Search for R-parity violating supersymmetry with the ATLAS detector
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for the ATLAS Collaboration
Outline

- ATLAS has an extensive search programme for both R-parity conserving (RPC) and violating (RPV) supersymmetric signatures
- I will focus on recent searches aiming primarily on RPV signatures
  - pair-produced resonances in four jets final states [ATLAS-CONF-2017-025]
  - B-L scalar-top pair production [ATLAS-CONF-2017-036]
  - lepton plus high jet multiplicity final state [arXiv:1704.08493]
- other searches with RPV interpretations are presented at EPS and/or can be found on our public results web page
R-parity violation

- definition of $R$-parity

$$P_{R} = (-1)^{3B+L+2s} = (-1)^{3(B-L)+2s}$$

- most general renormalisable, $R$-parity odd superpotential consistent with the gauge symmetry and field content of the MSSM

$$W_{RPV} = \frac{1}{2} \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \kappa_i L_i H_u + \frac{1}{2} \lambda''_{ijk} U^c_i D^c_j D^c_k$$

- acceptable proton decay rate can be assured by other discrete or continuous symmetries or with specific combinations of λ’s
  (e.g. only either lepton or baryon-number violation)
Pair-produced resonances in four jets final states

- **benchmark models**
  - top squark as lightest SUSY particle
  - couplings large enough for prompt decay, but small enough to forbid single-top-squark resonant production

- **signatures**
  - two jet pairs, each possibly containing a bottom quark, with same mass resonances

- **analysis strategy**
  - require at least four central high-momentum jets
  - put mass-dependent requirement on angular distance between jets in pairs $\Delta R_{\text{min}}$
  - define signal regions in angle of resonances to beams in global centre-of-mass frame and mass asymmetry, plus at least two $b$-jets for $\lambda^{''}_{3i3}$ region
  - final discriminant is average mass
  - data-driven multi-jet, MC-based ttbar background estimate
Pair-produced resonances in four jets final states

- **results**
  - no significant excess seen in any signal region
  - top-squark mass exclusion limits
    - 100 — 410 GeV in inclusive selection
    - 100 — 470 GeV and 480 — 610 GeV for decays to $b$-quarks ($b$-tag selection)
  - also place lower-mass limits for
    - pair production of scalar gluons (800 GeV)
    - vector colour octet resonances coupling only to light quarks (1500 GeV)
Lepton plus high jet multiplicity final state

- benchmark models
  - gluino and RH stop pair production
  - prompt decay of all sparticles
  - $\lambda'$ decay with equal light-lepton probability
  - stop pair production considers only pure bino or higgsino LSP (no lepton in wino LSP case)

- signatures
  - isolated lepton ($e, \mu$), $\geq 8-12$ jets, 0 or $\geq 3$ $b$-jets and little $E_T^{\text{miss}}$

- analysis strategy
  - no explicit $E_T^{\text{miss}}$ requirement requires stringent lepton identification and isolation to suppress fake or non-prompt lepton background
  - require at least one lepton ($e, \mu$)
  - dominant $tt\bar{t}$ and $W/Z+jets$ background (using parametrised extrapolations from lower jet multiplicities)
  - bins in jet and $b$-jet multiplicity used in model-dependent multi-bin fit
  - dedicated signal regions used in model-independent test

-- arXiv:1704.08493

13 TeV, 36.1/fb
Lepton plus high jet multiplicity final state

- **results**
  - no significant excess seen in any signal region
  - model-dependent lower limits on mass
    - for gluinos up to between 1.65 and 2.10 TeV (depending on model)
    - for stop up to between 1.1 and 1.25 TeV (depending on LSP nature)
  - also upper limit of 60 fb on four-top-production cross section \((6.5 \times \text{SM prediction})\)
    and model-independent upper limits on visible BSM cross section \(\sigma \cdot A \cdot \varepsilon\)

\[ m_{\text{gluino}} \geq 2.10 \text{ TeV} \quad m(\tilde{g}) \text{ [GeV]} \]

\[ m_{\text{gluino}} \geq 1.65 \text{ TeV} \quad m(\tilde{g}) \text{ [GeV]} \]
results

