Searches for Direct Pair Production of Third Generation Squarks with the ATLAS Detector

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This document summarises recent ATLAS results for searches for third generation squarks using 36.1 fb^{-1} of LHC proton-proton collision data collected at $\sqrt{s} = 13 \text{ TeV}$. Despite the absence of experimental evidence, weak scale supersymmetry remains one of the best motivated and studied Standard Model extensions. Supersymmetry can naturally solve the Standard Model hierarchy problem by preventing a large fine-tuning in the Higgs sector: a typical natural SUSY spectrum contains light third generation squarks (stops and sbottoms). Both R-Parity conserving and R-Parity violating scenarios are considered. The searches involve final states including jets, missing transverse momentum, electrons or muons. Simplified models predicting pair production of third generation squarks have been excluded at 95% CL up to about one TeV in the most favourable scenarios.

Keywords: Supersymmetry; Naturalness; Top and bottom squarks.

1. Introduction

Supersymmetry (SUSY)¹ provides an extension of the Standard Model (SM) by introducing partners of the known bosons and fermions differing by half-unit of spin. In the framework of R-parity^a conserving models, SUSY particles are produced in pairs and the lightest supersymmetric particle (LSP) is stable and a possible candidate for dark matter^{2,3}. In many models, the LSP is the lightest neutralino $\tilde{\chi}_1^0$. Introducing non-zero R-parity violating (RPV) couplings into supersymmetric models provides additional phenomenology: the most relevant fact is that the LSP is unstable and decays to SM particles. Naturalness considerations^{4,5} suggest that

^aR-parity is a discrete multiplicative symmetry defined as $R = 1^{3B+L+2s}$, where B is the baryon number, L the lepton number and s the spin.

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the supersymmetric partners of the third-generation SM quarks are the lightest coloured SUSY particles.

The ATLAS Collaboration⁶ is conducting an extensive search programme for both R-parity conserving (RPC) and RPV models. The benchmarks used for the optimisation of the selections are simplified models⁷ where only a few SUSY particles ($\tilde{t}_1$, $\tilde{b}_1$, $\tilde{\chi}_1^\pm, \tilde{\chi}_1^0$ and in some cases $\tilde{t}_2$ or $\tilde{\chi}_2^0$) compose the low-mass SUSY spectrum. Unknown sparticle masses are free parameters and each specific decay is assumed to occur with a 100% branching ratio (BR).

2. Summary of the Search Selections

The most recent results from ATLAS searches for direct production of third generation squarks are summarised in the following. All results are based on 36.1 fb^{-1} of integrated luminosity with the LHC operating at a centre-of-mass energy of 13 TeV during the years 2015-2016. The SM backgrounds contributing to each signal selection (denoted as signal regions, SRs) are typically estimated with the aid of MC simulation, except for the multi-jet and fake/non-prompt lepton backgrounds which are estimated using fully data-driven methods. Control regions (CRs), constructed to enhance a particular background and to be kinematically similar but distinct from the SRs, constrain the normalisation of the dominant SM background processes. The background expectation is determined separately in each SR through a profile likelihood fit. The systematic uncertainties are included as nuisance parameters in the fit. The background estimates in the SRs are validated by extrapolating the results of the likelihood fit in the CRs to dedicated validation regions (VRs), which are designed to be orthogonal to both the signal and the control regions and are usually kinematically closer to the SR than the CR.

2.1. Final states with no leptons

The analysis reported in Ref. 8 targets $\tilde{t}_1$ decays to undetected weakly interacting neutralinos, two b -quarks, and two hadronically decaying W bosons. Events are required to have large missing transverse momentum E_T^{miss} and four jets. Several selections have been defined, each targeting different signal masses and decays. Requirements are set on the mass of the two leading large-radius reconstructed jets, asking them to be consistent with a W boson or top quark. Recursive Jigsaw reconstruction techniques⁹ are used to target scenarios where $m(\tilde{t}_1) - m(\tilde{\chi}_1^0) \sim m(t)$. These techniques are based on an approximate reconstruction of the decays and rest frames of intermediate particles, assuming a known decay tree. A good agreement between the data and the estimated background is found in all the signal selections.

