Search for supersymmetry via resonant final states with the ATLAS detector

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Overview

- Introduction
- RPV sneutrino search in the $e\mu$ final state
- Scalar gluon search in the four jets final state
- Conclusion
ATLAS Detector

Muon Detectors  Tile Calorimeter  Liquid Argon Calorimeter

Toroid Magnets  Solenoid Magnet  SCT Tracker  Pixel Detector  TRT Tracker
Introduction to RPV Sneutrino Search

- R-parity in SUSY: \( R = (-1)^{3(B-L)+2S} \)
  - SM particles have \( R = 1 \), SUSY particles have \( R = -1 \)
- R-parity conservation \( \rightarrow \) SUSY particles are produced in pair
- R-parity violation \( \rightarrow \) lepton/baryon number violation, and singly-produced SUSY particles decaying to SM-only particles
- If B or L violations don’t happen at the same, proton will still be stable
- R-parity violating SUSY:
  - automatically generates neutrino masses and mixings
  - provides a possible way to understand the anomalies related to \( b \) to \( s \) transition (Phys Rev D 78 015009, 2008)
Introduction to RPV Snuetrino Search

\[ W_{\bar{\nu}p} = \frac{1}{2} \varepsilon_{ab} \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{E}_k + \varepsilon_{ab} \lambda'_{ijk} \hat{L}_i \hat{Q}_j \hat{D}_k + \frac{1}{2} \varepsilon_{\alpha\beta\gamma} \lambda''_{ijk} \hat{U}_i \hat{D}_j \hat{D}_k \]

- **L, Q**: doublet superfields of leptons and quarks
- **E, U and D**: singlet superfields of leptons, up and down type quarks
- **\( \lambda \)**: Yukawa couplings with \( i, j, k \) refer to fermion generation

Search for RPV sneutrino production with lepton number violating decay
- tau sneutrino \( \rightarrow e\mu \) (non-zero couplings \( \lambda'_{311}, \lambda_{312} \), and tau sneutrino is the LSP)
- \( e\mu \) channel considered due to its clean detector signature and low SM bkgs
- Tau sneutrinos used due to strong limits from other low energy experiments

Previous limits (\( \lambda'_{311} < 0.11, \lambda_{312} < 0.07 \) assuming \( M_{\text{squark}} = M_{\text{slepton}} = 100 \text{ GeV} \)) obtained from tau lepton branching ratio measurements at low energy

No u-quarks involved in the initial state due to the LQD term in the superpotential
Tau Sneutrino

- $d\bar{d} \rightarrow \tilde{\nu}_\tau \rightarrow e\mu$ events are generated with Herwig plus Jimmy

- LO cross section (assuming $\lambda'_{311}=0.11$ and $\lambda_{312}=0.07$):
  - 153 pb for sneutrino mass of 100 GeV (0.34 pb at the Tevatron)
  - 0.03 pb for sneutrino mass of 1 TeV

- NLO-LO k-factor:
  - Decreases from 1.6 to 1.3 for sneutrino mass from 100 GeV to 1 TeV

- Detector signature for the tau sneutrino signal:
  - Isolated electron and muon with opposite sign charge
  - High $e\mu$ invariant mass
  - Narrow width (~1 GeV for 1 TeV tau sneutrino)
  - Nearly back-to-back in azimuthal direction
  - Low jet multiplicity
  - Low missing transverse energy
Event Selection

- \( L = 0.87 \text{ fb}^{-1}\) (taken from March to June 2011)
- Triggered by a set of single electron and muon triggers

**Electron:**
- \( p_T > 25 \text{ GeV} \)
- In the calorimeter fiducial region: \( |\eta| < 1.37 \text{ or } 1.52 < |\eta| < 2.47 \)
- Isolated in the EM calorimeter
- Pass the shower shape requirement

**Muon:**
- \( p_T > 25 \text{ GeV, } |\eta| < 2.4 \)
- Reconstructed both in the inner tracker and in the muon spectrometer
- Isolated in the inner tracker

