Hiding and Finding Supersymmetry with R-Parity Violation

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Work in progress with Peter Graham and Surjeet Rajendran
Searches for SUSY at the LHC

- 0-6 jets + MET
- 7+ jets + MET
- 1-lepton + jets + MET
- Same-sign leptons (+ MET)
- Photons + MET
- 3+ leptons (+ MET)
- Leptons + $b$-jets + MET
- Many jets + $b$-jets + MET
- ...

Almost all searches updated to 20 fb$^{-1}$ of 8 TeV data
<table>
<thead>
<tr>
<th>Requirement</th>
<th>Channel</th>
<th>Multi-jet + flavour stream</th>
<th>Multi-jet + $M_T^E$ stream</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A (2-jets)</td>
<td>B (3-jets)</td>
<td>C (4-jets)</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ [GeV]</td>
<td>L M</td>
<td>M T</td>
<td>M T</td>
</tr>
<tr>
<td>$p_T(j_1)$ [GeV]</td>
<td></td>
<td></td>
<td>130</td>
</tr>
<tr>
<td>$p_T(j_2)$ [GeV]</td>
<td></td>
<td></td>
<td>60</td>
</tr>
<tr>
<td>$p_T(j_3)$ [GeV]</td>
<td></td>
<td></td>
<td>60</td>
</tr>
<tr>
<td>$p_T(j_4)$ [GeV]</td>
<td></td>
<td></td>
<td>–</td>
</tr>
<tr>
<td>$p_T(j_5)$ [GeV]</td>
<td></td>
<td></td>
<td>–</td>
</tr>
<tr>
<td>$p_T(j_6)$ [GeV]</td>
<td></td>
<td></td>
<td>–</td>
</tr>
<tr>
<td>$\Delta\phi(j_i, E_T^{\text{miss}}_{\text{min}} &gt; 0.4 (i = {1, 2, 3}) \ 0.2 (p_T &gt; 40 \text{ GeV \ jets})$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_T^{\text{miss}}/m_{\text{eff}}(Nj)$</td>
<td>0.2</td>
<td>–</td>
<td>0.3</td>
</tr>
<tr>
<td>$m_{\text{eff}}(\text{incl.})$ [GeV]</td>
<td>1000</td>
<td>1600</td>
<td>1800</td>
</tr>
</tbody>
</table>
Constraints on SUSY

Constrained almost to the kinematic limit (and similarly for CMSSM)
The dominant SUSY production processes involve valence quarks of the proton \((u, d)\)
“Natural” SUSY

Decoupling the first two generation squarks greatly reduces the SUSY production cross-section
Constraints on Natural SUSY

\[ \tilde{g} \rightarrow t\bar{t}\tilde{\chi}^0 \]
is also constrained to the kinematic limit

Fine tuning \( \sim 10\% \) or worse
Time to give up on the 8 TeV LHC?
Time to give up on the 8 TeV LHC?

NO!

My claim: SUSY can be hidden such that the squarks and gluinos lie well below the 8 TeV kinematic limit

Could they still be discovered in the data?
Hidden SUSY

All squarks are degenerate, ensuring large production cross-section.

Contrast to “natural” SUSY with low cross-section but distinctive events.
Why Hide SUSY?

![Graph showing the relationship between cross-section and squark/gluino mass](image-url)
R-Parity Violation (RPV)

\[ W_{\text{RPV}} = \mu_{L_i} L_i H_u + \lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \lambda''_{ijk} U_i D_j D_k \]

Lepton Number Violation
Baryon Number Violation

Pick only one to avoid proton decay
Constraints on RPV couplings

*UDD* couplings can induce double-nucleon annihilation:

\[ \rightarrow \lambda''_{112} \lesssim 10^{-6} \]

Lepton number violation induces neutrino masses:

\[ \rightarrow \lambda'_{i33} \lesssim 10^{-3} \]
Baryogenesis and RPV

$UDD$ couplings will wash out any cosmological baryon asymmetry

Neutralino LSP decay length < meter
→ baryon washout temperature < ~100 GeV
(Barry et. al. arXiv:1310.3853)

With lepton number violation, baryons are not washed out after the EW phase transition
How Not to Hide SUSY (very well)

If cascade decays producing W and Z bosons are allowed, many bounds come into effect, e.g.

\[ \tilde{q} \rightarrow q\tilde{\chi}^\pm \]

\[ \rightarrow qW^\pm \tilde{\chi}_0 \]

\[ \rightarrow 4qW^\pm \]
Simplified Model

Soft particles-- negligible for collider studies
Boosted decays

A light LSP can be produced with high boost from cascade decays

Decay products merge into a \((\text{high-}p_T)\) jet
Leptons from decay are not isolated!
Displaced Vertices

