LEFT-RIGHT SYMMETRIC MODEL WITHOUT HIGGS TRIPLETS

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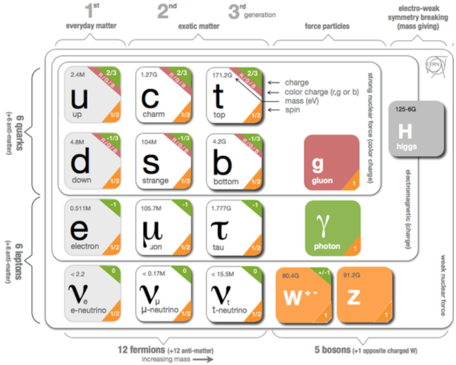
Outline

- Motivation
- Model (particle content, scalar sector, gauge sector)
- Radiative ν mass generation
- Low scale left-right
  - Constraints (Direct experimental constraints, $0\nu\beta\beta$, cosmological constraints, ..)
  - Fit to the data
- High scale left-right consistency
- Collider phenomenology
- Conclusion

	$SU(3)_C \times SU(2)_L \times U(1)_Y$
Matter	$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \sim (3, 2, \frac{1}{3})$ $\psi_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \sim (1, 2, -1)$ $e_R \sim (1, 1, -2), \;\; u_R \sim (3, 1, \frac{4}{3})$ $d_R \sim (3, 1, -\frac{2}{3})$
Higgs	$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \sim (1, 2, 1)$



- In Standard Model $M_\nu = 0$. But, ν flavor mix. $\nu_{aL} \leftrightarrow \nu_{bL}$

$$|\nu_\alpha\rangle = \sum U_{\alpha i}|\nu_i\rangle \Longrightarrow M_\nu \neq 0 \Longrightarrow \text{New physics beyond SM}$$

$$U_{PNMS} = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & e^{-i\delta}s_{13} \\ -c_{23}s_{12} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - c_{23}s_{12}s_{13}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.7$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.78}_{-0.75}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.570^{+0.018}_{-0.024}$	$0.407 \to 0.618$	$0.575^{+0.017}_{-0.021}$	$0.411 \to 0.621$
$\theta_{23}/^\circ$	$49.0^{+1.1}_{-1.4}$	$39.6 \to 51.8$	$49.3^{+1.0}_{-1.2}$	$39.9 \to 52.0$
$\sin^2\theta_{13}$	$0.02221^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02240^{+0.00062}_{-0.00062}$	$0.02053 \to 0.02436$
$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.61^{+0.12}_{-0.12}$	$8.24 \to 8.98$
$\delta_{\mathrm{CP}}/^\circ$	195^{+51}_{-25}	$107 \to 403$	286^{+27}_{-32}	$192 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.514^{+0.028}_{-0.027}$	$+2.431 \to +2.598$	$-2.497^{+0.028}_{-0.028}$	$-2.583 \to -2.412$

Origin of Parity Violation

- Parity is explicitly broken in standard model.
- Left-right models were introduced primarily to understand the origin of parity violation.

Mohapatra, Pati, Senjanovic: 74-75

- Gauge group:

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

- Fermion Representation:

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

- Higgs Representation

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \qquad \Delta_L = \begin{pmatrix} \Delta_L^+/\sqrt{2} & \Delta_L^{++} \\ \Delta_L^0 & -\Delta_L^+/\sqrt{2} \end{pmatrix}$$

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

Standard LR Model

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \qquad \eta^+$$

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

Babu, Mathur 88

- Under LR symmetry

$$Q_L \leftrightarrow Q_R \quad \psi_L \leftrightarrow \psi_R \quad \chi_L \leftrightarrow \chi_R \quad \Phi \leftrightarrow \Phi^\dagger \quad \eta^+ \leftrightarrow \eta^+ \quad W_L \leftrightarrow W_R$$

Comparison with Standard LR

Standard LR	Our Model
Higgs Sector:	
• $\Delta_L(1,3,2) + \Delta_R(3,1,2) + \Phi(2,2,0)$	• $\chi_L(1,2,1) + \chi_R(2,1,1) + \Phi(2,2,0) + \eta^+(1,1,2)$
• 2 charged and 2 doulbly charged scalars	• 3 charged scalars
Fermion masses:	
• $\langle\Phi\rangle \neq 0 \Rightarrow M_u, M_d, M_{\nu^D}$	• $\langle\Phi\rangle \neq 0 \Rightarrow M_u, M_d, M_{\nu^D}$
• $\langle\Delta_R\rangle \neq 0, \langle\Delta_L\rangle \neq 0$ $\Rightarrow$ Majorana mass for ν	• η^+ ensures Majorana mass for ν.

- Phenomenology of the model is distinct with respect to neutrino physics, Higgs boson physics and collider signals.

$$\langle\Phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}\kappa & 0\\ 0 & \kappa' e^{i\alpha}\end{pmatrix}, \quad \langle\chi_L\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_L e^{i\theta_L}\end{pmatrix}, \quad \langle\chi_R\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_R\end{pmatrix}$$

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

↓ $\langle\chi_R\rangle \neq 0 \Rightarrow M_{W_R}, M_{Z_R} \neq 0$

$$SU(2)_L \otimes U(1)_Y$$

↓ $\langle\Phi\rangle \neq 0 \Rightarrow M_{W_L}, M_Z \neq 0$
$\langle\chi_L\rangle \neq 0$

$$U(1)_{em}$$

Features of LRSM

- Parity is explicitly broken in SM. LR symmetric model restores parity.
- In LRSM hypecharge Y arises more coherently from less arbitary quantity $B-L$.
  In SM, electric charge is given by
  $$Q = T_L^3 + \frac{Y}{2}$$
  Y is an arbitrary parameter with no physical meaning.
  In LR models,
  $$Q = T_L^3 + T_R^3 + \frac{B-L}{2}$$
- ν_R exists as $SU(2)_R$ multiplet. $SU(2)_R$ breaking gives heavy Majorana right handed neutrino. Thus, smallness of left-handed neutrinos is naturally realized via see-saw mechanisms.

