Search for Signs of R-Parity Violating Supersymmetry in Multilepton Events with the ATLAS Detector

Max Goblirsch

IMPRS Young Scientists’ Workshop, Ringberg 2013

24.07.2013
Supersymmetry (SUSY) as an extension of the standard model

(One) Motivation: The Hierarchy Problem

- Higgs vacuum mass receives loop corrections from possible high-scale new physics
- Corrections scale $\propto \Lambda_{UV}^2$ with the cutoff scale
- Corrections scale $\propto m^2$ with masses of particles
- Recently, the Higgs mass was measured to be $m_H \sim 125$ GeV
- Planck-scale new physics: $M_{Pl}^2$ contributions fine-tuned down by 34 orders of magnitude?

**Possible Solution:** Symmetry

- Find a symmetry that automatically leads to cancellation of the loop terms
- Corrections from Bosons and Fermions have opposite signs
- Idea of a symmetry assigning a matching boson to every fermion

$^1$ pending sudden experimental evidence on the contrary
Supersymmetry (SUSY) as an extension of the standard model

Introduce a new symmetry transformation $Q$:

$$Q|\text{fermion}\rangle = |\text{boson}\rangle; \quad Q|\text{boson}\rangle = |\text{fermion}\rangle$$

→ Assign each particle in the standard model a **supersymmetric partner**
  - spins differ by $\frac{1}{2}$
  - all other properties unchanged

→ If there is SUSY, it must be a **broken** symmetry.

### Experimentally Observed

<table>
<thead>
<tr>
<th>Quarks</th>
<th>Gauge Bosons</th>
<th>Higgs Bosons</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u$</td>
<td>$\gamma$</td>
<td>$h^0$</td>
</tr>
<tr>
<td>$t$</td>
<td>$Z^0$</td>
<td>$H^0$</td>
</tr>
<tr>
<td>$d$</td>
<td>$W^\pm$</td>
<td>$A^0$</td>
</tr>
<tr>
<td>$b$</td>
<td>$\nu_e$</td>
<td></td>
</tr>
<tr>
<td>$s$</td>
<td>$\nu_\mu$</td>
<td></td>
</tr>
<tr>
<td>$c$</td>
<td>$\nu_\tau$</td>
<td></td>
</tr>
</tbody>
</table>

### Not Observed so far

<table>
<thead>
<tr>
<th>Gauginos</th>
<th>Squarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{\chi}_1^0$</td>
<td>$\tilde{u}$</td>
</tr>
<tr>
<td>$\tilde{\chi}_1^\pm$</td>
<td>$\tilde{c}$</td>
</tr>
<tr>
<td>$\tilde{\chi}_2^0$</td>
<td>$\tilde{d}$</td>
</tr>
<tr>
<td>$\tilde{\chi}_2^\pm$</td>
<td>$\tilde{s}$</td>
</tr>
<tr>
<td>$\tilde{\chi}_3^0$</td>
<td>$\tilde{\nu}_e$</td>
</tr>
<tr>
<td>$\tilde{\chi}_4^0$</td>
<td>$\tilde{\nu}_\mu$</td>
</tr>
<tr>
<td>$\tilde{\tau}$</td>
<td>$\tilde{\nu}_\tau$</td>
</tr>
</tbody>
</table>

Max Goblirsch (Ringberg 2013)
Writing down the allowed interaction terms in a (minimal) supersymmetric standard model, something interesting appears:

\[ W_{\Delta B,L} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k + \kappa_i L_i H_d \]

- \( i,j,k \): generation indices
- \( \lambda, \lambda', \lambda'', \kappa \): couplings.
- \( L, Q \): left-handed lepton/quark superfields (contain leptons and sleptons / quarks and squarks)
- \( E, D, U \): right handed lepton/ up-type quark / down-type quark superfields
- \( H_d \): Higgs superfield coupling to down-type fermions

Baryon and Lepton number (accidentally conserved in SM) violated

\( \lambda' \) and \( \lambda'' \) can mediate rapid proton decay

Max Goblirsch (Ringberg 2013)
\[ W_{\Delta B,L} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k + \kappa_i L_i H_d \]

What can we do about these terms?

