Physics Letters B 728 (2014) 198–201

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

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

ARTICLE INFO

Article history:
Received 18 October 2013
Received in revised form 14 November 2013
Accepted 19 November 2013
Available online 22 November 2013
Editor: J. Hisano

Keywords:
Neutrino mass
Dark matter

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

☆ This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited. Funded by SCOAP[3].

* Corresponding author.

0370-2693/$ – see front matter © 2013 The Authors. Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.physletb.2013.11.045

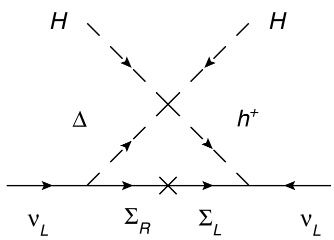

Fig. 1. The one-loop neutrino mass diagram.

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

In the scalar sector, the SM Higgs doublet

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

should be supplemented by a charged scalar singlet

$$h^+ \sim (1, 2), \tag{4}$$

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

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

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

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

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

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

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),

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

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

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

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

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

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

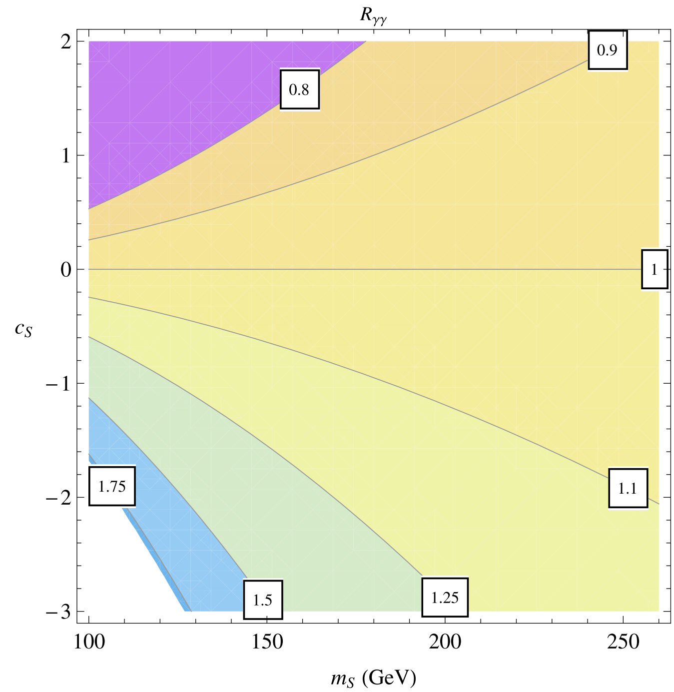

Fig. 2. Enhancement factor contours for the $h \to \gamma\gamma$ branching ratio $R_{\gamma\gamma}$ in dependence on scalar coupling c_S and the mass m_S of the lighter charged scalar.

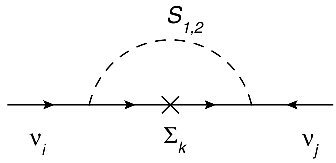

Fig. 3. The self-energy one-loop contribution.

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

$$\begin{pmatrix} h^- & \Delta^- \end{pmatrix} \begin{pmatrix} \mu_h^2 + \lambda_4 v_H^2 & \lambda_7 v_H^2 \\ \lambda_7 v_H^2 & \mu_\Delta^2 + 2\lambda_5 v_H^2 \end{pmatrix} \begin{pmatrix} h^+ \\ \Delta^+ \end{pmatrix}, \tag{11}$$

and the relation to the mass eigenstates is given by

$$\begin{pmatrix} h^+ \\ \Delta^+ \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} S_1^+ \\ S_2^+ \end{pmatrix}. \tag{12}$$

The diagonalization condition is given by

$$\mathrm{tg}(2\theta) = \frac{2\lambda_7 v_H^2}{\mu_h^2 + \lambda_4 v_H^2 - \mu_\Delta^2 - 2\lambda_5 v_H^2}, \tag{13}$$

and the masses of physical states are

$$m_{S_1}^2 = \left(\mu_h^2 + \lambda_4 v_H^2\right)\cos^2\theta + \left(\mu_\Delta^2 + 2\lambda_5 v_H^2\right)\sin^2\theta + 2\lambda_7 v_H^2 \sin\theta\cos\theta, \tag{14}$$

and

$$m_{S_2}^2 = \left(\mu_h^2 + \lambda_4 v_H^2\right)\sin^2\theta + \left(\mu_\Delta^2 + 2\lambda_5 v_H^2\right)\cos^2\theta - 2\lambda_7 v_H^2 \sin\theta\cos\theta. \tag{15}$$