Interactions

- Interaction of scalar η^+ with fermions

$$\mathcal{L}_Y \supset f_{ab}\left[\left(\psi^i_{aL} C \psi^j_{bL}\right)\epsilon_{ij}\eta^+ + \left(\psi^i_{aR} C \psi^j_{bR}\right)\epsilon_{ij}\eta^+\right] + \text{H.c.}$$

- Interaction of scalar Φ with fermions

$$\mathcal{L}_Y \supset y\overline{\psi}_L \Phi \psi_R + \widetilde{y}\overline{\psi}_L \widetilde{\Phi}\psi_R + \text{H.c.}$$

- Self interaction of Higgs particles by Higgs potential

$$\begin{aligned} V(\phi, \chi_L, \chi_R, \eta) &= V(\phi) + V(\chi_L, \chi_R) + V(\eta) + V(\text{cross-terms}) \\ &\supset \mu_4\left[\chi_L^\dagger \phi \chi_R + \chi_R^\dagger \phi^\dagger \chi_L\right] + \mu_5\left[\chi_L^+ \widetilde{\phi}\chi_R + \chi_R^+ \widetilde{\phi}^\dagger \chi_L\right] \\ &+ \left(\alpha_4\left[\chi_L^\top i\tau_2 \phi \chi_R \eta^- + \chi_R^\top i\tau_2 \phi^\dagger \chi_L \eta^-\right] + \text{H.c}\ .\right) \end{aligned}$$

- In the limit of $v_R >> v_L, \kappa, \kappa'$ and at the leading order in $\epsilon = \frac{\kappa'}{\kappa}, \epsilon' = \frac{v_L}{\kappa}$, expression for the Higgs state and their mass:

Higgs state	Mass
$H_1^+ \simeq (\cos\omega\ \epsilon - \sin\omega\ \epsilon')\phi_1^+ + \cos\omega\ \phi_2^+ - \sin\omega\ \chi_L^+$	$m^2_{H_1^+} \simeq \frac{v_R}{4}\{(\alpha_3 - \rho_{12})v_R - \sqrt{A}\}$
$H_2^+ \simeq -(\sin\omega\ \epsilon + \cos\omega\ \epsilon')\phi_1^+ - \sin\omega\ \phi_2^+ - \cos\omega\ \chi_L^+$	$m^2_{H_2^+} \simeq \frac{v_R}{4}\{(\alpha_3 - \rho_{12})v_R + \sqrt{A}\}$
$H_3^+ \simeq \eta^+$	$m^2_{H_3^+} \simeq \mu_\eta^2 + \frac{\alpha_7}{2}v_R^2$
$A_1 \simeq (\cos\omega\ \epsilon + \sin\omega\ \epsilon')\phi_1^{0i} + \cos\omega\ \phi_2^{0i} + \sin\omega\ \chi_L^{0i}$	$m^2_{A_1} \simeq m^2_{H_1^+}$
$A_2 \simeq (-\sin\omega\ \epsilon + \cos\omega\ \epsilon')\phi_1^{0i} - \sin\omega\ \phi_2^{0i} + \cos\omega\ \chi_L^{0i}$	$m^2_{A_2} \simeq m^2_{H_2^+}$
$h^0 \simeq \phi_1^{0r} + \epsilon\phi_2^{0r} + \epsilon'\chi_L^{0r} - \frac{\alpha_1\kappa}{2\rho_1 v_R}\chi_R^{0r}$	$m^2_{h^0} \simeq 2\kappa^2(\lambda_1 + 4\epsilon\lambda_4 - \frac{\alpha_1^2}{4\rho_1})$
$H_1^0 \simeq (\cos\omega\ \epsilon + \sin\omega\ \epsilon')\phi_1^{0r} - \cos\omega\ \phi_2^{0r} - \sin\omega\ \chi_L^{0r}$	$m^2_{H_1^0} \simeq m^2_{H_1^+}$
$H_2^0 \simeq (\sin\omega\ \epsilon - \cos\omega\ \epsilon')\phi_1^{0r} - \sin\omega\ \phi_2^{0r} + \cos\omega\ \chi_L^{0r}$	$m^2_{H_2^0} \simeq m^2_{H_2^+}$
$H_3^0 \simeq \chi_R^{0r} + \frac{\alpha_1\kappa}{2\rho_1 v_R}(\phi_1^{0r} + \epsilon\phi_2^{0r} + \epsilon'\chi_L^{0r})$	$m^2_{H_3^0} \simeq 2\rho_1 v_R^2$

h^0 is the standard model-like Higgs.

