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Radiative neutrino mass with scotogenic scalar triplet

Vedran Brdar, Ivica Picek, Branimir Radovčić *

Department of Physics, Faculty of Science, University of Zagreb, P.O.B. 331, HR-10002 Zagreb, Croatia

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ABSTRACT

We present a radiative one-loop neutrino mass model with hypercharge zero scalar triplet in conjunction with another charged singlet scalar and an additional vectorlike lepton doublet. We study three variants of this mass model: the first one without additional beyond-SM symmetry, the second with imposed DM-stabilizing discrete Z_2 symmetry, and the third in which this Z_2 symmetry is promoted to the gauge symmetry $U(1)_D$. The two latter cases are scotogenic, with a neutral component of the scalar triplet as a dark matter candidate. In first scotogenic model the Z_2-odd dark matter candidate is at the multi-TeV mass scale, so that all new degrees of freedom are beyond the direct reach of the LHC. In second scotogenic setup, with broken $U(1)_D$ symmetry the model may have LHC signatures or be relevant to astrophysical observations, depending on the scale of $U(1)_D$ breaking.

1. Introduction

The 126 GeV particle observed at the Large Hadron Collider (LHC) [1,2] corresponds to the *Higgs particle h* of the electroweak $SU(2)_L \times U(1)_Y$ extension [3] of the original Higgs model [4]. The Higgs explains masses of all SM particles, with neutrino masses as a possible exception. The proposed models of neutrino masses involve beyond SM degrees of freedom: new fermion multiplets, extra scalar multiplets or both of them.

In the present attempt to account both for the mechanism of neutrino mass and for the existence of a stable dark matter (DM) we put forward a variant of the scotogenic radiative neutrino mass model by Ma [5] realized by hypercharge zero triplet scalar field. A distinguished feature of such radiative neutrino mass model is that there is no need to introduce additional discrete Z_2 symmetry to eliminate the competing tree-level contribution.

An earlier study [6] of Weinberg operator generated at one-loop level has been followed by recent classifications of radiative neutrino mass models which provide dark matter candidates, in which the present model with zero hypercharge scalar triplet is listed as *type D* in [7] and *class T3-A* in [8].

While the proposed neutrino mass model is new, the newly introduced fields have been studied previously in different context. In particular, the neutral component of the scalar triplet which may be viable DM candidate has already been studied in several accounts [9–11]. Here, we have an interplay of this field with additional beyond SM fields, which depends on the variant of the proposed neutrino mass model. Therefore we expose in each section the piece of the phenomenology which is most relevant for a given variant of our model.

The Letter is structured as follows. In the next section we introduce the new fields and the radiative mass generation mechanism. In Section 3 we impose extra discrete Z_2 symmetry which enables that the neutrino masses are induced by the DM exchange so that the model is scotogenic. In Section 4 we study another scotogenic variant of the neutrino mass model where discrete Z_2 symmetry is replaced by $U(1)_D$ gauge symmetry. Thereby the hypercharge zero scalar triplet becomes complex. If we break $U(1)_D$ symmetry, the phenomenology of the model will depend on the scale of $U(1)_D$ breaking. The model may include interesting astrophysical implications [12] or may have LHC signatures [13]. In the concluding section we summarize the results of the proposed variants of the model and list the constraints which may be achieved for the model parameters.

2. Neutrino mass from an effective operator

The model is based on the electroweak gauge group $SU(2)_L \times U(1)_Y$, where the neutrino mass is generated by charged exotic particles in the loop diagram displayed in Fig. 1. The new charged particles are a component of the scalar triplet field and another charged singlet scalar and a component of the additional lepton doublet which is vectorlike. Thus, the SM leptons transforming as

$$L_L \equiv \left(\nu_L, l_L^-\right)^T \sim (2, -1), \qquad l_R \sim (1, -2), \tag{1}$$

should be supplemented by three generations of beyond SM vectorlike states

* Corresponding author.