The evaluation of the self-energy diagram gives

$$(\mathcal{M}_\nu)_{ij} = \cos\theta\sin\theta \sum_{k=1}^{3} \frac{[(g_1)_{ik}(g_2)_{jk} + (g_2)_{ik}(g_1)_{jk}]}{8\pi^2} \times M_{\Sigma_k}\left[\frac{m_{S_1}^2}{m_{S_1}^2 - M_{\Sigma_k}^2}\ln\frac{m_{S_1}^2}{M_{\Sigma_k}^2} - \frac{m_{S_2}^2}{m_{S_2}^2 - M_{\Sigma_k}^2}\ln\frac{m_{S_2}^2}{M_{\Sigma_k}^2}\right]. \tag{16}$$

For a small value of the parameter λ_7, when mass eigenstates S_1 and S_2 are approximately given by weak eigenstates h^+ and Δ^+, this expression reproduces the mass matrix given in Eq. (8). We list the expressions of Eq. (8) for equal scalar masses and for specified limits:

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

$$\mathcal{M}_{ij} = \sum_{k=1}^{3} \frac{[(g_1)_{ik}(g_2)_{jk} + (g_2)_{ik}(g_1)_{jk}]}{8\pi^2} \frac{\lambda_7 v_H^2}{M_{\Sigma_k}}\left(\ln\frac{M_{\Sigma_k}^2}{m_{\Delta^+}^2} - 1\right); \tag{17}$$

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

$$\mathcal{M}_{ij} = \sum_{k=1}^{3} \frac{[(g_1)_{ik}(g_2)_{jk} + (g_2)_{ik}(g_1)_{jk}]}{8\pi^2} \frac{\lambda_7 v_H^2 M_{\Sigma_k}}{m_{\Delta^+}^2}; \tag{18}$$

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

$$\mathcal{M}_{ij} = \sum_{k=1}^{3} \frac{[(g_1)_{ik}(g_2)_{jk} + (g_2)_{ik}(g_1)_{jk}]}{8\pi^2} \frac{\lambda_7 v_H^2 M_{\Sigma_k}}{m_{\Delta^+}^2 - M_{\Sigma_k}^2} \times \left(1 + \frac{M_{\Sigma_k}^2}{m_{\Delta^+}^2 - M_{\Sigma_k}^2}\ln\frac{M_{\Sigma_k}^2}{m_{\Delta^+}^2}\right), \tag{19}$$

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

Our unique DM candidate Δ^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 Δ^0 to gauge bosons with mass of Δ^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 $m_\nu \sim 0.1$ eV with mass values $M_\Sigma \sim m_{S_1} \sim m_{S_2} \sim 2$ TeV will be reproduced with slightly larger couplings $g_{1,2}$ and λ_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 Δ there are terms additional to those shown in Eq. (7),

$$\Delta V(H,\Delta) = \lambda_8\left(\Delta^\dagger \tau_a^{(3)}\Delta\right)^2 + \lambda_9\left(H^\dagger \tau_a^{(2)} H\right)\left(\Delta^\dagger \tau_a^{(3)}\Delta\right). \tag{20}$$

As explicated in [20], the quartic coupling λ_9 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 ~ 166 MeV from one loop with electroweak gauge bosons. The condition that the neutral component Δ^0 stays the lightest particle within the multiplet is that $\lambda_9 \leqslant 2.2 \times 10^{-2}(\frac{m_\Delta}{1\ \mathrm{TeV}})$.

More pronounced splitting between the charged and neutral component of the triplet Δ 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 Δ^+ 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 ζ doubly charged under $U(1)_D$, in which case there is a massive dark photon γ_D as well as a real scalar field ζ_R. Dark Higgs boson ζ_R will mix with the SM Higgs boson h in the most general scalar potential, and the dark photon γ_D may have kinetic mixing with the SM photon. Two alternative regimes have been explored recently. Very light dark force carriers γ_D and ζ_R in the MeV range may explain astrophysical observations such as the dark matter distribution in dwarf galactic halos [12]. In a regime where the $U(1)_D$ is broken near the electroweak scale, there could be additional SM Higgs decays to multilepton final states through the dark Higgs boson and the dark photon studied in [13]. In this case the experiments at the LHC probe for the possible existence of a $U(1)_D$ dark sector governed by the original Abelian Higgs model [4].

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 constraints the coupling λ_7 in Eq. (7).

In the first variant of the model where the additional particles may be in the mass range ~ 200 GeV, the couplings $g_{1,2}$ and λ_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 constraints the couplings λ_4 and λ_5 via contours shown in Fig. 2.

In the Z_2-scotogenic version of the model the neutral component Δ^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 λ_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 $U(1)_D$-charged scalar field ζ. 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.

Acknowledgement

This work is supported by the Croatian Ministry of Science, Education and Sports under Contract No. 119-0982930-1016.