Gauge sector

$$\mathcal{L}_{gauge} = (D_\mu \chi_L)^\dagger D_\mu \chi_L + (D_\mu \chi_R)^\dagger D_\mu \chi_R + tr\left[(D_\mu \Phi)^\dagger D_\mu \Phi\right]$$

$$D_\mu \chi_{L,R} = \partial_\mu \chi_{L,R} - \frac{1}{2} i g_{L,R}\, \vec{\tau} \cdot \vec{W}_{\mu L,R}\, \chi_{L,R} - \frac{1}{2} i g_{BL}\, \chi_{L,R} B_\mu \,,$$

$$D_\mu \Phi = \partial_\mu \Phi - \frac{1}{2} i g_L\, \vec{\tau} \cdot \vec{W}_{\mu L} \Phi + \frac{1}{2} i g_R\, \Phi\, \vec{\tau} \cdot \vec{W}_{\mu R}$$

- The mass eigenvalues are found in the limit of $v_R >> \kappa, \kappa', v_L$ ($\kappa_L = k^2 + \kappa'^2 + v_L^2$ and $\kappa_R = k^2 + \kappa'^2 + v_R^2$)

$$M^2_{W_1} \simeq \frac{1}{4} g_L^2 \kappa_L^2 \qquad W_1^+ = \cos\zeta\ W_L^+ + \sin\zeta\ W_R^+$$

$$M^2_{W_2} \simeq \frac{1}{4} g_R^2 v_R^2 \qquad W_2^+ = -\sin\zeta\ W_L^+ + \cos\zeta\ W_R^+$$

$$\tan 2\zeta = \frac{4 g_L g_R \kappa \kappa'}{g_R^2 \kappa_R^2 - g_L^2 \kappa_L^2}$$

- $|\zeta| \leq 4 \times 10^{-3}$: strangeness changing nonleptonic decays of hadrons; $b \to s\gamma$ decay.

$$M^2_{Z_1} \simeq \frac{1}{4}\left(g_Y^2 + g_L^2\right)\kappa_L^2 \qquad Z_1 = \cos\xi\ Z_L + \sin\xi\ Z_R$$

$$M^2_{Z_2} \simeq \frac{1}{4}\frac{g_R^4}{(g_R^2 - g_Y^2)} v_R^2 \qquad Z_2 = -\sin\xi\ Z_L + \cos\xi\ Z_R$$

$$\tan 2\xi \simeq \frac{2\,(g_R^2 \kappa_+^2 - g_Y^2 \kappa_L^2)\sqrt{(g_R^2 - g_Y^2)(g_R^2 + g_L^2)}}{g_R^4 \kappa_R^2}$$

- $\xi \leq 10^{-3}$ from electroweak precision observables, but automatically satisfied once the lower limit on the mass of Z_2 of about 5 TeV from LHC searches is imposed.

Fermion Masses

- $\langle\Phi\rangle \neq 0 \Rightarrow$ Quarks, charged leptons and Dirac neutrinos masses:

$$M_u = \frac{1}{\sqrt{2}}\left(Y\,\kappa + \widetilde{Y}\,\kappa' e^{-i\alpha}\right), \quad M_d = \frac{1}{\sqrt{2}}\left(Y\,\kappa' e^{i\alpha} + \widetilde{Y}\,\kappa\right)$$
$$M_\ell = \frac{1}{\sqrt{2}}\left(y\,\kappa' e^{i\alpha} + \widetilde{y}\,\kappa\right), \quad M_{\nu^D} = \frac{1}{\sqrt{2}}\left(y\,\kappa + \widetilde{y}\,\kappa' e^{-i\alpha}\right).$$

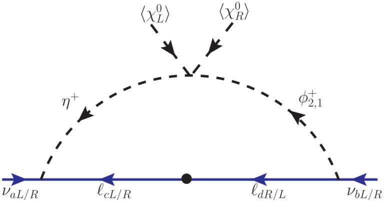
  - $\kappa = \kappa' \Rightarrow M_u = M_d$

- Neutrino mass matrix spanning (ν, ν^c) read:

$$\begin{pmatrix} M_\nu^L & M_{\nu^D} \\ M_{\nu^D}^T & M_\nu^R \end{pmatrix} \qquad M_\nu^{\text{light}} = M_\nu^L - M_{\nu^D}(M_\nu^R)^{-1}M_{\nu^D}^T = M_\nu^{II} - M_\nu^I$$

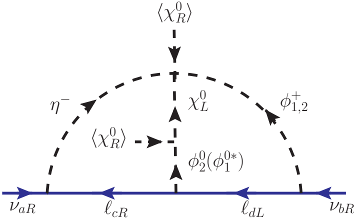
- M_ν^L and M_ν^R will arise through one-loop and two-loop radiative correction.

$$M_\nu^I >> M_\nu^{II} \Rightarrow \text{Type-I}$$
$$M_\nu^{II} >> M_\nu^I \Rightarrow \text{Type-II}$$



$$O_1 = c_1\, \Psi_R \Psi_R (\chi_L^T \Phi \chi_R)$$

$$c_1 \sim \frac{(y_\tau^2 f \alpha_4)}{16\pi^2}\left(\frac{1}{M^2}\right)$$



$$O_2 = c_2\, \Psi_R \Psi_R (\chi_R \chi_R)$$

$$c_2 \sim \frac{(y_\tau^2 f \alpha_4)}{(16\pi^2)^2}\left(\frac{\mu_4}{M^2}\right)$$

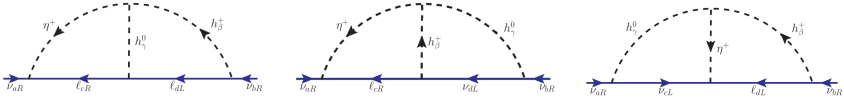
- The two-loop diagrams do not require electroweak symmetry breaking and dominate over the one-loop diagrams for the entire range of $W_R^\pm$ mass.

