Testing New TeV-scale Seesaw Mediators at the LHC

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Abstract

We propose TeV-scale Dirac fermions producing Majorana masses of the known neutrinos via tree-level seesaw, different from standard type I and III seesaw. The employed weak five-plet with nonzero hypercharge leads to new seesaw formula $m_\nu \sim v^6/M^5$ and to empirical masses $m_\nu \sim 10^{-1}$ eV for $M \sim$ TeV new states. There is a limited range of the parameter space with $M \lesssim$ a few 100 GeV where this dim 9 tree level contribution dominates over the competing dim 5 loop contributions. Accordingly, the proposed mechanism is testable at the LHC via specific signatures in decays of Dirac type heavy leptons produced by Drell-Yan fusion.

Seesaw model with fermionic five-plets

Our model [1, 2] is based on the standard model group (SMG) $SU(3)_C \times SU(2)_L \times U(1)_Y$ and the SM fermion content extended by the vectorlike Dirac five-plets of leptons $\Sigma_L = (\Sigma_L^{+++}, \Sigma_L^{++}, \Sigma_L^{+}, \Sigma_L^{0}, \Sigma_L^{-})$ and $\Sigma_R = (\Sigma_R^{+++}, \Sigma_R^{++}, \Sigma_R^{+}, \Sigma_R^{0}, \Sigma_R^{-})$, transforming under SMG as $(1,5,2)$, and forming a Dirac mass term $\mathcal{L}_{mass} = -M_\Sigma \overline{\Sigma_L}\Sigma_R + H.c.$. These new fermions in conjunction with additional scalar four-plets $\Phi_1 = (\Phi_1^0, \Phi_1^-, \Phi_1^{--}, \Phi_1^{---})$ and $\Phi_2 = (\Phi_2^+, \Phi_2^0, \Phi_2^-, \Phi_2^{--})$, transforming as $(1,4,-3)$ and $(1,4,-1)$, allow us to build the gauge invariant Yukawa terms

$$\mathcal{L}_Y = Y_1 \bar{l}_L \Sigma_R \Phi_1 + Y_2 \overline{\Sigma_L}(l_L)^c \Phi_2^* + \mathrm{H.c.}\,. \tag{1}$$

Here, the induced *vevs* v_{Φ_1} and v_{Φ_2} of new scalars lead to mass terms m_1 and m_2, and span the mass matrix in the basis ν_L, Σ_L^0, $(\Sigma_R^0)^c$:

$$\mathcal{L}_{\nu\Sigma^0} = -\frac{1}{2}\begin{pmatrix}\overline{\nu_L} & \overline{\Sigma_L^0} & \overline{(\Sigma_R^0)^c}\end{pmatrix}\begin{pmatrix}0 & m_2 & m_1\\ m_2 & 0 & M_\Sigma\\ m_1 & M_\Sigma & 0\end{pmatrix}\begin{pmatrix}(\nu_L)^c\\ (\Sigma_L^0)^c\\ \Sigma_R^0\end{pmatrix} + \mathrm{H.c.}\,. \tag{2}$$

Diagonalizing this matrix leads to a light neutrino with Majorana mass

$$m_\nu \sim \frac{m_1 m_2}{M_\Sigma} \sim \frac{Y_1 Y_2 v_{\Phi_1} v_{\Phi_2}}{M_\Sigma}\,. \tag{3}$$

The scalar potential contains the following relevant renormalizable terms

$$\begin{aligned} V(H,\Phi_1,\Phi_2) \sim\ & \mu_H^2 H^\dagger H + \mu_{\Phi_1}^2 \Phi_1^\dagger \Phi_1 + \mu_{\Phi_2}^2 \Phi_2^\dagger \Phi_2 + \lambda_H (H^\dagger H)^2 \\ & + \{\lambda_1 \Phi_1^* H^* H^* H^* + \mathrm{H.c.}\} + \{\lambda_2 \Phi_2^* H H^* H^* + \mathrm{H.c.}\} \\ & + \{\lambda_3 \Phi_1^* \Phi_2 H^* H^* + \mathrm{H.c.}\}\,, \end{aligned} \tag{4}$$

