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[Based on arXiv: 2012.13420]

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Motivation

Model (particle content, scalar sector, gauge sector)

Radiative $\nu$ 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
### Sketch of Standard Model

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

| Higgs           | $H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$ | $\sim (1, 2, 1)$ |

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

$$|\nu_\alpha\rangle = \sum U_{\alpha i} |\nu_i\rangle \implies M_\nu \neq 0 \implies \text{New physics beyond SM}$$
\[ U_{PNMS} = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & e^{-i\delta}s_{13} \\ -c_{23}s_{12} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - c_{23}s_{12}s_{13}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \]

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

- **Gauge group:**
  
  \[ SU(3)_C \otimes SU(2) \otimes SU(2) \otimes U(1)_{B-L} \]

- **Fermion Representation:**
  
  \[
  \begin{align*}
  & \left( \begin{array}{c} u \\ d \end{array} \right)_L \sim (2, 1, 1/3), & \left( \begin{array}{c} u \\ d \end{array} \right)_R \sim (1, 2, 1/3), & \left( \begin{array}{c} \nu_e \\ e \end{array} \right)_L \sim (2, 1, -1), & \left( \begin{array}{c} \nu_e \\ e \end{array} \right)_R \sim (1, 2, -1)
  \end{align*}
  \]

- **Higgs Representation**
  
  \[
  \Phi = \begin{pmatrix} \phi^0_1 & \phi^+_2 \\ \phi^-_1 & \phi^+_2 \end{pmatrix}, \quad \Delta_L = \begin{pmatrix} \Delta^+_L/\sqrt{2} & \Delta^{++}_L \\ \Delta^0_L & -\Delta^+_L/\sqrt{2} \end{pmatrix}, \\
  \Delta_R = \begin{pmatrix} \Delta^+_R/\sqrt{2} & \Delta^{++}_R \\ \Delta^0_R & -\Delta^+_R/\sqrt{2} \end{pmatrix}
  \]

- **Standard LR Model**

- **Under LR symmetry**
  
  \[
  Q_L \leftrightarrow Q_R, \quad \psi_L \leftrightarrow \psi_R, \quad \chi_L \leftrightarrow \chi_R, \quad \Phi \leftrightarrow \Phi^+, \quad \eta^+ \leftrightarrow \eta^+, \quad W_L \leftrightarrow W_R
  \]
**Higgs Sector:**
- $\Delta_L(1, 3, 2) + \Delta_R(3, 1, 2) + \Phi(2, 2, 0)$
- 2 charged and 2 doubly charged scalars

**Fermion masses:**
- $\langle \Phi \rangle \neq 0 \Rightarrow M_u, M_d, M_{\nu_D}$
- $\langle \Delta_R \rangle \neq 0, \langle \Delta_L \rangle \neq 0$
  $\Rightarrow$ Majorana mass for $\nu$
- $\langle \Phi \rangle \neq 0 \Rightarrow M_u, M_d, M_{\nu_D}$
- $\eta^+$ ensures Majorana mass for $\nu$.

**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 arbitrary 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,

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

- $\nu_R$ 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 $\eta^+$ with fermions**

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

- **Interaction of scalar $\Phi$ with fermions**

  \[ \mathcal{L}_Y \supset y \bar{\psi}_L \Phi \psi_R + \tilde{y} \bar{\psi}_L \tilde{\Phi} \psi_R + \text{H.c.} \]