Some more details

- One-loop radiative corrections:

$$(M_\nu^R)_{ab} = \frac{1}{8\pi^2}\left[f_{a\ell} M_\ell V_{5\beta}^{+} \left(y_{\ell b} V_{1\beta}^{\star +} - \widetilde{y}_{\ell b} V_{2\beta}^{\star +}\right) + (a \leftrightarrow b)\right] \log\left(\frac{m^2_{H_1^+}}{m^2_{H_\beta^+}}\right)$$

- Two-loop radiative corrections:



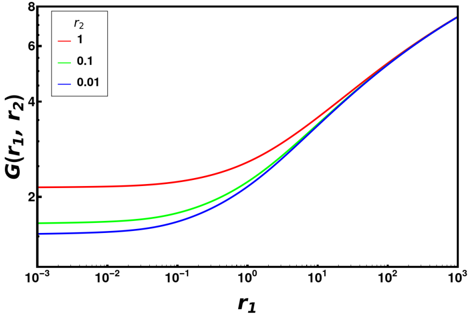
$$(M_\nu^R)_{ab} = \sqrt{2}\,\alpha_4 v_R \left(A_{1ab} + A_{2ab} + A_{3ab}\right)$$

$$\begin{aligned}
A_{1ab} &= \Big\{f_{ac}\left[y_{cd}^\star\, V_{2\gamma}^\star \{-V_{3\gamma}V_{1\beta} - V_{3\gamma}V_{2\beta} + V_{2\gamma}V_{3\beta}\} - \widetilde{y}_{cd}^\star V_{1\gamma}V_{3\beta}V_{1\gamma}^\star\right] \\
&\quad \left(y_{db}V_{1\beta}^\star - \widetilde{y}_{db}V_{2\beta}^\star\right) + (a \leftrightarrow b)\Big\}\, I_{cd}^{\eta\gamma\beta}\,, \\
A_{2ab} &= \Big\{f_{ac}\left(y_{cd}^\star V_{2\beta}^\star - \widetilde{y}_{cd}^\star V_{1\beta}^\star\right)\left[\widetilde{y}_{db}\, V_{2\gamma}^\star \{-V_{3\gamma}V_{1\beta} - V_{3\gamma}V_{2\beta} + V_{2\gamma}V_{3\beta}\}\right. \\
&\quad \left. - y_{db}V_{1\gamma}V_{3\beta}V_{1\gamma}^\star\right] + (a \leftrightarrow b)\Big\}\, I_{cd}^{\eta\beta\gamma}\,, \\
A_{3ab} &= \Big\{\left(y_{ca}V_{1\beta}^\star - \widetilde{y}_{ca}V_{2\beta}^\star\right) f_{cd}\left[\widetilde{y}_{db}\, V_{2\gamma}^\star \{-V_{3\gamma}V_{1\beta} - V_{3\gamma}V_{2\beta} + V_{2\gamma}V_{3\beta}\}\right. \\
&\quad \left. - y_{db}V_{1\gamma}V_{3\beta}V_{1\gamma}^\star\right] + (a \leftrightarrow b)\Big\}\, I_{cd}^{\beta\eta\gamma}\,.
\end{aligned} \tag{1}$$

$$I_{cd}^{\eta\gamma\beta} = \int\int \frac{d^4p}{(2\pi)^4}\frac{d^4q}{(2\pi)^4}\frac{q.p}{(q^2 - m_\eta^2)(q^2 - m_d^2)(p^2 - m^2_{H_\beta^+})(p^2 - m_c^2)((p-q)^2 - m^2_{H_\gamma^0})}$$

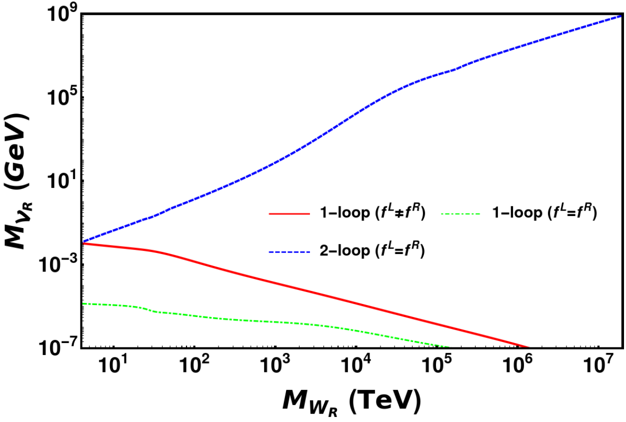
- Case with $M_{\nu^D} \ll M_\ell$ (low Scale LR) $\Rightarrow$ Flavor structure simplifies, $y, \tilde{y} \propto M_\ell$.

