To the bottom of the stop: calibration of bottom-quark jets identification algorithms and search for scalar top-quarks and dark matter with the Run I ATLAS data

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Citation for published version (APA):
Pani, P. (2014). To the bottom of the stop: calibration of bottom-quark jets identification algorithms and search for scalar top-quarks and dark matter with the Run I ATLAS data
Supersymmetry (SUSY) is one of the most appealing possible extensions of the Standard Model (SM). By introducing an additional symmetry that links fermions and bosons it predicts the existence of a full spectrum of new particles. Among those, a top squark with a mass below 1 TeV plays a key role for the success of the theory and it is becoming an interesting and challenging signature at the LHC. An introduction to the key ingredients of the minimal supersymmetric extension of the SM (the MSSM) will be given in this chapter, with particular attention to those elements that determine the phenomenology of the top squark or the assumptions that will be imposed in the models considered in this thesis. In addition to this, in the last section Dark Matter (DM) production in pp collisions will be described in the effective field theory approximation.

1.1 Introduction to the Standard Model

The Standard Model (SM) of particle physics [1-4], formulated in the ’60s and ’70s, describes three natural forces (weak, electromagnetic and strong) and the dynamics of all known subatomic particles in a single model. Its predictive power has been proven in recent decades with unprecedented precision. The SM is a non-abelian gauge theory invariant under the symmetry group

\[ SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \]  \hspace{1cm} (1.1)

where \( C, L \) and \( Y \) are the colour charge, the weak isospin and the hypercharge, respectively. The gauge bosons \( W^i; \ i = 1, 2, 3 \) and \( B \) are the mediators of the elec-
troweak interaction and the gluons $g$ are the carriers of the strong force. The matter sector of the SM is composed of three generations of fermions and anti-fermions. According to their transformation properties under $SU(3)_C$ they are divided into quarks (carrying colour charge) and leptons (colourless). Furthermore, the fermions are divided into left and right handed chirality eigenstates. The former transform as doublets under the weak interaction $SU(2)_L$ and the latter as singlets. In summary, the gauge eigenstates of the SM matter sector are:

$$\begin{pmatrix}
  u_L \\
  d_L \\
  c_L \\
  s_L \\
  t_L \\
  b_L \\
  \nu_e L \\
  \nu_{\mu} L \\
  \nu_{\tau} L \\
  e_R \\
  \mu_R \\
  \tau_R
\end{pmatrix}$$

In the SM, neutrinos are assumed to be purely left handed and massless. Experimental results have shown that this is not the case and neutrinos have masses. A number of extensions of the SM have been proposed to include right handed neutrinos, although a discussion on these theories is beyond the scope of this introduction.

Any particle mass terms in the SM Lagrangian are forbidden by the gauge symmetry. In 2012 the mechanism that spontaneously breaks the electroweak symmetry in the SM [11–13] giving masses to the particles was experimentally verified with the discovery of the Higgs boson by ATLAS and CMS [5, 6]. After spontaneous symmetry breaking, the electroweak gauge bosons acquire mass. Their mass eigenstates ($W^\pm$, $Z$ and $\gamma$) are:

$$W^\pm = \frac{1}{\sqrt{2}} (W^1 \mp W^2)$$

$$Z = \begin{pmatrix} 
\cos \theta_{W} & -\sin \theta_{W} \\
\sin \theta_{W} & \cos \theta_{W}
\end{pmatrix}
\begin{pmatrix} 
W^3 \\
B
\end{pmatrix}$$

where the Weinberg angle $\theta_{W}$ is defined by:

$$\sin \theta_{W} = \frac{e}{g_2}.$$ 

$e$ is the electric charge and, in this notation, it is the coupling of the electromagnetic interaction, while $g_2$ is the gauge coupling constant for $SU(2)_L$. The core of the Standard Model is characterised by 19 free parameters that have been determined experimentally. In addition there are mass and mixing parameters of the neutrino sector.

The measurement of the Higgs mass fixed the last free parameter of the theory.

Despite its predictive power and success, the SM is an incomplete theory. First of all, it does not include any mechanism that describes the fourth fundamental force,
gravity and it does not include any particle that could account for the non-baryonic content of the universe (Dark Matter). Secondly, the SM is believed to be not natural. Some of its parameters are characterised by large quantum loop corrections that can be cancelled out only by fine-tuned constants. For the Higgs mass they can be expressed for loops involving fermions as

\[ m^2_H \propto \frac{\lambda_f^2 N_f^2}{8\pi^2} \Lambda^2 \]  

where \( \lambda_f^2 \) and \( N_f^2 \) are the Yukawa coupling and the numbers of colours of fermion \( f \). Due to the Yukawa coupling, the dominant term to the correction will be the one coming from the top quark. \( \Lambda \) is the cut-off scale and can be seen as the scale where new physics appears and where the Standard Model is known not to be valid anymore. In the assumption that the SM is valid up to the Grand Unification or the Planck scale, the correction to the Higgs mass is extremely large. To obtain the experimentally measured value of 125.5 ± 0.2 (stat.) ±0.5 _0.6 (syst) GeV [15] a 16 digit fine tuning of these enormous corrections is needed. This is one of the reasons, falling under the name of naturalness, that are used to justify the existence of New Physics around the TeV-scale. This would lower the scale at which the SM is valid, fixing \( \Lambda \sim \) TeV and reduce the tuning of the Higgs mass. The definition and quantification of this naturalness concept is somewhat arbitrary, but it is naively clear that subtracting two numbers at a very high scale to obtain a parameter at the electroweak scale, fine-tuning them by 16 digits has a low degree of naturalness. Conversely, a cancellation of divergences arising from a symmetry of the theory is characterised by a high degree of naturalness.

