gg m_t + m_{\tilde{\chi}_1^0}$, since a large missing transverse energy in the event is expected anyway there.

4.2. Signal samples

The signal Monte Carlo (MC) models², generated for this analysis and successively passed through the simulation of the ATLAS detector³, are shown in Fig. 4.2. All the signal

¹The initial state radiation (ISR) and the final state radiation (FSR) are gluon emissions from partons respectively in the initial and final states.

²In the thesis each signal model, $\tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0$, is indicated as $m(\tilde{t}_1, \tilde{\chi}_1^0) = (X, Y)$ GeV where X and Y are respectively replaced by the corresponding top squark and neutralino masses.

³The simulation of the ATLAS detector is based on a detailed description of the detector geometry and of the simulation of particle interactions in the detector material with GEANT4 [92]. Due to

samples were generated using leading order (LO) matrix elements with up to two extra partons, with MADGRAPH5_AMC@NLO [94] v2.2.3 generator. The modelling of the SUSY decay chain, parton showering, hadronisation and the description of the underlying event were simulated with PYTHIA 8.186 [95]. Signal cross-sections were calculated to next-to-leading order (NLO) in the strong coupling constant, adding the resummation of soft gluon emission at next-to-leading-logarithmic accuracy (NLL) [96–98].

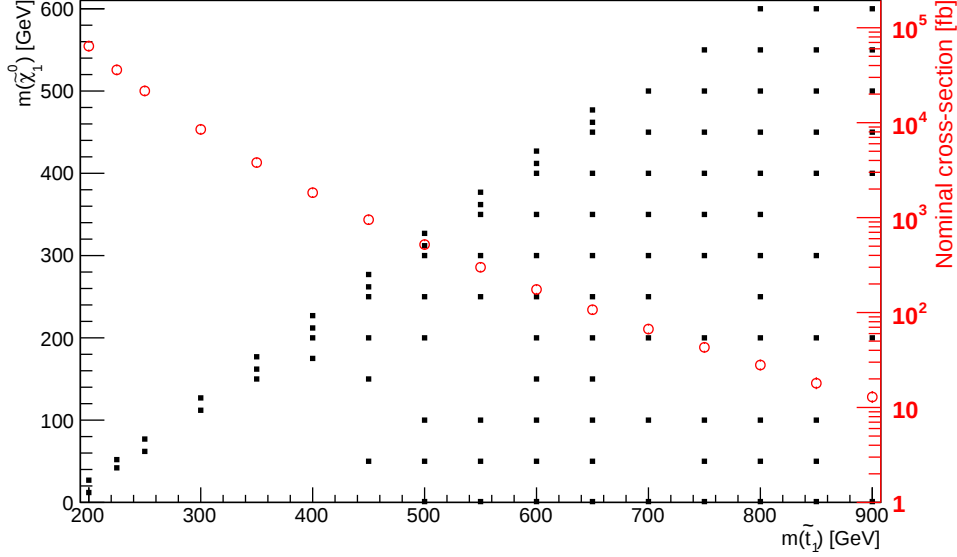


Figure 4.2.: Signal models considered for the analysis are marked with black boxes. The production cross-section, as a function of the $\tilde{t}_1$ mass, is also reported [41].

4.3. Background samples

The search for $\tilde{t}_1\tilde{t}_1^*$ production was performed looking for a final state with two opposite sign leptons (electrons or muons). A large number of Standard Model processes show the same signature and consequently they must be taken into account as backgrounds. For this reason, their Monte Carlo generation and their simulation in the ATLAS detector was performed.

The main background processes are listed below:

- $t\bar{t}$ production ($t\bar{t}$);
- single top production in Wt -channel (Wt);

the large CPU time needed by the GEANT4 simulation, an alternative fast simulation, referred to as ATLFast-II, parameterising the calorimeters response has been developed [93]. GEANT4 was used for the background samples simulation, ATLFast-II was instead used for the signal samples simulation.

- $t\bar{t}$ production in association with Z boson ($t\bar{t} + Z$);
- Z boson production and Drell-Yan processes in association with jets ($Z/\gamma^* + \text{jets}$);
- dibosons production, distinguishing between the processes with two leptons and two neutrinos in the final state (VV or $VV(\ell\nu\nu)$), mainly due to WW or ZZ with one Z going to invisible and the other decaying leptonically, and the ones with three or four leptons in the final state (VZ or $VZ(\ell\ell\nu, \ell\ell\ell)$) with only two leptons passing the analysis requests (see Sect. 4.5 and Sect. 4.7).

Other Standard Model processes, negligible with respect to the ones mentioned above, were merged all together and they are referred to as "Others" in this thesis. However a complete list of all the considered backgrounds is reported in Tab. 4.1; Fig. 4.3 shows instead a summary of the Standard Model total production cross-sections as measured by ATLAS [112].

Physics process	Event generator	Parton shower generator	Order of calculation
$Z/\gamma^* + \text{jets}$	SHERPA 2.2.1 [99]	SHERPA 2.2.1	NNLO [100]
$t\bar{t}$	POWHEG-BOX v2 [101]	PYTHIA 6.428 [102]	NNLO+NNLL [103–108]
Wt	POWHEG-BOX v2	PYTHIA 6.428	NNLO+NNLL [109]
$t\bar{t}W/Z/\gamma^*$	MADGRAPH5_AMC@NLO 2.2.2	PYTHIA 8.186	NLO
Dibosons	SHERPA 2.2.1	SHERPA 2.2.1	Generator NLO
$t\bar{t}H$	MADGRAPH5_AMC@NLO 2.2.2	HERWIG 2.7.1 [110]	NLO [111]
WH, ZH	MADGRAPH5_AMC@NLO 2.2.2	PYTHIA 8.186	NLO [111]
$t\bar{t}WW, t\bar{t}t\bar{t}$	MADGRAPH5_AMC@NLO 2.2.2	PYTHIA 8.186	NLO
$tZ, tWZ, t\bar{t}t$	MADGRAPH5_AMC@NLO 2.2.2	PYTHIA 8.186	LO
Tribosons	SHERPA 2.2.1	SHERPA 2.2.1	Generator LO, NLO

Table 4.1.: Simulated background event samples with the corresponding event generator, parton shower generator and order of calculation [1].

Another source of background is related to jets misidentified as leptons (*fake leptons*) and non-prompt leptons, collectively referred to as "FNP", i.e. fake and non-prompt leptons. Examples of FNP sources are semileptonic $t\bar{t}$, s - and t -channel single top quark, $W + \text{jets}$ and light- and heavy-flavour multi-jet QCD events. Their total contribution was estimated through a data-driven technique which make use of the (so-called) Matrix Method. A detailed description of the method is reported in App. A.

4.4. Data samples

The analysis described in this thesis considers the full 2015 and 2016 data statistics collected by the ATLAS experiment, to which data quality requirements, asking a full functional detector, were applied. The resulting integrated luminosity corresponds to 36.1 fb^{-1} . In addition to the data quality requirements mentioned before, the following *cleaning cuts* were applied to ensure that only data without any problem were selected:

- data event should not have error flags from electromagnetic calorimeter, hadronic calorimeter and SCT;

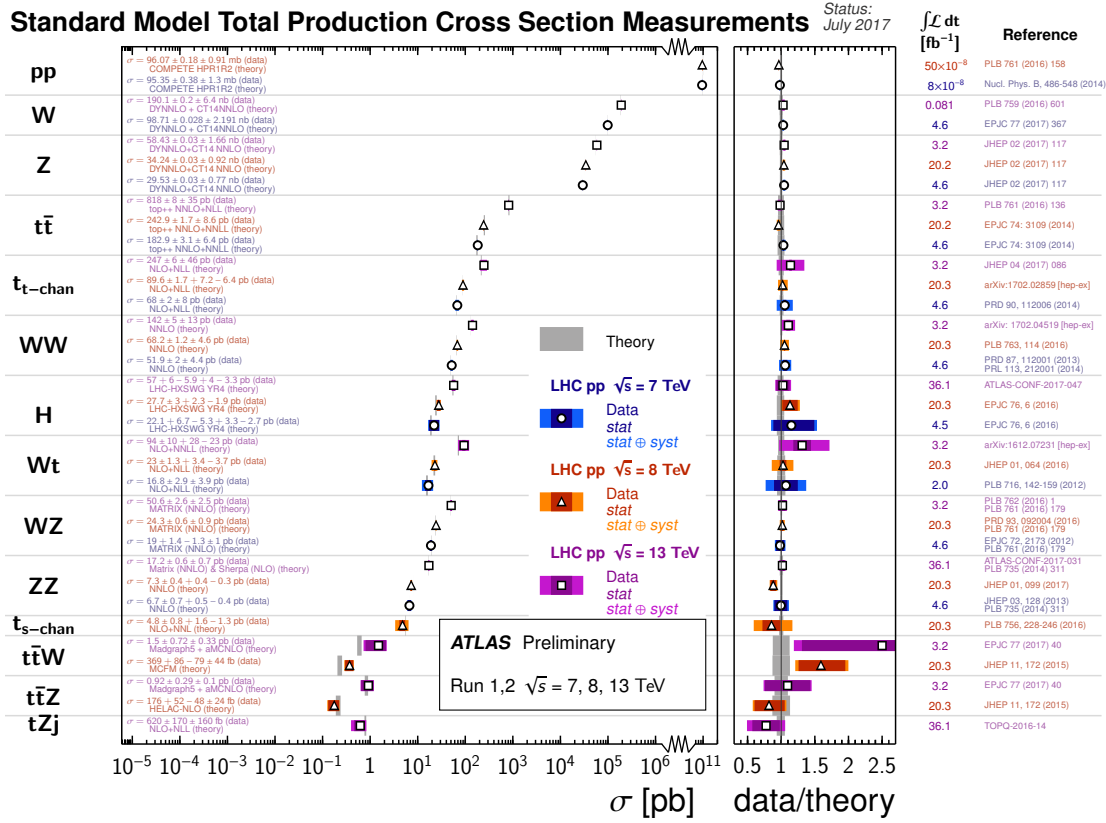


Figure 4.3.: Summary of several Standard Model total production cross-section measurements, corrected for leptonic branching fractions, compared to the corresponding theoretical expectations. All theoretical expectations were calculated at NLO or higher. The dark-colour error bar represents the statistical uncertainty. The lighter-color error bar represents the full uncertainty, including systematics and luminosity uncertainties. The data/theory ratio, luminosity used and reference for each measurement are also shown [112].

- data event should not be incomplete (i.e some detectors information was missing from the event);
- a primary vertex of each event was required to have at least two associated tracks;
- the event was rejected if a cosmic muon was present;
- the event was rejected if it contains at least one jet with $p_T > 20$ GeV not passing the *Loose* jet quality selection (Sect. 3.3.2).

4.5. Object definition

As already described in Sect. 3, the reconstruction (both in Monte Carlo and in real data) of electrons, photons, jets, muons and E_T^{miss} follow specific algorithms and, in order to accommodate different needs coming from several analyses, different definitions and selection criteria have been established. In Tab. 4.2 the definitions of the objects considered in this analysis are reported. For electrons and muons two different levels of selection, labelled as *baseline* and *signal*, were defined such that all the objects passing the signal criteria are also selected by the baseline ones; even if only signal leptons were taken into account for the final analysis results, a looser selection was necessary for the overlap removal procedure, described in Sect. 4.5.1, and for the estimation of the FNP background, as it is explained in App. A.

Object	Definition
Jets	·based on ant-k_t jet algorithm with $R = 0.4$, ·$p_T > 20$ GeV, $\eta < 2.5$, ·b-tagging performed with MV2c10 at the 77% operating point.
Electrons	Baseline:
	·Identification: Loose+B-layer, ·$E_T > 7$ GeV, $\eta < 2.47$.
Electrons	Signal:
	·baseline requirements, ·Identification: Medium, ·Isolation: GradientLoose, ·$E_T > 20$ GeV, ·$d_0/\sigma_{d_0} < 5$, $z_0 \sin \theta < 0.5$ mm.
Muons	Baseline:
	·Identification: Medium, ·$p_T > 7$ GeV, $\eta < 2.4$
Muons	Signal:
	·baseline requirements, ·Isolation: GradientLoose, $p_T > 20$ GeV, ·$d_0/\sigma_{d_0} < 3$, $z_0 \sin \theta < 0.5$ mm.
E_T^{miss}	·TST E_T^{miss} .

Table 4.2.: Summary of jet, electron, muon and missing transverse energy definitions [1].

4.5.1. Overlap removal

To avoid overlaps between reconstructed objects, which could lead to consider the same object under different categories, a dedicated procedure, called overlap removal (OR), was implemented. The OR was performed with baseline, non isolated electrons and

muons and with $p_T > 20$ GeV jets. More specifically, the procedure was implemented through the following steps:

- non b -tagged jets close to leptons (within $\Delta R = \sqrt{(\Delta y)^2 + (\Delta \phi)^2} < 0.2$) were rejected as they mostly originate from calorimeter energy deposits from electron shower or muon bremsstrahlung; instead, if a jet was b -tagged, it was kept and the lepton discarded since it likely comes from a semileptonic b -quark decay.
- Subsequently, electrons and muons close to the surviving jets (within $\Delta R < 0.4$) were discarded in order to reject FNP background coming from hadron decays.
- Any calo-tagged muon sharing an ID track with an electron was removed.
- Any electron sharing an ID track with the surviving muons was removed.

After the overlap removal procedure all the jets having $p_T < 60$ GeV, $|\eta| < 2.4$ and $JVT < 0.59$ were rejected in order to reduce pileup effects.

4.6. Systematic uncertainties

The background and signal predictions provided by the various MC simulations, which were compared to data as shown in Sect. 4.7, are affected by various sources of systematic uncertainties. Such uncertainties can be related to both detector and theoretical predictions. The most important instrumental uncertainties are due, for example, to the jet energy scale calibration, the jet energy resolution or the modelling of the missing transverse energy. Possible sources of theoretical uncertainties are, instead, the uncertainty associated to the specific choice of the Monte Carlo generator. A short description of the main systematic uncertainties is reported in the following, while in App. B tables showing the parameterisation used for the treatment of the various systematics in the analysis are reported.

4.6.1. Experimental systematics

The following experimental systematics, involving the objects reconstruction, the simulation of the pile-up, the luminosity measurement used to normalise all MC estimates, were expected to mainly affect the analysis, and therefore their effects were simulated and finally quoted in the total errors on the MC predictions:

- *Jet Energy Scale (JES)* and *Jet Energy Resolution (JER)* uncertainties: as suggested by their names, they are related to the uncertainties on the energy scale calibration and resolution of the jets, respectively.
- *JVT* uncertainty: the systematic error due to JVT are evaluated varying the corresponding scale factors within their uncertainties to produce up and down variations in the MC estimates.

- *b-tagging* uncertainty: as for the JVT systematic, the uncertainties are evaluated by propagating the b-tagging scale factors errors in the analysis.
- *Egamma scale and resolution* uncertainties: they are related to the electron and photon uncertainties on the energy scale and resolution.
- *Muon scale and resolution* uncertainties: they corresponds to the muon uncertainties on the momentum scale and resolution.
- *Electron and muon efficiency* uncertainties: as for the JVT and *b*-tagging uncertainties, the scale factors, relative to reconstruction, identification, isolation and trigger, are varied within their errors to produce up and down systematic variations in the MC estimates.
- E_T^{miss} uncertainties: they quantify the uncertainties on the resolution and scale of TST E_T^{miss} .
- *Pile-up reweighting* uncertainty: it is the uncertainty related to the re-weighting procedure used to reproduce in MC samples the observed distribution of the average number of collisions per bunch crossing ($\langle \mu \rangle$).
- *Luminosity* uncertainty: a 3.2% uncertainty in the luminosity measurement was taken into consideration. This uncertainty was derived, following a methodology similar to that detailed in [113], from a preliminary calibration of the luminosity scale using $x - y$ beam separation scans performed in August 2015 and May 2016.

4.6.2. Theoretical systematics

The following systematics, originating from theoretical assumptions, were expected to mainly affect the analysis, and therefore their effects were taken into account and finally quoted in the total errors on the MC predictions:

- *$t\bar{t}$ production generator* uncertainty: it is associated to the choice of a specific generator to estimate the Monte Carlo $t\bar{t}$ predictions and it is evaluated comparing at truth level the predictions of POWHEG+PYTHIA and MADGRAPH5_AMC@NLO+PYTHIA.
- *$t\bar{t}$ parton shower (PS)* uncertainty: it is associated to the choice of a specific showering model and it is assessed as the difference between the predictions of POWHEG using PYTHIA and HERWIG as shower simulators.
- *$t\bar{t}$ and Wt ISR/FSR* uncertainty: it is associated to the Initial State Radiation and Final State Radiation (ISR/FSR) models and it is estimated comparing the predictions of two POWHEG+PYTHIA samples where the radiation parameters are varied by a factor of two.

- *Wt interference* uncertainty: it's related to the different treatment of the interference between $t\bar{t}$ and Wt production processes. Beyond LO some of the Feynman diagrams contributing to Wt can be interpreted as the $t\bar{t}$ production at LO and, to avoid double counting, two different techniques have been developed [114]:

Diagram Removal (DR) where all $t\bar{t}$ -like diagrams are removed in the NLO Wt amplitudes,

Diagram Subtraction (DS) where the NLO Wt cross section is modified by implementing a subtraction term designed to cancel the $t\bar{t}$ contribution.

The full difference between these two methods must be considered as uncertainty.

- *Dibosons background modelling* uncertainties: they are estimated by varying up and down by a factor of two the renormalisation, factorisation and resummation scales used to generate the sample [115].
- *Cross-section* uncertainties: the theoretical uncertainties on the cross-sections of the various background processes must be considered for all the samples for which a normalisation procedure, in dedicated control regions (see Sect. 4.8), is not applied.

4.6.3. Fake and non-prompt leptons systematics

The uncertainties assigned to the FNP background were estimated. They take into account the limited statistics in the region, used to evaluate the fake rates, and the contamination from prompt leptons, in the regions used to measure the probabilities for loose fake or non-prompt leptons to satisfy the tight signal criteria.

4.7. Event selection

The analysis described in this thesis considers a final state with two opposite sign (OS) leptons, therefore events were selected using dilepton triggers; the complete list of the trigger items considered is reported in Tab. 4.3, together with the explanation of the relative trigger requests. The offline selection required that the leading lepton in the selected event had a $p_T(l_1)$ larger than 25 GeV (Fig. 4.4) and the subleading lepton a $p_T(l_2)$ larger than 20 GeV (Fig. 4.5).

The dilepton invariant mass (m_{ll}) was required to be larger than 20 GeV in order to reject low mass resonances without affecting the signal. Events with a same flavour (SF) leptons pair, with an invariant mass within a window of ± 20 GeV around the Z mass, were also discarded to suppress the $Z/\gamma^* + \text{jets}$ and $VV(ll\nu\nu)$ backgrounds (Fig. 4.6).

As already mentioned in Sect. 4.1, events with $E_T^{\text{miss}} > 200$ GeV (Fig. 4.7) and with at least three jets were selected, in such a way that the leading jet (j_1) could be interpreted as an initial state radiation jet, which is required to boost the missing momentum of the event (Fig. 4.8). These jets had to satisfy the requirement of $p_T > 25$ GeV and $|\eta| < 2.5$. The jet (N_{jets}) and b -tagged jet ($N_{b\text{-jets}}$) multiplicity distributions are shown in Fig. 4.9 and Fig. 4.10. Finally at least one b -tagged jet was also required, to further reduce the dibosons and $Z/\gamma^* + \text{jets}$ contributions as shown in Tab. 4.4.

Event category	Triggers
Double Electron	HLT_2e12_lhloose_L12EM10VH: · two electrons with $E_T > 12$ GeV satisfying the loose identification, · seeded by L1 trigger requiring two EM clusters with $E_T > 10$ GeV, · considered for 2015 data.
	HLT_2e15_lhvloose_nod0_L12EM13VH: · two electrons with $E_T > 15$ GeV satisfying the veryloose identification, · no transverse impact parameter cut applied, · seeded by L1 trigger requiring two EM clusters with $E_T > 13$ GeV. · considered for the data collected up to June 2016.
	HLT_2e17_lhvloose_nod0: · two electrons with $E_T > 17$ GeV satisfying the veryloose identification, · no transverse impact parameter cut applied. · considered for data collected after June 2016.
Double Muon	HLT_mu18_mu8noL1: · two muons with p_T greater than 18 GeV and 8 GeV respectively, · considered for 2015 data.
	HLT_mu20_mu8noL1: · two muons with p_T greater than 20 GeV and 8 GeV respectively. · considered for the data collected up to June 2016.
	HLT_mu22_mu8noL1: · two muons with p_T greater than 22 GeV and 8 GeV respectively. · considered for data collected after June 2016.
Electron-Muon	HLT_e17_lhloose_mu14: · one electron with $E_T > 17$ GeV satisfying the loose identification, · one muon with $p_T > 14$ GeV, · considered for 2015 data.
	HLT_e17_lhloose_nod0_mu14: · one electron with $E_T > 17$ GeV satisfying the loose identification, · no transverse impact parameter cut applied to the electron, · one muon with $p_T > 14$ GeV, · considered for 2016 data.

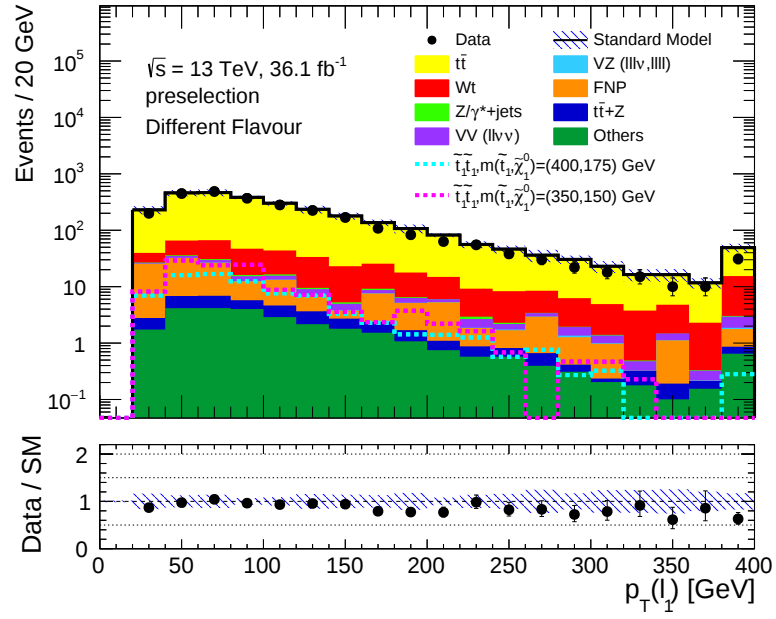
Table 4.3.: Trigger items considered for this analysis together with their trigger requests. Depending on LHC performance, triggers with tighter requests were considered to deal with the increase in the instantaneous luminosity.

A good agreement between data and MC and no pathological behaviour is observed at this selection level for all the variables considered in the selection. A summary of the preselection requirements for the same flavour (SF) and different flavour (DF) leptons pair final states is finally reported in Tab. 4.5.

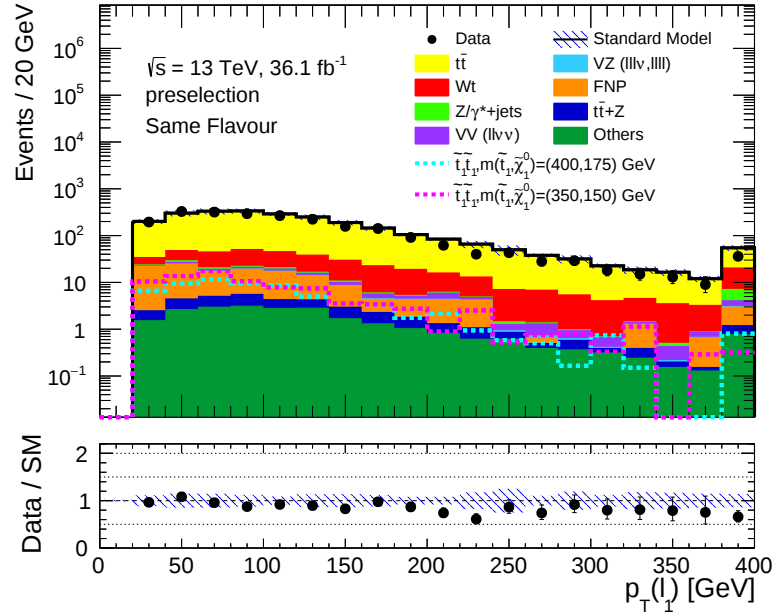
(a)			
DF events			
	b -tagged jet request applied	b -tagged jet request not applied	ϵ [%]
Total SM	3050 ± 300	3680 ± 340	83
$t\bar{t}$	2420 ± 290	270 ± 320	88
Wt	261 ± 20	306 ± 21	85
$Z/\gamma^* + \text{jets}$	7.2 ± 1.5	49 ± 4	15
$VV(ll\nu\nu)$	20 ± 5	163 ± 31	13
VZ	1.58 ± 0.23	9.9 ± 0.5	16
$t\bar{t} + Z$	15.6 ± 0.6	17.4 ± 0.8	90
FNPF	110 ± 50	140 ± 60	76
Others	27.4 ± 1.8	31.8 ± 2.0	86
$m(\tilde{t}_1, \tilde{\chi}_1^0) = (400, 175) \text{ GeV}$	78 ± 5	88 ± 4	89
$m(\tilde{t}_1, \tilde{\chi}_1^0) = (350, 150) \text{ GeV}$	116 ± 8	128 ± 8	90

(b)			
SF Events			
	b -tagged jet request applied	b -tagged jet request not applied	ϵ [%]
Total SM	2690 ± 240	3290 ± 270	82
$t\bar{t}$	2110 ± 230	2400 ± 250	88
Wt	243 ± 28	287 ± 32	85
$Z/\gamma^* + \text{jets}$	13.3 ± 1.5	74 ± 5	18
$VV(ll\nu\nu)$	19 ± 4	153 ± 29	12
VZ	1.89 ± 0.29	14.1 ± 0.7	13
$t\bar{t} + Z$	15.9 ± 0.9	17.8 ± 1.2	89
FNPF	109 ± 31	150 ± 40	74
Others	24.8 ± 1.6	30.0 ± 1.8	83
$m(\tilde{t}_1, \tilde{\chi}_1^0) = (400, 175) \text{ GeV}$	65.0 ± 2.2	71.8 ± 2.4	91
$m(\tilde{t}_1, \tilde{\chi}_1^0) = (350, 150) \text{ GeV}$	84 ± 5	94 ± 5	90

Table 4.4.: Impact of the b -tagged jet request at preselection level on all SM backgrounds and on two signal models for different flavour (a) and same flavour (b) events. The efficiency of the cut $N_{b-jets} \geq 1$ is reported together with the expected yields obtained applying or not applying the request. Dibosons and $Z/\gamma^* + \text{jets}$ are reduced of $\sim 85\%$, to be compared to a signal loss of $\sim 10\%$.

