SQUARK AND GLUINO SEARCHES WITH R-PARITY VIOLATING DECAYS AND LONG-LIVED PARTICLES IN ATLAS

D. BARBERIS
University of Genoa, Department of Physics,
Via Dodecaneso 33, I16146 Genova, Italy
on behalf of the ATLAS Collaboration [a]

A selection of searches for supersymmetry performed with the ATLAS experiment at LHC using data collected at centre-of-mass energies between 8 and 13 TeV, and optimized for R-parity-conserving and R-parity-violating models, are reinterpreted in SUSY models with variable coupling strengths. Limits are placed on simplified models of pair-produced gluinos decaying to final states enhanced or depleted with top quarks, and models of pair-produced top squarks. In a model of pair-produced gluinos decaying to final states enhanced with top quarks, a lower limit of 1.8 TeV on the gluino mass is set at 95% confidence level regardless of the RPV coupling value. Limits are set on models of gluino pair production decaying to light-flavor quarks, and models of top squark production. Limits are also placed on meta-stable gluinos decaying within the detector volume.

1 Introduction

Supersymmetry (SUSY) is a generalization of space-time symmetries which extends the Standard Model (SM) by introducing supersymmetric partners for every SM particle with identical quantum numbers except for a half-unit difference in spin. The scalar partners of the left- and right-handed quarks, the squarks $\tilde{q}_L$ and $\tilde{q}_R$, mix to form two mass eigenstates $\tilde{q}_1$ and $\tilde{q}_2$ ordered by increasing mass. Superpartners of the charged and neutral electroweak and Higgs bosons, so called winos, bino and higgsinos, also mix producing charginos ($\tilde{\chi}^{\pm}_{1,2}$) and neutralinos ($\tilde{\chi}^{0}_{1,2,3,4}$) with subscripts indicating increasing mass. Squarks and the fermionic partners of the gluons, the gluinos ($\tilde{g}$), could be produced in strong-interaction processes at the Large Hadron Collider (LHC) with large cross-sections.

In the most generic superpotential, the following Yukawa and bilinear couplings can lead to baryon- and lepton-number violation:

$$\mathcal{W}_{\mathrm{RPV}} = \frac{\lambda_{ijk}}{2} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{\lambda''_{ijk}}{2} \bar{U}_i \bar{D}_j \bar{D}_k + \kappa_i L_i H_u, \tag{1}$$

where i, j, and k are quark and lepton generation indices. The L_i and Q_i represent the lepton and quark $\mathrm{SU(2)_L}$ doublet superfields and H_u the Higgs superfield that couples to up-type quarks. The $\bar{E}_i$, $\bar{D}_i$ and $\bar{U}_i$ are the lepton, down-type quark and up-type quark $\mathrm{SU(2)_L}$ singlet superfields, respectively. The couplings are λ, λ', λ'', as well as κ which is a dimensional mass parameter. The λ and λ'' couplings are antisymmetric under the exchange of $i \to j$ and $j \to k$, respectively. While these terms are removed in many scenarios by imposing an additional $\mathcal{Z}_2$ symmetry (R-parity), the possibility that at least some of these R-parity violating (RPV) couplings are not zero is not ruled out experimentally.

In this paper the lightest neutralino, $\tilde{\chi}_1^0$, is assumed to be the lightest supersymmetric particle (LSP). If R-parity is conserved, SUSY particles are produced in pairs and decay either directly or via cascades to the LSP which is stable and escapes the detector unseen. Introducing non-zero RPV couplings renders the LSP unstable and allows decays to SM particles via the interactions in Eq. (1). The LSP lifetime depends on the RPV coupling strength as well as the masses of the sfermions involved in the decay. Most searches for RPV SUSY assume values of the coupling that are large enough to ensure prompt decays of the LSP. However, in the parameter space of small RPV couplings and/or large sfermion masses the LSP can become long-lived and decay after traversing a sizable distance within the detector volume. In the limit where the RPV coupling is vanishingly small the majority of LSP decays occur outside the detector volume, producing the same experimental signature as R-parity-conserving (RPC) SUSY. For high values of the coupling, the LSP decays promptly; as the coupling increases even further, squarks and gluinos can decay directly to SM particles via the large RPV coupling. Thus, scaling the value of the RPV coupling transitions the SUSY final state through several distinct regimes. Furthermore, non-zero RPV coupling values allow for single sparticle production.

