Spontaneous R-parity Violation in Supersymmetry

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My collaborators:

- Vernon Barger
- Pavel Fileviez Pérez
- Gabe Shaughnessy
1. Introduction: SUSY and R-parity

2. $B - L$ and R-parity
   - Spectrum
   - Pheno

3. Left-Right models and R-parity
   - Spectrum

4. Conclusion
Outline

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Several reasons to consider beyond the standard model physics:

- Neutrino masses, experimentally verified.
- A Dark matter candidate.
- A resolution to the gauge hierarchy problem.
- ...
Neutrino oscillation data indicates neutrinos are light, but massive.

Two possible mass terms for neutrinos:

- **Dirac**: \( m_D \, \nu_L \nu_R \)
- **Majorana**: \( m \, \nu_L \nu_L \)

But the SM:

- does not contain right-handed neutrinos \( \nu_R \),
- Might allow: \( \mathcal{L} \supset \frac{LH \, LH}{M} \sim \frac{v^2}{M} \nu_L \nu_L \); breaks the accidental \( U(1)_{B-L} \)

A theory that addresses neutrino masses should motivate \( \nu_R \) or \( M \).
Supersymmetry

SUSY can provide an elegant solution to the gauge hierarchy problem.

- Action invariant under Fermions $\leftrightarrow$ Bosons.
- Doubles the particle content, $\psi_f$ gets a partner $\phi_f$:
  \[ \mathcal{L} \supset Y \bar{\psi}_f \psi_f H + \lambda^2 H^2 \phi_f^2 \]
- Invariance $\Rightarrow Y = \lambda$.
- Stabilizes Higgs Mass:

\[ - \frac{2}{16\pi^2} Y^2 \Lambda^2_{UV} \]

Opposite signs cancel stabilizing the Higgs mass
The minimal supersymmetric standard model (MSSM):

\[ W_{\text{MSSM}} = y_u QH_u u^c + y_d QH_d d^c + y_e LH_d e^c + \mu H_u H_d \]

- Yukawa terms: \( \psi_i \psi_j \frac{\partial W^2}{\partial \Phi_i \partial \Phi_j} \).
- Also have gauge strength Yukawa terms: \( g_1 \tilde{e}^c e^c \tilde{B} \)

Potential = \( |F_i|^2 + \frac{1}{2} D^2_a + V_{\text{SUSY Breaking}} \)

- \(-F^*_\phi_i = \frac{\partial W}{\partial \phi_i}\);
- \(D_a = -g_a \phi^*_i T^{ij} \phi_j\)
- \(V_{\text{SUSY Breaking}} \supset m^2_{H_u}|H_u|^2 + m^2_\tilde{Q}|\tilde{Q}|^2 + \ldots\)

\[ \frac{\langle H_u \rangle}{\langle H_d \rangle} = \frac{v_u}{v_d} = \tan \beta, \quad v^2_u + v^2_d = 246^2 \text{ GeV}^2. \]
Unlike the SM, the MSSM does not have an accidental $U(1)_{B-L}$:

$$W_L = \frac{1}{2} \chi_{ij}^k L^i L^j e_k^c + \chi_{ij}^k L^i Q^j d_k^c + \mu_i L^i H_u$$

$$W_{\bar{B}} = \lambda^{ijk} u_i^c d_j^c d_k^c$$

- Including soft terms, there are 96 new parameters.
  - Allow for Majorana neutrino masses.
  - Introduces new, unobserved, processes.
Proton decay places the most stringent bounds on these interactions:

\[ \tau_p > 10^{32} \text{ years so } |\lambda'\lambda''| < 10^{-26} \]
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Introduction: SUSY and R-parity

R-Parity

Introduce a multiplicative discrete symmetry: R-parity.

\[ P_R = (-1)^{3(B-L)+2s} \]

- Examine general Yukawa coupling:

\[
\begin{array}{ccc|ccc}
\psi^c & \psi & \phi & \psi^c & \psi & \phi \\
(-1)^{2s} & -1 & -1 & 1 & 1 \\
\end{array}
\]

- \((-1)^{3(B-L)}\) separately conserved: \(B - L\) conservation.

Furthermore: \(P_R(\text{particles}) = 1\) \hspace{1cm} \(P_R(\text{sparticles}) = -1\)

- The LSP is stable and a dark matter candidate.

- Sparticles are produced in pairs at colliders. Cascade decay into the LSP, which escapes the detector as missing energy.
Pheno Studies

\[ \tau_p \sim |\lambda'\lambda''| \rightarrow \text{studies of: } \lambda'' = 0 \]

- Trilinear RPV: \( \lambda, \lambda' \lesssim 10^{-2} \).
- Bilinear RPV: \( W = \mu'_i L_i H_u; \mu' \lesssim 10^{-3} \text{ GeV} \)

But why R-parity?