The search described in Ref. 10 targets two sets of models. In the first set, the bottom squark decays directly into the lightest neutralino and a b quark. The search for this scenario requires two b -tagged jets, large transverse missing momentum, and no electrons or muons. Three alternative selections are optimized for different ranges of the mass of the supersymmetric particles exploiting the b -tagged jets cotransverse

mass, the minimum transverse mass between the four leading jets and the missing transverse momentum and the invariant mass of the two b -tagged jets for signal discrimination. The second set of models features a bottom or top squarks whose direct decay to the $\tilde{\chi}_1^0$ competes with the decay via an intermediate $\tilde{\chi}_1^\pm$. Two selections requiring two b -tagged jets, large transverse missing momentum, and one isolated electron or muon target this set of models. Data are found to be in agreement with the background prediction in all signal selections.

The search presented in Ref. 11 targets a model where the top squark is the LSP, is produced solely through strong interactions and decays through baryon-number-violating RPV couplings into two quarks. The expected signature is composed of four jets forming two pairs, each possibly containing a bottom quark, originating from a pair of equal mass resonances. The resonances are constructed by pairing the four leading jets using a minimisation of a pairing metric based on the angular distance of the jets in each pair. Requirements on the cosine of the angle that either of the resonances form with the beam line ($|\cos(\theta^*)|$) obtained in their centre-of-mass frame and a mass-asymmetry observable ($\mathcal{A}$) are used to reduce the SM background. The average mass (m_{ave}) of the two reconstructed resonances is used as the final discriminant and a counting experiment is performed in a mass-hypothesis-dependent mass window. No significant deviation from the background prediction is observed.

2.2. Final states with one lepton

The analysis presented in Ref. 12 selects final states with one isolated lepton, jets and $E_{\text{T}}^{\text{miss}}$. The search is based on 16 SRs. The results are extracted from each SR independently, either by counting events in a single region of phase-space and its associated CRs (cut-and-count technique) or by exploiting the shape information of a specific discriminating variable (shape-fit). Five SRs are dedicated to reach an optimal sensitivity to models with $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$, with a special attention to the compressed regime close to the kinematic boundary of $m(\tilde{t}_1) - m(\tilde{\chi}_1^0) \sim m(t)$, where the sensitivity is obtained by means of dedicated BDT-based selections, two exploiting initial state radiation requirements and one exploiting a recursive jig-saw approach⁹. Four SRs exploit instead soft-lepton requirements to target the four-body $\tilde{t}_1 \rightarrow bff'\tilde{\chi}_1^0$ final states and finally, three SRs are optimally sensitive to the models predicting $\tilde{t}_1$ decays via $\tilde{\chi}_1^\pm$. No significant deviations from SM expectations are observed.

The search described in Ref. 13 targets final states characterised by high jet multiplicity (≥ 8 up to more than ≥ 12), an isolated lepton and up to three b -tagged jets. Three different sets of jet- p_{T} thresholds (40 GeV, 60 GeV, 80 GeV on all jets) are used to guarantee sensitivity to a broad range of possible signal scenarios. Events are binned both in jet and b -tagged jet multiplicity. All jet- and b -tagged jet multiplicity bins are used in a simultaneous, model-dependent likelihood fit to constrain specific models. Model-independent tests used to search for hypothetical new-physics signals

are performed using individual likelihood fits to dedicated SRs with low expected SM contributions and defined by demanding a combination of either zero or at least three bottom-jets as well as eight to ten/twelve jets (again depending on the p_T threshold). No significant excess over SM expectation is observed.

2.3. Final states with two leptons

The analysis presented in Ref. 14 targets final states with exactly two opposite-charge leptons, electrons or muons, either same- or different-flavour. A same-flavour pair is accepted if found to be incompatible with a Z -boson decay. Three different sets of signal regions are designed in this analysis to be optimally sensitive to different decays of the top squark. Following the notation of Ref. 14, the 2-body regions target the decay of the top squark into either a top-neutralino or a b -chargino pair. These selections exploit a shape fit to the distribution of a specific transverse mass variable (m_{T2}), which is constructed to provide an end-point at the mass of the W -boson for the top pair background, which is the most important background for this selection. The 3-body selections instead target the decay of the top squark into $bW\tilde{\chi}_1^0$, under the condition that $m(W) + m(b) < \Delta m(\tilde{t}_1, \tilde{\chi}_1^0) < m(t)$. These selections exploit discriminative variables constructed using a recursive jag-saw approach⁹. Finally, the 4-body selections target compressed models with leptons characterised by soft momenta and exploits ratios of objects momenta and E_T^{miss} to enhance the soft topologies (considering $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) < m(W) + m(b)$). No significant deviation from the SM expectation has been observed.

