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# Search for top squarks in final states with one isolated lepton in $\sqrt{s}$ = 13 TeV $pp$ collisions with the ATLAS detector

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The result of a search for the direct pair production of top squarks, the supersymmetric partner of the top-quark, in final states with one isolated electron or muon, jets, and missing transverse momentum is reported. The search uses data from $pp$ collisions recorded at the LHC with the ATLAS detector at a centre-of-mass energy of $\sqrt{s}$ = 13 TeV corresponding to an integrated luminosity of 36 fb$^{-1}$. Dedicated analysis for the Higgsino LSP model is performed considering small mass splitting between electroweakinos and the realistic branching ratio of a top squark. No significant excess over the Standard Model predictions is observed. Exclusion limits at 95% confidence level in the Higgsino LSP model are set. The top squark mass is excluded up to 810 GeV for 2 GeV mass splitting between the chargino and the lightest neutralino. The results are also reinterpreted to set exclusion limits in a Bino-Higgsino mixed LSP model.

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## 1. Introduction

Supersymmetry (SUSY) [1–6] is one of the most attractive theories that provide a solution to the hierarchy problem. The superpartner of the top quark, top squark plays an important role in cancelling the divergence of the Higgs boson mass, and top squark lighter than $O(1)$ TeV is favoured in many theories [7, 8]. To avoid fine-tuning of the MSSM parameters, the natural SUSY [9, 10] is favoured. The naturalness suggests that the superpartner of the Higgs boson, Higgsino is expected to be the lightest supersymmetric particle, the LSP. In the Higgsino LSP scenario, the mass splitting between electroweakinos is relatively small, and three decay modes of a top squark ($t\tilde{\chi}_1^0$, $t\tilde{\chi}_2^0$, and $b\tilde{\chi}_1^{\pm}$) are allowed. A search that can cover these three decay modes is performed [11]. In this article, the dedicated search for top squark pair production under the Higgsino LSP scenario using the data recorded with the ATLAS detector [12] at the LHC [13] in 2015-16 is presented.

## 2. Higgsino LSP model

A Higgsino LSP model is considered for this search. The main feature of this model is the small mass splitting ($\Delta m$) between the $\tilde{\chi}_1^{\pm}$ and the LSP. The mass splitting varies between a few hundred MeV to a few tens of GeV. The top squark can decay into $t\tilde{\chi}_1^0$, $t\tilde{\chi}_2^0$, or $b\tilde{\chi}_1^{\pm}$ as shown in Figure 1. The branching ratios of these decay modes strongly depend on the composition of the $\tilde{t}_1$ and $\tan\beta$. Three scenarios: $\tilde{t}_1 \sim \tilde{t}_R$, $\tilde{t}_1 \sim \tilde{t}_L$, and large $\tan\beta$[1], are considered. The branching ratios of these scenarios are set to Br($t\tilde{\chi}_1^0$:$t\tilde{\chi}_2^0$:$b\tilde{\chi}_1^{\pm}$) = 25:25:50, 45:45:10, and 33:33:33 for the three scenarios above, respectively. In this signal model, the assumption of $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 2 \times \Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0)$ is always considered.

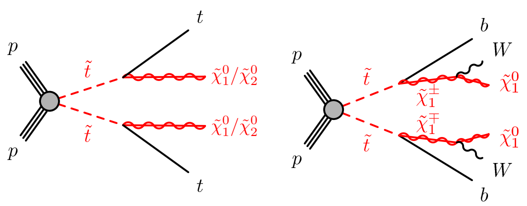


**Figure 1:** Feynman diagrams of $\tilde{t}_1 \to t + \tilde{\chi}_1^0/\tilde{\chi}_2^0$ (left) and $\tilde{t}_1 \to b + \tilde{\chi}_1^{\pm}$ (right).

## 3. Analysis strategy

Two types of selections are used to cover all the $\tilde{t}_1$ decay modes. The first one is the hard lepton selection for $\tilde{t}_1 \to t + \tilde{\chi}_1^0/\tilde{\chi}_2^0$ decay using a lepton with $p_{\mathrm{T}}^{\ell} > 25$ GeV, and the second one is the soft lepton selection for $\tilde{t}_1 \to b + \tilde{\chi}_1^{\pm}$ decay, where the minimum $p_{\mathrm{T}}^{\ell}$ is lowered to 5(4) GeV for the electron(muon) as shown in Figure 2 in order to maximise the acceptance of the low momentum leptons from the $\tilde{\chi}_1^{\pm}$ decay. Since the signal has undetectable LSPs in the final state, the signature is characterised by large $E_{\mathrm{T}}^{\mathrm{miss}}$. Hence, events are collected with the $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger with the offline selection of $E_{\mathrm{T}}^{\mathrm{miss}} > 230$ GeV. In both selections, large $E_{\mathrm{T}}^{\mathrm{miss}}$ ($p_{\mathrm{T}}^{W}$ for the soft lepton selection [2]),

[1] In the large $\tan\beta$ scenario, $\tilde{t}_1 \sim \tilde{t}_L$ and $\tan\beta$ =60 is assumed while $\tan\beta$ = 20 is used in the $\tilde{t}_1 \sim \tilde{t}_R$ or $\tilde{t}_L$ scenario.

