Left-Right Symmetry: Minimal Model and Radiative Neutrino Mass

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Phenomenology 2018 Symposium

Outline

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. Parity is explicitly broken by SM. LR symmetric model restores Parity.

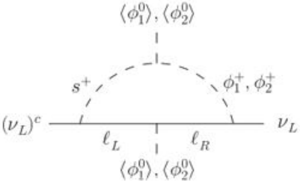
- ν_R exists for $SU(2)_R$ multiplet. $SU(2)_R$ breaking gives heavy Majorana right handed neutrino. Thus, smallness of left-handed neutrinos is naturally realized via see-saw mechanisms.

- In SM Y (hyper charge) is arbitrary quantum number whereas in LR symmetric model Y arises more coherently from less arbitrary quantity B-L.

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

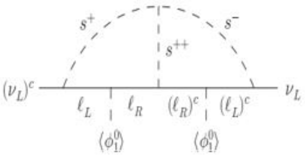
Generation of ν mass

- 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^{++}

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

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

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

LR Radiative Seesaw

Under L-R symmetry:

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

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:
$\mathcal{L}_Y \supset y_1 \overline{\psi_L} \phi\, \psi_R + y_2 \overline{\psi_L}\, \tilde{\phi} \psi_R + \text{h.c.}$

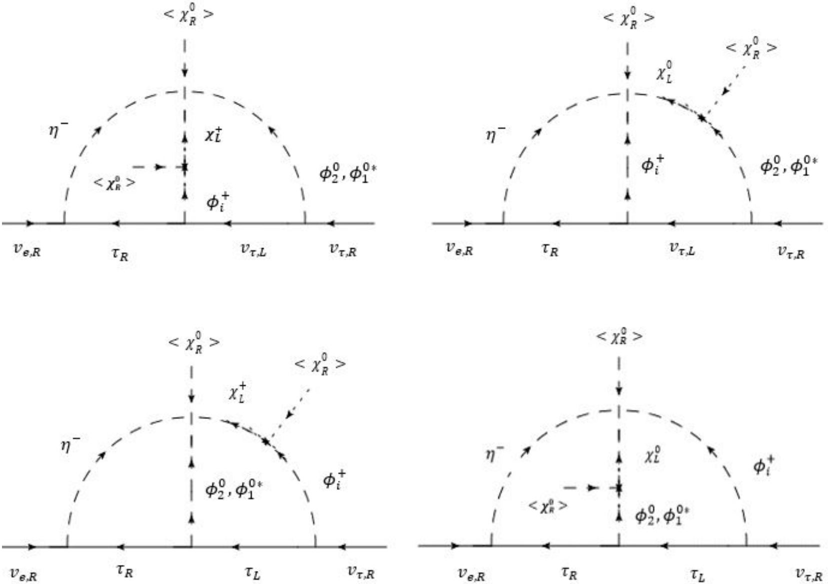
- Self Interaction of Higgs particles by Higgs potential:

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

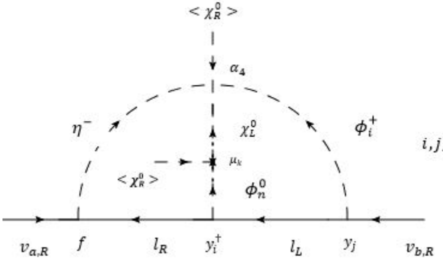
$$V(\phi, \chi_L, \chi_R, \eta) = V(\phi) + V(\chi_L, \chi_R) + V(\eta) + V(cross - terms)$$