### 1.2 Introduction to Supersymmetry

In the last decades a very large number of extensions of the SM have been proposed in order to solve these shortcomings of the model. Supersymmetry (SUSY) [16–24] is one of the most compelling possible extensions of the Standard Model. This theory is grounded on a generalisation of space-time transformation linking fermions and bosons. It bypasses the Coleman–Mandula theorem, that states the impossibility of combining space-time and internal symmetries in any but a trivial way [25], by introducing fermionic generators of symmetry transformations. In this way it was possible to introduce an additional symmetry, that was shown by Haag, Lopuzansky and Sohnius [26] to be the only possible extension of the known space-
### Table 1.1: Fields of the MSSM and their $SU(3) \otimes SU(2) \otimes U(1)$ quantum numbers. Only one generation of quarks and leptons is listed as an example.

<table>
<thead>
<tr>
<th>Sparticle</th>
<th>Field content</th>
<th>SM partner</th>
<th>Quantum numbers $SU(3)$</th>
<th>$SU(2)$</th>
<th>$U(1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>gluino</td>
<td>$\tilde{g}$</td>
<td>$g$</td>
<td>8</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>gauginos</td>
<td>$\tilde{W}^\pm, \tilde{W}^0$</td>
<td>$W^\pm, W^0$</td>
<td>1</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>$\tilde{B}$</td>
<td>$B$</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>sleptons</td>
<td>$(\tilde{\nu}, \tilde{\ell}^-)_L$</td>
<td>$(\nu, \ell^-)_L$</td>
<td>1</td>
<td>2</td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td>$\tilde{\ell}_R$</td>
<td>$\ell_R$</td>
<td>1</td>
<td>1</td>
<td>-2</td>
</tr>
<tr>
<td>squarks</td>
<td>$(\tilde{u}, \tilde{d})_L$</td>
<td>$(u, d)_L$</td>
<td>3</td>
<td>2</td>
<td>1/3</td>
</tr>
<tr>
<td></td>
<td>$\tilde{u}_R$</td>
<td>$u_R$</td>
<td>3</td>
<td>1</td>
<td>4/3</td>
</tr>
<tr>
<td></td>
<td>$\tilde{d}_R$</td>
<td>$d_R$</td>
<td>3</td>
<td>1</td>
<td>-2/3</td>
</tr>
<tr>
<td>higgsinos</td>
<td>$(\tilde{H}^0_d, \tilde{H}^-_d)$</td>
<td>$(H^0_d, H^-_d)$</td>
<td>1</td>
<td>2</td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td>$(\tilde{H}^+_d, \tilde{H}^0_d)$</td>
<td>$(H^+_d, H^0_d)$</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

1.2.1 The Minimal Supersymmetric Standard Model (MSSM)

In this thesis we will refer to the minimal supersymmetric extension of the SM, i.e. the MSSM. A brief overview of the model and the information relevant to the work in this thesis will be given in the following and further details can be found in Refs. [14, 44–47].

In order to supersymmetrize the SM we need to introduce a super-partner for every known particle with half a unit of spin difference, but otherwise with the same properties and quantum numbers (Table 1.1). SM particles and their partners are postulated to have an additional quantum number, the R-parity, that is assumed to be conserved:

$$R = (-1)^{3(B-L)+2S}.$$  (1.5)
\(B\) and \(L\) are the baryon and lepton numbers, respectively and \(S\) is the spin. The R-parity allows us to distinguish particles and super-partners and its conservation has important phenomenological consequences:

a) all sparticles are produced in pairs,

b) all decays of \(\text{SUSY}\) particles involve other \(\text{SUSY}\) particles in the final state,

c) the lightest \(\text{SUSY}\) particle is stable and does not decay.

In addition, R-parity conservation allows to eliminate all the lepton and baryon violating terms of the \(\text{MSSM}\) Lagrangian such that the \(\text{MSSM}\) obeys to the same conservation rules and symmetries of the \(\text{SM}\).

In the \(\text{SM}\) all matter fields (leptons and quarks) are spin half fermions and the gauge bosons have spin one. The super-partners of the fermions cannot have spin one since the only known consistent relativistic field theories for spin-one particles are those of gauge bosons that are not suitable to describe matter fields \([46]\). For this reason, the bosonic super-partners of the fermions should be scalars. The fermions and their partners form three generations of six chiral super-multiplets that represent the matter sector content of the \(\text{MSSM}\). In contrast to the \(\text{SM}\), the Higgs sector of the \(\text{MSSM}\) contains two chiral super-multiplets with two complex Higgs doublets \(H_D\) and \(H_U\) and their fermionic counterparts (higgsinos). This is the minimal structure needed to cancel out the gauge anomaly (a requirement of renormalizability of the theory), that arises if

\[
\sum_{\text{fermions}} Y \neq 0, \quad (1.6)
\]

where \(Y\) is the hypercharge. Two Higgs doublets is also the minimal structure required to give mass to both up and down type super-multiplets.