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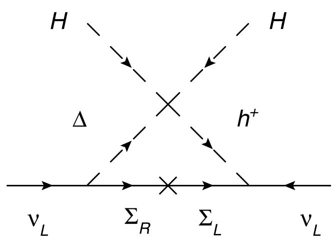

Fig. 1. The one-loop neutrino mass diagram.

$$\Sigma_R \equiv \left(\Sigma_R^0, \Sigma_R^-\right)^T \sim (2, -1),$$
$$\Sigma_L \equiv \left(\Sigma_L^0, \Sigma_L^-\right)^T \sim (2, -1). \qquad (2)$$

In the scalar sector, the SM Higgs doublet

$$H \equiv \left(H^+, H^0\right)^T \sim (2, 1), \qquad (3)$$

should be supplemented by a charged scalar singlet

$$h^+ \sim (1, 2), \qquad (4)$$

and an additional hypercharge zero triplet which in the matrix notation reads

$$\Delta = \frac{1}{\sqrt{2}} \sum_j \sigma_j \Delta^j = \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta^0 & \Delta^+ \\ \Delta^- & -\frac{1}{\sqrt{2}}\Delta^0 \end{pmatrix} \sim (3, 0). \qquad (5)$$

The gauge invariant Yukawa interactions and the mass terms involving new fermion and scalar fields are given by

$$\mathcal{L} = M\overline{\Sigma_L}\Sigma_R + \tilde{M}\overline{L_L}\Sigma_R + y\overline{\Sigma_L}Hl_R + g_1\overline{(L_L)^c}\Sigma_L h^+ + g_2\overline{L_L}\Delta\Sigma_R + g_3\overline{\Sigma_L}\Delta\Sigma_R + g_4\overline{(L_L)^c}L_L h^+ + \text{H.c.} \qquad (6)$$

Here y and $g_{1,2,3,4}$ are the Yukawa coupling matrices and M and $\tilde{M}$ are the mass matrices of the new lepton doublet. The mass term $\tilde{M}$ can be rotated away by a field redefinition, and for simplicity we drop the flavor indices altogether.

The gauge invariant scalar potential with extra charged singlet and real triplet field has a form

$$\begin{aligned} V\left(H, \Delta, h^+\right) = {} & -\mu_H^2 H^\dagger H + \lambda_1\left(H^\dagger H\right)^2 + \mu_h^2 h^- h^+ + \lambda_2\left(h^- h^+\right)^2 \\ & + \mu_\Delta^2 \mathrm{Tr}\left[\Delta^2\right] + \lambda_3\left(\mathrm{Tr}\left[\Delta^2\right]\right)^2 + \lambda_4 H^\dagger H h^- h^+ \\ & + \lambda_5 H^\dagger H \mathrm{Tr}\left[\Delta^2\right] + \lambda_6 h^- h^+ \mathrm{Tr}\left[\Delta^2\right] \\ & + \left(\lambda_7 H^\dagger \Delta \tilde{H} h^+ + \text{H.c.}\right) + \mu H^\dagger \Delta H. \end{aligned} \qquad (7)$$

The electroweak symmetry breaking proceeds in usual way via the vacuum expectation value (VEV) $v_H = 174$ GeV of the neutral component of the Higgs doublet. Note that without imposing Z_2 symmetry there is the trilinear μ term in Eq. (7) which induces a VEV for the neutral triplet component Δ^0. This VEV is constrained by electroweak measurements to be smaller than a few GeV.

The neutrino mass matrix obtained from an effective operator displayed in Fig. 1 is proportional to λ_7 coupling in Eq. (7),

$$\begin{aligned} \mathcal{M}_{ij} = {} & \sum_{k=1}^{3} \frac{[(g_1)_{ik}(g_2)_{jk} + (g_2)_{ik}(g_1)_{jk}]}{8\pi^2} \lambda_7 v_H^2 M_{\Sigma_k} \\ & \times \frac{M_{\Sigma_k}^2 m_{h^+}^2 \ln\frac{M_{\Sigma_k}^2}{m_{h^+}^2} + M_{\Sigma_k}^2 m_{\Delta^+}^2 \ln\frac{m_{\Delta^+}^2}{M_{\Sigma_k}^2} + m_{h^+}^2 m_{\Delta^+}^2 \ln\frac{m_{h^+}^2}{m_{\Delta^+}^2}}{(m_{h^+}^2 - m_{\Delta^+}^2)(M_{\Sigma_k}^2 - m_{h^+}^2)(M_{\Sigma_k}^2 - m_{\Delta^+}{}^2)}. \end{aligned} \qquad (8)$$