$$\begin{aligned}
= -\mu_1^2\, Tr(\phi^\dagger \phi) - \mu_2^2 \left[Tr(\tilde{\phi}\, \phi^\dagger) + Tr\left(\tilde{\phi}^\dagger\, \phi\right)\right] + \lambda_1 [Tr(\phi^\dagger \phi)]^2 + \lambda_2 \left\{ \left[Tr\left(\tilde{\phi}^\dagger\, \phi\right)\right]^2 + [Tr(\tilde{\phi}\, \phi^\dagger)]^2 \right\} \\
+ \lambda_3\, Tr(\tilde{\phi}\, \phi^\dagger)\, Tr\left(\tilde{\phi}^\dagger\, \phi\right) + \lambda_4\, Tr(\phi^\dagger \phi)[\, Tr(\tilde{\phi}\, \phi^\dagger) + Tr(\tilde{\phi}\, \phi^\dagger)\,] - \mu_3^2\, (\chi_L{}^\dagger \chi_L + \chi_R{}^\dagger \chi_R) \\
+ \rho_1 \left[(\chi_L{}^\dagger \chi_L)^2 + (\chi_R{}^\dagger \chi_R)^2 \right] + \rho_2\, \chi_L{}^\dagger \chi_L \chi_R{}^\dagger \chi_R - \mu_9^2\, |\eta|^2 + \rho_3\, |\eta|^4 + \alpha_1 |\eta|^2\, Tr(\phi^\dagger \phi) \\
+ \alpha_2\, |\eta|^2 \left[Tr(\tilde{\phi}\, \phi^\dagger) + Tr\left(\tilde{\phi}^\dagger\, \phi\right)\right] + \alpha_3\, |\eta|^2\, (\chi_L{}^\dagger \chi_L + \chi_R{}^\dagger \chi_R) \\
+ \mu_4\, [\chi_L{}^\dagger \phi\, \chi_R + \chi_R{}^\dagger \phi^\dagger \chi_L] + \mu_5\, \left[\chi_L{}^\dagger\, \tilde{\phi}\, \chi_R + \chi_R{}^\dagger\, \tilde{\phi}^\dagger\, \chi_L\right] \\
+ \mu_6\, (\chi_L{}^\dagger \chi_L + \chi_R{}^\dagger \chi_R)\, Tr(\phi^\dagger \phi) + \mu_7 \left(Tr(\tilde{\phi}\, \phi^\dagger)(\chi_L{}^\dagger \chi_L) + Tr\left(\tilde{\phi}^\dagger\, \phi\right)(\chi_R{}^\dagger \chi_R) \right) \\
+ \mu_7^* \left[Tr\left(\tilde{\phi}^\dagger\, \phi\right).(\chi_L{}^\dagger \chi_L) + Tr(\tilde{\phi}\, \phi^\dagger).(\chi_R{}^\dagger \chi_R)\right] + \mu_8 [\,\chi_L{}^\dagger \phi\, \phi^\dagger \chi_L + \chi_R{}^\dagger \phi^\dagger \phi\, \chi_R] \\
+ (\alpha_4\, [\chi_L{}^T i\, \tau_2 \phi\, \chi_R \eta^- + \chi_R{}^T i\, \tau_2 \phi^\dagger\, \chi_L \eta^-] + h.c.)
\end{aligned}$$

Loop Diagrams



Loop Diagram



$i, j, n = 1, 2 \quad i \neq n$

$\mu_k = \mu_4, \mu_5$

Case I: $M_\eta >> M_{\phi_j^+}, M_{\phi_n^0}, M_{\chi_L^0}$

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

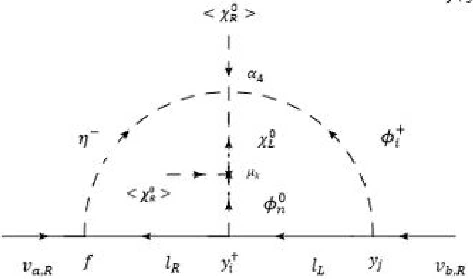
Case II: $M_{\phi_j^+}$ and $M_{\phi_n^0} \sim M >> M_{\chi_L^0}, M_\eta$

