EPJ Web of Conferences 95, 04048 (2015)
DOI: 10.1051/epjconf/ 20159504048

Searches for direct pair production of third generation squarks with the ATLAS detector

Martina Pagacova[1,a], on behalf of the ATLAS collaboration

[1]Institut für Physik, Albert-Ludwigs Universität, Hermann-Herder-Str. 3, 79104 Freiburg, Germany

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. If the masses of top and bottom squarks are below 1 TeV, the direct pair production cross-section is sufficient to produce observable signatures at the ATLAS detector and to probe various theoretical scenarios with the Large Hadron Collider (LHC) data at $\sqrt{s} = 8$ TeV. The most recent ATLAS results from searches for direct stop and sbottom pair production are presented in these proceedings. No evidence of deviations from the Standard Model expectation has been observed, and the limits have been set on the masses of the top and bottom squarks.

1 Introduction

Supersymmetry (SUSY) is an extension of the Standard Model (SM) which predicts the existence of a bosonic/fermionic partner for each known fermion/boson. In the framework of R-parity conserving models, SUSY particles are produced in pairs and the lightest of them (LSP) is stable, providing a dark matter particle candidate. In a large variety of models, this particle is the lightest neutralino $\tilde{\chi}_1^0$.

By introducing the scalar top quark ($\tilde{t}$) with mass below the TeV scale, SUSY can naturally resolve the gauge hierarchy problem. It would cancel the loop diagrams involving top quarks that are the dominant contribution to the divergence of the Higgs boson mass. The scalar partners of right-handed and left-handed quarks ($\tilde{q}_R$ and $\tilde{q}_L$) mix to form two mass eigentstates ($\tilde{q}_1$ and $\tilde{q}_2$). Since this mixing is proportional to the masses of SM quarks, the lightest stop ($\tilde{t}_1$) and sbottom ($\tilde{b}_1$) mass eigenstates can be much lighter than those of other quarks leading to large cross-sections at the LHC.

For this reason, ATLAS has an extensive search agenda for third generation SUSY particles which can be produced either directly in pairs (Figure 1) or through gluino-gluino production. In these proceedings, the most recent results of searches for the direct production with data collected by the ATLAS detector at $\sqrt{s} = 8$ TeV are summarized. No significant excess over the SM background prediction has been observed, and exclusion limits have been set on a variety of R-parity conserving supersymmetric models in which the lightest squark is of the third generation.

[a]e-mail: Martina.Pagacova@cern.ch

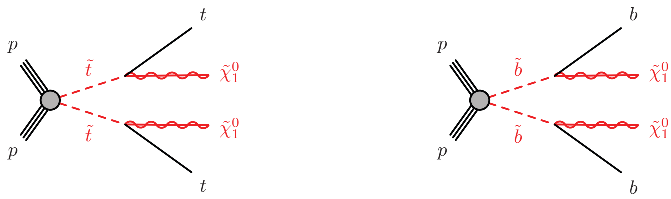


Figure 1: Leading order Feynman diagrams of stop and sbottom pair production.

2 Direct top squark pair production

The ATLAS searches for direct stop pair production have been performed in various channels, targeting a large variety of possible decay modes. Depending on the SUSY particle mass spectrum, in particular on the masses of the stop ($\tilde{t}_1$) and the lightest neutralino ($\tilde{\chi}_1^0$), the stop quark can decay into the following final states: $\tilde{t}_1 \to t\tilde{\chi}_1^0$, $\tilde{t}_1 \to bW\tilde{\chi}_1^0$, $\tilde{t}_1 \to bff'\tilde{\chi}_1^0$ and $\tilde{t}_1 \to c\tilde{\chi}_1^0$, where f and f' are two distinct fermions. Since these decays are allowed in different regions of the phase space (Figure 2), different searches and special techniques are needed to enhance the sensitivity. Another major stop decay ($\tilde{t}_1 \to b\tilde{\chi}_1^\pm$) is characterised by a 3-dimensional phase space determined by the mass hierarchy of the $\tilde{t}_1$, $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ particles. Under certain physically motivated assumptions, only a number of 2-dimensional planes of this space have been studied. In the following, more details are given on recent results from the zero-, one- and two-leptons channel searches.

