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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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.

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1. Introduction

The 126 GeV particle observed at the Large Hadron Collider (LHC) \cite{1,2} corresponds to the Higgs particle $h$ of the electroweak $SU(2)_L \times U(1)_Y$ extension \cite{3} of the original Higgs model \cite{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 \cite{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 \cite{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 \cite{7} and class T3-A in \cite{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 \cite{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 \cite{12} or may have LHC signatures \cite{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 $L_L \equiv \left(\nu_L, l^-_L\right)^T \sim (2, -1), \quad l_R \sim (1, -2), \quad (1)$ should be supplemented by three generations of beyond SM vectorlike states.

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and component of the Higgs doublet. Note that without imposing
symmetry there is the trilinear
symmetry there is an additional contribution to the neutrino
vacuum expectation value (VEV)
The electroweak symmetry breaking proceeds in usual way via the
gauge invariant Yukawa interactions and the mass terms in-
eration reads
\[ \Delta = \frac{1}{\sqrt{2}} \sum_j \sigma_j \Delta_j = \left( \frac{1}{\sqrt{2}} \Delta^0 - \frac{\Delta^+}{\sqrt{2}} \right) \sim (3, 0). \] (5)

The gauge invariant Yukawa interactions and the mass terms in-
volving new fermion and scalar fields are given by
\[ \mathcal{L} = M \sum_i \Sigma_i + M_1 \sum_i \Sigma_i + \frac{g_1}{2} \sum_i \Sigma_i h^+ + g_2 \sum_i \Sigma_i \sum_i H^+ \sum_i h^+ + g_3 \sum_i \Sigma_i \sum_i H^+ \sum_i h^+ + g_4 \sum_i \Sigma_i \sum_i H^+ \sum_i h^+ + \text{H.c.} \] (6)

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

The gauge invariant scalar potential with extra charged singlet
and real triplet field has a form
\[ V(H, \Delta, h^+) = -\frac{1}{4} \mu_1 H_H^+ + \lambda_1 (H^+ H)^2 + \mu_2 h^+ h^+ + \lambda_2 (h^+ h^+)^2 + \mu_3 \text{Tr}(\Delta^2) + \lambda_3 \text{Tr}(\Delta^2) \] + \mu_4 H^+ H_H^+ + \lambda_5 H^+ H_H^+ \text{Tr}(\Delta^2) + \lambda_6 h^+ h^+ \text{Tr}(\Delta^2) + \lambda_7 H^+ \text{Tr}(\Delta^2) + \text{H.c.} + \mu H^+ \Delta H. \] (7)

The electroweak symmetry breaking proceeds in usual way via the
vacuum expectation value (VEV) \( v_H = 174 \) GeV of the neutral com-
ponent of the Higgs doublet. Note that without imposing \( Z_2 \) sym-
metry there is the trilinear \( \mu \) term in Eq. (7) which induces a VEV
for the neutral triplet component \( \Delta^0 \). 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 \( \lambda_7 \) coupling in Eq. (7),
\[ \mathcal{M}_{ij} \equiv \frac{3}{8\pi^2} \frac{m_{\nu}^2}{m_{\nu}^2} \frac{m_{\nu}^2}{m_{\nu}^2} \lambda_7 \nu^2 H M_{\Sigma_i} \]
\[ \times \frac{M_{\Sigma_i}^2 m_{\nu_i}^2}{m_{\nu_i}^2} \ln \frac{m_{\Sigma_i}^2}{m_{\nu_i}^2} + \frac{M_{\Sigma_i}^2 m_{\nu_i}^2}{m_{\nu_i}^2} \ln \frac{m_{\Sigma_i}^2}{m_{\nu_i}^2} + \frac{m_{\nu_i}^2}{m_{\nu_i}^2} \ln \frac{m_{\nu_i}^2}{m_{\nu_i}^2}. \] (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
\[ \mathcal{M}_{ij} \sim \frac{1}{16\pi^2} g_4 y_i^2 \frac{\lambda_7}{\Lambda_{NP}} \frac{\nu^2}{\Lambda^2}, \] (9)
determined by the scale of new physics \( \Lambda_{NP} \) and by the SM
charged lepton Yukawa couplings \( y_i \). 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 sup-
pressed by charged lepton Yukawa factors, it gives a sub-leading
contribution to Eq. (8).

Assuming the mass values \( m_{S_1} \sim m_{S_2} \sim m_{h^+} \sim 200 \) GeV,
Eq. (8) achieves \( m_{\nu_i} \sim 0.1 \) eV for the couplings \( g_{1,2} \) and \( \lambda_7 \) of the
order \( 10^{-4} \).