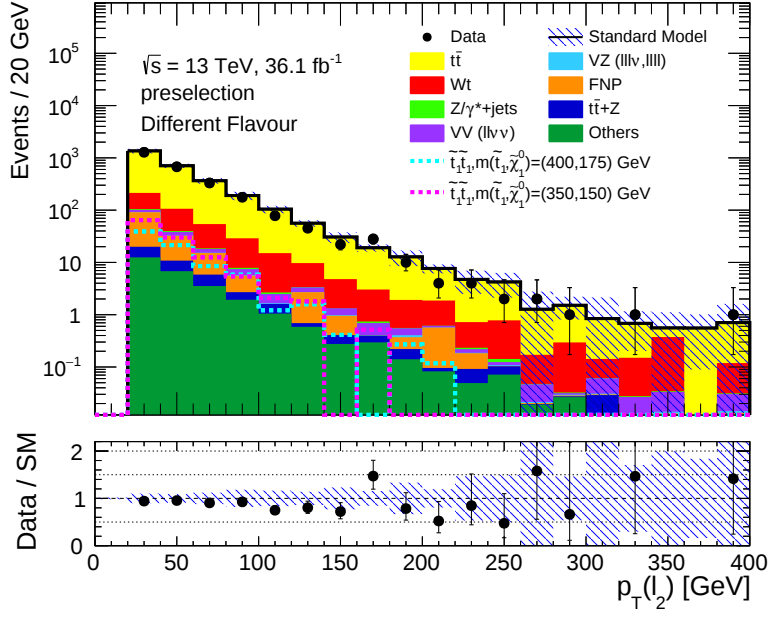


(a)

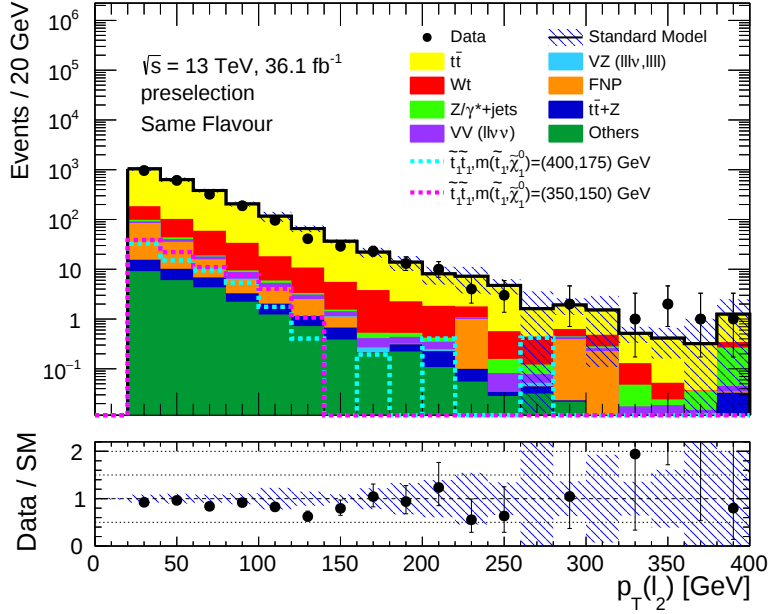


(b)

Figure 4.4.: p_T distribution of the leading lepton in events passing the preselection requirements in the cases of different flavour (a) and same flavour (b) leptons final states. The contributions of all the dominant SM backgrounds are shown, with the band representing the total uncertainty. The distributions of two signal models, superimposed to the full background, are also shown.

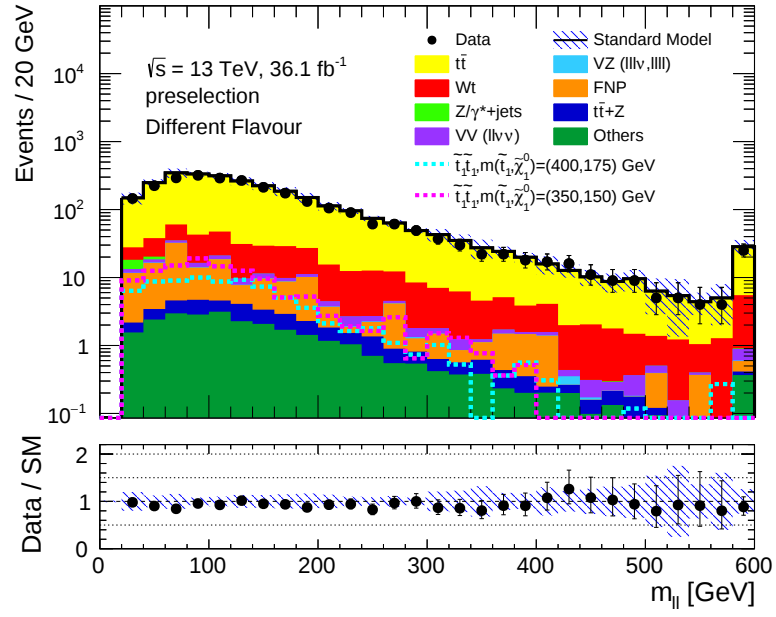


(a)

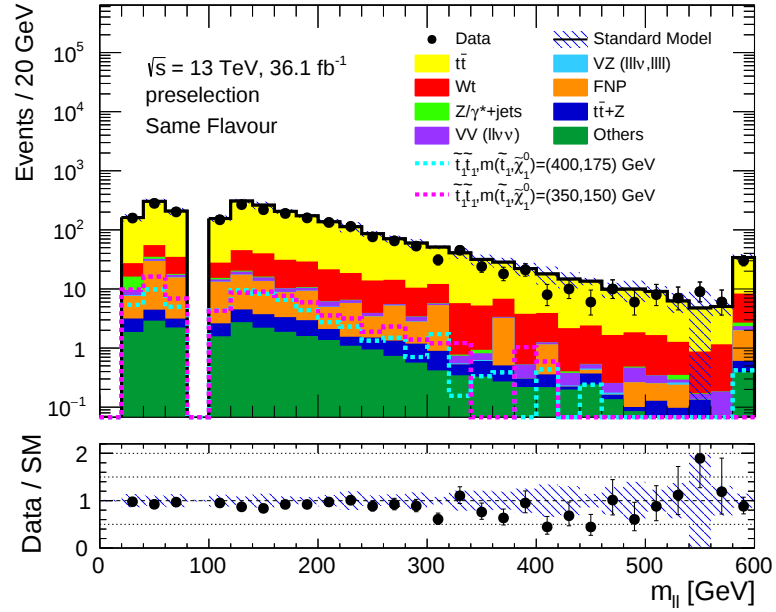


(b)

Figure 4.5.: p_T distribution of the subleading lepton in events passing the preselection requirements in the cases of different flavour (a) and same flavour (b) leptons final states. The contributions of all the dominant SM backgrounds are shown, with the band representing the total uncertainty. The distributions of two signal models, superimposed to the full background, are also shown.

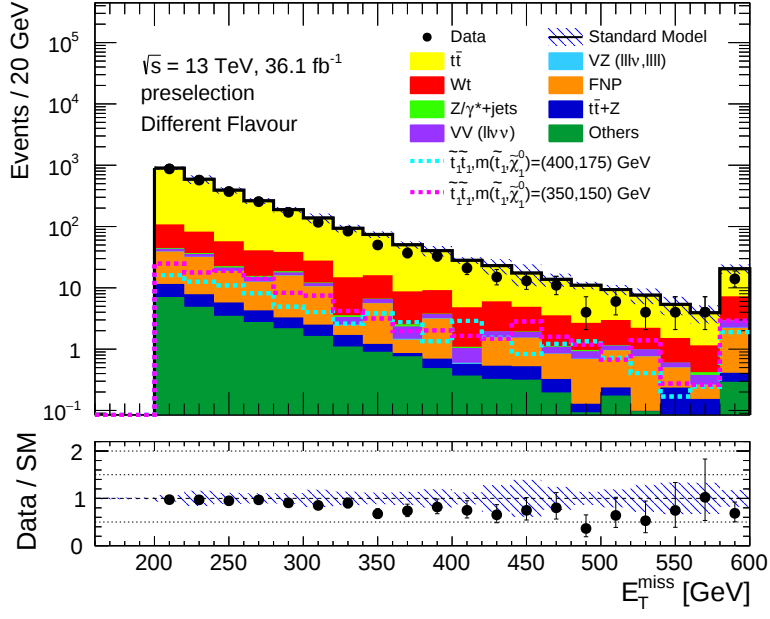


(a)

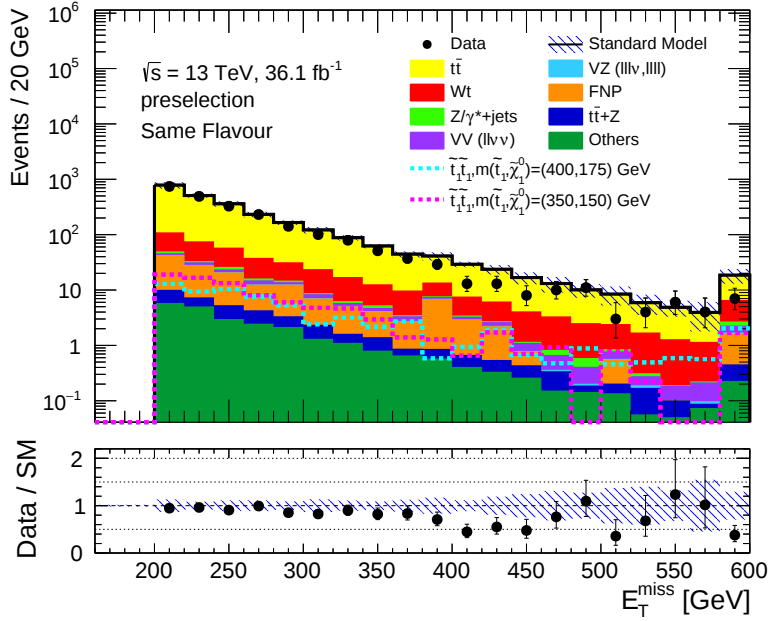


(b)

Figure 4.6.: m_{ll} distribution in events passing the preselection requirements in the cases of different flavour (a) and same flavour (b) leptons final states. The contributions of all the dominant SM backgrounds are shown, with the band representing the total uncertainty. The distributions of two signal models, superimposed to the full background, are also shown.

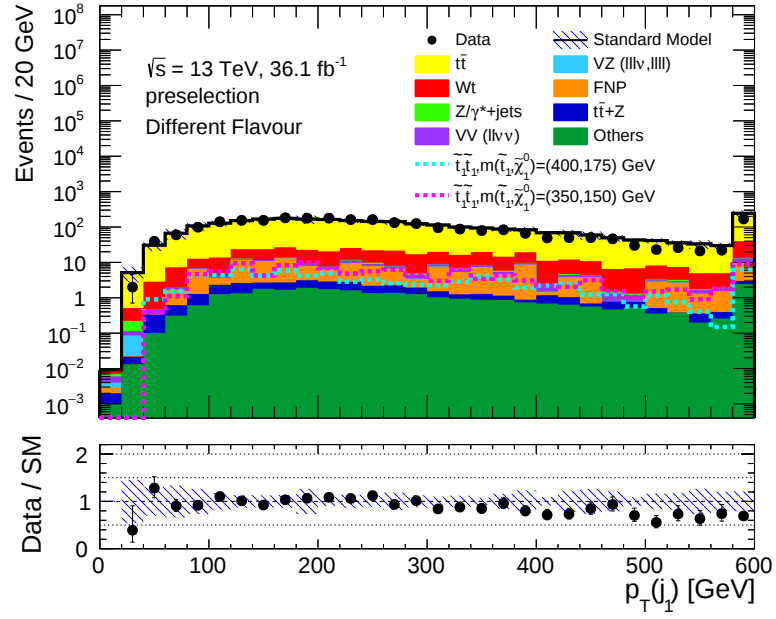


(a)

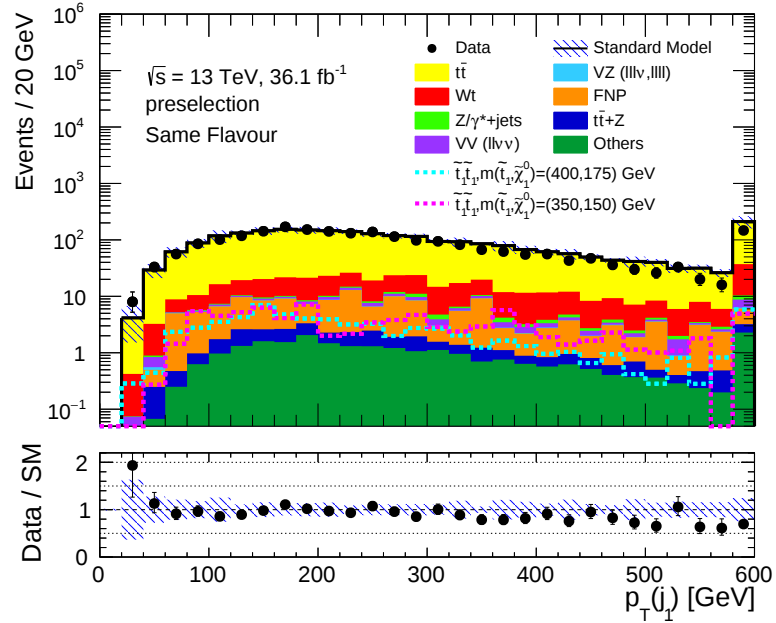


(b)

Figure 4.7.: E_T^{miss} distribution in events passing the preselection requirements in the cases of different flavour (a) and same flavour (b) leptons final states. The contributions of all the dominant SM backgrounds are shown, with the band representing the total uncertainty. The distributions of two signal models, superimposed to the full background, are also shown.

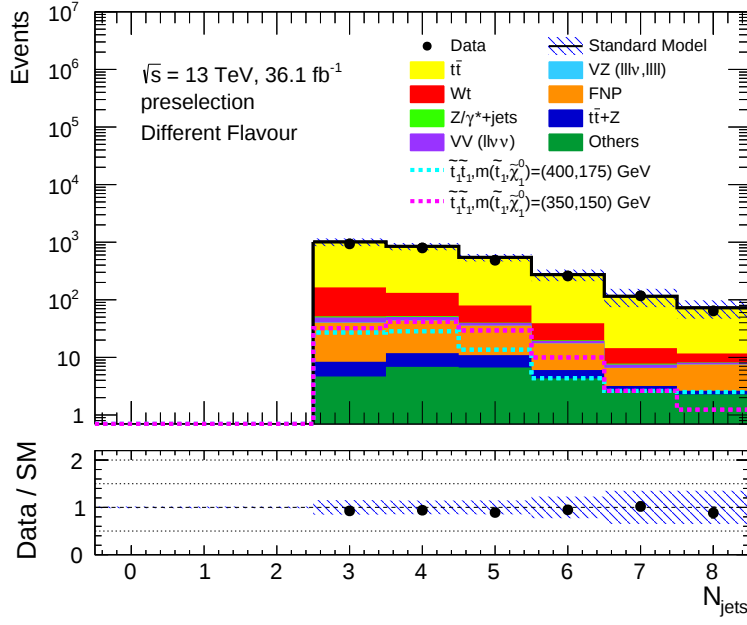


(a)

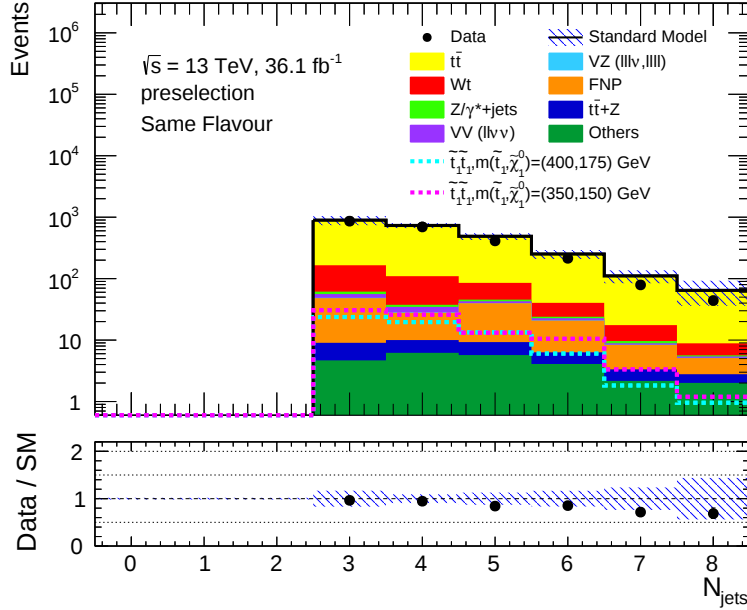


(b)

Figure 4.8.: $p_T(j_1)$ distribution in events passing the preselection requirements in the cases of different flavour (a) and same flavour (b) leptons final states. The contributions of all the dominant SM backgrounds are shown, with the band representing the total uncertainty. The distributions of two signal models, superimposed to the full background, are also shown.

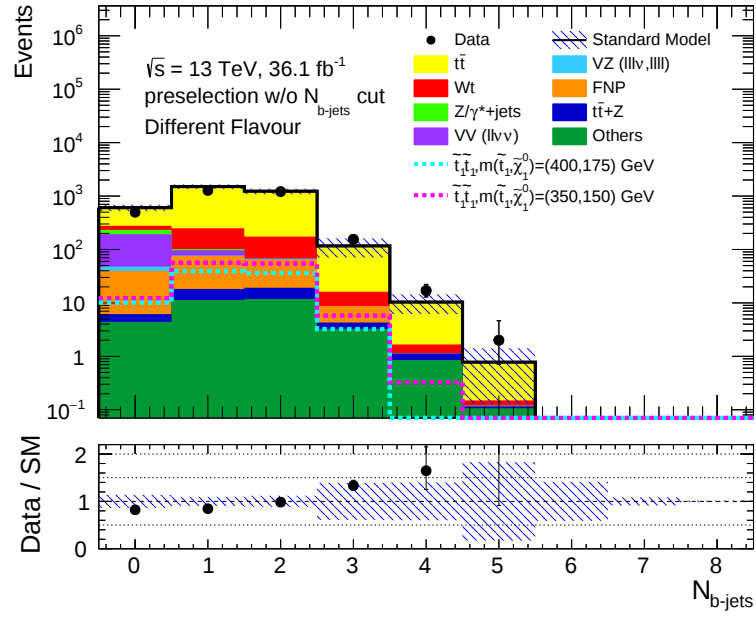


(a)

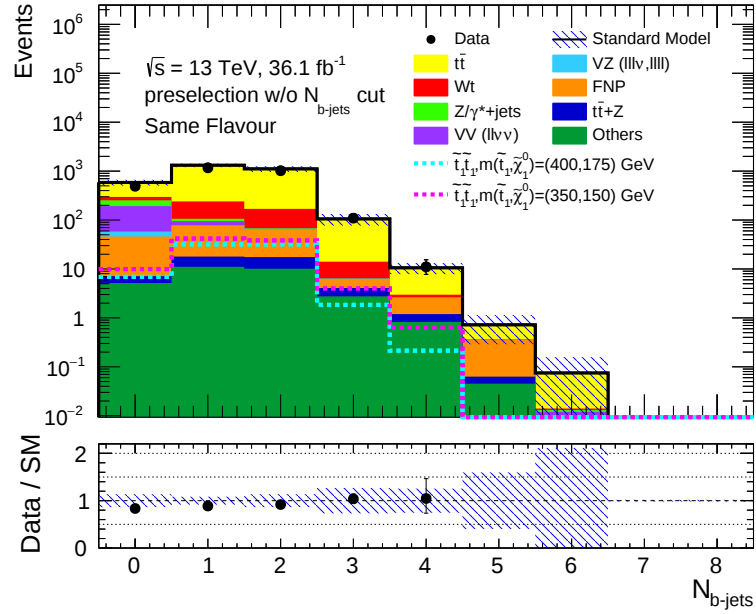


(b)

Figure 4.9.: N_{jets} distribution in events passing the preselection requirements in the cases of different flavour (a) and same flavour (b) leptons final states. The contributions of all the dominant SM backgrounds are shown, with the band representing the total uncertainty. The distributions of two signal models, superimposed to the full background, are also shown.



(a)



(b)

Figure 4.10.: N_{b-jets} distribution in events passing all the preselection requirements, with the exception of the b -tagged jet cut, in the cases of different flavour (a) and same flavour (b) leptons final states. The contributions of all the dominant SM backgrounds are shown, with the band representing the total uncertainty. The distributions of two signal models, superimposed to the full background, are also shown.

	DF	SF
Leptons	2 OS	2 OS
$p_T(l_1), p_T(l_2)$ [GeV]	$> 25, 20$	$> 25, 20$
m_{ll} [GeV]	> 20	$[20, 71] \cup [111, +\infty[$
E_T^{miss} [GeV]	> 200	> 200
N_{jets}	≥ 3	≥ 3
N_{b-jets}	≥ 1	≥ 1

Table 4.5.: Preselection cuts summary table.

4.7.1. Signal region definition

To discriminate signal events from SM backgrounds, the following kinematic variables were considered:

- *leptonic-based stransverse mass* (m_{T2}). The stransverse mass is a kinematic variable used to bound the masses of an unseen pair of particles which are presumed to have decayed semi-invisibly [116, 117]. This quantity is defined as

$$m_{T2}(\mathbf{p}_{T,1}, \mathbf{p}_{T,2}, \mathbf{q}_T) = \min_{\mathbf{q}_{T,1} + \mathbf{q}_{T,2} = \mathbf{q}_T} \{ \max[m_T(\mathbf{p}_{T,1}, \mathbf{q}_{T,1}), m_T(\mathbf{p}_{T,2}, \mathbf{q}_{T,2})] \} \quad (4.2)$$

where m_T is the transverse mass⁴, $\mathbf{p}_{T,1}$ and $\mathbf{p}_{T,2}$ are the transverse momentum vectors of two visible particles (assumed to be massless), and $\mathbf{q}_{T,1}$ and $\mathbf{q}_{T,2}$ are vectors with $\mathbf{q}_T = \mathbf{q}_{T,1} + \mathbf{q}_{T,2}$. The minimisation is performed over all the possible decompositions of $\mathbf{q}_T$. For $t\bar{t}$ or WW decays, if the transverse momenta of the two leptons in each event are taken as $\mathbf{p}_{T,1}$ and $\mathbf{p}_{T,2}$, and E_T^{miss} as $\mathbf{q}_T$, $m_{T2}(\ell, \ell, E_T^{\text{miss}})$ is bounded sharply from above by the mass of the W boson [118, 119]. Instead, for the SUSY model $\tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0$, the upper bound is not present and events with high m_{T2} value are expected.

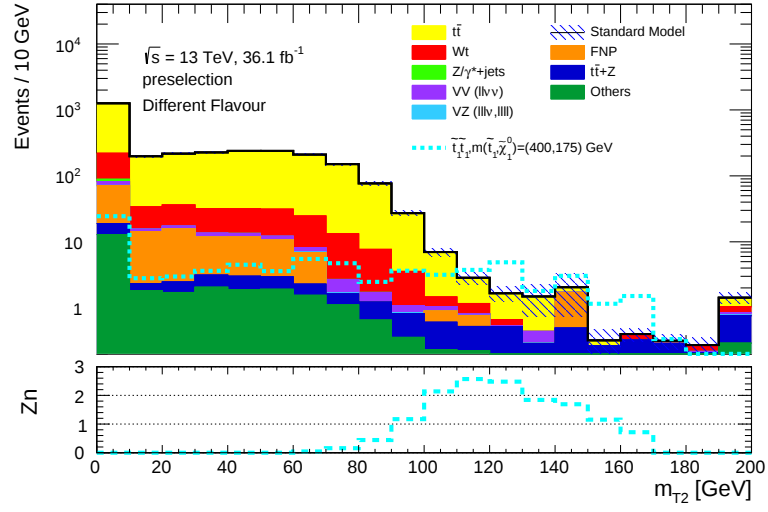
- R_{ll} defined as

$$R_{ll} = \frac{E_T^{\text{miss}}}{p_T(l_1) + p_T(l_2)} \quad (4.3)$$

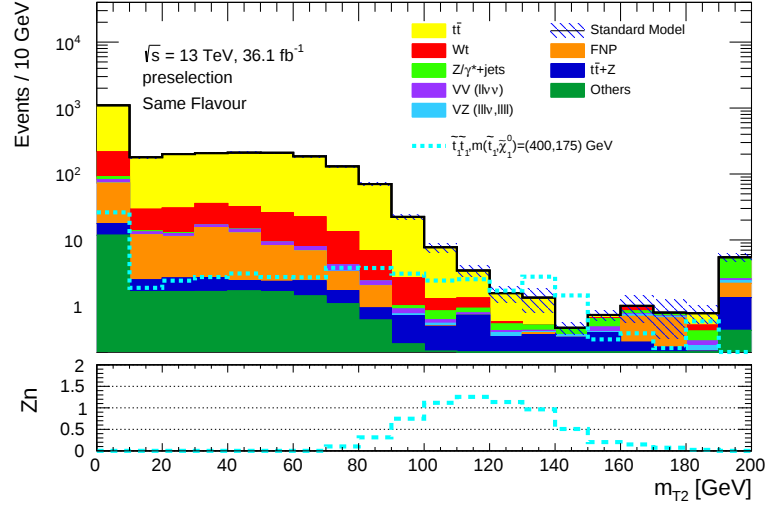
and used, given the topology of the signal events under study, to select events with highly energetic or collimated invisible particles in the final state.

Indeed two regions referred to as *signal regions* (SR), one for DF final state (SR_{DF}) and the other for SF case (SR_{SF}), were defined optimising the cuts on m_{T2} and R_{ll} with the

⁴Once massless or relativistic particles are assumed, the transverse mass of two particles is defined by the equation $m_T = \sqrt{2|\mathbf{p}_{T,1}||\mathbf{p}_{T,2}|(1 - \cos(\Delta\phi))}$, where $\Delta\phi$ is the angle between the particles with transverse momenta $\mathbf{p}_{T,1}$ and $\mathbf{p}_{T,2}$ in the plane perpendicular to the beam axis.



(a)

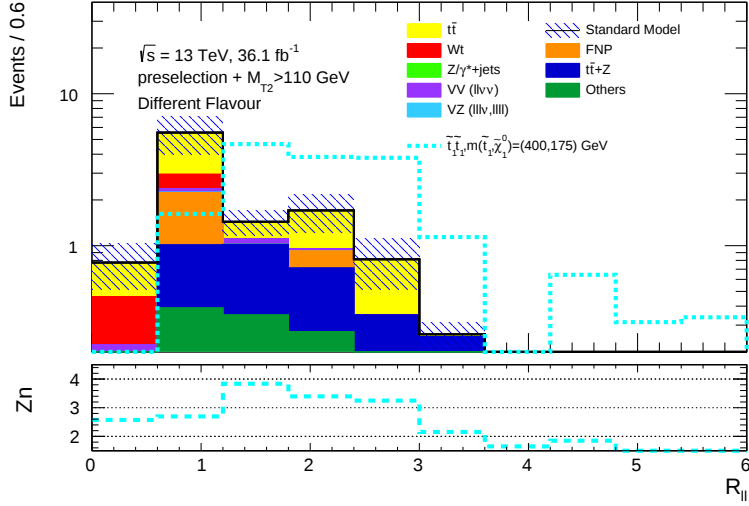


(b)

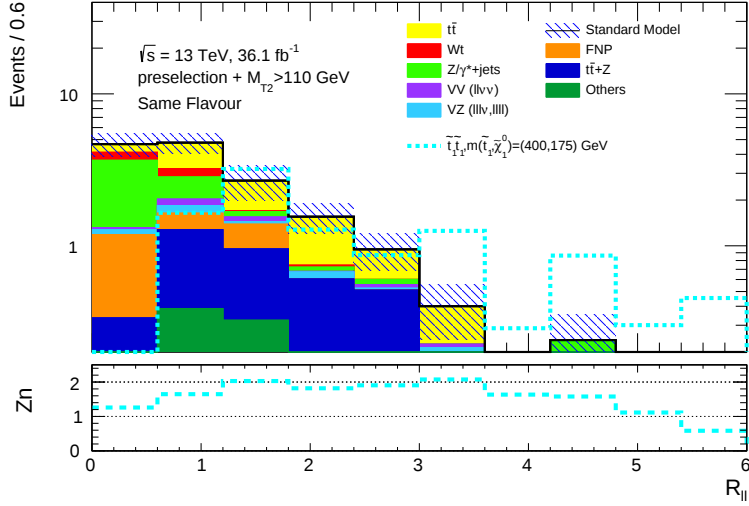
Figure 4.11.: m_{T2} distribution for events passing all the preselection requirements, in the cases of different flavour (a) and same flavour (b) leptons final state. The contributions from all the dominant SM backgrounds are shown, with the band representing the statistical uncertainty. The distribution of the benchmark signal model, superimposed to the full background, is also shown. The Zn plot shows that the best m_{T2} cut is around 110 GeV for DF and SF.

aim to maximise the discovery sensitivity⁵ Zn , after having assumed a 30% systematic

⁵The Zn significance is defined in order to take into account the uncertainties on the background [120].



