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Search for direct top squark pair production in final states with one isolated lepton using $21\ \mathrm{fb}^{-1}$ of data collected with the ATLAS detector

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Abstract. Naturalness arguments for weak-scale supersymmetry favour supersymmetric partners of the third generation quarks with masses not too far from those of their Standard Model counterparts. Top or bottom scalar quarks (or squarks) with masses less than a few hundred GeV can give rise to direct pair production rates at the LHC that can be observed in the data sample recorded by the ATLAS detector. This proceeding summarises the latest results of a search for top squark pair production in final states with one isolated lepton, jets, and missing transverse momentum in $\sqrt{s} = 8$ TeV pp collisions at the LHC, using 20.7 fb^{-1} of ATLAS data. Two top squark ($\tilde{t}$) decay scenarios are considered: the decay to a top quark and a stable undetected neutral particle ($\tilde{\chi}^0$), and the decay to a bottom quark and a chargino, where the chargino decays via an on- or off-shell W boson to the $\tilde{\chi}^0$. The data are found to be consistent with Standard Model expectations and have been reinterpreted in terms of various SUSY scenarios.

1 Introduction

Supersymmetry (SUSY,[1–9]) is a theory that provides an extension of the Standard Model (SM) by adding a full set of new particles. These particles, known as supersymmetric partners of the known fermions and bosons, differ by their Standard Model counterparts by half unit of spin. The existence of the supersymmetric partner of the top quark (top squark or stop) is the main ingredient if SUSY solves the gauge hierarchy problem ([10–15]). The stop is needed to cancel the diverging loop contributions to the Higgs mass coming from SM top quarks, provided that the $\tilde{t}$ mass is below the TeV range. These naturalness motivations and the wide range of exclusion limits obtained in the last years by the LHC experiments on SUSY searches favor a spectrum of SUSY particles that involve relatively light $\tilde{t}$ (and $\tilde{b}$) and heavy $\tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}$.

For this reason and especially after the discovery of a Higgs-like particle ([16, 17]), searches for stops have received increasing attention in the HEP community. These proceedings summarise the most recent results of a particularly sensitive search for stops, extensively described in Ref. [18], that considers events with one isolated lepton, jets, and missing transverse momentum. The analysis is based on 20.7 fb^{-1} of integrated luminosity provided by the LHC operating at a pp centre-of-mass

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energy of 8 TeV. The data have been recorded with the ATLAS detector, a general-purpose experiment extensively described in Ref. [19]. Requirements that ensure the quality of beam conditions, detector performance, and data are imposed.

The optimisation of this search and the interpretation of the results have been performed with the following common assumptions. A R-parity conserving minimal supersymmetric extension of the SM is assumed, where all particles are produced in pairs and decay in a chain of SUSY and SM particles. The lightest SUSY particle (LSP, a $\tilde{\chi}^0$ in this case) is stable and escapes the detector without interacting. Two stop decay channels have been considered:

1. $\tilde{t} \to t\, \tilde{\chi}^0$
2. $\tilde{t} \to b\, \tilde{\chi}^\pm \to b\, W^\pm \tilde{\chi}^0$

where $\tilde{\chi}^\pm$ stands for the chargino. The analysis has been separately optimised for both decay channels. In addition, the interpretation of the results is performed in terms of *simplified models*, where particles' unknown masses are free parameters and each decay is assumed to have 100% Branching Ratio (BR).

2 General analysis strategy

The general strategy of this analysis can be summarised in a few steps that are common to the majority of the ATLAS SUSY searches:

1. First of all a set of signal enhanced regions (SR) is defined. This selection is based on Monte Carlo (MC) simulation only and aims to extend the reach of the analysis to the largest number of signal models with the minimum number of SRs. Experimental data are kept blinded until the analysis is fully defined and frozen. SRs are optimised maximising the discovery potential.