- **Self interaction of Higgs particles by Higgs potential**

  \[
  V(\phi, \chi_L, \chi_R, \eta) = V(\phi) + V(\chi_L, \chi_R) + V(\eta) + V(\text{cross-terms}) \\
  \supset \mu_4 \left[ \chi_L^\dagger \phi \chi_R + \chi_R^\dagger \phi^\dagger \chi_L \right] + \mu_5 \left[ \chi_L^\dagger \bar{\phi} \chi_R + \chi_R^\dagger \bar{\phi}^\dagger \chi_L \right] \\
  + \left( \alpha_4 \left[ \chi_L^\dagger i \tau_2 \phi \chi_R \eta^- + \chi_R^\dagger i \tau_2 \phi^\dagger \chi_L \eta^- \right] + \text{H.c.} \right)
  \]
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 |
|-------------|------|
| $H^+_1 \simeq (\cos \omega \epsilon - \sin \omega \epsilon') \phi^+_1 + \cos \omega \phi^+_2 - \sin \omega \chi^+_L$ | $m^2_{H^+_1} \simeq \frac{v_R}{4} \{ (\alpha_3 - \rho_{12}) v_R - \sqrt{A} \}$ |
| $H^+_2 \simeq -(\sin \omega \epsilon + \cos \omega \epsilon') \phi^+_1 - \sin \omega \phi^+_2 - \cos \omega \chi^+_L$ | $m^2_{H^+_2} \simeq \frac{v_R}{4} \{ (\alpha_3 - \rho_{12}) v_R + \sqrt{A} \}$ |
| $H^+_3 \simeq \eta^+$ | $m^2_{H^+_3} \simeq \mu^2_\eta + \frac{\alpha_7}{2} v^2_R$ |
| $A^0_1 \simeq (\cos \omega \epsilon + \sin \omega \epsilon') \phi^{0i}_1 + \cos \omega \phi^{0i}_2 + \sin \omega \chi^{0i}_L$ | $m^2_{A^0_1} \simeq m^2_{H^+_1}$ |
| $A^0_2 \simeq (\cos \omega \epsilon + \sin \omega \epsilon') \phi^{0i}_1 - \sin \omega \phi^{0i}_2 + \cos \omega \chi^{0i}_L$ | $m^2_{A^0_1} \simeq m^2_{H^+_2}$ |
| $h^0 \simeq \phi^{0r}_1 + \epsilon \phi^{0r}_2 + \epsilon' \chi^{0r}_L - \frac{\alpha_1 \kappa}{2 \rho_1 v_R} \chi^{0r}_R$ | $m^2_{h^0} \simeq 2 \kappa^2 \left( \lambda_1 + 4 \epsilon \lambda_4 - \frac{\alpha_1^2}{4 \rho_1} \right)$ |
| $H^0_1 \simeq (\cos \omega \epsilon + \sin \omega \epsilon') \phi^{0r}_1 - \cos \omega \phi^{0r}_2 - \sin \omega \chi^{0r}_L$ | $m^2_{H^0_1} \simeq m^2_{H^+_1}$ |
| $H^0_2 \simeq (\sin \omega \epsilon - \cos \omega \epsilon') \phi^{0r}_1 - \sin \omega \phi^{0r}_2 + \cos \omega \chi^{0r}_L$ | $m^2_{H^0_2} \simeq m^2_{H^+_2}$ |
| $H^0_3 \simeq \chi^{0r}_R + \frac{\alpha_1 \kappa}{2 \rho_1 v_R} (\phi^{0r}_1 + \epsilon \phi^{0r}_2 + \epsilon' \chi^{0r}_L)$ | $m^2_{H^0_3} \simeq 2 \rho_1 v^2_R$ |

$h^0$ is the standard model-like Higgs.
\( \mathcal{L}_{gauge} = (D_{\mu} \chi_L)^\dagger D_{\mu} \chi_L + (D_{\mu} \chi_R)^\dagger D_{\mu} \chi_R + tr \left[ (D_{\mu} \Phi)^\dagger D_{\mu} \Phi \right] \)

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

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

- 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 \( \kappa_R = k^2 + \kappa'^2 + v_R^2 \))

\[
M_{W_1}^2 \approx \frac{1}{4} \frac{g^2_L}{\kappa_L^2}
M_{W_2}^2 \approx \frac{1}{4} \frac{g^2_R}{v_R^2}
W_1^+ = \cos \zeta \ W_L^+ + \sin \zeta \ W_R^+
W_2^+ = - \sin \zeta \ W_L^+ + \cos \zeta \ W_R^+
\]