[2] $p_{\mathrm{T}}^{W}$ is defined as the magnitude of the vectorial sum of the lepton $p_{\mathrm{T}}$ and $E_{\mathrm{T}}^{\mathrm{miss}}$.

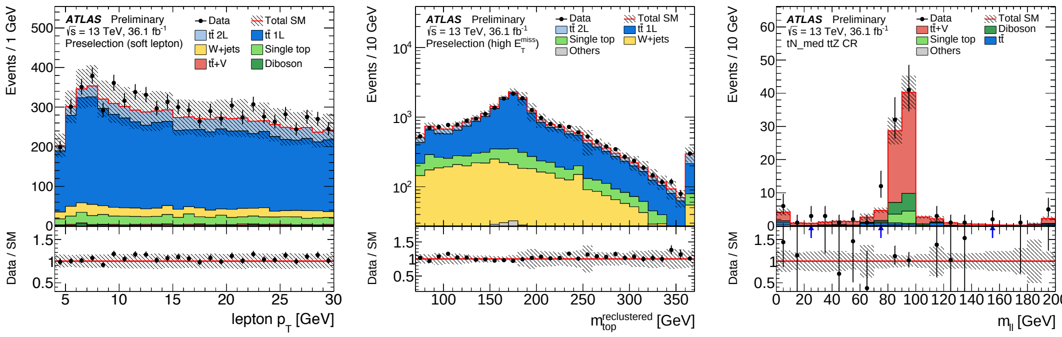


**Figure 2:** Comparisons of data and MC in the key variables [11]. The lepton $p_{\mathrm{T}}$ distribution of soft lepton selection (left) at preselection. The reclustered hadronic top mass of large-radius jet (middle). The invariant mass of two leptons for the $t\bar{t}+\mathrm{Z}(\rightarrow \nu\nu)$ background estimation (right).

at least one $b$-tagged jet, and large asymmetric $m_{\mathrm{T}2}$ ($am_{\mathrm{T}2}$) [14] is required. In the hard lepton selection, at least four jets and $m_{\mathrm{T}} > 160$ GeV [3] is applied to suppress the semileptonic $t\bar{t}$ and $W$+jets backgrounds. Since the decay products of top quarks from heavy $\tilde{t}_1$ tend to be collimated, the hadronic top reconstruction technique using large-radius jets provides additional discrimination, reducing dileptonic $t\bar{t}$ events. The reconstructed mass of the large-radius jets is shown in Figure 2. In the soft lepton selection targeting $\tilde{t}_1 \rightarrow b+\tilde{\chi}_1^{\pm}$, two high-$p_{\mathrm{T}}$ $b$-jets are required and events with low $m_{\mathrm{T}}$ are selected. Since the features of $\tilde{t}_1 \rightarrow b+\tilde{\chi}_1^{\pm}$ decay are low $p_{\mathrm{T}}$ leptons and large $E_{\mathrm{T}}^{\mathrm{miss}}$ while the background processes have high $p_{\mathrm{T}}$ leptons when requiring large $E_{\mathrm{T}}^{\mathrm{miss}}$, $p_{\mathrm{T}}^{\ell}/E_{\mathrm{T}}^{\mathrm{miss}}$ is a powerful discrimination variable.

The dominant background processes are $t\bar{t}$, $W$+jets, and single-top in both hard and soft lepton signal regions (SRs). In addition, $t\bar{t}+\mathrm{Z}(\rightarrow \nu\nu)$ is also an important background in the hard lepton SR and is estimated from $t\bar{t}+\mathrm{Z}(\rightarrow \ell\ell)$ events with three leptons and the invariant mass calculated with two of them are required to satisfy the mass of Z boson. The reconstructed mass of the Z boson candidates is shown in Figure 2. These backgrounds are normalised in the dedicated control regions (CRs) that are defined to enhance the purity of each background, and then extrapolated to the signal regions. The extrapolation is tested in the validation regions which are defined close to the SRs. The QCD (multi jets) background is estimated by the fake factor method [15] from the data and it turns out to be negligible in all regions.

## 4. Results

Figure 4 shows the results of the hard and soft lepton SRs. No significant excess is observed over the Standard Model predictions. Shape fits over $E_{\mathrm{T}}^{\mathrm{miss}}$ for the hard lepton SR and $p_{\mathrm{T}}^{\ell}/E_{\mathrm{T}}^{\mathrm{miss}}$ for the soft lepton SR are performed to exclude the signal models. Limits at 95% confidence level are derived from the combination of the shape fits in each SR and are shown in Figure 4.

