Left-Right Symmetry: Minimal Model, Radiative Neutrino Mass, and Leptogenesis

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Outline

1. Motivation
2. Radiative ν_R mass generation in Left-Right Symmetric Model
3. ν masses and oscillation
4. Baryogenesis through Resonant Leptogenesis
5. Conclusion

Motivation for LR Symmetric Models

- In Standard Model $M_\nu = 0$. But, beam of ν can oscillate in vacuum into ν of different flavors. $\nu_{aL} \leftrightarrow \nu_{bL}$. This implies $m_\nu \neq 0$, and requires new physics beyond SM.
- No ν_R in SM. Parity is explicitly broken by SM. LR symmetric model restores Parity.
- This model is based on $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. ν_R exists for $SU(2)_R$ multiplet. $SU(2)_R$ breaking gives heavy Majorana right handed neutrino. Thus, smallness of left-handed neutrinos is naturally realized via see-saw mechanisms.
- In SM Y (hypercharge) is arbitrary quantum number whereas in LR symmetric model Y arises more coherently from less arbitrary quantity B-L.

$$Y = T_R^3 + \frac{B-L}{2}$$

Motivation for Leptogenesis

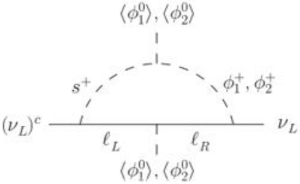
- An attractive way to understand matter antimatter asymmetry in the universe is through leptogenesis. Baryon asymmetry is defined as:

$$\eta_B \equiv \frac{n_B}{n_\gamma} = 6.1\,^{+0.3}_{-0.2} \times 10^{-10}$$

- Well motivated due to neutrino oscillation
- Leptogenesis can be done in the framework of seesaw mechanism
- Radiative RH neutrino mass naturally leads to resonant leptogenesis. Thus, observed matter-antimatter asymmetry of the universe is understood.

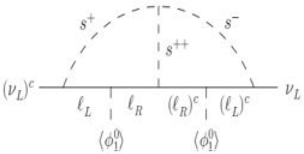
Generation of ν mass

- **Seesaw Mechanism**: Introduce ν_R . But it requires Yukawa coupling to be same order as of quark and charged leptons. But, observation shows $m_\nu << m_q$ or m_l.
  Introduce large Majorana mass scale Λ to suppress the neutrino mass via see-saw mechanism as $< \phi >^2 / \Lambda$.
- **Radiative correction**: Assumes $m_\nu = 0$ at tree level as SM and generates small mass of neutrino at 1-loop or 2-loop introducing new heavy scalar fields.



Zee Model

New particles: s^+ and second $SU(2)_L$ doublet ϕ



Zee-Babu Model

New particles: s^+ and s^{++}

Left-Right Symmetric Model

Gauge Group:

$$SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$

Fermion Representation:

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L \sim (2,1,1/3) \quad Q_R = \begin{pmatrix} u \\ d \end{pmatrix}_R \sim (1,2,1/3) \quad \psi_L = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \sim (2,1,-1) \quad \psi_R = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_R \sim (1,2,-1)$$

Higgs Representation:

$$\phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \quad \Delta_l = \begin{pmatrix} \frac{\Delta_L^+}{\sqrt{2}} & \Delta_L^{++} \\ \Delta_L^0 & -\frac{\Delta_L^+}{\sqrt{2}} \end{pmatrix}$$

$$\Delta_R = \begin{pmatrix} \frac{\Delta_R^+}{\sqrt{2}} & \Delta_R^{++} \\ \Delta_R^0 & -\frac{\Delta_R^+}{\sqrt{2}} \end{pmatrix}$$

Standard LR Model

$$\phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}$$

$$\chi_L = \begin{pmatrix} \chi_L^+ \\ \chi_L^0 \end{pmatrix} \qquad \chi_R = \begin{pmatrix} \chi_R^+ \\ \chi_R^0 \end{pmatrix} \qquad \eta^+$$

LR Radiative Seesaw

Under L-R symmetry:

$$\psi_L \leftrightarrow \psi_R \qquad \chi_L \leftrightarrow \chi_R \qquad \phi \leftrightarrow \phi^\dagger \qquad \eta^+ \leftrightarrow \eta^+ \qquad W^\pm \leftrightarrow W^\pm$$

