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Search for R-parity violating supersymmetry with the ATLAS detector

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R-parity violation introduces new signatures to be considered in the search for supersymmetry at the LHC. Strongly interacting resonances may decay to jets, sleptons may decay via lepton-flavour violating processes and lightest supersymmetric particles may decay into many particles with or without missing transverse momentum. The talk presents recent results from searches of supersymmetry in resonance production and R-parity violating signatures with the ATLAS detector.

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Introduction

Supersymmetry (SUSY) [1–6] is a theoretical extension of the external symmetries of the Standard Model of particle physics (SM). While it provides a potential solution to the naturalness problem [7, 8], it also introduces processes that violate both baryon number (B) and lepton number (L). To counteract immediate, though experimentally non-observed, consequences such as rapid proton decay or lepton-number-violating processes, it is a common approach to assume conservation of a new multiplicative quantum number called R-parity. It is defined as $R = (-1)^{3B+L+2s}$, where s is the spin of the particle. Assuming R-parity conservation (RPC) supersymmetric particles are produced in pairs and the lightest supersymmetric particle (LSP) is stable, and has neither electric nor colour charge.
Given the lack of any experimental evidence for signal of an RPC minimal supersymmetric SM (MSSM) [9, 10], one can either investigate less constrained models such as the phenomenological MSSM (pMSSM) [11, 12], or consider R-parity violating (RPV) SUSY [13, 14], as done in the following.

The most general renormalisable R-parity odd superpotential consistent with the gauge symmetry and field content of the MSSM includes terms [15]:

$$W = \varepsilon_{ab}\left[\underbrace{\underbrace{\frac{1}{2}\lambda_{ijk}L_i^a L_j^b \bar{E}_k}_{\text{LLE term}} + \underbrace{\lambda'_{ijk}L_i^a Q_j^b \bar{D}_j}_{\text{LQD term}} - \underbrace{\kappa_i L_i^a H_u^b}_{\text{LH term}}}_{\text{lepton-number violation}}\right] + \underbrace{\underbrace{\frac{1}{2}\varepsilon_{xyz}\lambda''_{ijk}\bar{U}_i^x \bar{D}_j^y \bar{D}_k^z}_{\text{UDD term}}}_{\text{baryon-number violation}}\,, \tag{1}$$

where λ_{ijk}, λ'_{ijk} and λ''_{ijk} are dimensionless Yukawa couplings, κ_i are mass dimension-one mixing parameters, and x, y and z are $SU(3)$ colour indices. By introducing other discrete or continuous symmetries or a suitable choice in couplings, RPV SUSY can provide an acceptable proton decay rate and be considered equally justified as RPC SUSY.

While the ATLAS Collaboration is conducting an extensive search programme for both RPC and RPV benchmark models [16], this contribution will focus solely on *recent* results from searches aiming at final states arising specifically from RPV benchmark models.
All searches use proton–proton collision data recorded by the ATLAS detector at a centre-of-mass energy of $\sqrt{s} = 13$ TeV in 2015 and 2016, and assume prompt decays of all SUSY particles involved. As the LSP is not stable and therefore does not give rise to missing transverse momentum (magnitude denoted as $E_{\mathrm{T}}^{\mathrm{miss}}$), none of the searches incorporates an explicit requirement on $E_{\mathrm{T}}^{\mathrm{miss}}$.

Four-jet final states from pair-produced resonances

Using 36.7 fb^{-1}of data, ATLAS performed a search [17] targeting a model where the top squark is the LSP, is produced solely through strong interactions and decays through baryon-number-violating RPV λ'' couplings (UDD term) into two quarks. The couplings are assumed large enough to ensure prompt decays and small enough to neglect resonant production of single top squarks.
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. As a result, only triggered events