$$(M_{\nu_R})_{ab} = \frac{2\sqrt{2}\,\alpha_4 v_R}{\kappa^2(1-\epsilon^2)^2\,(16\pi^2)^2}\,(fM_\ell^2 + M_\ell^2 f^T)\left\{C_{\beta\gamma}\,G\left(\frac{m_\eta^2}{m_{H_\gamma^0}^2}, \frac{m_{H_\beta^+}^2}{m_{H_\gamma^0}^2}\right) + C'_{\beta\gamma}\,G\left(\frac{m_\eta^2}{m_{H_\beta^+}^2}, \frac{m_{H_\gamma^0}^2}{m_{H_\beta^+}^2}\right)\right\}.$$



$$G(r_1, r_2) \;\rightarrow\; \begin{cases} -\dfrac{3}{2} - \dfrac{r}{2} + \dfrac{7}{4} r\log r & \text{for } r_1 = r_2 = r,\; r << 1 \\[2ex] -\dfrac{1}{2} - \dfrac{\pi^2}{6} + \dfrac{1}{4} r_1 \log r_1 & \text{for } r_2 = 1,\; r_1 << 1 \end{cases}$$

One-loop vs two-loop



- Maximum contribution to M_{ν_R} for $\alpha_4 = 3.0$ and $f_{\mu\tau} \simeq f_{e\tau} = 1.0$.

M_{W_R} (TeV)	5	10	15	30	50	100	10^4
M_{ν_R} (GeV)	0.0042	0.010	0.020	0.05	0.11	0.36	4.2×10^3

- Neutrino mass matrix is diagonalized by 6×6 unitary matrix:

$$U^\dagger M_\nu U^\star = \begin{pmatrix} m_{\nu_j} & 0 \\ 0 & M_{N_\alpha} \end{pmatrix} \leftrightarrow U = \begin{pmatrix} U_{\nu\nu} & U_{\nu N} \\ U_{N\nu} & U_{NN} \end{pmatrix}$$

$$m_{\nu_j} = \text{Diag}\,(m_1, m_2, m_3) \qquad M_{N_\alpha} = \text{Diag}\,(M_1, M_2, M_3)\ .$$

$U_{\nu N} \longrightarrow$ active-sterile mixing $\left(U_{\nu N} \sim \frac{M_{\nu^D}}{M_N} \right)$

$U^\star_{\nu\nu}$ is the usual PMNS matrix characterizing the mixing among light neutrinos.

$$s^2_{12} = \frac{|U_{e2}|^2}{1 - |U_{e3}|^2}, \qquad s^2_{13} = |U_{e3}|^2, \qquad s^2_{23} = \frac{|U_{\mu 3}|^2}{1 - |U_{e3}|^2}\ .$$

Low scale left-right symmetry

- For multi-TeV range of M_{W_R} (within reach of collider experiments)

  $\Rightarrow$ MeV range of M_{ν_R}.

  $\Rightarrow$ fit to the ν-oscillation data with $M_{\nu_R} \sim (1 - 100)$ MeV.

  $\Rightarrow$ satisfy experimental, cosmology and astrophysics constraints.

- Constraints on active-sterile neutrino mixing from visible final state particles in beta-decay, pion decay, kaon decay, muon decay, ...

Mass	1 MeV	5 MeV	10 MeV	30 MeV	50 MeV	100 MeV
$\lvert U_{eN}\rvert^2$	2.6×10^{-4} BD2	1.1×10^{-5} BOREXINO	3.5×10^{-6} BOREXINO	4.4×10^{-7} PIENU	1.2×10^{-7} PIENU	7.1×10^{-9} PIENU
$\lvert U_{\mu N}\rvert^2$	1.1×10^{-2} $\pi_{\mu 2}$ PSI	2.75×10^{-4} $\pi_{\mu 2}$ PSI	2.06×10^{-4} $\pi_{\mu 2}$ PSI	8.6×10^{-6} $\pi_{\mu 2}$ PIENU	2.35×10^{-4} $K_{\mu 2}$ KEK	3.76×10^{-6} $K_{\mu 2}$ KEK
$\lvert U_{\tau N}\rvert^2$	–	–	0.49 CHARM	0.021 CHARM	4.9×10^{-3} CHARM	5.1×10^{-4} CHARM

Neutrinoless double beta decay $0\nu\beta\beta$

- $0\nu\beta\beta$: $(A, Z) \longrightarrow (A, Z+2) + 2e^-$: If observed $\Longrightarrow$ evidence of lepton number violation $\Longrightarrow$ Majorana neutrino.
- Can shed light on unresolved issues in neutrino physics.
- $0\nu\beta\beta$ decay provides limits on the active-sterile mixing as a function of sterile neutrino mass.

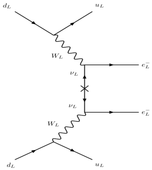
$$\frac{1}{T_{1/2}^{0\nu}} = G_{01}^{0\nu}\left(\left|\mathcal{M}_{\nu}^{0\nu}\eta_{\nu} + \mathcal{M}_{N}^{0\nu}\eta_{N_R}^{L}\right|^2 + \left|\mathcal{M}_{N}^{0\nu}\eta_{N_R}^{R}\right|^2 + \left|\mathcal{M}_{\lambda}^{0\nu}\eta_{\lambda} + \mathcal{M}_{\eta}^{0\nu}\eta_{\eta}\right|^2\right)$$

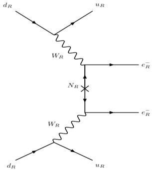
$G_{01}^{0\nu}$: Phase factor $\qquad$ $\mathcal{M}_{X}^{0\nu}$: Nuclear matrix element