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

\[
M_{Z_1}^2 \approx \frac{1}{4} \left( g_Y^2 + g_L^2 \right) \kappa_L^2
M_{Z_2}^2 \approx \frac{1}{4} \frac{g^4_R}{(g_Y^2 - g_R^2)} v_R^2
Z_1 = \cos \xi \ Z_L + \sin \xi \ Z_R
Z_2 = - \sin \xi \ Z_L + \cos \xi \ Z_R
\]

- \( \xi \leq 10^{-3} \) 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:

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

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

- Neutrino mass matrix spanning $(\nu, \nu^c)$ read:

\[
\begin{pmatrix}
M_{\nu L} & M_{\nu D} \\
M_{\nu D}^T & M_{\nu}^R
\end{pmatrix}
\]

\[
M_{\nu}^{\text{light}} = M_{\nu}^L - M_{\nu D} (M_{\nu}^R)^{-1} M_{\nu D}^T = M_{\nu}^{II} - M_{\nu}^{I}
\]

- $M_{\nu}^L$ and $M_{\nu}^R$ will arise through one-loop and two-loop radiative correction.

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

$M_{\nu}^{II} \gg M_{\nu}^{I} \Rightarrow$ Type-II
**Radiative $\nu_R$ Mass Generation**

\[ O_1 = c_1 \Psi_R \Psi_R (\chi_L^T \Phi \chi_R) \]
\[ c_1 \sim \frac{(y_T^2 f \alpha_4)}{16\pi^2} \left( \frac{1}{M^2} \right) \]

\[ O_2 = c_2 \Psi_R \Psi_R (\chi_R \chi_R) \]
\[ c_2 \sim \frac{(y_T^2 f \alpha_4)}{(16\pi^2)^2} \left( \frac{\mu_4}{M^2} \right) \]

- 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:**
  
  \[
  (M^R_{\nu})_{ab} = \frac{1}{8\pi^2} \left[ f_{a\ell} M_\ell V_{5\beta}^+ \left( y_{\ell b} V_{1\beta}^{*} - \tilde{y}_{\ell b} V_{2\beta}^{*} \right) + (a \leftrightarrow b) \right] \log \left( \frac{m^2_{H^+_1}}{m^2_{H^+_\beta}} \right)
  \]

- **Two-loop radiative corrections:**
  
  \[
  (M^R_{\nu})_{ab} = \sqrt{2} \alpha_4 v_R \left( A_{1ab} + A_{2ab} + A_{3ab} \right)
  \]

  \[
  A_{1ab} = \left\{ f_{ac} \left[ y^{*}_{\gamma\alpha} V_{2\gamma} \left\{ -V_{3\gamma} V_{1\beta} - V_{3\gamma} V_{2\beta} + V_{2\gamma} V_{3\beta} \right\} - \tilde{y}^{*}_{cd} V_{1\gamma} V_{3\beta} V_{1\gamma} \right] \right. \\
  \left. \left[ y_{db} V_{1\beta}^{*} - \tilde{y}_{db} V_{2\beta}^{*} \right] + (a \leftrightarrow b) \right\} \int \frac{d^4 p}{(2\pi)^4} \frac{d^4 q}{(2\pi)^4} \frac{q \cdot p}{(q^2 - m^2_{H^+_1})(q^2 - m^2_{H^+_\beta})(p^2 - m^2_{H^+_1})(p^2 - m^2_{H^+_\beta})((p - q)^2 - m^2_{H^0})}
  \]

  \[
  A_{2ab} = \left\{ f_{ac} \left[ y^{*}_{\gamma\alpha} V_{2\beta}^{*} - \tilde{y}^{*}_{cd} V_{1\beta}^{*} \right] \right. \\
  \left. \left[ \tilde{y}_{db} V_{2\gamma} \left\{ -V_{3\gamma} V_{1\beta} - V_{3\gamma} V_{2\beta} + V_{2\gamma} V_{3\beta} \right\} \right] \\
  - y_{db} V_{1\gamma} V_{3\beta} V_{1\gamma} ] + (a \leftrightarrow b) \right\} \int \frac{d^4 p}{(2\pi)^4} \frac{d^4 q}{(2\pi)^4} \frac{q \cdot p}{(q^2 - m^2_{H^+_1})(q^2 - m^2_{H^+_\beta})(p^2 - m^2_{H^+_1})(p^2 - m^2_{H^+_\beta})((p - q)^2 - m^2_{H^0})}
  \]