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

Since in the present form our model does not provide a vi-
able 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 am-
pitude. Using the same conventions and notations as in [16,17],
the enhancement factor with respect to the SM decay width reads
\[ R_{\gamma\gamma} = 1 + \sum_{S_i = S_1, S_2} \frac{Q_S^2 c_S v_H^2}{2} \frac{A_0(T_S)}{m_{S_i}^2 A_1(T_{S_i})} + N_c Q_s^4 A_2(T_S) \] (10)
where \( S_1 \) and \( S_2 \) are charged scalar mass eigenstates and \( c_S \)
are the couplings from \( c_s_{\nu_i} H h^0} \) terms, linked to the cou-
plings \( \lambda_4 \) and \( \lambda_5 \). 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
125 GeV discovered at the LHC corresponds to the SM Higgs and the measurement of an enhancement \( R_{\gamma\gamma} \) [1,2] may reveal the existence of the charged scalars or put constrains on the parameters of our model. Recent study [18] scrutinizes the LHC diphoton signal in purely hypercharge-zero scalar triplet extension of the SM.

3. Scotogenic model with \( Z_2 \) symmetry

Among the fields introduced in our model only the neutral component of the scalar triplet can be a DM candidate. However, in order to ensure DM stability, we have to assign a protective \( Z_2 \) symmetry to all new fields circulating in the loop diagram. In this way we arrive at a neutrino mass matrix evaluated by the self-energy diagram displayed in Fig. 3. Since the SM Higgs is \( Z_2 \) even there is mixing only between the \( Z_2 \) odd scalar singlet and scalar triplet. The initial mass matrix for these fields reads

\[
\begin{pmatrix}
\hbar^- & \Delta^-
\end{pmatrix}
\begin{pmatrix}
\mu_h^2 + \lambda_4 v_H^2 & \lambda_7 v_H^2 \\
\lambda_7 v_H^2 & \mu_\Delta^2 + 2\lambda_5 v_H^2
\end{pmatrix}
\begin{pmatrix}
h^+ \\ \Delta^+
\end{pmatrix},
\]

and the relation to the mass eigenstates is given by

\[
\begin{pmatrix}
h^+ \\ \Delta^+
\end{pmatrix} =
\begin{pmatrix}
\cos \theta & -\sin \theta \\
\sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
S_1^+ \\ S_2^+
\end{pmatrix}.
\]

The diagonalization condition is given by

\[
\tan(2\theta) = \frac{2\lambda_7 v_H^2}{\mu_h^2 + \lambda_4 v_H^2 - \mu_\Delta^2 - 2\lambda_5 v_H^2},
\]

and the masses of physical states are

\[
m_{S_1^+} = \left(\mu_h^2 + \lambda_4 v_H^2\right) \cos^2 \theta + \left(\mu_\Delta^2 + 2\lambda_5 v_H^2\right) \sin^2 \theta + 2\lambda_7 v_H^2 \sin \theta \cos \theta,
\]

and

\[
m_{S_2^+} = \left(\mu_h^2 + \lambda_4 v_H^2\right) \sin^2 \theta + \left(\mu_\Delta^2 + 2\lambda_5 v_H^2\right) \cos^2 \theta - 2\lambda_7 v_H^2 \sin \theta \cos \theta.
\]

The evaluation of the self-energy diagram gives

\[
\mathcal{M}_{ij} = \frac{3}{8\pi^2} \sum_{k=1}^{\Delta^3} \frac{[(g_1)_{ik}(g_2)_{jk} + (g_2)_{ik}(g_1)_{jk}] \lambda_7 v_H^2}{M_{\Sigma_k}} \ln \left(\frac{M_{\Sigma_k}^2}{m_{\Delta^3}^2} - 1\right).
\]

1) \( M_{\Sigma_k}^2 \gg m_{h^+}^2 = m_{\Delta^+}^2 \).

2) \( M_{\Sigma_k}^2 \ll m_{h^+}^2 = m_{\Delta^+}^2 \).

3) for whatever value of \( M_{\Sigma_k}^2 \) and \( m_{h^+}^2 = m_{\Delta^+}^2 \).

\[
\mathcal{M}_{ij} = \frac{3}{8\pi^2} \sum_{k=1}^{\Delta^3} \frac{[(g_1)_{ik}(g_2)_{jk} + (g_2)_{ik}(g_1)_{jk}] \lambda_7 v_H^2 M_{\Sigma_k}}{m_{\Delta^+}^2}
\]

\[
\times \left(1 + \frac{M_{\Sigma_k}^2}{m_{\Delta^+}^2 - M_{\Sigma_k}^2} \ln \left(\frac{M_{\Sigma_k}^2}{m_{\Delta^+}^2} - 1\right)\right),
\]

which agree with those in a recent study [19].