Final states with displaced decays can also emerge from models such as Split SUSY, where large mass hierarchies allow bound states involving SUSY particles (called R-hadrons) to obtain macroscopic lifetimes. Depending on the lifetime of these particles, SUSY searches targeting traditional simplified models can also provide sensitivity to these signatures.

2 SUSY models

The sensitivity of a suite of searches performed using the ATLAS experiment [1] at LHC is evaluated on a set of simplified SUSY models [2]. All models assume the existence of a non-zero baryon-number-violating RPV λ'' coupling. Lepton-number-violating couplings, λ and λ', are assumed to be zero. Within the set of λ''_{ijk} couplings, only one is considered to be non-zero in each simplified model, while the rest are assumed to be zero.[b] The antisymmetry condition $\lambda''_{ijk} = -\lambda''_{ikj}$ is respected, and is always implied when a model is described as having only one non-zero coupling. Supersymmetric scenarios featuring only baryon-number-violating RPV couplings are predicted in minimal flavor violation (MFV) SUSY. The LSP is assumed to be the lightest neutralino, $\tilde{\chi}_1^0$, which is purely bino-like and has a fixed mass of 200 GeV. The value of the mass is chosen to allow decays of the neutralino to a top quark. The choice of a bino-like neutralino is made for simplicity as the absence of a chargino in the particle spectrum reduces the number of possible squark or gluino decays. The nature of the neutralino has also an impact on its lifetime, *e.g.* a higgsino-like neutralino has a shorter lifetime due to the large Yukawa coupling to the stop.

Despite the usage of simplified models, the masses of all the squarks have to be specified even if they are not considered in the accessible sparticle spectrum, since the LSP lifetime depends on the choice of squark masses. The results are presented as a function of the RPV coupling strength, λ'', and as a function of the LSP lifetime and branching ratio. The correspondence

[b] The absence of lepton-number-violating couplings is enough to satisfy proton stability bounds. The choice of having only one non-zero baryonic coupling is made for simplicity and the availability of a theoretical upper limit.

between coupling strength and lifetime or branching ratio is determined by the choice of squark masses. The mean decay length for a bino-like lightest neutralino can be numerically estimated from:

$$L(cm) = \frac{0.9\beta\gamma}{\lambda''^2}\left(\frac{m(\tilde{q})}{100\ \text{GeV}}\right)^4\left(\frac{1\ \text{GeV}}{m(\tilde{\chi}_1^0)}\right)^5 \quad (2)$$

For a fixed value of the coupling higher squark masses lead to higher neutralino lifetimes. The computation of lifetime and branching ratios is performed with SPHENO 4.0.2 in combination with SARAH 4.12.0.

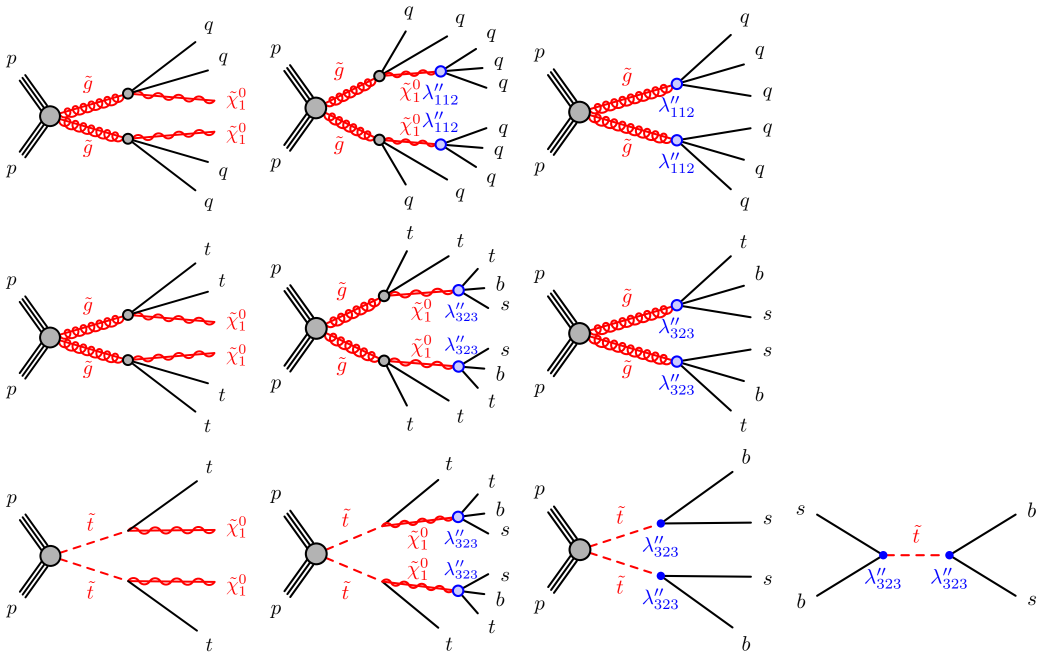

Figure 1 – Production and decay processes for the three RPV SUSY models considered: (top) Gqq model, (middle) Gtt model, and (bottom) stop model. For each model the dominant process varies with increasing λ'' coupling from left to right [2].

