Search for R-parity violating SUSY and long lived particles with the ATLAS detector

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Precision SM measurements support baryon and lepton number conservation, yet some MSSM couplings do not.

R-parity is an additional symmetry placed on MSSM that forbids such couplings generically.

Precision SM measurements rule out some RPV SUSY couplings, but collider searches are needed to cover full parameter space.
Lepton and high jet multiplicity

**ATLAS-CONF-2017-013**

- single lepton / large jet multiplicity
- 0-4+ bjets
- dominant bkgd: ttbar, W/Z + jets
- data driven bkgd estimate:
  - find b jet multiplicity templates at lower jet multiplicities
  - extrapolate to high jet multiplicity using scaling parameterization
Lepton and high jet multiplicity (cont…)

• no excess is seen
• limits set in various 2D mass planes.

<table>
<thead>
<tr>
<th>Process</th>
<th>≥ 8 jets</th>
<th>≥ 9 jets</th>
<th>≥ 10 jets</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0b</td>
<td>≥ 3 b</td>
<td>0b</td>
</tr>
<tr>
<td>tt+jets</td>
<td>4.0 ± 1.7</td>
<td>15.7 ± 2.3</td>
<td>0.44 ± 0.21</td>
</tr>
<tr>
<td>W+jets</td>
<td>9.0 ± 2.9</td>
<td>0.18 ± 0.07</td>
<td>1.2 ± 0.7</td>
</tr>
<tr>
<td>Others</td>
<td>2.3 ± 0.9</td>
<td>2.4 ± 0.7</td>
<td>0.16 ± 0.05</td>
</tr>
<tr>
<td>Z+jets</td>
<td>1.7 ± 0.5</td>
<td>0.06 ± 0.02</td>
<td>0.23 ± 0.14</td>
</tr>
<tr>
<td>Multijet</td>
<td>0.8 ± 0.4</td>
<td>&lt; 0.01</td>
<td>0.30 ± 0.15</td>
</tr>
<tr>
<td>Total Bkd. Data</td>
<td>17.8 ± 2.9</td>
<td>18.4 ± 2.2</td>
<td>2.3 ± 0.9</td>
</tr>
<tr>
<td>p_0 (σ)</td>
<td>0.27 (0.8)</td>
<td>0.5 (0)</td>
<td>0.34 (0.4)</td>
</tr>
</tbody>
</table>

gluino → neutralino

gluino → stop

stop → neutralino
Pair produced resonances to 4j

**ATLAS-CONF-2017-025**

- Two jet pairs formed from $\Delta R_{\text{min}}$
- $m_{\text{avg}}$ of jet pairs is used as discriminating variable
- Use ABCD method with $\mathcal{A}$ and $|\cos(\theta^*)|$
- Background: QCD (data driven)
• no excess is seen
• limits set for both inclusive/b-tag stop selections, as well as inclusive coloron model
Different flavor high-mass dileptons


\[ \nu \rightarrow e\mu \]

- 2 isolated leptons
- different flavor/charge

- Background:
  - WW, ttbar, single top, Z+jets
  - fake lepton (W+jet, QCD)

\begin{tabular}{|c|c|c|}
\hline
\textbf{Process} & \textbf{me} < 600 GeV & \textbf{me} > 600 GeV \\
\hline
Top quark & 1190 \pm 140 & 22 \pm 5 \\
Diboson & 159 \pm 17 & 4.9 \pm 0.9 \\
Multi-jet and W+jets & 55 \pm 11 & 2.7 \pm 1.7 \\
Z/\gamma^* \rightarrow \ell\ell & 14.5 \pm 2.0 & 0.18 \pm 0.04 \\
Total SM background & 1410 \pm 150 & 30 \pm 7 \\
SM+Z' (M_{Z'} = 2 \text{ TeV}) & - & 75 \pm 13 \\
SM+\bar{\nu}_\tau (M_{\bar{\nu}_\tau} = 2 \text{ TeV}) & - & 40 \pm 8 \\
SM+QBH RS n = 1 (M_{QBH} = 2 \text{ TeV}) & - & 44 \pm 9 \\
Data & 1463 & 25 \\
\hline
\end{tabular}

(a) e\mu channel

\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline
\textbf{Model} & \textbf{Expected Limit [TeV]} & \textbf{Observed Limit [TeV]} \\
& \textbf{e\mu} & \textbf{e\tau} & \textbf{\mu\tau} & \textbf{e\mu} & \textbf{e\tau} & \textbf{\mu\tau} \\
\hline
Z' & 3.2 & 2.7 & 2.6 & 3.0 & 2.7 & 2.6 \\
RPV SUSY \bar{\nu}_\tau & 2.5 & 2.1 & 2.0 & 2.3 & 2.2 & 1.9 \\
QBH ADD n = 6 & 4.6 & 4.1 & 3.9 & 4.5 & 4.1 & 3.9 \\
QBH RS n = 1 & 2.5 & 2.2 & 2.1 & 2.4 & 2.2 & 2.1 \\
\hline
\end{tabular}
There is no reason to expect most BSM particles to have negligible lifetime (i.e. prompt).

