Low Scale Left-Right Symmetry and Naturally Small Neutrino Mass

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Left-Right Symmetry

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

$$L_L = \begin{pmatrix} \nu_l \\ l \end{pmatrix}_L \sim (2,1,-1) \qquad L_R = \begin{pmatrix} \nu_l \\ l \end{pmatrix}_R \sim (1,2,-1)$$

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \sim (2,2,0)$$

- usual picture - $SU(2)$ triplets

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

symmetry breaking:

- $$SU(2)_R \times U(1)_{B-L} \xrightarrow{\langle \delta_R^0 \rangle} U(1)_Y$$
- $$SU(2)_L \times U(1)_Y \xrightarrow{\langle \delta_L^0 \rangle, \langle \phi_{1,2}^0 \rangle} U(1)_Q$$

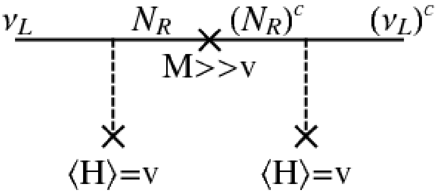
Neutrino Masses

$$\mathcal{L} \supset -\bar{L}_R\, Y\, \Phi^\dagger L_L - \bar{L}_R\, \tilde{Y}\, \tilde{\Phi}^\dagger L_L - \frac{1}{2}\bar{L}_L^c i\tau_2 \Delta_L Y_L L_L - \frac{1}{2}\bar{L}_R^c i\tau_2 \Delta_R Y_R L_R + \text{h.c.}$$

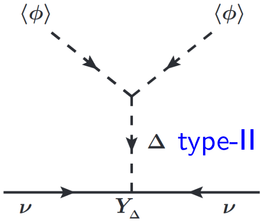
mass matrix of neutral leptons:

$$\begin{pmatrix} \bar{\nu}_L^c & \bar{N}_R \end{pmatrix} \begin{pmatrix} M_L & m_D^T \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R^c \end{pmatrix}$$

$$m_D = \frac{1}{\sqrt{2}} \left(Y \langle \phi_1^0 \rangle + \tilde{Y} \langle \phi_2^0 \rangle \right), \qquad M_L = \frac{1}{\sqrt{2}} Y_L \langle \delta_L^0 \rangle, \qquad M_R = \frac{1}{\sqrt{2}} Y_R \langle \delta_R^0 \rangle .$$



type-I seesaw



type-II seesaw

L-R Models

- The majority of the low scale L-R symmetric models constructed so far is at odds with the generation of "naturally" small neutrino masses
- The natural scenarios should employ the Dirac neutrino masses, m_ν^D, similar in size to the Dirac masses of charged leptons, m_l, and quarks, m_q,

$$m_\nu^D \approx m_q, m_l \, .$$

- In the vast majority of studies, L-R symmetry is broken by introducing the Higgs triplets, while the Higgs doublets are absent.
- The existence of higher representations (triplets) and the absence of low-dimensional representations (doublets) should have a certain reason and a proper physical explanation.
- original papers employed doublets → *e.g.* Senjanovic, Mohapatra Phys. Rev. D 12 (1975); Mohapatra, Sidhu Phys. Rev. D 16 (1977)

The model

- we employ scalar doublets

$$\chi_L = \begin{pmatrix} \chi_L^+ \\ \chi_L^0 \end{pmatrix} \sim (2,1,1)\,, \qquad \chi_R = \begin{pmatrix} \chi_R^+ \\ \chi_R^0 \end{pmatrix} \sim (1,2,1)\,.$$

- relations concerning symmetry breaking

$$\sqrt{\langle \chi_L^0 \rangle^2 + \langle \phi_1^0 \rangle^2 + \langle \phi_2^0 \rangle^2} \approx 246\,\mathrm{GeV},$$

$$\langle \chi_R^0 \rangle \gg \langle \chi_L^0 \rangle, \langle \phi_{1,2}^0 \rangle\,.$$

