Squark and gluino searches with R-parity violating decays and long-lived particles in ATLAS

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on behalf of the ATLAS Collaboration
### ATLAS SUSY Searches* - 95% CL Lower Limits

**December 2017**

<table>
<thead>
<tr>
<th>Model</th>
<th>$\ell$, $\mu$, $\tau$, $\gamma$</th>
<th>Jets</th>
<th>$E_T^{miss}$</th>
<th>Mass limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q\bar{q}, g+g\gamma$</td>
<td>0</td>
<td>2, 6 jets</td>
<td>Yes</td>
<td>36.1</td>
<td>1.57 TeV</td>
</tr>
<tr>
<td>$q\bar{q}, g+g\gamma$ (compressed)</td>
<td>1</td>
<td>3, 1 jets</td>
<td>Yes</td>
<td>36.1</td>
<td>1.67 TeV</td>
</tr>
<tr>
<td>$q\bar{q}, gg+g\gamma$</td>
<td>0</td>
<td>2, 6 jets</td>
<td>Yes</td>
<td>36.1</td>
<td>1.7 TeV</td>
</tr>
<tr>
<td>$q\bar{q}, gg+g\gamma$ (compressed)</td>
<td>2</td>
<td>4 jets</td>
<td>Yes</td>
<td>14.7</td>
<td>1.7 TeV</td>
</tr>
<tr>
<td>$q\bar{q}, gg+g\gamma$ (compressed)</td>
<td>3</td>
<td>1 jet</td>
<td>Yes</td>
<td>14.7</td>
<td>1.7 TeV</td>
</tr>
<tr>
<td>GMSB (NLSP)</td>
<td>1</td>
<td>γ</td>
<td>Yes</td>
<td>36.1</td>
<td>1.5 TeV</td>
</tr>
<tr>
<td>GMSB (NLSP)</td>
<td>2</td>
<td>γ</td>
<td>Yes</td>
<td>36.1</td>
<td>1.5 TeV</td>
</tr>
<tr>
<td>GMSB (NLSP)</td>
<td>3</td>
<td>γ</td>
<td>Yes</td>
<td>36.1</td>
<td>1.5 TeV</td>
</tr>
<tr>
<td>GMSB (NLSP)</td>
<td>4</td>
<td>γ</td>
<td>Yes</td>
<td>36.1</td>
<td>1.5 TeV</td>
</tr>
<tr>
<td>GMSB (NLSP)</td>
<td>5</td>
<td>γ</td>
<td>Yes</td>
<td>36.1</td>
<td>1.5 TeV</td>
</tr>
<tr>
<td>Gravitino LSP</td>
<td>6</td>
<td></td>
<td>Yes</td>
<td>20.3</td>
<td>2.05 TeV</td>
</tr>
<tr>
<td>0</td>
<td>monojet</td>
<td>Yes</td>
<td>20.3</td>
<td>2.05 TeV</td>
<td>m($\tilde{g}$)&lt;200 GeV, $m(t\tilde{t})$&lt;600 GeV, $m(t\tilde{t})$&lt;600 GeV</td>
</tr>
</tbody>
</table>

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.
Many ATLAS SUSY analyses

Exclusion plot in the neutralino vs gluino mass plane for prompt RPV decays

Exclusion plot in the neutralino vs gluino mass plane for RPC decays

Dario Barberis: ATLAS sparticles
So what's new here?

- All results in the previous slides are computed with respect to R-parity conserving (RPC) or maximally R-parity violating (RPV) models.
- But in the most generic superpotential, Yukawa couplings can lead to baryon and lepton-number violation:
  \[
  W_{\text{RPV}} = \frac{\lambda_{ijk}}{2} L_i L_j \tilde{E}_k + \lambda'_{ijk} L_i Q_j \tilde{D}_k + \frac{\lambda''_{ijk}}{2} U_i \tilde{D}_j \tilde{D}_k + \kappa_i L_i H_u
  \]
  - where \(i, j,\) and \(k\) are quark and lepton generation indices and the \(\lambda''\) parameters give the strength of the baryon-number violating RPV terms.
- If R-parity is conserved, SUSY particles are produced in pairs and decay to the LSP (the lightest supersymmetric particle \(\tilde{\chi}_1^0\)), which is stable and escapes the detector unseen.
- Non-zero RPV couplings make the LSP unstable and allow decays to SM particles.
  - The LSP lifetime depends on the RPV coupling strength as well as the masses of the superpartners of the quarks (squarks).
    - In the limit where the RPV coupling is vanishingly small the majority of LSP decays occur outside of the detector volume, producing the same experimental signature as RPC SUSY.
    - For high values of the coupling, the LSP decays promptly to jets; as the coupling increases even further, instead direct decays of the heavier SUSY particles dominate.
  - Thus, scaling the value of \(\lambda''\) transitions the SUSY final state through several distinct regimes.
• non-zero baryon-number-violating RPV $\lambda''$ couplings assumed, while lepton-number-violating couplings, $\lambda$ and $\lambda'$ are set to zero.

