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A one-loop neutrino mass model with $SU(2)_L$ multiplet fields

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Abstract

We propose a one-loop neutrino mass model with several $SU(2)_L$ multiplet fermions and scalar fields in which the inert feature of a scalar to realize the one-loop neutrino mass can be achieved by the cancellation among Higgs couplings thanks to non-trivial terms in the Higgs potential and to present it in a simpler way. Then we discuss our typical cut-off scale by computing renormalization group equation for $SU(2)_L$ gauge coupling, lepton flavor violations, muon anomalous magnetic moment, possibility of dark matter candidate, neutrino mass matrix satisfying the neutrino oscillation data. Finally, we search for our allowed parameter region to satisfy all the constraints, and discuss a possibility of detecting new charged particles at the large hadron collider.

1. Introductions

Radiatively induced neutrino mass models are one of the promising candidates to realize tiny neutrino masses with natural parameter spaces at TeV scale and to provide a dark matter (DM) candidate, both of which cannot be explained within the standard model (SM). In order to build such a radiative model, an inert scalar boson plays an important role and its inert feature can fre-

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quently be realized by imposing additional symmetry such as Z_2 symmetry [1–4] and/or $U(1)$ symmetry [5–7], which also play an role in stabilizing the DM. On the other hand, once we introduce large $SU(2)_L$ multiplet fields such as quartet [8,9], quintet [10,11], septet fields [12–14], we sometimes can evade imposing additional symmetries [15,16]. Then, the stability originates from a remnant symmetry after the spontaneous electroweak symmetry breaking due to the largeness of these multiplets. In addition, the cut-off scale of a model is determined by the renormalization group equations (RGEs) of $SU(2)_L$ gauge coupling, and it implies that a theory can be within TeV scale, depending on the number of multiplet fields. Thus a good testability could be provided in such a scenario.

Then, using large $SU(2)_L$ multiplet fields, we would like to realize one-loop neutrino generation by inert scalar field without imposing additional symmetry such as Z_2. In this case scalar quintet H_5 is minimal choice for inert multiplet since scalar multiplet smaller than quintet easily develop a vacuum expectation value (VEV) by renormalizable interaction with SM Higgs field H like H_4HHH for the quadruplet H_4. In addition we need quadruplet fermion ψ_4 to interact H_5 with the SM lepton doublet and septet scalar H_7 is also required to get Majorana mass term from ψ_4 by its VEV (Higgs triplet is also possible but it allows type-II seesaw mechanism [17,18]). We find that scalar quadruplet H_4 is needed to realize vacuum configuration in which the VEV of H_5 to be zero; in addition we can avoid dangerous massless Goldstone boson from scalar multiplets by non-trivial terms with these multiplets. Although number of exotic fields is smaller in other one-loop neutrino mass models like scotogenic model [1] they usually require additional discrete symmetry such as Z_2. We show the realization of one-loop neutrino mass without additional symmetry which result in introduction of several exotic multiplets.

In this letter, we introduce several multiplet fermions and scalar fields under the $SU(2)_L$ gauge symmetry. As a direct consequence of multiplet fields, our cut-off scale is of the order 10 PeV that could be tested by current or future experiments. In our model we do not impose additional symmetry and search for possible solution to obtain inert condition for generating neutrino mass at loop level. Then required inert feature can be realized not via a remnant symmetry but via cancellations among couplings in our scalar potential thanks to several non-trivial couplings [19]. In such a case, generally DM could decay into the SM particles, but we can control some parameters so that we can evade its too short lifetime without requiring too small couplings. Therefore our DM is long-lived particle which represents clear difference from the scenario where the stability of DM is due to an additional or remnant symmetry. We also discuss lepton flavor violations (LFVs), and anomalous magnetic moment (muon $g-2$), and search for allowed parameter region to satisfy all the constraints such as neutrino oscillation data, LFVs, DM relic density, and demonstrate the possibility of detecting new charged particles at the large hadron collider (LHC).

This letter is organized as follows. In Sec. 2, we review our model and formulate the Higgs sector, neutral fermion sector including active neutrinos. Then we discuss the RGE of the $SU(2)_L$ gauge coupling, LFVs, muon $g-2$, and our DM candidate. In Sec. 3, we explore the allowed region to satisfy all the constraints, and discuss production of our new fields (especially charged bosons) at the LHC. In Sec. 4, we devote the summary of our results and the conclusion.

