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Searches for direct stop production in events with two leptons in $\sqrt{s} = 8$ TeV pp collisions using $20\ \mathrm{fb}^{-1}$ of ATLAS data

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Abstract. Three searches for direct top squark pair production are presented. They target different decay modes, each with two leptons (electrons or muons) in the final state. The searches use 20.3 fb^{-1}of pp collision data at $\sqrt{s} = 8$ TeV collected by the ATLAS experiment at the Large Hadron Collider. No excesses over Standard Model expectations are observed, and the results are interpreted under the separate assumptions that the light top squark decays to a b-quark and the lightest chargino, or to a t-quark and the lightest neutralino.

1 Introduction

Supersymmetry (SUSY) is an extension to the Standard Model (SM) that provides a solution to the instability of the scalar SM sector with respect to new high-scale physics by introducing supersymmetric partners of the known fermions and bosons. These particles differ from their SM counterparts by half a unit of spin. In the framework of a generic R-parity conserving minimal supersymmetric extension of the SM (MSSM), SUSY particles are produced in pairs and the lightest supersymmetric particle (LSP) is stable, and provides a dark matter candidate. In a large variety of models, the LSP is the lightest neutralino, $\tilde{\chi}_1^0$. The existence of the supersymmetric partner of the top quark is the main ingredient if SUSY has to solve the gauge hierarchy problem [1, 2]. The top squark ($\tilde{t}$) is needed to cancel the diverging loop contributions to the Higgs mass coming from SM top quarks. The $\tilde{t}$ has two mass eigenstates predicted by the theory (the $\tilde{t}_1$ being the lightest): in order to preserve naturalness, the $\tilde{t}_1$ or both $\tilde{t}_1$ and $\tilde{t}_2$ need to be below the TeV range. The $\tilde{t}_2$ can also be heavy, as long as $\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$ is light enough. While these naturalness arguments favour light $\tilde{t}_1$, the results obtained by the LHC Run1 in generic SUSY searches favour a spectrum containing heavy $\tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}$.

These proceedings summarize the results of three different searches for stops in events with two isolated leptons (e, μ) with opposite charge, two b-quarks and significant missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$), described in Ref. [3, 4]. These searches are referred to as the "leptonic m_{T2}", "hadronic m_{T2}" and MVA analyses.

The $\tilde{t}_1$ can decay into a variety of final states, depending, amongst other factors, on the mass hierarchy of the lightest chargino ($\tilde{\chi}_1^{\pm}$) and the lightest neutralino ($\tilde{\chi}_1^0$). Three possible stop decay channels have been considered to optimize and interpret the results of the presented analyses: the first is given by the $\tilde{t}_1 \to b + \tilde{\chi}_1^{\pm}$ decay, with $m(\tilde{t}_1) - m(\tilde{\chi}_1^{\pm}) > m(b)$, and the $\tilde{\chi}_1^{\pm}$ subsequently decaying into

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the LSP and a real or virtual W boson. The second decay channel is $\tilde{t}_1 \to t + \tilde{\chi}_1^0$ with only on-shell top quarks considered, while the third case considers the $\tilde{t}_1 \to b + W + \tilde{\chi}_1^0$ three-body decay.

The analyses use 20.3 fb^{-1} of integrated luminosity provided by the LHC operating at a pp centre-of-mass energy of 8 TeV. The data have been recorded with the ATLAS detector, a general-purpose experiment extensively described in Ref. [5]. Requirements that ensure the quality of beam conditions, detector performance, and data are imposed.

In the following, the event selection used in the three analyses will be presented (Section 2) before describing the SM background estimation techniques (Section 3). The last section (Section 4) includes the interpretation of the observed results.