• **Gqq-Model:** $\lambda''_{112} \neq 0$, masses of 1st and 2nd generation squarks 3 TeV, other sparticle masses $> 5$ TeV $\rightarrow$ multi jet final state

• **Gtt-Model:** $\lambda''_{323} \neq 0$, masses of 3rd generation squarks 2.4 TeV, all other sparticle masses $> 5$ TeV $\rightarrow$ final states with $b$-jets and leptons

• **Stop-Model:** $\lambda''_{323} \neq 0$, light mostly right-handed stop $\rightarrow$ final states with $b$-jets and leptons
• inspired by Split-SUSY scenario
• only gluinos and EWikinos accessible at LHC, all other particles at PeV scale
• squark mediated gluino decays are suppressed (long lifetimes)
• gluinos hadronize to color singlet states – R-hadrons
• decays of the R-hadrons are largely defined by the decay of the underlying gluino
The mean decay length for a bino-like lightest neutralino can be numerically estimated from:

\[ L(\text{cm}) = 0.3(\beta \gamma) \left( \frac{m_\tilde{f}}{100 \text{ GeV}} \right)^4 \left( \frac{1 \text{ GeV}}{m_{\tilde{\chi}^0_1}} \right)^5 \left[ \frac{1}{\lambda_{ijk}^2} \lambda_{ijk}^2 \lambda_{ijk}^3 \right] \]

- Very small couplings produce very long-lived neutralinos (same as the RPC case)
- Larger couplings lead to shorter-lived neutralinos
- Very large couplings produce neutralinos that decay promptly

The impact on the mean decay positions within the detector can be large when we look at missing \( E_T \) and other event observables.

Triggering on missing \( E_T \) has different effects depending mainly on the neutralino lifetime, so on the RPV coupling strength.

Couplings affect lifetimes

\[ m_{\text{eff}} = p_T(\text{leptons}) + p_T(\text{jets}) + E_T^{\text{miss}} \]
Several analyses have been "reinterpreted" to study the dependences of the observed upper limits on the SUSY particle lifetimes and therefore on the λ" parameters.

Many simulated samples were generated to extract new acceptances for displaced vertices.

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:

- Jet energy scale uncertainties for displaced jets
  - The assigned uncertainty is below the percent level for decay lengths below 1 m, grows linearly reaching 30% at 1.6 m, and remains approximately constant until it reaches 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.

- b-tagging uncertainties for displaced jets
  - The extra systematic uncertainty assigned is 10% (20%) for event selections with 2 b-tags (4 b-tags) and signal lifetimes of 1 ns. The size of the uncertainty decreases (increases) for shorter (longer) lifetimes.
**Input analyses**

<table>
<thead>
<tr>
<th>Analysis name</th>
<th>Leptons</th>
<th>Jets / b-tags</th>
<th>$E_T^{\text{miss}}$ requirement</th>
<th>Representative cuts</th>
<th>Model targeted</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPC 0-lepton, 2-6 jets *) [1]</td>
<td>0</td>
<td>$\geq 4 / -$</td>
<td>$E_T^{\text{miss}}/m_{\text{eff}} &gt; 0.2$</td>
<td>$m_{\text{eff}} &gt; 3000$ GeV</td>
<td>Gqq, $R$-hadron</td>
</tr>
<tr>
<td>RPC 0-lepton, 7-11 jets [2]</td>
<td>0</td>
<td>$\geq 7 / -$</td>
<td>$E_T^{\text{miss}}/\sqrt{H_T} &gt; 5$ GeV$^{1/2}$</td>
<td>$- $</td>
<td>Gqq</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\geq 11 / \geq 2$</td>
<td></td>
<td></td>
<td>Gtt</td>
</tr>
<tr>
<td>RPC multi-$b$ [3]</td>
<td>0</td>
<td>$\geq 7 / \geq 3$</td>
<td>$E_T^{\text{miss}} &gt; 350$ GeV</td>
<td>$m_{\text{eff}} &gt; 2600$ GeV</td>
<td>Gtt</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>$\geq 5 / \geq 3$</td>
<td>$E_T^{\text{miss}} &gt; 500$ GeV</td>
<td>$m_{\text{eff}} &gt; 2200$ GeV</td>
<td>Gtt</td>
</tr>
<tr>
<td>RPV 1-lepton [4]</td>
<td>1</td>
<td>$\geq 10 / \geq 4$</td>
<td>$- $</td>
<td>$- $</td>
<td>Gtt, stop</td>
</tr>
<tr>
<td>RPC Stop 0-lepton [5]</td>
<td>0</td>
<td>$\geq 4 / \geq 2$</td>
<td>$E_T^{\text{miss}} &gt; 400$ GeV</td>
<td>$m_{\text{jet},R=1.2} &gt; 120$ GeV</td>
<td>stop</td>
</tr>
<tr>
<td>RPC Stop 1-lepton [6]</td>
<td>1</td>
<td>$\geq 4 / \geq 1$</td>
<td>$E_T^{\text{miss}} &gt; 250$ GeV</td>
<td>$m_T &gt; 160$ GeV</td>
<td>stop</td>
</tr>
<tr>
<td>RPC and RPV same-sign and three leptons [7]</td>
<td>2 SS or 3</td>
<td>$\geq 6 / \geq 2$</td>
<td>$E_T^{\text{miss}}/m_{\text{eff}} &lt; 0.15$</td>
<td>$m_{\text{eff}} &gt; 1800$ GeV</td>
<td>Gtt, stop</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\geq 6 / \geq 2$</td>
<td>$- $</td>
<td>$m_{\text{eff}} &gt; 2000$ GeV</td>
<td>Gtt, stop</td>
</tr>
<tr>
<td>RPV stop dijet pairs [8]</td>
<td>$- $</td>
<td>$\geq 4 / \geq 2$</td>
<td>$- $</td>
<td>$A &lt; 0.05$</td>
<td>stop</td>
</tr>
<tr>
<td>Dijet and TLA [9,10]</td>
<td>$- $</td>
<td>$\geq 2 / -$</td>
<td>$- $</td>
<td>$</td>
<td>y^*</td>
</tr>
</tbody>
</table>