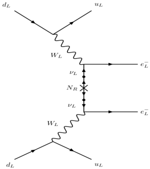
Isotope	$G_{01}^{0\nu}$ (yr^{-1})	Nuclear Matrix Elements $\mathcal{M}_{\nu}^{0\nu}$	$\mathcal{M}_{N}^{0\nu}$	$\mathcal{M}_{\lambda}^{0\nu}$	$\mathcal{M}_{\eta}^{0\nu}$
^{76}Ge	5.77×10^{-15}	2.58–6.64	233–412	1.75–3.76	235–637
^{136}Xe	3.56×10^{-14}	1.57–3.85	164–172	1.92–2.49	370–419

More details

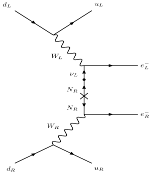
- η's are dimensionless parameters obtained from Feynman amplitudes.
  Low $W_R^{\pm}$ mass $\Rightarrow$ ν_R masses of a few MeV $\Rightarrow$ momentum transfer can be much heavier than sterile neutrino mass :

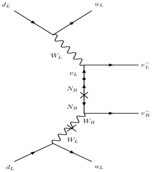






$$\eta_\nu = \frac{1}{m_e}\sum_{i=1}^{3} U_{ei}^2 m_{\nu_i} \qquad \eta_{N_R}^R = \frac{1}{m_e}\left(\frac{M_{W_L}}{M_{W_R}}\right)^4 \sum_{i=4}^{6} U_{4i}^{*2} M_{N_i} \qquad \eta_{N_R}^L = \frac{1}{m_e}\sum_{i=4}^{6} U_{ei}^2 M_{N_i}$$





$$\eta_\lambda = \left(\frac{M_{W_L}}{M_{W_R}}\right)^2 \sum_{i=1}^{3} U_{ei} U_{4i}^* \qquad \eta_\eta = \tan\xi \sum_{i=1}^{3} U_{ei} U_{4i}^*$$

Cosmological Constraints

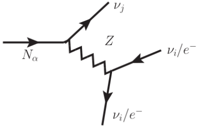
- Sterile neutrino (1-100 Mev) can upset successful prediction of big bang cosmology.
  - if ν_R are long lived $\Rightarrow$ contribute to effective number of neutrino species. (constrainted by Planck data).
    $\Rightarrow$ can overclose the universe.
- Structure of Right-handed neutrino:
  In Low W_R regime $\Rightarrow y, \widetilde{y} \propto M_\ell$:

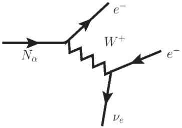
$$M_\nu^R = \mathcal{J} \begin{pmatrix} 0 & \frac{m_\mu^2}{m_\tau^2} f_{e\mu} & f_{e\tau} \\ \frac{m_\mu^2}{m_\tau^2} f_{e\mu} & 0 & f_{\mu\tau}(1 - \frac{m_\mu^2}{m_\tau^2}) \\ f_{e\tau} & f_{\mu\tau}(1 - \frac{m_\mu^2}{m_\tau^2}) & 0 \end{pmatrix}$$

$\Rightarrow$ Hierarchy between sterile neutrino. $(M_{N_1} << M_{N_2} \simeq M_{N_3})$

Decay of sterile neutrino

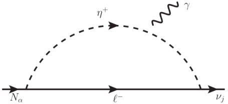
- MeV mass sterile neutrino (N) can decay into $\bar{\nu}_i \nu_i \nu_j$, $\nu_i e^+ e^-$, and $\nu_i \gamma$.

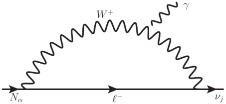




$$\Gamma(N_\alpha \to e^+ e^- \nu) = 2 \sum_j |U_{j\alpha}|^2 \frac{G_F^2 M_{N_\alpha}^5}{192\pi^3} \left[\left\{ \delta_{je} + (-\frac{1}{4} + \frac{1}{2}\sin^2\theta_w) \right\}^2 + \frac{1}{4}\sin^4\theta_w \right]$$

$$\Gamma(N_\alpha \to 3\nu) = 2 \sum_j |U_{j\alpha}|^2 \frac{1}{4} \frac{G_F^2 M_{N_\alpha}^5}{192\pi^3} (1+2+1)\,.$$





$$\Gamma(N_\alpha \to \nu\gamma) = 2 \times \left(\frac{\alpha M_{N_\alpha}^3 m_\tau^2}{128\pi^4} \right) \left[\left| \frac{f_{e\tau}^2 + f_{\mu\tau}^2}{m_\eta^2} \left\{ 1 + \log\left(\frac{m_\tau^2}{m_\eta^2} \right) \right\} \right|^2 + \left| \frac{g^2\,\zeta}{2M_{W_L}^2} \right|^2 \right]$$

- Radiative decay by η^+ lead to a lifetime of order 1 sec. $\Rightarrow$ consistent with big bang cosmology.

Supernova Energy Loss Constraints

- Obsevation of ν flux from SN 1987A (Kamiokande and IMB) $\Rightarrow$ information about neutrinos
- If $M_{\nu}^{R} \leq 10$ MeV and has charged current coupling $\Rightarrow \nu_R$ can be produced in the supernova core via $e^{-}p \longrightarrow \nu_R n \Rightarrow$ alters dynamics of supernova.
- Lower limit of 23 TeV on $W_R^{\pm}$ mass by demanding that the ν_R luminosity not exceed 10^{53} erg/sec for supernova 1987a.

  Barbieri and Mohapatra, 88.

Contd.