2 Event selection

The three different searches share a common preselection and some discriminatory event-level variables. The following event-level variables are defined:

- $m_{\ell\ell}$: the invariant mass of the two opposite-sign leptons.
- m_{T2} and $m_{\mathrm{T2}}^{\text{b-jet}}$: The stransverse mass is a kinematic variable that can be used to measure the masses of pair-produced semi-invisibly decaying heavy particles. This quantity is defined as:

$$m_{\mathrm{T2}}(\mathbf{p}_{\mathrm{T}}^1, \mathbf{p}_{\mathrm{T}}^2, \mathbf{q}_{\mathrm{T}}) = \min_{\mathbf{q}_{\mathrm{T}}^1+\mathbf{q}_{\mathrm{T}}^2=\mathbf{q}_{\mathrm{T}}} \left\{\max[\ m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}^1, \mathbf{q}_{\mathrm{T}}^1), m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}^2, \mathbf{q}_{\mathrm{T}}^2)\ ]\right\},$$

  where m_{T} indicates the transverse mass[1], $\mathbf{p}_{\mathrm{T}}^1$ and $\mathbf{p}_{\mathrm{T}}^2$ are the transverse momenta of two particles, and $\mathbf{q}_{\mathrm{T}}^1$ and $\mathbf{q}_{\mathrm{T}}^2$ are vectors which satisfy $\mathbf{q}_{\mathrm{T}}^1 + \mathbf{q}_{\mathrm{T}}^2 = \mathbf{q}_{\mathrm{T}}$. The minimisation is performed over all the possible decompositions of $\mathbf{q}_{\mathrm{T}}$. For top quark and W boson pair production, $m_{\mathrm{T2}}(\ell, \ell, E_{\mathrm{T}}^{\mathrm{miss}})$ (m_{T2}) is bound sharply from above by the mass of the W. In the $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$ decay mode the bound is strongly correlated with $m(\tilde{\chi}_1^{\pm}) - m(\tilde{\chi}_1^0)$.

  If the transverse momenta of the two reconstructed b-quarks in the event are taken as $\mathbf{p}_{\mathrm{T}}^1$ and $\mathbf{p}_{\mathrm{T}}^2$, and the lepton transverse momenta are added vectorially to the $E_{\mathrm{T}}^{\mathrm{miss}}$ in the event, the resulting $m_{\mathrm{T2}}(b, b, \ell + \ell + E_{\mathrm{T}}^{\mathrm{miss}})$ ($m_{\mathrm{T2}}^{\text{b-jet}}$)has a very different kinematic limit: for top pair production it is approximately bound by the mass of the top, whilst for the stop decays the bound is strongly correlated to $m(\tilde{t}_1) - m(\tilde{\chi}_1^{\pm})$.
- $\Delta\phi$: the azimuthal angle difference between the $\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}$ vector and the direction of the closest jet.
- $\Delta\phi_\ell$: the azimuthal angle difference between the $\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}$ vector and the direction of the most energetic lepton.
- $\Delta\phi_b$: the azimuthal angle between the $\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}$ vector and the $\mathbf{p}_{\mathrm{Tb}}^{\ell\ell} = \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}} + \mathbf{p}_{\mathrm{T}}^{\ell_1} + \mathbf{p}_{\mathrm{T}}^{\ell_2}$ vector. The $\mathbf{p}_{\mathrm{Tb}}^{\ell\ell}$ variable, with magnitude $p_{\mathrm{Tb}}^{\ell\ell}$, is the opposite of the vector sum of all the transverse hadronic activity in the event.
- m_{eff}: the scalar sum of the $E_{\mathrm{T}}^{\mathrm{miss}}$, the transverse momenta of the two leptons and of the two most energetic jets in each event.
- $\Delta\phi_{\ell\ell}$ ($\Delta\theta_{\ell\ell}$): the azimuthal (polar) angular distance between the two leptons.
- $\Delta\phi_{j\ell}$: the azimuthal distance between the most energetic jet and the leading lepton.

[1] $m_{\mathrm{T}} = \sqrt{2|\mathbf{p}_{\mathrm{T}}^1||\mathbf{p}_{\mathrm{T}}^2|(1-\cos(\phi))}$ where ϕ is the angle between the particles with transverse momenta $\mathbf{p}_{\mathrm{T}}^1$ and $\mathbf{p}_{\mathrm{T}}^2$ in the transverse plane.