- no significant excess seen in any signal region
- model-dependent lower limits on mass
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- and model-independent upper limits on visible BSM cross section \((\sigma \cdot A \cdot \varepsilon)\)

\[ m_{\tilde{g}} \geq 1.8 \text{ TeV} \]

\[ m_{\tilde{\chi}^0_1} \geq 1.1 - 1.24 \text{ TeV} \]

\[ m_{\tilde{\chi}^0_1} \geq 1.8 \text{ TeV} \]

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B-L scalar-top pairs

- benchmark models
  - additional local symmetry U(1)$_{B-L}$ (with right-handed neutrino supermultiplets)
  - highly suppressed couplings to prevent short proton lifetimes
  - stop pair production with prompt decays bottom quark and lepton

- signatures
  - two oppositely charged leptons and two $b$-jets

- analysis strategy
  - require at least two leptons ($e, \mu$), at least two jets (at least one $b$-tagged), leading leptons to have opposite charge, and agreement between reconstructed stop masses
  - require small mass asymmetry ($m_{b_{i}}^{\text{asym}} < 0.2$) and choose minimal pairing
  - signal regions defined via larger mass ($m_{b_{i}}^{0} > 800/1100$ GeV)
  - dominant backgrounds (ttbar, single top, Z+jets) estimated from MC normalised to data in control regions
B-L scalar-top pairs

- results
  - no significant excess seen in any signal region
  - multi-bin fit to control and signal regions, performed for various branching ratios
  - also model-independent upper limits on visible cross section of BSM processes
Summary

- ATLAS has an extensive search programme for both R-parity conserving (RPC) and violating (RPV) supersymmetric signatures
- presented a subset of searches aiming primarily on RPV signatures

other searches with RPV interpretations are presented at EPS and/or can be found on our public results web page
Multi-jet final states from gluino pair production

- benchmark models
  - only UDD coupling non-zero
  - gluino pair production independent of λ''
  - all possible λ'' flavour combinations equal
  - prompt gluino and neutralino decays
  - gluino masses between 900 and 1900 GeV, neutralino masses between 50 and 1650 GeV

- signatures
  - high multiplicity of jets, likely at least one bottom or top quark

- analysis strategy
  - require at least four central large-radius jets (anti-\(k_T\), R=1.0)
  - \(b\)-tag, \(b\)-veto, inclusive selection
  - primary signal—background discrimination based on total jet mass \(M_{\Sigma}\) (scalar sum of four leading central large-radius jets)
  - \(|\Delta\eta_{12}|\) to define control and validation regions
  - data-driven jet-mass template method to estimate background

ATLAS Preliminary 14.8 fb\(^{-1}\) data

- Data
- Prediction
- \(m_{\tilde{g}} = 1600\) GeV
- \(m_{\tilde{\chi}_1^0} = 650\) GeV
- \(m_{\tilde{g}} = 1200\) GeV

13 TeV, 14.8/\(fb\) ATLAS-CONF-2016-057

Multi-jet final states from gluino pair production

- **results**
  - no significant excess seen in any signal region
  - limits on gluino mass
    - between 1000 and 1550 GeV in cascade model
    - up to 1080 GeV in direct-decay model
  - also model-independent limits on production cross section

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**cascade model**

- Yellow band: Expected limit ($\pm 1 \sigma_{\text{exp}}$) for $\tilde{g} \rightarrow q\tilde{q}$, $\tilde{g} \rightarrow q\tilde{q}$
- Red band: Observed limit ($\pm 1 \sigma_{\text{SUSY}}$)
- Dashed line: Run 1 limit
- All limits at 95% CL

**direct decay**

- Yellow band: Expected limit ($\pm 1 \sigma_{\text{exp}}$) for $\tilde{g} \rightarrow q\tilde{q}$
- Green bands: Observed limit ($\pm 1 \sigma_{\text{Exp Limit}}$, $\pm 2 \sigma_{\text{Exp Limit}}$)
- Black band: 99 Cross-section (NLO+NLL)