Three simplified models are considered [c]:

Gqq model: the model contains light gluinos and the LSP, with non-zero λ''_{112} coupling and all other RPV couplings equal to zero. The gluinos are pair-produced and decay via off-shell squarks of the first and second generation. For low values of the RPV coupling the gluino decays as $\tilde{g} \to qq\tilde{\chi}_1^0$ ($q = u, d, s, c$) with the subsequent LSP decay, $\tilde{\chi}_1^0 \to qqq$. For larger values of the coupling the gluino can also decay as $\tilde{g} \to qqq$. The masses of the first and second generation squarks are assumed to be 3 TeV, while the masses of the other sparticles are set above 5 TeV, including third generation squarks.

Gtt model: the model contains light gluinos and the LSP, with non-zero λ''_{323} coupling and all other RPV couplings equal to zero. The gluinos are pair-produced and decay via off-shell top squarks. For low values of the RPV coupling the gluino decays as $\tilde{g} \to tt\tilde{\chi}_1^0$ with the subsequent LSP decay, $\tilde{\chi}_1^0 \to tbs$. For larger values of the coupling the gluino can also decay as $\tilde{g} \to tbs$. The masses of the third-generation squarks are assumed to be 2.4 TeV; the masses of the other sparticles are set above 5 TeV, including first- and second-generation squarks. The choice for the masses of third-generation squarks is made to ensure that the prompt decay regime is reached before the branching fraction of $\tilde{g} \to tbs$ becomes non-negligible.

[c] More complete information on the models considered for this analysis can be found in ref. [2] and the references therein.

Stop model: the model contains a light stop, $\tilde{t}_1$, which is the right-handed superpartner of the top quark, and the LSP, with non-zero λ''_{323} coupling and all other RPV couplings equal to zero. Stops are pair-produced and decay as $\tilde{t}_1 \to t\tilde{\chi}_1^0$ for low coupling values, or $\tilde{t}_1 \to bs$ for high coupling strengths. The LSP always decays as $\tilde{\chi}_1^0 \to tbs$. The masses of the other sparticles are set above 3 TeV, but since the RPV decay proceeds via the right-handed stop, which is already part of the simplified model, there is no impact from this choice on the lifetime or branching ratios. For high coupling values single stop resonant production is also considered, $pp \to \tilde{t}_1 \to bs$, leading to a di-jet final state which may provide stronger constraints on the stop mass than pair production at the LHC.

Figure 1 illustrates the production and decay modes considered in the three models, as a function of the λ'' coupling strength. For very small values of the coupling the decay of the LSP can be displaced. For higher values of the coupling the decay of the LSP is prompt and the diagrams in the middle column occur with 100% branching ratio. For even higher values of the coupling the direct decay of the gluino or stop (right column) occurs with increasing branching ratio, reaching 100% for λ'' values of order one. Direct decays of the gluino or stop are always prompt.

An additional simplified model inspired by Split SUSY is considered in this note, and referred to as the R-hadron model:

***R*-hadron model:** the gluino is kinematically accessible at LHC energies while the squarks have masses that are several orders of magnitude larger. The gluino decays via a highly virtual intermediate state resulting in macroscopic lifetimes. Unlike the models described above, the long-lived particle is the gluino, which decays to a stable LSP via RPC couplings as shown in the first diagram of Figure 1. The LSP is assumed to be the lightest neutralino, $\tilde{\chi}_1^0$, with a mass of 100 GeV. If the gluino lifetime is larger than the hadronization timescale of order 10^{-23} s, it will form a color-singlet state with SM quarks and gluons. This bound state is referred to as an R-hadron. The mass of the R-hadron is dictated by the mass of the gluino with additional contributions from the mass of the bound SM particles and the binding energy associated with the hadron.

3 Analyses and results

A set of nine ATLAS searches that are sensitive to the models described above are re-interpreted to set exclusion limits[2]. None of the analyses saw significant excesses above the SM expectation in datasets ranging from 3.2 fb^{-1} to 37 fb^{-1} of 13 TeV proton–proton collision data. An outline of each of the included analyses is presented below.