Finally the gauge sector consists of the gluons and their \(\text{gluino}\) super-partners and the \(SU(2)_L \otimes U(1)_Y\) gauge bosons and their \(\text{gaugino}\) super-partners.

### 1.2.2 Supersymmetry breaking

The fact that \(\text{SUSY}\) particles have not yet been observed leads to the conclusion that, if supersymmetry is realised, it is a broken symmetry. The mechanisms by which \(\text{SUSY}\) is broken is unknown and the Lagrangian is usually split into two components:

\[
\mathcal{L}_{\text{MSSM}} = \mathcal{L}_{\text{SUSY}} + \mathcal{L}_{\text{Soft}}, \quad (1.7)
\]
where the first term on the right side consists of the dynamics terms of the superfields and their interactions and the second contains the supersymmetry breaking terms. To ensure proper convergence of the theory at high energy, these SUSY-breaking terms have to be *soft*, which means that they must have mass dimension less than four. It can be proven [46] that it is impossible to construct a realistic model of spontaneously broken low-energy SUSY in which the supersymmetry breaking arises only from interactions of the particles of the MSSM. It is therefore assumed that there exists a *hidden sector* consisting of particles that are completely decoupled from the MSSM particles and which is responsible for breaking SUSY. $L_{Soft}$ is obtained by considering its most general form, without assumptions on the nature of this sector. $L_{Soft}$ can be written as [46]:

$$L_{Soft} = -\phi_i^*(m^2_{ij})\phi_j + \left(\frac{1}{3!}A_{ijk}\phi_i\phi_j\phi_k - \frac{1}{2}B_{ij}\phi_i\phi_j + C_i\phi_i + h.c.\right)$$

$$- \frac{1}{2} \sum_{a=1}^{3} (M_a\lambda^a\lambda^a + h.c.),$$

(1.8)

where $\phi_i$ is the scalar component of one of the MSSM superfields, with $m$ being interpreted as its mass, and $\lambda^a$ the gaugino fields, with $M$ their Majorana mass term. $A, B$ and $C$ are the trilinear, bilinear and linear scalar interaction terms.

The MSSM is characterised by 124 independent physical parameters [48] that arise either from the supersymmetric part of the Lagrangian ($L_{SUSY}$) or from the supersymmetry breaking term ($L_{Soft}$). The ones that will be relevant to understand the phenomenology and assumptions of the models considered in this thesis are described in the following:

- **$\mu$**: is the coefficient in the Higgs super-potential $W$ that gives the mass terms for the Higgs bosons and their partners ($W \sim \mu H_u H_d$) and is therefore called the *Higgs mass term*. Within the most used convention, the phase of $\mu$ is a physical parameter. However, due to possible large CP-violation due to this phase, $\mu$ is usually assumed to be real.

- **$M_a$ ($a = 1, 2, 3$)**: are the soft supersymmetry breaking gaugino mass parameters. Within the most used convention, a redefinition of phases always allows to define these numbers as real and positive.

- **$\tan \beta$**: is the ratio of the Higgs vacuum expectation values of the two Higgs doublets:

$$\tan \beta = \frac{v_u}{v_d}$$

(1.9)
the squark (and slepton) mass matrices that appear in $L_{soft}$: $M_{\tilde{q}}$ for the left handed squarks ($M_{\tilde{f}}$ for sleptons) and the right handed ones $M_{\tilde{u}}, M_{\tilde{d}}$ ($M_{\tilde{e}}$ for the sleptons).

1.2.3 Gauge eigenstates mixing in SUSY

The breaking mechanism of the Lagrangian causes the presence of mixing between the gauge eigenstates of the SUSY particles. It is important to understand the mass eigenstates of the theory and their gauge eigenstates content because they will characterise its phenomenology.

Each of the SM fermions has two supersymmetric partners $\tilde{f}_L$ and $\tilde{f}_R$ corresponding to the left and right handed fermion. In general, these two sparticles are not mass eigenstates and can mix. The mixing of the two sparticles is proportional to the mass of their fermion partner. In particular for the stop, the squared mass matrix can be approximately written as:

$$M_{\tilde{t}}^2 = \begin{pmatrix} (M_{\tilde{q}}^2)_3 + (1/2-2/3\sin^2\theta_W)M_Z^2 \cos 2\beta + m_t^2 & -m_t(\mathcal{A}^t + \mu \cot \beta) \\ -m_t(\mathcal{A}^t + \mu \cot \beta) & m_t^2 + 2/3M_Z^2 \cos 2\beta \sin^2\theta_W + m_t^2 \end{pmatrix}. \quad (1.10)$$

Here $(M_{\tilde{q}}^2)_3$ is the third component of the left-handed squarks mass matrix and $\mathcal{A}^t$ the matrix of trilinear interaction coefficients of the top squark. Therefore the mixing is expected to be small in general, with the exception of the third generation squarks. Since the off diagonal terms depend on the non negligible masses of their fermion partners, the third generation squarks involve substantial left-right mixing. Especially for the top squark a significant mixing of the left-right gauge eigenstates can occur and determine a large mass splitting between the two mass eigenstates, $\tilde{t}_1$ and $\tilde{t}_2$. In these conditions the lightest of the two, $\tilde{t}_1$, might be considerably lighter than the rest of the squarks.