**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV, 14.8 fb$^{-1}$
Pair-produced resonances in four jets final states

\[ \Delta R_{\text{min}} = \sum_{i=1,2} |\Delta R_i - 1| \]

\[ \Delta R_{\text{min}} > -0.002 \cdot (m_{\text{avg}}/\text{GeV} - 225) + 0.72 \quad \text{if } m_{\text{avg}} \leq 225 \text{ GeV} \]

\[ \Delta R_{\text{min}} > +0.0013 \cdot (m_{\text{avg}}/\text{GeV} - 225) + 0.72 \quad \text{if } m_{\text{avg}} > 225 \text{ GeV} \]

\[ \mathcal{A} = \frac{|m_1 - m_2|}{m_1 + m_2} \]

\[ m_{\text{avg}} = \frac{1}{2}(m_1 + m_2) \]
Lepton plus high jet multiplicity final state

- search done with different jet-p_T thresholds (40, 60, 80 GeV)
- b-tag multiplicity shape per jet slice from MC for W/Z+jets and data for ttbar
- model-independent approach assumes no significant signal in low jet-multiplicity bins
- multi-jets fake or non-prompt background estimated using matrix method and data control regions

\[
\begin{align*}
\tilde{t} & \rightarrow t\tilde{\chi}_1^0 \quad \text{bino-like LSP} \\
\tilde{t} & \rightarrow t\tilde{\chi}_2^0 \,(\approx 25\%), \quad \tilde{t} \rightarrow t\tilde{\chi}_1^0 \,(\approx 25\%), \quad \tilde{t} \rightarrow b\tilde{\chi}_1^+ \,(\approx 50\%) \quad \text{higgsino-like LSP} \\
\tilde{t} & \rightarrow \tilde{b}\tilde{s} \quad \text{wino-like LSP, no leptons}
\end{align*}
\]

13 TeV, 36.1 fb arXiv:1704.08493
# Lepton plus high jet multiplicity final state

<table>
<thead>
<tr>
<th>Jet multiplicity</th>
<th>0 b obs. [fb]</th>
<th>0 b exp. [fb]</th>
<th>≥ 3 b obs. [fb]</th>
<th>≥ 3 b exp. [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥ 10 jets ((p_T &gt; 40 \text{ GeV}))</td>
<td>0.32</td>
<td>0.36^{+0.16}_{-0.10}</td>
<td>0.57</td>
<td>0.54^{+0.24}_{-0.15}</td>
</tr>
<tr>
<td>≥ 11 jets ((p_T &gt; 40 \text{ GeV}))</td>
<td>0.17</td>
<td>0.16^{+0.08}_{-0.05}</td>
<td>0.33</td>
<td>0.25^{+0.12}_{-0.07}</td>
</tr>
<tr>
<td>≥ 12 jets ((p_T &gt; 40 \text{ GeV}))</td>
<td>0.08</td>
<td>0.09^{+0.05}_{-0.01}</td>
<td>0.17</td>
<td>0.13^{+0.07}_{-0.04}</td>
</tr>
<tr>
<td>≥ 8 jets ((p_T &gt; 60 \text{ GeV}))</td>
<td>0.73</td>
<td>0.71^{+0.27}_{-0.20}</td>
<td>1.02</td>
<td>1.03^{+0.39}_{-0.29}</td>
</tr>
<tr>
<td>≥ 9 jets ((p_T &gt; 60 \text{ GeV}))</td>
<td>0.35</td>
<td>0.28^{+0.12}_{-0.08}</td>
<td>0.19</td>
<td>0.32^{+0.15}_{-0.09}</td>
</tr>
<tr>
<td>≥ 10 jets ((p_T &gt; 60 \text{ GeV}))</td>
<td>0.12</td>
<td>0.14^{+0.07}_{-0.04}</td>
<td>0.11</td>
<td>0.15^{+0.08}_{-0.04}</td>
</tr>
<tr>
<td>≥ 8 jets ((p_T &gt; 80 \text{ GeV}))</td>
<td>0.38</td>
<td>0.31^{+0.14}_{-0.09}</td>
<td>0.21</td>
<td>0.28^{+0.13}_{-0.08}</td>
</tr>
<tr>
<td>≥ 9 jets ((p_T &gt; 80 \text{ GeV}))</td>
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<td>0.13^{+0.07}_{-0.04}</td>
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<td>0.08^{+0.04}_{-0.00}</td>
<td>0.08</td>
<td>0.08^{+0.04}_{-0.00}</td>
</tr>
</tbody>
</table>
to lower mass signals. Several other kinematic selections, common to both SRs, are defined to reduce the events. The signal regions are optimized using MC signal and background predictions, assuming pairings lead to a more uniform as