Interactions

- Interaction of scalar η^+ with fermions:

$$\mathcal{L}_Y \supset f_{ab}\,[(\psi^{i}_{aL} C\,\psi^{j}_{bL})\,\epsilon_{ij}\,\eta^+ + (\psi^{i}_{aR} C\,\psi^{j}_{bR})\,\epsilon_{ij}\,\eta^+\,] + \text{h. c.}$$

- Interaction of scalar ϕ with ferminos:

$$\mathcal{L}_Y \supset y\,\overline{\psi_L}\,\phi\,\psi_R + \tilde{y}\,\overline{\psi_L}\,\tilde{\phi}\,\psi_R + \text{h.c.}$$

- Self Interaction of Higgs particles by Higgs potential:

$$\mathcal{L}_{Higgs} = Tr[(D_\mu\phi)^\dagger (D_\mu\phi)] + |D_\mu\,\chi_L|^2 + |D_\mu\,\chi_R|^2 + V(\phi, \chi_L, \chi_R, \eta)$$

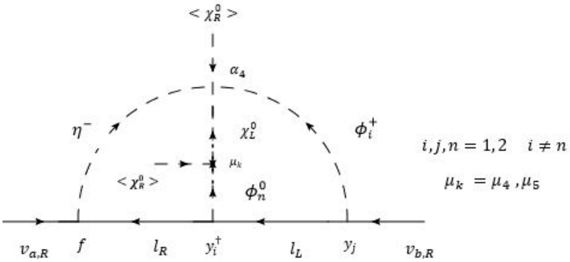
Higgs Potential:

$$V(\phi, \chi_L, \chi_R, \eta) = V(\phi) + V(\chi_L, \chi_R) + V(\eta) + V(cross - terms)$$

$$\supset \mu_4\,[\chi_L{}^\dagger\phi\,\chi_R + \chi_R{}^\dagger\phi^\dagger\,\chi_L] + \mu_5\,\left[\chi_L{}^\dagger\,\tilde{\phi}\,\chi_R + \chi_R{}^\dagger\,\tilde{\phi}^\dagger\,\chi_L\right]$$

$$+(\alpha_4\,[\chi_L{}^T i\,\tau_2\phi\,\chi_R\eta^- + \chi_R{}^T i\,\tau_2\phi^\dagger\,\chi_L\eta^-] + h.\,c.)$$

Loop Diagram ν_R mass generation



$M_{\phi_j^+}$ and $M_{\phi_n^0} \sim M >> M_{\chi_L^0}, M_\eta$

$$(M_{\nu R})_{ab} \approx \frac{1}{(16\pi^2)^2} c_{ij}(f y_i^\dagger y_j + y_j^T y_i^* f^T) \frac{\alpha_4 \mu_k v_R^2}{M^2(M^2 - M^2_{\chi_L^0})} \left[2M^2 \left(-1 + Log\left(\frac{M_\eta^2}{M^2}\right)\right) + M^2_{\chi_L^0} \left\{ -2 + \frac{\pi^2}{3} + 2Log\left(\frac{M^2_{\chi_L^0}}{M^2}\right) + Log\left(\frac{M_\eta^2}{M^2}\right) \left\{ 1 + Log\left(\frac{M^2_{\chi_L^0}}{M^2}\right)\right\}\right\}\right]$$

$$M_{v,R} \sim \frac{f\, y^2}{(16\,\pi^2)^2}\, v_R$$

Mass Matrices

After Symmetry breaking masses reads,

Charged Lepton: $M_l = y\kappa' + \tilde{y}\,\kappa^*$

Dirac Mass: $M_{\nu,D} = y\kappa + \tilde{y}\,\kappa'^*$

where $\langle\phi_1^0\rangle = \kappa$ and $\langle\phi_2^0\rangle = \kappa'$

In the limit $\tilde{y} \to 0$, $M_{l^+} \approx y\,\kappa'$ $M_{\nu,D} \approx y\kappa$

