Spontaneous R-parity Violation in Supersymmetry

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Outline

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The Standard Model

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 Masses

Neutrino oscillation data indicates neutrinos are light, but massive.

Two possible mass terms for neutrinos:

$$\text{Dirac}: \quad m_D\, \nu_L \nu_R$$
$$\text{Majorana}: \quad m\, \nu_L \nu_L$$

But the SM:

- does not contain right-handed neutrinos (ν_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 ν_R or M.

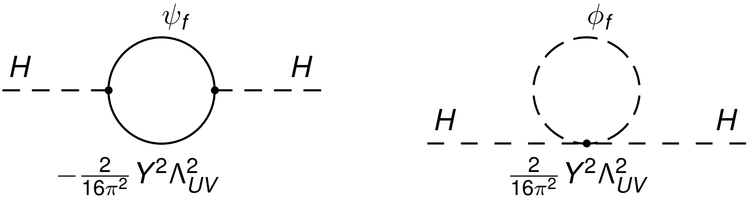
Supersymmetry

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

- Action invariant under Fermions $\leftrightarrow$ Bosons.
- Doubles the particle content, ψ_f gets a partner ϕ_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:



Opposite signs cancel stabilizing the Higgs mass

The MSSM

The minimal supersymmetric standard model (MSSM):

$$W_{MSSM} = y_u Q H_u u^c + y_d Q H_d d^c + y_e L H_d e^c + \mu H_u H_d$$

- 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 $= |F_i|^2 \; + \; \frac{1}{2} D_a^2 + V_{\text{SUSY Breaking}}$

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

$\frac{\langle H_u \rangle}{\langle H_d \rangle} \equiv \frac{v_u}{v_d} \equiv \tan\beta, \quad v_u^2 + v_d^2 = 246^2 \text{ GeV}^2.$

B and L Violation

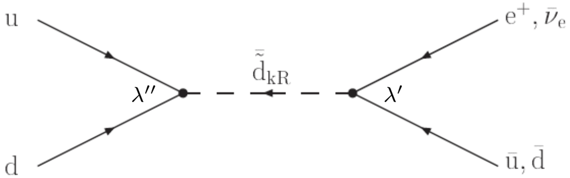
Unlike the SM, the MSSM does not have an accidental $U(1)_{B-L}$:

$$W_{\not{L}} = \frac{1}{2}\lambda_{ij}^{k} L^i L^j e_k^c + \lambda_{ij}^{\prime k} L^i Q^j d_k^c + \mu_i^{\prime} L^i H_u$$
$$W_{\not{B}} = \lambda^{\prime\prime ijk} u_i^c d_j^c d_k^c$$

- Including soft terms, there are 96 new parameters.
  - Allow for Majorana neutrino masses.
  - Introduces new,unobserved, processes.

Proton Decay

- Proton decay places the most stringent bounds on these interactions:



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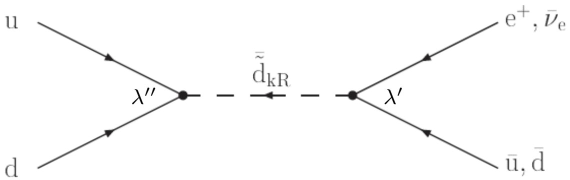

$$\tau_p > 10^{32} \text{ years so } |\lambda'\lambda''| < 10^{-26}$$

R-Parity

Introduce a multiplicative discrete symmetry: R-parity.

$$P_R = (-1)^{3(B-L)+2s}$$

- Examine general Yukawa coupling:

$$\begin{array}{cccc|c} & \psi^c & \psi & \phi & \psi^c\,\psi\,\phi \\ (-1)^{2s} & -1 & -1 & 1 & 1 \end{array}$$

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

Furthermore: $P_R(\text{particles}) = 1$ $\qquad$ $P_R(\text{sparticles}) = -1$

- 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

$\tau_p \sim |\lambda' \lambda''| \rightarrow$ studies of: $\lambda'' = 0$

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

But why R-parity?

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

Remember the connection to matter Parity

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Hints at a connection to $B - L$ symmetries.

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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 σ, $m_\sigma \lesssim$ 300KeV

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

- Introduce N, S and 3 ν^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 (ν^c and S) so very little Z coupling.