- we extend fermion sector with 3 generations of fermion singlet S

$$S \sim (1,1,0)$$

- The lepton masses are generated by the following Lagrangian

$$\mathcal{L} \supset -\bar{L}_R\, Y\, \Phi^\dagger L_L - \bar{L}_R\, \tilde{Y}\, \tilde{\Phi}^\dagger L_L - \bar{S}\, Y_L \tilde{\chi}_L^\dagger L_L - \bar{S}^c\, Y_R\, \tilde{\chi}_R^\dagger L_R - \frac{1}{2}\, \bar{S}^c\, \mu\, S + \mathrm{h.c.}$$

Neutrino masses through Inverse seesaw

- When the scalar fields acquire VEV, the mass matrix of neutral leptons is generated

$$\mathcal{M} = \begin{pmatrix} 0 & m_D^T & m_D'^T \\ m_D & 0 & M_D^T \\ m_D' & M_D & \mu \end{pmatrix}$$

$$m_D = \frac{1}{\sqrt{2}}\left(Y\langle\phi_1^0\rangle + \tilde{Y}\langle\phi_2^0\rangle\right), \qquad m_D' = \frac{1}{\sqrt{2}} Y_L\langle\chi_L^0\rangle\,, \qquad M_D = \frac{1}{\sqrt{2}} Y_R\langle\chi_R^0\rangle$$

- light neutrino mass matrix

linear seesaw — inverse seesaw

$$m_\nu \simeq \frac{\langle\chi_L^0\rangle}{\langle\chi_R^0\rangle}\left(m_D + m_D^T\right) - m_D^T\, M_D^{-1}\,\mu\,\left(M_D^T\right)^{-1} m_D\,.$$

- following quark-lepton similarity we require inverse seesaw dominance

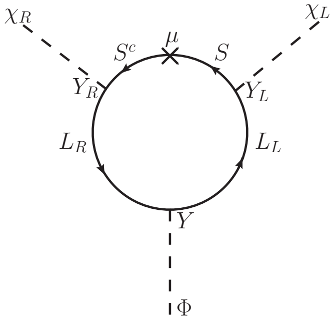
$$\frac{\langle\chi_L^0\rangle}{\langle\chi_R^0\rangle} < \frac{0.05\,\mathrm{eV}}{2\, m_D^{max}} \sim 10^{-12}$$

Suppressing $\langle \chi_L^0 \rangle$

In order to estimate $\langle \chi_L^0 \rangle$ we consider the following terms of the potential

$$V \supset h\,\chi_L^\dagger \tilde{\Phi} \chi_R - m_\chi^2 \chi_L^\dagger \chi_L$$

$$\langle \chi_L^0 \rangle = h \frac{\langle \phi_1^0 \rangle}{\langle \chi_R^0 \rangle} \Leftrightarrow h \lesssim 40\,\text{keV} \left(\frac{\langle \chi_R^0 \rangle}{10^5 \text{ GeV}} \right)^2$$



$$\langle \chi_L^0 \rangle \simeq \frac{1}{16\pi^2} \langle \chi_R^0 \rangle \frac{\langle \phi_1^0 \rangle}{\langle \chi_R^0 \rangle} \frac{\mu}{\langle \chi_R^0 \rangle}$$

for $\mu \simeq \mathcal{O}(10 - 100)$ keV
and $\langle \chi_R^0 \rangle = 10^5$ GeV
$\rightarrow \langle \chi_L^0 \rangle \simeq 10^{-14} \langle \chi_R^0 \rangle$

Inverse Seesaw and Screening

Inverse seesaw contribution can be rewritten as

$$m_\nu \approx \frac{\langle \phi_1^0 \rangle^2}{\langle \chi_R^0 \rangle^2} \, Y^T \, Y_R^{-1} \, \mu \left(Y_R^T \right)^{-1} \, Y$$