In each of the presented analyses, events are required to have exactly two opposite-sign (OS) leptons (electrons, muons). At least one of the selected leptons must have $p_{\mathrm{T}} > 25$ GeV in order for the event to be triggered with high efficiency, and $m_{\ell\ell} > 20$ GeV. If the event contains a third preselected electron or muon, the event is rejected.

2.1 Leptonic m_{T2} event selection

The leptonic m_{T2} selection is designed to be sensitive to the $\tilde{t}_1 \rightarrow b + \tilde{\chi}_1^{\pm}$ decay in models with large $m(\tilde{\chi}_1^{\pm}) - m(\tilde{\chi}_1^0)$, where large values of m_{T2} are expected. This analysis is also sensitive to the $\tilde{t}_1 \rightarrow b + W + \tilde{\chi}_1^0$ three-body decay.

Events with same-flavour leptons are required to have $m_{\ell\ell} < 71$ GeV or $m_{\ell\ell} > 111$ GeV in order to reduce the number of events from the on-shell decay of the Z boson.

Four signal regions (SRs) are then defined, as reported in Table 1. SR M90 provides sensitivity to scenarios with a small $m(\tilde{t}_1) - m(\tilde{\chi}_1^{\pm})$, so that the production of high p_{T} jets is not expected. SR M100 has a tight jet selection, providing sensitivity to scenarios with both large $m(\tilde{t}_1) - m(\tilde{\chi}_1^{\pm})$ where a larger hadronic activity is expected, and large $m(\tilde{\chi}_1^{\pm}) - m(\tilde{\chi}_1^0)$. SR M110 and M120 have a looser selection on jets, targeting scenarios with small to moderate values of $m(\tilde{t}_1) - m(\tilde{\chi}_1^{\pm})$ resulting in moderate jet activity.

SR	M90	M100	M110	M120
$\Delta\phi$	> 1.0			
$\Delta\phi_b$	< 1.5			
m_{T2} [GeV]	> 90	> 100	> 110	> 120
p_{T} 1st jet [GeV]	-	> 100	> 20	> 20
p_{T} 2nd jet [GeV]	-	> 50	> 20	> 20

Table 1. Signal regions used in the leptonic m_{T2} analysis.

2.2 Hadronic m_{T2} event selection

This selection is entirely complementary to that described in Section 2.1: the hadronic m_{T2} selection is designed to be sensitive to the $\tilde{t}_1 \rightarrow b + \tilde{\chi}_1^{\pm}$ decay in models with small $m(\tilde{\chi}_1^{\pm}) - m(\tilde{\chi}_1^0)$ and large $m(\tilde{t}_1) - m(\tilde{\chi}_1^{\pm})$, where energetic b-jets and relatively soft leptons are expected. One SR is defined, as reported in Table 2. The cut on m_{T2} ensures orthogonality with the leptonic m_{T2} selection described in Section 2.1.

	SR
$n_{b\mathrm{-jets}}$	$= 2$
lead. lepton p_{T} [GeV]	< 60
m_{T2} [GeV]	< 90
$m_{\mathrm{T2}}^{\text{b-jet}}$ [GeV]	> 160

Table 2. Signal region used in the hadronic m_{T2} analysis.

2.3 MVA event selection

This analysis targets $\tilde{t}_1 \to t\tilde{\chi}_1^0$ models using a multivariate analysis (MVA) technique based on boosted decision trees (BDT) and applying a gradient boosting algorithm (BDTG). Events are required to have at least two jets, a leading jet with $p_{\mathrm{T}} > 50$ GeV and $m_{\mathrm{eff}} > 300$ GeV. The selected events are first divided into four (not mutually exclusive) categories, with the requirements in each category designed to target a different region of the $m(\tilde{t}_1) - m(\tilde{\chi}_1^0)$ plane:

