Search for R-parity violating SUSY signatures with the ATLAS detector

SEARCH2012, Maryland

Shimpei Yamamoto (Univ. of Tokyo)
on behalf of the ATLAS collaboration

Outline

1. Introduction
2. RPV-SUSY searches at ATLAS
3. Summary
1. Introduction
Unexpected SUSY?

- SUSY with R-parity \((\equiv (-1)^{3(B-L)+2S})\) conservation (RPC) is really popular:
  - Provides elegant solutions to the dark matter and hierarchy problems.
  - Leads to natural GUT.

- But currently one can squeeze the parameter space:
  - No significant excess of events having large missing transverse momentum (Etmiss) at LHC searches.
  - Indication of \(m_H \sim 125\text{GeV}\).
  - Flavor constraints from \(b \to s \gamma\), \(B \to \tau \nu\), \(B_s \to \mu \mu\) etc.
  - Constraints from dark matter direct detection experiments.

- Some viable RPC models still survive, but we certainly must all possibilities.
R-parity violating SUSY

- There's no reason why R-parity should be exactly conserved... R-parity violating (RPV) terms are allowed in the superpotential:

\[
W = W_{MSSM} + \lambda_{ijk} L_i L_j \tilde{E}_k + \lambda'_{ijk} L_i Q_j \tilde{D}_k + \kappa_i L_i H_u + \lambda''_{ijk} \tilde{U}_i \tilde{D}_j \tilde{D}_k
\]

Lepton number violating (LNV)  
Baryon number violating (BNV)

- If all terms appear, proton becomes unstable...

\[
\tau_p \propto \frac{|\lambda'| |\lambda''|}{M_{SUSY}^2}
\]

- “Part of them need not to be zero” → Proton still stable & rich phenomenology
  - Resonant/associated single SUSY particle production is possible.
  - The lightest SUSY particle (LSP) is no longer stable.
    - Etmiss is diluted (or absent!)

- R-parity has played some roles.... advantages and disadvantages:
  - No dark matter candidate :
  - Could explain large mixing angles and hierarchical masses of neutrinos :-))
**RPV signatures**

So, what we’re looking for is...

<table>
<thead>
<tr>
<th>Signature</th>
<th>RPV scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>multileptons ((ee\mu\nu))</td>
<td>(\tilde{\chi}_1^0 - \text{LSP}(\lambda), \tilde{\tau} - \text{LSP}(\lambda))</td>
</tr>
<tr>
<td>multiple (\tau)s</td>
<td>(\tilde{\chi}_1^0 - \text{LSP}(\lambda), \tilde{\tau} - \text{LSP}(\lambda'))</td>
</tr>
<tr>
<td>like-sign dileptons</td>
<td>(LLE(\lambda), LQ\bar{D}(\lambda'))</td>
</tr>
<tr>
<td>dilepton resonance ((ll'))</td>
<td>(LLE \otimes LQ\bar{D}(\lambda\lambda'))</td>
</tr>
</tbody>
</table>
| late-decaying \(\tilde{\chi}_1^0\) | \(\tilde{\chi}_1^0 - \text{LSP}(\lambda), \tilde{\chi}_1^0 - \text{LSP}(\lambda')\) | (LNV)
| ...                                | ...                                               |

Also for bilinear RPV\((\kappa)\) and BNV \(\lambda''\).
RPV signatures

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<td>$L\tilde{L}$</td>
</tr>
<tr>
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</tr>
</tbody>
</table>

Also for **bilinear RPV** ($\kappa$) and **BNV** ($\lambda''$).
2. RPV-SUSY searches
Multilepton final state

NEW! 2 fb$^{-1}$
ATLAS-CONF-2012-035
4-lepton search

- Very low SM background, high signal-to-background ration
  - Promising channel to find something new!
  - Interpretations using the results already reported (ATLAS-CONF-2012-001)

**Selection:**
1. Single-lepton trigger followed by offline $p_T$ cut
   - $>25$ GeV for electron
   - $>20$ GeV for muon
2. 4 leptons with $p_T>10$ GeV
3. $E_T^\text{miss} > 50$ GeV
4. $|M_{SFOS(*)-M_Z}| > 10$ GeV (Z-veto)