  \[
  A_{3ab} = \left\{ (y_{ca} V_{1\beta}^{*} - \tilde{y}_{ca} V_{2\beta}^{*}) \right. \\
  \left. f_{cd} \left[ \tilde{y}_{db} V_{2\gamma} \left\{ -V_{3\gamma} V_{1\beta} - V_{3\gamma} V_{2\beta} + V_{2\gamma} V_{3\beta} \right\} \right] \\
  - y_{db} V_{1\gamma} V_{3\beta} V_{1\gamma} ] + (a \leftrightarrow b) \right\} \int \frac{d^4 p}{(2\pi)^4} \frac{d^4 q}{(2\pi)^4} \frac{q \cdot p}{(q^2 - m^2_{H^+_1})(q^2 - m^2_{H^+_\beta})(p^2 - m^2_{H^+_1})(p^2 - m^2_{H^+_\beta})((p - q)^2 - m^2_{H^0})}
  \]

  \[
  I_{\eta\gamma\beta}^{\eta\gamma\beta} = \int \int \frac{d^4 p}{(2\pi)^4} \frac{d^4 q}{(2\pi)^4} \frac{q \cdot p}{(q^2 - m^2_{H^+_1})(q^2 - m^2_{H^+_\beta})(p^2 - m^2_{H^+_1})(p^2 - m^2_{H^+_\beta})((p - q)^2 - m^2_{H^0})}
  \]
Case with $M_{\nu_D} \ll M_\ell$ (low Scale LR) ⇒ Flavor structure simplifies, $y, \tilde{y} \propto M_\ell$.

$$(M_{\nu_R})_{ab} = \frac{2\sqrt{2} \alpha_4 v_R}{\kappa^2 (1 - \epsilon^2)^2 (16 \pi^2)^2} \left( f M_\ell^2 + M_\ell^2 f^T \right) \left\{ C_{\beta\gamma} G \left( \frac{m_{\eta_1}^2}{m_{H_0}^2}, \frac{m_{H^+}^2}{m_{H_0}^2} \right) + C'_{\beta\gamma} G \left( \frac{m_{\eta_1}^2}{m_{H_0}^2}, \frac{m_{H^0}^2}{m_{H_0}^2} \right) \right\}.$$
One-loop vs two-loop

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

| $M_{W_R}$ (TeV) | 5   | 10  | 15  | 30  | 50  | 100 | $10^4$ |
|-----------------|-----|-----|-----|-----|-----|-----|--------|
| $M_{\nu_R}$ (GeV) | 0.0042 | 0.010 | 0.020 | 0.05 | 0.11 | 0.36 | $4.2 \times 10^3$ |
Neutrino mass matrix is diagonalized by $6 \times 6$ unitary matrix:

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

$$ m_{\nu j} = \text{Diag} (m_1, m_2, m_3) \quad M_{N\alpha} = \text{Diag} (M_1, M_2, M_3) \, . $$

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

$$ U_{\nu\nu}^\ast \text{ is the usual PMNS matrix characterizing the mixing among light neutrinos.} $$

$$ s_{12}^2 = \frac{|U_{e2}|^2}{1 - |U_{e3}|^2}, \quad s_{13}^2 = |U_{e3}|^2, \quad s_{23}^2 = \frac{|U_{\mu 3}|^2}{1 - |U_{e3}|^2} \, . $$
For multi-TeV range of $M_{W_R}$ (within reach of collider experiments)

$\Rightarrow$ MeV range of $M_{\nu_R}$.