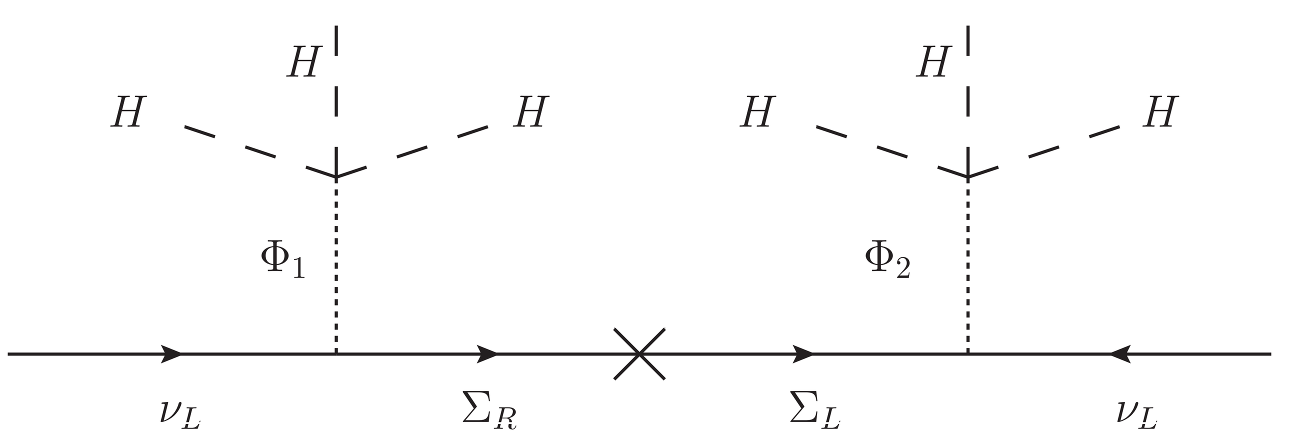
where the λ_1 and λ_2 terms lead to the induced *vevs*

$$v_{\Phi_1} \simeq -\lambda_1 \frac{v^3}{\mu_{\Phi_1}^2}\,,\quad v_{\Phi_2} \simeq -\lambda_2 \frac{v^3}{\mu_{\Phi_2}^2}\,, \tag{5}$$

constrained by the electroweak parameter $\rho = 1.0000^{+0.0011}_{-0.0007}$ to the bounds $v_{\Phi_1} \lesssim 1.9$ GeV and $v_{\Phi_2} \lesssim 2.4$ GeV. Eqs. (3) and (5) result in the light neutrino mass

$$m_\nu \sim \frac{Y_1 Y_2\, \lambda_1 \lambda_2\, v^6}{M_\Sigma\, \mu_{\Phi_1}^2\, \mu_{\Phi_2}^2}\,. \tag{6}$$