2. Model setup and constraints

In this section we formulate our model. As for the fermion sector, we introduce three families of vector-like fermions ψ with $(4, -1/2)$ charge under the $SU(2)_L \times U(1)_Y$ gauge symmetry. As for the scalar sector, we respectively add an $SU(2)_L$ quartet (H_4), quintet (H_5), and septet

Table 1
Charge assignments of the our lepton and scalar fields under $SU(2)_L \times U(1)_Y$, where the upper index a is the number of family that runs over 1-3 and all of them are singlet under $SU(3)_C$.

	L_L^a	e_R^a	ψ^a	H_2	H_4	H_5	H_7
$SU(2)_L$	**2**	**1**	**4**	**2**	**4**	**5**	**7**
$U(1)_Y$	$-\frac{1}{2}$	-1	$-\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	0	1

(H_7) complex scalar fields with $(1/2, 0, 1)$ charge under the $U(1)_Y$ gauge symmetry in addition to the SM-like Higgs that is denoted by H_2, where the quintet H_5 is expected to be an inert scalar field. Here we write the nonzero vacuum expectation values (VEVs) of H_2, H_4, and H_7 by $\langle H_2\rangle \equiv v_H/\sqrt{2}$, $\langle H_4\rangle \equiv v_4/\sqrt{2}$ and $\langle H_7\rangle \equiv v_7/\sqrt{2}$, respectively, which induces the spontaneous electroweak symmetry breaking. All the field contents and their assignments are summarized in Table 1, where the quark sector is exactly the same as the SM. The renormalizable Yukawa Lagrangian under these symmetries is given by

$$-\mathcal{L}_\ell = y_{\ell_{aa}} \bar{L}_L^a H_2 e_R^a + f_{ab}[\bar{L}_L^a H_5 (\psi_R)^b] + g_{L_{aa}}[(\bar{\psi}_L^c)^a H_7 \psi_L^a] + g_{R_{aa}}[(\bar{\psi}_R^c)^a H_7 \psi_R^a] \\ + M_{D_{aa}} \bar{\psi}_R^a \psi_L^a + \text{h.c.}, \tag{1}$$

where $SU(2)_L$ index is omitted assuming it is contracted to be gauge invariant inside bracket $[\cdots]$, upper indices $(a, b) = 1$-3 are the number of families, and y_ℓ and either of $g_{L/R}$ or M_D are assumed to be diagonal matrix with real parameters without loss of generality. Here, we assume $g_{L/R}$ and M_D to be diagonal for simplicity. The mass matrix of charged-lepton is defined by $m_\ell = y_\ell v/\sqrt{2}$. Here we assign lepton number 1 to ψ so that the source of lepton number violation is only the terms with coupling g_{ab} and g'_{ab} in the Lagrangian requiring the lepton number is conserved at high scale.

2.1. Scalar sector

Scalar potential and VEVs: The scalar potential in our model is given by

$$\mathcal{V} = -M_2^2 H_2^\dagger H_2 + M_4^2 H_4^\dagger H_4 + M_7^2 H_7^\dagger H_7 + \lambda_H (H_2^\dagger H_2)^2 \\ + \mu_H^2 [H_5^2] + \mu_1 [H_2 \tilde{H}_4 H_5] + \mu_2 [H_4^T \tilde{H}_7 H_4] + \lambda_0 [H_2^T H_2 H_5 H_7^*] \\ + \lambda_1 [H_2 H_4 H_5 \tilde{H}_7] + \lambda_2 [H_2^\dagger H_2 H_4^\dagger H_2] + \text{h.c.} + V_{tri}, \tag{2}$$

where V_{tri} is the trivial quartic terms containing $H_{4,5,7}$. From the conditions of $\partial\mathcal{V}/\partial v_5 = 0$ and $\langle H_5\rangle = 0$, we find the following relation:

$$v_4 = \frac{3\sqrt{10} v_7 v_2 \lambda_0}{\sqrt{30} v_7 \lambda_1 + 15\mu_1}. \tag{3}$$

Then, the stable conditions to the H_4 and H_7 lead to the following equations:

$$v_2 = \frac{3}{8}\left(\frac{\lambda_2}{\lambda_H} v_4 + \sqrt{\frac{\lambda_2^2}{\lambda_H^2} v_4^2 + \frac{64 M_2^2}{9\lambda_H}}\right), \quad v_4 = \frac{5 v_2^3 \lambda_2}{2\sqrt{3}(10 M_4^2 + \sqrt{30}\mu_2)},$$