- we assume screening of the Dirac structures (Lindner et al. JHEP 2005)

$$Y = Y_R$$

$$\xi \equiv \frac{\langle \phi_1^0 \rangle}{\langle \chi_R^0 \rangle} = \frac{m_{D\,i}}{M_{D\,i}} \to m_\nu \approx \xi^2 \mu$$

- neutrino part of the leptonic mixing matrix $U_{\mathrm{PMNS}} = U_l^\dagger U_\nu$ arising from the hidden sector S

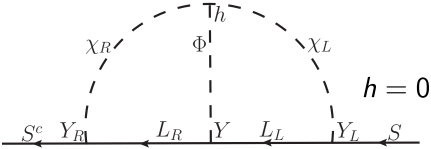
$U_l \approx V_{\mathrm{CKM}}$, $\qquad U_\nu \sim U_{\mathrm{TBM}}$ or U_{BM}

consequence of unification $\qquad$ hidden sector

- accurately reproducing rector mixing angle $\theta_{13} \approx 8.5^\circ$

Quark-lepton similarity and flavor symmetries

- We assume the *q*-*l* similarity $Y \approx Y_u$
- The screening and the *q*-*l* similarity conditions determine the phenomenology of this scenario
- Flavor Symmetries: The matrices Y and Y_R can be diagonal simultaneously due to the $G_{\text{basis}} = Z_2 \times Z_2$ symmetry with $(-,-)$, $(+,-)$, $(-,+)$ charges for the three generations of fermions
- symmetries can impose μ that is (approximatively) diagonalized by tribimaximal matrix. Radiative corrections?



$$\Delta\mu_{jj} \simeq \frac{1}{(16\pi^2)^2}\, Y^*_{Lj}\, Y_{Rj}\, Y_j\, h$$

$$h = 0.1\,\text{MeV} \rightarrow \Delta\mu_{33} \sim 10\,\text{eV} \ll \mu \sim 0.1\text{MeV}$$

Heavy neutral leptons in the model

- Diagonalize $$\mathcal{M} = \begin{pmatrix} 0 & m_D & 0 \\ m_D & 0 & M_D \\ 0 & M_D & \mu \end{pmatrix}$$

$$\mathcal{U} = \begin{pmatrix} U_{\text{PMNS}} & -\vec{s}_N s_\xi \, U_l^\dagger & \vec{c}_N s_\xi \, U_l^\dagger \\ 0 & \frac{1}{\sqrt{2}}\mathbb{1} & \frac{1}{\sqrt{2}}\mathbb{1} \\ -s_\xi \, U_\nu & -\vec{s}_N \, \mathbb{1} & \vec{c}_N \mathbb{1} \end{pmatrix}$$

$$s_\xi = \frac{\xi}{\sqrt{1+\xi^2}} \approx \xi$$

$$s_N^i \approx \frac{1}{\sqrt{2}} \left[1 - \frac{\mu_{ii}}{4 M_{D\,i}} \right]$$

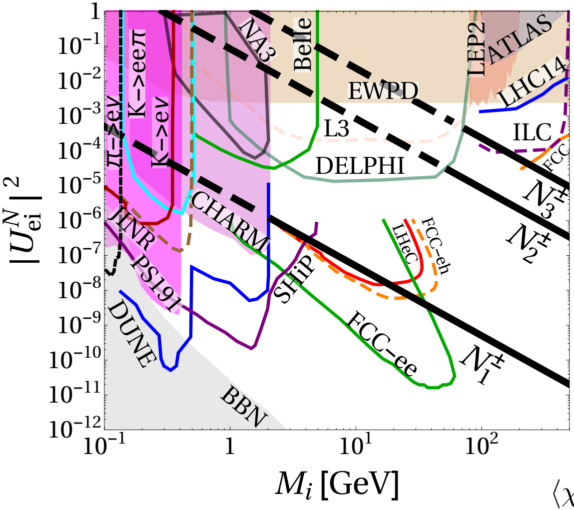
Masses: $$M_i^- = -M_{Di}\sqrt{1+\xi^2} + \frac{1}{2}\mu_{ii} \,, \qquad M_i^+ = M_{Di}\sqrt{1+\xi^2} + \frac{1}{2}\mu_{ii} \,.$$