Small R-parity violating couplings \(\rightarrow\) Macroscopic LSP decay length (> .1 mm)

Leptons, \(b\)-jets not reconstructed
Simulation techniques

Use the MadGraph-PYTHIA-PGS package

Modified PGS to more closely mimic ATLAS/CMS $b$-jet tagging and lepton isolation

Our signal efficiencies generally match official ATLAS/CMS results to within 30%
Searches for baryonic RPV

ATLAS search for baryonic RPV: requires many very high-\(p_T\) jets

Official interpretation assumes the squarks are decoupled
Constraints on baryonic RPV

Bound is much tighter when the squarks are not decoupled

Only relevant signal region is 7 jets with $p_T > 180$ GeV

Same bounds apply even for moderately displaced decays
Lepton Number Breaking: The Other RPV

Constraints are stronger—why consider it?

• Baryogenesis can occur anytime during or after the electroweak phase transition

• Avoid proton decay to gravitino

• Neutrino masses suggest that lepton number may not be a perfect symmetry

• A different class of signatures!
Taus + Jets from LRPV

Assume:
• LQD couplings are larger than LLE couplings
• Neutral Higgsino is the LSP
• Sleptons are lighter than squarks

Then the LSP decays dominantly to tau + 2 jets:
Constraints on $\tilde{\chi}^0 \rightarrow \tau qq$

$100 \text{ GeV} \tilde{\chi}^0 \rightarrow \tau qq$

Tuning can be comparable to baryonic RPV case

Tau decay gives measurable missing energy
Charged lepton + jets

More generally there are a few ways to avoid decays to neutrinos with LRPV:

- Higgsino LSP
- Decay through operator $\frac{H_d Q U E}{\Lambda}$
- Large slepton left-right mixing
A light LSP is produced with large boost from squark/gluino decays.

LSP decay products merge into single jet $\rightarrow$ squark production no longer gives multijet signature.
Most same-sign lepton selections require MET; don’t make use of high jet multiplicity

Reduced efficiency due to identify leptons due to LSP boost
Boosted Limit \( \tilde{\chi}^0 \rightarrow \mu qq \)

Constraints are similar to baryonic RPV, though every SUSY event contains two muons

Search for non-isolated leptons?
A displaced decay to electron+jets is not explicitly constrained by any searches.

Could the CMS displaced dijet search have sensitivity?
“Generic” LRPV: \[ \tilde{\chi}^0 \rightarrow \mu qq, \nu qq \]

MET is highly suppressed compared to R-parity conserving case, but MET searches are still effective.
Boosted $\tilde{\chi}^0 \rightarrow \mu qq, \nu qq$

A light squark window exists if the LSP is produced with large boost.
Bilinear RPV

\[ W \supset \mu_{L,i}(L_i H_u + D_i H_u^c) + \mu H_d H_u \]

$L$ and $H_d$ mix with angle $\mu_L/\mu$, giving trilinears:

\[ W \supset \epsilon_i y_{jk}^e L_i L_j E_k + \epsilon_i y_{jk}^d L_i Q_j D_k \quad \epsilon_i \equiv \frac{\mu_{L,i}}{\mu} \]

Dominant operator is $\epsilon_i y_b L_i Q_3 D_3$:

\[ m_{\tilde{\chi}^0} < m_t \quad \tilde{\chi}^0 \rightarrow \nu b \bar{b} \]
7 TeV Constraints on $\tilde{\chi}^0 \rightarrow \nu b\bar{b}$

Stable massless neutralino
Constraints on $\tilde{\chi}^0 \rightarrow \nu b\bar{b}$

Light squark window is now closed by jets + MET searches, but displaced decays could still be observed.
Summary

All of these RPV scenarios are much less constrained than R-parity conservation.
Summary

Lepton number violation is competitive with baryon violation for a boosted LSP

$\tilde{\chi}^0$ decay modes

- $qqq$
- $\tau qq$
- $\mu qq$
- $\mu qq/\nu qq$
- $vbb$
- Stable
Conclusions

RPV models can allow for light squarks and for gluinos as light as 1 TeV

1 TeV squarks+gluino $\rightarrow$ 4000 events at 8 TeV LHC

Lepton number violating models are not necessarily more constrained than baryon violation
Conclusions

All of the models that hide have very little MET but many hard jets

LHC searches so far have searched for MET + X, leptons + X: for RPV we need Multijet + X, where X should include one or more leptons, very low MET, displaced vertices

Searches accepting non-isolated leptons may be necessary to probe models with boosted particles

There is still potential for discovery at 8 TeV!
Backup
A more realistic spectrum
Light superpartners are still allowed in a spectrum with a higgsino AND a very light LSP.