2. The modelling of the major backgrounds of the analysis is achieved through a semi data-driven approach based on background enriched control regions (CR). These regions are designed to be as kinematically close as possible to the SRs, but orthogonal to them. They have a high purity with respect to the targeted background process and have low signal contamination. They are used to derive the MC normalisation directly from data and extrapolate it into the SRs. This approach allows to absorb a number of systematic uncertainties in the extrapolation CR→SR.

3. The goodness of the CR→SR extrapolation is probed with the use of validation regions (VR). They are usually designed to be in between the CR and the SR selections.

4. At the very end the experimental data are unblinded and a standard statistics procedure is used to determine whether an excess in the SRs is observed. Otherwise, the results are interpreted in terms of limits on selected models using the CLs procedure.

3 Signal selection and background modelling

As mentioned in the introduction, this analysis is investigating final states that involve one isolated lepton, at least four energetic jets and missing transverse momentum. The preliminary selections applied throughout the whole analysis are

1. A combination of electron, muon and $E_{\mathrm{T}}^{\mathrm{miss}}$ triggers;

2. exactly 1 isolated electron or muon. $p_{\mathrm{T}} \geqslant 25$ GeV;

3. $N_{\mathrm{jets}} \geq 4$, with jet $p_{\mathrm{T}} > 80, 60, 40, 25$ GeV;

4. at least one or two b-tagged jet among the four selected jets.

The main background of this analysis is top quark pair production ($t\bar{t}$). The second dominant background comes from processes in which a W boson is produced in association with jets. A number of processes characterised by a cross section orders of magnitude smaller than the two dominant backgrounds but still comparable with the signal models targeted in this analysis become relevant in the final SR, namely single top production, $t\bar{t}$ production in association with vector bosons (W/Z), diboson production. The two main background are controlled by means of two dedicated CRs, while the subdominant processes modelling is based on MC simulation.

3.1 Signal and background discrimination

Many parameters determine the final state kinematics of the signal models targeted in this analysis, in particular $m_{\tilde{t}}$, $m_{\tilde{\chi}^0}$, $\Delta m(\tilde{\chi}^{\pm}, \tilde{\chi}^0)$ and $\Delta m(\tilde{t}, \tilde{\chi}^{\pm}/\tilde{\chi}^0)$.

The main challenge in background discrimination comes from the fact that the signal kinematics are very similar to top pair production, especially for low $\tilde{t}$ masses. Furthermore, for $m(\tilde{t}) \sim m(t)$ the stop cross section is about 15% that of the SM $t\bar{t}$ and it decreases for higher stop masses.

A number of variables that aim to describe or reconstruct the kinematics of the event are exploited in order to obtain discrimination power between signal and background and are described in the following.

- $\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}$ Missing transverse momentum due to one or more particles (e.g. $\tilde{\chi}^0$) escaping undetected from the detector.
- $\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{\mathrm{H}_{\mathrm{T}}}$ The $E_{\mathrm{T}}^{\mathrm{miss}}$ significance quantifies how likely the measured missing momentum is entirely an effect of mismeasurement of highly energetic jets in the event. The hadronic energy of the event, H_{T}, is the scalar sum of the four selected jets in the event.
- $\Delta\phi(j_1/j_2, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$ minimal azimuthal (transverse) separation between any of the two leading jets and the direction of the missing transverse momentum vector.
- $\mathbf{m}_{\mathbf{T}}$ Transverse mass between the lepton and the $E_{\mathrm{T}}^{\mathrm{miss}}$.
- $\mathbf{m}_{\mathbf{eff}}$ Effective mass of the event. It is the scalar sum of H_{T}, lepton p_{T} and $E_{\mathrm{T}}^{\mathrm{miss}}$.
- $\mathrm{aM}_{\mathrm{T2}}$ and $\mathrm{M}_{\mathrm{T2}}{}^{\tau}$ ([20–22]) are two different definitions of stransverse mass, targeting dileptonic and hadronic tau top decays respectively. The general definition of the stransverse mass [23] is:

$$m_{\mathrm{T2}} \equiv \min_{\vec{q}_T + \vec{r}_T = \vec{p}_{\mathrm{T}}^{\mathrm{miss}}} \{\max\left[m_{\mathrm{T}}(\vec{p}_{\mathrm{a}}, \vec{q}_{\mathrm{T}}), m_T(\vec{p}_{\mathrm{b}}, \vec{r}_{\mathrm{T}})\right]\}, \quad (1)$$