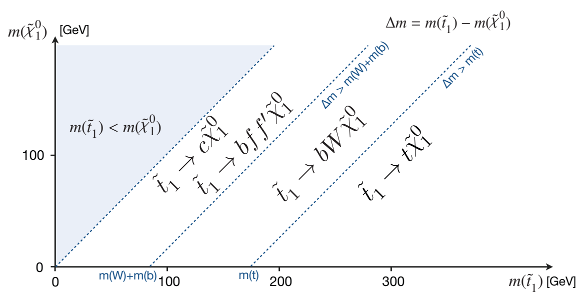


Figure 2: Illustration of stop decay modes as a function of the masses of the stop ($\tilde{t}_1$) and the lightest neutralino ($\tilde{\chi}_1^0$).

2.1 0 lepton decay mode

The search for direct top squark pair production in the all-hadronic channel is described in [1]. A nominal experimental signature of this analysis consists of six jets (two of which originate from b-quarks), no reconstructed electrons or muons and significant missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$). Three sets of signal regions are defined to provide sensitivity to three possible kinematic topologies. A first category requires at least six distinct jets plus $E_{\mathrm{T}}^{\mathrm{miss}}$. These signal jets are then used to reconstruct the two top candidates. To enhance the sensitivity to the $\tilde{t}_1 \to t\tilde{\chi}_1^0$ decay mode, a second category of the events with four or five reconstructed jets is considered. If the top quarks are strongly Lorentz-boosted, their decay products can merge and this final state can occur. They are constructed by re-clustering the standard anti-k_t jets with cone radius of R=0.4 into anti-k_t jets with cone radius of R=1.0. Finally, a third category of events with exactly five jets targets mainly the case when at least one top squark decays via $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_1^{\pm} \to W^{(*)}\tilde{\chi}_1^0$. The main background, coming from $t\bar{t}$ events, is rejected by the requirement on the transverse mass calculated from the $E_{\mathrm{T}}^{\mathrm{miss}}$ and the b-tagged jet closest in ϕ to the $\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}$ direction:

$$m_{\mathrm{T}}^{b,min} = \sqrt{2p_{\mathrm{T}}^{b}E_{\mathrm{T}}^{\mathrm{miss}}[1 - \cos\Delta\phi(\mathbf{p}_{\mathrm{T}}^{b}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})]} > 175 \text{ GeV} \qquad (1)$$

The 95% CL exclusion contours for the $\tilde{t}_1 \to t\tilde{\chi}_1^0$ decay mode are shown in the left part of figure 3.

Another fully hadronic final state search [4] addresses two different decay channels, $\tilde{t}_1 \to bff'\tilde{\chi}_1^0$ and $\tilde{t}_1 \to c\tilde{\chi}_1^0$. If the mass difference $\Delta m \equiv m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$ is smaller than the sum of the W boson and b-quark masses, the dominant decay mode of the top squark is the loop decay to a charm quark and the lightest neutralino. The final state is then characterized by two jets from the hadronization of the charm quarks and $E_{\mathrm{T}}^{\mathrm{miss}}$. Since this scenario is challenging, the presence of a hard jet coming from initial-state radiation is used to enhance the signal and suppress the multijet background. Two approaches, targeting different Δm regions, have been performed in order to maximize the analysis sensitivity: "monojet-like" and c-tagged selection. The former is optimized for $\Delta m \leq 20$ GeV, where c-jets are too soft to be reconstructed, and the signal is identified mainly by the presence of a high energetic ISR jet. The latter, dedicated to moderate $\Delta m \geq 20$ GeV, takes advantage of c-tagging. In this case, the charm jets tagged using multivariate techniques are boosted enough to be detected. The limits placed on the $\tilde{t}_1 - \tilde{\chi}_1^0$ mass plane are shown in the right part of figure 3. Additionally, this analysis is sensitive to the direct sbottom pair production scenario where the sbottom decays into a bottom quark and the lightest neutralino.