Our unique DM candidate \( \Delta^0 \) is hypercharge-less DM which does not couple directly to \( Z \) boson. Accordingly, it is not ruled out by direct-detection experiments. However, there are constraints from the relic abundance for DM. As shown in [9–11,20], its correct value can be achieved by annihilations of \( \Delta^0 \) to gauge bosons with mass of \( \Delta^0 \) in the multi-TeV range, and thus out of the reach of the LHC. Therefore, the other states must be even heavier so that this scotogenic variant of the model leads to purely virtual beyond SM physics at the LHC. Neutrino masses \( m_\nu \approx 0.1 \) eV with mass values \( M_\Sigma \sim m_\tau \sim m_{S_2} \approx 2 \) TeV will be reproduced with slightly larger couplings \( g_{1,2} \) and \( \lambda_7 \) of the order \( 10^{-3} \). Due to high mass of the new states, lepton flavor violation is out of present experimental reach.

4. Scotogenic model with \( U(1)_D \) gauge symmetry

Let us introduce a variant of our model based on \( SU(2)_L \times U(1)_Y \times U(1)_D \) gauge symmetry, where an extra \( U(1)_D \) gauge factor has been introduced to stabilize the DM candidate. Using \( U(1)_D \) gauge symmetry avoids the breaking of \( Z_2 \) by quantum gravity, which is a serious problem for any discrete symmetry. All SM fields are uncharged under the new gauge group and all newly introduced states are singly \( U(1)_D \) charged. Thereby, the real triplet field becomes complex and, for a given relic density, the mass of a complex multiplet DM candidate is smaller by a factor \( \sqrt{2} \) compared to the real multiplet case. Also, for complex triplet \( \Delta \) there are terms additional to those shown in Eq. (7),

\[
\Delta V(H, \Delta) = \lambda_8 (\Delta^+_D t_3^e)^2 + \lambda_9 (H^+_D t_3^e H) (\Delta^+_D t_3^e)^2,
\]

as explicated in [20], the quartic coupling \( \lambda_8 \) generates a mass splitting making a half of the charged fields of the multiplet lighter than the neutral component at tree level. This may be compensated by an additional splitting \( \sim 166 \) MeV from one loop with electroweak gauge bosons. The condition that the neutral component \( \Delta^0 \) stays the lightest particle within the multiplet is that \( \lambda_8 \leq 2.2 \times 10^{-2} \).

More pronounced splitting between the charged and neutral component of the triplet \( \Delta \) may arise due to a mixing between the charged triplet and the charged singlet scalar in Eq. (12). There is a portion of the parameter space where the charged \( \Delta^+ \) is considerably heavier, so that annihilations to force carriers may become important [12].

For this reason we should distinguish the scenario with an exact \( U(1)_D \) gauge symmetry from a setup where \( U(1)_D \) is broken.
to $Z_2$ by a complex singlet scalar field $\xi$ doubly charged under $U(1)_D$, which may be broken by a VEV of the doubly $U(1)_D$-charged scalar field $\xi$. There are two extreme regimes explored recently in [12] and [13] which are relevant for explanation of observed dwarf galaxies or may be tested at the LHC, respectively.

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5. Conclusions

The present neutrino mass model is minimal in a sense that the new fields do not exceed multiplet higher than adjoint. The hypercharge-less scalar triplet $\Delta = (\Delta^+, \Delta^0, \Delta^-) \sim (3,0)$ completed with appropriate charged scalar singlet $h^+ \sim (1,2)$ and vectorlike fermion doublet $\Sigma \sim (2,-1)$ closes the radiative neutrino mass loop diagram which constrains the coupling $\lambda_7$ in Eq. (7).

In the first variant of the model where the additional particles may be in the mass range $\sim 200$ GeV, the couplings $g_{1,2}$ and $\lambda_7$ should be of the order $10^{-4}$ to reproduce the neutrino masses $m_\nu \sim 0.1$ eV. In addition, the Higgs diphoton signal at the LHC constrains the couplings $\lambda_4$ and $\lambda_5$ via contours shown in Fig. 2.

In the $Z_2$-scotogenic version of the model the neutral component $\Delta^0$ is without VEV and can saturate the observed relic density $h^2\Omega_{CDM} = 0.1199(27)$ [21] if $m_\Delta = 2.5$ TeV [9]. Accordingly, the rest of the beyond SM states are heavy and stay out of direct reach of the LHC, while the neutrino masses $m_\nu \sim 0.1$ eV will be reproduced with slightly larger couplings $g_{1,2}$ and $\lambda_7$ of the order $10^{-3}$.

The phenomenology becomes richer upon promoting DM-stabilizing discrete $Z_2$ symmetry to the gauge symmetry $U(1)_D$, which may be broken by a VEV of the doubly charged scalar field $\xi$. There are two extreme regimes explored recently in [12] and [13] which are relevant for explanation of observed dwarf galaxies or may be tested at the LHC, respectively.

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