  The variable is calculated by minimisation over all the possible decompositions of p_T^{miss} into the vectors $\vec{q}_{\mathrm{T}}$ and $\vec{r}_{\mathrm{T}}$. For $\mathrm{aM}_{\mathrm{T2}}$, a, b are chosen as the system between the lepton and one b-jet and the other b-jet in the event, respectively. In this case one of the missing particles is assumed to have the W mass, so that the distribution presents an endpoint at the top mass. In the case of $\mathrm{M}_{\mathrm{T2}}{}^{\tau}$, a, b are the leading light flavour jet and the lepton and in this case the distribution presents an endpoint at the W mass.

- $\mathcal{N}_{\mathrm{iso}}^{\mathrm{trk}}$ Number of isolated tracks in addition to the lepton selected in the event. Additional tracks are vetoed in order to suppress events 1-prong taus or extra leptons.

- m_{jjj} The hadronic top mass. The jet-jet pair with an invariant mass above 60 GeV which has the smallest ΔR is selected to form the hadronic W boson. The mass m_{jjj} is reconstructed from the third jet closest in ΔR to the hadronic W boson momentum vector. This reconstructed mass of the hadronic top is required to be between 130 and 205 GeV.

3.2 Signal and control regions selections

All these variables have been exploited to build six SRs: three regions targeting $\tilde{t} \rightarrow t\tilde{\chi}^0$ decays (SRtNX) and the other three targeting $\tilde{t} \rightarrow b\tilde{\chi}^{\pm}$ ones (SRbCX). Five of these regions are treated as a counting experiment in a single bin. In order to achieve sensitivity for a particularly challenging scenario where the mass difference between the top and the stop is small (*compressed scenario*), a shape fit strategy (based on m_{T} and $E_{\mathrm{T}}^{\mathrm{miss}}$) has been employed. The selections applied before the fit are listed as SRtN1. A summary of the SR selections is shown in Table 1 and few representative

Requirement	**SRtN1**	**SRtN2**	**SRtN3**
Number of b-jets $\geq$	1	1	1
$\Delta\phi(j_1/j_2, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$ [rad] >	0.8/0.8	0/0.8	0.8/0.8
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV] >	100$^{(*)}$	200	275
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ [GeV$^{1/2}$] >	5	13	11
m_{T} [GeV] >	60$^{(*)}$	140	200
aM_{T2} [GeV] >	-	170	175
$\mathrm{M}_{\mathrm{T2}}{}^{\tau}$ [GeV] >	-	-	80
m_{had} top cut	Yes	Yes	Yes

Requirement	**SRbC1**	**SRbC2**	**SRbC3**
Number of b-jets $\geq$	1	2	2
$\Delta\phi(j_1/j_2, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$ [rad] >	0.8/0.8	0.8/0.8	0.8/0.8
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ [GeV$^{1/2}$] >	7	8	8
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV] >	160	160	
m_{T} [GeV] >	120	120	120
m_{eff} [GeV] >	-	550	700
p_{T} (two lead b-jets) [GeV] >	25/0	100/50	120/90
aM_{T2} [GeV] >	-	175	200
$\mathcal{N}_{\mathrm{iso}}^{\mathrm{trk}}$ veto	Yes	Yes	Yes

Table 1. Signal region definition. SRtNX have been optimised to target the $\tilde{t} \rightarrow t\,\tilde{\chi}^0$ decay channel and SRbCX target the $\tilde{t} \rightarrow b\,\tilde{\chi}^{\pm}$ decay. SRtN1 is the foundation for a shape fit in the variables labelled with $^{(*)}$ and applies looser cuts. [18]