- non-negligible lifetimes arise from:
  - Small couplings, heavy mediators, small mass splittings, etc…
  - for example wino-like LSP scenarios favor long-lived charginos with lifetimes of a fraction of a ns
- semi-stable decays inside the detector typically require non-standard analyses
Disappearing track

ATLAS-CONF-2017-017

- look for high pT partial track in ID
- IBL allows for pixel tracklets
- SM Background:
  - hadronic decay, photon emission, combinatoric
  - smear standard tracks to reproduce pixel tracklet pT spectrum
  - fit and extrapolate pT spectra
Disappearing track (cont…)

• no excess is seen
• limits set for both strong and electroweak production

High $E_T^{miss}$ region

<table>
<thead>
<tr>
<th>Electroweak channel</th>
<th>Strong channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(m_{\tilde{\chi}^\pm}, \tau_{\tilde{\chi}^\pm}) = (400 \text{ GeV}, 0.2 \text{ ns})$</td>
<td>$(m_{\tilde{g}}, m_{\tilde{\chi}^\pm}, \tau_{\tilde{\chi}^\pm}) = (1600 \text{ GeV}, 500 \text{ GeV}, 0.2 \text{ ns})$</td>
</tr>
</tbody>
</table>

Number of observed events with $p_T > 100 \text{ GeV}$

| Hadron+electron background | $6.1 \pm 0.6$ | $2.08 \pm 0.35$ |
| Muon background | $0.1549 \pm 0.0022$ | $0.0385 \pm 0.0005$ |
| Fake background | $5.5 \pm 3.3$ | $0.0 \pm 0.8$ |
| Total background | $11.8 \pm 3.1$ | $2.1 \pm 0.9$ |
| Expected signal | $10.4 \pm 1.7$ | $4.1 \pm 0.5$ |
| CL$_B$ | 0.39 | 0.702 |
| Observed $\sigma_{vis}^{95\%}$ [fb] | $0.22$ | $0.14$ |
| Expected $\sigma_{vis}^{95\%}$ [fb] | $0.24^{+0.10}_{-0.07}$ | $0.11^{+0.06}_{-0.04}$ |

Hadron+electron background

Total background

Expected signal

CL$_B$
ATLAS-CONF-2017-026

- re-run ID tracking with loosened IP constraints
- low background:
  - hadronic interactions
  - random track crossing
  - merged vertices
- uses data-driven methods to predict all backgrounds

Displaced multi-track vertices

- ATLAS Preliminary
- $\sqrt{s} = 13$ TeV, $L = 32.7$ fb$^{-1}$

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**reco. eff.**

- ATLAS Simulation Preliminary
- $\sqrt{s} = 13$ TeV
- Split-SUSY Model, $\tilde{q} \rightarrow q \tilde{\chi}_1^0$,
- $R$-hadron: $m(\tilde{g}) = 1200$ GeV, $m(\tilde{q}) = 100$ GeV, $\tau = 1$ ns

**material veto**

- ATLAS Preliminary
- $\sqrt{s} = 13$ TeV, $L = 32.7$ fb$^{-1}$
- $2\tau$-hadron:

**combinatoric crossing**

- ATLAS Preliminary
- $\sqrt{s} = 13$ TeV, $L = 32.7$ fb$^{-1}$, Region0

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N. Bernard
• no excess is seen
• limits set as function of neutralino $\tau$, and in $\tau$-gluino mass plane
Heavy long lived charged R-hadrons

• R-hadron mass from p and $\beta/\beta\gamma$ measurements
• $\beta\gamma$ from dE/dx measurement in silicon pixel
• $\beta$ from time-of-flight in tile calorimeter
• data-driven bkgd estimate (pdf of p, $\beta,\beta\gamma$ in sideband randomly sampled)

• Background:
  • large dE/dx track (i.e. cosmic muon or $Z\rightarrow\mu\mu$)

Metastable heavy charged particles

ATLAS
\( \sqrt{s} = 13 \text{ TeV} \)
- Data Pixel w/o IBL
- Data Pixel
- MC Pixel w/o IBL
- MC Pixel

Selection region | Background exp. | Data
--- | --- | ---
Metastable \( R \)-hadron | 11.1 ± 1.7 ± 0.7 | 11
Stable \( R \)-hadron | 17.2 ± 2.6 ± 1.2 | 16

\( \tau: 10 \text{ ns} \)

\( \tau - m \)

ATLAS
\( \sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \)
- metastable \( \tilde{g} (\tau = 10 \text{ ns}) \)

\( g \rightarrow Q \bar{Q}, \ m(Q) = 100 \text{ GeV} \)

\( \chi^2 > \chi^2_{\text{cut}}, m(Q) = 100 \text{ GeV} \)

\( \text{Background:} \)
- jets/leptons with large ionization
- overlapping tracks


- \( R \)-hadron mass from ionization energy left in silicon
- IBL layer narrows dE/dx distribution
- data-driven bkgd estimation
Long lived neutral particles decaying in HCAL