- **(C1)** $E_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV: provides good sensitivity for $m(\tilde{t}_1)$ in the range 200-450 GeV;
- **(C2)** $E_{\mathrm{T}}^{\mathrm{miss}} > 80$ GeV: provides good sensitivity along the $m(\tilde{t}_1) = m(t) + m(\tilde{\chi}_1^0)$ line;
- **(C3)** $E_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV and leading lepton $p_{\mathrm{T}} > 50$ GeV: provides good sensitivity for $m(\tilde{t}_1)$ in the range 400-500 GeV and > 500 GeV for high neutralino masses;
- **(C4)** $E_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV and leading lepton $p_{\mathrm{T}} > 80$ GeV: provides good sensitivity for $m(\tilde{t}_1) > 500$ GeV.

Events are then further divided into those containing a same flavour lepton pair (SF) and those containing a different flavour lepton pair (DF).

A BDTG discriminant is employed to further optimise the regions described above. The following variables are given as input to the BDTG: $E_{\mathrm{T}}^{\mathrm{miss}}$, m_{ll}, m_{T2}, $\Delta\phi_{\ell\ell}$, $\Delta\theta_{\ell\ell}$, $\Delta\phi_l$ and $\Delta\phi_{jl}$.

Several BDTGs are trained using simulated background samples and various representative signal samples appropriate for each region C1 to C4. The value of the cut on the BDTG output is chosen to maximise sensitivity to the signal points considered, resulting in eleven final SRs (seven for DF events, four for SF events) used in the analysis.

3 Standard Model background determination

In each analysis prompt lepton backgrounds are taken directly from the MC, or, in the case of the dominant backgrounds, normalised in dedicated control regions (CRs) and then extrapolated to the signal regions using MC simulation. The observed number of events in the CRs are used to generate SM background estimates in each of the SRs via a profile likelihood fit. Each systematic uncertainty source is treated as a nuisance parameter in the fit, constrained with a Gaussian function which takes into account correlations between sample estimates.

The dominant detector-related systematic effects are those due to uncertainties on the jet energy scale (JES) and resolution (JER) , and where used, on the b-tagging efficiency. The leading theoretical uncertainties are those due to the modeling of the top backgrounds. Systematic uncertainties are also taken into account for expected signal yields: the typical cross section uncertainty is 15% for the top squark signal.

The contributions from all other background processes are fixed at the MC expectation in the case of prompt lepton backgrounds, and estimated using a data-driven technique in the case of non-prompt (or fake) lepton backgrounds.

The following sections describe the CRs defined for each analysis.

3.1 Leptonic m_{T2} background determination

The dominant SM background contributions in the SRs are top and W pair production. Other diboson processes are also expected to contribute significantly: WZ in its 3-lepton decay mode, and ZZ decaying to two leptons and two neutrinos. CRs are defined for each of these backgrounds, the definitions of which are given in Table 3. Additional SM processes yielding two isolated leptons and

$E_{\mathrm{T}}^{\mathrm{miss}}$ (Wt, Z+jets, $t\bar{t}W$ and $t\bar{t}Z$), and providing a sub-dominant contribution to the SRs are determined from MC simulation. The fake lepton background is a small contribution (less than 10% of the total background).

	$\mathrm{CRT_L}$	$\mathrm{CRW_L}$	$\mathrm{CRZ_L}$
flavour	DF	DF	SF
$m_{\ell\ell}$ [GeV]	-	-	71-111
m_{T2} [GeV]	40-80	40-80	> 90
$p_{b,ll}$ [GeV]	> 30	< 15	-
$\Delta\phi$	> 1.0	> 1.0	> 1.0
$\Delta\phi_b$	< 1.5	< 1.5	< 1.5

Table 3. Definitions of the CRs in the leptonic m_{T2} analysis: $\mathrm{CRT_L}$ (used to constrain $t\bar{t}$), $\mathrm{CRW_L}$ (used to constrain WW) and $\mathrm{CRZ_L}$ (used to constrain WZ and ZZ).