- Many new parameters - not predictive.
- Is there a mechanism?

Remember the connection to matter Parity

\[ P_M = (-1)^{3(B-L)}. \]

Hints at a connection to \( B - L \) symmetries.
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*Hints at a connection to $B - L$ symmetries.*
Global $B - L$

Early models: MSSM with a global $U(1)_{B-L}$ (Aulakh and Mohapatra 1982).

Broken by $\langle \tilde{\nu} \rangle \neq 0$.

- The Majoron ($J$) is the Goldstone associated with breaking $B - L$.
- The CP-even partner is $\sigma$, $m_\sigma \lesssim 300$KeV

Ruled out by invisible $Z$ decay from LEP II $Z \rightarrow J + \sigma$.

- Introduce $N$, $S$ and 3 $\nu^c$ with $L = (0, 1, -1)$ (Masiero and Valle 1990)

$$\Delta W = y_\nu L H_u \nu^c + y_N \nu^c S$$

- Now the Majoron is mostly singlet ($\nu^c$ and $S$) so very little $Z$ coupling.
Several issues:

- Singlets and $\nu^c$ are not motivated
- Replaced a discrete symmetry with a continuous one.
- Have to deal with the Majoron.

Gauging B-L addresses all these issues:

- Right-handed neutrinos are necessary for anomaly cancellation.
- A local symmetry is more aesthetic.
- The Majoron is eaten and is no longer physical.
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Simple MSSM extension: $SU(2)_L \times U(1)_Y \times U(1)_{B-L}$:

$$W = W_{MSSM} + Y_\nu L^T i\sigma_2 H_u \nu^c$$

$$\langle \tilde{L} \rangle = \begin{pmatrix} \frac{1}{\sqrt{2}} v_L \\ 0 \end{pmatrix} \quad \langle \tilde{\nu}^c \rangle = \frac{1}{\sqrt{2}} v_R$$

$$\langle V_F \rangle = \frac{1}{4} Y_\nu^2 (v_R^2 v_u^2 + v_R^2 v_L^2 + v_L^2 v_u^2) + \frac{1}{2} \mu^2 (v_u^2 + v_d^2) + \frac{1}{\sqrt{2}} Y_\nu \mu v_L v_d v_R$$

$$\langle V_D \rangle = \frac{1}{32} \left[ g_2^2 (v_u^2 - v_d^2 - v_L^2)^2 + g_1^2 (v_u^2 - v_d^2 - v_L^2)^2 + g_{BL}^2 (v_R^2 - v_L^2)^2 \right]$$

$$\langle V_S \rangle = \frac{1}{2} m_{\nu R}^2 v_L^2 + \frac{1}{2} m_{\nu c}^2 v_R^2 + \frac{1}{2} m_{H_u}^2 v_u^2 + \frac{1}{2} m_{H_d}^2 v_d^2 - 2b v_u v_d - \frac{1}{\sqrt{2}} a_L v_u v_L v_R$$
R-parity Through Local $B - L$


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For $v_R \gg v_u, v_d \gg v_L$

$$v_R = \sqrt{-\frac{8m_{\tilde{\nu}c}}{g_{BL}^2}}$$

$$v_L = \frac{(y_{\nu \mu}v_d - a_{\nu}v_u)v_R}{\sqrt{2} \left( m_L^2 - \frac{1}{8} g_{BL}^2 v_R^2 \right)}$$

$v_u$ and $v_d$ as in the MSSM
But R-Parity Violation Can Be Scary!
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Lepton number violation?
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Lepton number violation?

Dark Matter?

RPV

p
But R-Parity Violation Can Be Scary!

- Lepton number violation?
- Dark Matter?
- Proton decay?!
Not Necessarily
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Lepton num. is safe: $\lambda, \lambda'$ suppressed by $\nu$ masses.
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Dark matter candidate: Long-lived gravitino LSP.
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**Lepton num. is safe:** $\lambda, \lambda'$ suppressed by $\nu$ masses.