Main characteristics of the most sensitive signal region per analysis. Only an illustrative subset of the cuts that define each signal region are included here. A dash (-) is used to indicate that the variable is not used in the analysis selection. The requirement of two same-sign leptons is denoted as SS.

*) The RPC 0-lepton 2-6 jets analysis was modified to use a relaxed jet cleaning procedure.
**Gqq models**

- RPC OL 2–6 jets, OL 7–11 jets: provide limits on lifetimes down to 1 ns
- Limiting factor: MET cut (with decreasing neutralino lifetime MET decreases)

$\Rightarrow$ intermediate and large $\lambda''_{112}$ not covered

The RPV OL analysis (not shown here) is expected to fill this region.
Gtt models

- many tops in final state $\rightarrow$ moderate MET across whole $\lambda''_{323}$ range
  - RPC $\geq 3$ b-jets: provides strongest limits at small $\lambda''_{323}$. With increasing BR$(g\rightarrow tbs)$ sensitivity drops due to lower MET
  - RPC OL 7-11 jets: stable limits across the whole range
  - RPC-RPV SS/3L: RPV regions improve sensitivity at large $\lambda''_{323}$
  - RPV 1L: provides strongest limits at moderate and high $\lambda''_{323}$

Entire $\lambda''_{323}$ range covered by various analyses, $m$(gluino) limits always $\geq 1.8$ TeV.
Stop models

- **RPC Stop 0L/1L**: best limits at low $\lambda''_{323}$. Absence of high MET quickly reduce sensitivity at moderate lifetimes/$\lambda''_{323}$.
- **RPV1L**: starts to set limits at higher $\lambda''_{323}$, leaving a gap in exclusion
- **Dijet pair**: limits at very high $\lambda''_{323}$
- **Dijet & TLA**: very strong limits 2.4 TeV, since they are sensitive to resonant stop production

Weakest points arise in transitions between the analyses.

Contours of $\chi^0_1$ lifetime and BR(stop→bs), overlaid since they depend on $\lambda''_{323}$ and stop mass values
R-hadron models

\( \tilde{g} (R\text{-hadron}) \rightarrow q\bar{q} \tilde{\chi}_1^0; m(\tilde{\chi}_1^0) = 100 \text{ GeV} \)

**RPC OL 2-6 jets:** places strongest limits for the lowest lifetime values, and provides strong limits until the decay of the R-hadron reaches the calorimeters.

**Pixel dE/dx analysis takes over** as soon as the R-hadron track can be reconstructed before decaying.

R-hadron lifetime

**95% CL limits not included**

**Theory SUSY \( \sigma \)**

**Preliminary ATLAS Status: December 2017**
Conclusions

- 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 $\lambda$:
  - 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.
  - The stop model shows large variations in the limits as well: stops up to 2.4 TeV can be excluded at high values of $\lambda$, but no limits can be established for values of $\lambda \sim 10^{-4}$, 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.

- Future searches with more data can be optimized to further increase the sensitivity throughout the RPV phase-space.
Analysis references

1) RPC 0-lepton, 2-6 jets: arXiv:1712.02332 [hep-ex]
7) RPC and RPV same-sign and 3-leptons (SS/3L): arXiv:1706.03731 [hep-ex]
10) TLA: ATLAS-CONF-2016-030
11) This reinterpretation analysis: ATLAS-CONF-2018-003