- Exactly one electron and one muon in the event with opposite-sign charge
- No requirements placed on the number of jets and missing transverse energy (to make the search more generic)
Backgrounds

- **Physics backgrounds** (with real electron and muon in the final state):
  - $Z/\gamma^* \rightarrow \tau\tau$, top pair, single top, $WW$, $WZ$ and $ZZ$
  - Estimated using MC simulation corrected for data/MC differences
- **Instrumental backgrounds** (mainly electron or (and) muon come from a jet or a photon):
  - W/Z+\gamma: estimated using MC simulation
  - QCD dijet, W/Z+jets: estimated using data-driven 4×4 matrix method
    - Define loose and tight lepton definitions
    - Apply on all events to get $N_{TT}$, $N_{TL}$, $N_{LT}$, $N_{LL}$
    - Determine efficiency ($\varepsilon$) and fake rate ($f$) for a lepton that has passed the loose definition to also pass the tight definition
  - Solve 4×4 matrix to get $N_{RR}$, $N_{RF}$, $N_{FR}$, $N_{FF}$

$$
\begin{bmatrix}
N_{TT} \\
N_{TL} \\
N_{LT} \\
N_{LL}
\end{bmatrix} =
\begin{bmatrix}
rr & rf & fr & ff \\
r(1-r) & r(1-f) & f(1-r) & f(1-f) \\
(1-r)r & (1-r)f & (1-f)r & (1-f)f \\
(1-r)(1-r) & (1-r)(1-f) & (1-f)(1-r) & (1-f)(1-f)
\end{bmatrix}
\begin{bmatrix}
N_{RR} \\
N_{RF} \\
N_{FR} \\
N_{FF}
\end{bmatrix}
$$
### Data and MC predictions

<table>
<thead>
<tr>
<th>Process</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z/\gamma^* \rightarrow \tau\tau$</td>
<td>$614 \pm 53$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$1281 \pm 168$</td>
</tr>
<tr>
<td>$WW$</td>
<td>$318 \pm 24$</td>
</tr>
<tr>
<td>Single top</td>
<td>$125 \pm 17$</td>
</tr>
<tr>
<td>$WZ$</td>
<td>$18.2 \pm 1.9$</td>
</tr>
<tr>
<td>$W/Z + \gamma$</td>
<td>$67 \pm 11$</td>
</tr>
<tr>
<td>Jet instrumental background</td>
<td>$984 \pm 105$</td>
</tr>
<tr>
<td>Total background</td>
<td>$3408 \pm 230$</td>
</tr>
<tr>
<td>Data</td>
<td>$3338$</td>
</tr>
</tbody>
</table>

Good agreement between data and MC for all events
Data and MC predictions (I)
KS test probability: 56%
Data are consistent with the absence of a new physics signal
Electron $p_T = 341$ GeV
Muon $p_T = 216$ GeV
$M_{e\mu} = 662$ GeV
Missing $E_T = 132$ GeV

Highest mass $e\mu$ event
## Data and MC predictions

<table>
<thead>
<tr>
<th>$m_{e\mu}$ (GeV)</th>
<th>Data</th>
<th>SM prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 200</td>
<td>224</td>
<td>236 ± 21</td>
</tr>
<tr>
<td>&gt; 250</td>
<td>119</td>
<td>111 ± 11</td>
</tr>
<tr>
<td>&gt; 300</td>
<td>51</td>
<td>55 ± 6</td>
</tr>
<tr>
<td>&gt; 350</td>
<td>29</td>
<td>30 ± 4</td>
</tr>
<tr>
<td>&gt; 400</td>
<td>18</td>
<td>14.2 ± 2.2</td>
</tr>
<tr>
<td>&gt; 450</td>
<td>9</td>
<td>8.2 ± 1.5</td>
</tr>
<tr>
<td>&gt; 500</td>
<td>7</td>
<td>5.3 ± 1.1</td>
</tr>
<tr>
<td>&gt; 550</td>
<td>3</td>
<td>3.4 ± 0.8</td>
</tr>
<tr>
<td>&gt; 600</td>
<td>3</td>
<td>2.2 ± 0.7</td>
</tr>
<tr>
<td>&gt; 650</td>
<td>1</td>
<td>0.9 ± 0.4</td>
</tr>
<tr>
<td>&gt; 700</td>
<td>0</td>
<td>0.8 ± 0.4</td>
</tr>
</tbody>
</table>