- However we find significantly weaker, with the lower limit on $W_R^{\pm}$ as low as 4.6 TeV.
  - Computed the exact cross section ($e^- + p \to \nu_R + n$) for the production of ν_R inside supernova: 3.3 times smaller.
  - Included an important interference effect between the $W_R^{\pm}$ contribution and the $W_L^{\pm} - W_R^{\pm}$ mixed contribution in the production cross section.
  - Average electron energy to be ~ 150 MeV, as opposed to 300 MeV.

- The effective interactions involving the leptons and quarks

$$\mathcal{L} = \frac{4G_F \cos\theta_C}{\sqrt{2}} \left[-\sin\zeta\, \overline{d_L}\gamma^\mu u_L + \cos\zeta\, \frac{M_{W_L}^2}{M_{W_R}^2}\, \overline{d_R}\gamma^\mu u_R \right] (\overline{\nu}_R \gamma_\mu e_R)$$

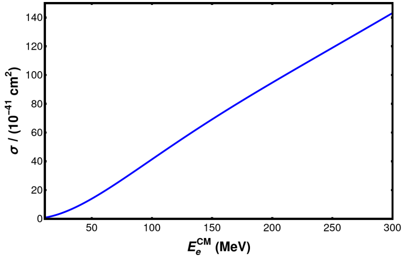
  - Convert into hadronic Lagrangian; Strong interaction are parity conserving $\Rightarrow$ interference leads to suppression factor

$$\Rightarrow B = -\sin\zeta + \cos\zeta\, \frac{M_{W_L}^2}{M_{W_R}^2}$$

- Scattering corss section for $e^-\ (p_p) + p\ (p_p) \longrightarrow \nu\ (p_\nu) + n\ (p_n)$

$$\frac{d\sigma}{dt} = \frac{1}{64\pi} \frac{G_F^2 \cos^2\theta_C |B|^2}{(s - m_p^2 - m_e^2)^2 - 4m_p^2 m_e^2} |\mathcal{M}^2|$$

$$\mathcal{M} = \bar{u}_\nu \gamma^\alpha (1+\gamma_5)\, u_e \cdot \bar{u}_n \left(f_1 \gamma_\alpha + g_1 \gamma_\alpha \gamma_5 + i f_2 \sigma_{\alpha\beta} \frac{q^\beta}{2M} + g_2 \frac{q_\alpha}{M}\gamma_5 \right) u_p$$



$\sigma = 69.2 \times 10^{-41}\text{cm}^2$ for electron energy of 150 MeV

Fit: Low W_R mass

- Take $f_{e\mu} = 0$ $\Rightarrow$ One ν_R mass is zero, while two other are Degenerate.
  $\Rightarrow$ one of light neutrino mass is zero

Oscillation parameters	3σ allowed range	Model Fits	
	NuFit5.0	Fit1	Fit2
$\Delta m^2_{21}\,(10^{-5}$ eV$^2)$	6.82 - 8.04	7.40	7.45
$\Delta m^2_{31}\,(10^{-3}$ eV$^2)$	2.435 - 2.598	2.49	2.48
$\sin^2\theta_{12}$	0.269 - 0.343	0.325	0.316
$\sin^2\theta_{23}$	0.415 - 0.616	0.537	0.561
$\sin^2\theta_{13}$	0.02032 - 0.02410	0.0221	0.0220
$\delta_{CP}/^\circ$	120 - 369	274	275

	m_η (TeV)	m_{ν_R} (MeV)	M_{W_R} (TeV)	α_4	τ (s)	$m_{\beta\beta}$ (eV)
Fit1	4.0	4.2	4.0	3.0	0.97	0.009
Fit2	4.0	10	6.0	4.0	0.072	0.017

Inconsistency with type-II scenario

- No Fit to type-II scenario in Low scale LR.

$$\begin{pmatrix} M_\nu^L & M_{\nu^D} \\ M_{\nu^D}^T & M_\nu^R \end{pmatrix} \qquad M_\nu^{\text{light}} = M_\nu^L - M_{\nu^D}(M_\nu^R)^{-1}M_{\nu^D}^T = M_\nu^{II} - M_\nu^I$$

- In the limit of small mixing between scalars:

$$M_\nu = \begin{pmatrix} \varepsilon\frac{\kappa + v_L}{v_R}\mathcal{F}' & M_{\nu^D} \\ M_{\nu^D}^T & \varepsilon^2 v_R \alpha_4 \mathcal{F} \end{pmatrix} \quad \Longrightarrow \quad \boxed{M_\nu^{II} \lesssim \frac{\varepsilon^3 M_\ell}{\kappa} M_\nu^I \; ; \; \varepsilon = \frac{1}{16\pi^2}}$$