(a)



(b)

Figure 4.12.: R_{II} distribution for events passing all the preselection cuts plus the request of $m_{T2} > 110$ GeV, in the cases of different flavour (a) and same flavour (b) leptons final state. The contributions from all the dominant SM backgrounds are shown, with the band representing the statistical uncertainty. The distribution of the benchmark signal model, superimposed to the full background, is also shown. The Zn plot shows that the best R_{II} cut is around 1.2 for DF and SF.

They are incorporated in the significance by convoluting the Poisson probability that the back-

uncertainty on the expected SM backgrounds and considered as benchmark the signal model $m(\tilde{t}_1, \tilde{\chi}_1^0) = (400, 175)$ GeV. Fig. 4.11 and Fig. 4.12 show the Zn behaviour as a function of m_{T2} and R_{ll} variables. For both cases the best SR definition was found by applying the following requests:

- $m_{T2} > 110$ GeV,
- $R_{ll} > 1.2$.

In Fig. 4.13 the expected Zn for the full signal grid show a good sensitivity in the compressed region for $\tilde{t}_1$ mass around 450 GeV. These results were obtained assuming, as for the SRs definition, a 30% of total uncertainty on the total SM background. Unfortunately this assumption was proved to be too optimistic, once all the systematic uncertainties were taken into account; it was in fact estimated a total uncertainty of $\sim 40\%$ and $\sim 36\%$ for SR_{DF} and SR_{SF} respectively.

A summary of the cuts applied for the SRs definition is reported in Tab. 4.6. Details about the SRs composition of the expected background are reported in Tab. 4.7. The expected yields for the various signal models are instead shown in Fig. 4.14.

	SR_{DF}	SR_{SF}
Lepton flavour	DF	SF
$p_T(l_1), p_T(l_2)$ [GeV]	$> 25, 20$	$> 25, 20$
m_{ll} [GeV]	> 20	$[20, 71] \cup [111, +\infty[$
E_T^{miss} [GeV]	> 200	> 200
N_{jets}	≥ 3	≥ 3
N_{b-jets}	≥ 1	≥ 1
m_{T2} [GeV]	> 110	> 110
R_{ll}	> 1.2	> 1.2

Table 4.6.: Event selection criteria of SR_{DF} and SR_{SF} .

ground fluctuates to the observed signal, with a Gaussian background probability density function $G(b; N_b, \delta N_b)$ with mean N_b and standard deviation δN_b . Given these assumptions, the probability p that the background fluctuates by chance to the measured value N_{data} or above is given by

$$p = A \int_0^{+\infty} db G(b; N_b, \delta N_b) \sum_{i=N_{data}}^{+\infty} \frac{e^{-b} b^i}{i!}$$

where A is a normalisation factor. The probability p is then transformed into the *standard deviations* using the formula

$$Z_n = \sqrt{2} \text{erf}^{-1}(1 - 2p).$$

The ROOT [121] library provides functions to calculate p and Zn .

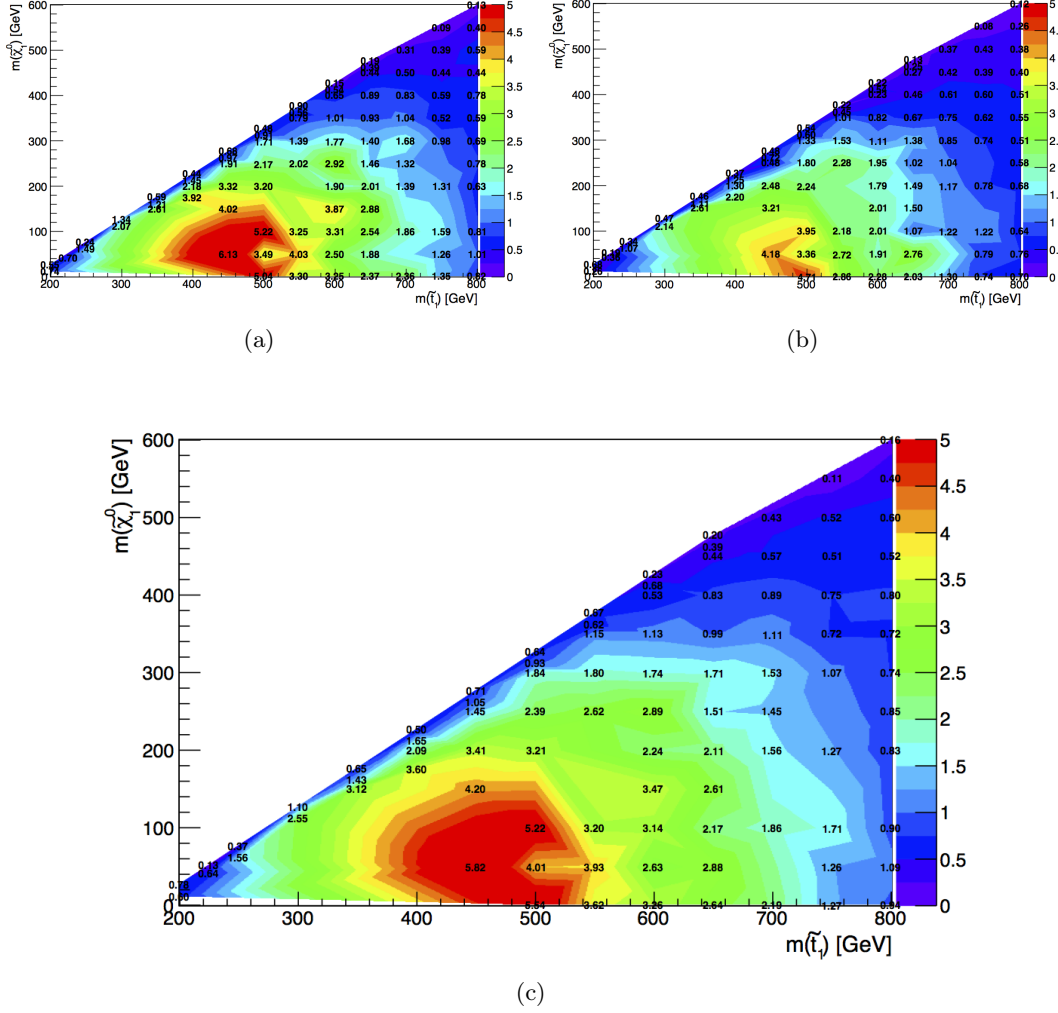
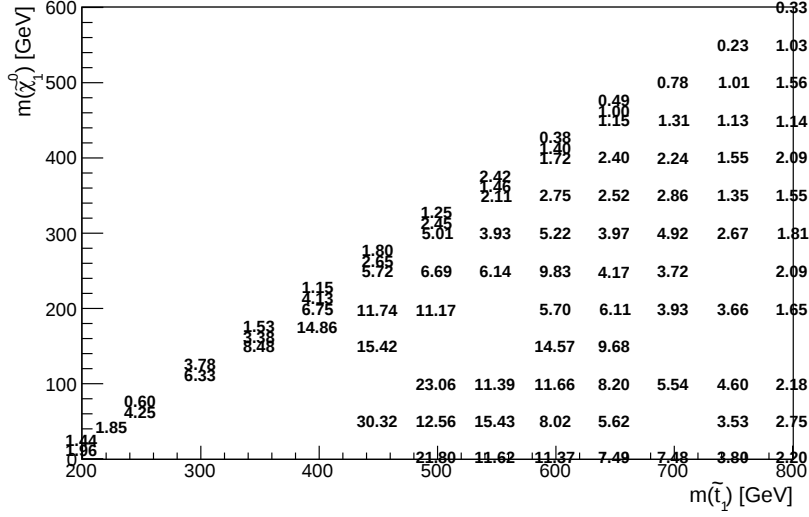


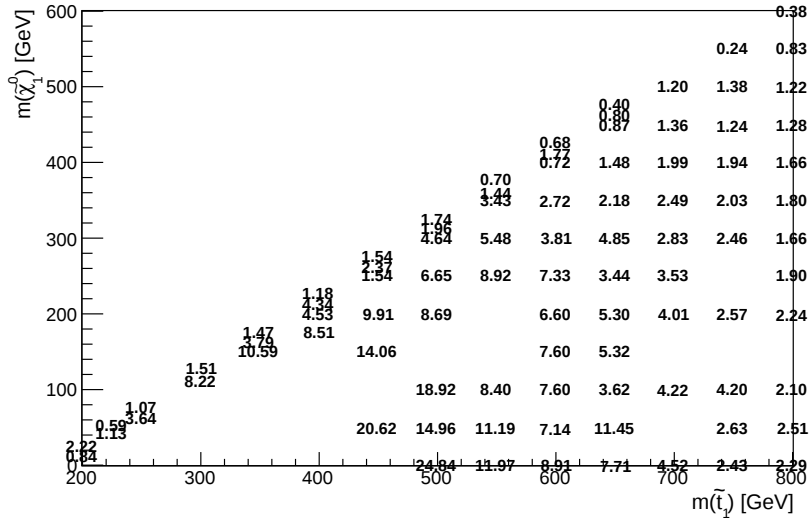
Figure 4.13.: Sensitivity plots for SR_{DF} (a), SR_{SF} (b) and merging both SRs (c). Numbers and color scale shows the significance obtained along the $\tilde{t}_1 - \tilde{\chi}_1^0$ mass plane assuming only a 30% of systematic uncertainty on the total SM background. A better sensitivity is observed in the sum of the contributions coming from the two SRs.

	SR _{DF}	SR _{SF}
Total SM	4.2 ± 1.7	5.8 ± 2.1
$t\bar{t}$	1.6 ± 1.5	2.3 ± 1.5
$t\bar{t} + Z$	1.70 ± 0.35	1.93 ± 0.32
Wt	$0.00^{+0.22}_{-0.00}$	$0.05^{+0.09}_{-0.05}$
$Z/\gamma^* + \text{jets}$	-	$0.3^{+0.5}_{-0.3}$
$VV(l\nu\nu)$	0.11 ± 0.04	0.15 ± 0.05
VZ	0.007 ± 0.002	0.18 ± 0.04
FNP	$0.00^{+0.02}_{-0.00}$	$0.2^{+0.4}_{-0.2}$
Others	0.81 ± 0.15	0.67 ± 0.13

Table 4.7.: Expected yields of the expected backgrounds in SR_{DF} and SR_{SF} for an integrated luminosity of 36.1 fb⁻¹. The errors take into account statistical plus systematic uncertainties. Negative errors are truncated when reaching zero event yield. Entries marked "-" indicate a negligible background contribution.



(a)



(b)

Figure 4.14.: Signal yields relative to SR_{DF} (a) and SR_{SF} (b) for an integrated luminosity of 36.1 fb^{-1} .

4.8. Background estimation

As shown in Tab. 4.7, the dominant SM background contribution to the SRs is due to $t\bar{t}$ and $t\bar{t} + Z$ processes. In order to improve their estimation and not just rely on the estimates provided directly by MC, the background evaluation strategy assumes that they have to be normalised to data in dedicated regions, referred to as *control regions* (CR) and labelled as $\text{CR}_{t\bar{t}}$ and $\text{CR}_{t\bar{t}+Z}$, mainly dominated by $t\bar{t}$ and $t\bar{t} + Z$ events respectively. The obtained *normalisation factors* (also called *scale factors*) are then applied to the SRs yields of $t\bar{t}$ and $t\bar{t} + Z$ as described in the following. In order to have a correct background normalisation in the signal regions, each CR must be kinematically close to the SRs, but orthogonal to them, and with a negligible signal contamination given that, as it will be explained, the background estimation procedure does not consider the signal contribution.

In each CR the number of observed events in the data $N^{\text{obs}}(\text{CR})$ is related to the various backgrounds, estimated by Monte Carlo, by the equation

$$N^{\text{obs}}(\text{CR}) = \mu_{t\bar{t}} N_{t\bar{t}}(\text{CR}) + \mu_{t\bar{t}+Z} N_{t\bar{t}+Z}(\text{CR}) + \sum_i N_{\text{bkg}_i}(\text{CR}), \quad (4.4)$$

where $N_{t\bar{t}}(\text{CR})$ and $N_{t\bar{t}+Z}(\text{CR})$ are the yields predicted by the Monte Carlo in the specific CR for $t\bar{t}$ and $t\bar{t} + Z$ respectively, while the sum is performed on the remaining source of backgrounds that are taken directly from Monte Carlo or determined from data as FNP. An estimation of the scale factors, $\mu_{t\bar{t}}$ and $\mu_{t\bar{t}+Z}$, is thus possible by solving the equation system defined by Eq. 4.4 and the expected background (N_{Bkg}) in the SRs can be then given by

$$N_{\text{Bkg}}(\text{SR}) = \mu_{t\bar{t}} N_{t\bar{t}}(\text{SR}) + \mu_{t\bar{t}+Z} N_{t\bar{t}+Z}(\text{SR}) + \sum_i N_{\text{bkg}_i}(\text{SR}), \quad (4.5)$$

For a correct estimation of $\mu_{t\bar{t}}$ and $\mu_{t\bar{t}+Z}$, systematic uncertainties must be included. In this analysis, to correctly take into account all uncertainties and their correlations, the background estimate was performed with the HISTFITTER package [122]. HISTFITTER is an high-level user-interface built on top of the software packages ROOT, ROOFIT [123], HISTFACTORY [124] and ROOSTATS [125]. ROOFIT and HISTFACTORY are used to build parametric models, ROOFIT to fit these models and ROOSTATS to perform statistical tests⁶. In particular HISTFITTER bases all its computation on the maximum likelihood method.

The most general likelihood that can be implemented in HISTFITTER can be described by the following form⁷

$$\begin{aligned} L(\mathbf{n}, \boldsymbol{\theta}^0 | \mu_{\text{sig}}, \mathbf{s}, \boldsymbol{\mu}_{\text{bkg}}, \mathbf{b}, \boldsymbol{\theta}) &= p_{\text{SR}} \times p_{\text{CR}} \times C(\boldsymbol{\theta}^0, \boldsymbol{\theta}) \\ &= \prod_{j \in \text{SR}} p_j(\mathbf{n}_j | \lambda_j(\mu_{\text{sig}}, s_j, \boldsymbol{\mu}_{\text{bkg}}, \mathbf{b}_j, \boldsymbol{\theta})) \times \prod_{i \in \text{CR}} p_i(\mathbf{n}_i | \lambda_i(\mu_{\text{sig}}, s_i, \boldsymbol{\mu}_{\text{bkg}}, \mathbf{b}_i, \boldsymbol{\theta})) \times C(\boldsymbol{\theta}^0, \boldsymbol{\theta}) \end{aligned} \quad (4.6)$$

⁶In this thesis HISTFITTER was also used for the statistical interpretation of the final results.

⁷In eq. 4.6 all the symbols in bold must be considered as a vector of parameters.

where p_{SR} and p_{CR} are the products of Poisson distributions counting the expected signal (s) and background(b) events and the observed events ($\mathbf{n}$) in each signal and control regions, while $C(\boldsymbol{\theta}^0, \boldsymbol{\theta})$ is an additional constraint term describing the parameters $\boldsymbol{\theta}$, called *nuisance parameters*, having central values given by $\boldsymbol{\theta}^0$ and used to parametrised the various uncertainties. In particular two different types of parameterisation has been considered:

- in the first one the generic nuisance parameter, usually indicated as α , is described by a gaussian distribution centred on zero and of width one, so that zero corresponds to the nominal rate in all the regions, while ± 1 corresponds to the *up* and *down* variation due to the uncertainty.
- in the second one the generic nuisance parameter, usually referred to as γ , follows again a gaussian distribution but this time with mean equal to 1 and sigma given by the relative error of the uncertainty under study.

The first case is used for the systematic uncertainties, the latter is considered instead for the statistical uncertainty.

At this point, it is clear that the only free parameters of the likelihood are:

- the background scale factors (μ_{bkg}),
- the signal scale factor (μ_{sig}) usually referred to as *signal strength*,
- the nuisance parameters ($\boldsymbol{\theta}$).

However, for the determination of $t\bar{t}$ and $t\bar{t} + Z$ scale factors, a simplified likelihood, not taking into account the SRs Poisson terms and the signal contribution in the CRs, was defined and then maximised. This procedure, called *background-only fit*, does not introduce any bias provided that control regions must have a negligible signal contamination.

Before applying the obtained scale factors to the signal regions, the results are anyway validated in dedicated regions, referred to as validation regions (VR), that are orthogonal to both CRs and SRs but kinematically even more close to the SRs with respect to the CRs. A good agreement between data and MC in VRs, after the application of the scale factors, provides in fact a solid basis on the idea that the background modelling is under control.

4.8.1. $t\bar{t}$ control region definition

The choice of the $t\bar{t}$ control region was based on the event selection criteria listed in Tab. 4.8. The orthogonality to the SRs is provided by inverting the cut on the R_{ll} variable and requiring an $m_{T2} \in [60, 100]$ GeV.

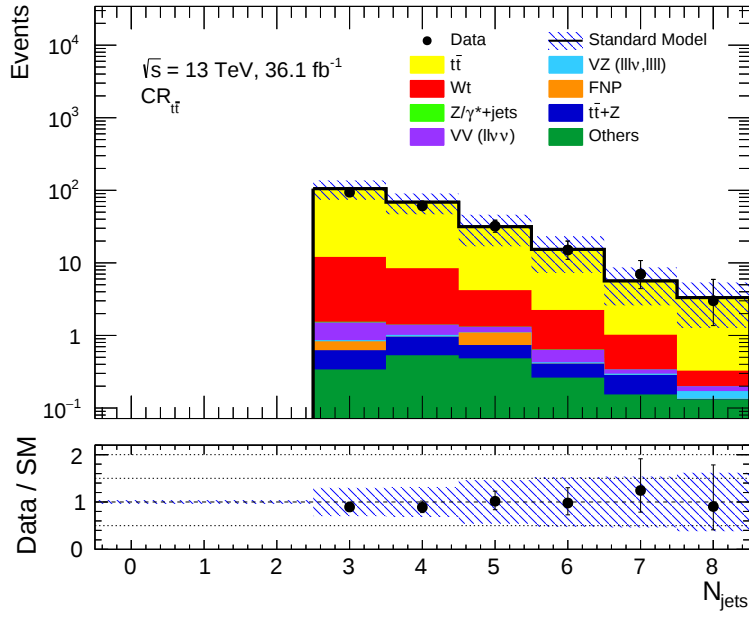
The expected yields in MC and observed events for the $\text{CR}_{t\bar{t}}$ are reported in Tab. 4.11. The signal contamination was found to be negligible (2-3%). Some plots showing data versus MC comparisons before performing the fit procedure are reported for events in the $\text{CR}_{t\bar{t}}$: Fig. 4.15 shows the jet multiplicity together with b -tagged jet distribution, while Fig. 4.16 and Fig. 4.17 show m_{T2} , E_T^{miss} and R_{ll} distributions.

$\text{CR}_{t\bar{t}}$	
Lepton flavour	DF or SF
$p_T(l_1), p_T(l_2)$ [GeV]	$> 25, 20$
m_{ll} [GeV]	> 20 if DF, $[20, 71] \cup [111, +\infty[$ if SF
E_T^{miss} [GeV]	> 200
N_{jets}	≥ 3
N_{b-jets}	≥ 1
m_{T2} [GeV]	$[60, 100]$
R_{ll}	< 1.2

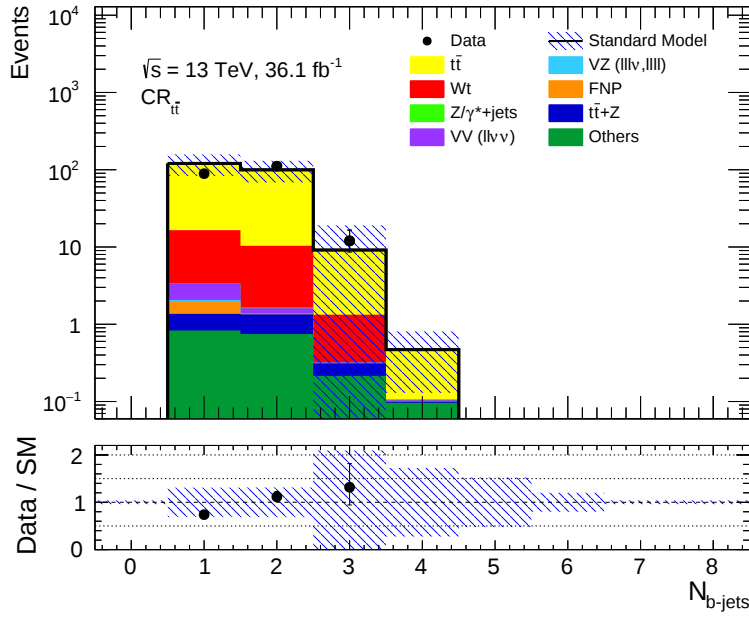
Table 4.8.: Event selection criteria of the $t\bar{t}$ CR.

$\text{CR}_{t\bar{t}}$	
Observed events	212
Total SM	230 ± 70
$t\bar{t}$	200 ± 70
$t\bar{t} + Z$	1.23 ± 0.18
Wt	23 ± 7
$Z/\gamma^* + jets$	0.054 ± 0.024
$VV(ll\nu\nu)$	1.53 ± 0.29
VZ	0.16 ± 0.07
FNP	-
Others	1.90 ± 0.12
$m(\tilde{t}_1, \tilde{\chi}_1^0) = (400, 175)$ GeV	5.0 ± 0.8
$m(\tilde{t}_1, \tilde{\chi}_1^0) = (350, 150)$ GeV	7.0 ± 1.0

Table 4.9.: Expected MC yields and observed events for $\text{CR}_{t\bar{t}}$, for an integrated luminosity of 36.1 fb^{-1} . The expected signal contribution is also reported. The errors take into account statistical plus systematic uncertainties. Entries marked "-" indicate a negligible background contribution.

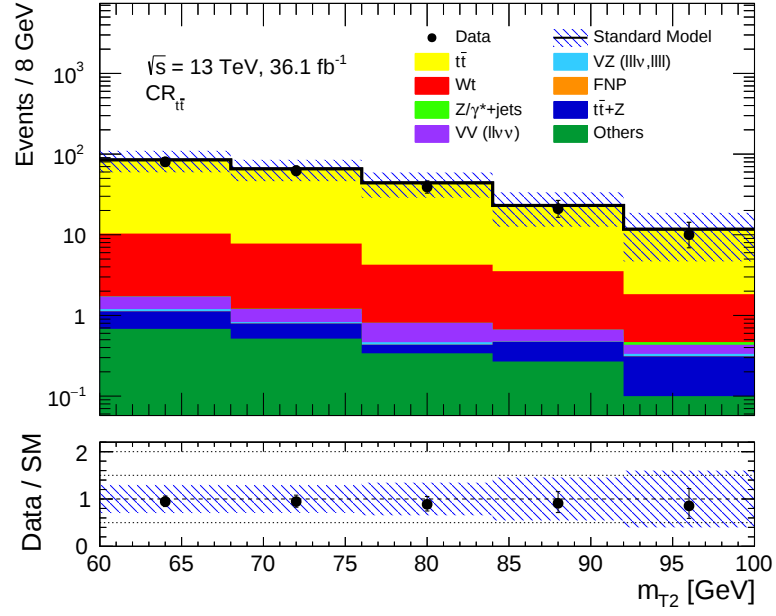


(a)

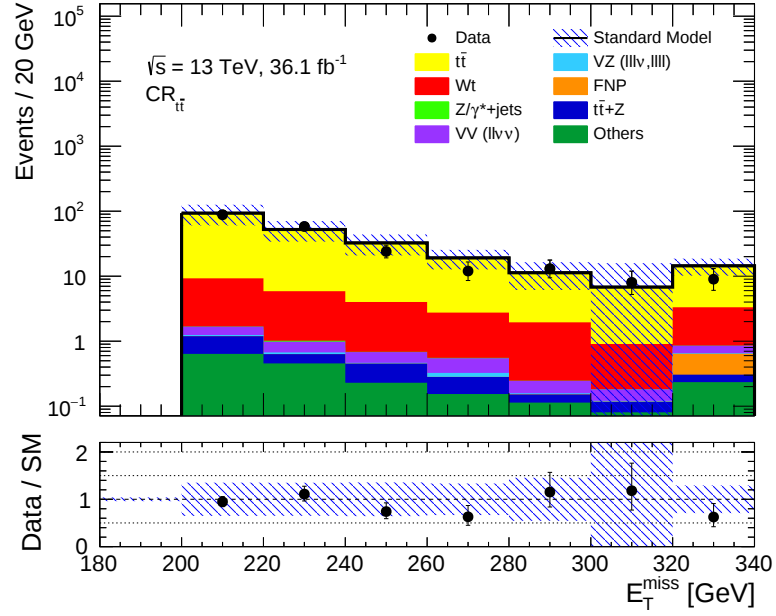


(b)

Figure 4.15.: Jet multiplicity (a) and b -tagged jet (b) distributions for events passing all $\text{CR}_{t\bar{t}}$ requirements. The contributions from all the dominant SM backgrounds are shown, with the band representing the total uncertainty.



(a)



(b)

Figure 4.16.: m_{T2} (a) and E_T^{miss} (b) distributions for events passing all $CR_{t\bar{t}}$ requirements. The contributions from all the dominant SM backgrounds are shown, with the band representing the total uncertainty.

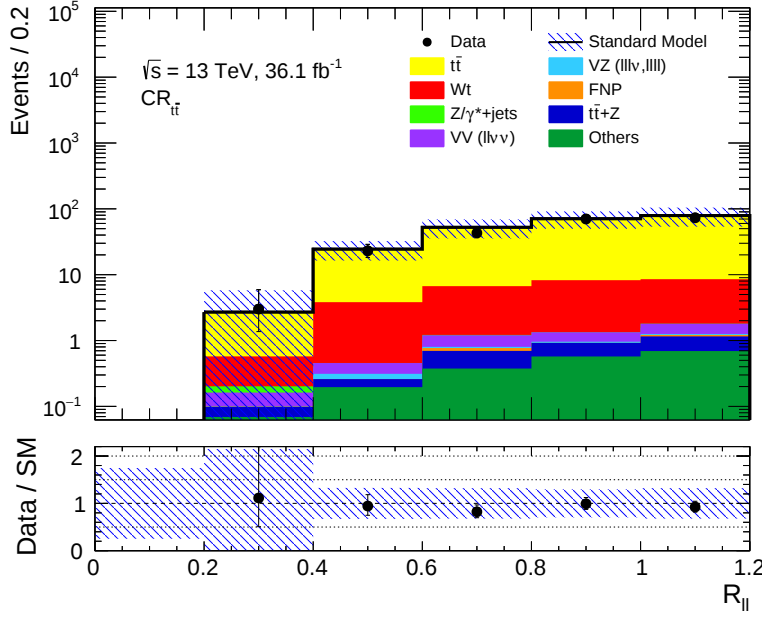


Figure 4.17.: $R_{||}$ distribution for events passing all $\text{CR}_{t\bar{t}}$ requirements. The contributions from all the dominant SM backgrounds are shown, with the band representing the total uncertainty.