Fig. 1: Novel Seesaw Diagram



Testability at the LHC

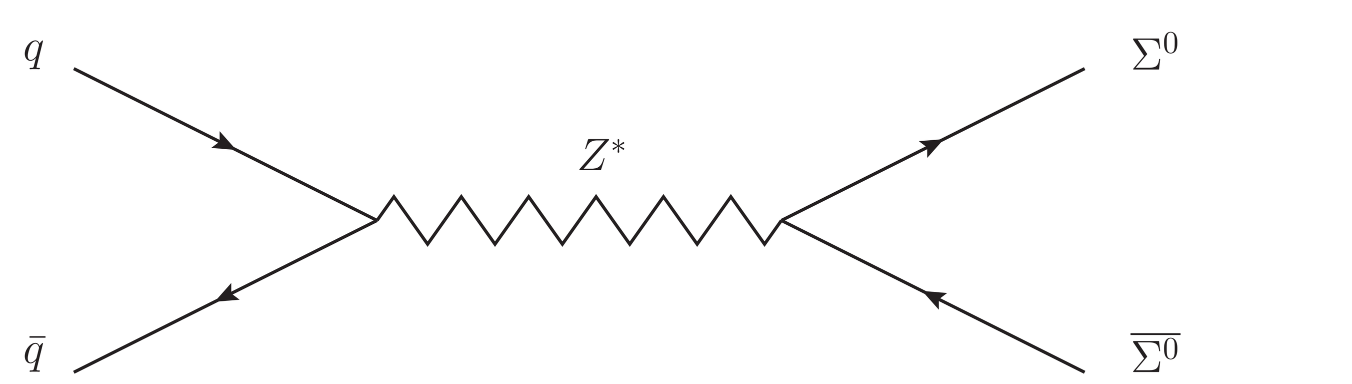
We estimate the high energy scale of our model from eq. (6) which reflects the fact that it is generated from the dimension nine operator shown in Fig. 1. It can be compared to the model by Babu et al. [3] which produced dimension seven operator. Assuming degenerate high scale mass parameters and the moderate values $Y_1 \sim Y_2 \sim \lambda_1 \sim \lambda_2 \sim 10^{-2}$ we obtain $\Lambda_{NP} \simeq 580$ GeV and *vevs* $v_{\Phi_1} \simeq 80$ MeV, $v_{\Phi_2} \simeq 60$ MeV from eq. (5).

By closing $(H^\dagger H)$ legs in Fig. 1 we obtain dimension seven and five operator at one and two loop level, respectively. However, the dimension five operator generated at one loop level by λ_3 term in eq. (4), giving contribution $Y_1 Y_2 \lambda_3 v^2/16\pi^2 M_\Sigma$, turns out to be the most important. For a reasonable assumption $\lambda_1 \cdot \lambda_2 \simeq \lambda_3$ the loop level contribution is smaller then the tree level one if $\Lambda_{NP} < \sqrt{4\pi}v \simeq 620$ GeV. A non-discovery of the new states of a few 100 GeV at the LHC would strongly disfavour a tree level generation of neutrino masses, relegating it to a loop-level mass generation.

Production

Associated production of the pairs $(\Sigma^{+++}, \overline{\Sigma^{++}})$, $(\Sigma^{++}, \overline{\Sigma^{+}})$, $(\Sigma^{+}, \overline{\Sigma^{0}})$, $(\Sigma^{0}, \overline{\Sigma^{-}})$ via a charged current is a crucial test of the five-plet nature of new leptons. Direct pair production of neutral states $(\Sigma^{0}, \overline{\Sigma^{0}})$ via a neutral current in Fig. 2 is possible for our states with non-zero weak charges, and makes a crucial difference to the type I and III seesaws.

Fig. 2: Drell-Yan Production



Decays of the five-plet states

The states of the five-plet type at hand are characterized by small mass splitting within a multiplet [4]. So that the cascade decays are suppressed. Since our states mix with SM particles due to lepton number conserving (LNC) and LNV Yukawa terms in eq.(1) they will decay to SM particles:

$$\begin{aligned} \Sigma^0 &\to W^\pm l^\mp, Z\nu, H^0\nu \\ \Sigma^+ &\to W^+\nu, Zl^+, H^0 l^+ \\ \Sigma^- &\to W^-\nu, Zl^-, H^0 l^- \\ \Sigma^{++} &\to W^+ l^+ \\ \Sigma^{+++} &\to W^+ W^+ l^+ \end{aligned} \tag{7}$$

The relative rates of LNV and LNC decays of Σ^0 are determined by the relative strengths of LNC and LNV Yukawa couplings Y_1 and Y_2, and respective mass terms m_1 and m_2. LNV decays lead to same sign dileptons and the jets as an appealing signature

$$\begin{aligned} q\bar{q}' &\to W^* \to \Sigma^+\overline{\Sigma^0} \to l^+ Z l^+ W^- \to l^+ l^+ jj\,, \\ q\bar{q} &\to Z^* \to \Sigma^0\overline{\Sigma^0} \to l^\pm W^\mp l^\pm W^\mp \to l^\pm l^\pm jj\,. \end{aligned} \tag{8}$$

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