Neutrino mass matrix reads:

$$(\nu \quad \nu^c) \begin{pmatrix} M_L^M & M_{\nu,D} \\ (M_{\nu,D})^T & M_{\nu,R} \end{pmatrix} \begin{pmatrix} \nu \\ \nu^c \end{pmatrix}$$

$$M_\nu^{light} = M_L^M - (M_{\nu,D})\ (M_{\nu,R})^{-1}\ (M_{\nu,D})^T = M_0\,[-M_I + \beta\,M_{II}]$$

Mass Matrices

$$M_{\nu}^{light} = M_0 \left[-M_I + \ \beta\, M_{II}\right]$$

$$= M_0 \left\{ + \beta \begin{bmatrix} 0 & c & a \\ c & 0 & b \\ a & b & 0 \end{bmatrix} - \begin{bmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{bmatrix} \begin{bmatrix} 0 & c & a \\ c & 0 & b \\ a & b & 0 \end{bmatrix}^{-1} \begin{bmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{bmatrix} \right\}$$

$$\beta = |\beta|\, e^{I\,\theta}\,,\ c = f_{et}\, m_\mu^2\,,\quad a = f_{et} m_\tau^2,\quad b = f_{\mu t} m_\tau^2$$

Oscillation fit

With the choice of parameters,

$$x_1 = \frac{f_{e\mu}}{f_{e\tau}} = 15.815, \qquad x_2 = \frac{f_{\mu\tau}}{f_{e\tau}} = 0.46, \qquad |\beta| = 0.007, \qquad \theta = 1.94\pi$$

$$M_\nu^{light} = M_0 \begin{pmatrix} 4.99306\times10^{-6} & 0.0194153 - 0.00399911\,i & 0.340289 - 0.0634688\,i \\ 0.0194153 - 0.00399911\,i & 0.943868 & -0.837058 - 0.030187\,i \\ 0.340289 - 0.0634688\,i & -0.837058 - 0.030187\,i & 1.059 \end{pmatrix}$$

$$\frac{\Delta m_{21}^2}{\Delta m_{31}^2} \approx \frac{1}{35}, \quad \theta_{13} \approx 8.30^\circ, \qquad \theta_{12} \approx 33.57^\circ, \qquad \theta_{23} \approx 41.2^\circ, \qquad \delta \approx 1.27\,\pi,$$

$$m_3 > m_2 > m_1 \ \ (Normal\ hierarchy)$$

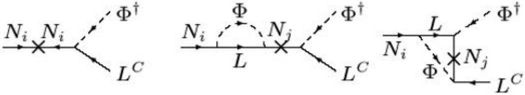
Parameter	Fit (exp.) 1σ	Fit Theo.
$\frac{\Delta m_{21}^2}{\Delta m_{31}^2}$	0.0296	0.0296 ± 0.0025
θ_{12}	$33.62^{+0.78}_{-0.76}$	$33.62^{+0.75}_{-0.80}$
θ_{13}	$8.54^{+0.15}_{-0.15}$	$8.54^{+0.15}_{-0.19}$
θ_{23}	$40.68^{+1.9}_{-3.6}$	$40.68^{+0.95}_{-1.07}$
δ/π (3 σ)	1.38 (1.0 ,1.9)	(1, 1.87)

Leptogenesis Ingredients

- Lepton Asymmetry is generated by CP violation in N_R decay.

$$\epsilon_1 = \frac{\Gamma(N_1 \to \phi\, L) - \Gamma(N_1 \to \phi^\dagger\, \bar{L})}{\Gamma(N_1 \to \phi\, L) + \Gamma(N_1 \to \phi^\dagger\, \bar{L})}$$

- Asymmetry arises from the interference of tree-level and one loop amplitudes.



- Out-of-equilibrium condition

$$\Gamma_{N_1} \leq H(T = \mathrm{M}_{N_1})$$

- Conversion of L into B through Sphaleron processes
- For nearly degenerate heavy Majorana states (Resonant Leptogenesis), the CP asymmetry gets enhanced and is given by:

$$\epsilon_2 = \frac{Im\left(\hat{Y}^\dagger \hat{Y}\right)^2_{32}}{\left(\hat{Y}^\dagger \hat{Y}\right)_{22}\left(\hat{Y}^\dagger \hat{Y}\right)_{33}} \frac{(M_3^2 - M_2^2)M_2\Gamma_3}{(M_3^2 - M_2^2)^2 + M_2^2\Gamma_3^2} \quad , \quad \Gamma_i = \frac{\left(\hat{Y}^\dagger \hat{Y}\right)_{ii} M_i}{8\,\pi}$$