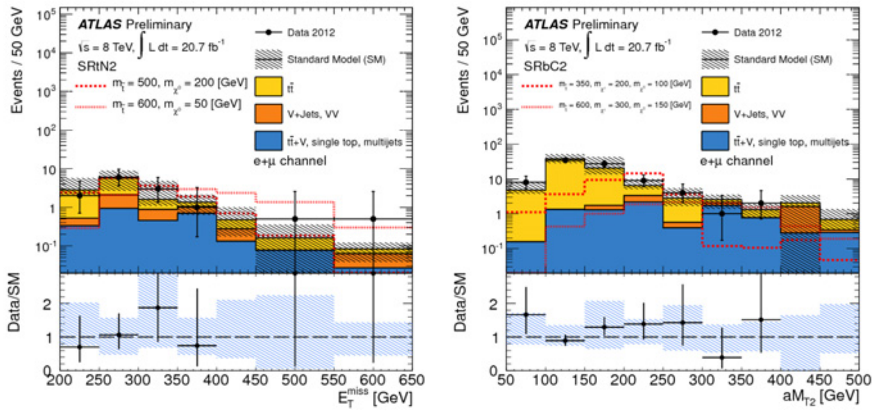


Figure 1. For two signal regions one characteristic distribution is shown, with the full event selection of the signal region applied, except for the requirement on the shown quantity [18].

distributions for each region is shown in Figure 1. A schematic illustration of the shape fit binning is shown in Figure 2.

The main background contribution of the five single-bin regions is determined by means of two CRs for each SR, one dominated by $t\bar{t}$ events and one, exploiting a b-jets veto, dominated by W+jets. Orthogonality is obtained lowering the m_T cut to the W mass window (60 GeV < m_T < 90 GeV). The $t\bar{t}$ yields fitted in the control regions are validated in dedicated top validation regions (TVR) that differ

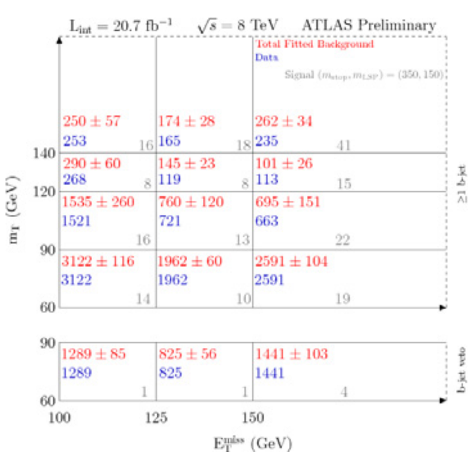
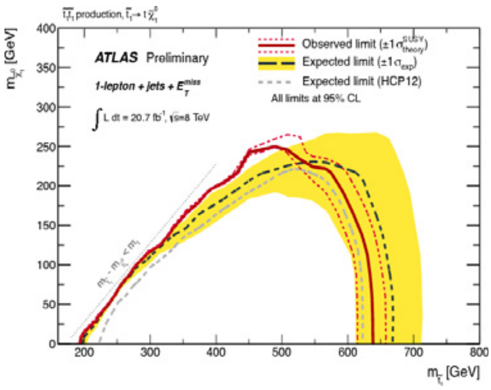
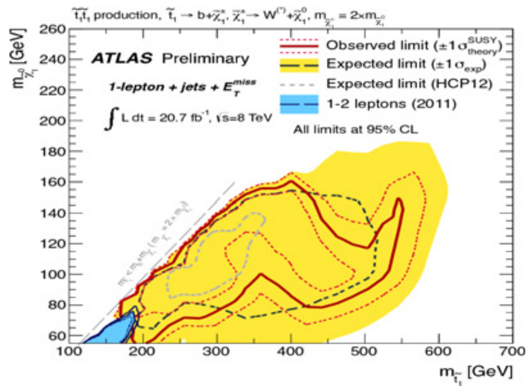