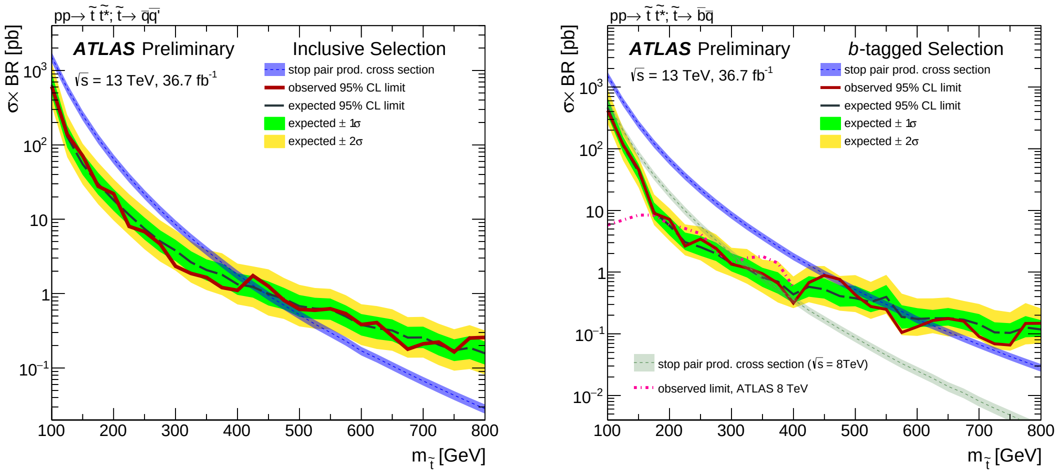

Figure 1: The 95% confidence-level upper limit on the cross section × branching ratio compared to the theoretical cross section for the direct pair-production of top squark with decays into (left) two quarks and (right) a bottom quark and a light quark [17].

with at least four jets with transverse momentum $p_{\mathrm{T}} > 120$ GeV and pseudorapidity $|\eta| < 2.4$ are considered in the search. Taking advantage of a topology where the resonances are produced with significant p_{T}, hence close-by decay products, 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 (ΔR_{min}). To reduce non-resonant multi-jet background, an upper limit, based on the average mass of the two resonances, is required on the pairing metric. Multi-jet background, frequently originating from t-channel gluon exchange, is suppressed by requiring small values for the cosine of the angle that either of the resonances form with the beam line ($|\cos(\theta^*)|$) obtain in their centre-of-mass frame. As both resonances are expected to have equal mass, a mass-asymmetry observable ($\mathscr{A}$) is used to further reduce background.

Inclusive signal regions (SR), targeting resonance decays into light-quark of gluon jets, are defined requiring small value for both $|\cos(\theta^*)|$ and $\mathscr{A}$. A dedicated bottom-tagged SR is defined by additionally demanding at least two bottom-tagged jets in the event. 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.

Background stemming from multi-jet production is estimated from data using an ABCD-like method in the $|\cos(\theta^*)| - \mathscr{A}$ plane, predicting both normalisation and shape in m_{ave}. Contributions from $t\bar{t}$ pair production, only relevant in the bottom-tagged selection at small m_{ave}, are estimated from simulation.

As no significant deviation from the background prediction is seen in any of the signal regions, this search excludes[1] top squark masses between 100 GeV and 410 GeV for decays into two quarks. For decays to a bottom quark and a light quark, masses between 100 GeV and 470 GeV as well as 480 GeV and 610 GeV are excluded. See Figure 1 for details. In addition, this search puts limits on the pair production of scalar gluons with decays into two gluons as well as vector-colour-

[1] All exclusion limits stated here and below are derived at 95% confidence level.

octet resonances coupling only to light quarks reaching lower mass limits of 800 GeV and 1.5 TeV, respectively.

Lepton + multi-jet final states

Using 36.1 fb^{-1}of data, ATLAS sought [18] for final states characterised by high jet multiplicity (≥ 8 up to ≥ 12), an isolated lepton (e, μ) and either zero or at least three bottom-tagged jets. RPV benchmark models are based on pair production of gluinos as well as right-handed scalar top quarks, with the latter decaying into a top quark and either pure bino or pure higgsino LSP.
The search is performed using events triggered by a single-electron or a single-muon trigger and by using three different sets of jet-p_{T} thresholds (40 GeV, 60 GeV, 80 GeV on all jets) to guarantee sensitivity to a broad range of possible signal scenarios. Events are binned both in jet and bottom-jet multiplicity, from five to inclusive ten/twelve (depending on the p_{T} threshold) and from zero to inclusive four, respectively.
All jet- and bottom-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).
The dominant W/Z+jets and $t\bar{t}$+jets backgrounds are estimated in a data-driven way using parameterised extrapolations, based on observables at intermediate jet multiplicity, to predict the bottom-tagged jet-multiplicity distribution in SRs at high jet multiplicities. The minor but non-negligible multi-jet background contributing through fake or non-prompt leptons is estimated from data using a matrix method.
As no significant excess over SM expectation is observed, results are interpreted in simplified models of RPV SUSY scenarios as well as in the form of model-independent upper limits on the visible cross section of new physics beyond the SM (BSM). For the benchmark models under consideration, the former approach excludes gluino masses up to between 1.65 TeV and 2.10 TeV (depending on the RPV coupling in question; UDD or LQD term) and top-squark masses up to between 1.10 TeV and 1.25 TeV (depending on the nature of the LSP). See Figure 2 for exclusion contours. In addition this search places a 60 fb (roughly 6.5 $\times$ SM) upper limit on the cross section of SM four-top-quark production.