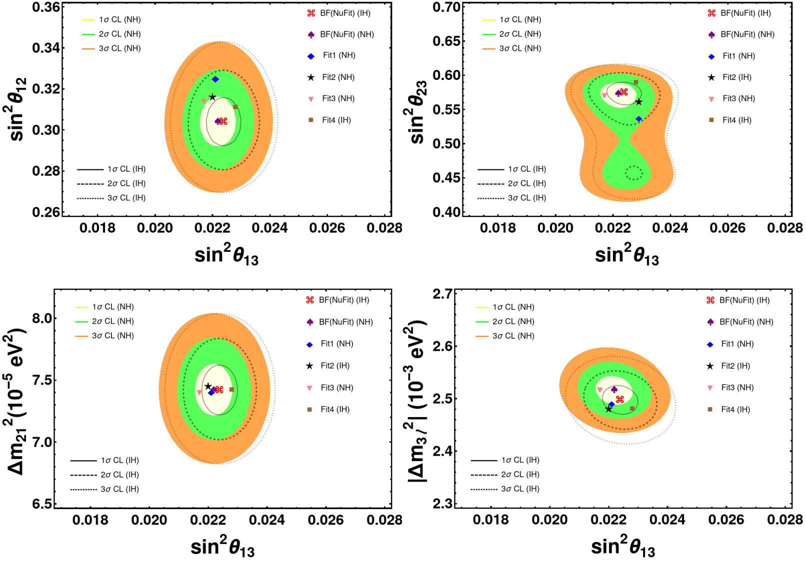
- Fine-tuning to make $M_{\nu^D} = 0 \Rightarrow$ type-II dominance; however cannot obtain correct neutrino oscillation pattern.

- Model is consistent with high $W_R^\pm$ mass, well above LHC reach; enough parameter to fit with neutrino oscillation data.
- Dirac neutrino mass M_{ν^D} can be arbitrary and large, unlike low scale $W_R^\pm$ scheme.
- Simple assumption: take $\kappa' = 0$ and $y << \widetilde{y}$

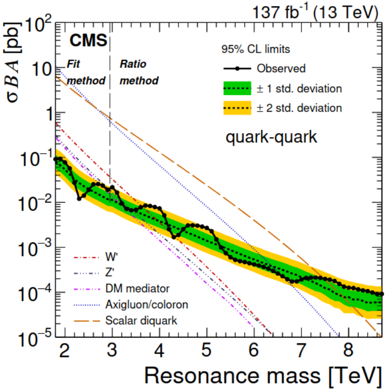
$$\Rightarrow M_\ell = \frac{1}{\sqrt{2}}\,\widetilde{y}\kappa\,, \quad M_{\nu^D} = \frac{1}{\sqrt{2}}\,y\kappa\,.$$

$\Rightarrow$ Same flavor structure as in low-scale LR

Neutrino Oscillation Fit



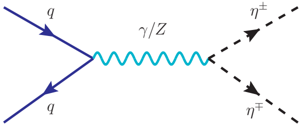
- The $W_R^\pm$ gauge bosons as well as other new particles in the model can be produced at the LHC.
- W_R boson can be resonantly produced when kinematically allowed, which then decays into jj.

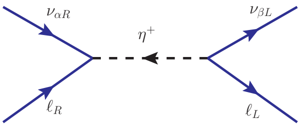


1911.03947

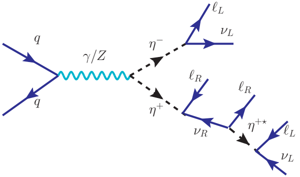
- Lower limit of 3.6 TeV on the W_R mass.

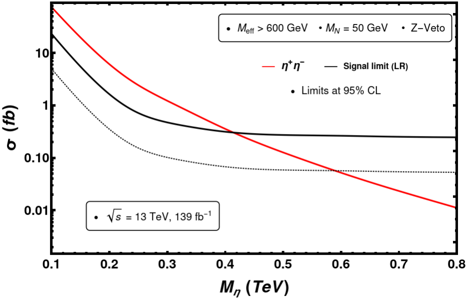
- Focus on $\eta^{\pm}$ and ν_R ; Both can be light $\Rightarrow$ opens possibility of production of ν_R via η^{+}.
- $M_{\nu_R} << M_{W_R}$ due to two loop suppression. Thus few GeV $M_{\nu_R} \Rightarrow$ very heavy M_{W_R}.
- $\eta^{+}\eta^{-}$ can be pair-produced via the Drell-Yan process mediated by the Z and photon.
- The $\eta^{+} \rightarrow \ell_R^{+}\nu_R, \ell_L^{+}\nu_L$. The $\nu_R \rightarrow \ell_R + \ell_L + \nu_L$ through a virtual $\eta^{\pm}$. This would lead to interesting multi-lepton signals.





- Three possibilities:
  - $pp \to \ell^+\ell^- \not{E}_T$ • $pp \to 4l + \not{E}_T$ • $pp \to 6l + \not{E}_T$
- $pp \to 4l + \not{E}_T$





The current limit on mass of $\eta^\pm$ is 410 GeV

- $pp \to 6l + \not{E}_T$: no current searches available. Expect half the number of events with much suppressed background.

Conclusion

- A simple and minimal left-right symmetric model which does not use the conventional Higgs triplets have been presented.
- Majorana masses for the ν_R are induced through two-loop diagrams involving a singly charged scalar field η^+, which do not rely on electroweak symmetry breaking, unlike the one-loop diagrams.
- This model naturally exhibits a hierarchy in the masses of ν_R and W_R. If the W_R gauge boson has a mass in the $(5 - 20)$ TeV range, the ν_R fields will have masses of a few tens of MeV.
- Model is consistent with low energy constraints, as well as constraints arising from cosmology and astrophysics.

Conclusion

- The model presented admits type-I seesaw mechanism for the entire range of W_R mass ranging from a few TeV to the GUT scale of order 10^{16} GeV.
- Model has excellent fits to neutrino oscillation parameters for low W_R scenario as well for high W_R scenario.
- Collider implications arising from the production and decays of the η^+ scalar have been studied. The current limit on the η^+ mass is 410 GeV, which can be improvecd to 585 at the high luminosity run of the LHC.

Thank You