3.2 Hadronic m_{T2} background determination

Top quark pair and single top quark (Wt channel) production contribute significantly to the background event yields in the SR for this analysis. The next most significant SM background contributions are those arising from misidentified (fake) leptons. The remainder of the background is composed of Z/γ^*+jets and WW. The contribution from other diboson processes, WZ and ZZ, is negligible.

CRs are defined for the $t\bar{t}$ and $Z/\gamma^*(\to ee,\mu\mu)$+jets backgrounds. The definitions of these regions are given in Table 4.

	$\mathrm{CRT_H}$	$\mathrm{CRZ_H}$
b-jets	$= 1$	$= 2$
lead. lep. p_{T} [GeV]	< 60	> 60
$m_{\ell\ell}$ [GeV]	< 81 or > 101	$81 < m_{\ell\ell} < 101$
m_{T2} [GeV]	< 90	< 90
$m_{\mathrm{T2}}^{\text{b-jet}}$ [GeV]	> 160	> 160

Table 4. Definitions of the CRs in the hadronic m_{T2} analysis: $\mathrm{CRT_H}$ (used to constrain $t\bar{t}$), $\mathrm{CRZ_H}$ (used to constrain Z/γ^*+jets decays to ee and $\mu\mu$).

3.3 MVA background determination

The dominant SM background processes are top quark pair production and diboson production. The Z/γ^*+jets contribution, relevant only for the SF channel, is suppressed by the BDTG requirement. CRs are defined for $t\bar{t}$. In addition to the application of all non-BDTG SR cuts, the following selections are applied in the CRs: $m_{\mathrm{T2}} > 90$ GeV and, in SF events, $m_{\ell\ell}$ must be less than 61 GeV or greater than 121 GeV.

4 Results

No excess was observed in data with respect to the background estimate, and thus the results were interpreted in terms of simplified models for the two stop decay channels, assuming 100% BR to the targeted channel. The interpretation of the results of the three analyses presented are shown in Figs. 1-3. Figs. 1 and 2 show also the limit on $\sigma \times$ BR for each signal model taken into account in these interpretations.

Targeting the top squark decay to $b + \tilde{\chi}_1^{\pm}$, a supersymmetric $\tilde{t}_1$ with a mass between 150 and 442 GeV decaying to a b quark and a chargino is excluded at 95% CL for a chargino approximately degenerate with the top squark and a massless lightest neutralino (Fig. 1). For a 300 GeV $\tilde{t}_1$, chargino masses between 100 and 150 GeV and between 160 and 290 GeV are excluded (Fig. 2) for a neutralino mass equal to 50 GeV.

Figure 3 shows the results for models where the top squark decays to $t + \tilde{\chi}_1^0$. Top squark masses between ~220 GeV and ~520 GeV are excluded at 95% CL for a massless neutralino. In the case of a top squark decaying to $bW\tilde{\chi}_1^0$, for a value of $m(\tilde{t}_1) - m(\tilde{\chi}_1^0)$ equal to 90 GeV, 130 GeV, and 160 GeV top squark masses lower than 155 GeV, 220 GeV, and 200 GeV respectively are excluded.