$B-L$ scalar-top-pair final states

Based on a data set of 36.1 fb^{-1}, ATLAS conducted a search [19] for scalar top pairs decaying through an RPV coupling (LQD term) to two oppositely charged leptons and two bottom quarks. This final state is motivated by a benchmark model that introduced an additional local symmetry $U(1)_{B-L}$ to the SM with right-handed neutrino supermultiplets. In such minimal supersymmetric extension, $B-L$ symmetry is spontaneously broken due to a vacuum expectation value for a right-handed scalar neutrino and the RPV couplings, being related to the neutrino masses, are highly suppressed, hence making the model consistent with experimental bounds on proton decay.

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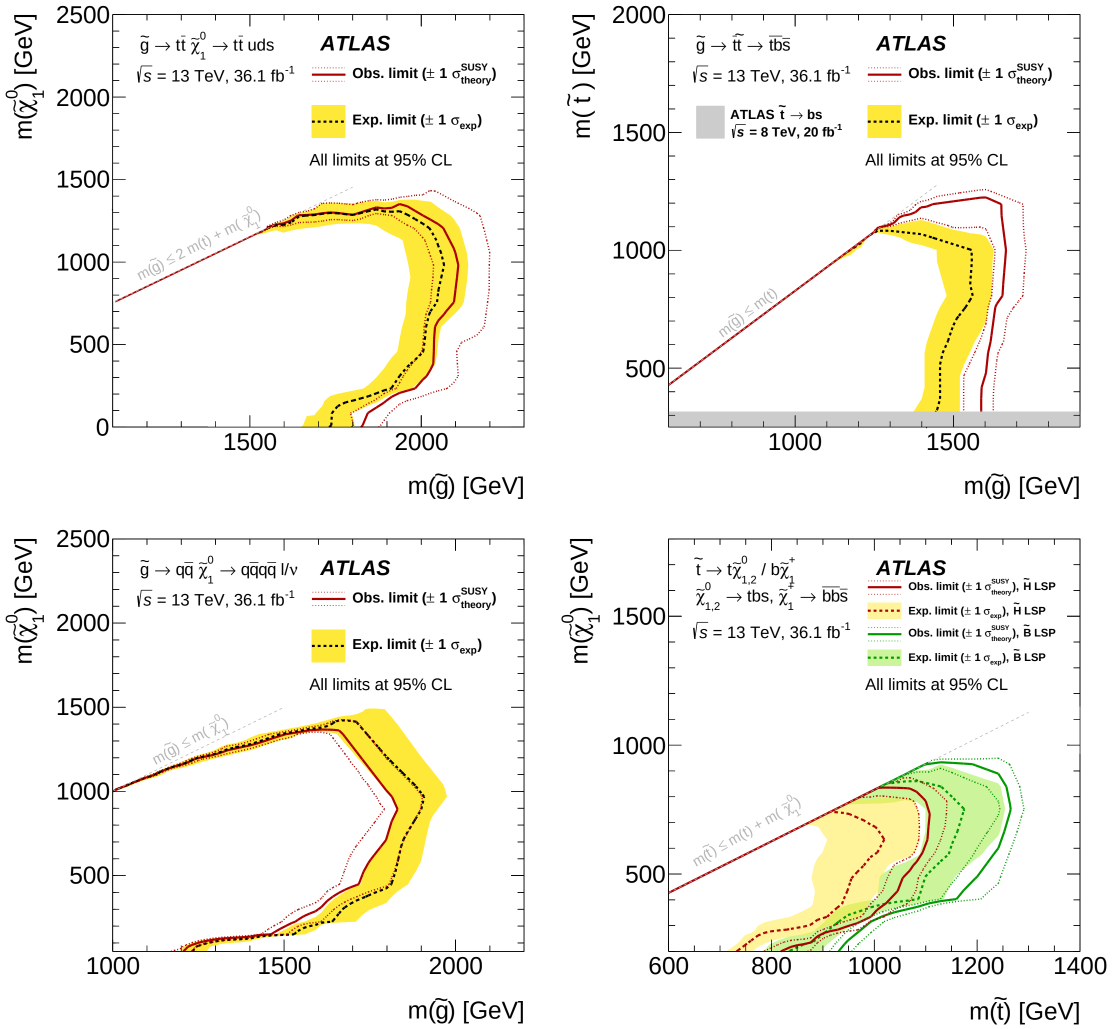

