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Searches for supersymmetry in resonance production, R-parity violating signatures and events with long-lived particles with the ATLAS detector

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R-parity violation introduces many viable signatures to the search for supersymmetry at the LHC. Strongly interacting resonances and lightest supersymmetric particles may decay into many leptons or jets with or without missing transverse momentum. Several supersymmetric models also predict massive long-lived supersymmetric particles. Such particles may be detected through abnormal specific energy loss, appearing or disappearing tracks, displaced vertices, long time-of-flight or late calorimetric energy deposits. The talk presents recent results from searches of supersymmetry in resonance production, R-parity violating signatures and events with long-lived particles with the ATLAS detector.

XXVI International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS2018)
16-20 April 2018
Kobe, Japan

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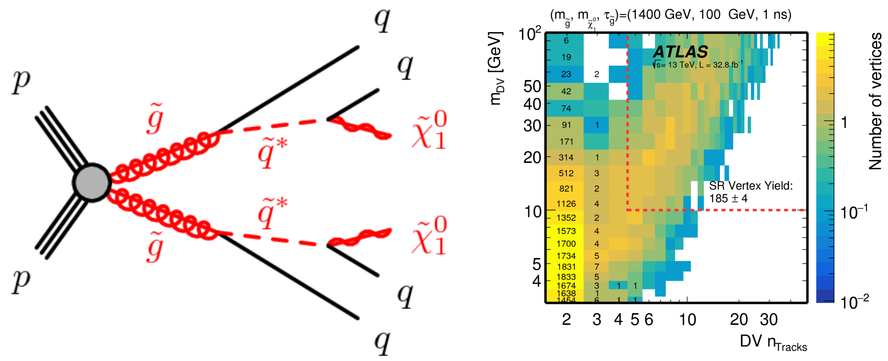
PoS(DIS2018)081

1. Introduction

Supersymmetry (SUSY) [1]-[3] is one of the best-motivated extensions of the Standard Model (SM). In its minimal realization (the MSSM) [4] it predicts a new bosonic (fermionic) partner for each fundamental SM fermion (boson), as well as an additional Higgs doublet. If R-parity [5] is conserved (RPC) the lightest supersymmetric particle (LSP) is stable and can be the lightest neutralino $\tilde{\chi}_1^0$. In many models, the LSP can be a dark-matter candidate and produce signatures with large missing transverse momentum. If instead R-parity is violated (RPV), the LSP decay can generate events with high jet and lepton multiplicity. Other signatures that could point to phyiscs beyond the standard model are signatures with long-lived particles (LLP), like the ones predicted by Hidden Valley models , some RPV SUSY models, or some Split SUSY models [6]. A review of three searches with the ATLAS detector [7] using Run 2 data of the LHC is presented, where long-lived particles where looked for in events with displaced vertices [8], as well as two searches that used RPV models as benchmark, one for direct s-top production [9] and another one with same sign leptons, jets, and no missing energy requirements [10].

2. Search for long-lived massive particles in events with displaced vertices

This search uses as benchmark a simplified model inspired by Split SUSY [8], where the gluino ($\tilde{g}$), is kinematically accessible at LHC energies while the squarks ($\tilde{q}$), have masses that are several orders of magnitude larger. Figure 1(a) shows pair-production of gluinos decaying to two quarks and the lightest supersymmetric particle (LSP), assumed to be the lightest neutralino ($\tilde{\chi}_1^0$). The $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$ decay is suppressed as it proceeds via a highly virtual squark. Depending on the scale of the squark mass, the gluino lifetime can be above the hadronization time scale. Therefore, the long-lived gluino, which transforms as a color octet, is expected to hadronize with SM particles and form a bound color-singlet state known as an R-hadron. This search attempts to reconstruct the decays of massive R-hadrons as displaced vertices (DVs). The analysis searched for LLP decays occurring O (1-100) mm from the reconstructed primary vertex (PV), and is sensitive to decays of both electrically charged and neutral states emerging from the PV. The analysis targets final states with at least one DV with a high reconstructed mass and a large track multiplicity in events with large missing transverse momentum $E_{\mathrm{T}}^{\mathrm{miss}}$. In order to recover tracks from DVs, an additional large-radius tracking (LRT) algorithm pass [11] was performed, using only hits not already associated with tracks reconstructed by the standard ATLAS tracking algorithm. To improve signal sensitivity, the full event selection criteria that were used in the construction of the signal region require that the event be recorded by an $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger and satisfy $E_{\mathrm{T}}^{\mathrm{miss}} > 250$ GeV. The DV candidates were required to have the vertex position within $R < 300$ mm and $|z| < 300$ mm, to be separated by at least 4 mm in the transverse plane from all reconstructed PVs, not to be in a region that is material-rich or affected by disabled detector modules and to have a vertex fit $\chi^2/N_{\mathrm{DOF}} < 5$. On top of that, vertices were required to have at least five associated tracks and a reconstructed invariant mass $m_{\mathrm{DV}} > 10$ GeV. The entirety of the background expected for this search is instrumental in origin. Three sources of such backgrounds were considered. Hadronic interactions can give rise to DVs far from the interaction point, especially where there is material in the detector. Decays of short-lived SM particles can occur close to each other and be combined into high-mass vertices