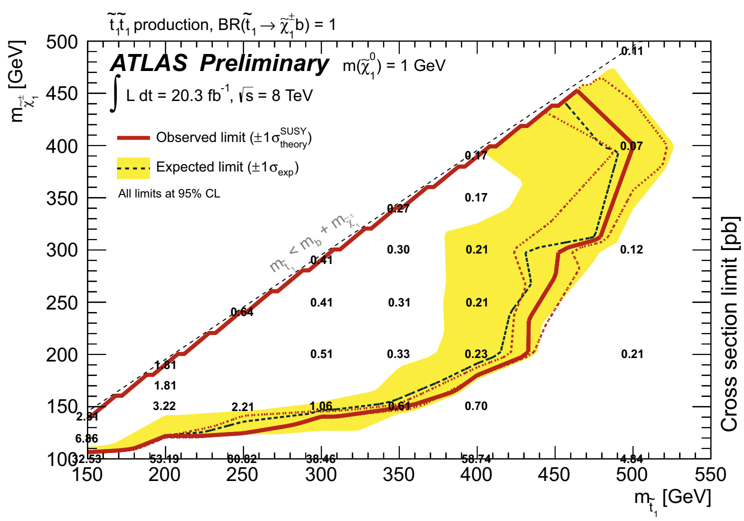

Figure 1. Expected and observed 95% CL excluded regions assuming $m(\tilde{\chi}_1^0) = 1$ GeV and $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$ with 100% BR. The figure shows the interpretation of the results of the leptonic m_{T2} analysis in the $(\tilde{t}_1, \tilde{\chi}_1^{\pm})$ plane. The excluded cross section times BR for each signal point is reported. [3]

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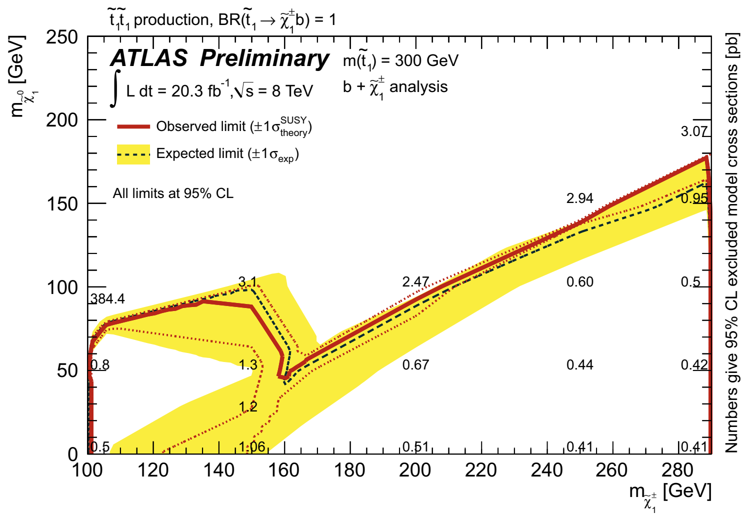

Figure 2. Expected and observed 95% CL excluded regions assuming $m(\tilde{t}_1) = 300$ GeV and $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$ with 100% BR. The figure shows the combined interpretation of the results of both the leptonic and hadronic m_{T2} analyses in the $(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0)$ plane. The excluded cross section times BR for each signal point is reported. [4]

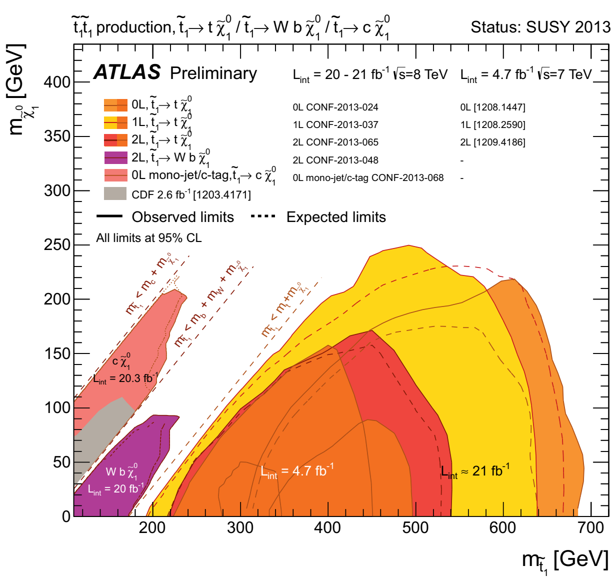

Figure 3. Expected and observed 95% CL excluded regions in different $\tilde{t}_1$ decay scenarios. The figure shows the results of the MVA analysis (in red) together with the results from the other ATLAS stop searches in the $(\tilde{t}_1, \tilde{\chi}_1^0)$ plane and $\tilde{t}_1 \to t\tilde{\chi}_1^0$ with 100% BR. The purple region shows the results from the leptonic m_{T2} analysis in the case of the stop three body decay $\tilde{t}_1 \to bW\tilde{\chi}_1^0$. [6]