RPC 0-lepton, 2-6 jets: the analysis searches for pair production of squarks or gluinos in final states with jets and MET, while vetoing electrons or muons. Two strategies are used: one based on the m_{eff} variable, and a second one based on recursive jigsaw reconstruction. The search sets an exclusion limit on the gluino mass around 2 TeV in a simplified model with RPC, equivalent to the Gqq model considered in this note in the limit of a vanishingly small $lambda''$ coupling.

RPC 0-lepton, 7-11 jets: the analysis searches for gluinos which decay via long chains of particles, yielding a final state with high jet multiplicity and moderate MET. The models targeted by this search do not map directly to the models considered in this note; in simplified models with long decay chains of SUSY particles, the analysis sets limits of up to 1.8 TeV on the gluino mass. Given the high jet multiplicity in events with moderate λ'' coupling, and the possibility to obtain moderate MET due to misreconstruction of jets from late decays, this search has potential sensitivity to the Gqq and Gtt models.

RPC multi-b: the analysis targets gluino production with the subsequent decay to top quarks and a neutralino, in a scenario equivalent to the Gtt model in the RPC limit. The search requires high jet and b-jet multiplicity, moderate MET and large m_{eff}. Gluino masses up to 2 Tev are excluded for a 200 GeV neutralino mass.

RPV 1-lepton: the analysis searches for gluinos and stops in models with RPV couplings, yielding final states with at least one lepton, very high jet multiplicity and either no b-jets or many b-jets. The search also sets limits on the gluino mass for two models that are similar to the Gtt model considered here, in the the regime where the LSP decay is prompt and the gluino decays only to $\tilde{g} \to tt\tilde{\chi}_1^0$, or only to $\tilde{g} \to tbs$.

RPC stop 0-lepton, stop 1-lepton: both analyses search for stop pair production in a $t\bar{t}$+MET final state, with either both tops decaying hadronically, or one top decaying hadronically and the other leptonically. Both searches set an exclusion limit on the stop mass around 1 TeV in a simplified model with RPC, equivalent to the stop model considered in this note in the limit of a vanishingly small λ'' coupling.

RPC and RPV same-sign and 3-leptons (SS/3L): the analysis covers a large variety of models including both RPC and RPV scenarios. Among the targeted scenarios are the three distinct regimes of the Gtt model described before, as well as final states compatible with the stop model with a prompt decay of the neutralino.

RPV stop dijet pairs: the analysis targets stop pair production with the subsequent decay to a b-quark and s-quark, in a scenario equivalent to the stop model considered in this note in the regime with very high RPV coupling. Stop masses up to 610 GeV are excluded assuming decays only to $\tilde{t} \to bs$.

Dijet and TLA: For very high coupling values, single stop resonant production is also considered, $pp \to \tilde{t}_1 \to bs$, leading to a di-jet final state. The offline dijet search and the trigger-level-analysis (TLA) dijet search are reinterpreted to set limits in this regime. Both analyses search for a localized excess in the dijet mass spectrum, with small rapidity separation.

All analyses implement the full set of uncertainties described in the respective publication. In addition, the analyses that are sensitive to signals with sizable lifetime include two additional uncertainties to account for possible differences between data and simulation modeling of displaced signals. The jet energy scale uncertainties for displaced jets are below the percent level for decay lengths below 1 m, grow linearly reaching 30% at 1.6 m, and remain approximately constant until the end of the calorimeter. The jet reconstruction efficiency decreases quickly while approaching the end of the calorimeter, dropping below 10% for decay lengths larger than 3 m. The b-tagging uncertainties for displaced jets generate an extra systematic uncertainty of 10% (20%) for event selections with 2 b-tags (4 b-tags) and signal lifetimes of 1 ns. The size of this uncertainty decreases (increases) for shorter (longer) lifetimes.

Results are provided in the context of three RPV SUSY benchmark models and the R-hadron model, using the nine ATLAS analyses described previously. In all cases except for the dijet analyses, the profile likelihood-ratio test is used to establish 95% confidence intervals using the CL_s prescription. In the dijet analyses a Bayesian procedure is used to set 95% credibility-level upper limits on generic Gaussian resonances. Individual limits from each analysis are reported, and no combination is performed due to substantial overlaps in signal region definitions and in order to highlight the performance of the approach of each analysis. Figure 2 shows the observed and expected lower gluino mass limits obtained in the four considered models; the excluded regions are the areas below the curves.

