New Ways to Leptogenesis with Gauged B-L Symmetry

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Why gauged B-L symmetry?

- Naturally introduces right handed neutrinos (RHN)
- Generates mass of RHN only through spontaneous symmetry breaking (SSB), protects it from Planck scale
- In the supersymmetry context naturally understands R-parity $R = (-1)^{3(B-L)+2S}$
- Explains baryon asymmetry through leptogenesis

Minimal supersymmetric B-L gauge model

In addition to MSSM particles, introduce RHN for each family, and Higgs $\overline{\Delta}, \ \Delta, \ S$ with B-L charge assignment:

e^c	L	(u^c, d^c)	Q	N	Δ	$\bar{\Delta}$	S
1	-1	-1/3	1/3	1	-2	2	0

Superpotential:

$$\begin{aligned} W &= W_{\rm MSSM} + W^{(B-L)} \ , \\ W^{(B-L)} &= \lambda S(\Delta\bar{\Delta} - M^2) + \frac{1}{2} f_{ij} N_i N_j \Delta + Y_\nu^{\alpha i} L_\alpha N_i H_u \end{aligned}$$

$\langle S \rangle = 0$ and $\langle \Delta\bar{\Delta} \rangle = M^2$ after B-L symmetry breaking.

Mass spectrum

Rewrite the fields in unitary gauge:

$$\Delta \;=\; (|M| + \frac{1}{\sqrt{2}}\Delta_0)e^{q_\Delta g_B \Delta'} \,, \qquad \bar{\Delta} = (|M| + \frac{1}{\sqrt{2}}\Delta_0)e^{-q_\Delta g_B \Delta' + i\phi_{M^2}} \,,$$

$$\mathcal{V}_B \;=\; \mathcal{V}_B^0 - \Delta' - \Delta'^{\dagger} \,, \qquad \Phi_i \to e^{q_i g_B \Delta'}\Phi_i \,.$$

Δ' is eaten up by B-L gauge boson.

Masses of gauge bosons, gauginos $M_{\mathcal{V}_{B-L}} = 2g_B|M|$

Mass of $(\Delta_0,\ S)$ $M_\Delta = \sqrt{2}|\lambda||M|$

Mass of RHN $M_{N_i} = |f_i||M|$

Gauge bosons are heavy, can be integrated out.

leave the effective superpotential

$$W(\Delta_0, N) = \lambda S e^{i\phi_{M^2}}\left(|M|\sqrt{2}\Delta_0 + \frac{1}{2}\Delta_0^2\right) + \frac{1}{2}f_{ij}(|M| + \frac{1}{\sqrt{2}}\Delta_0)N_iN_j + Y_\nu^{\alpha i}L_\alpha N_i H_u$$

ϕ_{M^2} is the argument of M^2

Application of gauged B-L model to leptogenesis

Soft terms of supersymmetry breaking generate mass splitting for the four degenerate real Higgs fields. Nonzero phases of soft terms generate CP violation. This satisfies the condition of soft leptogenesis.

$\Delta_0 \to \tilde{N} + \tilde{N},\ \Delta_0 \to \tilde{N}^* \tilde{N}^*$ have different widths. This asymmetry is then converted into ordinary lepton asymmetry in the decays of $\tilde{N} \to L\tilde{H}_u$.
The produced lepton asymmetry will be used to address the problem of baryon asymmetry.

SUSY breaking mass spectrum

Potential $V = V_F + V_{\rm Soft}$.

$$V_{\rm soft} = \lambda M^2 (A_\lambda - C_\lambda) S + A_\lambda \lambda e^{i\phi_{M^2}} S(\sqrt{2}|M|\Delta_0 + \frac{1}{2}\Delta_0^2) + \frac{1}{2} A_f f_{ij} (|M| + \frac{1}{\sqrt{2}}\Delta_0)\tilde{N}_i \tilde{N}_j + {\rm h.c.} + m_i^2 |\Phi_i|^2$$

S acquires VEV, proportional to soft terms.