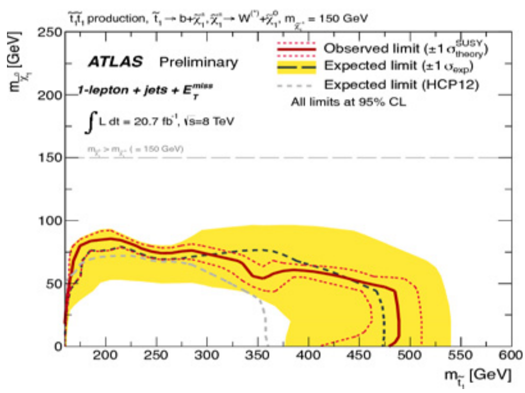
Figure 2. Schematic illustration of the shape-fit binning. These 12 bins in E_T^{miss} and m_T variables are sensitive to stop models while also being enriched with $t\bar{t}$ background. An additional three bins are defined (bottom part) with a b-veto, leading to W+jets events as the dominant contribution [18].



(a) BR($\tilde{t} \to t\tilde{\chi}^0$) = 100%



(b) BR($\tilde{t} \to b\tilde{\chi}^{\pm}$) = 100% and $m_{\tilde{\chi}^{\pm}} = 2\ m_{\tilde{\chi}^0}$



(c) BR($\tilde{t} \to b\tilde{\chi}^{\pm}$) = 100% and $m_{\tilde{\chi}^{\pm}}$ = 150 GeV

Figure 3. Expected (black dashed) and observed (red solid) 95% CL excluded region (inside the curve) in the plane of ($\tilde{t}$- $\tilde{\chi}^0$) for different decays and assumptions. All uncertainties except the theoretical signal cross-section uncertainties are included. The contours of the yellow band around the expected limit are the $\pm 1\sigma$ results. The dotted red lines illustrate the change in the observed limit for $\pm 1\sigma$ variation of the signal cross-section theoretical uncertainty [18].

from the control region in their m_T requirement, which is 90 GeV $< m_T <$ 120 GeV for the latter. There is thus no event overlap with the associated CR nor SR.

4 Results and conclusions

A simultaneous likelihood fit for each signal region and the two associated control regions is performed to normalise the $t\bar{t}$ and W+jets background estimates and to determine or limit a potential signal contribution. For the SRtN1 shape selection, the $t\bar{t}$ and W+jets backgrounds, together with a potential signal contribution, are simultaneously fitted in 15 mutually exclusive bins (c.f. Figure 2). In order to minimise the MC dependence on the E_T^{miss} modelling, the $t\bar{t}$ and W+jets backgrounds are separately normalised in each E_T^{miss} slice.

All systematics considered in this analysis are treated as nuisance parameters with Gaussian shapes in a fit based on the profile likelihood method. The most relevant systematic for this analysis are $t\bar{t}$ theoretical uncertainties. These are evaluated by comparing different event generators (PowHeg and ALPGEN), parton shower modelling (PYTHIA and HERWIG), by varying ISR/FSR and QCD scale parameters and result in a contribution in the uncertainties of $7 - 42\%$. The second most important systematic is the W+jets modelling (25% with an additional 28% for the W+heavy-flavour component). Experimental uncertainties affect the signal and background yields estimated from MC events and are dominated by the uncertainties in jet energy scale, jet energy resolution, b-tagging, and modelling of multiple pp interactions. Since no excess was observed in data with respect to the background estimates, the results were interpreted in terms of simplified models for the two stop decay channels. The results in the ($\tilde{t}$- $\tilde{\chi}^0$) mass plane for both decay channels are shown in Figure 3. For the $\tilde{t} \to b\tilde{\chi}^{\pm}$ decay the results are interpreted assuming either $m_{\tilde{\chi}^{\pm}} = 2 \times m_{\tilde{\chi}^0}$ or $m_{\tilde{\chi}^{\pm}} = 150$ GeV.

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