The lepton–jet pair of each of them must be consistent with the associated single-lepton trigger. This trigger requirement is highly

factors are applied to events to compensate for di

observables. A fourth VR is constructed to validate the extrapolation of the

provide a statistically independent cross-check of the background prediction in regions with a negligible

kinematic variables. The VRs are disjoint from both the CRs and SRs, and are constructed to fall between

are determined through a likelihood fit 

contamination from other backgrounds and the benchmark signals.

The distribution of predicted signal and background events is shown for the SR800 region in Fig.

The identification, reconstruction, isolation, and trigger e

ID, the electron is removed. Any jet that is not

are removed from consideration in the subsequent steps. If an electron and muon share a track in the

75

are determined through a likelihood fit 

ee

decays, 16% (16%) for events with two

asym

(with correctly reconstructed top masses falling well below the signal region requirements. However, top

background processes involving a top quark is suppressed through the requirement on

ee

! 

b

jets

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m

CR

Z

0

m

VR

m

b

CR

Z

VR

m

b

VR

H

VR

Z

> 1000 GeV

invariant mass of two same-flavor leptons, with \( m_{\ell\ell} > 300 \) GeV

\( m_{b\ell}^{\text{rej}} < 150 \) GeV

\[
\begin{array}{c|ccccc|ccc}
\text{Region} & N_b & m_{b\ell}^0 [\text{GeV}] & m_{b\ell}^1 \text{(rej)} [\text{GeV}] & H_T [\text{GeV}] & m_{\ell\ell} [\text{GeV}] & m_{CT} [\text{GeV}] \\
\hline
\text{SR800} & \geq 1 & > 800 & > 150 & > 1000 & > 300 & - \\
\text{SR1100} & \geq 1 & > 1100 & > 150 & > 1000 & > 300 & - \\
\text{CRtt} & \geq 1 & [200,500] & < 150 & [600,800] & > 300 & < 200^* \\
\text{CRst} & = 2 & [200,500] & < 150 & < 800 & > 120 & > 200 \\
\text{CRZ} & \geq 1 & > 700 & - & > 1000 & [76.2,106.2] & - \\
\hline
\text{VR}m_{b\ell}^0 & \geq 1 & > 500 & < 150 & [600,800] & > 300 & - \\
\text{VR}m_{b\ell}^1 \text{(rej)} & \geq 1 & [200,500] & > 150 & [600,800] & > 300 & - \\
\text{VR}H_T & \geq 1 & [200,500] & < 150 & > 800 & > 300 & - \\
\text{VRZ} & = 0 & [500,800] & > 150 & > 1000 & > 300 & - \\
\end{array}
\]
B-L scalar-top pairs