(a) (b)

Figure 1: (a) Pair-production of gluinos decaying through $\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$ via a virtual squark $\tilde{q}^*$. (b) Two-dimensional distributions of m_{DV} and track multiplicity are shown for DVs in events that satisfy all signal region event selection criteria. The dashed line represents the boundary of the signal region requirements, and the expected signal yield in this region is shown [8].

with large track multiplicities, in particular in the regions closest to the beams. Finally, low-mass vertices from decays of SM particles or hadronic interactions can be promoted to higher mass if accidentally crossed by an unrelated track at a large angle. The observed yields are consistent with the expected background in the validation regions, with 0 events observed (0.02 ± 0.02 expected) in the SRs. The two-dimensional distribution of m_{DV} and track multiplicity is shown in Figure 1(b) for events that satisfy the full event-level selection. The final SR yields are highlighted.

3. Search for $B-L$ R-parity violating top quarks

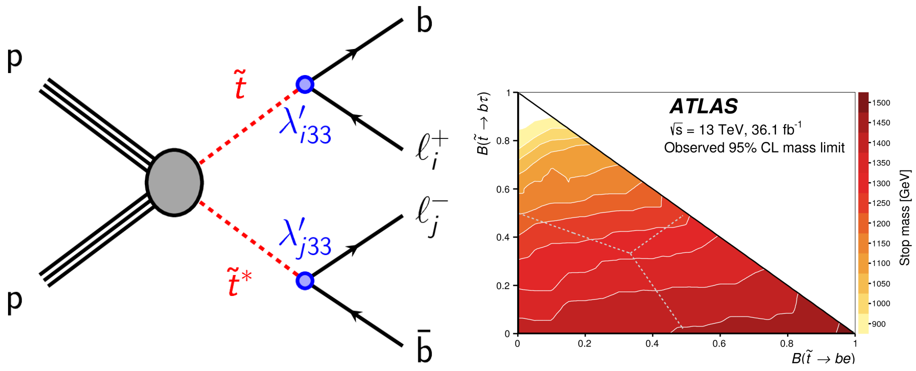
The benchmark model for this search considers an additional local symmetry $U(1)_{B-L}$ to the Standard Model with right-handed neutrino supermultiplets [9]. This minimal $B-L$ model violates lepton number but not baryon number. At the LHC, the most noticeable effect is that the LSP is no longer stable and can now decay via RPV processes, and it also may now carry color and electric charge. This leads to unique signatures that are forbidden in conventional models with R-parity conservation. A novel possibility is a top squark or s-top ($\tilde{t}$) as the LSP with a rapid RPV decay. This search looked for direct s-top pair production, with the RPV decay of each $\tilde{t}$ to a b-quark and a charged lepton ($\tilde{t} \to bl$), as shown in Figure 2(a). In contrast to R-parity conserving searches for $\tilde{t}$, there is no significant missing transverse momentum in the decay. The experimental signature is two oppositely charged leptons of any flavor and two b-jets. In this analysis, only events with electron or muon signatures were selected, and final states were split by flavour into ee, $e\mu$, and $\mu\mu$ selections. At least one of the two jets was required to be identified as initiated by a b-quark. Events were chosen in which the two reconstructed bl pairs have roughly equal mass. To identify the pair production of s-tops, events were required to have at least two leptons and two jets. At least one of the two leading jets must be b-tagged. The selected leptons were required to have opposite charge, and one of them must be consistent with the associated single-lepton trigger. The lepton-jet pair from each $\tilde{t}$ decay generally reconstructs the invariant mass m_{bl} of the original $\tilde{t}$. As the two masses should be roughly equal, the pairing that minimizes the mass asymmetry between m_{bl}^0 (larger mass) and m_{bl}^1 was chosen, defined as