4.8.2. $t\bar{t} + Z$ control region definition

The contribution in the SR of $t\bar{t} + Z$ production process, that is one of the dominant background for the current analysis, is given by those events in which the $t\bar{t}$ decays leptonically while the Z boson decays into invisible. In order to normalise its contribution to the observed data, a CR characterised by a high purity of this background is needed. However, it is quite difficult to achieve a reasonable purity for the $t\bar{t} + Z$ while keeping the request for two opposite sign leptons, due to high $t\bar{t}$ contamination. A three leptons final states was therefore preferred for the control region $\text{CR}_{t\bar{t}+Z}$ definition, selecting those $t\bar{t} + Z$ events where the Z decays leptonically while the $t\bar{t}$ decays in semi-leptonic channel. In this way the orthogonality between SRs and $\text{CR}_{t\bar{t}+Z}$ is ensured. To achieve a highest selection efficiency for $t\bar{t} + Z$ events, the invariant mass among all the leptons pairs with same flavour but opposite charge was computed, and only the events having at least one pair with an invariant mass between 71 GeV and 111 GeV were accepted. In case that more than one leptons pair satisfied this condition, the pair with m_{ll} nearest to the nominal Z mass was considered as coming from the Z decay. At least four jets, with only one b -tagged jet, or at least three jets, with at least one b -tagged, were finally required to select the top hadronic decay.

Once the three leptons events sample was selected, the aim was to select $t\bar{t} + Z$ events whose kinematics, regardless of subsequent $t\bar{t}$ and Z decays, emulates the one charac-

terising the SRs. To do this it was necessary to introduce a new variable deputising for m_{T2} in the three leptons selection. Since in the SRs the E_T^{miss} contribution to m_{T2} is enlarged for $t\bar{t} + Z$ by the two neutrinos coming from the Z , it was decided for the three leptons case to add to the transverse missing energy the transverse momenta of the two leptons, coming from the Z , for the definition of the new variable $E_{T,\text{corr}}^{\text{miss}}$. A high $E_{T,\text{corr}}^{\text{miss}}$ cut should behave as a high m_{T2} cut for the two leptons selection⁸.

The final selection for $\text{CR}_{t\bar{t}+Z}$ is reported in Tab. 4.10. The expected MC yields and the observed events are instead shown in Tab. 4.11. Some plots showing data versus MC comparisons before performing the fit procedure are reported for events in the $\text{CR}_{t\bar{t}+Z}$: $E_{T,\text{corr}}^{\text{miss}}$ and E_T^{miss} are shown in Fig. 4.18, while Fig. 4.19 shows the jet multiplicity together with b-tagged jet distribution.

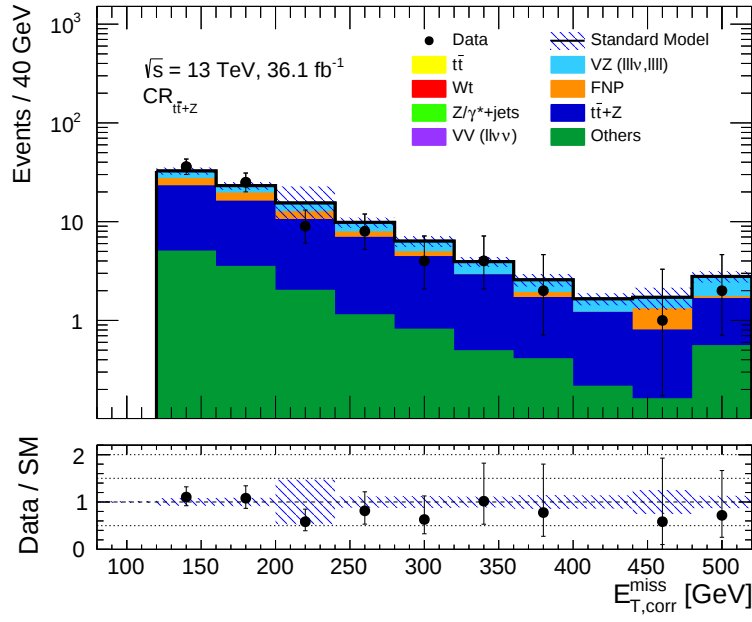
$\text{CR}_{t\bar{t}+Z}$	
n_{lep}	3
m_{ll} [GeV] (SF OS pair)	[71,111]
Jet requirements	$N_{jets} > 2$ and $N_{b-jets} > 1$ $N_{jets} > 3$ and $N_{b-jets} = 1$
$E_{T,\text{corr}}^{\text{miss}}$	> 120

Table 4.10.: Event selection criteria of the $t\bar{t} + Z$ CR.

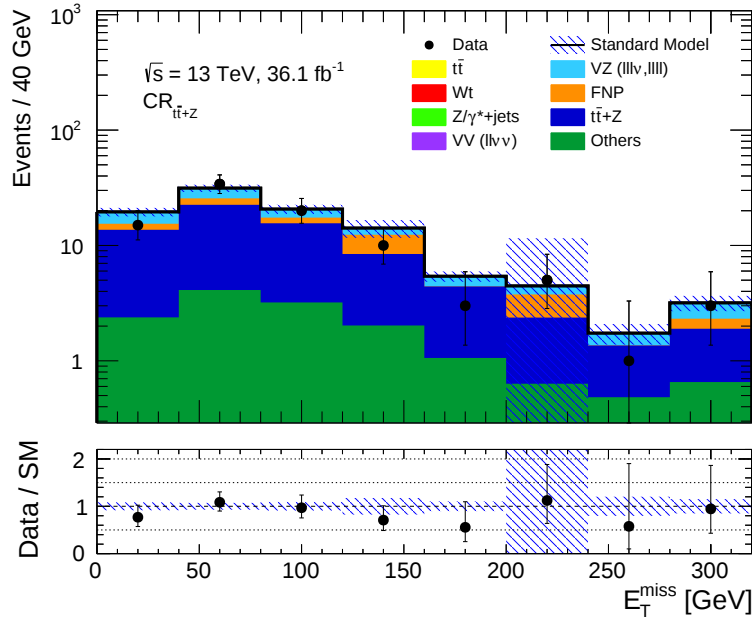
$\text{CR}_{t\bar{t}+Z}$	
Observed events	91
Total SM events	100 ± 9
$t\bar{t} + Z$ events	55.7 ± 3.1
VZ events	17.7 ± 2.2
FNP events	12 ± 7
Others events	14.5 ± 1.0

Table 4.11.: Expected MC yields and observed events for $\text{CR}_{t\bar{t}+Z}$, for an integrated luminosity of 36.1 fb^{-1} . The errors take into account statistical plus systematic uncertainties.

⁸The $\text{CR}_{t\bar{t}+Z}$ definition has been inspired by the $t\bar{t} + Z$ estimate described in [126]

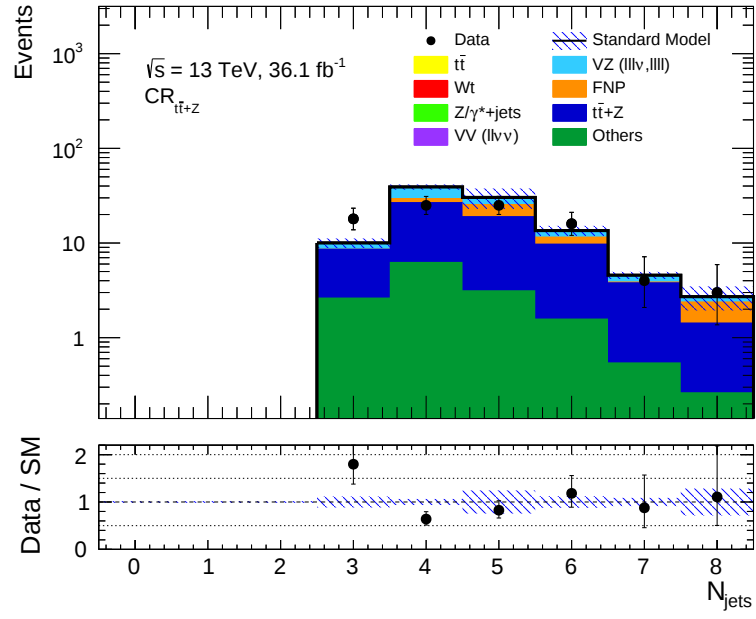


(a)

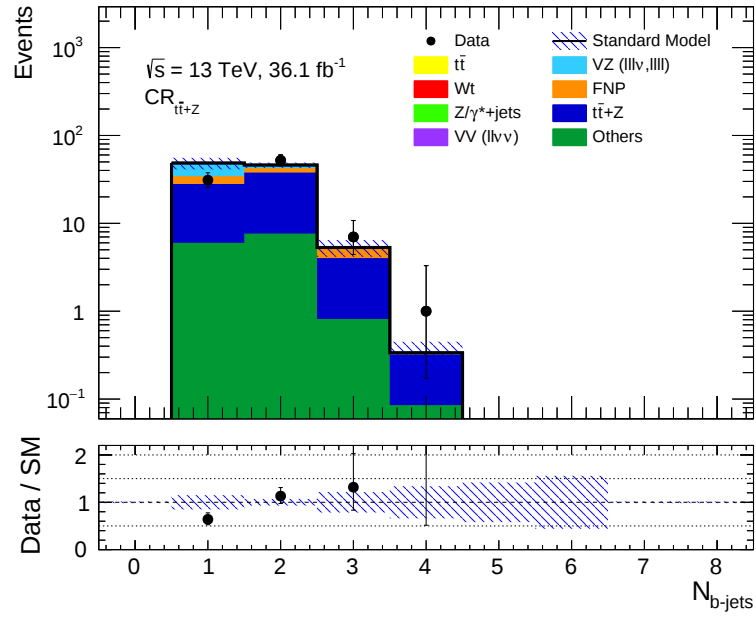


(b)

Figure 4.18.: $E_{T,\text{corr}}^{\text{miss}}$ (a) and E_T^{miss} (b) distributions for events passing all $\text{CR}_{t\bar{t}+Z}$ criteria. The contributions from all the dominant SM backgrounds are shown, with the band representing the total uncertainty.



(a)



(b)

Figure 4.19.: N_{jets} (a) and N_{b-jets} (b) distributions for events passing all $CR_{t\bar{t}+Z}$ criteria. The contributions from all the dominant SM backgrounds are shown, with the band representing the total uncertainty.

4.8.3. Validation region definition

The semi-data driven estimation of both $t\bar{t}$ and $t\bar{t}+Z$ processes contribution was validated in a single defined validation region, defined to be as much as possible close to the SRs. The cuts applied for the definition of the validation region are reported in Tab. 4.12. The region is orthogonal to the SRs thanks to the request $R_{ll} < 1.2$.

VR	
Lepton flavour	DF or SF
$p_T(l_1), p_T(l_2)$ [GeV]	$> 25, 20$
m_{ll} [GeV]	> 20 if DF, $[20, 71] \cup [111, +\infty[$ if SF
E_T^{miss} [GeV]	> 200
N_{jets}	≥ 3
N_{b-jets}	≥ 1
m_{T2} [GeV]	> 100
R_{ll}	< 1.2

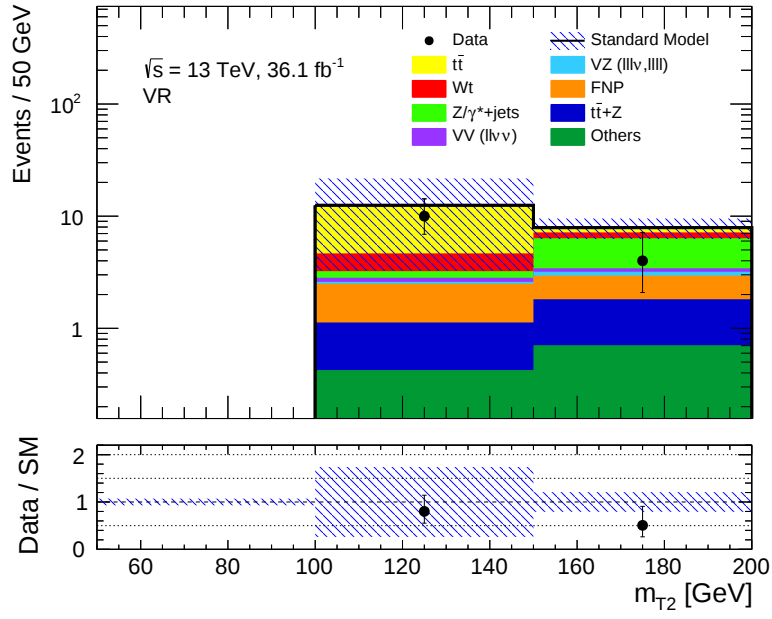
Table 4.12.: Event selection criteria of the validation region.

	VR
Observed events	14
Total SM	20 ± 10
$t\bar{t}$	8 ± 6
$t\bar{t} + Z$	1.81 ± 0.27
Wt	2.2 ± 0.6
Z/γ^*+jets	3.3 ± 0.5
$VV(ll\nu\nu)$	0.46 ± 0.18
VZ	0.35 ± 0.07
FNP	2^{+7}_{-2}
Others	1.13 ± 0.15
$m(\tilde{t}_1, \tilde{\chi}_1^0) = (400, 175)$ GeV	3.6 ± 1.8
$m(\tilde{t}_1, \tilde{\chi}_1^0) = (350, 150)$ GeV	2.7 ± 0.6

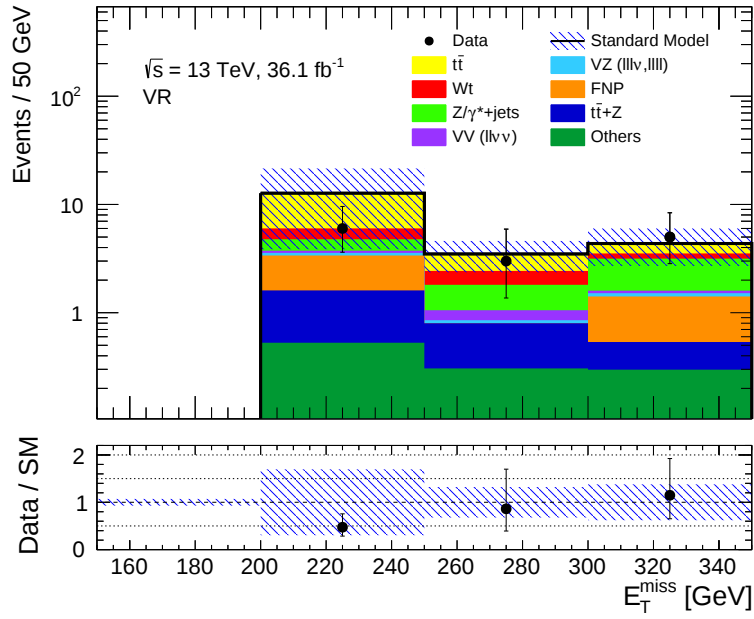
Table 4.13.: Expected MC yields and observed events for the validation region, for an integrated luminosity of 36.1 fb^{-1} . The expected signal contribution is also reported. The errors take into account statistical plus systematic uncertainties.

The expected MC yields and the observed events are listed in Tab. 4.13. Some plots

showing data versus MC comparisons before performing the fit procedure are reported for events in the VR: Fig. 4.20 and Fig. 4.21 show the distributions of E_T^{miss} , m_{T2} and R_{ll} in the validation region.



(a)



(b)

Figure 4.20.: m_{T2} (a) and E_T^{miss} (b) distributions for events passing the VR selection. The contributions from all the dominant SM backgrounds are shown, with the band representing the total uncertainty.

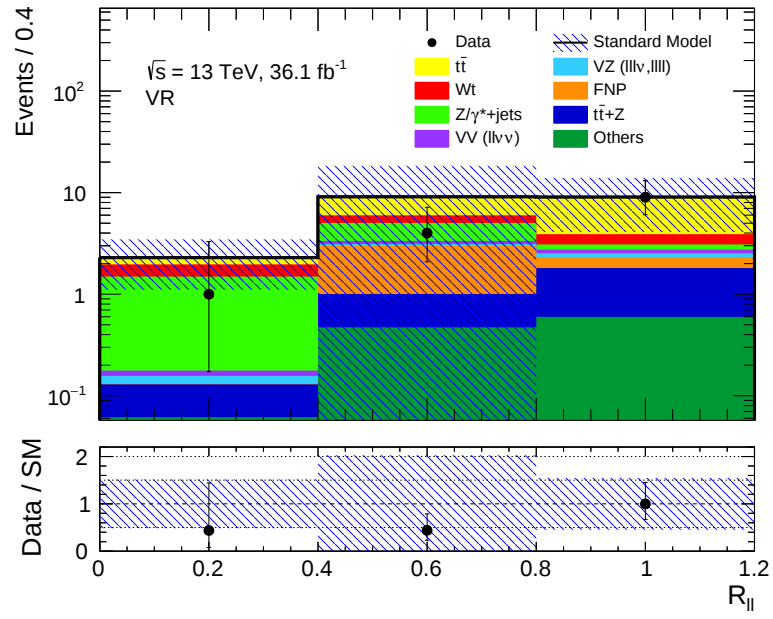


Figure 4.21.: $R_{||}$ distribution for events passing the VR selection. The contributions from all the dominant SM backgrounds are shown, with the band representing the total uncertainty.

4.8.4. Results

After the application of the background-only fit procedure previously described, the fit-estimated background scale factors were applied to the expected background rates for all the analysis regions. The observed events in data and the MC after-fit yields are reported in Tab. 4.14 and in Tab. 4.15. The fit-estimated scale factors are reported in Tab. 4.16. Fig. 4.22 shows the final estimate for all the free parameters in the fit. The correlations, provided by the background-only fit procedure, between $\mu_{t\bar{t}}$, $\mu_{t\bar{t}+Z}$ and the nuisance parameters are shown in Fig. 4.23. No pathological fit behaviour is observed.

The distributions of several kinematic variables in the control regions, after the application of the scale factors provided by the fit, are reported in Figg. 4.24 - 4.28 and show a good agreement between data and the fit-corrected MC. Fig. 4.29 and Fig. 4.30, relative to the events in the VR, confirm a Monte Carlo compatible with the observed data within one sigma, underlying a good MC modelling at high m_{T2} after the background-only fit.

	CR _{$t\bar{t}$}	CR _{$t\bar{t}+Z$}	VR
Observed events	212	91	14
Estimated total SM events	212 ± 15	91 ± 10	19 ± 8
Estimated $t\bar{t}$	184 ± 16	-	8 ± 4
Estimated $t\bar{t} + Z$	1.03 ± 0.32	47 ± 12	1.5 ± 0.5
Wt	23 ± 7	-	2.2 ± 0.6
$Z/\gamma^* + \text{jets}$	0.054 ± 0.024	-	3.3 ± 0.5
$VV(ll\nu\nu)$	1.53 ± 0.29	-	0.46 ± 0.18
VZ	0.16 ± 0.07	17.7 ± 2.2	0.35 ± 0.07
FNP	-	12 ± 7	2^{+7}_{-2}
Others	1.91 ± 0.12	14.6 ± 1.0	1.13 ± 0.15
Nominal MC $t\bar{t}$	200 ± 70	-	8 ± 6
Nominal MC $t\bar{t} + Z$	1.23 ± 0.18	55.7 ± 3.1	1.81 ± 0.27
$m(\tilde{t}_1, \tilde{\chi}_1^0) = (400, 175) \text{ GeV}$	5.0 ± 0.8	0.00 ± 0.00	3.6 ± 1.8
$m(\tilde{t}_1, \tilde{\chi}_1^0) = (350, 150) \text{ GeV}$	7.0 ± 1.0	0.00 ± 0.00	2.7 ± 0.6

Table 4.14.: MC expected yields and observed events for control and validation regions, after the background-only fit procedure, for an integrated luminosity of 36.1 fb^{-1} . The nominal predictions from MC simulation are also given for the backgrounds $t\bar{t}$ and $t\bar{t} + Z$. For each region the expected benchmark signal contribution is also reported. Errors take into account statistical plus systematic uncertainties. Entries marked "-" indicate a negligible background contribution.

Concerning the SRs, no significant excess was found in the data with respect to the

	SR _{DF}	SR _{SF}
Observed events	7	11
Estimated total SM	3.8 ± 1.5	5.3 ± 1.8
Estimated $t\bar{t}$	1.4 ± 1.2	2.1 ± 1.3
Estimated $t\bar{t} + Z$	1.4 ± 0.5	1.6 ± 0.5
Wt	$0.00^{+0.23}_{-0.00}$	$0.05^{+0.09}_{-0.05}$
$Z/\gamma^* + \text{jets}$	-	$0.3^{+0.5}_{-0.3}$
$VV(l\nu\nu)$	0.11 ± 0.04	0.15 ± 0.05
VZ	0.007 ± 0.002	0.18 ± 0.04
FNP	$0.00^{+0.02}_{-0.00}$	$0.2^{+0.4}_{-0.2}$
Others	0.81 ± 0.15	0.67 ± 0.13
Nominal MC $t\bar{t}$	1.6 ± 1.5	2.3 ± 1.5
Nominal MC $t\bar{t} + Z$	1.70 ± 0.35	1.93 ± 0.32
$m(\tilde{t}_1, \tilde{\chi}_1^0) = (400, 175) \text{ GeV}$	14.86 ± 2.32	8.51 ± 1.31
$m(\tilde{t}_1, \tilde{\chi}_1^0) = (350, 150) \text{ GeV}$	8.48 ± 3.13	10.59 ± 2.76

Table 4.15.: Expected MC yields and observed events for signal regions, after the background-only fit procedure, for an integrated luminosity of 36.1 fb^{-1} . The nominal predictions from MC simulation are also given for the backgrounds $t\bar{t}$ and $t\bar{t} + Z$. For each SR the expected benchmark signal contribution is also reported. Errors take into account statistical plus systematic uncertainties.

	Value
$\mu_{t\bar{t}}$	0.92 ± 0.33
$\mu_{t\bar{t}+Z}$	0.84 ± 0.23

Table 4.16.: Scale factors from the background-only fit. The scale factors errors takes into account all the uncertainties considered in the background-only fit procedure.

MC predictions, as shown by the m_{T2} distribution plots (Fig. 4.31). A significance of 1.17 and 1.64 was in fact quoted for SR_{DF} and SR_{SF} respectively.

The main uncertainties affecting the MC fit predictions in the SRs are related to

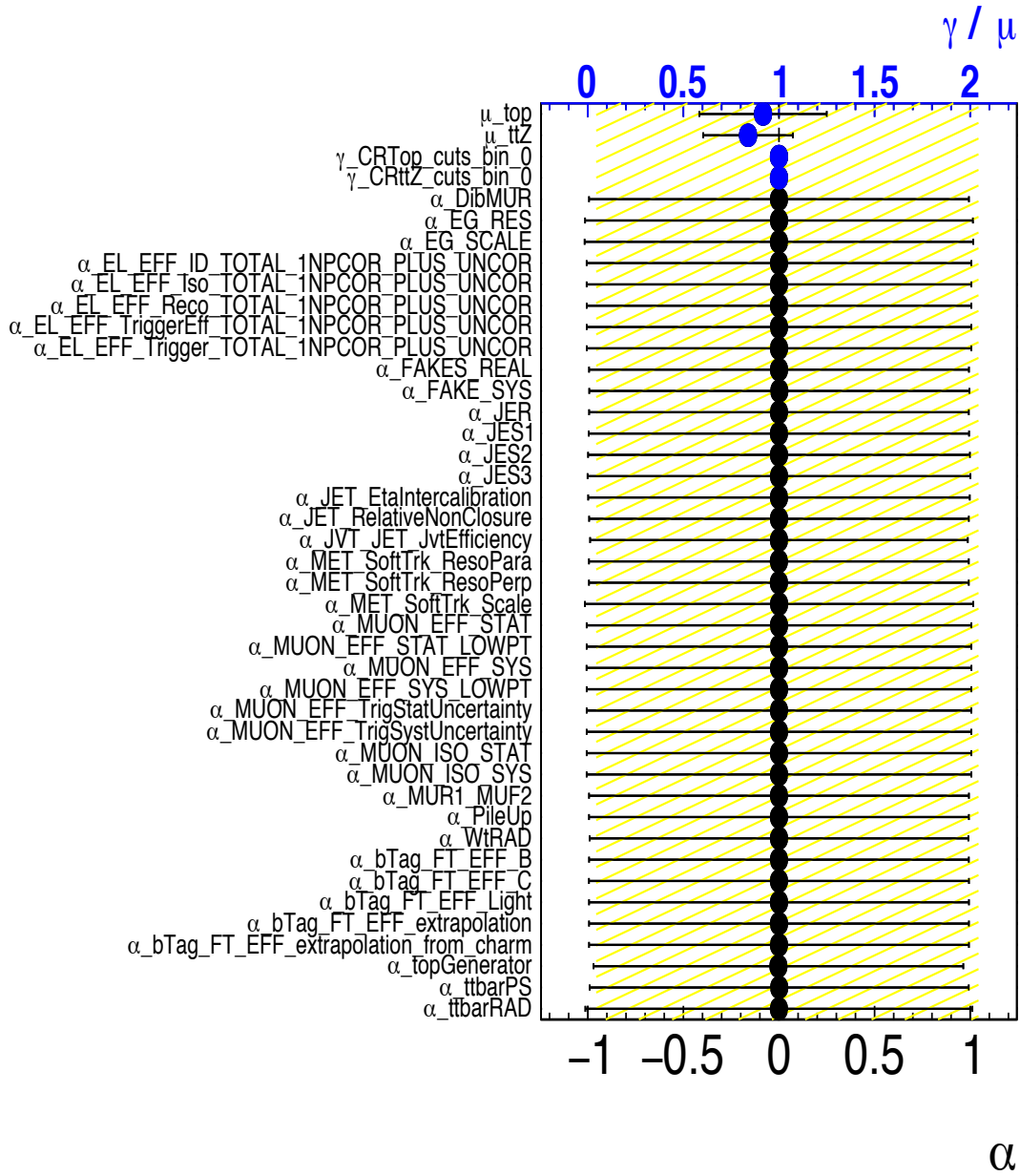


Figure 4.22.: Fit parameter results. As expected, all nuisance parameters α related to systematic uncertainties (see App. B for their parameterisation) show a fit value around 0 and an associated error close to 1, while the nuisance parameters γ , having an estimated value around 1, present errors equal to the total statistical errors of $\text{CR}_{t\bar{t}}$ (2.7%) and $\text{CR}_{t\bar{t}+Z}$ (3.6%). The final scale factor values with their errors are also reported.