**Minimal supersymmetric standard model (MSSM):** Impose conservation of a new quantum number, **R-Parity**

\[ R_P = (-1)^{2s+3(B-L)} \begin{cases} +1 & (\text{particles}) \\ -1 & (\text{sparticles}) \end{cases} \]

**Consequences of R-Parity Conservation (RPC)**

- B/L violating terms forbidden
- SUSY particles can only be created in pairs
- the lightest SUSY particle (LSP) is **stable** and electrically neutral

→ dark matter candidate!
Typical MSSM SUSY searches

- Conserved R-Parity: SUSY Particles produced in **pairs**
- Cascade decays to the LSP and standard model particles
- finally, the LSPs escape the detector
  → apparent non-conservation of transverse momentum: $E_T^{\text{Miss}} = |\sum \vec{p}_T| > 0$

**Typical Search strategy:** Cascade particles and high $E_T^{\text{Miss}}$
The situation today

- 2 years of searches at $\sqrt{s} = 7/8$ TeV
- Wide variety of search channels
- common result: everything **consistent** with standard model

Many popular models almost completely excluded
No SUSY (within our reach)?
Or is it cleverly hidden?

### ATLAS SUSY Searches* - 95% CL Lower Limits

**Status:** LP 2013

<table>
<thead>
<tr>
<th>Model</th>
<th>e, $\mu$, $\tau$, $\gamma$, Jets</th>
<th>$E_{\text{miss}}^T$</th>
<th>$\int L , \text{dt} [fb^{-1}]$</th>
<th>Mass limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSUGRA/CMSSM</td>
<td>1 e, $\mu$, $\tau$, $\gamma$, 3-6 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.2 TeV</td>
<td>any $m(\tilde{q})$</td>
</tr>
<tr>
<td>MSUGRA/CMSSM</td>
<td>0</td>
<td>7-10 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.1 TeV</td>
</tr>
<tr>
<td>$\tilde{q}_1$, $\tilde{q}_2$</td>
<td>0</td>
<td>2-6 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>$740$ GeV</td>
</tr>
<tr>
<td>$\tilde{q}_1$, $\tilde{q}_2$</td>
<td>0</td>
<td>3-6 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>$1.3$ TeV</td>
</tr>
<tr>
<td>$\tilde{q}_1$, $\tilde{q}_2$</td>
<td>1 e, $\mu$, $\tau$, $\gamma$, $3qW$</td>
<td>Yes</td>
<td>20.3</td>
<td>$1.18$ TeV</td>
<td>$m(\tilde{q})$, $m(\tilde{\chi}_1^0)$</td>
</tr>
<tr>
<td>$\tilde{q}_1$, $\tilde{q}_2$</td>
<td>2 e, $\mu$, $\tau$, $\gamma$, 3 jets</td>
<td>Yes</td>
<td>20.7</td>
<td>$1.1$ TeV</td>
<td>$m(\tilde{q})$, $m(\tilde{\chi}_1^0)$</td>
</tr>
<tr>
<td>GMSB (f NLSP)</td>
<td>2 e, $\mu$, $\tau$, $\gamma$, 0-2 jets</td>
<td>Yes</td>
<td>20.7</td>
<td>$1.24$ TeV</td>
<td>$m(\tilde{q})$, $m(\tilde{\chi}_1^0)$</td>
</tr>
<tr>
<td>GMSB (f NLSP)</td>
<td>0</td>
<td>2 e, $\mu$, $\tau$, $\gamma$, 0-2 jets</td>
<td>Yes</td>
<td>20.7</td>
<td>$1.4$ TeV</td>
</tr>
<tr>
<td>GGM (bino NLSP)</td>
<td>$\gamma$</td>
<td>1 b</td>
<td>Yes</td>
<td>4.8</td>
<td>$1.07$ TeV</td>
</tr>
<tr>
<td>GGM (bino NLSP)</td>
<td>$\gamma$</td>
<td>0</td>
<td>Yes</td>
<td>4.8</td>
<td>$619$ GeV</td>
</tr>
<tr>
<td>GGM (higgsino-bino NLSP)</td>
<td>$\gamma$</td>
<td>1 b</td>
<td>Yes</td>
<td>4.8</td>
<td>$600$ GeV</td>
</tr>
<tr>
<td>GGM (higgsino NLSP)</td>
<td>0</td>
<td>2 e, $\mu$, $\tau$, $\gamma$, 0-3 jets</td>
<td>Yes</td>
<td>5.8</td>
<td>$635$ GeV</td>
</tr>
<tr>
<td>Gravitino LSP</td>
<td></td>
<td></td>
<td>Yes</td>
<td>13.2</td>
<td>$300$ GeV</td>
</tr>
<tr>
<td>$\tilde{g} \rightarrow b\ell \tilde{Z}$</td>
<td>0</td>
<td>3 b</td>
<td>Yes</td>
<td>20.1</td>
<td></td>
</tr>
<tr>
<td>$\tilde{g} \rightarrow t\bar{t} \tilde{Z}$</td>
<td>0</td>
<td>7-10 jets</td>
<td>Yes</td>
<td>20.3</td>
<td></td>
</tr>
<tr>
<td>$\tilde{g} \rightarrow b\tilde{g}$</td>
<td>0</td>
<td>3 b</td>
<td>Yes</td>
<td>20.3</td>
<td></td>
</tr>
<tr>
<td>$\tilde{g} \rightarrow t\bar{t} \tilde{g}$</td>
<td>0</td>
<td>3 b</td>
<td>Yes</td>
<td>20.3</td>
<td></td>
</tr>
<tr>
<td>$\tilde{g} \rightarrow tt\tilde{g}$</td>
<td>0</td>
<td>3 b</td>
<td>Yes</td>
<td>20.3</td>
<td></td>
</tr>
</tbody>
</table>

