R-Parity Conserving Minimal B-L Model

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Three $N^c$ for anomaly free

Gives Neutrinos Mass term via $W \supset Y_\nu L H_u N^c$

Forbids $R$-Parity breaking terms

$$W_R = \epsilon L H_u + \lambda L L E^c + \lambda' Q L D^c + \lambda'' U^c D^c D^c$$

When sneutrino develops a nonzero VEV, $U(1)_{B-L}$ is broken by $\langle N_i^c \rangle \neq 0$

$R$-Parity is broken

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$1$Barger, Perez, and Spinner Phys. Rev. Lett. 102, 181802, 2009
Neutralino no longer DM candidate,
Gravitino $\Psi_{3/2}$ has the longest lifetime for viable DM

The neutralinos mix with the B-L gauginos and neutrinos in
one mass matrix$^{23}$:

$$M = \begin{pmatrix}
0_{3 \times 3} & \frac{(Y_\nu)_{jl} v_u}{\sqrt{2}} & -\frac{g_{BL} v_{Lj}}{2} & -\frac{g_1 v_{Lj}}{2} & -\frac{g_2 v_{Lj}}{2} & 0_{3 \times 1} & \frac{(Y_\nu)_{jK} v_{RK}}{\sqrt{2}} \\
\frac{(Y_\nu)_{ji} v_u}{\sqrt{2}} & 0_{3 \times 3} & \frac{g_{BL} v_{RJ}}{2} & 0_{3 \times 1} & 0_{3 \times 1} & 0_{3 \times 1} & \frac{(Y_\nu)_{kJ} v_{Lk}}{\sqrt{2}} \\
-\frac{g_{BL} v_{Li}}{2} & \frac{g_{BL} v_{RI}}{2} & M_{BL} & 0 & 0 & 0 & 0 \\
-\frac{g_1 v_{Li}}{2} & 0_{1 \times 3} & 0 & M_1 & 0 & \frac{g_1 v_d}{2} & \frac{g_1 v_u}{2} \\
-\frac{g_2 v_{Li}}{2} & 0_{1 \times 3} & 0 & 0 & M_2 & \frac{g_2 v_d}{2} & \frac{g_2 v_u}{2} \\
0 & 0 & 0 & \frac{g_1 v_d}{2} & \frac{g_2 v_d}{2} & 0 & -\mu \\
\frac{(Y_\nu)_{Ki} v_{RK}}{\sqrt{2}} & \frac{(Y_\nu)_{lk} v_{Lk}}{\sqrt{2}} & 0 & -\frac{g_1 v_u}{2} & -\frac{g_2 v_u}{2} & -\mu & 0
\end{pmatrix}.$$
Is there a way to preserve $R$-Parity while spontaneously breaking $B$-$L$?
Assign one $N^c_i$ even $R$-Parity and call it $\phi_{BL}$

B-L radiatively broken by $\langle \phi_{BL} \rangle = v_{BL}$, while $N^c_i$ will have a zero VEV

Gauge anomaly still absent due to charge assignment not changing
The approximate RGE’s for B-L gauge sector and soft masses are\(^4\)

\[
16\pi^2 \frac{d g_{BL}}{d \ln \mu} = 16 g_{BL}^3
\]

\[
8\pi^2 \frac{d M_{BL}}{d \ln \mu} = 16 g_{BL}^2 M_{BL}
\]

\[
8\pi^2 \frac{d m_{\tilde{N}_i}^2}{d \ln \mu} = g_{BL}^2 \left[ (m_{\tilde{N}_1}^2 + m_{\tilde{N}_2}^2 + m_{\phi_{BL}}^2) - 4 M_{BL}^2 \right].
\]

\[
8\pi^2 \frac{d m_{\phi_{BL}}^2}{d \ln \mu} = g_{BL}^2 \left[ (m_{\tilde{N}_1}^2 + m_{\tilde{N}_2}^2 + m_{\phi_{BL}}^2) - 4 M_{BL}^2 \right].
\]

Radiative Symmetry Breaking

- Setting $m_{\phi}^2 < m_{\tilde{N}_c}^2$ at the GUT scale drives $m_{\phi}^2$ negative at low energies.

$$m_{\phi}(\Lambda) = 2 \text{ TeV}, \quad m_{\tilde{N}_1}(\Lambda) = 7 \text{ TeV}, \quad m_{\tilde{N}_2}(\Lambda) = 8 \text{ TeV},$$

$$M_{BL}(\Lambda) = 1 \text{ TeV}, \quad g_{BL}(\Lambda) = \sqrt{\frac{4\pi}{30}}, \quad \Lambda = 2.0 \times 10^{16} \text{ GeV}$$
Neutrino Mass

- $R$-Parity conserved
- Neutrinos are Dirac

\[ W \supset Y_{ij} L_i H_u N_j^c \]

where $i=1,2,3$ and $j=1,2$
- lightest neutrino is massless
- $m_\nu = \frac{v_u Y_{ij}}{\sqrt{2}}$ (3x2 matrix)
- We may parameterize $m_\nu = U_{MNS}^\dagger D_{NH/IH}$, where

\[
D_{NH} = \begin{pmatrix}
0 & 0 \\
m_2 & 0 \\
0 & m_3
\end{pmatrix}
\quad \quad
D_{IH} = \begin{pmatrix}
m_1 & 0 \\
0 & m_2 \\
0 & 0
\end{pmatrix}
\]
Collider Phenomenology

- $Z'$ resonance at $m_{Z'} = g_{BL} \nu_{BL} = \mathcal{O}(\text{TeV})$ at LHC
- Invisible decay width of $Z'$ due to 1 massless neutrino and 2 generations of Dirac neutrinos

![Graph showing the decay width as a function of $M_{\mu\mu}$ (GeV)]
LSP neutralino still DM candidate with an additional candidate of $\tilde{\phi}_{BL}-\lambda_{BL}$ mixed state via

$$M = \begin{pmatrix} 0 & m_{Z'} \\ m_{Z'} & M_{1/2} \end{pmatrix}$$

For the new candidate the annihilation process

$\tilde{\chi}\tilde{\chi} \rightarrow Z' \rightarrow q\bar{q}, l\bar{l}$

Relic density $\Omega_{\tilde{\chi}} h^2 \approx 0.1$ is satisfied for $m_{\tilde{\chi}} \approx \frac{1}{2} m_{Z'}$

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Introducing gauged U(1) B-L to ensure $R$-Parity conservation

- Neutrinos are Dirac
- One massless neutrino
- B-L can be radiatively broken by a $R$-Parity even scalar by running of RGE’s
- New LSP DM candidate
- LHC $Z'$ gauge boson detection could probe right handed neutrino nature