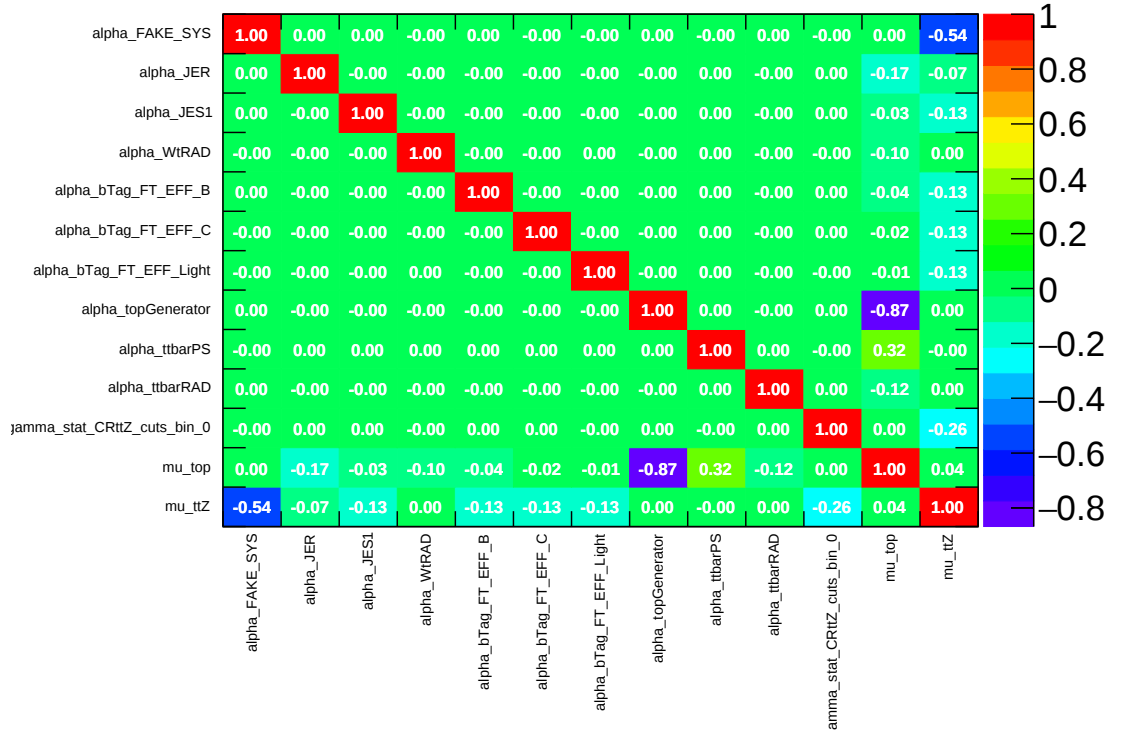
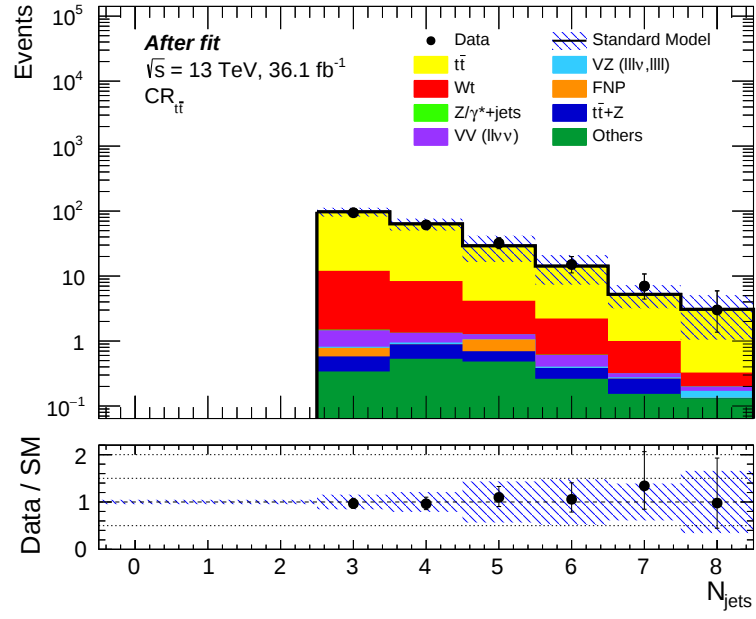


Figure 4.23.: Correlation matrix from the background-only fit procedure. All nuisance parameters showing a correlation, greater (lower) than $+(-)0.1$, with at least one of the scale factors are reported. Strong correlation is present for those nuisance parameters associated with the main uncertainties in the control regions (see App. C).

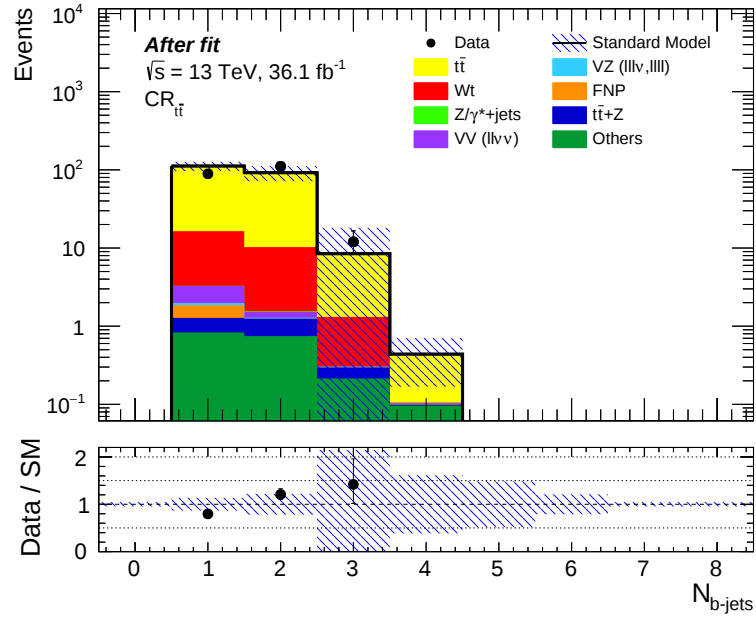
the E_T^{miss} modelling, statistics, jet energy scale and resolution, as can be observed in Tab. 4.17. In both SRs it was found a total error higher than the prevision (30% error, see Sect. 4.7.1). The tables listing the breakdown of all the uncertainties region by region are in App. C.

	SR _{DF}	SR _{SF}
Estimated total SM	3.8	5.3
Total background uncertainty	± 1.5 [39.05%]	± 1.8 [34.83%]
α_{JES1}	21.8%	9.7%
α_{JER}	16.0%	11.5%
$\alpha_{\text{MET_SoftTrk_ResoPara}}$	15.5%	20.1%
$\gamma_{\text{stat_HighStopMass_DF_cuts_bin_0}}$	15.0%	0.00%
$\mu_{t\bar{t}}$	13.8%	14.5%
$\alpha_{\text{MET_SoftTrk_Scale}}$	13.4%	3.8%
$\alpha_{\text{MET_SoftTrk_ResoPerp}}$	13.0%	16.9%
$\mu_{t\bar{t}+Z}$	10.5%	8.6%
α_{ttbarRAD}	9.4%	3.2%
$\alpha_{\text{topGenerator}}$	8.4%	8.9%
α_{WtRAD}	5.4%	0.00%
α_{PileUp}	4.4%	2.7%
$\alpha_{\text{JET_EtaIntercalibration}}$	3.3%	3.7%
α_{JES2}	2.2%	4.9%
α_{JES3}	1.1%	5.9%
α_{DibMUR}	0.60%	0.60%
$\alpha_{\text{FAKE_SYS}}$	0.42%	6.6%
α_{ttbarPS}	0.26%	5.7%
α_{WtDS}	0.02%	0.60%
$\gamma_{\text{stat_HighStopMass_SF_cuts_bin_0}}$	0.00%	14.8%
$\alpha_{\text{FAKES_REAL}}$	0.00%	4.0%

Table 4.17.: Breakdown of the dominant systematic uncertainties on MC background fit estimates for both signal regions. Note that the individual uncertainties can be correlated, and do not necessarily add up quadratically to the total background uncertainty. The percentages indicate the size of the uncertainty relatively to the total estimated background. The uncertainties highlighted in red contribute with more than 10% uncertainty in one of the two SRs.

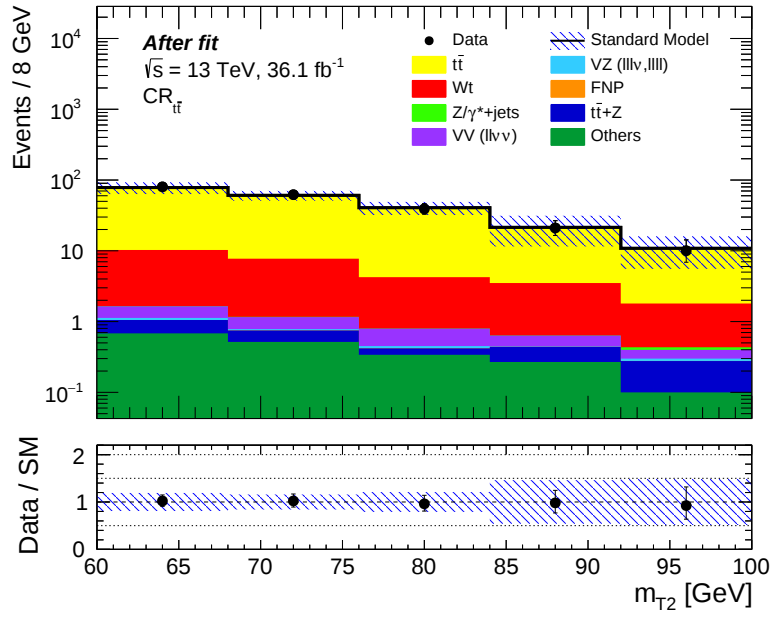


(a)

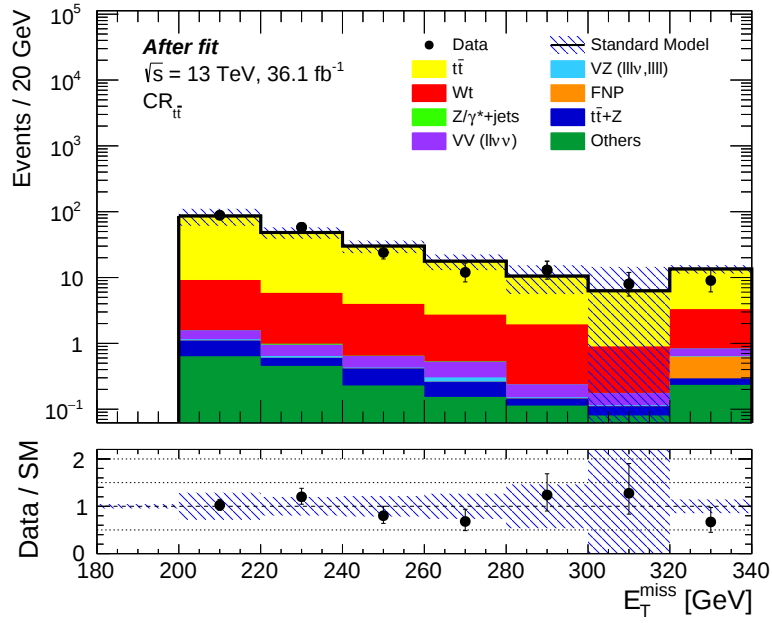


(b)

Figure 4.24.: N_{jets} (a) and N_{b-jets} (b) distributions after the background-only fit for events in the $CR_{t\bar{t}}$. The contributions from all the dominant SM backgrounds are shown, with the band representing the total uncertainty.



(a)



(b)

Figure 4.25.: m_{T2} (a) and E_T^{miss} (b) distributions after the background-only fit for events in the $CR_{t\bar{t}}$. The contributions from all the dominant SM backgrounds are shown, with the band representing the total uncertainty.

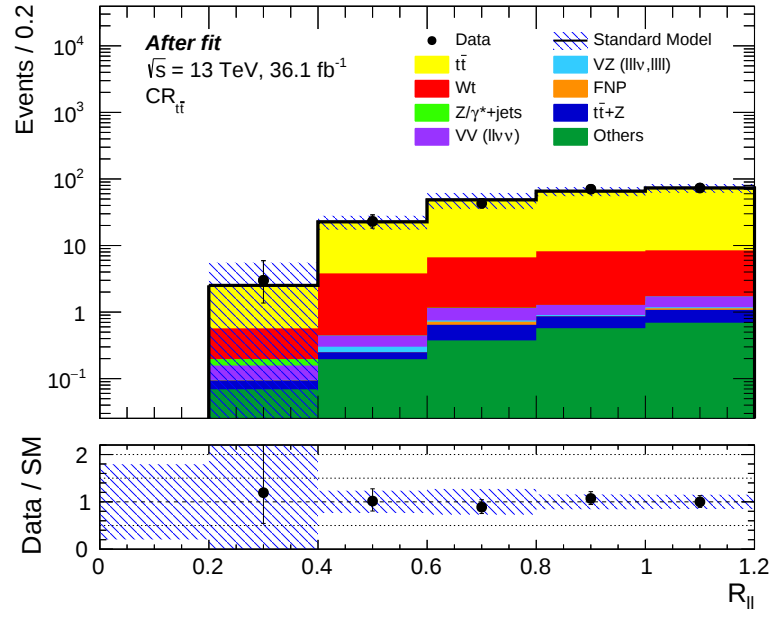
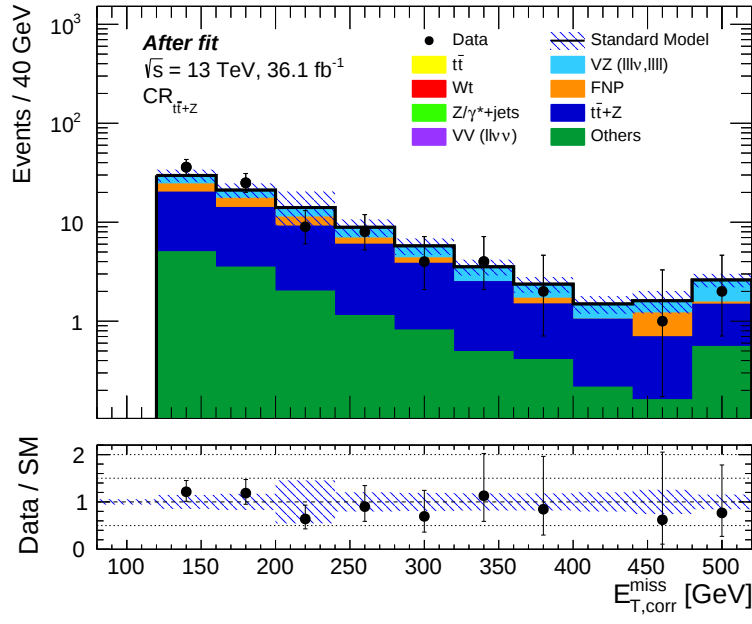
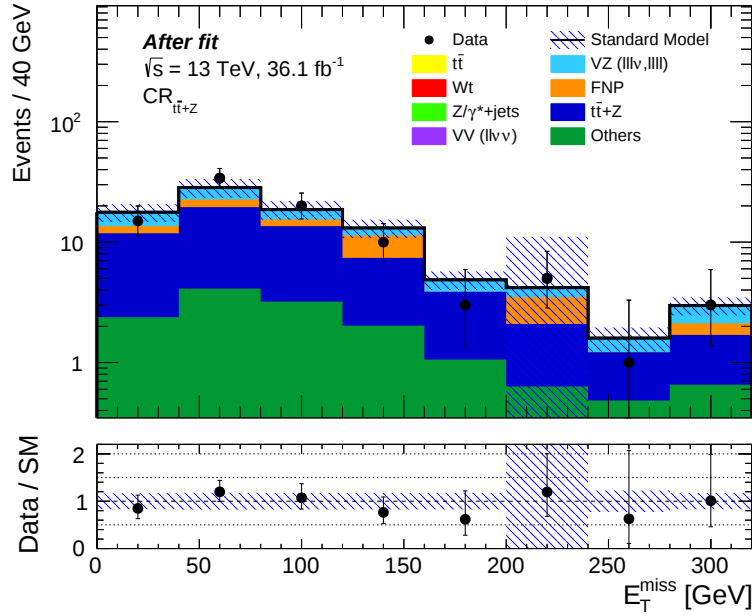


Figure 4.26.: R_{II} distributions after the background-only fit for events in the $CR_{t\bar{t}}$. The contributions from all the dominant SM backgrounds are shown, with the band representing the total uncertainty.

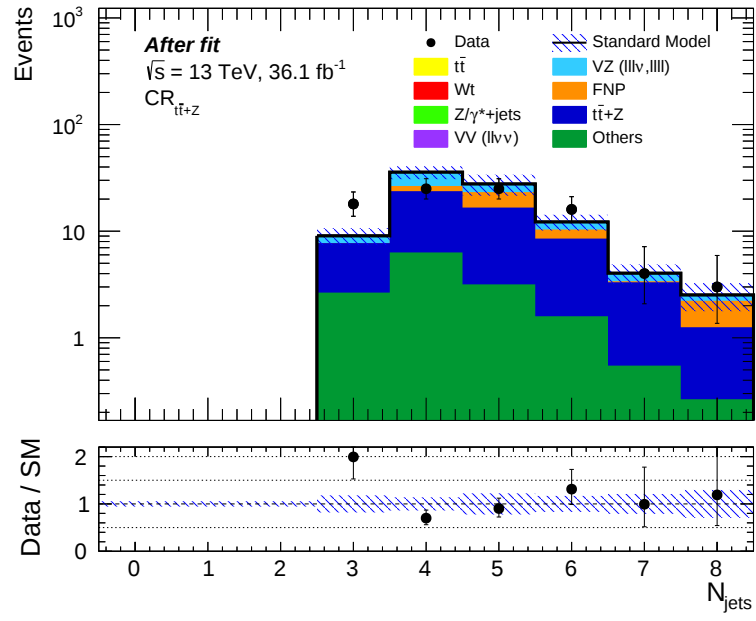


(a)

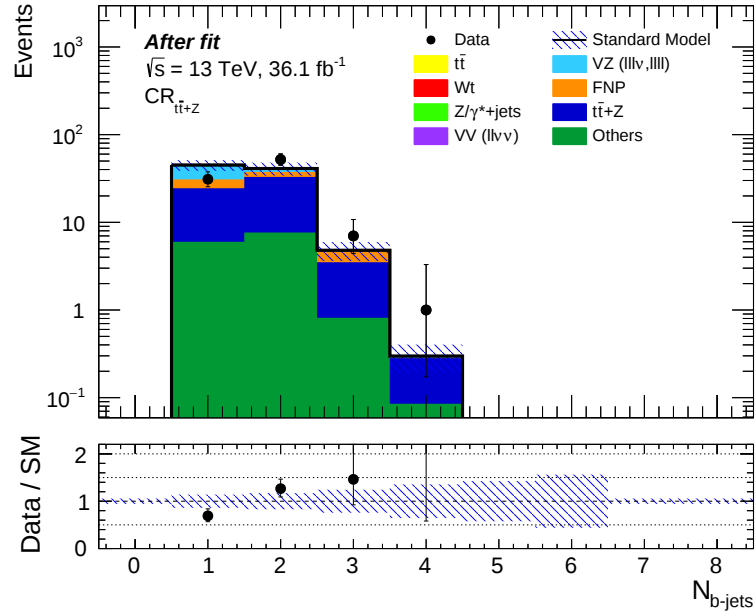


(b)

Figure 4.27.: $E_{T,corr}^{miss}$ (a) and E_T^{miss} (b) distributions for events in $CR_{t\bar{t}+Z}$ and after the fit-estimated scale factor application. The contributions from all the dominant SM backgrounds are shown, with the band representing the total uncertainty.

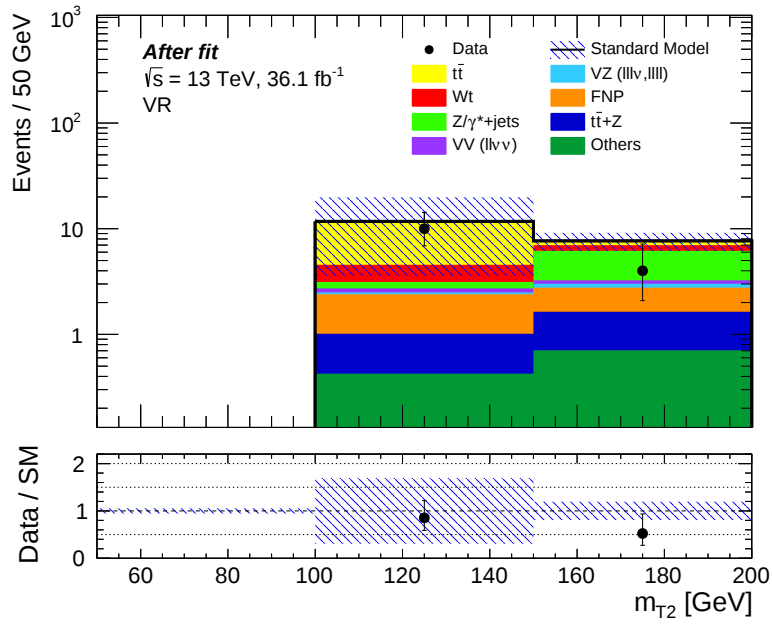


(a)

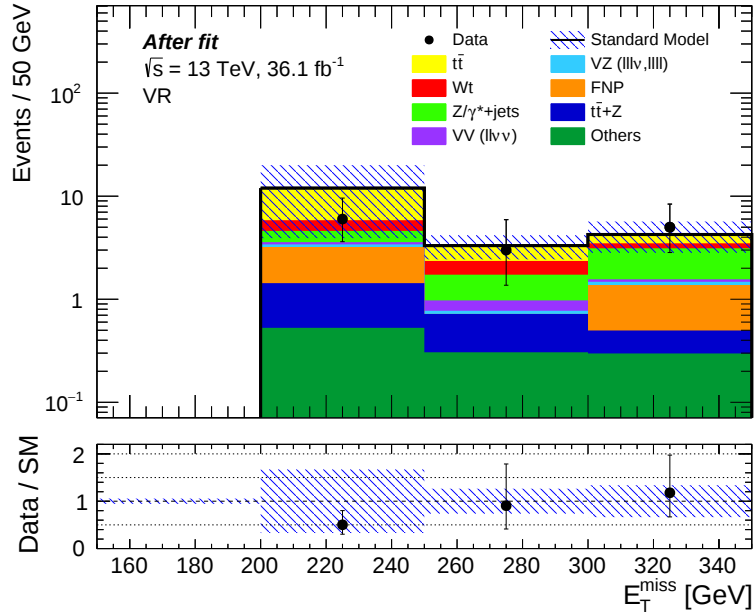


(b)

Figure 4.28.: N_{jets} (a) and N_{b-jets} (b) distributions for events in $CR_{t\bar{t}+Z}$ and after the fit-estimated scale factors application. The contributions from all the dominant SM backgrounds are shown, with the band representing the total uncertainty.



(a)



(b)

Figure 4.29.: m_{T2} (a) and E_T^{miss} (b) distributions for events in the VR and after the fit-estimated scale factors application. The contributions from all the dominant SM backgrounds are shown, with the band representing the total uncertainty.

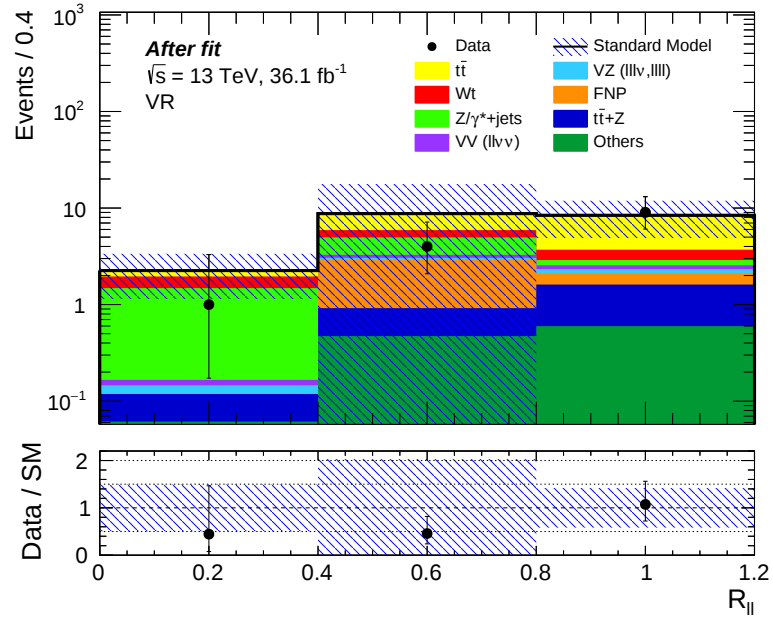
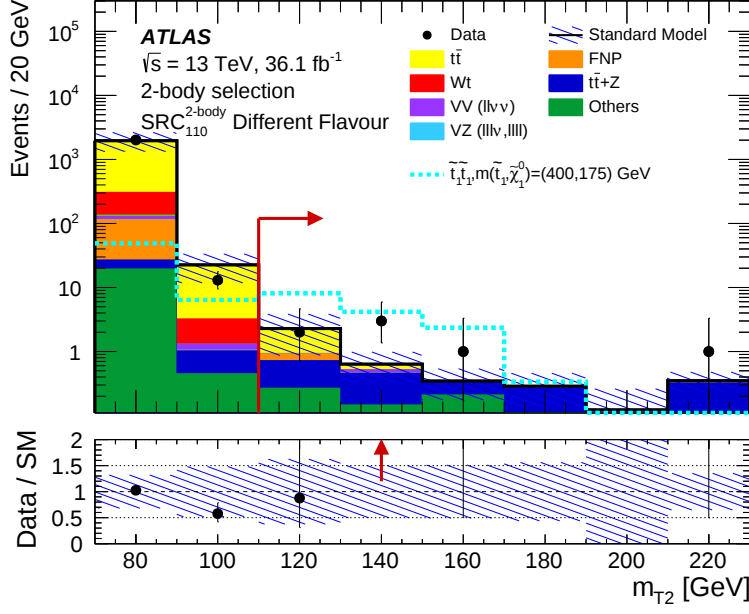
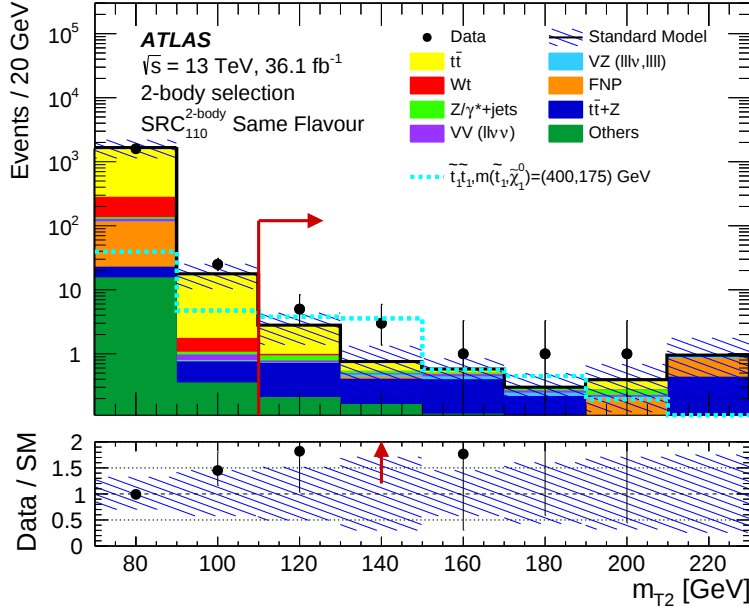


Figure 4.30.: R_{ll} distribution for events in the VR and after the fit-estimated scale factors application. The contributions from all the dominant SM backgrounds are shown, with the band representing the total uncertainty.



(a)



(b)

Figure 4.31.: SR_{DF} (a) and SR_{SF} (b) m_{T2} distributions after the background-only fit for events passing all the SR criteria, except the one on m_{T2} . The contributions from all the dominant SM backgrounds are shown, with the band representing the total uncertainty. The distributions of the benchmark signal model $m(\tilde{t}_1, \tilde{\chi}_1^0) = (400, 175) \text{ GeV}$, superimposed to the full background, is also shown. Red arrow indicates the final cut applied in the signal region [1].