### 3rd gen. squarks

**Direct production**

| $b_1$, $b_2$, $b_3$ | 0 | 2 b | Yes | 20.1 | $b_1$, $b_2$, $b_3$ | 100-630 GeV | ATLAS-CONF-2013-053 |
| $b_1$, $b_2$, $b_3$ | 2 e, $\mu$, $\tau$, $\gamma$, 0-3 b | Yes | 20.3 | $b_1$, $b_2$, $b_3$ | 430 GeV | ATLAS-CONF-2013-037 |
| $b_1$, $b_2$, $b_3$ | 1 e, $\mu$, $\tau$, $\gamma$, 0-3 b | Yes | 20.3 | $b_1$, $b_2$, $b_3$ | 167 GeV | ATLAS-CONF-2013-037 |
| $b_1$, $b_2$, $b_3$ | 1 e, $\mu$, $\tau$, $\gamma$, 0-3 b | Yes | 20.3 | $b_1$, $b_2$, $b_3$ | 220 GeV | ATLAS-CONF-2013-037 |
| $b_1$, $b_2$, $b_3$ | 1 e, $\mu$, $\tau$, $\gamma$, 0-3 b | Yes | 20.3 | $b_1$, $b_2$, $b_3$ | 150-440 GeV | ATLAS-CONF-2013-037 |
| $b_1$, $b_2$, $b_3$ | 1 e, $\mu$, $\tau$, $\gamma$, 0-3 b | Yes | 20.3 | $b_1$, $b_2$, $b_3$ | 150-580 GeV | ATLAS-CONF-2013-037 |
| $b_1$, $b_2$, $b_3$ | 1 e, $\mu$, $\tau$, $\gamma$, 0-3 b | Yes | 20.3 | $b_1$, $b_2$, $b_3$ | 200-510 GeV | ATLAS-CONF-2013-037 |
| $b_1$, $b_2$, $b_3$ | 1 e, $\mu$, $\tau$, $\gamma$, 0-3 b | Yes | 20.3 | $b_1$, $b_2$, $b_3$ | 320-600 GeV | ATLAS-CONF-2013-037 |
| $b_1$, $b_2$, $b_3$ | 1 e, $\mu$, $\tau$, $\gamma$, 0-3 b | Yes | 20.3 | $b_1$, $b_2$, $b_3$ | 300-600 GeV | ATLAS-CONF-2013-037 |
| $b_1$, $b_2$, $b_3$ | 1 e, $\mu$, $\tau$, $\gamma$, 0-3 b | Yes | 20.3 | $b_1$, $b_2$, $b_3$ | 500 GeV | ATLAS-CONF-2013-037 |
| $b_1$, $b_2$, $b_3$ | 1 e, $\mu$, $\tau$, $\gamma$, 0-3 b | Yes | 20.3 | $b_1$, $b_2$, $b_3$ | 520 GeV | ATLAS-CONF-2013-037 |

### 3rd gen. sparticle production

| $b_1$, $b_2$, $b_3$ | 0 | 3 b | Yes | 20.3 | | ATLAS-CONF-2013-053 |
| $b_1$, $b_2$, $b_3$ | 3 e, $\mu$, $\tau$, $\gamma$, 0-3 b | Yes | 20.3 | | ATLAS-CONF-2013-053 |
| $b_1$, $b_2$, $b_3$ | 3 e, $\mu$, $\tau$, $\gamma$, 0-3 b | Yes | 20.3 | | ATLAS-CONF-2013-053 |