**Dark matter candidate:** Long-lived gravitino LSP.

**Less free parameters:** spontaneous not explicit.
The pros

**Plus**

- **Minimal**: particle content = MSSM + anomaly cancellation.
- **Predictive**: no singlets, no vector-like pairs; $M_{B-L} = m_{SUSY}$.
- **Neutrino Masses**: at tree level.
- **Testable**: Relationship between $Z'$ and R-parity violation.
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Breaking B-L:  $|\mu_X|^2 + m_X^2 < 0$ new $\mu$ problem

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Compare to R-parity conserving models

<table>
<thead>
<tr>
<th>R-parity conservation</th>
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Boson Masses

Gauge boson mass

\[ M_{Z'}^2 = \frac{1}{4} g_{BL}^2 v_R^2 : \quad \frac{M_{Z'}}{g_{BL}} > 5 \text{ TeV}; \quad v_R \gtrsim 10 \text{ TeV} \]

Higgs masses as in MSSM (no \( B - L \) charge). Using \( v_L, y_\nu, a_\nu \rightarrow 0 \):

- **Neutral sleptons**
  - \( \text{Im} \tilde{\nu}^c \): The \( B - L \) goldstone boson
  - \( \text{Re} \nu^c \): \( m_{H_\nu}^2 = \frac{1}{4} g_{BL} v_R^2 = M_{Z'}^2 \)

\[ m_{\tilde{\nu}}^2 = m_L^2 - \frac{1}{8} g_{BL}^2 v_R^2 - \frac{1}{8} (g_1^2 + g_2^2) (v_u^2 - v_d^2) \]

- **Charged sleptons**

\[ m_{\tilde{e}_L}^2 = m_L^2 - \frac{1}{8} g_{BL}^2 v_R^2 + \frac{1}{8} (g_2^2 - g_1^2) (v_u^2 - v_d^2) \]

\[ m_{\tilde{e}_R}^2 = m_{\tilde{e}_c}^2 + \frac{1}{8} g_{BL}^2 v_R^2 + \frac{1}{4} g_1^2 (v_u^2 - v_d^2) \]
Neutrino Masses

Basis: \((\nu, \nu^c, \tilde{B}', \tilde{B}, \tilde{W}_L, \tilde{H}_d^0, \tilde{H}_u^0)\)

\[
\begin{pmatrix}
0 & -\frac{1}{\sqrt{2}} y_\nu v_u & -\frac{1}{2} g_{BL} v_L & -\frac{1}{2} g_1 v_L & \frac{1}{2} g_2 v_L & 0 & \frac{1}{\sqrt{2}} y_\nu v_R \\
-\frac{1}{\sqrt{2}} y_\nu v_u & 0 & \frac{1}{2} g_{BL} v_R & 0 & 0 & 0 & \frac{1}{\sqrt{2}} y_\nu v_L \\
-\frac{1}{2} g_{BL} v_L & \frac{1}{2} g_{BL} v_R & M_{BL} & 0 & 0 & 0 & 0 \\
-\frac{1}{2} g_1 v_L & 0 & 0 & M_1 & 0 & -\frac{1}{2} g_1 v_d & \frac{1}{2} g_1 v_u \\
\frac{1}{2} g_2 v_L & 0 & 0 & 0 & M_2 & \frac{1}{2} g_2 v_d & -\frac{1}{2} g_2 v_u \\
0 & 0 & 0 & -\frac{1}{2} g_1 v_d & \frac{1}{2} g_2 v_d & 0 & -\mu \\
\frac{1}{\sqrt{2}} y_\nu v_R & \frac{1}{\sqrt{2}} y_\nu v_L & 0 & \frac{1}{2} g_1 v_u & -\frac{1}{2} g_2 v_u & -\mu & 0
\end{pmatrix}
\]

Complicated; two helpful limits:

- \(y_\nu \rightarrow 0 \) \( m_\nu \sim \frac{\mu v_L^2}{2 v_d v_u} < 10^{-9} \) GeV ; therefore \( \nu_L < 10^{-3} \) GeV
- \( \nu_L \rightarrow 0 \) \( m_\nu \sim \frac{g^2 v_d^2 y_\nu^2 v_R^2}{\mu^2 M_\chi} < 10^{-9} \) GeV ; therefore \( y_\nu < 10^{-5} \)
Testing the connection between $Z'$ and R-parity violation.

- New production mechanism for sparticles, especially sleptons:

\[
\tilde{\nu}_i \rightarrow e_i e_j
\]

LSP $\tilde{\nu}$ has lepton flavor violating decays

\[
\tilde{\nu}_i \rightarrow e_i e_j \sim \frac{(y_e)_i (y_{\nu})_{jk} (v_R)_k}{\mu} \sim \lambda_{ij}
\]

$Z' \rightarrow e\mu e\mu, \mu\tau \mu\tau$ possible

Studied by Lee PLB 2008 but no specific R-parity model.
Z' decays

Testing the connection between \( Z' \) and R-parity violation.