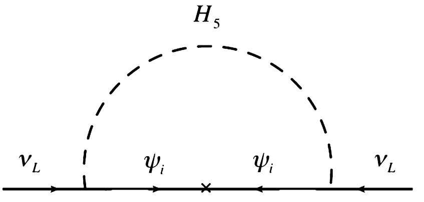

Fig. 1. The diagram inducing active neutrino mass.

$$v_7 = -\sqrt{\frac{3}{10}}\frac{v_4^2\mu_2}{2M_7^2}, \tag{4}$$

where we have ignored contributions from terms in V_{tri} assuming corresponding couplings are negligibly small; we can always find a solution satisfying the inert condition including such terms. Solving Eqs. (3) and (4), one rewrites VEVs and one parameter in terms of the other parameters. In addition to the above conditions, we also need to consider the constraint from ρ parameter, which is given by the following relation at tree level:

$$\rho \approx \frac{v_2^2 + \frac{11}{2}v_4^2 + 22v_7^2}{v_2^2 + v_4^2 + 4v_7^2}, \tag{5}$$

where the experimental values is given by $\rho = 1.0004^{+0.0003}_{-0.0004}$ at 2σ confidential level [20]. Then, we have, e.g., the solutions of $(v_2, v_4, v_7) \approx (246, 2.18, 1.03)$ GeV, where $v_2^2 + v_4^2 + 4v_7^2 \approx$ 246 GeV^2.

2.2. Neutral fermion masses

Heavier neutral sector: After the spontaneously electroweak symmetry breaking, extra neutral fermion mass matrix in basis of $\Psi_R^0 \equiv (\psi_R^0, \psi_L^{0c})^T$ is given by

$$M_N = \begin{bmatrix} \mu_R & M_D^T \\ M_D & \mu_L \end{bmatrix}, \tag{6}$$

where $\mu_R \equiv \sqrt{\frac{3}{10}}g_R v_7$ and $\mu_L \equiv \sqrt{\frac{3}{10}}g_L^* v_7$. Since we can suppose hierarchy of mass parameters to be $\mu_{L/R} << M_D$, the mixing is expected to be maximal. Thus, we formulate the eigenstates in terms of the flavor eigenstate as follows:

$$\psi_R^0 = \frac{i}{\sqrt{2}}\psi_{1_R} - \frac{i}{\sqrt{2}}\psi_{2_L}^c, \quad \psi_L^{0c} = \frac{1}{\sqrt{2}}\psi_{1_R} + \frac{1}{\sqrt{2}}\psi_{2_L}^c, \tag{7}$$

where ψ_{1_R} and $\psi_{2_L}^c$ represent the mass eigenstates, and their masses are respectively given by $M_a \equiv M_D - (\mu_R + \mu_L)/2$ (a=1-3) $M_b \equiv M_D + (\mu_R + \mu_L)/2$ (b=4-6).

Active neutrino sector: In our scenario, active neutrino mass is induced at one-loop level, where $\psi_{1,2}$ and H_5 propagate inside a loop diagram as in Fig. 1, and the masses of real and imaginary part of electrically neutral component of H_5 are respectively denoted by m_R and m_I. As a result the active neutrino mass matrix is obtained such that

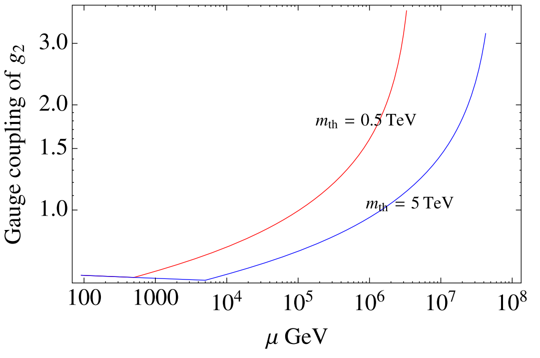

Fig. 2. The running of g_2 in terms of a reference energy of μ, where the red line corresponds to m_{th} =0.5 TeV, while the blue one does m_{th} =5 TeV. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