Max Goblirsch (Ringberg 2013)

Multilepton RPV SUSY

24.07.2013 6 / 22
R-Parity violation

Subject of growing interest: R-Parity violation (RPV)

- Drop the assumption of R-Parity conservation, allow (some of) the terms we encountered earlier
- Proton stabilized in other ways (no fundamental problems)

$$W_{RPV} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k + \kappa_i L_i H_d$$

Consequences of R-Parity violation

- The LSP no longer needs to be stable and neutral
- Lose dark matter candidate
- SUSY particles can decay into standard model particles
- Could escape traditional, $E_T^{\text{Miss}}$ based searches
One promising search channel: Multileptons

\[ W_{\text{RPV}} = \lambda_{ijk} L_i L_j \bar{E}_k + \ldots \]

- \( \lambda_{ijk} \) terms: L-violating slepton-lepton-neutrino vertex
- allow for the LSP to decay into leptons and neutrinos!
- example: \( \lambda_{121} > 0 \): \( \chi_1^0 \to e^+ \mu^- \nu_e \)
- lower \( E_T^{\text{miss}} \) compared to 'conventional' SUSY scenarios, as LSP decays produce visible particles, but at least 4 leptons
Study **Simplified RPV models**

→ simplified: only 2 SUSY particles contribute
- **Bino-like neutralino** ($\tilde{\chi}_1^0$) LSP
- One next-to-lightest SUSY particle (NLSP) (several choices)
- all other sparticles **decoupled** to very high masses (4.5 TeV)

Choose a **single** $\lambda_{ijk}$ parameter to be non zero
→ study $\lambda_{121}, \lambda_{122}, \lambda_{133}, \lambda_{233}$ as representative sample

- expect at least 4 leptons + $E_T^{\text{miss}}$
The ATLAS detector

- High Luminosity, multi purpose detector at the Large Hadron Collider in Geneva
- Record p-p-collisions at $\sqrt{s} = 7\,(2011)/8\,(2012)$ TeV
- Total dataset: $4.7\text{fb}^{-1}\,(2011)/20.4\text{fb}^{-1}\,(2012)$
The ATLAS detector

High Luminosity, multi purpose detector at the Large Hadron Collider in Geneva

Record p-p-collisions at $\sqrt{s} = 7(2011)/8(2012)$ TeV
Which **Standard Model processes** do we need to consider as backgrounds?

- separate based on number of **prompt** (from the primary interaction) leptons

### 4 prompt leptons
- Di- and Triboson production ($Z\bar{Z}$, $WWZ$)
- Higgs decays ($H \rightarrow 4\ell$, $ZH \rightarrow WWZ \rightarrow 4\ell 2\nu$)
- Estimate contributions using Monte-Carlo simulation

### fewer than 4 prompt leptons
- $Z$+jets (secondary leptons from jets)
- Top quark pairs (secondary leptons from $b \rightarrow c\ell\nu$)
- Di/Triboson processes ($WW$, $WZ$, $WWW$)
- Estimate contributions using data-driven techniques

Challenge: Suppress background as much as possible while avoiding rejection of signal events
Event Selection

Main requirement:

- At least 4 isolated leptons
  - isolated leptons: not surrounded by further activity (jets)
  - effect: separate prompt from secondary leptons

hadronic tau decays

- 7 out of 9 possible $\lambda_{ijk}$ indices contain third generation ($i/j/k = 3$) indices
- to be sensitive, need to take tau lepton decays into account
- allow a hadronic tau decay ($\tau \to W^*\nu; \ W^* \to$ hadrons) to replace one lepton
- challenging separation from jets - multivariate techniques
- 2 event categories: $4\ell, \ 3\ell 1\tau \ (\ell = e, \mu)$

<table>
<thead>
<tr>
<th>$ij$</th>
<th>$k = 1$</th>
<th>$k = 2$</th>
<th>$k = 3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ij = 12$</td>
<td>$ee\nu/e\mu\mu$</td>
<td>$e\mu\nu/\mu\mu\nu$</td>
<td>$e\tau\nu/\tau\tau\nu$</td>
</tr>
<tr>
<td>$ij = 13$</td>
<td>$e\nu/e\tau\nu$</td>
<td>$e\mu\nu/\mu\tau\nu$</td>
<td>$e\nu/e\tau\nu$</td>
</tr>
<tr>
<td>$ij = 23$</td>
<td>$e\nu/e\tau\nu$</td>
<td>$e\mu\nu/\mu\tau\nu$</td>
<td>$e\nu/e\tau\nu$</td>
</tr>
</tbody>
</table>
Veto of Z bosons