RH Neutrino Mass Matrix and Yukawa Matrix

- For $\tilde{y} = 0$ and y diagonal and Real,

$$M_{\nu,R} = (f\, y^2 + y^2 f^{\mathsf{T}})\, J = J \begin{bmatrix} 0 & \varepsilon & a \\ \varepsilon & 0 & b \\ a & b & 0 \end{bmatrix} \qquad \boxed{\varepsilon = f_{et} \frac{m_\mu^2}{k'^2},\ a = f_{et} \frac{m_\tau^2}{k'^2},\ b = f_{\mu t} \frac{m_\tau^2}{k'^2}}$$

- Can be diagonalized by $O^{\mathsf{T}} M O = M_{diag}$

$$M_1 = J\lambda_1, \qquad M_2 = J\lambda_2, \qquad M_3 = J\lambda_3$$

$$\lambda_1 = \frac{2\,a\,b\,\varepsilon}{a^2 + b^2}, \qquad \lambda_2 = \sqrt{a^2 + b^2} + \frac{a\,b\,\varepsilon}{a^2 + b^2}, \qquad \lambda_3 = \sqrt{a^2 + b^2} - \frac{a\,b\,\varepsilon}{a^2 + b^2}$$

- This leads to mass splitting in two heavy N_2 and N_3 states unlike two lighter states.

- f is real anti-symmetric matrix. To generate CP violation, introduce $\tilde{y} \ll y$. Writing Yukawa Neutrino interaction in mass basis. ($\tilde{y}$ *is the coupling of scalar* $\tilde{\phi}$ *with fermions*)

$$\mathcal{L}_Y \supset \phi\, \overline{\nu_{iL}}\, \hat{Y} N_j \quad \text{where } \hat{Y} = \frac{k\,y + k'\,\tilde{y}}{\sqrt{k^2 + k'^2}} . O$$

Lower Bound on M_1

$$\Gamma_D < H\ (T = M_1)$$

$$\frac{(\hat{Y}Y)_{11}\, M_1}{8\,\pi} < 1.66\, g_*^{1/2} \frac{T^2}{M_{pl}}\Bigg|_{T = M_{pl}}$$

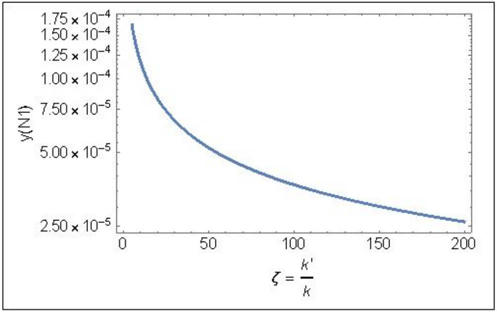
$For\ \zeta = 100,$ $\boxed{M_1 \gtrsim 4 \times 10^6\ GeV}$

From neutrino oscillation,

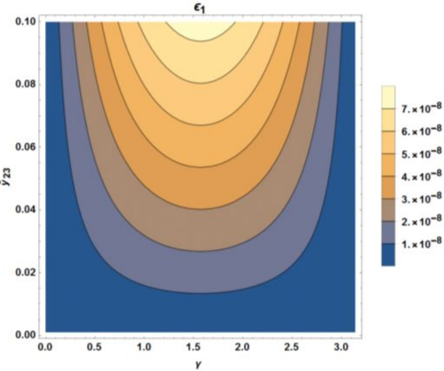
$$x_1 = \frac{f_{e\mu}}{f_{e\tau}} = 15.815, \qquad x_2 = \frac{f_{\mu\tau}}{f_{e\tau}} = 0.46$$