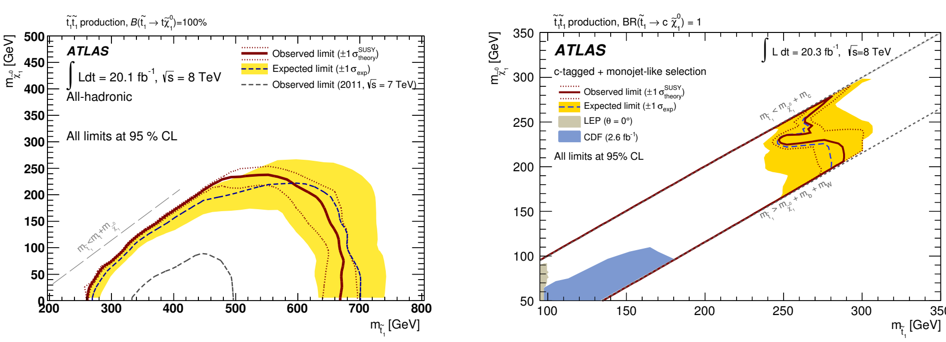


Figure 3: Observed and expected exclusion limits at 95% confidence level (CL) on direct top squark production for fully hadronic decays: $\tilde{t}_1 \to c\tilde{\chi}_1^0$ (right) and $\tilde{t}_1 \to t\tilde{\chi}_1^0$ (left).

2.2 1 lepton decay mode

The final state with exactly one isolated charged electron or muon, several jets and a significant $E_{\mathrm{T}}^{\mathrm{miss}}$ allows to target several stop decay chain scenarios. Therefore, the dedicated search [2] requires different analysis approaches for different regions of the parameter space of SUSY simplified model. The semileptonic $t\bar{t}$ and W+jets events have a similar signature as the signal events and are thus significantly suppressed by requiring the transverse mass (m_{T}) to be above the W boson mass. The dominant background after this requirement comes from the dileptonic $t\bar{t}$ events. These are reduced by a specific set of variables developed for this purpose: am_{T2} and m^{τ}_{T2}. Both are variants of the stransverse mass variable m_{T2} [9]. Figure 4 (left plot) shows the expected and observed exclusion limits for the lightest stop decay. The results from two-, three- and four-body decay chain studies are depicted.

2.3 2 leptons decay mode

Direct stop pair production has been also studied in the final state with two oppositely charged isolated leptons (e, μ), exactly two b-jets and significant $E_{\mathrm{T}}^{\mathrm{miss}}$. The results of three different analyses can be found in [3]. Two of them target the $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$ decay mode and their strategy is based on a powerful discriminant variable called the stransverse mass m_{T2}:

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

where m_{T} indicates the transverse mass, $\mathbf{p}_{\mathrm{T}}^1$ and $\mathbf{p}_{\mathrm{T}}^2$ are the transverse momentum vectors of two particles. The leptonic m_{T2} selection has been designed to be sensitive to the $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$ decay. Since for $t\bar{t}$ and WW decays, $m_{\mathrm{T2}}(l, l, E_{\mathrm{T}}^{\mathrm{miss}})$ is bounded sharply from above by the mass of the W boson, large values of this variable have been selected to suppress the background. On the other hand, the hadronic m_{T2} selection, optimized for the three-body $\tilde{t}_1 \to bW\tilde{\chi}_1^0$ decay, requires exactly two b-jets and large $m_{\mathrm{T2}}(b, b, l + l + E_{\mathrm{T}}^{\mathrm{miss}})$. These two selections are orthogonal and their results have been combined. Finally, the third analysis uses an multivariate technique and targets the on-shell top $\tilde{t}_1 \to t\tilde{\chi}_1^0$ decay. Figure 4 (right plot) shows the limits on the mass of a top squark decaying with 100% BR into $bW\tilde{\chi}_1^0$ derived by the leptonic m_{T2} analysis.