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\bar{q} \rightarrow \tilde{\nu}_i \rightarrow e_i e_j
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Studied by Lee PLB 2008 but no specific R-parity model.
LSP decay:

- $\tilde{\chi}^0_1 \rightarrow \nu_L \ Z, \ l^+ \ W^-$

- Due to lepton - neutralino/chargino mixings

SUSY discovery no longer dependent on missing energy signals.

For a gravitino LSP, these decays are possible for the NLSP.
A gravitino LSP decays to SM particles without R-Parity.

For a light enough gravitino, $\tilde{G} \rightarrow \gamma \nu$

Suppressed by both $M_P$ and R-parity ($\sim m_\nu$); Takayama and Yamaguchi 2000

Therefore $\Gamma \sim \frac{m_{3/2}^3 v_L^2}{M_P^2 m_\chi^{02}}$

$\tau \sim 10^{26} \text{ sec} \times \left( \frac{m_\chi^0}{1000 \text{ GeV}} \right)^2 \left( \frac{1 \text{ GeV}}{m_{3/2}} \right)^3 \left( \frac{10^{-4} \text{ GeV}}{v_L} \right)^2$

For $m_{3/2} > 1 \text{ KeV}$, the gravitino is a cold dark matter candidate.
Outline

1. Introduction: SUSY and R-parity

2. $B - L$ and R-parity
   - Spectrum
   - Pheno

3. Left-Right models and R-parity
   - Spectrum

4. Conclusion
Why Left-Right?

There are many motivations for studying $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$:

- The vacuum prefers $\nu_R \gg \nu_{ew}$: suppresses $V+A$ interactions.
- Hints at *unification* since its gauge group is a subgroup of $SO(10)$.
- Can implement *leptogenesis*.
- *Electric charge* is on a more physical footing:
  
  $$Q = l_{3L} + l_{3R} + \frac{1}{2} (B - L)$$

- And of course, *neutrino masses*. 
Traditional SUSY left-right models contain $B - L$ even triplet fields.

- Automatic R-parity conservation.
- Can also implement type I seesaw mechanism.

But automatic R-parity conservation is hard; requires one of the following:

- An extra singlet.
- Non-renormalizable terms.
- Or more complicated breaking structure.

We can avoid all of this by applying the same mechanism as before.
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</tr>
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The Simplest SLRM

P. Fileviez Pérez and SS: **PLB ’09**

\[
W = Y_Q Q^T i\sigma_2 \Phi i\sigma_2 Q^C + Y_L L^T i\sigma_2 \Phi i\sigma_2 L^C \\
+ \mu \text{Tr} \left( \Phi^T i\sigma_2 \Phi i\sigma_2 \right)
\]

with

\[
Q = \begin{pmatrix} u \\ d \end{pmatrix} \quad Q^c = \begin{pmatrix} u^c \\ d^c \end{pmatrix} \quad L = \begin{pmatrix} \nu \\ e \end{pmatrix} \quad L^c = \begin{pmatrix} \nu^c \\ e^c \end{pmatrix}
\]

And under parity:

\[
Q \leftrightarrow Q^c^* \quad L \leftrightarrow L^c^* \quad \Phi \leftrightarrow \Phi^\dagger
\]

So that \( g_L = g_R \), \( Y_Q \) and \( Y_L \) are hermitian and \( \mu \) is real.
Gauge bosons:

- \( M_{W'}^2 \sim \frac{1}{4} g_R^2 v_R^2 \gtrsim 700 \) (1600) GeV: direct (indirect).
- \( M_{Z'}^2 \sim \frac{1}{4} (g_R^2 + g_{BL}^2) v_R^2 \gtrsim 1000 \) (2000) GeV

Scalar masses:

- Left-handed sleptons masses as before.
- Right-handed sleptons eaten; neutral CP-even, \( m \sim M_{W'} \)
- \( m_{H^+}^2 - m_{A^0}^2 \sim 2M_W^2 \) instead of \( M_W^2 \)
- MSSM heavy Higgses \( (H^0, A^0, H^+) \) masses at right-handed scale.
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$\mathcal{R}_p + \nu^c$

$\langle \nu^c \rangle \sim m_{\text{susy}}$

MSSM+Z'

R-parity Violation
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Gravitino LSP long-lived
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Gravitino LSP long-lived

Minimal and predictive
$G \supset B - L$

$R_p + \nu^c$

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MSSM+$Z'$

R-parity Violation

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Gravitino LSP long-lived

$Z' \rightarrow e_ie_j$

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\[ R_p + \nu^c \]

\[ \langle \nu^c \rangle \sim m_{\text{susy}} \]

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Minimal and predictive

\[ Z' \rightarrow e_i e_j \]

\[ \nu \text{ masses} \]