4.9. Result interpretation

The search for the lightest top squark $\tilde{t}_1$ decaying to top and $\tilde{\chi}_1^0$ described in this analysis shows no significant excess. This allows to compute upper-limits on the visible cross section⁹, σ_{vis} , and the exclusion limits in the mass plane $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$. They were computed using the HISTFITTER package, where it is implemented the statistical test $\tilde{q}_\mu$ defined on the basis of the *profile likelihood ratio*:

$$\lambda(\mu) = \frac{L(\mu, \hat{\boldsymbol{\theta}}_\mu)}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})} \quad (4.7)$$

with μ signal strength and $\boldsymbol{\theta}$ set of nuisance parameters¹⁰ [127, 128]. The denominator is the maximised likelihood obtained leaving as free parameters both μ and $\boldsymbol{\theta}$; $\hat{\mu}$ and $\hat{\boldsymbol{\theta}}$ are therefore the values maximising the likelihood. Instead in the numerator $\hat{\boldsymbol{\theta}}_\mu$ denotes the value of $\boldsymbol{\theta}$ that maximises the likelihood for a specific μ . By construction, the quantity $\lambda(\mu)$ can vary between 0 and 1, becoming close to 1 when an agreement between the observation and the hypothesis under study ($\mu = 0$ or $\mu = 1$) has been found. In particular $\tilde{q}_\mu$ can be written as:

$$\tilde{q}_\mu = -2 \ln \lambda(\mu) \quad \text{with } 0 \leq \hat{\mu} \leq \mu \quad (4.8)$$

where the strength $\hat{\mu} \geq 0$ is driven by the physics need for the signal rate to be positive, while the upper constraint $\hat{\mu} \leq \mu$ is assumed to guarantee a one-sided confidence interval and to avoid to consider, as signal evidence, upward fluctuations of the data such that $\hat{\mu} > \mu$.

By using the statistical test $\tilde{q}_\mu$, it is possible to exclude a specific signal model or to compute the upper-limit on the visible cross-section using the *CLs method* [129]. This method is introduced to not exclude signals for which an analysis has little or no sensitivity; for example in cases where the expected number of signal events is much smaller than the background and, consequently, the $\tilde{q}_\mu$ distributions under the background-only and signal+background hypotheses almost overlap each other. Assuming signal plus background hypothesis as null hypothesis, the observed value $\tilde{q}_\mu^{\text{obs}}$ of the statistical test $\tilde{q}_\mu$ for the given signal strength ($\mu = 1$) is computed and, subsequently, the p -values for the signal+background (p_{s+b}) and background-only (p_b) hypotheses are estimated as

$$p_{s+b} \equiv CL_{s+b} = \int_{\tilde{q}_{\mu=1}^{\text{obs}}}^{+\infty} f(\tilde{q}_\mu | \mu = 1, \hat{\boldsymbol{\theta}}_\mu) d\tilde{q}_\mu \quad (4.9)$$

$$p_b \equiv 1 - CL_b = \int_{-\infty}^{\tilde{q}_{\mu=1}^{\text{obs}}} f(\tilde{q}_\mu | \mu = 0, \hat{\boldsymbol{\theta}}_\mu) d\tilde{q}_\mu \quad (4.10)$$

⁹The visible cross-section is defined as $\sigma \times \epsilon \times \mathcal{A}$ where σ is the cross-section of the signal model under investigation, ϵ is the selection efficiency, defined as the ratio between SR events at reconstruction level and signal region events at truth level, and $\mathcal{A}$ is the acceptance of kinematic cuts, defined as the ratio at truth level between the events passing the SR selection and the total number of generated events.

¹⁰The additional parameters of the likelihood, that are redundant for the description of the method, have been not mentioned here.

where $f(\tilde{q}_\mu|\mu = 1, \hat{\hat{\theta}}_\mu)$ and $f(\tilde{q}_\mu|\mu = 0, \hat{\hat{\theta}}_\mu)$ are respectively the distributions of the test variables $\tilde{q}_\mu$ for the signal+background and background-only hypothesis (see Fig. 4.32). The CLs is therefore calculated as

$$CL_s = \frac{CL_{s+b}}{CL_b} = \frac{p_{s+b}}{1 - p_b} \quad (4.11)$$

and for all models showing a CL_s value lower than 0.05 the signal+background hypothesis is rejected and the models are considered excluded with a 95% Confidence Level (CL). An expected CL_s can be defined using, instead of $\tilde{q}_\mu^{obs}$, the median ($\tilde{q}_{med}$) of the distribution $f(\tilde{q}_\mu|\mu = 0, \hat{\hat{\theta}}_\mu)$. To this value it is also possible to associate $\pm 1\sigma$, $\pm 2\sigma$ errors considering the extremes of the intervals centered in $\tilde{q}_{med}$ and associated to the 68% or the 95% of $f(\tilde{q}_\mu|\mu = 0, \hat{\hat{\theta}}_\mu)$ distribution.

For the exclusion limits, the method just described is applied for each signal model, building a likelihood that takes into account both signal regions and control regions. A contour exclusion plot, selecting the mass region with a CL_s value lower than 0.05, is then obtained. Instead, for the upper-limit on the visible cross-section, only the contribution of each SR is considered and for each of them a likelihood based on a dummy signal, without any associated error, is considered. A scan varying the number of signal events (N_s) is performed to evaluate, giving the estimated total SM with its error and the observed data, the number of signal events (S_{obs}^{95}) needed to have a CL_s lower than 0.05; from this estimated value, σ_{vis} is computed as the ratio between S_{obs}^{95} and the integrated luminosity considered in the analysis. At the same time, it is also possible to define an expected upper-limit on the number of signal events (S_{exp}^{95}), considering the N_s value needed to have an expected CL_s lower than 0.05.

In the case in which an excess over the MC background estimates is observed in data and there is, therefore, the need to quantify the significance of this excess, the following statistical test is used

$$q_0 = -2 \ln \lambda(0) \quad \hat{\mu} \geq 0 \quad (4.12)$$

with $\lambda(0)$ profile likelihood ratio for $\mu = 0$. Assuming as null hypothesis the background-only hypothesis, the disagreement is quantified with the p -value corresponding to a given experimental observation q_0^{obs} as follows:

$$p_0 = \int_{q_0^{obs}}^{+\infty} f(q_0|0, \hat{\hat{\theta}}_0) dq_0. \quad (4.13)$$

In the next sections the details of the analysis interpretation in terms of upper-limit on the visible cross-section and of exclusion limits are provided [127, 128].

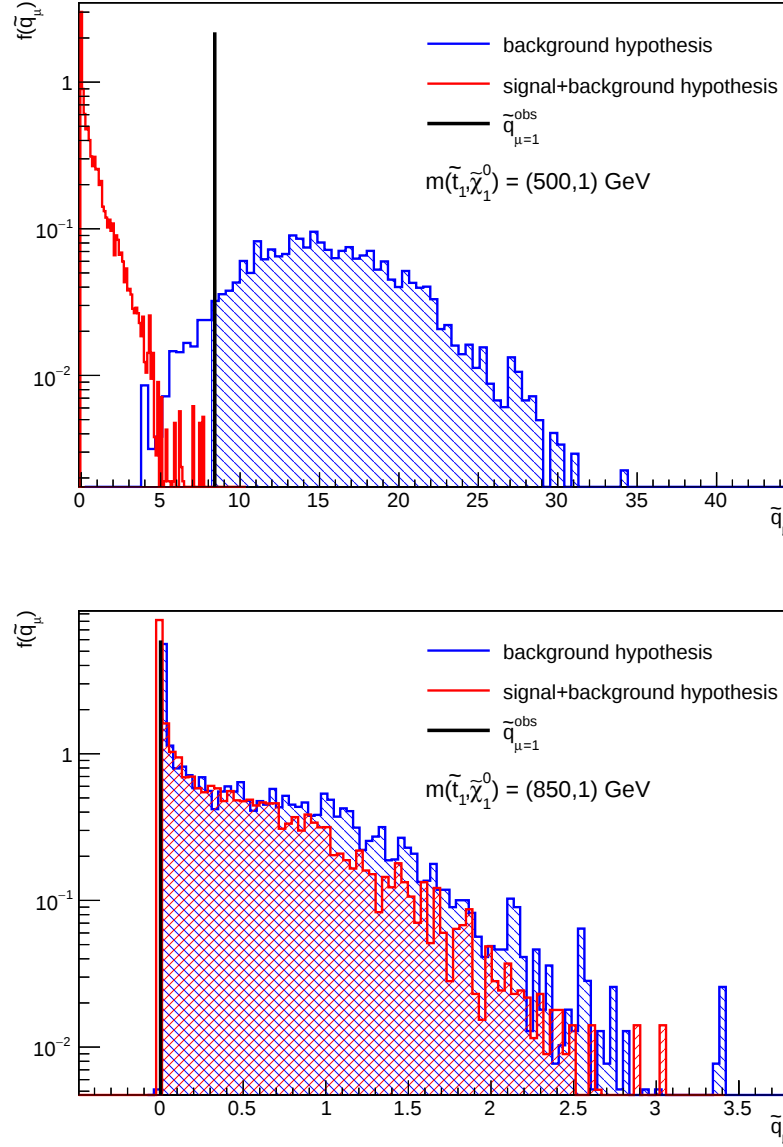


Figure 4.32.: Distribution of the test variable $\tilde{q}_\mu$ under the signal+background and background-only hypotheses for the signal models $m(\tilde{t}_1, \tilde{\chi}_1^0) = (500, 1)$ GeV (a) and $m(\tilde{t}_1, \tilde{\chi}_1^0) = (850, 1)$ GeV (b). The integral of the shaded red area corresponds to CL_{s+b} , while the integral of the shaded blue area corresponds to CL_b . As expected $f(\tilde{q}_\mu|\mu = 1, \hat{\theta}_\mu)$ and $f(\tilde{q}_\mu|\mu = 0, \hat{\theta}_\mu)$ overlap almost totally for the signal model $m(\tilde{t}_1, \tilde{\chi}_1^0) = (850, 1)$ GeV where the amount of signal events is much smaller than the total estimated SM in both SRs.

4.9.1. Upper-limit on the visible cross-section

In Tab. 4.18 the upper-limits on the visible cross-section for both SRs in the analysis are reported. Fig. 4.33 shows the scans on the number of signal events (N_s) performed for each SRs to obtain the upper-limits on S_{obs}^{95} , from which σ_{vis} is computed, and on S_{exp}^{95} .

	Observed events	Estimated total SM	σ_{vis} [fb]	S_{obs}^{95}	S_{exp}^{95}	p_0
SR _{DF}	7	3.8 ± 1.5	0.26	9.5	$6.3^{+2.5}_{-1.6}$	0.12
SR _{SF}	11	5.3 ± 1.8	0.36	13.0	$7.4^{+3.1}_{-2.0}$	0.05

Table 4.18.: Upper-limits on the visible cross-section of new physics for both SRs in the analysis. The upper-limits on the expected and observed number of signal events are also reported together with p_0 .

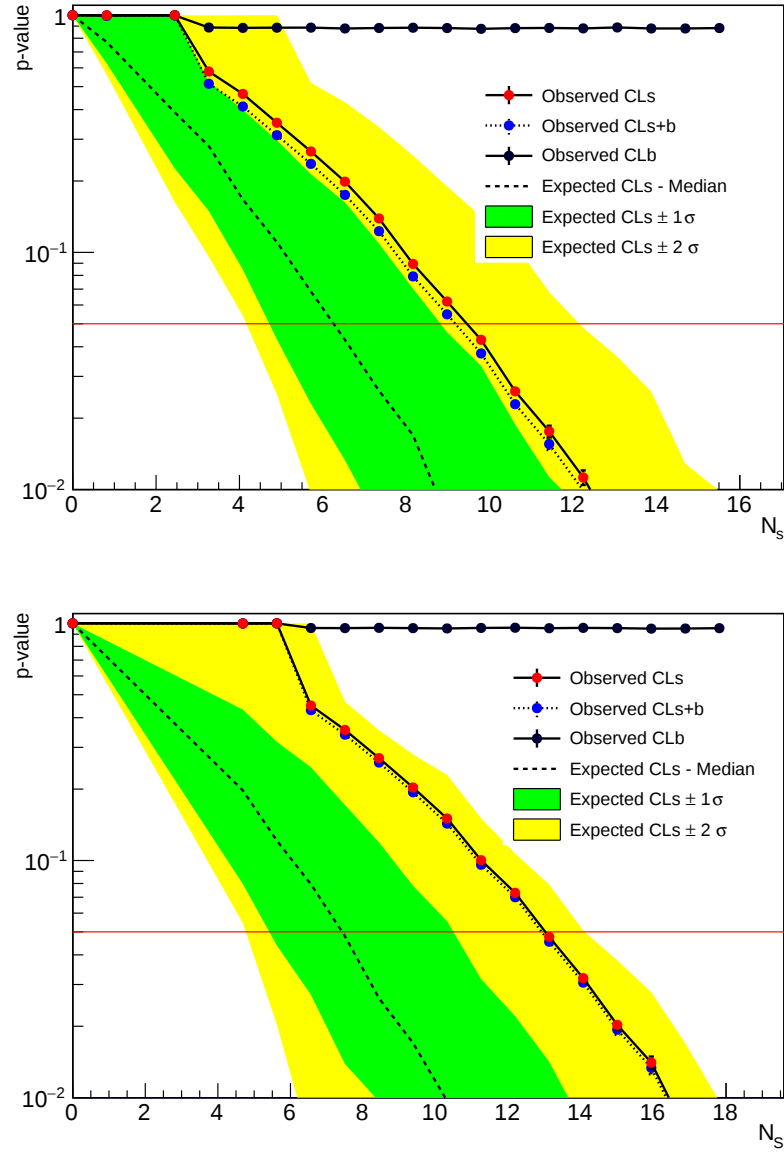


Figure 4.33.: Scan on a dummy signal N_s for the evaluation of the upper-limit on the visible cross-section for SR_{DF} (a) and for SR_{SF} (b). The observed CLs , together with CL_{s+b} and CL_b , and the expected CLs , with its $\pm 1\sigma$, $\pm 2\sigma$ error bands, are shown.

4.9.2. Exclusion limits

The exclusion contour for the simplified model $\tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0$, with a branching ratio of 100%, is plotted in Fig. 4.34, in the plane $(m_{\tilde{t}_1}, \Delta m(\tilde{t}_1, \tilde{\chi}_1^0) - m_t)$, and in Fig. 4.35 in

the $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})$ mass plane. In particular, Fig. 4.34 shows how much the excluded and observed exclusion contours are close to the kinematic border $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) = m_t$. As already mentioned, both SRs and both CRs are considered for the likelihood definition.

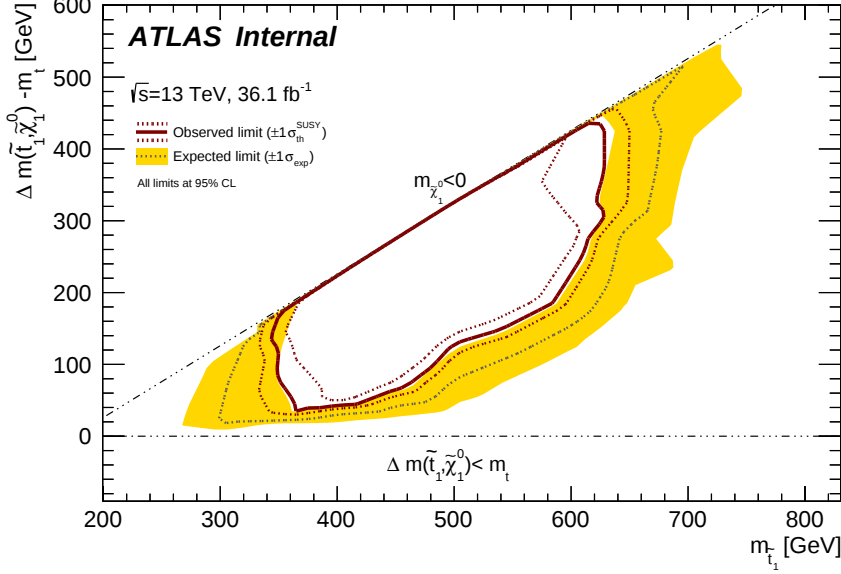


Figure 4.34.: Exclusion plot in the plane $(m_{\tilde{t}_1}, \Delta m(\tilde{t}_1, \tilde{\chi}_1^0) - m_t)$. The dashed grey line and the shaded yellow band represent the expected exclusion limit with its $\pm 1\sigma$ uncertainty. The solid red line represents the observed exclusion limit. The expected and observed limits do not include the effect of the theoretical uncertainties on the signal cross-section. This is instead shown on the observed limit by the dotted red lines, after varying the signal cross-section by $\pm 1\sigma$.

The analysis was then able to improve, both in the compressed and in the bulk regions, the Run1 results of the search for $\tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0$ in the final state with two leptons (Fig. 4.35) [130]. Due to the over-fluctuation in the data, the observed contour excludes a smaller area with respect to the expected one. According to this analysis, a top squark mass up to 620 GeV is excluded for a massless neutralino, while a neutralino mass up to ~ 220 GeV is excluded for $m_{\tilde{t}_1} \in [450, 600]$ GeV. The CLs values of the various signal models considered are reported in App. D.

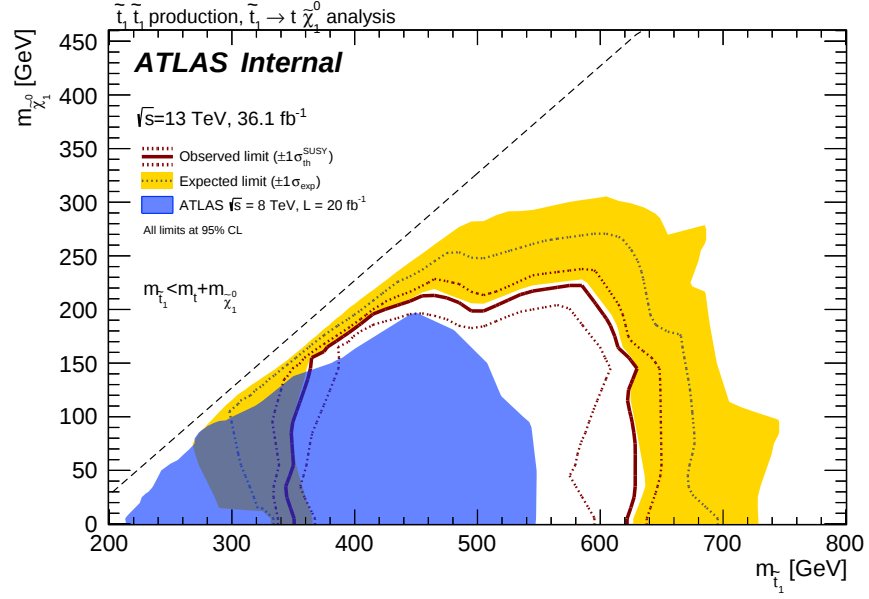


Figure 4.35.: Exclusion plot in the mass plane $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})$. The dashed grey line and the shaded yellow band represent the expected exclusion limit with its $\pm 1\sigma$ uncertainty. The solid red line represents the observed exclusion limit. The expected and observed limits do not include the effect of the theoretical uncertainties on the signal cross-section. This is instead shown on the observed limit by the dotted red lines, after varying the signal cross-section by $\pm 1\sigma$. The shaded blue area shows the observed exclusion plot from the ATLAS Run1 analysis targeting $\tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0$ in a two leptons final state [130].

4.10. Combined results

The search described in this thesis is published in the paper “*Search for direct top squark pair production with two leptons in $\sqrt{s} = 13\text{ TeV}$ pp collisions with the ATLAS detector*” [1] together with three additional analyses targeting $\tilde{t}_1 \rightarrow t^{(*)} + \tilde{\chi}_1^0$. The top quark was assumed on-shell (as in this analysis), or off-shell, to fully cover the kinematic region $m_{\tilde{t}_1} > m_{\tilde{\chi}_1^0}$ in the $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})$ mass plane. No significant excess was observed for any of the analyses and a comprehensive exclusion plot was performed. For each signal model the four analyses were tested and the one showing the lowest expected CLs was selected as best SR for the final exclusion plot.

In this section, the analysis described in this thesis is referred as $\text{SRC}_{110}^{2\text{-body}}$ while the remaining analyses are labelled as:

- $\text{SRB}_{140}^{2\text{-body}}$ for the analysis targeting $\tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0$ with large $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0)$ for which an higher m_{T2} cut is possible ($m_{T2} > 140\text{ GeV}$) due to the larger amount of E_T^{miss} coming from $\tilde{\chi}_1^0$.
- $\text{SR}^{3\text{-body}}$ for the analysis targeting $\tilde{t}_1 \rightarrow b + W + \tilde{\chi}_1^0$, based on the *Recursive Jigsaw*

technique¹¹.

- $\text{SR}^{4\text{-body}}$ for the analysis targeting $\tilde{t}_1 \rightarrow b + f + f' + \tilde{\chi}_1^0$, based on E_T^{miss} trigger selection because of the presence of soft leptons in the final state.

Fig. 4.36 shows the best SR selected for each signal model. As expected, $\text{SR}_{110}^{2\text{-body}}$ prevails in the compressed region for which this analysis was optimised. The final, comprehensive exclusion plot is shown in Fig. 4.37.

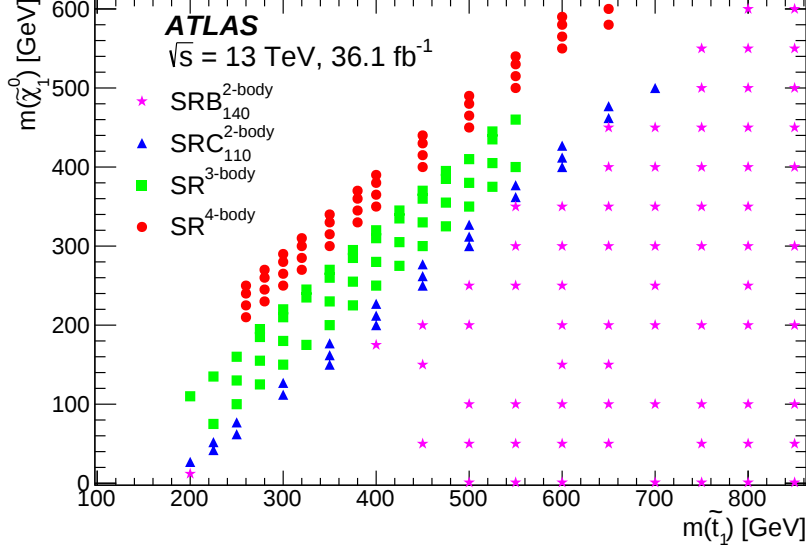


Figure 4.36.: Best signal region per signal grid point for the simplified model with a $\tilde{t}_1$ pair production, assuming $\tilde{t}_1$ decaying via $\tilde{t}_1 \rightarrow t^* + \tilde{\chi}_1^0$ with 100% branching ratio.

¹¹The Recursive Jigsaw technique takes the measured information in an event (the observable objects with their four-momenta and the missing transverse energy) and, through a series of assumptions and algorithms, reorganizes them in such a way to obtain a (user-imposed) reasonable decay tree[131].

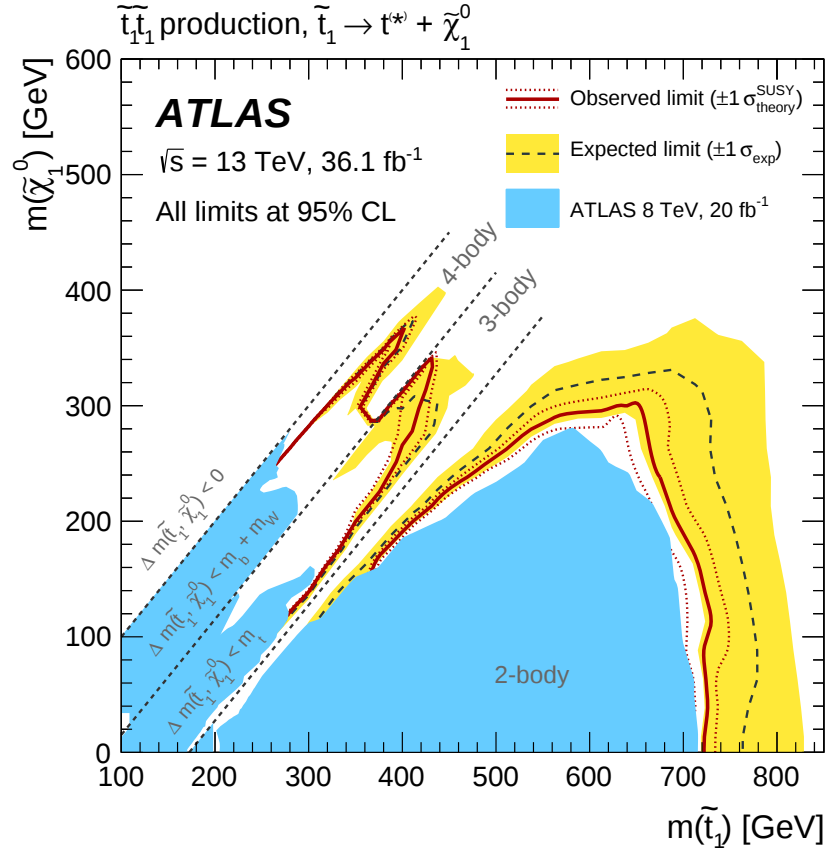


Figure 4.37.: Exclusion plot for a simplified model assuming $\tilde{t}_1$ pair production, decaying via $\tilde{t}_1 \rightarrow t^{(*)} + \tilde{\chi}_1^0$ with a 100% branching ratio. The dashed grey line and the shaded yellow band are the expected limit with its $\pm 1\sigma$ uncertainty. The solid red line shows the observed limit. The expected and observed limits do not include the effect of the theoretical uncertainties in the signal cross-section. The dotted red lines show the effect on the observed limit when varying the signal cross-section by $\pm 1\sigma$ of its uncertainty. The blue areas show the observed exclusion from the ATLAS $\sqrt{s} = 8$ TeV analyses [1,132].

4.11. Perspectives

As expected, the developed analysis showed the best sensitivity in the compressed region with respect to the other analyses targeting $\tilde{t}_1 \rightarrow t^{(*)} + \tilde{\chi}_1^0$ in a final state with two opposite sign leptons (Fig. 4.36). However, in both SRs, it was found a total uncertainty higher than the prevision (30%) and, consequently, a deterioration in the sensitivity was observed with respect to the initial estimate (Fig. 4.13). Therefore, for a reinterpretation of the analysis with the full Run2 data, it will be necessary to perform dedicated studies to understand if it could be possible to define a new set of SRs less sensitive to the E_T^{miss}

modelling, jet energy scale and resolution uncertainties.

Finally, in the future it will become also important to develop analyses that look not only to simplified models but also at more complex scenarios, such as the phenomenological MSSM, where different decay processes can be involved at the same time.

Conclusion

In my work for writing Ph.D. thesis, I focused my attention on the search for top squark pair production in a R -parity simplified model, where the top squark decays into a top quark and a neutralino. The analysis was developed looking for final states containing two opposite-charge leptons, at least three jets and large missing transverse momentum and considering the whole 2015 and 2016 data sample, collected by the ATLAS experiment at $\sqrt{s} = 13$ TeV and corresponding to an integrated luminosity of 36.1 fb^{-1} .

An analysis strategy based on the variables m_{T2} and R_U was developed but no significant excess was found. Therefore, upper-limits on the visible cross-section and exclusion limits in the mass plane $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})$, for the process under study, were defined with a confidence level of 95%. As shown in Fig. 4.35 a relevant improvement with respect to the Run1 exclusion limits was reached, targeting the same decay process, especially in the compressed region ($m_{\tilde{t}_1} \approx m_t + m_{\tilde{\chi}_1^0}$), but also for high $\tilde{t}_1$ mass. Finally, it was possible to exclude the existence of a top squark with masses up to 620 GeV for a massless neutralino and $\tilde{\chi}_1^0$ masses up to ~ 220 GeV for $m_{\tilde{t}_1} \in [450, 600]$ GeV.