$$m_\nu = \sum_{\alpha=1}^{6} \frac{f_{i\alpha} M_\alpha f^T_{\alpha j}}{8(4\pi)^2} \left[\frac{r^\alpha_R \ln r^\alpha_R}{1 - r^\alpha_R} - \frac{r^\alpha_I \ln r^\alpha_I}{1 - r^\alpha_I} \right], \tag{8}$$

where $r^\alpha_{R/I} \equiv \frac{m^2_{R/I}}{M^2_\alpha}$. Neutrino mass eigenvalues (D_ν) are given by $D_\nu = U_{\rm MNS} m_\nu U^T_{\rm MNS}$, where $U_{\rm MNS}$ is the MNS matrix. Once we define $m_\nu \equiv f \mathcal{M} f^T$, one can rewrite f in terms of the other parameters [21,22] as follows:

$$f_{ik} = \sum_{\alpha=1}^{6} U^\dagger_{ij} \sqrt{D_{\nu_{jj}}}\, O_{j\alpha} \sqrt{\mathcal{M}_{\alpha\alpha}}\, V^*_{\alpha k}, \tag{9}$$

where O is a three by six arbitrary matrix, satisfying $O O^T = 1$, and $|f| \lesssim \sqrt{4\pi}$ is imposed not to exceed the perturbative limit.

2.3. Analysis of other phenomenological formulas

Beta function of $SU(2)_L$ gauge coupling g_2 : Here we estimate the running of gauge coupling of g_2 in the presence of several new multiplet fields of $SU(2)_L$. The new contribution to g_2 from fermions (with three families) and bosons are respectively given by [13,23]

$$\Delta b^f_{g_2} = \frac{10}{3}, \ \Delta b^b_{g_2} = \frac{43}{3}. \tag{10}$$

Then one finds that the resulting flow of $g_2(\mu)$ is then given by the Fig. 2. This figure shows that the red line is relevant up to the mass scale $\mu = \mathcal{O}(1)$ PeV in case of m_{th} =0.5 TeV, while the blue line is relevant up to the mass scale $\mu = \mathcal{O}(10)$ PeV in case of m_{th} =5 TeV.

Lepton flavor violations (LFVs): LFV decays $\ell_i \to \ell_j \gamma$ arise from the term associated with coupling f at one-loop level, and its form can be given by [24,25]

$$\mathrm{BR}(\ell_i \to \ell_j \gamma) = \frac{48\pi^3 \alpha_{\rm em} C_{ij}}{\mathrm{G}^2_{\rm F} m^2_{\ell_i}} \left(|a_{R_{ij}}|^2 + |a_{L_{ij}}|^2 \right), \tag{11}$$

where

$$a_{R_{ij}} = \sum_{\alpha=1}^{3} \frac{f_{j\alpha} m_{\ell_i} f^\dagger_{\alpha i}}{(4\pi)^2} \Bigg[-\frac{1}{12} G(m_a, M_{\pm_\alpha}) + G(M_\alpha, m_\pm) + G(M_{3+\alpha}, m_\pm) + \frac{1}{4}\left[2G(M_{\pm_\alpha}, m_{\pm\pm}) + G(m_{\pm\pm}, M_{\pm_\alpha})\right] - G(M_{\pm\pm_\alpha}, m_\pm) - 2G(m_\pm, M_{\pm\pm_\alpha}) \Bigg], \tag{12}$$

and

$$G(m_a, m_b) \equiv \int_0^1 dx \int_0^{1-x} dy \frac{xy}{(x^2 - x)m^2_{\ell_i} + x m_a^2 + (1-x) m_b^2}, \tag{13}$$

where $a_L = a_R(m_{\ell_i} \to m_{\ell_j})$.

New contributions to the muon anomalous magnetic moment (muon $g-2$: Δa_μ): We obtain Δa_μ from the same diagrams for LFVs and it can be formulated by the following expression

$$\Delta a_\mu \approx -m_\mu [a_{L_{\mu\mu}} + a_{R_{\mu\mu}}] = -2 m_\mu a_{L_{\mu\mu}}, \tag{14}$$

where $a_{L_{\mu\mu}} = a_{R_{\mu\mu}}$ has been applied. In Eq. (12), one finds that the first term and the last two terms provide positive contributions, while the other terms do the negative contributions. When mediated masses are same value for all the modes; $(m \equiv) m_a = m_\pm = m_{\pm\pm} = M_\pm = M_{\pm\pm} = M_{\pm\pm}$, one simplifies the formula of a_R as

$$a_{R_{ij}} \approx -\frac{1}{3} \sum_{\alpha=1}^{3} \frac{f_{j\alpha} m_{\ell_i} f^\dagger_{\alpha i}}{(4\pi)^2} G(m, m). \tag{15}$$

Thus one would have positive contribution to the muon $g-2$, and we use the allowed range of $\Delta a_\mu = (26.1 \pm 8.0) \times 10^{-10}$ in our numerical analysis below.