The results are reinterpreted in the well-tempered neutralino [16] scenario where the LSP is an admixture state of Bino-Higgsino, motivated by the cosmologically observed dark matter relic

[3] The transverse mass $m_{\mathrm{T}}$ is defined as $m_{\mathrm{T}}^2 = 2p_{\mathrm{T}}^{\ell}E_{\mathrm{T}}^{\mathrm{miss}}[1-\cos(\Delta\phi)]$, where $\Delta\phi$ is the azimuthal angle between the lepton and the missing transverse-momentum direction.

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density [17]. Limits are set in both $\tilde{t}_1 \sim \tilde{t}_L$ and $\tilde{t}_1 \sim \tilde{t}_R$ scenarios. In the $\tilde{t}_1 \sim \tilde{t}_L$ scenario, $\tilde{b}_1$ pair production also contributes. No observed limit is set in $\tilde{t}_1 \sim \tilde{t}_R$ scenario due to a mild excess of the observed data in the soft lepton SR.

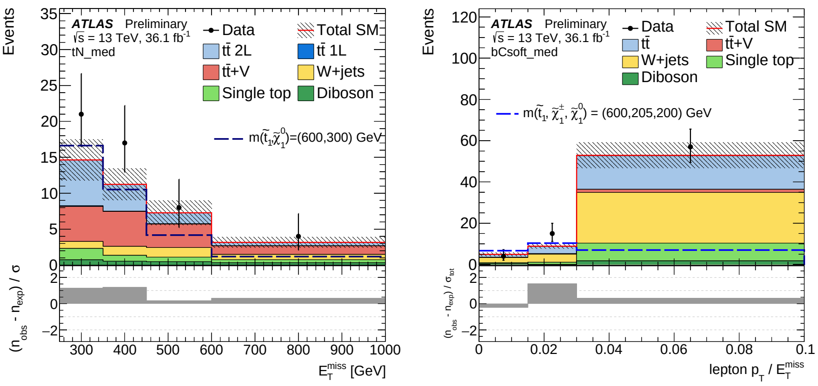


**Figure 3:** The shape-fit distribution of $E_{\mathrm{T}}^{\mathrm{miss}}$ in the hard lepton SR (left) and $p_{\mathrm{T}}^{\ell}/E_{\mathrm{T}}^{\mathrm{miss}}$ in the soft lepton SR (right) [11]. The binning in the shape-fit is same as shown in these plots.

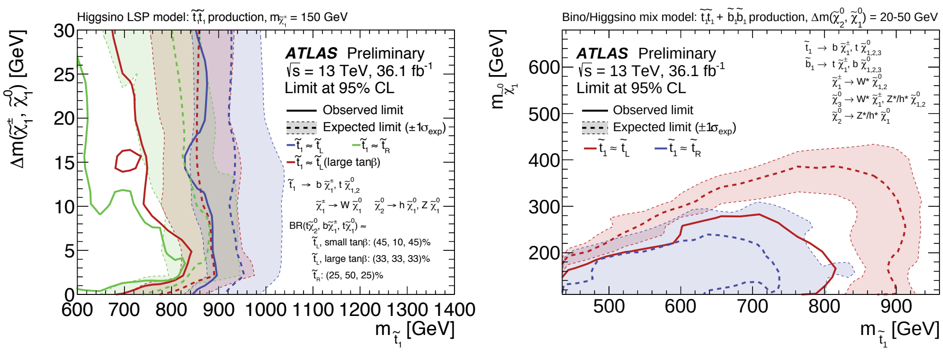


**Figure 4:** Expected and observed 95% excluded regions in the Higgsino LSP model (left) and the well-tempered model (right) [11]. For the Higgsino LSP model, the plane of $m_{\tilde{t}_1}$ versus $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0)$ is shown. In the well-tempered neutralino model, the plane of $m_{\tilde{t}_1}$ versus $m_{\tilde{\chi}_1^0}$ is shown and limits are set for $\tilde{t}_1 \sim \tilde{t}_R$ and $\tilde{t}_1 \sim \tilde{t}_L$ respectively. Bottom squarks pair productions are also considered in the $\tilde{t}_1 \sim \tilde{t}_L$ scenario.

## 5. Conclusion

The first dedicated search for the top squark pair production decaying into Higgsino LSP is performed. The search uses 36.1 fb$^{-1}$ $pp$ collision data at $\sqrt{s} = 13$ TeV recorded by the ATLAS detector. To cover various Higgsino LSP scenarios, the hard and soft lepton SRs are built and the minimum $p_{\mathrm{T}}^{\ell}$ is lowered to 5(4) GeV for electron(muon). The observed data is consistent with the background predictions. Top squark masses below 810 GeV are excluded at $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) = 2$ GeV. The results are also reinterpreted in the well-tempered neutralino scenario.

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