$\Rightarrow$ fit to the $\nu$-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 | $|U_{eN}|^2$ | $|U_{\mu N}|^2$ | $|U_{\tau N}|^2$ |
|------|-------------|-----------------|-----------------|
| 1 MeV | $2.6 \times 10^{-4}$ BD2 | $1.1 \times 10^{-5}$ BOREXINO | $1.1 \times 10^{-2}$ $\pi_{\mu 2}$ PSI |
| 5 MeV | $1.1 \times 10^{-5}$ BOREXINO | $2.75 \times 10^{-4}$ $\pi_{\mu 2}$ PSI | $2.06 \times 10^{-4}$ $\pi_{\mu 2}$ PSI |
| 10 MeV | $3.5 \times 10^{-6}$ BOREXINO | $2.06 \times 10^{-4}$ $\pi_{\mu 2}$ PSI | $8.6 \times 10^{-6}$ $\pi_{\mu 2}$ PIENU |
| 30 MeV | $4.4 \times 10^{-7}$ PIENU | $8.6 \times 10^{-6}$ $\pi_{\mu 2}$ PIENU | $2.35 \times 10^{-4}$ $K_{\mu 2}$ KEK |
| 50 MeV | $1.2 \times 10^{-7}$ PIENU | $2.35 \times 10^{-4}$ $K_{\mu 2}$ KEK | $3.76 \times 10^{-6}$ $K_{\mu 2}$ KEK |
| 100 MeV | $7.1 \times 10^{-9}$ PIENU | $3.76 \times 10^{-6}$ $K_{\mu 2}$ KEK | $5.1 \times 10^{-4}$ CHARM |

- $U_{eN}$
- $U_{\mu N}$
- $U_{\tau N}$

- **Direct experimental constraints**
**Neutrinoless Double Beta Decay $0\nu\beta\beta$**

- **$0\nu\beta\beta$:** $(A, Z) \rightarrow (A, Z + 2) + 2e^-$: If observed $\Rightarrow$ evidence of lepton number violation $\Rightarrow$ 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.

\[
\frac{1}{T_{1/2}^{0\nu}} = G_{01}^{0\nu} \left( |M_{\nu}^{0\nu} \eta_{\nu} + M_{N}^{0\nu} \eta_{NR}\eta_{NR}^L|^2 + |M_{N}^{0\nu} \eta_{NR}\eta_{NR}^R|^2 + |M_{\lambda}^{0\nu} \eta_{\lambda} + M_{\eta}^{0\nu} \eta_{\eta}|^2 \right)
\]

$G_{01}^{0\nu}$: Phase factor \quad $M_{\chi}^{0\nu}$: Nuclear matrix element

| Isotope | $G_{01}^{0\nu}$ $(\text{yr}^{-1})$ | Nuclear Matrix Elements |
|---------|----------------------------------|------------------------|
| $^{76}\text{Ge}$ | $5.77 \times 10^{-15}$ | $2.58 - 6.64$ | $233 - 412$ | $1.75 - 3.76$ | $235 - 637$ |
| $^{136}\text{Xe}$ | $3.56 \times 10^{-14}$ | $1.57 - 3.85$ | $164 - 172$ | $1.92 - 2.49$ | $370 - 419$ |
η’s are dimensionless parameters obtained from Feynman amplitudes.

Low $W_R^{\pm}$ mass $\Rightarrow \nu_R$ masses of a few MeV $\Rightarrow$ momentum transfer can be much heavier than sterile neutrino mass:

$$\eta_\nu = \frac{1}{m_e} \sum_{i=1}^{3} U_{e i}^2 m_{\nu_i}$$

$$\eta_{NR}^R = \frac{1}{m_e} \left( \frac{M_{W_L}}{M_{W_R}} \right)^4 \sum_{i=4}^{6} U_{4i}^{*2} m_{N_i}$$

$$\eta_{NR}^L = \frac{1}{m_e} \sum_{i=4}^{6} U_{e i}^2 m_{N_i}$$

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

$$\eta_\eta = \tan \xi \sum_{i=1}^{3} U_{e i} U_{4i}^{*}$$
Cosmological Constraints

- Sterile neutrino (1-100 Mev) can upset successful prediction of big bang cosmology.
  - if $\nu_R$ are long lived $\Rightarrow$ contribute to effective number of neutrino species. (constrained by Planck data).
  $\Rightarrow$ can overclose the universe.