Neglecting μ yields

$$\nu_\alpha = U_{\text{PMNS}} \, \nu - \frac{1}{\sqrt{2}} s_\xi \, U_l^\dagger (N^- - N^+)$$

$$\left| U_{\alpha i}^{N^-} \right|^2 = \left| U_{\alpha i}^{N^+} \right|^2 = \frac{1}{2} s_\xi^2 \left| U_{l\,\alpha i} \right|^2 = \frac{1}{2} \left(\frac{m_{D\,i}}{M_i} \right)^2 \left| U_{l\,\alpha i} \right|^2$$

mixing of $N_i^{\pm}$ in ν_e



constraints from: Deppisch et al. "Neutrinos and Collider Physics"

future collider searches: Antusch et al. (2017)

$$|U^N_{e1}|^2 \approx \frac{1}{2}\left(\frac{m_{D1}}{M_1}\right)^2 \approx \frac{m_u^2}{2M_1^2}$$

Limit: $M_1 \geq 2\,\text{GeV}$

- *q*-*l* similarity and screening :

$$M_2 = M_1 m_c/m_u > 600\ \text{GeV}$$
$$M_3 = M_1 m_t/m_u \geq 10^5\ \text{GeV}$$

$$\langle \chi_R^0 \rangle \approx \sqrt{2}\, M_3 \geq 2 \times 10^5\ \text{GeV}$$

mixing of $N_i^{\pm}$ in ν_μ and ν_τ

constraints from: Deppisch et al. "Neutrinos and Collider Physics"

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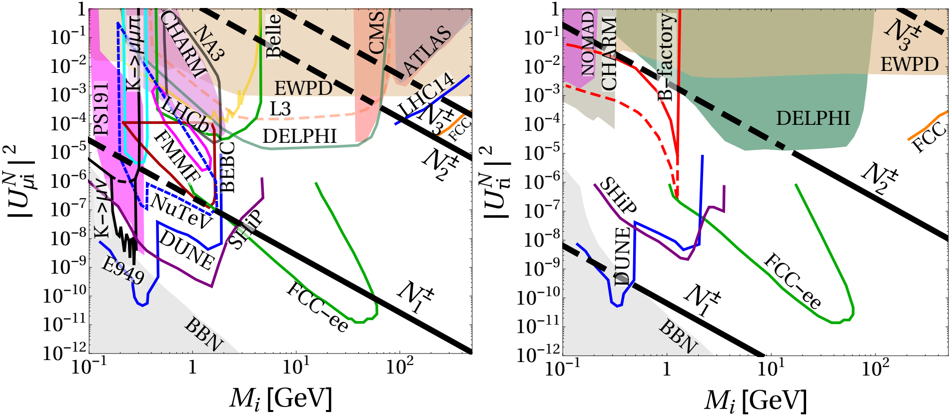

in the absence of screening, bounds are $M_2, M_3 \gtrsim 100$ GeV and therefore the hierarchy of the heavy leptons can be much weaker

Summary

- left-right symmetric model with doublets and naturally generated neutrino masses via inverse seesaw by employing large Dirac neutrino mass terms
- rich phenomenology : heavy lepton searches discussed here ;
  signatures from $0\nu 2\beta$ experiments, leptogenesis, corrections to Higgs mass...
- very interesting scenario with two S fields (S_L and S_R) per generation : keV-DM candidate

Future colliders :

- quark-lepton similarity and screening yields $\langle \chi_R^0 \rangle > 10^5$ GeV
- for 100 TeV collider, gauge and scalar sector still testable
- for $\langle \chi_R^0 \rangle = 500$ TeV, only fermion sector is testable
- how many models is there (and how natural they are) and how big is the parameter space for the discovery of heavy neutral fermions?
- should the choice on which colliders to build in future strongly depend on their sensisitivity to heavy fermion sector?