Charged scalar contribution to $h \to \gamma\gamma$ decay: Interactions among SM Higgs field and large multiplet scalars affect the branching ratio of $h \to \gamma\gamma$ process via charged scalar loop. Here we write the relevant interactions such that

$$\mathcal{V} \supset \sum_{\Phi = H_4, H_5, H_7} \lambda_{H\Phi} (H_2^\dagger H_2)(\Phi^\dagger \Phi) \supset \sum_{\Phi = H_4, H_5, H_7} \lambda_{H\Phi} v_2 h (\Phi^\dagger \Phi), \tag{16}$$

where $\Phi^\dagger \Phi$ provide sum of charged scalar bilinear terms. Then we obtain decay width of $h \to \gamma\gamma$ at one-loop level as [26]

$$\Gamma_{h\to\gamma\gamma} \simeq \frac{\alpha_{em}^2 m_h^3}{256\pi^3} \left| \frac{4}{3v_2} A_{1/2}(\tau_t) + \frac{1}{v_2} A_1(\tau_W) + \sum_{\Phi} \sum_{\Phi_i} Q^2_{\Phi_i} \frac{\lambda_{H\Phi}}{2m_\Phi^2} A_0(\tau_\Phi) \right|^2, \tag{17}$$

where Φ_i indicates components in the multiplet Φ and Q_{Φ_i} is its electric charge, and $\tau_f = 4m_f^2/m_h^2$. The loop functions are given by

$$A_0(x) = -x^2[x^{-1} - [\sin^{-1}(1/\sqrt{x})]^2], \tag{18}$$

$$A_{1/2}(x) = 2x^2[x^{-1} + (x^{-1} - 1)[\sin^{-1}(1/\sqrt{x})]^2], \tag{19}$$

$$A_1(x) = -x^2[2x^{-2} + 3x^{-1} + 3(2x^{-1} - 1)[\sin^{-1}(1/\sqrt{x})]^2] \tag{20}$$

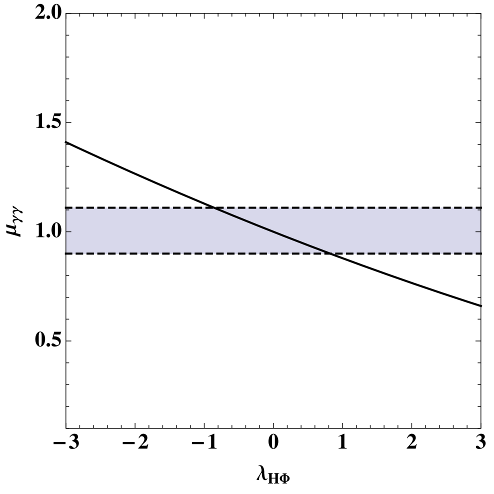

Fig. 3. $\mu_{\gamma\gamma} \equiv BR(h \to \gamma\gamma)_{\text{SM+exotic}}/BR(h \to \gamma\gamma)_{\text{SM}}$ as a function of $\lambda_{H\Phi}$ assuming they are same value for $\Phi = H_4, H_5, H_7$ and masses of corresponding multiplets are $(1, 5, 1)$ TeV. The shaded region is 1σ region from the LHC data [27].

where $x < 1$ is assumed and subscript of $A_{0,1/2,1}(x)$ correspond to spin of particle in loop diagram. We then estimate $\mu_{\gamma\gamma} \equiv BR(h \to \gamma\gamma)_{\text{SM+exotic}}/BR(h \to \gamma\gamma)_{\text{SM}}$ assuming Higgs production cross section is the same as in the SM. In Fig. 3, we show the $\mu_{\gamma\gamma}$ as a function of $\lambda_{H\Phi}$ assuming they are same value for $\Phi = (H_4, H_5, H_7)$ and masses of corresponding multiplets are $(1, 5, 1)$ TeV. The value of $\mu_{\gamma\gamma}$ is constrained by the current LHC data [27,28] and we indicate 1σ region in the plot. We thus find that $|\lambda_{H\Phi}|$ is required to be less than around 1 for TeV scale scalar masses.

