RPV Decays of Chargino and Neutralino LSPs in the B-L MSSM

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Table of Contents

B-L MSSM

- The $B - L$ extension of the MSSM arises naturally in the context of heterotic $E_8 \times E_8$ string theory; [Ambroso,Ovrut,arXiv:1005.5392].
- $SO(10)$ unification at $M_U \approx 3 \times 10^{16}$GeV;
- Two Wilson lines break $SO(10)$ to $SU(3)_C \otimes SU(2)_L \otimes U(1)_{T_{3R}} \otimes U(1)_{B-L}$ gauge group below the Calabi-Yau scale;
- Introduces 3 species of right-handed neutrinos for an anomaly-free theory;
- $B - L$ broken by a right-handed sneutrino VEV.

$$U(1)_{3R} \otimes U(1)_{B-L} \rightarrow U(1)_Y ,$$

and the Z_R boson is produced (constraints lift $B - L$ breaking scale > 4.1 TeV).

Matter Content

The spectrum is exactly that of the MSSM with three extra right-handed neutrino chiral multiplets (one per family).

- The superpotential of the $B - L$ MSSM is given by

$$W = Y_u Q H_u u^c - Y_d Q H_d d^c - Y_e L H_d e^c + Y_\nu L H_u \nu^c + \mu H_u H_d \ .$$

- The soft supersymmetry breaking Lagrangian is given by

$$\begin{aligned} -\mathcal{L}_{\text{soft}} = &\Big(\frac{1}{2} M_3 \tilde{g}^2 + \frac{1}{2} M_2 \tilde{W}^2 + \frac{1}{2} M_R \tilde{W}_R^2 + \frac{1}{2} M_{BL} \tilde{B'}^2 \\ &+ a_u \tilde{Q} H_u \tilde{u}^c - a_d \tilde{Q} H_d \tilde{d}^c - a_e \tilde{L} H_d \tilde{e}^c + a_\nu \tilde{L} H_u \tilde{\nu}^c + b H_u H_d + h.c. \Big) \\ &+ m_{\tilde{Q}}^2 |\tilde{Q}|^2 + m_{\tilde{u}^c}^2 |\tilde{u}^c|^2 + m_{\tilde{d}^c}^2 |\tilde{d}^c|^2 + m_{\tilde{L}}^2 |\tilde{L}|^2 + m_{\tilde{\nu}^c}^2 |\tilde{\nu}^c|^2 \\ &+ m_{\tilde{e}^c}^2 |\tilde{e}^c|^2 + m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 \ . \end{aligned}$$

No CP-violation $\longrightarrow$ real parameters

R-Parity

Problem: Most general MSSM superpotential allows for baryon and lepton number violating terms at tree level and, therefore, rapid proton decay.

- Typical solution: add an *ad-hoc* R-parity defined as

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

- However, the lightest supersymmetric particle (LSP) is stable and therfore must be neutral to avoid a disallowed density of charged relics $\Rightarrow$ R-parity severely narrows the SUSY phenomenological landscape.
- Our $B-L$ MSSM model: $B-L$ arises naturally from string theory; a third generation sneutrino aquires a VEV and hence $B-L$ is broken at low energy ($U(1)_{3R} \otimes U(1)_{B-L} \to U(1)_Y$), with small RPV couplings.

RPV couplings

After the right handed sneutrino aquires a VEV v_R, there are two sources of RPV couplings in the Lagrangian:

- The RPV operators in the superpotential:

$$W \supset \epsilon_i \, e_i \, H_u^+ - \frac{1}{\sqrt{2}} Y_{e\,i} \, v_{L\,i} \, H_d^- \, e_i^c \ ,$$

where

$$\boxed{\epsilon_i \equiv \frac{1}{\sqrt{2}} Y_{\nu\,i3} v_R, \quad v_{L\,i} = \frac{\frac{v_R}{\sqrt{2}} \left(Y_{\nu_{i3}}^* \mu v_d - a_{\nu_{i3}}^* v_u \right)}{m_{\tilde{L}_i}^2 - \frac{g_2^2}{8} (v_u^2 - v_d^2) - \frac{g_{BL}^2}{8} v_R^2}} \ .$$

- The RPV operators in the super-covariant derivatives:

$$\mathcal{L} \supset -\frac{1}{2} v_{L\,i}^* \left[g_2 \left(\sqrt{2}\, e_i \tilde{W}^+ + \nu_{L_i} \tilde{W}^0 \right) - g_{BL} \nu_{L_i} \tilde{B}' \right] - \frac{1}{2} v_R \left[-g_R \nu_3^c \tilde{W}_R + g_{BL} \nu_3^c \tilde{B}' \right] + \text{h.c.}$$