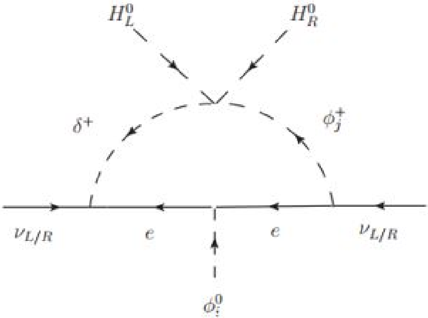
$$(M_{\nu R})_{ab} \approx \frac{1}{(16\pi^2)^2} c_{ij}(f y_i^\dagger y_j + y_j^T y_i^* f^T) \frac{\alpha_4 \mu_k v_R^2}{M^2(M^2 - M_{\chi_L^0}^2)}\left[2M^2\left(-1+Log\left(\frac{M_\eta^2}{M^2}\right)\right)+M_{\chi_L^0}^2\left\{-2+\frac{\pi^2}{3}+2Log\left(\frac{M_{\chi_L^0}^2}{M^2}\right)+Log\left(\frac{M_\eta^2}{M^2}\right)\left\{1+Log\left(\frac{M_{\chi_L^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

Case III: $M_{\phi_n^0}$ and $M_{\chi_L^0} >> M_{\phi_j^+}, M_\eta$

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

$f, y \sim 1$





$$If\ v_R \sim 10^7\, GeV,\ \ M_{v,R} \sim \frac{f\, y^2}{(16\,\pi^2)^2}\, v_R \ \sim 1\ \text{TeV}$$

$$If\ v_R \sim 10^{14}\, GeV,\ \ M_{v,R} \sim \frac{f\, y^2}{(16\,\pi^2)^2}\, v_R \sim 10^7\ \text{TeV}$$

$$M_{\nu,R} \sim 0.4\ \text{GeV}$$

Ref: Perez, Murgui, Ohmer

Mass Matrices

After Symmetry breaking masses reads,

Charged Lepton: $M_l = y_1 \kappa' + y_2 \kappa^*$ Dirac Mass: $M_{\nu,D} = y_1 \kappa + y_2 \kappa'^*$

Where κ and κ' are vacuum expectation value for ϕ_1^0 and ϕ_2^0.

In the limit $y_2 \rightarrow 0$, $M_{l^+} \approx y_1 \kappa'$ $M_{\nu,D} \approx y_1 \kappa$

Neutrino mass matrix reads:

$$M_\nu^{light} \approx -(M_{\nu,D})\,(M_{\nu,R})^{-1}\,(M_{\nu,D})^T \approx -\frac{k^2}{J} y_1 \left(f\, y_1^\dagger y_1 + y_1^T y_1^* f^T\right)^{-1} y_1 \qquad \text{(type I)}$$

(y_1 to be diagonal)

$$M_\nu^{light} = \alpha \begin{bmatrix} \frac{f_{\mu\tau} m_e^2 (m_\tau^2 - m_\mu^2)}{f_{e\mu} f_{e\tau} (m_\tau^2 - m_e^2)(m_\mu^2 - m_e^2)} & \frac{-m_e m_\mu}{f_{e\mu}(m_\mu^2 - m_e^2)} & \frac{-m_e m_\tau}{f_{e\tau}(m_\tau^2 - m_e^2)} \\ \frac{-m_e m_\mu}{f_{e\mu}(m_\mu^2 - m_e^2)} & \frac{f_{e\tau} m_\mu^2 (m_\tau^2 - m_e^2)}{f_{e\mu} f_{\mu\tau} (m_\tau^2 - m_\mu^2)(m_\mu^2 - m_e^2)} & \frac{-m_\mu m_\tau}{f_{\mu\tau}(m_\tau^2 - m_\mu^2)} \\ \frac{-m_e m_\tau}{f_{e\tau}(m_\tau^2 - m_e^2)} & \frac{-m_\mu m_\tau}{f_{\mu\tau}(m_\tau^2 - m_\mu^2)} & \frac{f_{e\mu} m_\tau^2 (m_\mu^2 - m_e^2)}{f_{e\tau} f_{\mu\tau} (m_\tau^2 - m_e^2)(m_\tau^2 - m_\mu^2)} \end{bmatrix}$$