- Structure of Right-handed neutrino:
  - In Low $W_R$ regime $\Rightarrow \gamma, \tilde{\gamma} \propto M_\ell$:

  $$
  M^R_\gamma = J
  \begin{pmatrix}
  0 & \frac{m^2_\mu}{m^2_\tau} f_{e\mu} & f_{e\tau} \\
  \frac{m^2_\mu}{m^2_\tau} f_{e\mu} & 0 & f_{\mu\tau} \left(1 - \frac{m^2_\mu}{m^2_\tau}\right) \\
  f_{e\tau} & f_{\mu\tau} \left(1 - \frac{m^2_\mu}{m^2_\tau}\right) & 0
  \end{pmatrix}
  $$

  $\Rightarrow$ Hierarchy between sterile neutrino. ($M_{N_1} << M_{N_2} \simeq M_{N_3}$)
• MeV mass sterile neutrino ($N$) can decay into $\bar{\nu}_i \nu_i \gamma$, $\nu_i e^+ e^-$, and $\nu_i \gamma$.

\[
\Gamma(N_\alpha \rightarrow e^+ e^- \nu) = 2 \sum_j |U_{j\alpha}|^2 \frac{G_F^2 M_5^5 N_\alpha}{192 \pi^3} \left[ \left\{ \delta_{je} + \left( -\frac{1}{4} + \frac{1}{2} \sin^2 \theta_W \right) \right\}^2 + \frac{1}{4} \sin^4 \theta_W \right]
\]

\[
\Gamma(N_\alpha \rightarrow 3\nu) = 2 \sum_j |U_{j\alpha}|^2 \frac{1}{4} \frac{G_F^2 M_5^5 N_\alpha}{192 \pi^3} (1 + 2 + 1)
\]

\[
\Gamma(N_\alpha \rightarrow \nu \gamma) = 2 \times \left( \frac{\alpha M_5^3}{128 \pi^4} \right) \left[ \left\{ f_{e\tau}^2 + f_{\mu\tau}^2 \right\} \left\{ 1 + \log \left( \frac{m_\tau^2}{m_\eta^2} \right) \right\}^2 + \frac{g^2 \zeta}{2M_{W_L}^2} \right]^2
\]

• Radiative decay by $\eta^+$ lead to a lifetime of order 1 sec. $\Rightarrow$ consistent with big bang cosmology.
- Observation of $\nu$ flux from SN 1987A (Kamiokande and IMB) \implies \text{information about neutrinos}

- If $M_{\nu}^R \leq 10$ MeV and has charged current coupling \implies $\nu_R$ can be produced in the supernova core via $e^- p \rightarrow \nu_R n \implies \text{alters dynamics of supernova.}$

- Lower limit of 23 TeV on $W_{\nu_R}^\pm$ mass by demanding that the $\nu_R$ luminosity not exceed $10^{53}$ erg/sec for supernova 1987a.

  Barbieri and Mohapatra, 88.
However we find significantly weaker, with the lower limit on $W_R^{\pm}$ as low as 4.6 TeV.

- Computed the exact cross section $(e^- + p \rightarrow \nu_R + n)$ for the production of $\nu_R$ 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 $\sim 150$ MeV, as opposed to 300 MeV.
**Some More Details**

- The effective interactions involving the leptons and quarks

\[
\mathcal{L} = \frac{4G_F \cos \theta_C}{\sqrt{2}} \left[ -\sin \zeta \bar{d}_L \gamma^\mu u_L + \cos \zeta \frac{M_{WL}^2}{M_{WR}^2} \bar{d}_R \gamma^\mu u_R \right] (\bar{\nu}_R \gamma_\mu e_R)
\]

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

\[
\Rightarrow B = -\sin \zeta + \cos \zeta \frac{M_{WL}^2}{M_{WR}^2}
\]

- Scattering cross section for \(e^- (p_p) + p (p_p) \rightarrow \nu (p_\nu) + n (p_n)\)

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

\[
M = \bar{u}_\nu \gamma^\alpha (1 + \gamma_5) u_e \cdot \bar{u}_n \left( f_1 \gamma^\alpha + g_1 \gamma^\alpha \gamma_5 + if_2 \sigma_{\alpha\beta} \frac{q^\beta}{2M} + g_2 \frac{q^\alpha}{M} \gamma_5 \right) u_p
\]