(*) Same Flavor Opposite Sign

<table>
<thead>
<tr>
<th></th>
<th>w/o Z-veto</th>
<th>W/ Z-veto</th>
</tr>
</thead>
<tbody>
<tr>
<td>BG exp.</td>
<td>1.7±0.9</td>
<td>0.7±0.8</td>
</tr>
<tr>
<td>Observed</td>
<td>4</td>
<td>0</td>
</tr>
</tbody>
</table>

Limits on visible cross section of BSM: $<3.5(1.5)$ fb w(w/o) Z-veto
**BG breakdown**

- Very high S/B ratio, but hard to estimate SM BG processes with very low rates.
  - BG estimation fully based on MC.
  - Validation regions to confirm that nothing goes wrong in the BG model.

<table>
<thead>
<tr>
<th></th>
<th>≥4 leptons + Etmiss&gt;50GeV</th>
<th>+ Z-veto</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ttbar</strong></td>
<td>0.17±0.14</td>
<td>0.13±0.11</td>
</tr>
<tr>
<td><strong>single t</strong></td>
<td>0±0.04</td>
<td>0±0.04</td>
</tr>
<tr>
<td><strong>ttbar+V</strong></td>
<td>0.48±0.21</td>
<td>0.07±0.04</td>
</tr>
<tr>
<td><strong>ZZ</strong></td>
<td>0.44±0.19</td>
<td>0.019±0.020</td>
</tr>
<tr>
<td><strong>WZ</strong></td>
<td>0.25±0.10</td>
<td>0.09±0.05</td>
</tr>
<tr>
<td><strong>WW</strong></td>
<td>0±0.015</td>
<td>0±0.015</td>
</tr>
<tr>
<td><strong>Zγ</strong></td>
<td>0±0.5</td>
<td>0±0.5</td>
</tr>
<tr>
<td><strong>Z+LF-jets</strong></td>
<td>0.33±0.67</td>
<td>0.33±0.67</td>
</tr>
<tr>
<td><strong>Z+HF-jets</strong></td>
<td>0.024±0.035</td>
<td>0.024±0.035</td>
</tr>
<tr>
<td><strong>Drell-Yan</strong></td>
<td>0±0.05</td>
<td>0±0.05</td>
</tr>
<tr>
<td><strong>BG Total</strong></td>
<td>1.7±0.9</td>
<td>0.7±0.8</td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td>4</td>
<td>0</td>
</tr>
</tbody>
</table>

**Validation samples**
- **ZZ**: 4 leptons + low Etmiss(<50GeV)
  - MC : 23±5
  - Data : 20
- **Top**: 2 OFOS leptons + 2 fakes (reversed isolation) + 1 b-tagged jet.
  - MC : 8.4±0.8
  - Data : 8

“Z+light-flavor jets” dominates and large uncertainty due the limited MC statistics.
Signal Model

- BC1-like \( \tan \beta \)-\( m_{1/2} \) grid with \( \tilde{\tau} \)-LSP (hep-ph/0609263, arXiv:1008.1580v2)
  - \( m_0 = A_0 = 0, \mu > 0, \lambda_{121} = 0.032 \) (at \( M_{\text{GUT}} \))

- Production mode:
  - Strong, weak( \( \tilde{\chi}^0, \tilde{\chi}^{\pm} \)), stau-pair; slepton-pair

- Decay channel:

<table>
<thead>
<tr>
<th>Mass [GeV]</th>
<th>Channel</th>
<th>BR</th>
<th>Channel</th>
<th>BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tilde{\tau}^- )</td>
<td>148</td>
<td>( \tau^-\mu^+e^-\nu_{e} )</td>
<td>50.1%</td>
<td>( \tau^-e^+\nu_{\mu} )</td>
</tr>
<tr>
<td>( \tilde{e}_R^- )</td>
<td>161</td>
<td>( e^-\nu_{\mu} )</td>
<td>50.0%</td>
<td>( \mu^-\nu_{e} )</td>
</tr>
<tr>
<td>( \tilde{\mu}_R^- )</td>
<td>161</td>
<td>( \tilde{\tau}_1^\pm\tau^+\mu^- )</td>
<td>99.9%</td>
<td></td>
</tr>
<tr>
<td>( \tilde{\chi}_1^0 )</td>
<td>162</td>
<td>( \tilde{\tau}_1^\pm\tau^+ )</td>
<td>99.6%</td>
<td></td>
</tr>
</tbody>
</table>