The charged gauginos and higgsinos mix into four physical states called charginos: $\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$ (where it is assumed $m(\tilde{\chi}_1^\pm) < m(\tilde{\chi}_2^\pm)$). The mixing is described at tree level by a $2 \times 2$ complex mass matrix that is a function of $M_2, \beta$ and $\mu$:

$$\mathcal{M}_{\tilde{\chi}} = \begin{pmatrix} M_2 & \sqrt{2}M_W \sin \beta \\ \sqrt{2}M_W \cos \beta & \mu \end{pmatrix}. \quad (1.11)$$

In the same way the neutral gauginos and higgsinos mix into four physical states called neutralinos: $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$ (index ordered in mass). The mixing is described
at tree level by a $4 \times 4$ symmetric complex mass matrix and again depends only on $M_1, M_2, \tan \beta$ and $\mu$:

$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_W \tan \theta_W \cos \beta & -M_W \tan \theta_W \sin \beta \\ M_2 & M_W \cos \beta & 0 & -\mu \\ -M_W \tan \theta_W \sin \beta & M_W \sin \beta & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix},$$

(1.12)

where $\theta_W$ is the weak mixing angle. If $\tilde{\chi}_1^0$ is the lightest SUSY particle (as we will assume in this thesis), due to R-parity conservation it is stable. In this scenario, $\tilde{\chi}_1^0$ represents a natural Dark Matter candidate, as further discussed in Section 1.4.

In general the three parameters $\mu, M_1$ and $M_2$ are completely arbitrary. However, in Grand Unification Theories (GUT) $M_1$ and $M_2$ are equal at the high scale ($\Lambda_{\text{GUT}}$) where the gauge couplings are presumed to unify:

$$M_1(\Lambda_{\text{GUT}}) = M_2(\Lambda_{\text{GUT}}).$$

(1.13)

At the scale of the $Z$ mass $m_Z$ we can determine using the renormalisation group equations that:

$$M_1(m_Z) \approx \frac{1}{2} M_2(m_Z).$$

(1.14)

The last condition is also known under the name of gaugino universality assumption. Secondly, $\mu$ is related to the $Z$ mass by:

$$m_Z^2 = 2 m_{Hd}^2 - m_{Hu}^2 \tan^2 \beta - 2 \mu^2,$$

(1.15)

where $m_{Hd}$ and $m_{Hu}$ are couplings of the quadratic terms of $H_d$ and $H_u$ in the SUSY Higgs potential. Naturalness arguments require $\mu$ to be of the same scale as $m_Z$ in order to have a reasonably little amount of fine-tuning among the parameters.

According to the relative hierarchy between these three parameters $\mu, M_1$ and $M_2$, the mixture of higgsinos ($\tilde{H}$), winos ($\tilde{W}$) and bino ($\tilde{B}^0$) that contribute to the lightest chargino and neutralino differs. In the phenomenology considered in this thesis the neutralino is considered to be mostly bino-like and it is assumed that

$$M_1 < M_2 < |\mu|.$$

(1.16)

This condition together with the one in Eq (1.14) implies:

$$m(\tilde{\chi}^\pm) \approx 2 m(\tilde{\chi}_1^0).$$

(1.17)
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The afore mentioned hypothesis, however, is not the one favoured by naturalness arguments. A natural definition of \( \mu \) is achieved if \( \mu \sim m_Z \), where the hierarchy with the other parameters \( M_1 \) and \( M_2 \) could be:

\[
|\mu| \ll M_1, M_2. \tag{1.18}
\]

This relation implies the lightest neutralino and charginos being higgsino-like and very close in mass:

\[
m(\tilde{\chi}^\pm) \approx m(\tilde{\chi}_1^0) \approx |\mu|. \tag{1.19}
\]

Otherwise it could be that \( \mu, M_1 \) and \( M_2 \) have similar magnitude, which would lead to a \( \tilde{\chi}_1^0 \) composed of a equal mixture of higgsinos, winos and bino. Despite its naturalness, the condition of Eq. (1.19) is characterised by a phenomenology that is more difficult to detect at the LHC. In this thesis the neutralino is assumed to be bino-like. This does not comply to the most natural definition of the \( \mu \) parameter but still allows for a natural definition of the Higgs mass.

1.3 The supersymmetric partner of the top quark

1.3.1 Proton-proton collisions at the LHC

The Large Hadron Collider (LHC) accelerates and collides protons at a centre-of-mass of 8 TeV. The proton constituents (partons) are three valence quarks, two up-type and one down-type, gluons, and the sea quarks and antiquarks, constantly created and annihilated due to quantum fluctuations. The cross section of two protons in an arbitrary final state \( X (pp \to X) \) can be described in terms of a partonic cross section convoluted with the Parton Distribution Functions (PDFs) of the partons inside the protons:

\[
\sigma_{pp \to X} = \sum_{i,j} \int_0^1 dx_1 \int_0^1 dx_2 f_i(x_1, \mu_f^2) f_j(x_2, \mu_f^2) \hat{\sigma}_{ij \to X} \left( x_1 p_1, x_2 p_2, \alpha_s(\mu_f^2), \frac{Q^2}{\mu_f^2}, \frac{Q^2}{\mu_f^2} \right). \tag{1.20}
\]