$$m_{bl}^{\text{asym}} = \frac{m_{bl}^0 - m_{bl}^1}{m_{bl}^0 + m_{bl}^1}.$$

Events were selected to have small mass asymmetry $m_{bl}^{\text{asym}} < 0.2$, which reduces the contamination from background processes. Two nested signal regions (SRs) were constructed to optimize the identification of signal over background events. The signal regions were optimized using MC signal and background predictions, assuming $\tilde{t}$ decays of $B(\tilde{t} \to be) = B(\tilde{t} \to b\mu) = 50\%$. A primary kinematic selection of the signal regions was on m_{bl}^0, with SR800 requiring $m_{bl}^0 > 800$ GeV and SR1100 requiring $m_{bl}^0 > 1100$ GeV. Other kinematic selections, common to both SRs, were defined to reduce the contribution from the largest backgrounds. As the $\tilde{t}$ decay products are generally very energetic, a selection on their p_T sum was applied, such that $H_{\text{T}} > 1000$ GeV. To reduce contamination from Z+jets events, a requirement was placed on the invariant mass of two same-flavor leptons, with $m_{ll} > 300$ GeV. The minor backgrounds from diboson, $t\bar{t} + V$, and W+jets processes were estimated directly from MC simulation and the normalization was corrected to the highest-order theoretical cross section available. For the dominant $t\bar{t}$, single-top, and Z+jets backgrounds, the expected yield in the SRs was estimated by scaling each MC prediction by a normalization factor (NF) derived from three dedicated control regions (CRs), one for each background process. Each control region was defined to be kinematically close to the SRs while inverting or relaxing specific selections to enhance the contribution from the targeted background process while reducing the contamination from other backgrounds and the benchmark signals. Validation regions (VRs) were defined to test the extrapolation from the CRs to SRs over the relevant kinematic variables. Good agreement was observed in all validation regions, with differences between the data and SM prediction below 1σ. The observed lower limits on the $\tilde{t}$ mass at 95% CL as a function of $\tilde{t}$ branching ratios are shown in Figure 2(b). The sum of $B(\tilde{t} \to be)$, $B(\tilde{t} \to b\mu)$, and $B(\tilde{t} \to b\tau)$ was assumed to be unity everywhere, and points of equality are marked by a dotted gray line. The limits were obtained using the nominal $\tilde{t}$ cross-section predictions. As the branching ratio $B(\tilde{t} \to b\tau)$ increases, the expected number of events with electrons or muons in the final state decreases, reducing the mass reach of the exclusion.

4. SUSY RPV search with two same-sign leptons in the final state

In the case of non-zero RPV couplings in the baryonic sector, as proposed in scenarios with minimal flavour violation, it is possible to have a gluino decaying to a neutralino LSP that further decays to SM particles via a non-zero RPV coupling in the leptonic sector ($\lambda^{'}$), as shown in Figure 3(a). Lower $E_{\text{T}}^{\text{miss}}$ is expected in these scenarios, as there is no stable LSP, and the $E_{\text{T}}^{\text{miss}}$ originates from neutrinos produced in the neutralino decays. This search used this scenario to look for RPV SUSY in events with two same sign leptons, more than six jets and little missing transverse energy [10]. The reducible background for this process, which includes events containing electrons with mismeasured charge, came mainly from the production of top quark pairs, and events containing at least one fake or non-prompt (FNP) lepton. The FNP lepton mainly originates from heavy-flavour hadron decays in events containing top quarks, or W or Z bosons. Hadrons misidentified as