**Good agreement between data and predictions for events with high $e\mu$ invariant mass**
## Systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>Fractional uncertainty (%)</th>
<th>Relations with backgrounds</th>
<th>Relation with signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>4.5%</td>
<td>related to all bkg samples</td>
<td>related</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>1%</td>
<td>related to all bkg samples</td>
<td>related</td>
</tr>
<tr>
<td>Electron reco and ID efficiency</td>
<td>2%</td>
<td>related to all bkg samples</td>
<td>related</td>
</tr>
<tr>
<td>Muon reco and ID efficiency</td>
<td>1%</td>
<td>related to all bkg samples</td>
<td>related</td>
</tr>
<tr>
<td>$Z/\gamma^* \rightarrow \tau\tau$ cross section</td>
<td>5%</td>
<td>related to $Z/\gamma^* \rightarrow \tau\tau$ sample</td>
<td>unrelated</td>
</tr>
<tr>
<td>$ZZ$ cross section</td>
<td>5%</td>
<td>related to $ZZ$ sample</td>
<td>unrelated</td>
</tr>
<tr>
<td>$WW$ cross section</td>
<td>5%</td>
<td>related to $WW$ sample</td>
<td>unrelated</td>
</tr>
<tr>
<td>$WZ$ cross section</td>
<td>7%</td>
<td>related to $WZ$ sample</td>
<td>unrelated</td>
</tr>
<tr>
<td>$t\bar{t}$ cross section</td>
<td>12%</td>
<td>related to $t\bar{t}$ sample</td>
<td>unrelated</td>
</tr>
<tr>
<td>$Wt$ cross section</td>
<td>12%</td>
<td>related to $Wt$ sample</td>
<td>unrelated</td>
</tr>
<tr>
<td>$W\gamma$ cross section</td>
<td>10%</td>
<td>related to $W\gamma$ sample</td>
<td>unrelated</td>
</tr>
<tr>
<td>$Z\gamma$ cross section</td>
<td>10%</td>
<td>related to $Z\gamma$ sample</td>
<td>unrelated</td>
</tr>
</tbody>
</table>
Limits

- Cross section limit: 130 fb at 100 GeV and 11 fb at 1 TeV
- Tau sneutrinos with a mass below 0.44 (0.65) TeV are excluded assuming $\lambda'_{311}=0.01, \lambda_{312}=0.01$ and $\lambda'_{311}=0.10, \lambda_{312}=0.05$
- The limits obtained extend 7 (14) times beyond the previous ATLAS results using 35 pb$^{-1}$ of data (PRL 106, 251801, 2011)
- Limits on $\lambda'_{311}$ are better than the D0 results for sneutrino mass $>270$ GeV assuming $\lambda_{312}=0.07$
Introduction to Scalar Gluon Search

- Challenging to search for SUSY with fully hadronic final states without leptons and missing transverse energy.
- Pair production of scalar gluon (sgluon) occurs in several models: MRSSM, the N=1/N=2 hybrid model, SM extension with new gauge group “hypercolor” etc.
- Sgluon cross section implemented as an external process to PYTHIA based on the calculations from Phys Lett. B 672, 2009: $\sigma=7.5$ nb at 100 GeV, 100 pb at 225 GeV.
- Pythia is then used to decay the sgluon to two jets.