Let us observe that in the present scenario without imposed Z_2 symmetry there is an additional contribution to the neutrino masses from dimension seven operator, without introducing the vectorlike lepton doublet fields. It is displayed in Fig. 2 of Ref. [14] and gives a contribution

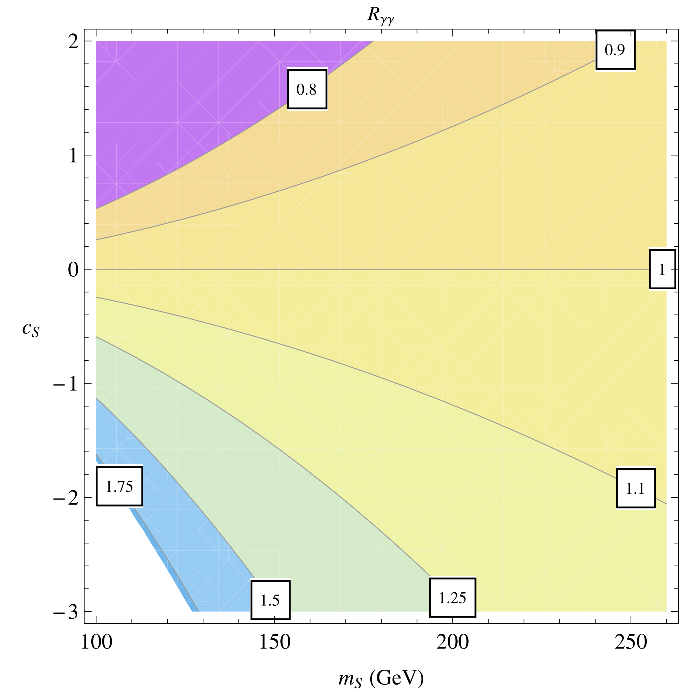

Fig. 2. Enhancement factor contours for the $h \to \gamma\gamma$ branching ratio $R_{\gamma\gamma}$ in dependence on scalar coupling c_S and the mass m_S of the lighter charged scalar.

$$\mathcal{M}_{ij} \sim \frac{1}{16\pi^2} g_4 y_l^2 \lambda_7 \frac{\mu}{\Lambda_{NP}} \frac{v_H^4}{\Lambda_{NP}^3}, \qquad (9)$$

determined by the scale of new physics Λ_{NP} and by the SM charged lepton Yukawa couplings y_l. As explicated in [14], this contribution which corresponds to a simplified version of the Zee model [15] is already ruled out by data if it were the dominant contribution. As a term of higher dimension which is further suppressed by charged lepton Yukawa factors, it gives a sub-leading contribution to Eq. (8).

Assuming the mass values $M_\Sigma \sim m_{\Delta^+} \sim m_{h^+} \sim 200$ GeV, Eq. (8) achieves $m_\nu \sim 0.1$ eV for the couplings $g_{1,2}$ and λ_7 of the order 10^{-4}.

The new fields participating in neutrino mass generation have been explored separately in different context. They may be sufficiently light to be produced and studied at the LHC.

Since in the present form our model does not provide a viable DM candidate, the charged scalars can be sufficiently light to produce observable effects in the LHC diphoton Higgs signal. On the other hand, the measured $h \to \gamma\gamma$ signal constrains the couplings of new charged scalar states which affect this loop amplitude. Using the same conventions and notations as in [16,17], the enhancement factor with respect to the SM decay width reads

$$R_{\gamma\gamma} = \left| 1 + \sum_{S=S_1,S_2} Q_S^2 \frac{c_S}{2} \frac{v_H^2}{m_S^2} \frac{A_0(\tau_S)}{A_1(\tau_W) + N_c Q_t^2 A_{1/2}(\tau_t)} \right|^2, \qquad (10)$$

where S_1 and S_2 are charged scalar mass eigenstates and c_S are the couplings from $c_S v_H h^0 S_{1,2}^\dagger S_{1,2}$ terms, linked to the couplings λ_4 and λ_5. In Fig. 2 we plot this enhancement as a function of the scalar coupling for lighter among two charged scalars S_1 and S_2. In the present variant of the model the state with mass