Figure 2: Observed and expected 95% confidence-level exclusion contours on the $\tilde{g}$, $\tilde{t}$ and/or $\tilde{\chi}_1^0$ masses [18].

Events considered in the search are required to be triggered by a single-electron or a single-muon trigger, and contain at least two leptons (e, μ) and at least two jets. Selecting the objects with the highest p_{T}, at least one of the two leading jets must be bottom-tagged and the two leading leptons must be of opposite charge. The final lepton–jet pairing is based on a minimisation of a mass asymmetry observable ($m_{b\ell}^{\mathrm{asym}}$). An upper bound on $m_{b\ell}^{\mathrm{asym}}$ 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 ($t\bar{t}$, single-top and Z+jets). SRs are defined by requiring minimal values (> 800 GeV and > 1100 GeV) on the larger of the two pairing masses.

The dominant backgrounds are estimated by normalising each expected simulation-based yield using dedicated control regions (CR) in data. Contributions from minor backgrounds (di-boson, $t\bar{t}$+V and W+jets) are estimated from simulation scaled to highest order theoretical cross section available.

No significant excess over the SM prediction is observed, hence the search derives model-independent

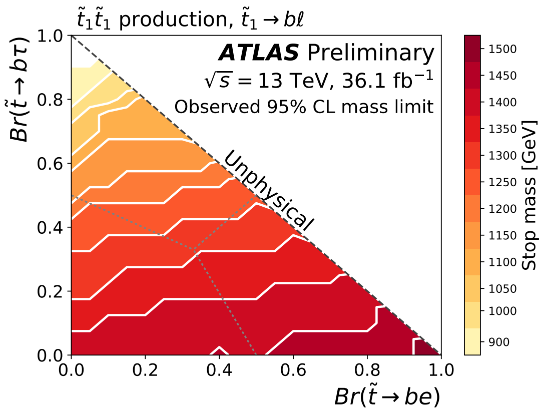

Figure 3: The observed mass limit as a function of top-squark branching ratios. The sum of branching ratios for each lepton flavour is assumed to be unity everywhere, and points of equality are marked by a dotted gray line. This limit is obtained using the nominal top-squark cross-section prediction. The mass limit shown corresponds to the highest-mass sample which is excluded [19].

upper limits on the cross section of potential new physics for each SR, as well as exclusion limits for the above mentioned benchmark models, using a simultaneous fit to the CRs and the target SRs. Limits are set on the top-squark mass, depending on the branching ratio, between 600 GeV (large τ decay branching ratio) to 1.5 TeV (100% e branching ratio), as summarised in Figure 3.

Conclusion

The ATLAS Collaboration is performing a broad variety of searches for SUSY signatures, of both RPC and RPV nature [16]. This contribution is merely highlighting *recent* results of searches aiming primarily on signatures motivated by RPV models. Until now, none of the searches summarised here, and in fact other SUSY searches performed by the ATLAS or CMS Collaboration, have shown any significant deviation from the background prediction in any of the signal regions. Instead searches are placing increasingly stringent limits on visible cross sections of possible new physics as well as masses of hypothetical SUSY particle, thereby encouraging searches in even more unconventional parameter-spaces, such as RPV SUSY.

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