The partonic cross section of the hard scattering, \( \sigma_{ij \to X} \), describes the production of products \( X \) at energy scale \( Q \) from the partons \( i \) and \( j \) with momenta \( x_1 p_1 \) and

\(^1\) The centre-of-mass was 7 TeV in 2010-2011.
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$x_2 p_2, p_1$ and $p_2$ being the momenta of the incoming protons. It is typically calculated in perturbation theory, to Leading Order (LO), Next-to-Leading Order (NLO), or even higher orders. The PDFs, $f_i(x_1)$ and $f_i(x_2)$, parametrise the probability of having parton $i$ and $j$ from each of the two incoming protons with momentum fraction $x_1$ and $x_2$. The shapes of the PDFs are determined by a fit to data from experimental observables in various processes [49–54] and extrapolated using the DGLAP evolution equation [55–59].

The scales $\mu_r^2$ and $\mu_f^2$ are the renormalisation and factorisation scales, respectively. The former indicates the scale at which $s$ is evaluated and the latter indicates the scale at which the PDFs are evaluated and at which the long and short distance effects are assumed to factorise.

1.3.2 Motivations for a light top squark

If SUSY is realised, the most abundant sparticles produced at the LHC are those with masses accessible to the collider’s energy that couple the strongest to the proton constituents. The production cross section for different pairs of sparticles as a function of their mass is shown in Figure 1.1. First and second generation squarks and gluinos are the particles that are produced with the highest cross section at a

Figure 1.1: Sparticle production cross section as a function of the average of the masses of the particles produced in the process. The dark blue line describes the cross section for direct production of top squark pairs and it is the relevant cross section for this analysis. The cross sections have been calculated using Prospino [60].

$\sqrt{S} = 8 \text{ TeV}$

$\sigma_{\text{tot}} [\text{pb}]: \text{pp} \rightarrow \text{SUSY}$

$m_{\text{average}} [\text{GeV}]$

$\sigma_{\text{tot}} [\text{pb}]: \text{pp} \rightarrow \text{SUSY}$

$\sqrt{S} = 8 \text{ TeV}$

$m_{\text{average}} [\text{GeV}]$
Figure 1.2: Feynman diagrams for the production of squarks and gluinos in lowest order. The diagrams without and with crossed final-state lines [e.g. in (b)] represent t- and u-channel diagrams, respectively. The diagrams in (c) and the last diagram in (d) are a result of the Majorana nature of gluinos. Note that some of the above diagrams contribute only for specific flavours and chiralities of the squarks [6].
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Figure 1.3: Exclusion limits at 95% confidence level for a simplified phenomenological MSSM scenario where only strong production of gluinos and first- and second-generation squarks is considered. Three values of $\tilde{\chi}_1^0$ masses are considered. The dashed lines show the expected limits with $1\sigma$ uncertainty band in yellow on the lowest $\tilde{\chi}_1^0$ mass assumption. Observed limits are indicated by solid curves. Areas to the left and below the curves are excluded. The dotted lines indicate the observed exclusion varying the signal cross section by $1\sigma$ uncertainty. Previous results from ATLAS are represented by the shaded light blue area [62].

given mass; the leading order Feynman diagrams for squark and gluino production at the LHC are shown in Figure 1.2. Searches at 7 and 8 TeV centre-of-mass energy in ATLAS (as well as in CMS) have already excluded a large amount of the parameter space, pushing the lower limits of these particles over the TeV scale [2] (see Figure 1.3).

Due to these more and more stringent limits on squarks and gluinos, an increasing attention is being devoted to the third generation partners and in particular to

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2) It is important to realise when speaking about SUSY limits that given the large amount of free parameters of the theory each limit comes with certain assumptions that need to be taken into account when interpreting the results. In addition, there is always a corner of the parameter space where the assumption does not hold and that is not excluded by the most inclusive and powerful search.
The supersymmetric partner of the top quark, the stop. Since top quarks are not among the constituents of the proton, the $t$-channel diagram is not available for scalar top production (Figure 1.4), hence they are produced with a cross section that is an order of magnitude smaller than that of the first two generation squarks and gluinos. They have a challenging signature due to their similarity to the top quark. Despite the challenge, a number of motivations justify the interest in dedicated searches for top squark direct production.

First of all, the enhanced mixing between the two partners of the right and left handed tops ($\tilde{t}_L$ and $\tilde{t}_R$) might imply a large mass difference between the two physical states $\tilde{t}_1$ and $\tilde{t}_2$. This would lead to a mass hierarchy inversion in the SUSY spectrum, with the $\tilde{t}_1$ as the lightest squark, much lighter than the current limits for the first and second generation squarks.

In addition, top squarks are the main ingredient for the SUSY solution to the hierarchy problem of the SM. In fact, each of the supersymmetric partners of the SM particles contribute to $\delta m_H^2$ (Eq. 1.4) with opposite sign and cancel the quadratic dependence on $\Lambda$. If SUSY masses were equal to SM particle masses, the cancellation would be exact. Otherwise, it is reduced to a logarithmic divergence:

$$\delta m_H^2 \propto \frac{\lambda_f^2 N_f}{8\pi^2} (m_{f}^2 - m_{\tilde{f}}^2) \ln \left( \frac{\Lambda^2}{m_{\tilde{f}}^2} \right)$$  \hspace{1cm} (1.21)

Following Eq (1.21), the naturalness is re-established by means of an additional symmetry, if the mass difference between the top quark and its partner is between...
a few hundred GeV to a few TeV.