The work for this thesis is an important part of the paper *Search for direct top squark pair production with two leptons in $\sqrt{s} = 13 \text{ TeV}$ pp collisions with the ATLAS detector*, published on The European Physical Journal C on December 2017 [1], and it was used to obtain the final exclusion plot for a simplified model assuming $\tilde{t}_1$ pair production, decaying via $\tilde{t}_1 \rightarrow t^{(*)} + \tilde{\chi}_1^0$ with a 100% branching ratio, in the mass plane $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})$, as it was described in Sect. 4.10.

Appendix A.

Matrix Method for the mis-identified and non-prompt leptons background estimation

The mis-identified and non-prompt leptons background was estimated through a data-driven technique, known as Matrix Method [133, 134]. In order to implement this procedure, two leptons categories were defined, referred to as “loose” and “tight”, respectively corresponding to the “baseline” and “signal” selection criteria described in Sect. 4.5. The basic purpose of this method is to estimate how many tight leptons are actually real prompt leptons (R) and how many are fake or non-prompt leptons (F).

On the basis of these two categories, the *real efficiency* r , defined as the efficiency with which a loose real prompt lepton satisfies also the tight selection, and the *fake rate* f , defined as the rate with which a loose non-prompt or fake lepton passes also the tight selection, are measured. Once the real efficiency and the fake rate are measured (with procedures that will be discussed in the following), they are exploited in the construction of a matrix, defined as:

$$M = \begin{pmatrix} r^2 & rf & fr & f^2 \\ r(1-r) & r(1-f) & f(1-r) & f(1-f) \\ (1-r)r & (1-r)f & (1-f)r & (1-f)f \\ (1-r)^2 & (1-r)(1-f) & (1-f)(1-r) & (1-f)^2 \end{pmatrix}.$$

The number of events with a loose-loose (N_{LL}), loose-tight (N_{TL} and N_{LT}), and tight-tight (N_{TT}) leptons pairs can be in principle estimated from the data events sample, and then, inverting the equation

$$\begin{pmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{pmatrix} = M \begin{pmatrix} N_{LL}^{RR} \\ N_{LL}^{RF} \\ N_{LL}^{FR} \\ N_{LL}^{FF} \end{pmatrix},$$

the numbers of real-real (N_{LL}^{RR}), real-fake (N_{LL}^{RF}), fake-real (N_{LL}^{FR}) and fake-fake (N_{LL}^{FF}) loose leptons pairs can be extracted.

Appendix A. Fake and non-prompt leptons estimation

Finally, the number of events with at least one fake tight lepton can be obtained as

$$N_{TT}^{FNP} = r f N_{LL}^{RF} + f r N_{LL}^{FR} + f^2 N_{LL}^{FF}.$$

In practice, the real efficiency and the fake rate are actually estimated as a function of the lepton kinematics (in particular as a function of the lepton p_T and η) and this procedure is applied event by event, exploiting a matrix that is specific for each event with two loose leptons l_1 and l_2 :

$$M(l_1 l_2) = \begin{pmatrix} r_1 r_2 & r_1 f_2 & f_1 r_2 & f_1 f_2 \\ r_1(1-r_2) & r_1(1-f_2) & f_1(1-r_2) & f_1(1-f_2) \\ (1-r_1)r_2 & (1-r_1)f_2 & (1-f_1)r_2 & (1-f_1)f_2 \\ (1-r_1)(1-r_2) & (1-r_1)(1-f_2) & (1-f_1)(1-r_2) & (1-f_1)(1-f_2) \end{pmatrix}.$$

In the case of a single observed event, the obtained N_{LL}^{FF} , N_{LL}^{FR} and N_{LL}^{RF} represent the “probabilities”, for that event, to contain a fake-fake, a fake-real or a real-fake loose leptons pair, and can thus be renamed as: p_{LL}^{FF} , p_{LL}^{FR} and p_{LL}^{RF} .

Finally, the probability for that event to contain at least one fake tight lepton is given by

$$w_i = p_{TT}^{RF} + p_{TT}^{FR} + p_{TT}^{FF} = p_{LL}^{RF} r_1 f_2 + p_{LL}^{FR} f_1 r_2 + p_{LL}^{FF} f_1 f_2$$

The sum of the probabilities w_i of all the events (computed, for example, for each bin of an histogram) is the FNP background estimate.

Measurement of real efficiency

The real efficiency estimate was computed on a sample of Z candidate events selected with the main single lepton triggers. The events were required to have two loose electrons or muons with $|\eta| < 2.5$ and an invariant mass between 81 GeV and 101 GeV: when one tight lepton with $p_T > 30$ GeV, matched to the trigger, was tagged, the second lepton was taken as a probe and the fraction of loose probe leptons which passed the tight cuts (i.e. the real probability) was measured.

Each of the two leptons can be used as a probe if the other one pass the tag criteria.

The real probability was measured as a function of the lepton p_T and η (two-dimensional binning). The results as a function of one variable only, integrating over the other one, are shown in Fig. A.1 and Fig. A.2 for electrons and muons respectively.

Measurement of fake rate

The fake rate was measured by selecting a same sign $e\mu$ events sample, with a tag-and-probe method similar to the one used to measure the real efficiencies. This method relies

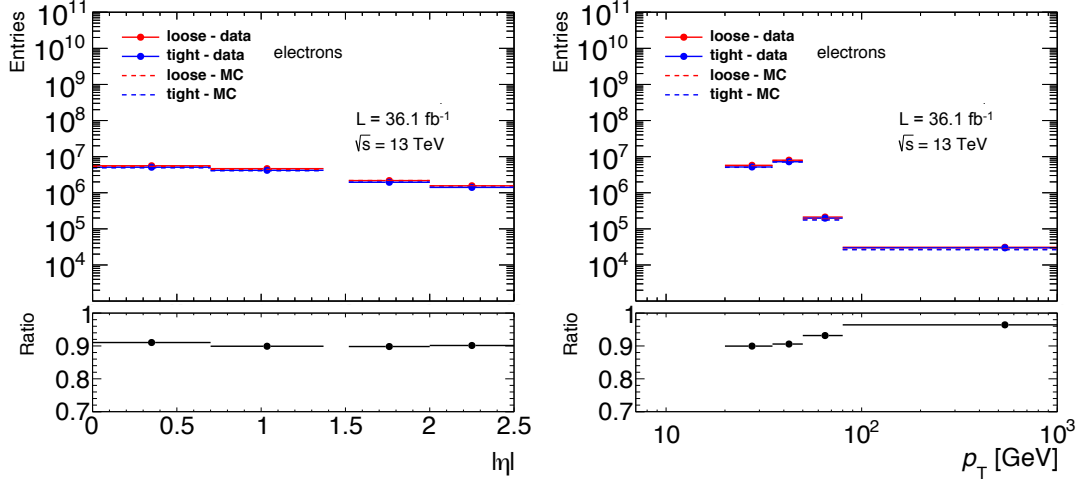


Figure A.1.: Distribution of the pseudorapidity and p_T for loose and tight probe electron candidates in Z events. The ratio, representing the r efficiency, is also shown.

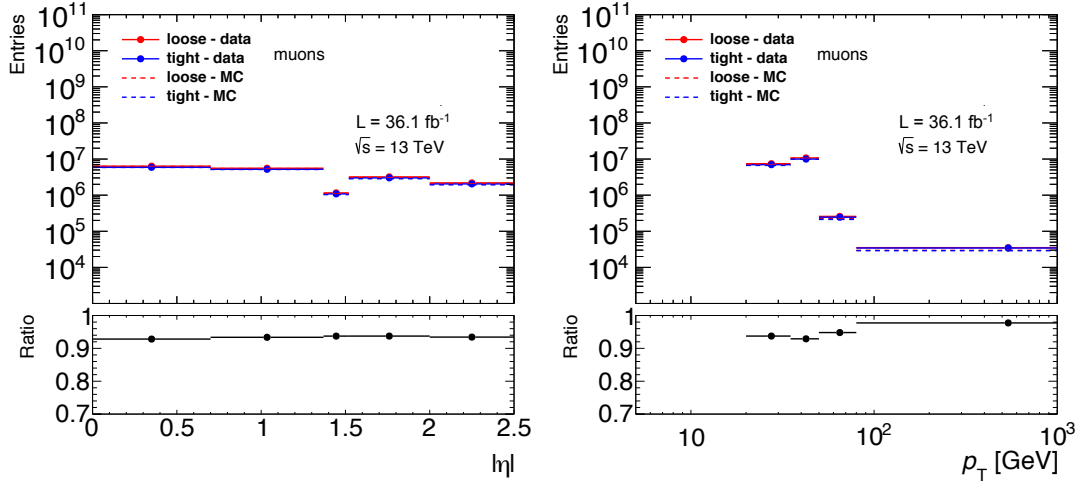


Figure A.2.: Distribution of the pseudorapidity and p_T for loose and tight probe muons candidates in Z events. The ratio, representing the r efficiency, is also shown.

Appendix A. Fake and non-prompt leptons estimation

on the small amount of SM processes that can result in a same sign $e\mu$ final state, so that when a tight lepton is selected, the other one is most likely to be fake. This measurement can be biased by processes containing two real opposite sign, different flavours leptons, like $t\bar{t}$ and $Z \rightarrow \tau\tau$ or WW , in which the charge of the electron is wrongly identified. This contamination was evaluated from MC simulations.

As for the real efficiency, the fake rate was measured as a function of the lepton p_T and η (two-dimensional binning). The results as a function of one variable only, integrating over the other one, are shown in Fig. A.3 and Fig. A.4 for electrons and muons respectively.

Validation of the method

The FNP estimation was validated using a same sign two-lepton event selection, where the contribution of this background is expected to be dominant. A validation region, VR^{FNP} , was defined, for same flavours events, imposing the same preselection cuts used in the main analysis with the exception of the Z veto.

The distributions of some key analysis variables, are shown in Fig. A.5 - Fig. A.9 for electrons and muons. An overall good agreement is observed.

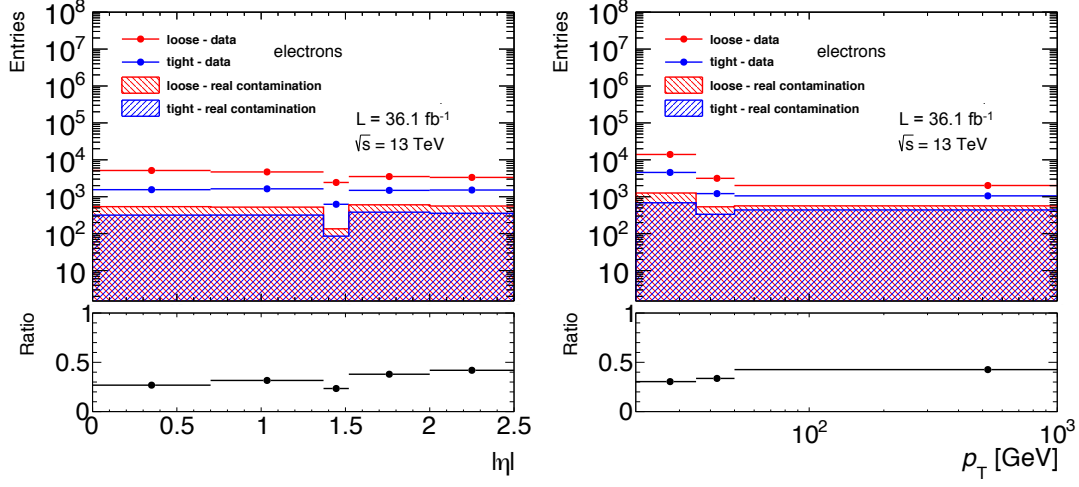


Figure A.3.: Distribution of the pseudorapidity and p_T for loose and tight probe electron candidates in the same sign $e\mu$ selection. The ratio, representing the f rate, is also shown, evaluated after the real contamination subtraction.

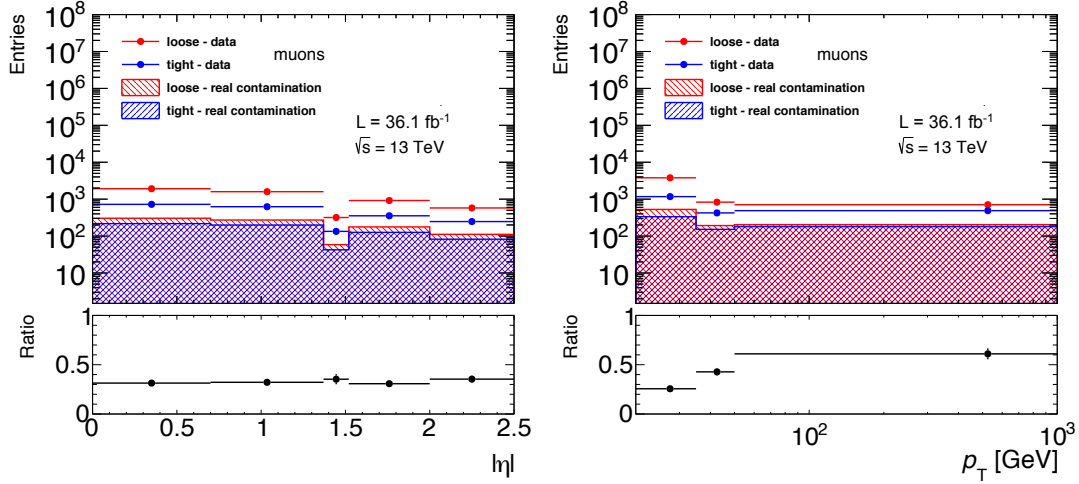
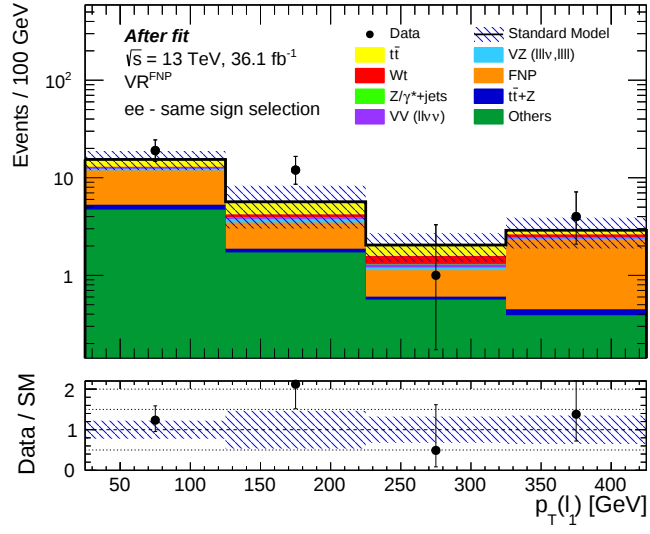
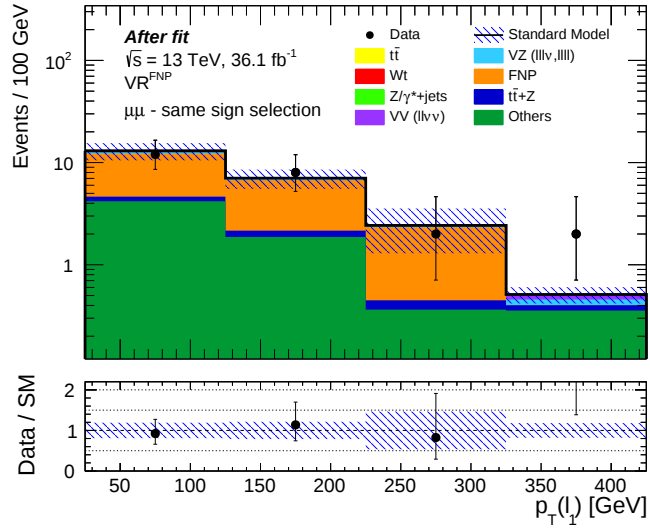


Figure A.4.: Distribution of the pseudorapidity and p_T for loose and tight probe muons candidates in the same sign $e\mu$ selection. The ratio, representing the f rate, is also shown, evaluated after the real contamination subtraction.

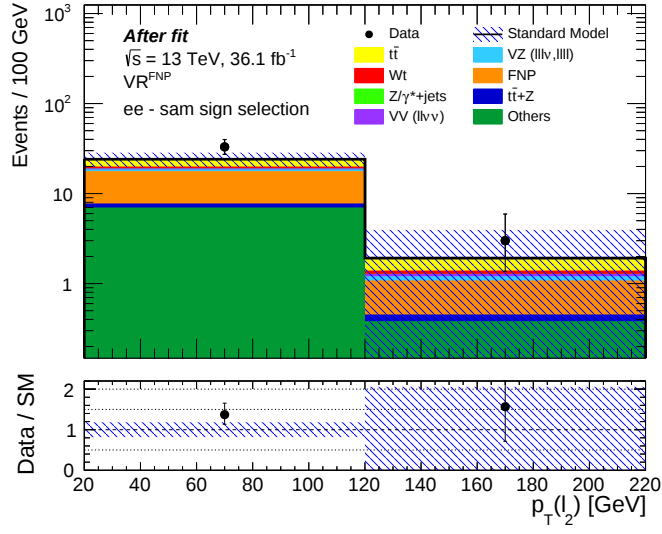


(a)

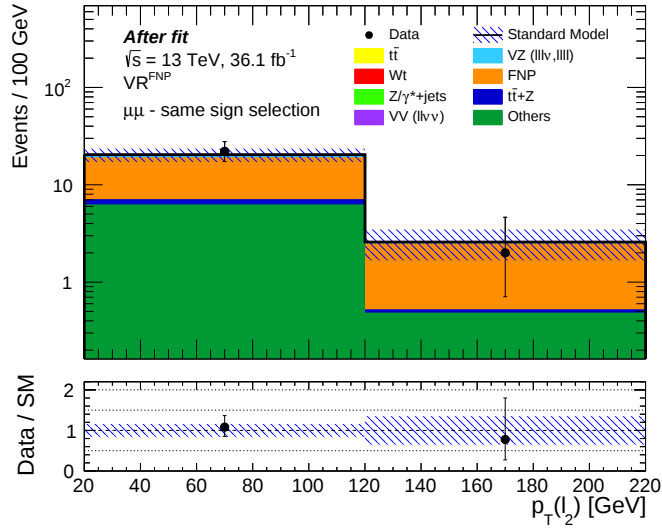


(b)

Figure A.5.: Validation plots for electrons (a) and muons (b) relative to $p_T(l_1)$ distribution. The uncertainty bands represent the total uncertainty.



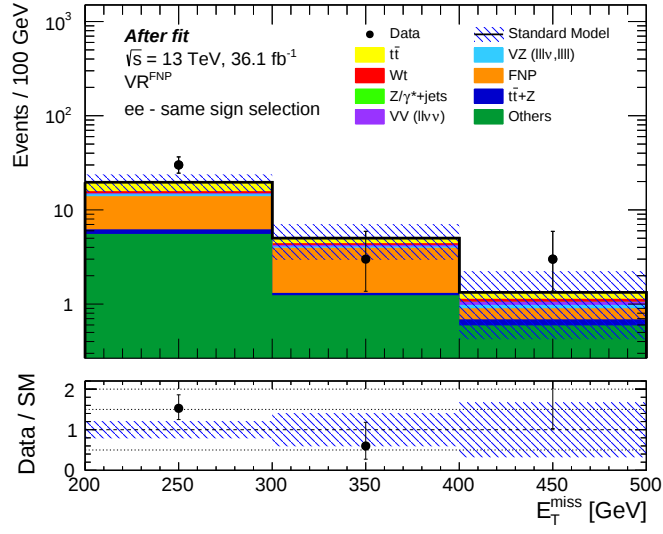
(a)



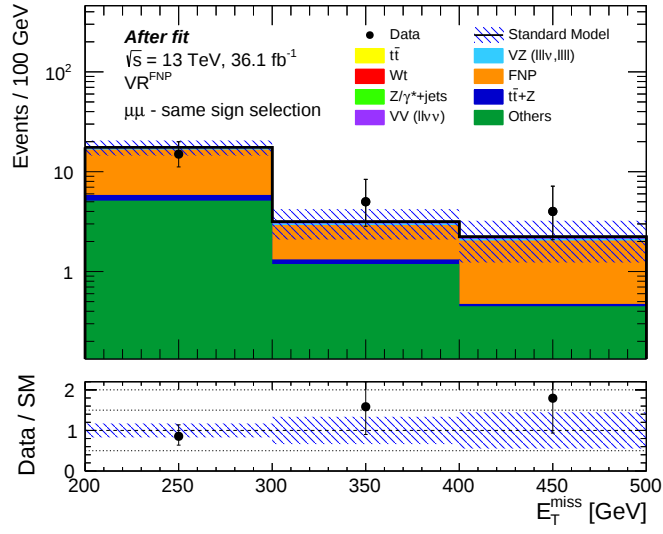
(b)

Figure A.6.: Validation plots for electrons (a) and muons (b) relative to $p_T(l_2)$ distribution. The uncertainty bands represent the total uncertainty.

Appendix A. Fake and non-prompt leptons estimation

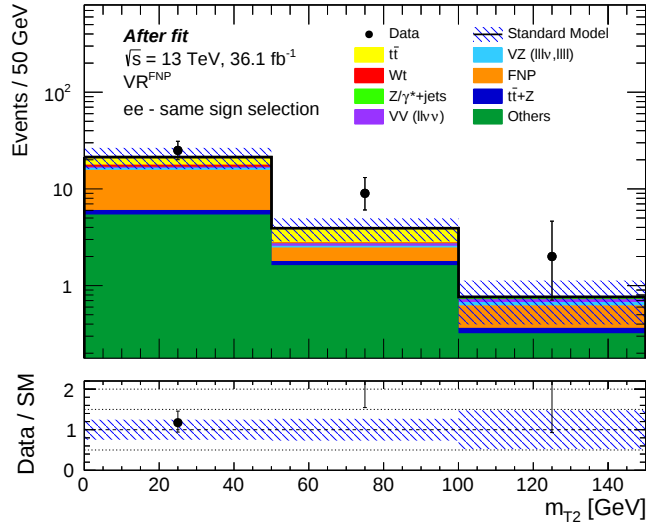


(a)

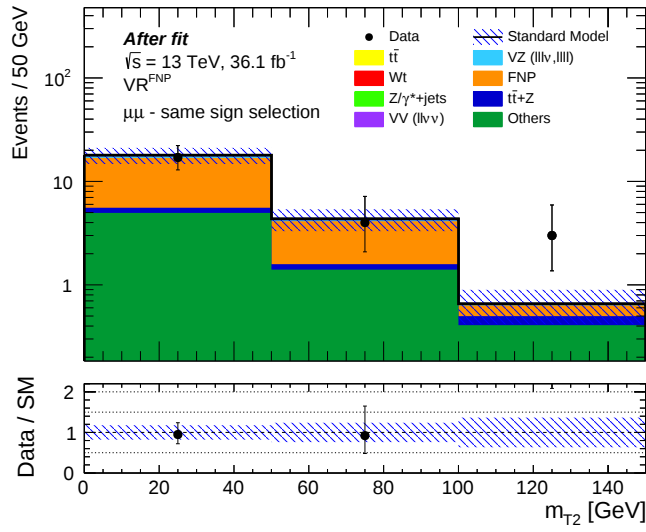


(b)

Figure A.7.: Validation plots for electrons (a) and muons (b) relative to E_T^{miss} distribution. The uncertainty bands represent the total uncertainty.



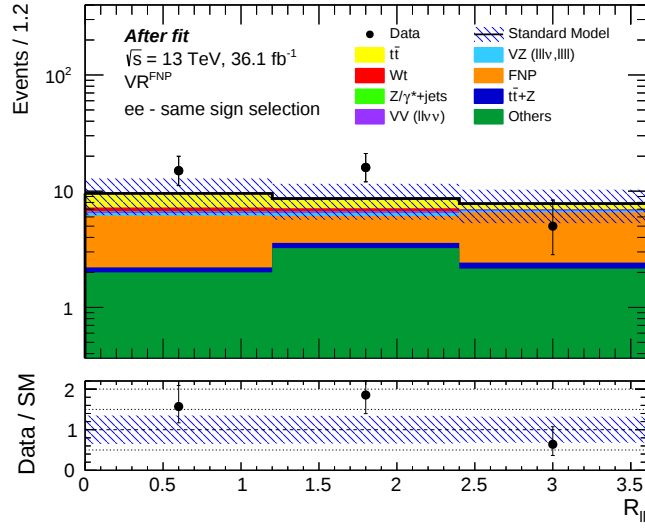
(a)



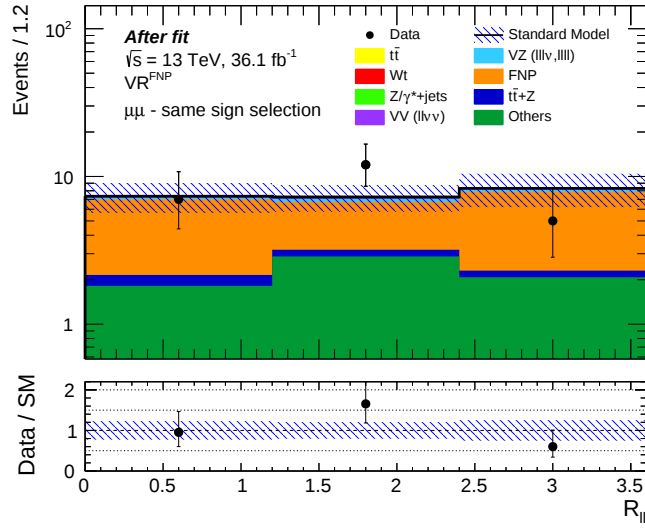
(b)

Figure A.8.: Validation plots for electrons (a) and muons (b) relative to m_{T2} distribution. The uncertainty bands represent the total uncertainty.

Appendix A. Fake and non-prompt leptons estimation



(a)



(b)

Figure A.9.: Validation plots for electrons (a) and muons (b) relative to R_{ll} distribution. The uncertainty bands represent the total uncertainty.

Appendix B.

Systematics parameterisation

Tab. B.1, Tab. B.2 and Tab. B.3 show the parameterisation considered for the treatment of the main systematics uncertainties.

Parameters names	Description
α_{JER}	jet energy resolution uncertainty
$\alpha_{\text{JES1}}, \alpha_{\text{JES2}}, \alpha_{\text{JES3}}$	reduce set of parameters to treat jet energy scale uncertainty ¹
$\alpha_{\text{JET_EtaIntercalibration}}$	uncertainty on the $ \eta $ –intercalibration correction needed to correct differences in jet response as function of η
$\alpha_{\text{JET_RelativeNonClosure}}$	uncertainty due to different detector-simulation configurations used in the analysis and in the calibration
$\alpha_{\text{JVT_JET_JvtEfficiency}}$	JVT uncertainty
$\alpha_{\text{bTag_FT_EFF_B}}$	b –tagging uncertainties for small R –jets obtained propagating the scale factors errors in the analysis
$\alpha_{\text{bTag_FT_EFF_C}}$	
$\alpha_{\text{bTag_FT_EFF_Light}}$	
$\alpha_{\text{bTag_FT_EFF_extrapolation}}$	b –tagging uncertainties on the extrapolation to high P_T jets obtained propagating the scale factors errors in the analysis
$\alpha_{\text{bTag_FT_EFF_extrapolation_from_charm}}$	b –tagging uncertainties relative to τ –jets obtained propagating the scale factors errors in the analysis
$\alpha_{\text{MET_SoftTrk_ResoPara}}$	transversal resolution uncertainty
$\alpha_{\text{MET_SoftTrk_ResoPerp}}$	longitudinal resolution uncertainty
$\alpha_{\text{MET_SoftTrk_Scale}}$	longitudinal scale uncertainty
α_{PileUp}	pile-up reweighting uncertainty

Table B.1.: Parameterisation used for the treatment of jet, b –tag, E_T^{miss} and pile-up uncertainties.