\( m_{1/2} = 400 \text{GeV}, \tan \beta = 13 \) (BC1 benchmark)

- Final state:
  - \( 2e^\pm, 2(e \text{ or } \mu), 2\text{taus} + \text{Etmiss} \)

4-body decay
Production process

- Weak prod. dominates for most of parameter space.
- Stau-pair prod. dominates at high-\(\tan \beta\) region.

**Figure 11:** Relative contribution to the signal expectation from strong production (top left), gaugino-\(\tilde{\tau}\) (bottom left) and other production processes as a function of \(m_{\tilde{\tau}}\) and \(m_{1/2}\). The solid shaded areas are excluded from this analysis, see Figure 4.

LEP limit (\(m_{\text{stau}}>81.9\text{GeV}\))

Higgs bound

Neutralino-LSP

tachyonic stau
Interpretation

- Selection cuts with Z-veto.
- Limits on BC1-like grid:
  - $m_{1/2} < \sim 800\text{GeV}$ (corresponding gluino mass $\sim 1770\text{GeV}$) for $\tan\beta < 40$

(Poor acceptance for $\tan\beta > 40$ due to a small 4-body decay branch and a significant lifetime of stau.)
2. RPV-SUSY searches

\[ e - \mu \] resonance
RPV tau sneutrino with LNV-decay:

- **Signature:** \( e^- \mu^+ \) resonance
  - Excess expected in \( m_{e\mu} \) distribution
  - Low SM background.

\[
\lambda'_{311} \neq 0 \land \lambda_{312} \neq 0
\]

- **Selection:**
  - Exactly one electron and one muon with “opposite-sign charge”
  - No requirements on jets and Etmiss
**BG estimate**

- SM background processes:
  - \( Z/\gamma^* (\rightarrow \tau\tau) \), top, diboson
  - Estimated using MC

- Instrumental background (**jet/\gamma faking to a lepton**)
  - \( W/Z+\gamma \) by MC
  - QCD/W+jets background derived using a data-driven matrix method:

\[
\begin{bmatrix}
N_{TT} \\
N_{TL} \\
N_{LT} \\
N_{LL}
\end{bmatrix} =
\begin{bmatrix}
rr & rf & fr & ff \\
(1-r)r & (1-f)r & (1-f)r & (1-f)fr \\
(1-r)r & (1-f)r & (1-f)f & (1-r)f(1-f) \\
(1-r)(1-r) & (1-r)(1-f) & (1-f)(1-r) & (1-f)(1-f)
\end{bmatrix}
\begin{bmatrix}
N_{RR} \\
N_{RF} \\
N_{FR} \\
N_{FF}
\end{bmatrix}
\]

1) Define loose/tight lepton definitions apply on all events to get \( N_{TT}, N_{TL}, N_{LT} \) and \( N_{LL} \).
2) Estimate efficiency \( (r) \) and fake rate \( (f) \) for a lepton that has passed the loose definition to also pass the tight definition.
3) Solve 4×4 matrix and obtain \( RF, FR, FF \) contributions to \( TT \).

The efficiency “\( r \)” is measured using \( Z \rightarrow ll \) events selected with one tight (tag) and one loose (probe) leptons with \( 80 < m_{ll} < 100 \text{GeV} \).

The jet fake rate “\( f \)” is measured using QCD jet events; e.g. for electrons

- Select two same-sign electrons passing loose criteria but one fails tight (tag).
- Veto real lepton from Z: \( m_{ee} < 70 \text{ or } > 110 \text{GeV}, \Delta \phi_{ee} > 2 \)
Results

- Primary contributions to the systematic uncertainty on the BG estimation come from the theoretical cross section uncertainties.
  - 12% for top pair production (dominant BG) and 5-10% for the others.