**ATLAS Preliminary**

\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

SR800

<table>
<thead>
<tr>
<th>Observed yield</th>
<th>\text{ee}</th>
<th>\text{e\mu}</th>
<th>\mu\mu</th>
<th>\text{inclusive}</th>
<th>\text{ee}</th>
<th>\text{e\mu}</th>
<th>\mu\mu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total post-fit bkg yield</td>
<td>5.2 ± 1.4</td>
<td>1.8 ± 0.5</td>
<td>2.1 ± 0.8</td>
<td>1.35 ± 0.32</td>
<td>1.2 ± 0.6</td>
<td>0.51 ± 0.22</td>
<td>0.44 ± 0.39</td>
</tr>
<tr>
<td>Post-fit single-top yield</td>
<td>2.0 ± 1.3</td>
<td>0.6 ± 0.4</td>
<td>1.1 ± 0.7</td>
<td>0.32 ± 0.20</td>
<td>0.32 ± 0.29</td>
<td>0.11 ± 0.10</td>
<td>0.21 ± 0.19</td>
</tr>
<tr>
<td>Post-fit Z+jets yield</td>
<td>1.40 ± 0.33</td>
<td>0.80 ± 0.24</td>
<td>0.01 ± 0.01</td>
<td>0.59 ± 0.14</td>
<td>0.47 ± 0.15</td>
<td>0.28 ± 0.10</td>
<td>–</td>
</tr>
<tr>
<td>Post-fit (tt) yield</td>
<td>1.0 ± 0.5</td>
<td>0.27 ± 0.14</td>
<td>0.54 ± 0.25</td>
<td>0.21 ± 0.10</td>
<td>0.21 ± 0.55</td>
<td>0.06 ± 0.16</td>
<td>0.13 ± 0.34</td>
</tr>
<tr>
<td>Post-fit diboson yield</td>
<td>0.64 ± 0.23</td>
<td>0.14 ± 0.05</td>
<td>0.31 ± 0.12</td>
<td>0.19 ± 0.08</td>
<td>0.13 ± 0.05</td>
<td>0.06 ± 0.03</td>
<td>0.07 ± 0.03</td>
</tr>
<tr>
<td>Post-fit (tt + V) yield</td>
<td>0.12 ± 0.03</td>
<td>0.01 ± 0.01</td>
<td>0.07 ± 0.02</td>
<td>0.04 ± 0.02</td>
<td>0.03 ± 0.01</td>
<td>–</td>
<td>0.01 ± 0.01</td>
</tr>
<tr>
<td>Post-fit (W+jets) yield</td>
<td>0.03 ± 0.03</td>
<td>–</td>
<td>0.04 ± 0.04</td>
<td>–</td>
<td>0.01 ± 0.02</td>
<td>–</td>
<td>0.01 ± 0.02</td>
</tr>
<tr>
<td>Total MC bkg yield</td>
<td>4.9 ± 1.2</td>
<td>1.7 ± 0.4</td>
<td>2.0 ± 0.7</td>
<td>1.23 ± 0.28</td>
<td>1.1 ± 0.6</td>
<td>0.46 ± 0.21</td>
<td>0.43 ± 0.40</td>
</tr>
<tr>
<td>MC single-top yield</td>
<td>1.9 ± 1.0</td>
<td>0.57 ± 0.34</td>
<td>1.0 ± 0.6</td>
<td>0.29 ± 0.17</td>
<td>0.29 ± 0.25</td>
<td>0.10 ± 0.08</td>
<td>0.19 ± 0.17</td>
</tr>
<tr>
<td>MC Z+jets yield</td>
<td>1.15 ± 0.21</td>
<td>0.65 ± 0.17</td>
<td>0.01 ± 0.01</td>
<td>0.48 ± 0.09</td>
<td>0.38 ± 0.10</td>
<td>0.23 ± 0.07</td>
<td>–</td>
</tr>
<tr>
<td>MC (tt) yield</td>
<td>1.1 ± 0.5</td>
<td>0.29 ± 0.14</td>
<td>0.57 ± 0.26</td>
<td>0.22 ± 0.10</td>
<td>0.29 ± 0.57</td>
<td>0.07 ± 0.18</td>
<td>0.14 ± 0.36</td>
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<td>0.12 ± 0.03</td>
<td>0.01 ± 0.01</td>
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<td>–</td>
<td>0.01 ± 0.02</td>
<td>–</td>
<td>0.01 ± 0.02</td>
</tr>
</tbody>
</table>

\[ \Delta_{\text{BSM}} \text{ exp (95\% CL)} = 6.4^{+3.0}_{-1.9} \times 4.1^{+1.8}_{-1.1} \times 4.0^{+2.2}_{-0.9} \times 3.9^{+1.6}_{-0.7} \times 3.9^{+2.4}_{-0.5} \times 3.0^{+1.3}_{-0.0} \times 3.0^{+1.3}_{-0.0} \times 3.1^{+0.6}_{-0.1} \]

\[ \Delta_{\text{BSM}} \text{ obs (95\% CL)} = 4.0 \times 3.0 \times 3.0 \times 4.8 \times 3.9 \times 3.0 \times 3.1 \times 4.1 \]

\[ \sigma_{\text{BSM}} \text{ [fb]} = 0.11 \times 0.08 \times 0.08 \times 0.13 \times 0.11 \times 0.08 \times 0.08 \times 0.11 \]

\text{13 TeV, 36.1 fb} \text{ ATLAS-CONF-2017-036}