![Diagram of quark annihilation and gluon fusion](image_url)
Event Selection

- L = 34 pb⁻¹ (taken from March to October 2010)
- Trigger: at least four jets with \( p_T > 5 \text{ GeV} \)
- At least four jets are required with \( p_T > 0.55 \times M_{\text{sgluon}} \) (\( M_{\text{sgluon}} \) from 100 GeV to 200 GeV)
- Four highest \( p_T \) jets are paired by minimizing \( |\Delta R_{\text{pair}1-1}| + |\Delta R_{\text{pair}2-1}| \) (due to the boost, the two jets from sgluon decays tend to have \( \Delta R \approx 1 \))
- Events are removed if a jet-jet-pairing has \( \Delta R_{\text{jj}} > 1.6 \)
- Relative mass difference between the two pairs: \( |M_1-M_2| / |M_1+M_2| < 7.5\% \)
- Scattering angle of the sgluon in the four jets rest frame: \( |\cos \theta^*| < 0.5 \)
  - Dominant QCD multijet backgrounds tend to be forward due to the exchange of t-channel gluon
  - Sgluon signal tends to be produced centrally
Data and MC Comparisons

QCD MC sample: ALPGEN + HERWIG + JIMMY

Good data/MC agreement observed, but large statistical uncertainty on the QCD MC simulation, need to use data driven method
Data-driven Background Estimation

- ABCD method with one signal region (A) and three background-dominated regions (B, C, D) → $\cos \theta^*$ and $|M_1-M_2|/(M_1+M_2)$ (small correlation found for these two variables)
  - Region A: $|\cos \theta^*| < 0.5$ and $|M_1-M_2|/(M_1+M_2) < 7.5\%$
  - Region B: $|\cos \theta^*| > 0.7$ and $|M_1-M_2|/(M_1+M_2) < 7.5\%$
  - Region C: $|\cos \theta^*| < 0.5$ and $|M_1-M_2|/(M_1+M_2) > 7.5\%$
  - Region D: $|\cos \theta^*| > 0.7$ and $|M_1-M_2|/(M_1+M_2) > 7.5\%$
- Shape of the background in signal region A is determined in region B (either from the original average reconstructed mass distribution or from a fit to the original distribution, $f(x) = (x-p1)^p2 \cdot e^{-x\cdot p3-x^2\cdot p4}$)
- Signal contamination in B, C and D regions are removed
- Normalization is derived from ratio of events in the control sample: $N_B \times N_C/N_D$
- ABCD method is applied to QCD MC simulation for validation
Data-driven Background Estimation

Four different sgluon mass points considered (100 GeV $\rightarrow$ 200 GeV)
## Systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>JES</td>
<td>Signal peak center $\pm 2%$</td>
</tr>
<tr>
<td></td>
<td>Signal efficiency $\pm 15%$</td>
</tr>
<tr>
<td>JER</td>
<td>Signal peak width $\pm 10%$</td>
</tr>
<tr>
<td>ABCD</td>
<td>Bkg prediction $1 - 10%$</td>
</tr>
<tr>
<td>PDF</td>
<td>Signal efficiency $\pm 2%$</td>
</tr>
<tr>
<td>L</td>
<td>Signal normalization $\pm 3.4%$</td>
</tr>
<tr>
<td>MC stat.</td>
<td>Signal normalization in $A(B,C,D) \pm 5(16, 5, 16)%$</td>
</tr>
<tr>
<td>Trigger</td>
<td>Signal normalization $(\text{eff} = 99%) \pm 1%$</td>
</tr>
</tbody>
</table>
Limits

- Cross section limit: 1 nb at 100 GeV and 350 pb at 190 GeV
- Exclude sgluon with $100 < M < 185$ GeV at 95% C.L. with a mass window of 5 GeV around 140 GeV
Conclusion

- Search for RPV tau sneutrino decaying to $e\mu$ ($L = fb^{-1}$)
  - Good agreement between data and MC predictions for high invariant mass $e\mu$ events
  - Better limits set for sneutrino mass vs couplings
- Search for pair-produced scalar particles decaying to four-jets ($L=34 pb^{-1}$):
  - Good agreement between data and predictions for average reconstructed mass
  - First limits obtained for this search at low mass
- Continuing to analyze more data to search for SUSY at ATLAS
Backup
Tau branching ratio measurement

- Processes contributing to the measurement of $\lambda_{312}$

- Processes contributing to the measurement of $\lambda'_{311}$