The search described in Ref. 15 targets the production of top squark pairs decaying through an RPV coupling to two oppositely charged leptons and two b -quarks. The leptons and jets with the highest p_T are selected and at least one of the two leading jets is required to be b -tagged. The final lepton-jet pairing is based on a minimisation of a mass asymmetry observable ($m_{b\ell}^{\text{asym}}$). An upper bound on $m_{b\ell}^{\text{asym}}$ as well as lower bounds on the scalar sum of all four momenta (H_T) and the invariant mass of any two same-flavour leptons ($m_{\ell\ell}$) are used to reduce the contribution of the largest backgrounds. SRs are defined by requiring minimal values on the larger of the two pairing masses. No significant excess over the SM prediction is observed.

2.4. Final states with Higgs- or Z -bosons

The analysis presented in Ref. 16 targets direct top squark pair production decaying via long decay chains involving Z or Higgs bosons. Two sets of three SRs each, named $3\ell 1b$ and $1\ell 4b$ regions, have been designed to target the charged lepton decays of the Z boson or the hadronic decays of the Higgs boson, respectively. They select events with either a same-flavour opposite-sign dilepton pair with invariant mass compatible with a Z boson or a pair of jets compatible with a Standard Model Higgs boson. Data is found to be in good agreement with the SM predictions. The results of this analysis are interpreted in dedicated simplified models where the lightest

stop decays with 100% BR into a $t\text{-}\tilde{\chi}_2^0$ pair and considerably extends the previous ATLAS limits for these final states.

3. Interpretation of the Results

The results of the analyses summarised in this proceedings contribution are used to set 95% CL model-independent upper limits on the cross section of potential new physics for each selection, as well as 95% CL exclusion limits for a selected set of benchmark models.

Fig. 1. Exclusion contours at 95% confidence-level for simplified models assuming $\tilde{t}_1 \rightarrow b \tilde{\chi}_2^0$ (a) or $\tilde{b}_1 \rightarrow b \tilde{\chi}_2^0$ (b) pair production. The results are shown as a function of the masses of the SUSY particles involved in the decay. The dashed lines show the expected limits, while the solid lines show the observed limits.

Fig. 2. Upper limit on the cross section $\times$ branching ratio, computed at 95% confidence-level, compared to the theoretical cross section for the direct pair-production of top squark with decays into a bottom quark and a light quark¹¹ (a). Observed and expected 95% confidence-level exclusion contours for a simplified model assuming $\tilde{t}_1$ pair production¹³ (b). The dashed lines show the expected limits, while the solid lines show the observed limits.

Figure 1 shows the observed 95% CL exclusion limits in models considering the pair production of third generation squarks with R-parity conservation. The lower limit on the top squark mass is about 960 GeV for a light neutralino, while for $m(\tilde{t}_1) - m(\tilde{\chi}_1^0) \sim m(t)$ the range $235 \text{ GeV} < m(\tilde{t}_1) < 590 \text{ GeV}$ is excluded. Similar limits have been set for bottom squarks, consistently with the expectation of many SUSY models, that predict a top and a bottom squark to have similar masses.

Figure 2 shows the observed 95% CL exclusion limits in simplified models considering the pair production of top squarks in the context of R-parity violating SUSY scenarios. The limit on the top squark mass is about 620 GeV in the first set of models, while extends up to about 1.2 TeV for $\tilde{\chi}_1^0$ masses below 750 GeV in the second case.

4. Conclusions

A summary of the most recent top and bottom squark direct production are summarised in this proceedings contribution. The results are interpreted in terms of exclusion limits in a broad range of models, ranging from R-parity conserving to R-parity violating models. Limits close to the TeV range in $m(\tilde{t}_1)$ and $m(\tilde{b}_1)$ are obtained in the most favourable scenarios.

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