Higgs mass matrix

$$\mathcal{M}^2_{boson} = M^2_\Delta \begin{pmatrix} 1 & \kappa_R + \kappa'_R & 0 & \kappa_I - \kappa'_I \\ \kappa_R + \kappa'_R & 1 & -\kappa'_I & 0 \\ 0 & -\kappa'_I & 1 & -\kappa'_R \\ \kappa_I - \kappa'_I & 0 & -\kappa'_R & 1 \end{pmatrix}$$

In the basis $({\rm Re}(\Delta_0), {\rm Re}(S), {\rm Im}(\Delta_0), {\rm Im}(S))$

Eigenvalues of real scalar Higgs masses

$$M^2_{X_{1,2}} = M^2_\Delta \left(1 + \Delta_{12} \mp \Delta_{14}\right) \ , \qquad M^2_{X_{3,4}} = M^2_\Delta \left(1 - \Delta_{12} \pm \Delta_{14}\right)$$

with

$$\Delta_{12} = \frac{|\lambda v_S|}{M_\Delta} \ , \qquad \Delta_{14} = \frac{\left||A_\lambda| + \lambda v_S e^{i\phi_{M^2}}\right|}{M_\Delta}$$

SUSY breaking mass spectrum

Mass eigenstates of scalar RHN:

$$\tilde{N}_+ = \frac{1}{\sqrt{2}}(e^{ix}\tilde{N} + e^{-ix}\tilde{N}^*) \ , \qquad \tilde{N}_- = \frac{1}{\sqrt{2}i}(e^{ix}\tilde{N} - e^{-ix}\tilde{N}^*)$$

with mass

$$M^2_{\tilde{N}_+} = |M_N|^2 + |M_N| \left| A_f + \frac{C_\lambda - A_\lambda}{2} \right| \ , \qquad M^2_{\tilde{N}_-} = |M_N|^2 - |M_N| \left| A_f + \frac{C_\lambda - A_\lambda}{2} \right| \ .$$

Decays of scalar Higgs

To avoid gravitino problem, we set $M_\Delta \sim (10^6 - 10^8)\ \mathrm{GeV}$, out-of-equilibrium requires $|f| \leq 10^{-5}$, if furthermore choose $|\lambda| \leq 0.09$, the dominant decay of X_i scalars is to RHN.

The coupling constant:

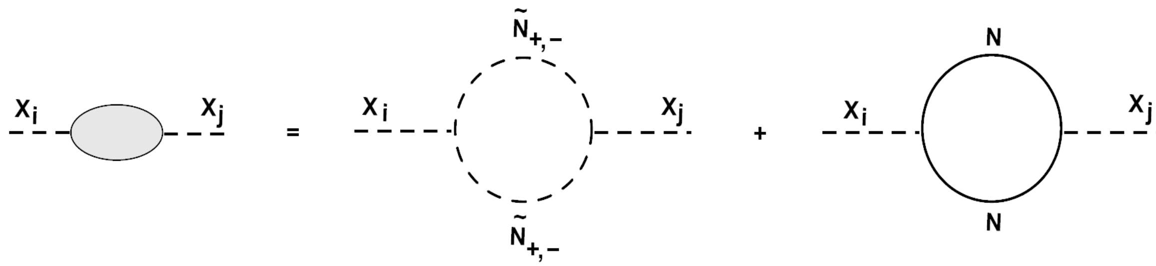
$$F_{\tilde{N}\tilde{N}i} \;=\; \frac{f}{4}\left(a_1+a_2+M_\Delta e^{i\omega},\ -i(a_1-a_2+M_\Delta e^{i\omega}),\ a_1+a_2-M_\Delta e^{i\omega},\ -i(a_1-a_2-M_\Delta e^{i\omega})\right)_i$$

$$F_{|\tilde{N}|i} \;=\; \frac{|f||M_N|}{\sqrt{2}}\left(c_\alpha,\ s_\alpha,\ c_\alpha,\ s_\alpha\right)_i \qquad Y_F = \frac{f e^{-i\alpha}}{4\sqrt{2}}\left(1,\ i,\ 1,\ i\right)$$

$$\text{with} \qquad a_1 = \frac{C_\lambda - A_\lambda}{2} e^{i\alpha}\ , \qquad a_2 = A_f e^{-i\alpha}\ , \qquad \omega = \beta - \phi_\lambda - \phi_{M^2}\ .$$

