Discovery Potential for Slepton LSPs in R-Parity Violating SUSY

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Outline

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   - LSP Candidates

2 Stau LSPs at the LHC
   - Multi Lepton Final States
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Introduction

R-Parity Violation

MSSM with R-parity violation (RPV)

General superpotential of the MSSM superfields:

\[
W_{Rp} = (Y_E)_{ij} L_i H_d \bar{E}_j + (Y_D)_{ij} Q_i H_d \bar{D}_j + (Y_U)_{ij} Q_i H_u \bar{U}_j + \mu H_d H_u,
\]

\[
W_{Rp} = \frac{1}{2} \lambda_{ijk} L_i L_j \bar{E}_k + \chi'_{ijk} L_i Q_j \bar{D}_k + \frac{1}{2} \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k + \kappa_i L_i H_u.
\]

The lepton/baryon number violating terms lead to proton decay. It is sufficient to suppress \(\Delta L \neq 0\) or \(\Delta B \neq 0\) terms to keep proton stable.

[Dreiner, Luhn, Thormeier, Phys.Rev.D73:075007,2006]
Effects of RPV

What will change if R-parity is violated?

- Sparticles can be produced singly, possible on resonance.
- Neutrino masses can be generated.
- The RGEs get additional contributions.
- The lightest supersymmetric particle (LSP) is not stable anymore.
  ⇒ The LSP is no dark matter (DM) candidate.
  ⇒ The LSP can be charged.

LSP candidates

\[ \tilde{\chi}_1^0, \tilde{\chi}_1^\pm, \tilde{\ell}^\pm_{L/Rj}, \tilde{\tau}_1, \tilde{\nu}_i, \tilde{q}_{L/Rj}, \tilde{b}_1, \tilde{t}_1, \tilde{g} \]

Potential other DM RPV candidates:

Assume mSUGRA framework \cite{Allanach:2004sk}.

\[
\lambda \lesssim O(10^{-2}), \quad M_0 = 100 \text{ GeV}, \quad A_0 = -100 \text{ GeV}, \quad \mu > 0.
\]

\[\tilde{\tau}_1 \text{ LSP as well motivated as } \tilde{\chi}_1^0 \text{ LSP.}\]
What is the $\tilde{\tau}_1$ LSP discovery potential with early LHC data?

Benchmark scenario BC1

- $M_0 = A_0 = 0$
- $\lambda_{121} = 0.032$
- $\tan \beta = 13$
- $M_{1/2} = 400$ GeV
- $\text{sgn}(\mu) = +1$.

LHC Phenomenology of BC1

4-body decay of $\tilde{\tau}_1$ LSP

Promising LHC signatures:

$$PP \rightarrow \tilde{q}_R \tilde{q}_R$$
$$\rightarrow (q\tilde{\chi}_1^0)(q\tilde{\chi}_1^0)$$
$$\rightarrow (q\tau\tilde{\tau}_1)(q\tau\tilde{\tau}_1)$$
$$\lambda_{121} \rightarrow (q\tau\ell\ell\nu)(q\tau\ell\ell\nu)$$

- Excess of electrons and muons.
- Easy to identify in early LHC data.
Electron Multiplicity at $\sqrt{S} = 7$ TeV for BC1

Note: Fast detector simulation included using Delphes.
Electron $p_T$ Distribution at $\sqrt{S} = 7$ TeV for BC1

$p_T$ of hardest electron

Note: Fast detector simulation included using Delphes.
Cutflow for BC1

# events for 1fb$^{-1}$ at $\sqrt{s} = 7$ TeV.

<table>
<thead>
<tr>
<th>cut</th>
<th>signal</th>
<th>$t\bar{t}$</th>
<th>$S/\sqrt{B}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>no cuts</td>
<td>283</td>
<td>156000</td>
<td>0.2</td>
</tr>
<tr>
<td>$p_T(1st \mu^{\pm}) &gt; 40$ GeV</td>
<td>142</td>
<td>16745</td>
<td>0.3</td>
</tr>
<tr>
<td>$p_T(1st e^{\pm}) &gt; 32$ GeV</td>
<td>126</td>
<td>1492</td>
<td>2.9</td>
</tr>
<tr>
<td>$p_T(2nd e^{\pm}) &gt; 7$ GeV</td>
<td>114</td>
<td>166</td>
<td>8.4</td>
</tr>
<tr>
<td>$\sum p_T^\ell &gt; 230$ GeV</td>
<td>86</td>
<td>14</td>
<td>22</td>
</tr>
<tr>
<td>$HT' &gt; 300$ GeV</td>
<td>57</td>
<td>3.4</td>
<td>31</td>
</tr>
</tbody>
</table>

with $HT'$ the $p_T$ sum of the four hardest jets.