1.3.3 Top squark phenomenology

If the top squark exists, and plays a role in solving the hierarchy problem, it can be produced at the LHC and it is not unlikely that ATLAS, with 20 fb$^{-1}$ of data collected at a centre-of-mass energy of 8 TeV, can find it. The top squark production cross section in proton-proton collisions depends on the stop mass as shown in Figure 1.1. The cross sections for masses between 100 GeV and 700 GeV span five orders of magnitude, varying from 560 pb to 8 fb.

A number of decay modes might be accessible to top squarks of these masses, depending on the masses of the rest of the particles of the SUSY spectrum:

- a) $\tilde{t} \rightarrow b \tilde{\chi}^\pm \rightarrow b W^\pm \tilde{\chi}^0$ (with on/off-shell W)
- b) $\tilde{t} \rightarrow t \tilde{\chi}^0$
- c) $\tilde{t} \rightarrow b W^\pm \tilde{\chi}^0$ (via off-shell top)
- d) $\tilde{t} \rightarrow c \tilde{\chi}^0$
- e) $\tilde{t} \rightarrow b f \tilde{f}' \tilde{\chi}^0$

A schematic representation of the parameter space ($m_{\tilde{t}}, m_{\tilde{\chi}^0}$) where these five decay modes are accessible is shown in Figure 1.5. All decay modes except the first one are dominating for different regions of the parameter space, while the $\tilde{t} \rightarrow b \tilde{\chi}^\pm$ decay mode is always kinematically allowed if $m(\tilde{\chi}^0) < m(\tilde{\chi}^\pm) < (m(\tilde{t}) - m(b))$.

The last two decays d) and e) have a specific signature that cannot be addressed with the requirements applied in this analysis and have been investigated in other searches exploiting charm and soft lepton identification techniques [9, 64]. Diagrams of the three decay channels considered in this analysis a), b) and c) are presented in Figure 1.6. Signal cross sections are calculated to NLO in the strong coupling constant, adding the resummation of soft gluon emission at Next-to-Leading Logarithm (NLL) accuracy (NLO+NLL) [63, 65, 67].

R-parity conservation is the assumption of the MSSM that has the most striking impact on the phenomenology of the stop and its decay. It implies that top squarks are produced in pairs and that the lightest particle of the decay chain (hereby assumed to be the lightest neutralino) is stable.
In order to simplify the treatment of each of the stop decays considered in this thesis an additional constraint is imposed: the so called simplified model assumption. This assumption considers each decay mode separately:

I. the decay is assumed to have 100% branching ratio. Since two top squarks are produced in each event due to R-parity conservation, this implies that both squarks decay in the same, symmetric way. When the chargino is involved in the decay chain, also the $\tilde{\chi}^\pm \rightarrow W^\pm \tilde{\chi}^0$ branching ratio is assumed to be 100%. This also means that any interference between the diagrams of the different decay channels is assumed to be zero.

II. All masses of sparticles not involved in the decay chain are assumed to be very high.

III. All masses of the sparticles involved in the decay chain are treated as free parameters. Signal models with different parameter assumptions are investigated.

\[ m(t) = m(b) + m(W^\pm) + m(\tilde{c}^0) \]
\[ m(t) < m(c^0) \] is kinematically forbidden. The $t \rightarrow b \tilde{\chi}^\pm b W^\pm \tilde{\chi}^0$ decay is always possible if $m(t) > m(b) + m(\tilde{c}^0)$.

\[ m(\tilde{t}) \]
\[ m(\tilde{b}) + m(\tilde{c}^0) \]
\[ m(t) + m(\tilde{c}^0) \]
\[ m(t) = m(\tilde{c}^0) + m(\tilde{c}^0) \]

\[ \text{Figure 1.5: Schematic representation of all possible decays of the top squark. The grey dashed lines indicate the kinematic boundaries for the various decay channels and the region } m(\tilde{t}) < m(\tilde{c}^0) \text{ is kinematically forbidden. The } t \rightarrow b \tilde{\chi}^\pm \rightarrow b W^\pm \tilde{\chi}^0 \text{ decay is always possible if } m(\tilde{t}) > m(b) + m(\tilde{c}^0). \]
The supersymmetric partner of the top quark

Physics beyond the SM

The simplified model condition is partially relaxed in one particular set of signal models. As visible in Figure 1.6, \( \tilde{t} \rightarrow t \tilde{\chi}^0 \) and \( \tilde{t} \rightarrow b \tilde{\chi}^\pm \) decay modes overlap in a large portion of parameter space. In this region, there is little justification in imposing 100% branching ratio in either of the decay modes, if the sum of the chargino and the b-quark masses is smaller than the stop mass. Therefore these two decays are both allowed to take place and different branching ratio combinations (\( \tilde{t} \rightarrow t \tilde{\chi}^0, \tilde{t} \rightarrow b \tilde{\chi}^\pm \)) are tested (25--75%, 50--50%, 75--25%). Also in this case, no interference between the diagrams is considered. The final topology will be referred to as asymmetric because in a certain fraction of events each of the two top squarks decay in a different mode.