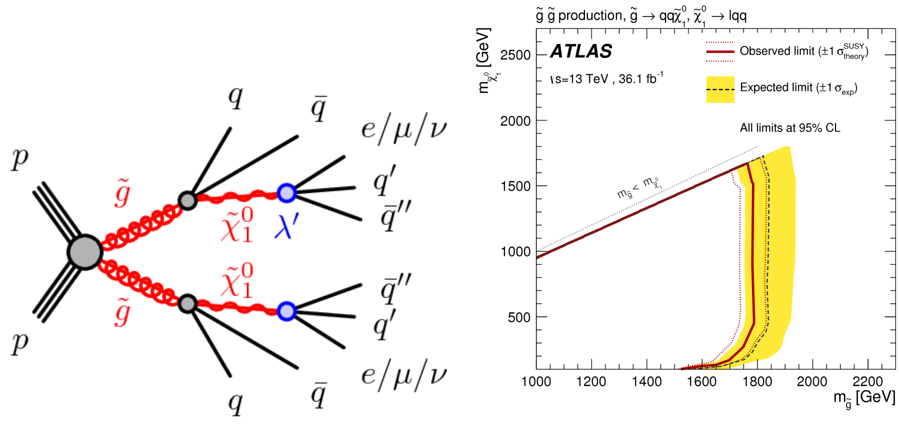
(a) (b)

Figure 2: (a) s-top pair production, with $\tilde{t}$ and anti-$\tilde{t}$ decay to a charged lepton of any flavor and a b-quark through an R-parity-violating coupling $\lambda^{'}$. (b) Observed lower limits on the $\tilde{t}$ mass at 95% CL as a function of $\tilde{t}$ branching fractions [9].

leptons, electrons from photon conversions and leptons from pion or kaon decays in flight are other possible sources. Data-driven methods were used for the estimation of this reducible background in the signal and validation regions. The irreducible background comes from events with two same-sign prompt leptons and was estimated using MC simulation samples. Since diboson and $t\bar{t}V$ events were the main irreducible backgrounds in the signal regions, dedicated validation regions (VR) with an enhanced contribution from these processes, and small signal contamination, were defined to verify the background predictions from the simulation. The uncertainty in the FNP lepton rate amounts to 30% at low p_{T}, and can reach 85% for muons with $p_{\mathrm{T}} > 40$ GeV, and 50% for electrons with $p_{\mathrm{T}} > 20$ GeV. The uncertainty in the electron charge-flip probability mainly originates from the number of events in the regions used in the charge-flip probability measurement and the uncertainty related to the background subtraction from the mass peak of the Z boson. The relative error in the charge-flip rate is below 20% (30%) for signal (candidate) electrons with p_{T} above 20 GeV. The systematic uncertainties related to the estimated background from same-sign prompt leptons arise from the experimental uncertainties (jet energy scale calibration, jet energy resolution and b-tagging efficiency) as well as theoretical modelling and theoretical cross-section uncertainties. Exclusion limits at 95% CL were set on the masses of the gluino and the neutralino. A simplified model was used, corresponding to a single production mode and with 100% branching ratio to a specific decay chain, with the masses of the SUSY particles not involved in the process set to very high values. Figure 3(b) shows the exclusion limit, where the diagonal line indicates the kinematic limit for the decay. The mass range of the exclusion was extended compared to previous searches, and a generic exclusion of gluinos with masses below 1.3 TeV was obtained.

5. Conclusions

ATLAS has published a large number of searches for Supersymmetry and Long-lived particles with Run 1 and Run 2 LHC data. Here three such searches with Run 2 data were presented. The long-lived particle search presented used a dedicated algorithm to reconstruct displaced vertices



(a) (b)

Figure 3: (a) Gluino pair prodction in the RPV SUSY scenario considered. (b) Observed and expected exclusion limits on the $\tilde{g}$-$\tilde{\chi}_1^0$ mass plane in the context of a RPV SUSY scenario with simplified mass spectrum [10].

as a possible signal for BSM physics, in this case, a Split SUSY model. Also a search for s-top direct production in RPV scenarios was presented, where no deviation from the SM expectation was found. The last search presented, with two same-sign leptons, large jet multiplicity and low E_T^{miss}, obtained exclusion limits on the $\tilde{g}$-$\tilde{\chi}_1^0$ mass plane, improving results from previous searches.

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