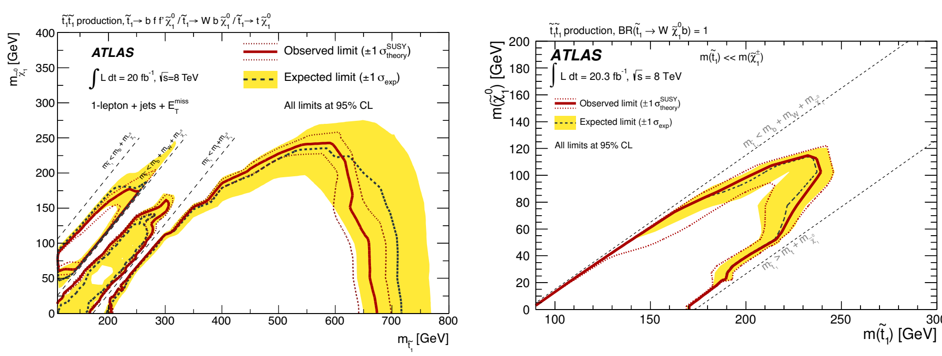
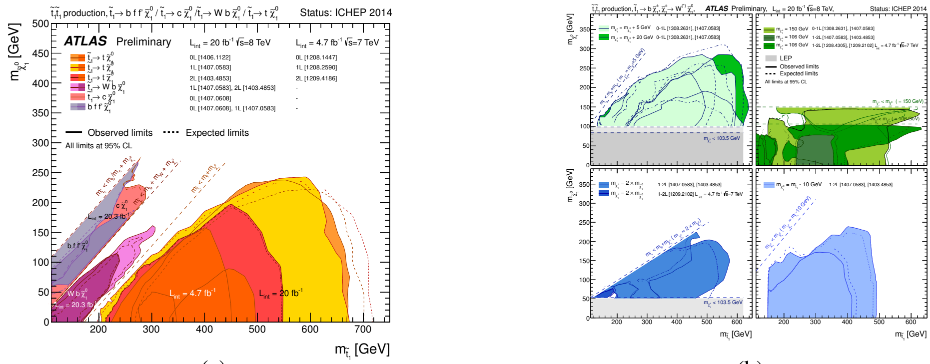


Figure 4: Observed and expected exclusion limits at 95% confidence level (CL) on direct top squark production for $\tilde{t}_1 \to bW\tilde{\chi}_1^0$ decay (right) and $\tilde{t}_1 \to t\tilde{\chi}_1^0$, $\tilde{t}_1 \to bW\tilde{\chi}_1^0$ and $\tilde{t}_1 \to bff'\tilde{\chi}_1^0$ decays (left).

2.4 Summary and other scenario

Figure 5 shows the summary of exclusion limits for direct $\tilde{t}_1$ pair production. Four decay modes, studied by different analyses, are considered separately with 100% branching ratio (BR): $\tilde{t}_1 \to t\tilde{\chi}_1^0$, $\tilde{t}_1 \to bW\tilde{\chi}_1^0$, $\tilde{t}_1 \to bff'\tilde{\chi}_1^0$ and $\tilde{t}_1 \to c\tilde{\chi}_1^0$. Obtained limits are shown in figure 5a. Figure 5b summarized the results of all searches targeting the $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm} \to bW^{(*)}\tilde{\chi}_1^0$ decay mode which is assumed with 100% BR. Various hypotheses on the $\tilde{t}_1$, $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^0$ mass hierarchy have been used.