Chargino and Neutralino States

The RPV couplings ϵ_i and v_{L_i} extend the chargino and neutralino gauge eigenstates:

$$\psi^+ = (\tilde{W}^+, \tilde{H}_u^+, {e^c}_i) \qquad \psi^- = (\tilde{W}^-, \tilde{H}_d^-, e_i)$$

$$\psi^0 = \left(\tilde{W}_R, \tilde{W}_0, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{B}', \nu_3^c, \nu_1, \nu_2, \nu_3\right).$$

These states can be combined into mass terms inside the Lagrangian of the form

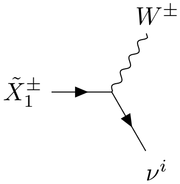
$$\mathcal{L} \supset -\frac{1}{2}\left(\psi^0\right)^T \mathcal{M}_{\tilde{\chi}^0}\psi^0 - \frac{1}{2}\left(\psi^+\,\psi^-\right)\begin{pmatrix} 0 & {\mathcal{M}_{\tilde{\chi}^\pm}}^T \\ \mathcal{M}_{\tilde{\chi}^\pm} & 0 \end{pmatrix}\begin{pmatrix}\psi^+ \\ \psi^-\end{pmatrix} + h.c.$$

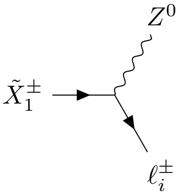
The mass eigenstates $\chi^\pm$, χ^0 are related to the gauge eigenstates $\psi^\pm$, ψ^0 by the unitary matrices $\mathcal{V}$, $\mathcal{U}$, $\mathcal{N}$, which diagonalize the mass mixing matrices:

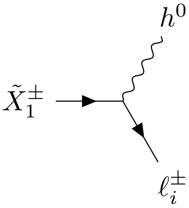
$$\mathcal{M}^D_{\tilde{\chi}^\pm} = \mathcal{U}^*\mathcal{M}_{\tilde{\chi}^\pm}\mathcal{V}^{-1} \qquad \mathcal{M}^D_{\tilde{\chi}^0} = \mathcal{N}^*\mathcal{M}_{\tilde{\chi}^0}\mathcal{N}^\dagger ,$$
$$\Rightarrow \tilde{\chi}^+ = \mathcal{U}\psi^+ , \quad \chi^- = \mathcal{V}\psi^- , \quad \tilde{\chi}^0 = \mathcal{N}\psi^0 .$$

Chargino Decay Channels

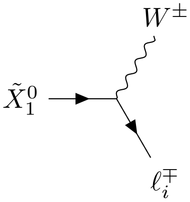
- After diagonalization: $\tilde{\chi}^{\pm} = (\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^{\pm}, e_1^{\pm}, e_2^{\pm}, e_3^{\pm})$. 3 possible RPV decay modes:

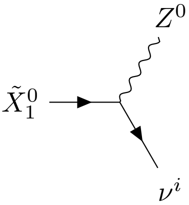


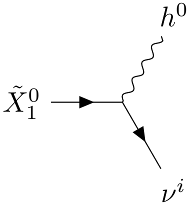




- After diagonalization: $\tilde{\chi}^0 = (\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_5^0, \tilde{\chi}_6^0, \nu_1, \nu_2, \nu_3)$. 3 possible RPV decay modes:







Simulation - RGE run initial input

- The decay rates have complicated analytic expressions, which depend on the matrices $\mathcal{U}$, $\mathcal{V}$ and $\mathcal{N}$, the RPV couplings ϵ_i and v_L^i, as well as other mass parameters and gauge couplings.
- A computer simulation [Ovrut, Purves, Spinner arXiv:1412.6103] allows us to compute the LSP decay rates numerically and analyze which decay channel dominates statistically.
- We scatter all 24 dimensionful soft supersymmetry breaking parameters in the interval, with a log-uniform distribution.

$$\left[\ \frac{M}{f}, Mf\ \right] \quad \text{where} \quad M = 1.5\ \text{TeV}\ ,\ f = 6.7\ .$$

Parameter	Range	Prior
$m_{\tilde{q}_1} = m_{\tilde{q}_2},\ m_{\tilde{q}_3}: \quad \tilde{q} = \tilde{Q}, \tilde{u}^c, \tilde{d}^c$	(224GeV−10TeV)	log
$m_{\tilde{l}_1},\ m_{\tilde{l}_2},\ m_{\tilde{l}_3}: \quad \tilde{l} = \tilde{L}, \tilde{e}^c, \tilde{\nu}^c$	(224GeV−10TeV)	log
$m_{H_u},\ m_{H_d}$	(224GeV−10TeV)	log
$\lvert A_f \rvert: \quad f = t, b, \tau$	(224GeV−10TeV)	log
$\lvert M_a \rvert: \quad a = R,\ BL,\ 2,\ 3$	(224GeV−10TeV)	log
$\tan\beta = \frac{v_u}{v_d}$	(1.2-65)	flat
Sign of $\mu, a_f, M_a: \quad f = t, b, \tau \quad a = R, BL, 2, 3$	[-,+]	flat

Simulation: Experimental Constraints - RGE flow

We run an RGE analysis to simulate possible initial conditions in agreement with current experimental constraints.