- dedicated cal-ratio trigger
- BDT selects signal based on jet log($E_H/E_{EM}$), etc…
- 2 cal-ratio jets passing BDT

Background:
- Non-collision bkgd, QCD multijet

<table>
<thead>
<tr>
<th>Region</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>Estimated $A = BC/D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR : $p_T,1 &gt; 150$ GeV; $p_T,2 &gt; 120$ GeV :</td>
<td>24</td>
<td>16</td>
<td>39</td>
<td>34</td>
<td>$18.0 \pm 6.3$</td>
</tr>
<tr>
<td>VR : $p_T,1 &gt; 140$ GeV; $80$ GeV $&lt; p_T,2 &lt; 120$ GeV :</td>
<td>15</td>
<td>14</td>
<td>84</td>
<td>77</td>
<td>$15.3 \pm 4.7$</td>
</tr>
<tr>
<td>BDT boundary $= 0.15$</td>
<td>42</td>
<td>38</td>
<td>57</td>
<td>53</td>
<td>$40 \pm 10$</td>
</tr>
<tr>
<td>BDT boundary $= 0.2$</td>
<td>72</td>
<td>64</td>
<td>27</td>
<td>27</td>
<td>$60 \pm 19$</td>
</tr>
</tbody>
</table>

**ATLAS-CONF-2016-103**

ATLAS Preliminary

- $\gamma^* \rightarrow ss\Phi \rightarrow s\bar{s}f\bar{f}$
- $\Phi$ proper decay length $[m]$
- $s \sim 2 - 10^{-1}$
- $m_\Phi \sim 1 - 10^3$ GeV
- BDT selects signal based on jet log($E_H/E_{EM}$), etc…
- 2 cal-ratio jets passing BDT
- Background: Non-collision bkgd, QCD multijet

**Global Efficiency**

<table>
<thead>
<tr>
<th>$s$ proper decay length [m]</th>
<th>0.001</th>
<th>0.01</th>
<th>0.1</th>
<th>1</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{BR}{\sigma} \times 10^9$</td>
<td>0.05</td>
<td>0.04</td>
<td>0.03</td>
<td>0.02</td>
<td>0.01</td>
</tr>
</tbody>
</table>

**95% CL Upper Limit on $\alpha \times BR$ [pb]**

<table>
<thead>
<tr>
<th>$s$ proper decay length [m]</th>
<th>0.001</th>
<th>0.01</th>
<th>0.1</th>
<th>1</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{BR}{\sigma} \times 10^9$</td>
<td>1</td>
<td>0.5</td>
<td>0.1</td>
<td>0.05</td>
<td>0.01</td>
</tr>
</tbody>
</table>

**ATLAS Preliminary**

- $\sqrt{s} = 13$ TeV, $3.2$ fb$^{-1}$
- $s$-jet passes CalRatio trigger
- $m_\Phi = 600$ GeV
- $m_\gamma = 100$ GeV
- $m_\gamma = 150$ GeV
- $m_\gamma = 200$ GeV
- $m_\gamma = 250$ GeV
- $m_\gamma = 600$ GeV
- $m_\gamma = 400$ GeV
- $m_\gamma = 50$ GeV
- $m_\gamma = 100$ GeV
- $m_\gamma = 500$ GeV
- $m_\gamma = 1000$ GeV

**ATLAS Preliminary**

- $\sum BDT = 0.15$
- $\sum BDT = 0.1$
- $\sum BDT = 0.05$

**ATLAS Preliminary**

- $\sum BDT = 0.15$
- $\sum BDT = 0.1$
Displaced lepton jets

- low mass $\gamma_d$ leaves collimated decay products.
- dedicated HLT narrow scan muon trigger
- ABCD method removes background (LJ iso - $\Delta\phi$)
- Background:
  - QCD, cosmic muons, Non-collision bkgd

### Table

<table>
<thead>
<tr>
<th>Category</th>
<th>Observed events</th>
<th>Expected background</th>
</tr>
</thead>
<tbody>
<tr>
<td>All events</td>
<td>285</td>
<td>$231 \pm 12 \text{ (stat)} \pm 62 \text{ (syst)}$</td>
</tr>
<tr>
<td>Type2–Type2 excluded</td>
<td>46</td>
<td>$31.8 \pm 3.8 \text{ (stat)} \pm 8.6 \text{ (syst)}$</td>
</tr>
<tr>
<td>Type2–Type2 only</td>
<td>239</td>
<td>$241 \pm 41 \text{ (stat)} \pm 65 \text{ (syst)}$</td>
</tr>
</tbody>
</table>

**ATLAS-CONF-2016-042**

**2$\gamma_d$**

**4$\gamma_d$**
• RPV SUSY and long lived particle searches are crucial for maximizing the ATLAS program’s sensitivity to BSM physics.

• Such analyses are often difficult and require non-standard techniques, but there are already numerous interesting results for Run II.

• These results have chipped away at the relevant parameter spaces, but there is still a lot of space left!