Even under the simplified model assumptions, the \( \tilde{t} \rightarrow b \tilde{\chi}^\pm \) decay mode is characterised by a 3-dimensional parameter space determined by the masses of the three particles involved in the chain (\( \tilde{t}, \tilde{\chi}^\pm, \tilde{\chi}^0 \)). ATLAS has pursued the strategy of cutting this space in bidimensional slices, fixing certain particle masses or relating them according to certain physics-driven motivations:
**Gaugino universality:** the assumption that gauge couplings unify at the grand unification scale favours the condition (Sec. 1.2.1):

\[ m(\tilde{\chi}^\pm) \approx 2 m(\tilde{\chi}^0) \quad (1.22) \]

The set of models used as a benchmark for \( \tilde{t} \to b \tilde{\chi}^\pm \) selection optimisation span the parameter space of \((m_{\tilde{t}}, m_{\tilde{\chi}^0})\) and assume the relation in Eq. (1.22) between the chargino and the neutralino masses.

**Mass degeneracy:** a particularly challenging scenario is the case in which the top squark and the chargino masses are very similar to each other. This hypothesis is tested considering a set of models that span the parameter space \((m_{\tilde{t}}, m_{\tilde{\chi}^0})\) and require \(m(\tilde{t}) - m(\tilde{\chi}^+) = 10\) GeV.

**Fixed masses:** a convenient approach (orthogonal to the ones listed so far) is fixing one of the sparticle masses to a certain value and vary the other two parameters. This is done with the following assumptions:

a) \( m(\tilde{t}) = 300\) GeV  

b) \( m(\tilde{\chi}^+) = 106\) or \(150\) GeV  

c) \( m(\tilde{\chi}^0) = 0\).

Searches with different final states allow a complementary coverage of these selected models, as summarised in Table 1.2. The models where one lepton final states are expected to have major sensitivity are the ones considered in this thesis.

---

3) The 106 GeV value is chosen just above the LEP chargino mass limit.
The connection between top quarks, neutralinos and Dark Matter

Astrophysical observations have provided compelling proof for the existence of a non-baryonic dark component of the universe: Dark Matter (DM). The DM abundance has been precisely measured \([69-73]\) and corresponds to 27% of the total universe content. The nature of DM is not known, but from the theoretical point of view the most studied candidate is represented by a Weakly Interacting Massive Particle (WIMP): a neutral particle with weak-scale mass and weak interactions, whose thermal relic density may naturally fit the observed DM abundance. R-parity conserving SUSY models provide a natural WIMP candidate for DM: the neutralino. In the last chapter of this thesis, the signal selections used to search for \(\tilde{t} \rightarrow t \tilde{\chi}^0\) will be used to interpret the results in terms of DM models.

Searches for DM particles, indicated in the following with the symbol \(\chi\), are performed using three orthogonal approaches:

a) Direct detection searches that exploit the high local DM density (~ 0.3 GeV/cm\(^3\)) to detect WIMP scattering on nuclei: \(\chi + N \rightarrow \chi + N\), where \(N\) is a nucleon.

b) Indirect (astrophysical) searches that look for DM annihilation processes and exploit the Majorana nature of WIMP: \(\chi\chi \rightarrow SM \text{ SM}\), where SM represents any SM particle.

c) LHC searches that look for processes where DM is directly produced: \(pp \rightarrow \chi\chi + X\). Since DM is revealed as missing transverse momentum, \(X\), that might be a quark, a photon or a gauge boson, determines the strategy of the search.
Figure 1.7: Dotted and solid lines show the most recent upper limits at 90% confidence level (99% for CoGeNT) on WIMP-nucleon scattering cross section. The most favourable regions for DM candidates reported by DAMA, CRESS and CDMS Collaborations are shown as filled contours. The ATLAS 7 TeV results for contact operator D5 are shown as a black solid line and has a reach to lower DM masses than the direct detection experiments.
Table 1.3: Most important contact operators describing the interaction of a Dirac or complex scalar DM particles ($\chi$) with quarks or gluons \cite{76}. $G_\chi$ is the coupling of the contact operator and it is defined in Eq. (1.25).

Table 1.4: Factors used in Eqs. (1.26) and (1.27) for converting $M_*$ into $\chi$-nucleon cross section \cite{76}.

Tantalising (although controversial) hints of a DM particle with mass of a few GeV are coming from direct detection experiments such as DAMA and CoGent (\cite{74,75}). The most recent results in terms of WIMP-nucleon scattering cross section upper limits and observations are shown in Figure 1.7. As visible in the plot, LHC searches are most effective for highly boosted, light WIMPs, therefore it is becoming extremely important to probe DM production in order to confirm, or contradict such claims.