CP violation in scalar Higgs decays

CP violation is generated through the interference of tree level and loop level decay. We consider wave function corrections:



with absorptive parts

$$\Pi^B_{ij}(p^2) \;=\; \frac{1}{32\pi}\left(2K_{++}F_{++\,i}F_{++\,j} + 2K_{--}F_{--\,i}F_{--\,j} + K_{+-}F_{+-\,i}F_{+-\,j}\right) \;,$$

$$\text{where} \qquad K_{ab} = \left(1 - 2\frac{M^2_{\tilde{N}_a} + M^2_{\tilde{N}_b}}{p^2} + \frac{(M^2_{\tilde{N}_a} - M^2_{\tilde{N}_b})^2}{p^4}\right)^{1/2}$$

$$\Pi^F_{ij}(p^2) = \frac{1}{8\pi}p^2(1 - 4M^2_N/p^2)^{1/2}\left(Y_F^\dagger Y_F + Y_F^T Y_F^*\right)_{ij}$$

$$\text{with} \qquad Y_F = \frac{fe^{-i\alpha}}{4\sqrt{2}}\,(1,\; i,\; 1,\; i) \;.$$

The CP violation parameter in the scalar decays is

$$\epsilon_{\tilde{N}} = \sum_i \frac{\Gamma(X_i \to \tilde{N}\tilde{N}) - \Gamma(X_i \to \tilde{N}^*\tilde{N}^*)}{\Gamma(X_i \to \tilde{N}\tilde{N}) + \Gamma(X_i \to \tilde{N}^*\tilde{N}^*)}$$

$$= 4\left[\frac{2\Delta_{12}\Gamma/M_\Delta}{4\Delta_{12}^2 + (\Gamma/M_\Delta)^2} \cdot \frac{\hat{A}_1}{M_\Delta} + \frac{2\Delta_{14}\Gamma/M_\Delta}{4\Delta_{14}^2 + (\Gamma/M_\Delta)^2} \cdot \frac{\hat{A}_2}{M_\Delta}\right]$$

This lepton asymmetry is completely converted into lepton asymmetry in the MSSM sector and then converted into baryon asymmetry through sphaleron interactions.

Leptogenesis

At zero temperature, the decay of $\tilde{N} \to L\tilde{H}_u$ and $\tilde{N} \to \tilde{L}^* H_u^*$ cancel each other, but net lepton number violation is generated through temperature effect. The baryon asymmetry through $\tilde{N}$ decavs is

$$\frac{\tilde{n}_B}{s} \simeq -8.6 \cdot 10^{-4} \epsilon_{\tilde{N}} \eta$$

η is efficient factor.

Choose $\hat{A}_2 \approx 3M_{\mathrm{SUSY}}$ $\quad \Delta_{14} \approx \frac{1}{300}\frac{M_{\mathrm{SUSY}}}{M_\Delta}$ $\quad M_\Delta \approx 10^8$ GeV

We have

$$\epsilon_{\tilde{N}} \gtrsim 10^{-6}$$

with $\eta \sim 0.1$, $\left(\frac{n_B}{s}\right)_{\mathrm{exp}} = (8.75 \pm 0.23) \cdot 10^{-11}$ can be satisfied.

Conclusion

- We have built a SUSY model based on gauged B-L symmetry
- We studied the mass spectrum of particle after symmetry breaking
- Through soft symmetry breaking, we studied the CP violating decays of scalar particles to scalar RHN
- We studied the generation of baryon asymmetry in the universe through the scalar decays and showed that the observed baryon asymmetry can be satisfied under some reasonable choice of parameters.