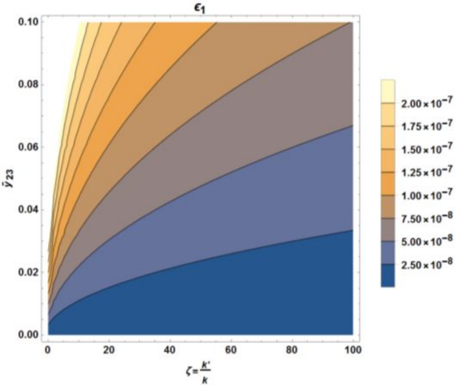
$$M_2 \gtrsim 8.77 \times 10^7\ GeV$$

$$M_3 \gtrsim 8.43 \times 10^7\ GeV$$



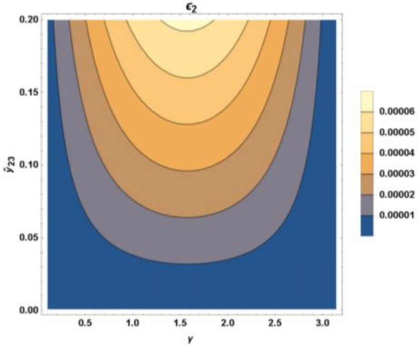
$$\epsilon_1 = \frac{\sum_j Im\,\{[(\tilde{Y}^\dagger \tilde{Y})_{1j}]^2\}}{8\,\pi\,(\tilde{Y}^\dagger \tilde{Y})_{11}} \cdot g(x_j) \quad , \quad x_j = \frac{M_j}{M_1} \qquad g(x) = \sqrt{x}\left[\frac{1}{1-x} + 1 - (1+x)\ln\left(\frac{1+x}{x}\right)\right] \; , \; \tilde{y}_{23} = |\tilde{y}_{23}|e^{I\gamma}$$

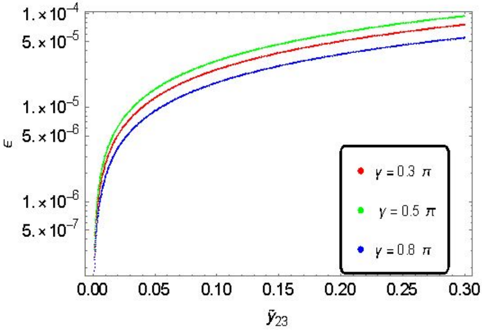




N_1 decay doesn't produce Baryon Asymmetry.

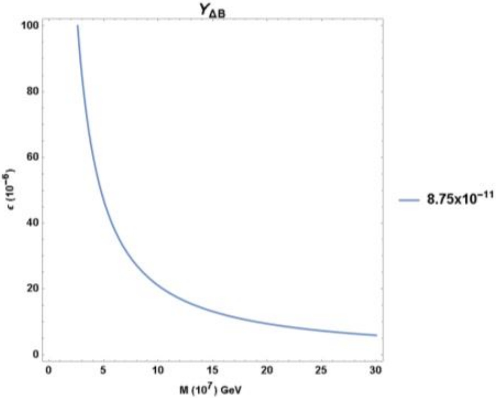
CP Asymmetry with Resonant Leptogenesis

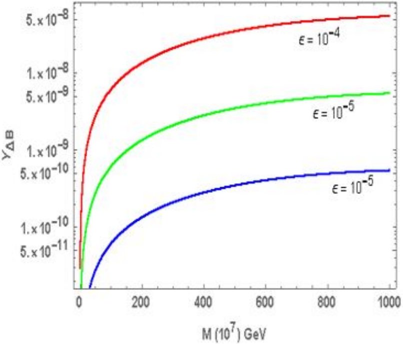




$$\frac{n_B}{s} \approx -1.48 \times 10^{-3}(k_f^2 \epsilon_2 + k_f^3 \epsilon_3) \ ,$$

$$k_f^{2,3} \approx \left[\frac{3.3 \times 10^{-3}\, eV}{\widetilde{m}_{2,3}} + \left(\frac{\widetilde{m}_{2,3}}{0.55 \times 10^{-3}\, eV}\right)^{1.16}\right]^{-1} \ , \ \widetilde{m}_i = \frac{<h^o>^2}{M_i}\left(\widehat{Y}^\dagger \widehat{Y}\right)_{ii}$$





Summary

- LR Symmetric model with Higgs doublet having no triplet is studied.
- η^+ is added as doublet by itself cannot generate RH ν Majorana mass.
- $m_{\nu R} << m_{wR}$ due to 2-loop suppression. However, this is still large enough to realize see-saw.
- Resonant leptogenesis naturally gives the observed Baryon asymmetry.
- This model allows parameters which is in good agreement with neutrino oscillation experiment.

Thank You