(a) (b)

Figure 5: Summary of the dedicated ATLAS searches for top squark pair production. Exclusion limits at 95% CL are shown in the $\tilde{t}_1 - \tilde{\chi}_1^0$ mass plane for $\tilde{t}_1 \to t\tilde{\chi}_1^0$, $\tilde{t}_1 \to bW\tilde{\chi}_1^0$, $\tilde{t}_1 \to bff'\tilde{\chi}_1^0$ and $\tilde{t}_1 \to c\tilde{\chi}_1^0$ decays (a) and for $\tilde{t}_1 \to b\tilde{\chi}_1^\pm \to bW^{(*)}\tilde{\chi}_1^0$ decay (b).

As seen in figure 5, the analyses studying the $\tilde{t}_1 \to t\tilde{\chi}_1^0$ decay have currently little sensitivity to scenarios where $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \approx m_t$. In this region, the signal kinematic signature is similar with SM top pair production. As a consequence, direct stop pair production searches have been extended to other scenario based on the direct pair production of the heavier top squark state $\tilde{t}_2$ [5]. If $\tilde{t}_2$ is not too heavy and decays exclusively to Z boson and $\tilde{t}_1$, the signal can be discriminated from SM background.

3 Direct bottom squark pair production

The ATLAS experiment performed also the searches for the direct sbottom pair production. Three main decay modes have been studied by three different analyses: $\tilde{b}_1 \to b\tilde{\chi}_1^0$, $\tilde{b}_1 \to t\tilde{\chi}_1^\pm \to tW^{(*)}\tilde{\chi}_1^0$ and $\tilde{b}_1 \to b\tilde{\chi}_2^0 \to bh\tilde{\chi}_1^0$.

3.1 0 lepton decay mode

The search in final state with two b-jets, $E_{\mathrm{T}}^{\mathrm{miss}}$ and lepton veto [6] is sensitive to the $\tilde{b}_1 \to b\tilde{\chi}_1^0$ decay mode. Two sets of signal regions are defined to enhance the sensitivity in the regions with large or small mass splitting between the squark and the lightest neutralino. The first signal region, targeting large $\Delta m \equiv m_{\tilde{b}_1} - m_{\tilde{\chi}_1^0}$, requires two b-tagged high-p_{T} leading jets. These are identified as products of the two sbottom decays. Moreover, a requirement on the contransverse mass [10] is applied to reduce $t\bar{t}$ background. The contransverse mass is defined as an invariant and a powerful variable defined in the following way:

$$m_{\mathrm{CT}}^2(v_1, v_2) = [E_{\mathrm{T}}(v_1) + E_{\mathrm{T}}(v_2)]^2 - [\mathbf{p}_{\mathrm{T}}(v_1) - \mathbf{p}_{\mathrm{T}}(v_2)]^2 \tag{3}$$

where v_1 and v_2 are two b-jets from the sbottom decay in this analysis. The second signal region, sensitive to small Δm, selects events with a hard jet produced by initial-state radiation. Therefore, the leading jet is required to be almost back-to-back to $E_{\mathrm{T}}^{\mathrm{miss}}$ in ϕ and not to be b-tagged. The left part of the figure 6 shows the limits of this simplified model. Besides this final state, the analysis is also targeting direct stop pair production with subsequent decay into a bottom quark and the lightest chargino.

Another analysis searching for a pair of sbottom quarks in fully hadronic final state assumes that $\tilde{b}_1$ decays exclusively via $\tilde{b}_1 \to b\tilde{\chi}_2^0 \to bh\tilde{\chi}_1^0$ [7]. Since it selects the events with at least three b-jets and large $E_{\mathrm{T}}^{\mathrm{miss}}$, it is sensitive mainly to the signal where both Higgs bosons decay into $b\bar{b}$.