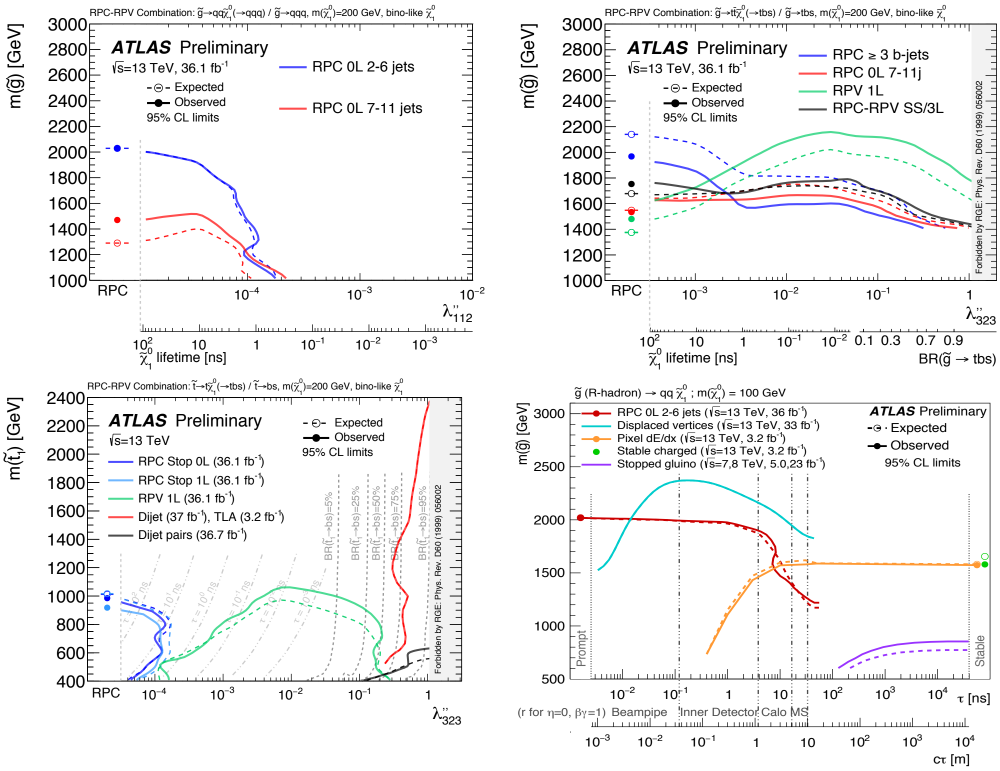

Figure 2 – Top-left: exclusion limits for the Gqq model as a function of λ''_{112} and $m(\tilde{g})$. Top-right: exclusion limits for the Gtt model as a function of λ''_{323} and $m(\tilde{g})$. Bottom-left: exclusion limits for the stop model as a function of λ''_{323} and $m(\tilde{t})$. Bottom-right: exclusion limits for the R-hadron model, as a function of the R-hadron lifetime and the gluino mass [2].

4 Conclusions

This paper describes the reinterpretation of analyses performed by the ATLAS experiment at LHC using models with variable R-parity coupling strength and R-hadron lifetime. Four simplified models, three targeting RPV scenarios and one targeting R-hadrons, are analyzed. The large variations in final state, and therefore in sensitivity, as a function of the R-parity coupling strength motivate a thorough examination of the full ATLAS SUSY program's coverage. Different degrees of sensitivity are observed as a function of λ'': in the gluino model with large branching fractions to top quarks, gluinos are excluded up to masses of 1.8 TeV, over the full range of lifetime and RPV coupling strengths. In the gluino model with decays to first and second generation quarks, the differences are even more striking: for low values of the coupling, gluino masses are excluded up to 2.0 TeV, but at high values of λ'' no limits are set. The stop model shows large variations in the limits as well: stop masses up to 2.4 TeV can be excluded at high values of λ'', but no limits can be established for values of $\lambda'' \approx 10^{-4}$, equivalent to neutralino lifetimes around 1 ns. Gluinos in models with short lived R-hadrons can also be excluded up to masses of 2.0 TeV by the re-interpretation of existing RPC-targeting analyses.

References

1. ATLAS Collaboration, 2008, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST 3 S08003
2. ATLAS Collaboration, *Reinterpretation of searches for supersymmetry in models with variable R-parity-violating coupling strength and long-lived R-hadrons*, ATLAS-CONF-2018-003, 13 March 2018, http://cds.cern.ch/record/2308391/files/ATLAS-CONF-2018-003.pdf