- ✔ $B - L$ gauge symmetry breaking

$$M_{Z_R} > 4.1 \text{ TeV}$$

- ✔ EW symmetry breaking

$$M_{Z^0} = 91.1876 \pm 0.0021 \text{ GeV}, \quad M_{W^\pm} = 80.379 \pm 0.012 \text{ GeV}$$

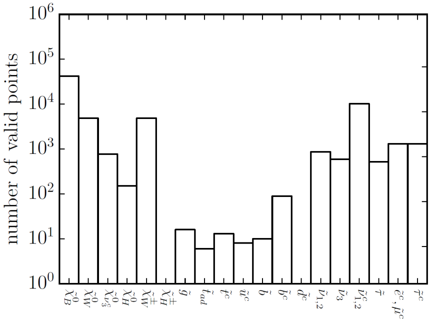
- ✔ Sparticle masses

SUSY Particle	Lower Bound
Left-handed sneutrinos	45.6 GeV
Charginos, sleptons	100 GeV
Squarks, except stop or bottom LSP	1000 GeV
Stop LSP (admixture)	550 GeV
Stop LSP (right-handed)	400 GeV
Sbottom LSP	500 GeV
Gluino	1300 GeV

- ✔ Higgs boson mass

$$M_{h^0} = 124.97 \pm 0.72 \text{ GeV}$$

Final Particle Spectra



A histogram of the LSPs associated with a random scan of 100 million initial data points.

stop/ sbottom LSP

<100 points

[Marshall,Ovrut,Purves, arXiv:1401.7989]

Wino Chargino LSP

4,869 points

Wino Neutralino LSP

4,858 points

[Dumitru,Ovrut,Purves, arXiv:1811.05581]

Bino Neutralino LSP

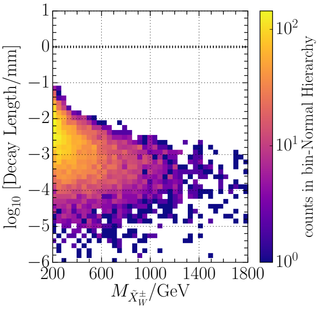
42,039 points

[Dumitru,Herwig,Ovrut, arXiv:1906.03174]

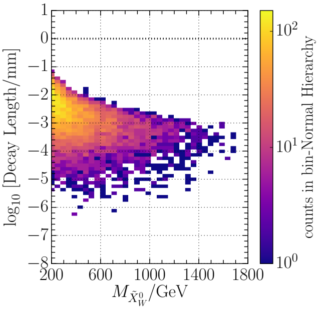
LSP RPV Decays - Promptness

A decay process is prompt if its decay length

$$L = c \times \frac{1}{\Gamma} < 1mm \; .$$



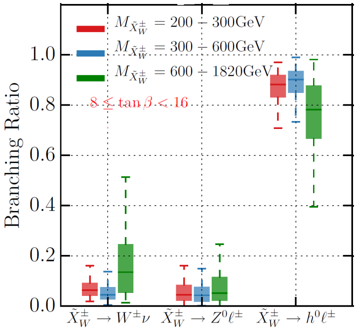
(a) Wino chargino LSP



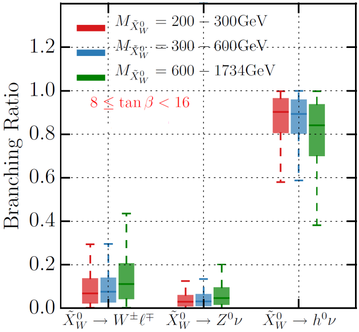
(b) Wino neutralino LSP

Scans of the Wino chargino and Wino neutralino LSP decay lengths in millimeters, for the normal hierarchy.

Branching Ratios



Branching ratios for the three possible decay channels of the Wino chargino LSP.



Branching ratios for the three possible decay channels of the Wino neutralino LSP.

Conclusions

- In the B-L MSSM, the third generation sneutrino VEV breaks R-parity at TeV scale $\rightarrow$ the LSP can decay into SM particles.
- RGE flow simulation - SUSY can exist just above the TeV scale, in agreement with most current experimental bounds. [Ovrut, Purves, Spinner arXiv:1412.6103]
- The Wino chargino $\tilde{X}_W^{\pm}$ has three RPV decay channels: $W^{\pm}\nu$, $Z^0\ell^{\pm}$, $h^0\ell^{\pm}$. The Wino neutralino $\tilde{X}_W^0$ has three RPV decay channels: $W^{\pm}\ell^{\mp}$, $Z^0\nu$, $h^0\ell^{\nu}$. [Dumitru, Ovrut, Purves, arXiv:1810.11035]
- The Wino chargino and Wino neutralino can have masses between 200-1800 GeV and can decay promptly at LHC, into SM particles $\rightarrow$ possible detection in the near future. [Dumitru, Ovrut, Purves, arXiv:1811.05581]