3.2 2 same-sign leptons decay mode

The analysis searching for direct sbottom pair production in the events with two same-sign leptons or three leptons, jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ is described in [8]. It has been designed to cover a large variety of SUSY processes, among others also the $\tilde{b}_1 \to t\tilde{\chi}_1^{\pm} \to tW^{(*)}\tilde{\chi}_1^0$ decay chain. Leptons of the same-charge arise from the decay of top quarks and W bosons (on-shell or off-shell). Since this search benefits from low SM backgrounds, relatively loose requirements on $E_{\mathrm{T}}^{\mathrm{miss}}$ could be used. Two scenarios have been considered with two different assumptions about the masses of the neutralino and the chargino: $m_{\tilde{\chi}_1^0} = 60$ GeV and $m_{\tilde{\chi}_1^{\pm}} = 2m_{\tilde{\chi}_1^0}$. The limits of the latter one as a function of $m_{\tilde{b}_1}$ and $m_{\tilde{\chi}_1^0}$ are shown in the right part of the figure 6.

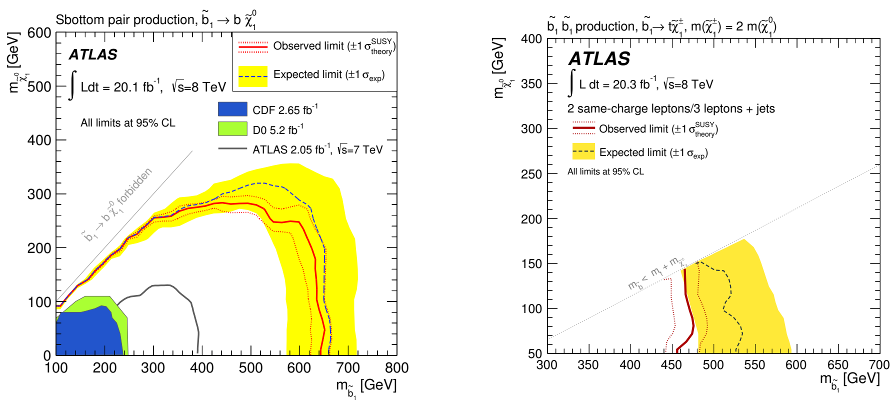


Figure 6: Observed and expected exclusion limits at 95% confidence level (CL) on direct bottom squark production for $\tilde{b}_1 \to t\tilde{\chi}_1^{\pm}$ decay with $m_{\tilde{\chi}_1^{\pm}} = 2m_{\tilde{\chi}_1^0}$ (right) and $\tilde{b}_1 \to b\tilde{\chi}_1^0$ (left).

4 Conclusion

ATLAS has searched for the direct production of the third generation squarks using the full 2012 dataset of LHC pp collisions at $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of 20 fb^{-1}. Many analyses targeted different regions of the SUSY parameter space and probed the existence of stop and sbottom quarks. No deviation from the Standard Model expectation has been observed and exclusion limits have been set in the $\tilde{t}_1 - \tilde{\chi}_1^0$ mass plane and the $\tilde{b}_1 - \tilde{\chi}_1^0$ mass plane.

References

[1] ATLAS Collaboration, JHEP **09** (2014) 015, arXiv:1406.1122

[2] ATLAS Collaboration, JHEP, to appear, arXiv:1407.0583

[3] ATLAS Collaboration, JHEP **06** (2014) 124, arXiv:1403.4853

[4] ATLAS Collaboration, Phys. Rev. **D.** 90, 052008 (2014), arXiv:1407.0608

[5] ATLAS Collaboration, Eur. Phys. J. **C** (2014) 74:2883, arXiv:1403.5222

[6] ATLAS Collaboration, JHEP **10** (2013) 189, arXiv:1308.2631

[7] ATLAS Collaboration, JHEP, to appear, arXiv:1407.0600

[8] ATLAS Collaboration, JHEP **06** (2014) 035, arXiv:1404.2500

[9] C. G. Lester and D. J. Summers, *Measuring masses of semiinvisibly decaying particles pair produced at hadron colliders*, Phys. Lett. **B** 463 (1999) 99-103, hep-ph/9906349

[10] D. Tovey, *On measuring the masses of pair-produced semi-invisibly decaying particles at hadron colliders*, JHEP **04** (2008) 034, arXiv:0802.2879