References

[1] G. Aad, et al., ATLAS Collaboration, Observation of a new particle in the search for the standard model Higgs boson with the ATLAS detector at the LHC, Phys. Lett. B 716 (2012) 1, arXiv:1207.7214 [hep-ex].
[2] S. Chatrchyan, et al., CMS Collaboration, Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, Phys. Lett. B 716 (2012) 30, arXiv:1207.7235 [hep-ex].
[3] S. Weinberg, A model of leptons, Phys. Rev. Lett. 19 (1967) 1264.
[4] F. Englert, R. Brout, Broken symmetry and the mass of gauge vector mesons, Phys. Rev. Lett. 13 (1964) 321;
P.W. Higgs, Broken symmetries and the masses of gauge bosons, Phys. Rev. Lett. 13 (1964) 508;
G.S. Guralnik, C.R. Hagen, T.W.B. Kibble, Global conservation laws and massless particles, Phys. Rev. Lett. 13 (1964) 585.
[5] E. Ma, Verifiable radiative seesaw mechanism of neutrino mass and dark matter, Phys. Rev. D 73 (2006) 077301, arXiv:hep-ph/0601225.
[6] F. Bonnet, M. Hirsch, T. Ota, W. Winter, Systematic study of the $d = 5$ Weinberg operator at one-loop order, J. High Energy Phys. 1207 (2012) 153, arXiv:1204.5862 [hep-ph].
[7] S.S.C. Law, K.L. McDonald, A class of inert N-tuplet models with radiative neutrino mass and dark matter, arXiv:1305.6467 [hep-ph].
[8] D. Restrepo, O. Zapata, C. Yaguna, Models with radiative neutrino masses and viable dark matter candidates, arXiv:1308.3655 [hep-ph].
[9] M. Cirelli, N. Fornengo, A. Strumia, Minimal dark matter, Nucl. Phys. B 753 (2006) 178, arXiv:hep-ph/0512090;
M. Cirelli, A. Strumia, M. Tamburini, Cosmology and astrophysics of minimal dark matter, Nucl. Phys. B 787 (2007) 152, arXiv:0706.4071 [hep-ph].
[10] P. Fileviez Perez, H.H. Patel, M.J. Ramsey-Musolf, K. Wang, Triplet scalars and dark matter at the LHC, Phys. Rev. D 79 (2009) 055024, arXiv:0811.3957 [hep-ph].
[11] T. Araki, C.Q. Geng, K.I. Nagao, Dark matter in inert triplet models, Phys. Rev. D 83 (2011) 075014, arXiv:1102.4906 [hep-ph].
[12] E. Ma, I. Picek, B. Radovčić, New scotogenic model of neutrino mass with $U(1)_D$ gauge interaction, Phys. Lett. B 726 (2013) 744, arXiv:1308.5313 [hep-ph].
[13] C.-F. Chang, E. Ma, T.-C. Yuan, Multilepton Higgs decays through the dark portal, arXiv:1308.6071 [hep-ph].
[14] S.S.C. Law, K.L. McDonald, The simplest models of radiative neutrino mass: excluding simplified Zee models and beyond, arXiv:1303.6384 [hep-ph].
[15] A. Zee, A theory of lepton number violation, neutrino Majorana mass, and oscillation, Phys. Lett. B 93 (1980) 389;
A. Zee, Phys. Lett. B 95 (1980) 461 (Erratum).
[16] M. Carena, I. Low, C.E.M. Wagner, Implications of a modified Higgs to diphoton decay width, J. High Energy Phys. 1208 (2012) 060, arXiv:1206.1082 [hep-ph].
[17] I. Picek, B. Radovčić, Enhancement of $h \to \gamma\gamma$ by seesaw-motivated exotic scalars, Phys. Lett. B 719 (2013) 404, arXiv:1210.6449 [hep-ph].
[18] L. Wang, X.-F. Han, LHC diphoton Higgs signal in the Higgs triplet model with $Y = 0$, arXiv:1303.4490 [hep-ph].
[19] K.L. McDonald, Probing exotic fermions from a seesaw/radiative model at the LHC, arXiv:1310.0609 [hep-ph].
[20] T. Hambye, F.-S. Ling, L. Lopez Honorez, J. Rocher, Scalar multiplet dark matter, J. High Energy Phys. 0907 (2009) 090, arXiv:0903.4010 [hep-ph];
T. Hambye, F.-S. Ling, L. Lopez Honorez, J. Rocher, J. High Energy Phys. 1005 (2010) 066 (Erratum).
[21] P.A.R. Ade, et al., Planck Collaboration, Planck 2013 results. XVI. Cosmological parameters, arXiv:1303.5076 [astro-ph.CO].