Appendix B. Systematics parameterisation

Parameters names	Description
$\alpha_{\text{EG_RES}}$	electron and photon energy resolution uncertainty
$\alpha_{\text{EG_SCALE}}$	electron and photon energy scale uncertainty
$\alpha_{\text{EL_EFF_ID}}$	electron inner detector efficiency uncertainty
$\alpha_{\text{EL_EFF_Iso}}$	electron isolation scale factors uncertainty
$\alpha_{\text{EL_EFF_Reco}}$	electron reconstruction scale factors uncertainty
$\alpha_{\text{EL_EFF_Trigger}}$	electron trigger scale factors uncertainty
$\alpha_{\text{MUONS_ID}}$	muon P_T resolution uncertainty from inner detector
$\alpha_{\text{MUONS_MS}}$	muon P_T resolution uncertainty from muon spectrometer
$\alpha_{\text{MUONS_SCALE}}$	muon P_T scale uncertainty
$\alpha_{\text{MUON_EFF_STAT_LOWPT}}$	statistical component of the reconstruction and identification scale factors uncertainties for $P_T < 15$ GeV
$\alpha_{\text{MUON_EFF_STAT}}$	statistical component of the reconstruction and identification scale factors uncertainties for $P_T > 15$ GeV
$\alpha_{\text{MUON_EFF_SYS_LOWPT}}$	systematic component of the reconstruction and identification scale factors uncertainties for $P_T < 15$ GeV
$\alpha_{\text{MUON_EFF_SYS}}$	systematic component of the reconstruction and identification scale factors uncertainties for $P_T > 15$ GeV
$\alpha_{\text{MUON_EFF_TrigStatUncertainty}}$	statistical component of the trigger scale factors uncertainty
$\alpha_{\text{MUON_EFF_TrigSystUncertainty}}$	systematic component of the trigger scale factors uncertainty
$\alpha_{\text{MUON_ISO_STAT}}$	statistical component of the isolation scale factors uncertainty
$\alpha_{\text{MUON_ISO_SYS}}$	systematic component of the isolation scale factors uncertainty

Table B.2.: Parameterisation used for the treatment of muon and electron uncertainties.

¹The most accurate understanding of the JES uncertainty is provided by 60+ independent sources. However in this analysis a representation constructed of three parameters (JES1, JES2, JES3) was considered. More details can be found in [135].

Parameters names	Description
α_FAKE_SYS	FNP uncertainty on the limited statistics in the region used for the fake rate estimation
α_FAKES_REAL	FNP uncertainty on the contamination from prompt leptons
α_DibMUR	VV, VZ renormalisation uncertainty
α_MUR1_MUF2	VV, VZ factorisation uncertainty
α_WtRAD	Wt ISR/FSR uncertainty
α_WtDS	Wt interference uncertainty
$\alpha_ttbarRAD$	tt ISR/FSR uncertainty
$\alpha_ttbarPS$	tt parton shower uncertainty
$\alpha_topGenerator$	tt generator uncertainty

Table B.3.: Parameterisation used for the treatment of the FNP uncertainties and the main backgrounds theoretical uncertainties.

Appendix C.

Uncertainties breakdown

The breakdown for the dominant systematic uncertainties after the breakdown-only fit are reported for the various control, validation and signal regions from Tab. C.1 to Tab. C.5. The total background uncertainty is not given by adding in quadrature the individual uncertainty because of their correlation. To let the reader the possibility to better evaluate the impact of each uncertainty, all the values are shown up to the second decimal digit.

Appendix C. Uncertainties breakdown

	Total SM background	$t\bar{t}$	$t\bar{t} + Z$
Estimated background	211.74	184.19	1.03
Total background incertaintly	± 14.58 [6.88%]	± 16.27 [8.84%]	± 0.32 [31.52%]
$\mu_{t\bar{t}}$	± 66.94 [31.6%]	± 66.94 [36.3%]	-
$\alpha_{\text{topGenerator}}$	± 57.05 [26.9%]	± 57.05 [31.0%]	-
α_{ttbarPS}	± 21.71 [10.3%]	± 21.71 [11.8%]	-
α_{JER}	± 11.28 [5.3%]	± 10.73 [5.8%]	± 0.11 [11.1%]
α_{ttbarRAD}	± 7.77 [3.7%]	± 7.77 [4.2%]	-
α_{WtRAD}	± 6.97 [3.3%]	-	-
$\alpha_{\text{MET_SoftTrk_ResoPara}}$	± 6.69 [3.2%]	± 7.10 [3.9%]	± 0.04 [3.5%]
$\alpha_{\text{MET_SoftTrk_ResoPerp}}$	± 6.64 [3.1%]	± 7.26 [3.9%]	± 0.01 [1.3%]
$\gamma_{\text{stat_CRTop_cuts_bin_0}}$	± 5.74 [2.7%]	± 4.99 [2.7%]	± 0.03 [2.7%]
$\alpha_{\text{MET_SoftTrk_Scale}}$	± 4.21 [2.0%]	± 4.04 [2.2%]	± 0.00 [0.38%]
$\alpha_{\text{bTag_FT_EFF_B}}$	± 3.06 [1.4%]	± 2.61 [1.4%]	± 0.01 [1.2%]
$\alpha_{\text{MUON_EFF_SYS}}$	± 2.69 [1.3%]	± 2.34 [1.3%]	± 0.01 [1.3%]
α_{PileUp}	± 2.35 [1.1%]	± 1.53 [0.83%]	± 0.05 [4.9%]
α_{JES1}	± 2.31 [1.1%]	± 2.41 [1.3%]	± 0.06 [5.4%]
$\alpha_{\text{EG_SCALE}}$	± 2.06 [0.97%]	± 1.84 [1.0%]	± 0.03 [2.8%]
$\alpha_{\text{EL_EFF_ID}}$	± 2.04 [0.97%]	± 1.75 [0.95%]	± 0.01 [1.0%]
$\alpha_{\text{EL_EFF_Iso}}$	± 1.88 [0.89%]	± 1.59 [0.86%]	± 0.01 [1.0%]
$\alpha_{\text{bTag_FT_EFF_C}}$	± 1.41 [0.67%]	± 1.15 [0.62%]	± 0.01 [0.73%]
α_{JES2}	± 1.24 [0.58%]	± 1.42 [0.77%]	± 0.01 [0.56%]
$\alpha_{\text{JVT_JET_JvtEfficiency}}$	± 1.12 [0.53%]	± 0.98 [0.53%]	± 0.00 [0.21%]
$\alpha_{\text{JET_EtaIntercalibration}}$	± 0.71 [0.33%]	± 0.53 [0.29%]	± 0.00 [0.42%]
$\alpha_{\text{bTag_FT_EFF_Light}}$	± 0.57 [0.27%]	± 0.06 [0.03%]	± 0.01 [0.76%]
$\alpha_{\text{MUON_ISO_SYS}}$	± 0.52 [0.25%]	± 0.45 [0.24%]	± 0.00 [0.26%]
$\alpha_{\text{EL_EFF_Reco}}$	± 0.45 [0.21%]	± 0.39 [0.21%]	± 0.00 [0.26%]
$\alpha_{\text{MUON_EFF_STAT}}$	± 0.44 [0.21%]	± 0.38 [0.21%]	± 0.00 [0.25%]
$\alpha_{\text{EG_RES}}$	± 0.31 [0.14%]	± 0.34 [0.18%]	± 0.01 [0.81%]
$\mu_{t\bar{t}+Z}$	± 0.29 [0.14%]	-	± 0.29 [28.0%]
$\alpha_{\text{EL_EFF_Trigger}}$	± 0.28 [0.13%]	± 0.24 [0.13%]	± 0.00 [0.10%]
α_{JES3}	± 0.26 [0.12%]	± 0.66 [0.36%]	± 0.01 [0.78%]
α_{DibMUR}	± 0.24 [0.11%]	-	-
$\alpha_{\text{JET_RelativeNonClosure}}$	± 0.20 [0.09%]	-	-
$\alpha_{\text{bTag_FT_EFF_extrapolation}}$	± 0.13 [0.06%]	± 0.09 [0.05%]	± 0.00 [0.15%]
$\alpha_{\text{MUON_ISO_STAT}}$	± 0.10 [0.05%]	± 0.09 [0.05%]	± 0.00 [0.05%]
$\alpha_{\text{MUR1_MUF2}}$	± 0.05 [0.02%]	-	-

Table C.1.: Breakdown of the dominant systematic uncertainties on the total SM background (first column) and, separately, on the two main backgrounds ($t\bar{t}$ and $t\bar{t} + Z$) of the analysis (last two columns) for the $CR_{t\bar{t}}$, after the background-only fit. Note that the individual uncertainties can be correlated, and do not necessarily add up quadratically to the total background uncertainty. The percentages show the size of the uncertainty relative to the related expected background.

	Total SM background	$t\bar{t}$	$t\bar{t} + Z$
Estimated background	91.01	-	46.67
Total background uncertainty	± 9.53 [10.47%]	-	± 12.35 [26.45%]
$\mu_{t\bar{t}+Z}$	± 13.07 [14.4%]	-	± 13.07 [28.0%]
$\alpha_{\text{FAKE_SYS}}$	± 6.97 [7.7%]	-	-
$\gamma_{\text{stat_CRttZ_cuts_bin_0}}$	± 3.32 [3.6%]	-	± 1.70 [3.6%]
$\alpha_{\text{bTag_FT_EFF_C}}$	± 1.73 [1.9%]	-	± 0.31 [0.66%]
$\alpha_{\text{bTag_FT_EFF_Light}}$	± 1.68 [1.8%]	-	± 0.11 [0.23%]
α_{JES1}	± 1.68 [1.8%]	-	± 1.04 [2.2%]
$\alpha_{\text{bTag_FT_EFF_B}}$	± 1.66 [1.8%]	-	± 0.95 [2.0%]
$\alpha_{\text{FAKES_REAL}}$	± 1.28 [1.4%]	-	-
$\alpha_{\text{MUON_EFF_SYS}}$	± 1.12 [1.2%]	-	± 0.65 [1.4%]
$\alpha_{\text{EL_EFF_ID}}$	± 1.03 [1.1%]	-	± 0.60 [1.3%]
$\alpha_{\text{MET_SoftTrk_ResoPara}}$	± 0.94 [1.0%]	-	± 0.29 [0.62%]
α_{JER}	± 0.93 [1.0%]	-	± 0.30 [0.65%]
$\alpha_{\text{MET_SoftTrk_ResoPerp}}$	± 0.72 [0.79%]	-	± 0.09 [0.20%]
$\alpha_{\text{EL_EFF_Iso}}$	± 0.52 [0.58%]	-	± 0.31 [0.67%]
$\alpha_{\text{JVT_JET_JvtEfficiency}}$	± 0.45 [0.50%]	-	± 0.26 [0.56%]
α_{JES2}	± 0.30 [0.33%]	-	± 0.16 [0.34%]
$\alpha_{\text{MUON_ISO_SYS}}$	± 0.27 [0.30%]	-	± 0.16 [0.34%]
α_{PileUp}	± 0.26 [0.29%]	-	± 0.54 [1.2%]
$\alpha_{\text{MUON_EFF_STAT}}$	± 0.26 [0.29%]	-	± 0.15 [0.32%]
$\alpha_{\text{EL_EFF_Reco}}$	± 0.25 [0.27%]	-	± 0.14 [0.31%]
α_{JES3}	± 0.24 [0.27%]	-	± 0.16 [0.34%]
$\alpha_{\text{EG_SCALE}}$	± 0.19 [0.20%]	-	± 0.10 [0.21%]
$\alpha_{\text{JET_EtaIntercalibration}}$	± 0.16 [0.17%]	-	± 0.09 [0.20%]
$\alpha_{\text{EL_EFF_Trigger}}$	± 0.15 [0.16%]	-	± 0.09 [0.19%]
$\alpha_{\text{MET_SoftTrk_Scale}}$	± 0.08 [0.09%]	-	± 0.04 [0.09%]
$\alpha_{\text{bTag_FT_EFF_extrapolation}}$	± 0.07 [0.08%]	-	± 0.02 [0.04%]
$\alpha_{\text{EG_RES}}$	± 0.05 [0.05%]	-	± 0.02 [0.04%]
$\alpha_{\text{MUON_ISO_STAT}}$	± 0.04 [0.05%]	-	± 0.02 [0.05%]
$\alpha_{\text{bTag_FT_EFF_extrapolation_from_charm}}$	± 0.03 [0.03%]	-	± 0.01 [0.03%]

Table C.2.: Breakdown of the dominant systematic uncertainties on the total SM background (first column) and, separately, on the two main backgrounds ($t\bar{t}$ and $t\bar{t}+Z$) of the analysis (last two columns) for the $CR_{t\bar{t}+Z}$, after the background-only fit. Note that the individual uncertainties can be correlated, and do not necessarily add up quadratically to the total background uncertainty. The percentages show the size of the uncertainty relative to the related expected background.

Appendix C. Uncertainties breakdown

	Total SM background	$t\bar{t}$	$t\bar{t} + Z$
Estimated background	19.37	7.82	1.52
Total background incertaintly	± 8.17 [42.18%]	± 3.76 [48.10%]	± 0.48 [31.82%]
$\alpha_{_FAKE_SYS}$	± 7.19 [37.1%]	-	-
$\alpha_{_topGenerator}$	± 4.71 [24.3%]	± 4.71 [60.2%]	-
$\mu_{t\bar{t}}$	± 2.84 [14.7%]	± 2.84 [36.3%]	-
$\gamma_{_stat_VR_cuts_bin_0}$	± 2.04 [10.5%]	± 0.82 [10.5%]	± 0.16 [10.5%]
$\alpha_{_ttbarPS}$	± 1.57 [8.1%]	± 1.57 [20.0%]	-
$\alpha_{_JER}$	± 0.90 [4.7%]	± 0.42 [5.4%]	± 0.10 [6.8%]
$\alpha_{_MET_SoftTrk_Scale}$	± 0.87 [4.5%]	± 0.72 [9.2%]	± 0.04 [2.5%]
$\alpha_{_ttbarRAD}$	± 0.86 [4.4%]	± 0.86 [11.0%]	-
$\alpha_{_PileUp}$	± 0.83 [4.3%]	± 0.69 [8.8%]	± 0.09 [5.7%]
$\alpha_{_WtRAD}$	± 0.44 [2.3%]	-	-
$\mu_{t\bar{t}+Z}$	± 0.43 [2.2%]	-	± 0.43 [28.0%]
$\alpha_{_MET_SoftTrk_ResoPerp}$	± 0.40 [2.1%]	± 0.49 [6.2%]	± 0.01 [0.83%]
$\alpha_{_bTag_FT_EFF_Light}$	± 0.30 [1.5%]	± 0.05 [0.61%]	± 0.01 [0.69%]
$\alpha_{_FAKES_REAL}$	± 0.24 [1.2%]	-	-
$\alpha_{_JES1}$	± 0.23 [1.2%]	± 0.04 [0.52%]	± 0.05 [3.2%]
$\alpha_{_MUON_EFF_SYS}$	± 0.20 [1.0%]	± 0.00 [0.04%]	± 0.00 [0.17%]
$\alpha_{_EG_SCALE}$	± 0.17 [0.86%]	± 0.04 [0.57%]	± 0.02 [1.0%]
$\alpha_{_bTag_FT_EFF_C}$	± 0.15 [0.75%]	± 0.09 [1.1%]	± 0.01 [0.77%]
$\alpha_{_MET_SoftTrk_ResoPara}$	± 0.14 [0.72%]	± 0.17 [2.2%]	± 0.02 [1.1%]
$\alpha_{_DibMUR}$	± 0.10 [0.51%]	-	-
$\alpha_{_EL_EFF_Iso}$	± 0.08 [0.42%]	± 0.01 [0.19%]	± 0.01 [0.40%]
$\alpha_{_MUON_ISO_SYS}$	± 0.07 [0.38%]	± 0.01 [0.07%]	± 0.00 [0.01%]
$\alpha_{_JET_RelativeNonClosure}$	± 0.06 [0.33%]	-	-
$\alpha_{_bTag_FT_EFF_B}$	± 0.06 [0.32%]	± 0.07 [0.88%]	± 0.02 [1.0%]
$\alpha_{_EL_EFF_ID}$	± 0.06 [0.32%]	± 0.02 [0.24%]	± 0.00 [0.19%]
$\alpha_{_JET_EtaIntercalibration}$	± 0.04 [0.21%]	± 0.12 [1.5%]	± 0.00 [0.12%]
$\alpha_{_JES2}$	± 0.03 [0.18%]	± 0.27 [3.5%]	± 0.03 [2.3%]
$\alpha_{_JES3}$	± 0.03 [0.15%]	± 0.26 [3.3%]	± 0.01 [0.78%]
$\alpha_{_bTag_FT_EFF_extrapolation_from_charm}$	± 0.02 [0.11%]	-	± 0.00 [0.24%]
$\alpha_{_JVT_JET_JvtEfficiency}$	± 0.00 [0.02%]	± 0.03 [0.38%]	± 0.00 [0.27%]
$\alpha_{_EG_RES}$	± 0.00 [0.01%]	± 0.06 [0.77%]	± 0.01 [0.45%]

Table C.3.: Breakdown of the dominant systematic uncertainties on the total SM background (first column) and, separately, on the two main backgrounds ($t\bar{t}$ and $t\bar{t} + Z$) of the analysis (last two columns) for the VR, after the background-only fit. Note that the individual uncertainties can be correlated, and do not necessarily add up quadratically to the total background uncertainty. The percentages show the size of the uncertainty relative to the related expected background.

	Total SM background	$t\bar{t}$	$t\bar{t} + Z$
Estimated background	3.79	1.44	1.43
Total background uncertainty	± 1.48 [39.05%]	± 1.24 [86.42%]	± 0.49 [34.20%]
α_{JES1}	± 0.83 [21.8%]	± 0.80 [55.7%]	± 0.03 [2.4%]
α_{JER}	± 0.61 [16.0%]	± 0.59 [40.7%]	± 0.05 [3.7%]
$\alpha_{\text{MET_SoftTrk_ResoPara}}$	± 0.59 [15.5%]	± 0.43 [29.8%]	± 0.12 [8.6%]
$\gamma_{\text{stat_HighStopMass_DF_cuts_bin_0}}$	± 0.57 [15.0%]	± 0.22 [15.0%]	± 0.21 [15.0%]
$\mu_{t\bar{t}}$	± 0.52 [13.8%]	± 0.52 [36.3%]	-
$\alpha_{\text{MET_SoftTrk_Scale}}$	± 0.51 [13.4%]	± 0.46 [32.1%]	± 0.01 [0.42%]
$\alpha_{\text{MET_SoftTrk_ResoPerp}}$	± 0.49 [13.0%]	± 0.33 [22.8%]	± 0.13 [8.9%]
$\mu_{t\bar{t}+Z}$	± 0.40 [10.5%]	-	± 0.40 [28.0%]
α_{ttbarRAD}	± 0.35 [9.4%]	± 0.35 [24.7%]	-
$\alpha_{\text{topGenerator}}$	± 0.32 [8.4%]	± 0.32 [22.3%]	-
α_{WtRAD}	± 0.21 [5.4%]	-	-
α_{PileUp}	± 0.17 [4.4%]	± 0.23 [16.0%]	± 0.00 [0.10%]
$\alpha_{\text{JET_EtaIntercalibration}}$	± 0.13 [3.3%]	± 0.12 [8.5%]	± 0.01 [0.97%]
α_{JES2}	± 0.08 [2.2%]	± 0.01 [0.73%]	± 0.04 [2.9%]
α_{JES3}	± 0.04 [1.1%]	± 0.04 [2.7%]	± 0.02 [1.3%]
α_{DibMUR}	± 0.02 [0.60%]	-	-
$\alpha_{\text{bTag_FT_EFF_B}}$	± 0.01 [0.39%]	± 0.04 [3.0%]	± 0.01 [0.84%]

Table C.4.: Breakdown of the dominant systematic uncertainties on the total SM background (first column) and, separately, on the two main backgrounds ($t\bar{t}$ and $t\bar{t} + Z$) of the analysis (last two columns) for the SR with Different Flavour selection, after the background-only fit. Note that the individual uncertainties can be correlated, and do not necessarily add up quadratically to the total background uncertainty. The percentages show the size of the uncertainty relative to the related expected background.

Appendix C. Uncertainties breakdown

	Total SM background	$t\bar{t}$	$t\bar{t} + Z$
Estimated background	5.28	2.11	1.62
Total background uncertainty	± 1.84 [34.83%]	± 1.27 [59.85%]	± 0.52 [31.94%]
$\alpha_{\text{MET_SoftTrk_ResoPara}}$	± 1.06 [20.1%]	± 0.63 [29.8%]	± 0.05 [2.9%]
$\alpha_{\text{MET_SoftTrk_ResoPerp}}$	± 0.89 [16.9%]	± 0.48 [22.8%]	± 0.05 [3.2%]
$\gamma_{\text{stat_HighStopMass_SF_cuts_bin_0}}$	± 0.78 [14.8%]	± 0.31 [14.8%]	± 0.24 [14.8%]
$\mu_{t\bar{t}}$	± 0.77 [14.5%]	± 0.77 [36.3%]	-
α_{JER}	± 0.61 [11.5%]	± 0.52 [24.6%]	± 0.02 [1.4%]
α_{JES1}	± 0.51 [9.7%]	± 0.47 [22.2%]	± 0.06 [3.5%]
$\alpha_{\text{topGenerator}}$	± 0.47 [8.9%]	± 0.47 [22.3%]	-
$\mu_{t\bar{t}+Z}$	± 0.45 [8.6%]	-	± 0.45 [28.0%]
$\alpha_{\text{FAKE_SYS}}$	± 0.35 [6.6%]	-	-
α_{JES3}	± 0.31 [5.9%]	± 0.34 [15.9%]	± 0.04 [2.5%]
α_{ttbarPS}	± 0.30 [5.7%]	± 0.30 [14.1%]	-
α_{JES2}	± 0.26 [4.9%]	± 0.24 [11.5%]	± 0.00 [0.23%]
$\alpha_{\text{FAKES_REAL}}$	± 0.21 [4.0%]	-	-
$\alpha_{\text{MET_SoftTrk_Scale}}$	± 0.20 [3.8%]	± 0.12 [5.5%]	± 0.01 [0.57%]
$\alpha_{\text{JET_EtaIntercalibration}}$	± 0.19 [3.7%]	± 0.19 [9.1%]	± 0.01 [0.61%]
α_{ttbarRAD}	± 0.17 [3.2%]	± 0.17 [8.1%]	-
α_{PileUp}	± 0.14 [2.7%]	± 0.17 [7.9%]	± 0.05 [3.2%]
α_{DibMUR}	± 0.03 [0.60%]	-	-
α_{WtDS}	± 0.03 [0.60%]	-	-
$\alpha_{\text{EG_SCALE}}$	± 0.01 [0.26%]	± 0.02 [1.0%]	± 0.01 [0.54%]
$\alpha_{\text{bTag_FT_EFF_C}}$	± 0.00 [0.05%]	± 0.04 [2.0%]	± 0.00 [0.07%]

Table C.5.: Breakdown of the dominant systematic uncertainties on the total SM background (first column) and, separately, on the two main backgrounds ($t\bar{t}$ and $t\bar{t} + Z$) of the analysis (last two columns) for the SR with Same Flavour selection, after the background-only fit. Note that the individual uncertainties can be correlated, and do not necessarily add up quadratically to the total background uncertainty. The percentages show the size of the uncertainty relative to the related expected background.

Appendix D.

Exclusion plot

The exclusion plots showing expected and observed CLs are reported respectively in Fig. D.1 and Fig. D.2.

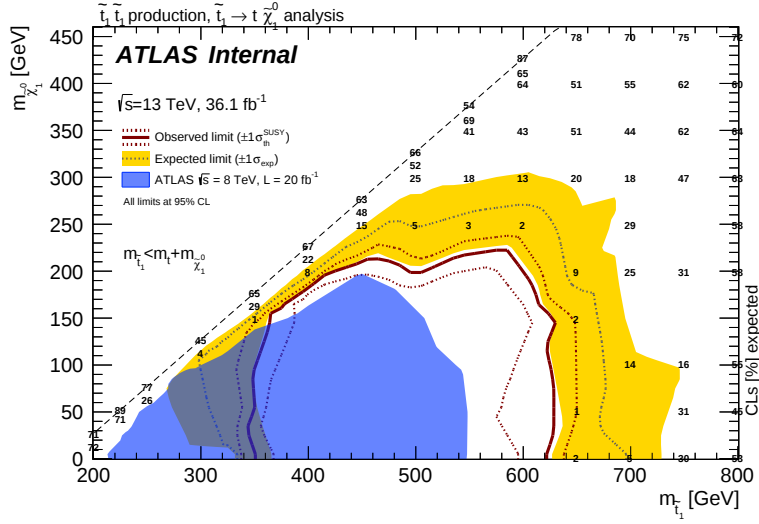


Figure D.1.: Contour exclusion plot in the masses plane $m_{\tilde{t}_1}$ and $m_{\tilde{\chi}_1^0}$. The dashed grey line and the shaded yellow band are the expected limit with its $\pm 1\sigma$ uncertainty. The solid red line shows the observed limit. The expected and observed limits do not include the effect of the theoretical uncertainties in the signal cross-section. The dotted red lines show the effect on the observed limit when varying the signal cross-section by $\pm 1\sigma$ of its uncertainty. For each signal model the expected CLs value is also reported. The shaded blue area shows the observed exclusion contour from the ATLAS Run1 analysis targeting $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ in a 2 lepton final state [130].

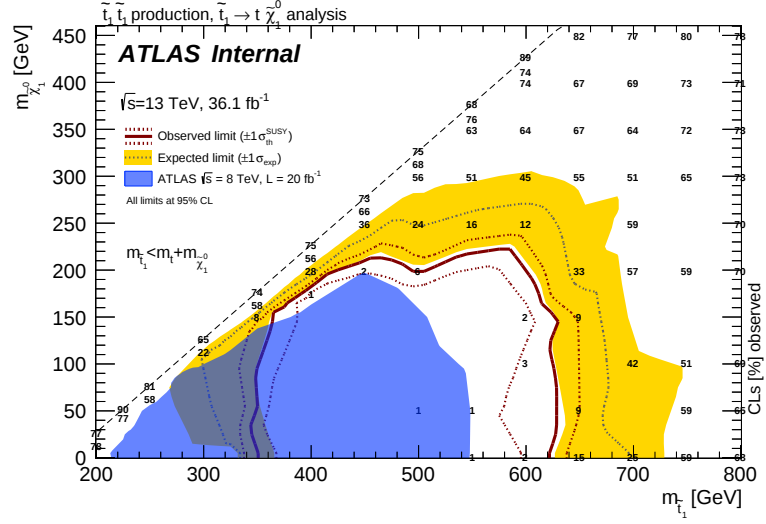


Figure D.2.: Contour exclusion plot in the masses plane $m_{\tilde{t}_1}$ and $m_{\tilde{\chi}_1^0}$. The dashed grey line and the shaded yellow band are the expected limit with its $\pm 1\sigma$ uncertainty. The solid red line shows the observed limit. The expected and observed limits do not include the effect of the theoretical uncertainties in the signal cross-section. The dotted red lines show the effect on the observed limit when varying the signal cross-section by $\pm 1\sigma$ of its uncertainty. For each signal model the observed CLs value is also reported. The shaded blue area shows the observed exclusion contour from the ATLAS Run1 analysis targeting $\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$ in a 2 lepton final state [130].

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