**Table: Process Number of events**

<table>
<thead>
<tr>
<th>Process</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>ttbar</td>
<td>1580 ± 170</td>
</tr>
<tr>
<td>Jet fake (QCD, W+jets)</td>
<td>1175 ± 120</td>
</tr>
<tr>
<td>Z/\gamma^* (\rightarrow \tau\tau)</td>
<td>750 ± 60</td>
</tr>
<tr>
<td>WW</td>
<td>380 ± 31</td>
</tr>
<tr>
<td>single t</td>
<td>154 ± 16</td>
</tr>
<tr>
<td>W/Z+\gamma</td>
<td>82 ± 13</td>
</tr>
<tr>
<td>ZZ</td>
<td>22.4 ± 2.3</td>
</tr>
<tr>
<td>BG total</td>
<td>4145 ± 250</td>
</tr>
</tbody>
</table>

**Data**

|         | 4053 |

Result: no significant excess observed. (KS-test prob: 56%)
Interpretations

- Limits on $\sigma(pp \rightarrow \tilde{\nu}_\tau) \times BR(\tilde{\nu}_\tau \rightarrow e\mu)$ as a function of $m_{\tilde{\nu}_\tau}$
  - tau-sneutrino having a mass below 1.32 (1.45) TeV are excluded assuming $\lambda'_{311} = 0.10(0.11)$ and $\lambda_{312} = 0.05(0.07)$
- Limits on $\lambda'_{311}$ coupling as a function of $m_{\tilde{\nu}_\tau}$ for various values of $\lambda_{312}$
  - sneutrino mass $> 270$ GeV assuming $\lambda_{312} = 0.07$ (most stringent limit to date)
2. RPV-SUSY searches
Late-decaying $\tilde{\chi}_1^0$-LSP
Neutralino-LSP decay

- $\tilde{\chi}_1^0$ could decay via non-zero $\lambda, \lambda'$ couplings:
  
  \[
  LL\overline{E}(\lambda) : \tilde{\chi}_1^0 \rightarrow ll' + \nu
  \]
  
  \[
  LQ\overline{D}(\lambda') : \tilde{\chi}_1^0 \rightarrow \left( e, \mu, \tau \right) + 2 \text{ jets}
  \]

- The lifetime is proportional to $(\lambda)^{-2}, (\lambda')^{-2}$
  - Decay prompt for $\lambda, \lambda' \approx 10^{-5}$.
  - If the RPV coupling is smaller than that (e.g. $\approx 10^{-7}$), a decay vertex with a significant distance from its production point can be seen.

→ Perform a search using a displaced vertex (DV) reconstruction technique.
  - The result presented today is based on 2010 data, non-zero $\lambda'$ with muon final states.
  - More to come using 2011 full dataset covering variety of signatures:
    - Final states including e/tau
Displaced vertex

- **Vertexing:**
  1. Select tracks with \( p_T > 1 \text{GeV} \) and \( |d_0| > 2 \text{mm} \) wrt the primary vertices (PVs).
  2. Make 2-track “seed” vertices.
  3. Make all possible N-track combinations, then iteratively split, merge, remove tracks etc. until there are no tracks shared between vertices.

- **Selection:**
  1. Vertex in \( |z| < 300 \text{mm} \) and \( r < 180 \text{mm} \)
  2. Vertex \( \chi^2/\text{DOF} < 5 \)
  3. \( |r_{DV} - r_{PV}| > 4 \text{mm} \)
  4. One muon with \( p_T > 45 \text{GeV} \)
  5. Material veto (hadronic interactions, dominant background)

**Efficiency**

- \( m_q = 700 \text{ GeV} \), \( m_\chi = 494 \text{ GeV} \)
- \( m_q = 700 \text{ GeV} \), \( m_\chi = 108 \text{ GeV} \)
In addition, the and distributions of data and MC events in the control region.