Beyond global $B-L$

Several issues:

- Singlets and ν^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.
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R-parity Through Local $B-L$

V. Barger P. Fileviez Pérez and SS: **Phys.Rev.Lett.102:181802,2009**

Simple MSSM extension: $SU(2)_L \times U(1)_Y \times U(1)_{B-L}$:

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

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

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

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

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Minimizing

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

$$v_R = \sqrt{\frac{-8 m^2_{\tilde{\nu}^c}}{g^2_{BL}}}$$

$$v_L = \frac{(y_\nu \mu v_d - a_\nu \, v_u) \, v_R}{\sqrt{2} \left(m^2_{\tilde{L}} - \frac{1}{8} g^2_{BL} v^2_R \right)}$$

v_u and v_d as in the MSSM

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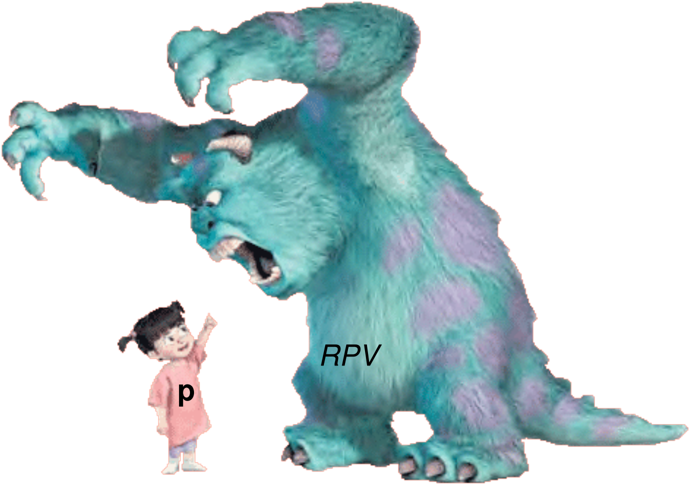

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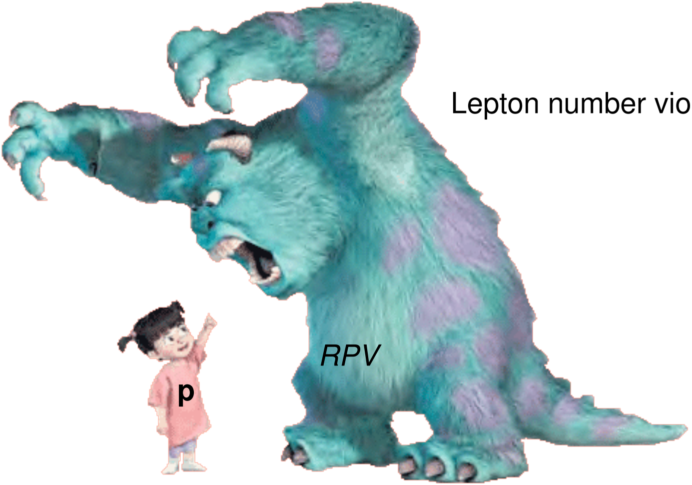
Lepton number violation?



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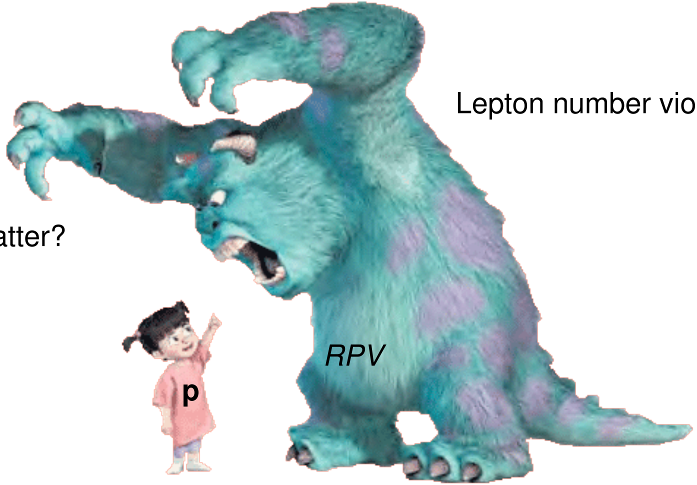