$\Rightarrow$ $S/B \approx 17$.

$\Rightarrow$ Systematic uncertainty of SM backgrounds not problematic.

$\Rightarrow$ Discovery of BC1 possible with early data!
Cuts work well beyond BC1.
Efficiency better for low $\tan \beta$ ($\rightarrow$ heavier $\tilde{\tau}_1$ LSP.).
Discovery Potential at $\sqrt{S} = 7$ TeV

minimal luminosity in $\text{pb}^{-1}$ for $S/\sqrt{B} > 5$

- Scenarios with $\tilde{m}_{\text{squark}} \lesssim 1$ TeV can be tested with $200\text{pb}^{-1}$.
- Low-tan $\beta$ scenarios easier to discover ($\rightarrow$ heavier $\tilde{\tau}_1$ LSP).
Summary

- Including R-parity violation allows $\tilde{\tau}_1$ LSP in mSUGRA.
- $\tilde{\tau}_1$ LSP might decay via 4-body decay.
- Promising LHC signature for early data: multi-lepton final states.
- Discovery with $\mathcal{O}(10^{pb^{-1}} - 100^{pb^{-1}})$ possible.

Outlook

- Scenario BC1 will be found or excluded next year!
- Investigate other decay modes of the $\tilde{\tau}_1$ LSP, e.g. $\tilde{\tau}_1 \rightarrow u\bar{d}$ via $\lambda'_{311}$.
- Investigate $\tilde{e}_R$ LSP scenarios.
  [Dreiner, SG, Stefaniak, work in progress]
Assume: $PP \rightarrow \tilde{q}\tilde{q} \rightarrow (q\tilde{\chi}_1^0)(q\tilde{\chi}_1^0) \rightarrow (q\tau\tilde{\tau}_1)(q\tau\tilde{\tau}_1)$.

<table>
<thead>
<tr>
<th>coupling</th>
<th>$\tilde{\tau}_1^+$ decay</th>
<th>LHC signature</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_{121} = -\lambda_{211}$</td>
<td>$\tau^+\mu^+e^-\bar{\nu}_e$</td>
<td>$2j + 4\tau + 4\ell + E_T$</td>
</tr>
<tr>
<td></td>
<td>$\tau^+\mu^-e^+\nu_e$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^+e^+e^-\bar{\nu}_\mu$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^-e^-e^+\nu_\mu$</td>
<td></td>
</tr>
<tr>
<td>$\lambda_{122} = -\lambda_{212}$</td>
<td>$\tau^+\mu^+\mu^-\bar{\nu}_e$</td>
<td>$2j + 4\tau + 4\ell + E_T$</td>
</tr>
<tr>
<td></td>
<td>$\tau^+\mu^-\mu^+\nu_e$</td>
<td>with $\ell = e, \mu$</td>
</tr>
<tr>
<td></td>
<td>$\tau^+e^+\mu^-\bar{\nu}_\mu$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^-e^-\mu^+\nu_\mu$</td>
<td></td>
</tr>
<tr>
<td>$\lambda_{131} = -\lambda_{311}$</td>
<td>$e^+\nu_e$</td>
<td></td>
</tr>
<tr>
<td>$\lambda_{132} = -\lambda_{312}$</td>
<td>$\mu^+\nu_e$</td>
<td></td>
</tr>
<tr>
<td>$\lambda_{231} = -\lambda_{321}$</td>
<td>$e^+\nu_\mu$</td>
<td>$2j + 2\tau + 2\ell + E_T$</td>
</tr>
<tr>
<td>$\lambda_{232} = -\lambda_{322}$</td>
<td>$\mu^+\nu_\mu$</td>
<td></td>
</tr>
<tr>
<td>$\lambda_{123} = -\lambda_{213}$</td>
<td>$\mu^+\bar{\nu}_e$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$e^+\bar{\nu}_\mu$</td>
<td></td>
</tr>
<tr>
<td>$\lambda_{133} = -\lambda_{313}$</td>
<td>$e^+\bar{\nu}_\tau$</td>
<td>$2j + 2\tau + 2\ell + E_T$</td>
</tr>
<tr>
<td></td>
<td>$\tau^+\bar{\nu}_e$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^+\nu_e$</td>
<td></td>
</tr>
<tr>
<td>$\lambda_{233} = -\lambda_{323}$</td>
<td>$\mu^+\bar{\nu}_\tau$</td>
<td>$2j + 3\tau + 1\ell + E_T$</td>
</tr>
<tr>
<td></td>
<td>$\tau^+\bar{\nu}_\mu$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau^+\nu_\mu$</td>
<td></td>
</tr>
</tbody>
</table>
\[ PP \rightarrow \tilde{q}\tilde{q} \rightarrow (q\tilde{\chi}_1^0)(q\tilde{\chi}_1^0) \rightarrow (q\tau\tilde{\tau}_1)(q\tau\tilde{\tau}_1). \]