- Many backgrounds contain lepton pairs from $Z \rightarrow \ell\ell$ decays
- Apply a **Z veto**: Reject events containing a lepton pair with invariant mass within 10 GeV of the Z resonance
- no significant effect on signal, powerful suppression of background

Final selection

- Use properties of SUSY events
  - neutrinos from LSP decay: moderate $E_T^{\text{Miss}}$
  - cascade activity: many high momentum objects
- useful quantity: **effective mass** $m_{\text{eff}} = \sum_{\text{leptons}} |\vec{p}_T| + \sum_{\text{jets}} |\vec{p}_T| + E_T^{\text{Miss}}$
- require $E_T^{\text{Miss}}$ or $m_{\text{eff}}$ to pass a certain threshold
- almost complete suppression of standard model processes, high efficiency on signal
**Results**

- **4ℓ0τ event category:**
  - main surviving background: 4 prompt leptons
  - very low background expectation - expect 1.6 SM events
  - observe 1 event - in agreement with SM

---

Max Goblirsch  (Ringberg 2013)  
Multilepton RPV SUSY  
24.07.2013 15 / 22
$3\ell 1\tau$ event category:

- events with non-prompt leptons become important background
- jets misidentified as hadronic taus
- overall background level again very low (2 events)
- observe 4 events
- well within uncertainty of the background estimation ($\rho_0 = 0.13$)
No excess over SM observed, place upper limits on possible signal

- exclusion plot: region excluded within the model at 95% CL
- area to the left of the red band is **excluded**
- for $\lambda_{121} > 0$: strongest exclusion.
- Only $e, \mu$ in final states, high acceptance and efficiency
for $\lambda_{133} > 0$: weaker limits

- tau decays in all possible final states
  - more challenging, reduced selection efficiency

\[
\begin{align*}
\text{Observed limit (} \pm 1 \sigma_{\text{theory}}) \\
\text{Expected limit (} \pm 1 \sigma_{\exp}) \\
\text{not explored}
\end{align*}
\]

$\int L \, dt = 20.7 \, \text{fb}^{-1}, \sqrt{s} = 8 \, \text{TeV}$

All limits at 95% CL
The story so far

- Conventional RPC SUSY searches at the LHC observe no deviation from the SM
- Non-observation is starting to exclude the most popular models
- Searches have been extended into the realm of R-Parity violation
- and again, no signs of SUSY
- Are we done until 2015?

Max Goblirsch (Ringberg 2013)
One more loophole!

- So far, we considered the case where $\lambda$ is of a sufficient magnitude for prompt LSP decays
- what happens when we go to lower values?

- study finite LSP lifetimes
- main concept: finite lifetime $\rightarrow$ decay vertex is spatially displaced from the interaction point
- How far does the sensitivity of the 4-lepton search reach?
- requirements that reject displaced leptons from $b$ decays and cosmic muons will then reject signal
- If our sensitivity runs out, can we complement it somehow?
- what is our maximum reach?
Preliminary study

- Simulate LSP lifetimes from 0.001 to 10000 ps
- study acceptance of the 4l analysis
- also study acceptance of a potential complementary analysis

→ **displaced lepton pairs**: look for two leptons coming from a displaced vertex

- 4 leptons lose sensitivity at 1 ps
- displaced lepton pairs become sensitive above 20 ps
- total reach: up to $10^4$ ps - LSPs start to decay outside the tracking volume
Conclusions, Outlook

- **SUSY** is a hot topic for LHC searches
  - possible solution to the **Hierarchy problem**
  - most natural models (low fine tuning) expect masses in the TeV range or below

- Recent searches have set strong limits on conventional, R-Parity conserving SUSY
  - already straining the boundaries of natural SUSY

- Extend scope of searches - **R-Parity violation**
  - New signatures, including **Multilepton** events
  - could have been missed by conventional searches

- Next step - **Long lived signatures**
  - can be caused by a weak RPV coupling
  - could have been missed by all previous ATLAS analyses . . .
  - SUSY could still be hiding in plain sight