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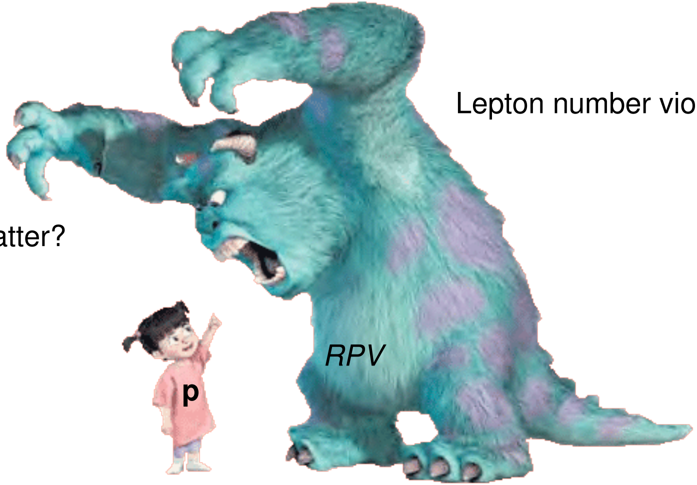
Dark Matter?



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Dark matter candidate: Long-lived gravitino LSP.

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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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Compare to R-parity conserving models

	R-parity conservation	R-parity violation
Fields:	$X, \bar{X}, \nu^c$	ν^c
Breaking B-L:	$\|\mu_X\|^2 + m_X^2 < 0$ new μ problem	$m_{\nu^c}^2 < 0$
	or	
Fields:	$X, \bar{X}, S, \nu^c$	ν^c
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Boson Masses

Gauge boson mass

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

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

- Neutral sleptons
  - Im $\tilde{\nu}^c$: The $B-L$ goldstone boson
  - Re ν^c: $m_{H_\nu}^2 = \frac{1}{4} g_{BL} v_R^2 = M_{Z'}^2$
  - $m_{\tilde{\nu}}^2 = m_{\tilde{L}}^2 - \frac{1}{8} g_{BL}^2 v_R^2 - \frac{1}{8}\left(g_1^2 + g_2^2\right)\left(v_u^2 - v_d^2\right)$
- Charged sleptons
  - $m_{\tilde{e}_L}^2 = m_{\tilde{L}}^2 - \frac{1}{8} g_{BL}^2 v_R^2 + \frac{1}{8}\left(g_2^2 - g_1^2\right)\left(v_u^2 - v_d^2\right)$
  - $m_{\tilde{e}_R}^2 = m_{\tilde{e}^c}^2 + \frac{1}{8} g_{BL}^2 v_R^2 + \frac{1}{4} g_1^2 \left(v_u^2 - v_d^2\right)$

Neutrino Masses

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

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

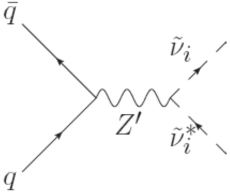
Complicated; two helpful limits:

- $y_\nu \to 0\ m_\nu \sim \frac{\mu v_L^2}{2 v_d v_u} < 10^{-9}$ GeV ; therefore $v_L < 10^{-3}$ GeV
- $v_L \to 0\ m_\nu \sim \frac{g^2 v_d^2\ y_\nu^2 v_R^2}{\mu^2 M_\chi} < 10^{-9}$ GeV ; therefore $y_\nu < 10^{-5}$

Z' decays

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

- New production mechanism for sparticles, especially sleptons:



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

$$\tilde{\nu}_i \longrightarrow e_i e_j$$

$$\sim \frac{(y_e)_i (y_\nu)_{jk} (v_R)_k}{\mu} \sim \lambda_{ij}$$

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

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

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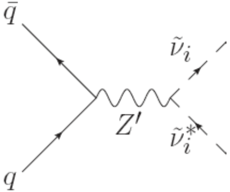

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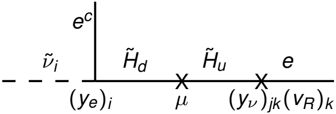

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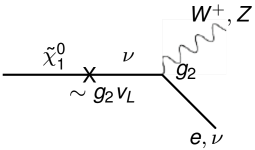
LSP

LSP decay:

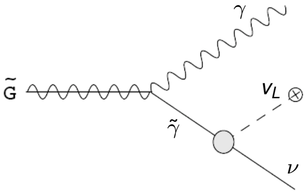
- $\tilde{\chi}^0_1 \rightarrow \nu_L\, Z,\, l^+\, W^-$
- Due to lepton - neutralino/chargino mixings



- SUSY discovery no longer dependent on missing energy signals.
- For a gravitino LSP, these decays are possible for the NLSP.