<table>
<thead>
<tr>
<th>coupling ( \lambda'_{1jk} )</th>
<th>( \tilde{\tau}_1^+ ) decay</th>
<th>LHC signature</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau^+ u_j \bar{d}_k e^+ )</td>
<td>( 6j + 4\tau + \ell\ell )</td>
<td></td>
</tr>
<tr>
<td>( \tau^+ u_j \bar{d}_k e^- )</td>
<td>( 6j + 4\tau + \ell + \not{E}_T )</td>
<td></td>
</tr>
<tr>
<td>( \tau^+ d_j \bar{d}_k \bar{\nu}_e )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \tau^+ d_j \bar{d}_k \nu_e )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>coupling ( \lambda'_{2jk} )</th>
<th>( \tilde{\tau}_1^+ ) decay</th>
<th>LHC signature</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau^+ u_j d_k \mu^+ )</td>
<td>( 6j + 4\tau + \not{E}_T )</td>
<td></td>
</tr>
<tr>
<td>( \tau^+ u_j \bar{d}_k \mu^- )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \tau^+ d_j d_k \bar{\nu}_\mu )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \tau^+ d_j d_k \nu_\mu )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>coupling ( \lambda'_{3jk} )</th>
<th>( u_j d_k )</th>
<th>LHC signature</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 6j + 2\tau )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Assume: $PP \rightarrow \tilde{q}\tilde{q} \rightarrow (q\tilde{\chi}_1^0)(q\tilde{\chi}_1^0) \rightarrow (q\tau\tilde{\tau}_1)(q\tau\tilde{\tau}_1)$.

\[
\begin{array}{c|c|c}
\text{coupling} & \tilde{\tau}_1^+ \text{ decay} & \text{LHC signature} \\
\chi''_{i,j,k} & \tau^+ u_i d_j d_k & 8j + 2\tau \\
\tau^+ \bar{u}_i \bar{d}_j \bar{d}_k &
\end{array}
\]
Mass Reconstruction in BC1

With 1000 signal events (after cuts):

- Take hardest lepton.
- Find nearest lepton in $\Delta R$ with opposite charge.
- Find nearest tau lepton (to vector sum of leptons).

Note: $m_{\tilde{\tau}_1} = 147$ GeV.