Without hints of SUSY, DM searches in pp collisions are performed with a model-independent, Effective Field Theory (EFT) approach. Interactions between DM particles and the SM sector are parametrised by a set of effective (non-renormalizable) operators, generated after integrating out heavy mediators. Dimension six operators

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<tbody>
<tr>
<td>D1</td>
<td>$1.6 \times 10^{-37}$</td>
<td>20</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>D5</td>
<td>$1.38 \times 10^{-37}$</td>
<td>300</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>D9</td>
<td>$9.18 \times 10^{-40}$</td>
<td>300</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>D11</td>
<td>$3.83 \times 10^{-41}$</td>
<td>100</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>C1</td>
<td>$2.56 \times 10^{-36}$</td>
<td>100</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>C5</td>
<td>$7.4 \times 10^{-39}$</td>
<td>100</td>
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describe the interactions with quarks and are of the form:

\[ \mathcal{L}_{\text{eff}} = G_\chi \sum_{\text{quarks}} \mathcal{O}(\chi, q), \]  
(1.23)

while dimension seven operators describe the interaction with gluons (\(G\)):

\[ \mathcal{L}_{\text{eff}} = G_\chi \mathcal{O}(\chi, G). \]  
(1.24)

\(\mathcal{O}\) is one of all possible operators (up to a certain order) that can be considered in the contact interaction of DM with quarks (and gluons) and can be classified in a systematic way \([76, 77]\). The most important operators for Dirac and complex scalar \(\chi\) from Ref. \([76]\) are summarised in Table 1.3. The coupling constant, \(G_\chi\), is fixed to lead to the correct relic density for WIMPs. This is related to the mass of the mediator of the interaction, \(M_\psi\), and the couplings of the mediator to \(\chi\) and quarks, \(g_q, g_\chi\):

\[ G_\chi = \frac{g_q g_\chi}{M_\psi^2} \equiv \frac{1}{M_*^2}. \]  
(1.25)

For each operator the relic abundance, direct detection signal, and collider prediction depend on a single parameter, the reduced coupling \(M_*\), through which they can be simply related. This parameter can also be easily compared among the three types of DM searches. For convenience this parameter can be converted into a DM-nucleon scattering cross section. The exact formula will depend on the contact operator that is considered \([76]\):

\[ \sigma^D(\chi, n) = \kappa \text{c} \text{m}^2 \left( \frac{\mu_\chi}{1 \text{ GeV}} \right)^2 \left( \frac{C}{M_*} \right)^y \]  
(1.26)

\[ \sigma^C(\chi, n) = \kappa \text{c} \text{m}^2 \left( \frac{\mu_\chi}{1 \text{ GeV}} \right)^2 \left( \frac{B}{m_\chi} \right)^2 \left( \frac{C}{M_*} \right)^y. \]  
(1.27)

The reduced mass \(\mu_\chi\) is defined as:

\[ \mu_\chi = \frac{m_\chi \cdot m_n}{m_\chi + m_n}, \]  
(1.28)

with \(m_n\) the nucleon mass and \(m_\chi\) the DM mass. \(\kappa, B, C\) and the exponent \(y\) are listed in Table 1.4 for the most important operators.

It is important to realise that while for direct and astrophysical DM searches the EFT description is completely justified by the energy scales involved, at the LHC
situation is different. In this case the energies can be very high and the processes one wishes to describe in terms of effective operators can actually occur at an energy beyond the validity of the EFT itself. A rough estimate of the EFT validity [78] for s-channel mediator exchange is furnished by $M_\psi > 2m_\chi$, that accounting for different

**Figure 1.8:** Combination of current collider-based upper limits at 90% confidence level on the spin independent WIMP-nucleon cross section for major contact operators listed in Table 1.3 [78].

**Figure 1.9:** Dominant Feynman diagrams for dark matter production in conjunction with heavy quarks [79].
Physics beyond the SM  Top quarks, neutralinos and Dark Matter

Figure 1.10: Collider based limits at 90% confidence level on $M_*$ from Ref. [78] for scalar interaction of Dirac and complex scalar DM (D1 and C1 operators, respectively) are indicated by the solid blue curve. Values below the line are excluded. The green line indicates the limit on $M_*$ for which WIMPs can couple to quarks or gluons exclusively via the given operator and account entirely for the relic density measured by WMAP.

Factors in the operators translates into the following $M_*$ validity ranges:

\[
\sqrt{\frac{M_\chi^2}{m_q}} > \frac{m_\chi}{2\pi} \quad (D1) \\
M_* > \frac{m_\chi}{2\pi} \quad (D5, D9, D11, C5) \\
\frac{M_*^2}{m_q} > \frac{m_\chi}{8\pi^2} \quad (C1).
\]

A more complete discussion on the limits of EFT at the LHC can be found in Ref. [80].

A summary of the current collider-based limits in the context of effective field theories is given in Figure 1.8 [78]. The results combine the most recent collider upper limits on:

\[ pp \rightarrow \chi\bar{\chi} + X, \]

with $X$ being a gluon, a quark, a photon or a $W^*$ or $Z$ boson. The couplings of some of the operators listed in Table 1.3 have a dependence on the quark mass. This implies that the production cross section for $pp \rightarrow \chi\chi q$ will be enhanced for heavy flavour quarks (bottom and especially top quarks, Fig. 1.9) and dedicated searches will improve the current limits (Figure 1.10). In Chapter 3 a re-interpretation of the
stop search in the $t\bar{t} + E_T^{\text{miss}}$ final state described in Part 3 of this thesis will be presented in terms of limits for the operators that have a quark mass dependence (D1, C1). DM masses of 10, 50, 100, 200, 400, 700, 1000 GeV, are considered. The highest sensitivity for searches in ATLAS is at low DM masses, i.e. $m_\chi < 100$ GeV.