Dark Matter

- 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



$$\mathcal{M} \sim \frac{v_L}{M_P m_\chi^0}$$

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

Outline

Why Left-Right?

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

- The vacuum prefers $v_R \gg v_{ew}$: 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:

$$Q = I_{3L} + I_{3R} + \frac{1}{2}(B - L)$$

- And of course, *neutrino masses*.

Automatic R-parity conservation

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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SLRM Particle Content

Field content:

Fields	$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
Q	$(2, 1, +\frac{1}{3})$
Q^c	$(1, 2, -\frac{1}{3})$
L	$(2, 1, -1)$
L^c	$(1, 2, +1)$
Φ	$(2, 2, 0)$
Δ^c	$(1, 3, -2)$
$\bar{\Delta}^c$	$(1, 3, +2)$
Δ	$(3, 1, 2)$
$\bar{\Delta}$	$(3, 1, -2)$

SLRM Particle Content

New field content:

Fields	$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
Q	$(2, 1, +\frac{1}{3})$
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The Simplest SLRM

P. Fileviez Pérez and SS: **PLB '09**

$$W = Y_Q\, Q^T\, i\sigma_2\, \Phi\, i\sigma_2\, Q^C \;+\; Y_L\, L^T\, i\sigma_2\, \Phi\, i\sigma_2\, L^C$$
$$+\,\mu\, \mathrm{Tr}\left(\Phi^T\, i\sigma_2\, \Phi\, i\sigma_2\right)$$

wtih

$$Q = \begin{pmatrix} u \\ d \end{pmatrix} \qquad Q^c = \begin{pmatrix} u^c \\ d^c \end{pmatrix} \qquad L = \begin{pmatrix} \nu \\ e \end{pmatrix} \qquad L^c = \begin{pmatrix} \nu^c \\ e^c \end{pmatrix}$$

And under parity:

$$Q \leftrightarrow Q^{c*} \qquad L \leftrightarrow L^{c*} \qquad \Phi \leftrightarrow \Phi^\dagger$$

So that $g_L = g_R$, Y_Q and Y_L are hermitian and μ is real.

Boson Masses

Gauge bosons:

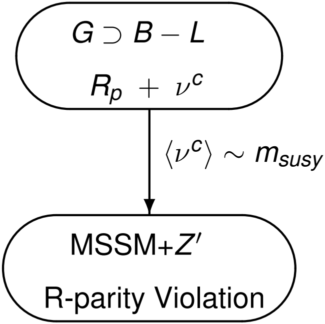
- $M_{W'}^2 \sim \frac{1}{4} g_R^2 v_R^2 \gtrsim 700\ (1600)$ GeV: direct (indirect).
- $M_{Z'}^2 \sim \frac{1}{4}\left(g_R^2 + g_{BL}^2\right) v_R^2 \gtrsim 1000\ (2000)$ GeV

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.