$\Rightarrow$ Mass reconstruction difficult (→ combinatorial backgrounds).
Muon Multiplicity at $\sqrt{S} = 7$ TeV for BC1

# isolated muons with $p_T > 6$ GeV and $|\eta| < 2.7$
Jet Multiplicity at $\sqrt{S} = 7$ TeV for BC1

# jets with $p_T > 20$ GeV and $|\eta| < 5.0$
Jet $p_T$ Distribution at $\sqrt{S} = 7$ TeV for BC1

$p_T$ of hardest jet
TauMultiplicity at $\sqrt{S} = 7$ TeV for BC1

# jets with $p_T > 10$ GeV and $|\eta| < 2.5$
Summary and Outlook

Tau ID with Delphes

ID efficiency in $Z \rightarrow \tau\tau + 1\text{jet}$ for Delphes

Fake rate in $Z \rightarrow \tau\tau + 1\text{jet}$ for Delphes

ID efficiency in BC 1 for Delphes

Fake rate in BC 1 for Delphes
Summary and Outlook

Tau ID with PGS

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1.0
0.7
0.4
0.1

0.0
20
40
60
80
100
120

ID efficiency in $Z \rightarrow \tau \tau + 1$jet for PGS

Fake rate in $Z \rightarrow \tau \tau + 1$jet for PGS

1.0
0.5
0.0
0.005
0.010
0.015
0.020
0.025

20
40
60
80
100

ID efficiency in BC 1 for PGS

Fake rate in BC 1 for PGS
Missing Energy in BC1

Summary and Outlook

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Summary and Outlook

Discovery Potential at \( \sqrt{S} = 7 \text{ TeV} \)

\( S/\sqrt{B} \) for \( fb^{-1} \) at \( \sqrt{S} = 7 \text{ TeV} \).

![Graph showing discovery potential with \( \tan(\beta) \) on the y-axis and \( M_{1/2} \) on the x-axis, with color coding for \( S/\sqrt{B} \).]
Significance includes 50% systematic uncertainty for SM backgrounds.
# selected signal events for fb$^{-1}$ at $\sqrt{S} = 7$ TeV.
Summary and Outlook

$\tilde{\tau}_1$ LSP Parameter Space

LSP mass

![Graph showing LSP mass parameter space with axes $\tan(\beta)$ and $M_{1/2}$ in GeV, and color scale indicating $m_{\tilde{\tau}_1}$ in GeV.](image)
$\tilde{\tau}_1$ LSP Parameter Space

$M_{1/2}$ [GeV] vs $\tan \beta$ with a color scale indicating $|m_{\tilde{\chi}^0_1} - m_{\tilde{\tau}_1}|$ [GeV].
Summary and Outlook

\( \tilde{\tau}_1 \) LSP Parameter Space

![Plot of \( \tan \beta \) vs. \( M_{1/2} \) with color scale for \( m_\tilde{g} \) in GeV]
\tilde{\tau}_1 \text{ LSP Parameter Space}
What is the $\tilde{e}_R$ LSP discovery potential with early LHC data?

[Dreiner, SG, Stefaniak, work in progress]
Large R-Parity couplings can change RGE running of the $\tilde{\nu}_R$ mass. [Dreiner, SG, Phys.Lett.B679:45-50,2009]

$M_0 = 150$ GeV, $M_{1/2} = 300$ GeV, $A_0 = -1000$ GeV, $\tan \beta = 10$, sgn($\mu$) = +1

$\Rightarrow \tilde{\nu}_R$ good candidate for LSP.
Summary and Outlook

LHC Phenomenology of $\tilde{e}_R$ LSP

decay chain for $\tilde{q}_R$

Promising LHC signatures:

$$PP \to \tilde{q}_R \tilde{q}_R$$
$$\to (q\tilde{\chi}_1^0)(q\tilde{\chi}_1^0)$$
$$\to (qe\tilde{e}_R)(qe\tilde{e}_R)$$
$$\lambda_{231} \to (qe\mu\nu_\tau)(qe\tau\nu_\mu)$$

- 4 charged leptons in the final state.
- Easy to identify in early LHC data.
Discovery Potential at $\sqrt{S} = 7$ TeV

Cuts: $N_\ell \geq 3$, $N_j \geq 2$, $M_Z + 10\text{GeV} \leq M_{\ell^+\ell^-} \leq M_Z - 10\text{GeV}$, $M_{\text{eff}} > 300\text{GeV}$.

Scenarios with $\tilde{m}_{\text{squark}} \lesssim 1$ TeV can be tested with 500 pb$^{-1}$.

Smaller significances for $m_{\tilde{e}_R} \approx m_{\tilde{\chi}_1^0}$. 

Sebastian Grab (SCIPP)  
Santa Cruz, May 2010