Figure 5: Comparison of the $N_{\text{VTX}^{\text{trk}}}$ and $r_{\text{DV}}$ in control region (no material veto)

Data/MC reasonably agree. Materials are well described in MC.
Result & interpretation

- **Signal region:**
  - \( m_{DV} > 10 \text{GeV} \)
  - # of tracks in DV \( \geq 4 \)
- **SM MC background expectation**
  - \( N_{BG} < 0.03 \)
- **No signal observed.**

- **Exclude** \( \varepsilon \times \sigma_{DV} > 0.09 \text{pb} @95\% \text{ CL} \)
- **Interpretation** \( (\lambda'_{2ij} \neq 0) \):
  - \( m(\text{squark}) = 150 \text{GeV} \) excluded.
  - Limits on \( \tilde{\chi}_1^0 \) lifetime

![Signal region](image)

![Cross-section x B.F.](image)
2. RPV-SUSY searches
LNV with bilinear terms
Bilinear RPV

- Bilinear RPV (bRPV) terms introduce neutrino masses and mixings.
  - Currently constrained by neutrino oscillation experiments.

- bRPV terms can be embedded in any RPC-SUSY model:
  - bRPV in mSUGRA:
    - Same cascades as in RPC scenarios
    - LSP may decay, but results in "lepton+Emiss+jets" final states (most of LSP decays involve leptons/taus/neutrinos).
    - bRPV parameters are motivated by the neutrino oscillation parameters.
    - bRPV interpretation based on the 1-lepton analysis result with 1 fb⁻¹.
- **Signal region:**
  - Exactly one isolated muon with $p_T > 20\text{GeV}$
  - (electrons are highly suppressed in the model)
  - $\geq 4$ jets with $p_T > 40\text{GeV}$
  - Leading jet with $p_T > 60\text{GeV}$
  - $\Delta\phi$ (jets, $E_{T_{miss}}$) $> 0.2$
  - $M_T > 100\text{GeV}$
  - $E_{T_{miss}} > 200\text{GeV}$
  - $E_{T_{miss}}/M_{eff} > 0.15$
  - $M_{eff} > 500\text{GeV}$

**SR & BG estimate**

**BG estimation:**
- **$W+jets$, top**
  - Normalize MC to data in background specific control regions (WR,TR).

<table>
<thead>
<tr>
<th></th>
<th>WR</th>
<th>TR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Delta\phi$ (jets, $E_{T_{miss}}$) $&gt; 0.2$</td>
<td>$40 &lt; M_T &lt; 80\text{GeV}$</td>
</tr>
<tr>
<td>$30 &lt; E_{T_{miss}} &lt; 80\text{GeV}$</td>
<td>$M_{eff} &gt; 300\text{GeV}$</td>
<td>$N(b\text{-jet})=0$</td>
</tr>
<tr>
<td>$M_{eff} &gt; 300\text{GeV}$</td>
<td>$N(b\text{-jet})\geq 1$</td>
<td>$N(b\text{-jet})=0$</td>
</tr>
</tbody>
</table>

- Extrapolate to Signal Regions using MC shapes
- **QCD** by the matrix method.
bRPV interpretations were done in “1-lepton + Etmiss” RPC-SUSY search.
- Observed: 7
- BG exp.: 6±2.7
Summary

- No sign of RPC SUSY yet... unexpected SUSY could be there.
- R-parity is conserved or violated?
  - Pros and cons on both.
  - RPC-SUSY parameter space is being squeezed... all possibilities should be considered.

- ATLAS is trying to cover possible RPV signatures:
  - 4 results were presented in context of LLE, LQD and bilinear RPV (LNV) SUSY.
  - Many analyses are being performed.
    - More to come in coming months (BNV, variety of signatures...)

- Also keep a close eye on 8TeV collision data to find something unexpected!!
Backup
Before applying Etmiss cut, 24 events remain.
- Branching ratio of stau 4-body decay and lifetime.

In this Appendix, the characteristics of the BC1-like model are illustrated. Figure 4 shows the regions theoretically forbidden region producing tachyons, a region with a four-body decay (left) and the $\tilde{\tau}_1$ lifetime (right) as a function of $\tan\beta$. Figure 5 shows the lifetime and the four-body decay branching fraction of the $\tilde{\tau}_1$.

The solid shaded areas are excluded from this analysis, while Figure 5 shows the lifetime and the four-body decay branching fraction of the $\tilde{\tau}_1$.

Some details of the expected analysis results are shown in this Appendix. Figure 6 shows the expected fractional contribution to SR2 from each process group after the full event selection.