For type II,

$$M_\nu^{light} = \beta \begin{bmatrix} 0 & f_{e\mu}(m_\mu^2 - m_e^2) & f_{e\tau}(m_\tau^2 - m_e^2) \\ f_{e\mu}(m_\mu^2 - m_e^2) & 0 & f_{\mu\tau}(m_\tau^2 - m_\mu^2) \\ f_{e\tau}(m_\tau^2 - m_e^2) & f_{\mu\tau}(m_\tau^2 - m_\mu^2) & 0 \end{bmatrix} \qquad (\beta \propto v_L)$$

Mass Matrices

$y = \frac{f_{\mu\tau}}{f_{e\tau}}$ and $x = \frac{f_{e\mu}}{f_{e\tau}}$

$$M_\nu^{light} = \alpha' \begin{bmatrix} \frac{1.116 \times 10^{-5}\, y^2}{x} & \frac{-2.417 \times 10^{-8}\, y}{x} & -1.438\, y \\ \frac{-2.417 \times 10^{-8}\, y}{x} & \frac{0.502}{x} & -0.029 \\ -1.438\, y & -0.029 & 0.0017\, x \end{bmatrix}$$

$\frac{m3}{m2} \approx 7, \quad \theta_{23} \approx 48^\circ \ , \ \theta_{12} \approx 35^\circ$ (Cannot fit all three)

In general, $y_2 \neq 0$, But choose $\kappa' = 0$ and $y_2 < y_1$,

$$M_{l^+} \approx y_2\, \kappa^+ \qquad M_{\nu,D} \approx y_1\, \kappa$$

$$M_\nu^{light} \approx - \frac{k^2}{j} y_1 (f\, y_1^\dagger y_1 + y_1^T y_1^* f^T)^{-1}\ y_1$$ $(\, y_1\, not\ diagonal)$

$\frac{m3}{m2} \approx 7, \quad \theta_{23} \approx 47^\circ \ , \ \theta_{12} \approx 33^\circ , \theta_{13} \approx 8^\circ$

Prediction of the Model

$$M_{\upsilon,R} \sim \frac{f\, y^2}{(16\,\pi^2)^2} \frac{\mu_k\ \alpha_4\ \upsilon_R^2}{M^2}$$

$$M_{\upsilon,L} \sim \frac{f\, y^2}{(16\,\pi^2)^2} \frac{\mu_k\ \alpha_4 \upsilon_L^2}{M^2}$$

$$\frac{M_{\upsilon,L}}{M_{\upsilon,R}} \sim \frac{\upsilon_L^2}{\upsilon_R^2} \quad \Rightarrow \quad M_{\upsilon,R} \sim M_{\upsilon,L} \frac{\upsilon_R^2}{\upsilon_L^2} \leq (10^{-10} GeV) \frac{\upsilon_R^2}{\upsilon_L^2}$$

$\upsilon_L \sim (1-100)\ GeV$

$$\upsilon_R \geq (10^5) \sqrt{\frac{M_{\upsilon,R}}{GeV}}$$

Note: 1) $M_{W_R} \sim \upsilon_R$, $if\ W_R\ is\ discovered\ at\ LHC \Rightarrow \upsilon_R\ is\ small \Rightarrow M_{\upsilon R}\ has\ to\ be\ small$

2) No Δ^{++}

Summary

- Triplet is bigger representation than doublet. Thus, LR Symmetric Model with Higgs doublet is studied.
- η^+ is added as doublet by itself cannot generate RH ν Majorana mass.
- v_R ranging from 10^7 to 10^{16} would work.
- $m_{\nu R} << m_{wR}$ due to 2-loop suppression. However, this is still large enough to realize see-saw.

Thank You