Outline

Conclusion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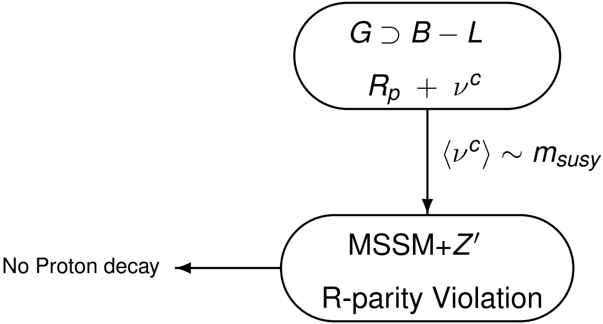
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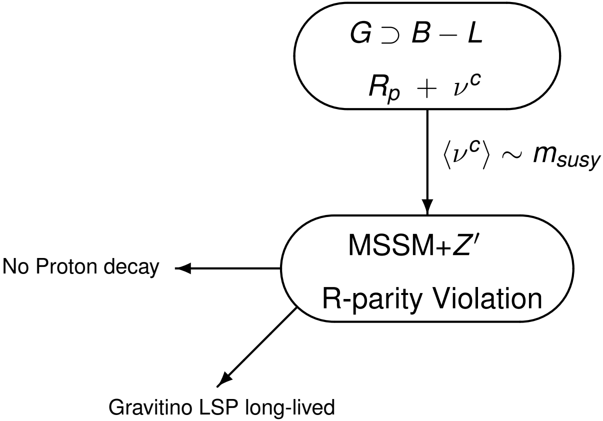
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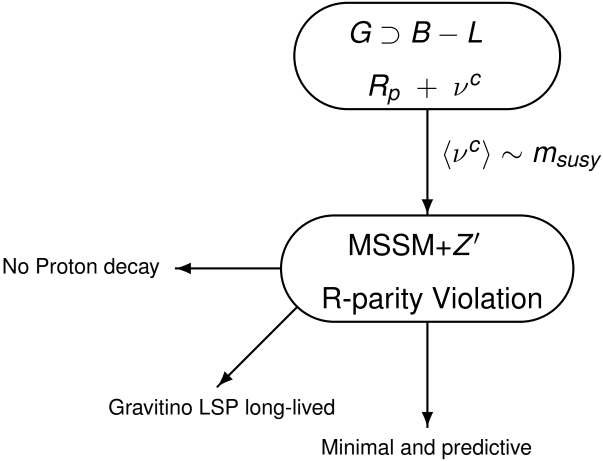
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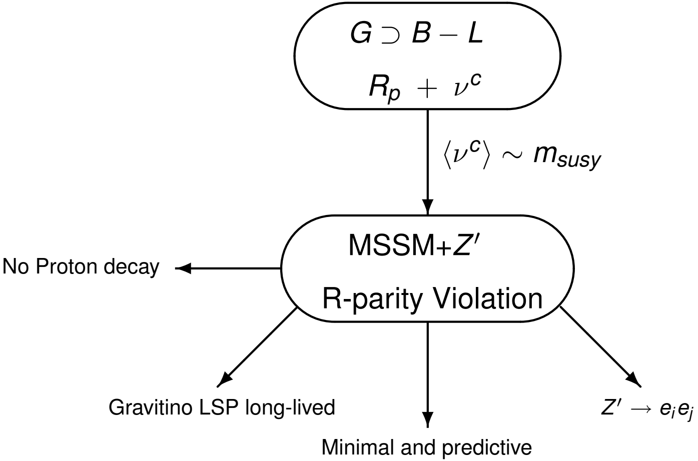

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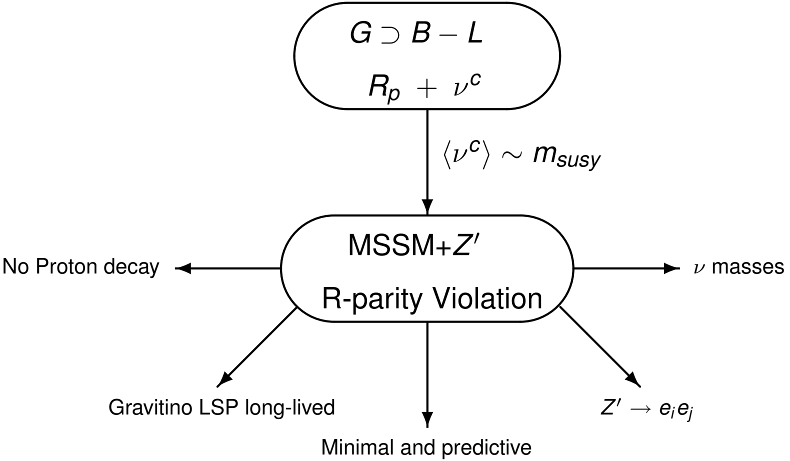
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