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

\[
E_{e}^{\text{CM}} \text{ (MeV)}\]
Take $f_{e\mu} = 0$ ⇒ One $\nu_R$ mass is zero, while two other are Degenerate.
⇒ one of light neutrino mass is zero

| Oscillation parameters | $3\sigma$ allowed range | Model Fits |
|------------------------|--------------------------|------------|
|                        | NuFit5.0 | Fit1 | Fit2 |
| $\Delta m_{21}^2 (10^{-5} \text{ eV}^2)$ | 6.82 - 8.04 | 7.40 | 7.45 |
| $\Delta m_{31}^2 (10^{-3} \text{ eV}^2)$ | 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 |

| $m_\eta$ (TeV) | $m_{\nu_R}$ (MeV) | $M_{W_R}$ (TeV) | $\alpha_4$ | $\tau$ (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 |
No Fit to type-II scenario in Low scale LR.

\[
\begin{pmatrix}
M_{\nu}^L & M_{\nu}^D \\
M_{\nu D}^T & M_{\nu}^R
\end{pmatrix}
\]

\[M_{\nu}^{\text{light}} = M_{\nu}^L - M_{\nu D} (M_{\nu}^R)^{-1} M_{\nu D}^T = M_{\nu}^{I\text{I}} - M_{\nu}^I\]

In the limit of small mixing between scalars:

\[
M_{\nu} = \begin{pmatrix}
\varepsilon \kappa + v_L \\
\nu_R \\
M_{\nu}^T
\end{pmatrix}
\begin{pmatrix}
M_{\nu D} \\
\varepsilon^2 \nu_R \alpha_4 \mathcal{F}
\end{pmatrix}
\]

\[M_{\nu}^{I\text{I}} \lesssim \frac{\varepsilon^3 M_\ell}{\kappa} M_{\nu}^I; \quad \varepsilon = \frac{1}{16 \pi^2}\]

Fine-tuning to make \(M_{\nu D} = 0\) ⇒ 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 $M_{\nu_D}$ can be arbitrary and large, unlike low scale $W_R^\pm$ scheme.

Simple assumption: take $\kappa' = 0$ and $y << \tilde{y}$

\[ M_\ell = \frac{1}{\sqrt{2}} \tilde{y}_\kappa , \quad M_{\nu_D} = \frac{1}{\sqrt{2}} y_\kappa . \]

⇒ Same flavor structure as in low-scale LR
Neutrino Oscillation Fit

\begin{align*}
\sin^2 \theta_{12} & \quad \sin^2 \theta_{23} \\
\Delta m^2_{21} & \quad |\Delta m^2_{31}| \\
\end{align*}
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 $jj$.

Lower limit of 3.6 TeV on the $W_R$ mass.
Collider Implications

- Focus on $\eta^\pm$ and $\nu_R$; Both can be light $\Rightarrow$ opens possibility of production of $\nu_R$ via $\eta^+$.  

- $M_{\nu_R} << M_{W_R}$ 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.
Collider Implications

- Three possibilities:
  - $pp \rightarrow \ell^+ \ell^- E_T$
  - $pp \rightarrow 4l + E_T$
  - $pp \rightarrow 6l + E_T$

- $pp \rightarrow 4l + E_T$

- $pp \rightarrow 6l + E_T$: no current searches available. Expect half the number of events with much suppressed background.

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

- A simple and minimal left-right symmetric model which does not use the conventional Higgs triplets have been presented.

- Majorana masses for the $\nu_R$ are induced through two-loop diagrams involving a singly charged scalar field $\eta^+$, which do not rely on electroweak symmetry breaking, unlike the one-loop diagrams.

- This model naturally exhibits a hierarchy in the masses of $\nu_R$ and $W_R$. If the $W_R$ gauge boson has a mass in the $(5 - 20)$ TeV range, the $\nu_R$ 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.
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 $\eta^+$ scalar have been studied. The current limit on the $\eta^+$ mass is 410 GeV, which can be improved to 585 at the high luminosity run of the LHC.
Thank You