<u>*Dark matter candidate*</u>: In our case, the lightest neutral fermion among $\psi_{1,2}$ can be a DM candidate, which comes from $SU(2)_L$ quintet field with $-1/2$ charge under $U(1)_Y$. Here we firstly require that higher-dimensional operator inducing decay of the DM is not induced by the physics above cut-off scale so that decay of DM can only be induced via renormalizable Lagrangian in the model. Assuming the dominant contribution to explain the relic density originates from gauge interactions in the kinetic terms, the typical mass range is $M_{DM} \gtrsim 2.4$ TeV where $M_{DM} = 2.4 \pm 0.06$ TeV is estimated by perturbative calculation [16] and heavier mass is required including non-perturbative Sommerfeld enhancement effect [29]. Then the typical order of spin independent cross section for DM-nucleon scattering via Z-portal is at around 1.6×10^{-45} cm^2 [16] for $M_{DM} \simeq 2.4$ TeV, which marginally satisfies the current experimental data of direct detection searches such as LUX [30], XENON1T [31], and PandaX-II [32]; the direct detection constraint is weaker for heavier DM mass. In the numerical analysis, below, we fix the DM mass to be 2.4 TeV as a reference value for simplicity. One feature of our model is possible instability of DM since we do not impose additional symmetry at TeV scale. We thus have to estimate the decay of DM so that the life time $\tau_{DM} = \Gamma_{DM}^{-1}$ does not exceed the age of universe that is around 4.35×10^{17} second. The main decay channel arises from interactions associated with couplings f and λ_0, when we neglect the effect of mixing among neutral bosons. Then the three body decay ratio of $\Gamma(DM \to \nu_i hh)$ via the neutral component of H_5 is given by

$$\Gamma(DM \to \nu_i hh) \approx \frac{\lambda_0^2 |f_{1i}|^2 M_{DM}^3 v_7^2}{7680 m_R^4 \pi^3} \lesssim \frac{\lambda_0^2 |\text{Max}[f_{1i}]|^2 M_{DM}^3 v_7^2}{7680 m_R^4 \pi^3}, \tag{21}$$

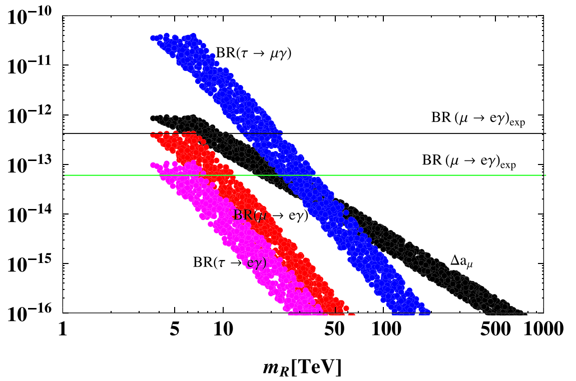

Fig. 4. Various LFV processes and Δa_μ in terms of m_R, where $BR(\mu \to e\gamma)$, $BR(\tau \to e\gamma)$, $BR(\tau \to \mu\gamma)$, and Δa_μ are respectively colored by red, magenta, blue, and black. The black horizontal line shows the current upper limit of the experiment [33,34], while the green one does the future upper limit of the experiment [33,35].

where we assume the final states to be massless, $m_R \approx m_I$, M_{DM} is the mass of DM, and h is the SM Higgs. In the numerical analysis, we will estimate the lifetime and show the allowed region, where we take the maximum value of $|f_{1a}|$.[1]

3. Numerical analysis and phenomenology

Here we carry out numerical analysis to discuss consistency of our model under the constraints discussed in previous section. Then we discuss collider physics focusing on charged scalar bosons in the model.

Numerical analyses: In our numerical analysis, we assume all the mass of $\psi_{1,2}$ to be the mass of DM; 2.4 TeV, and all the component of H_5 except m_I to be degenerate, where $m_I = 1.1 m_R$. These assumptions are reasonable in the aspect of oblique parameters in the multiplet fields [20]. Also we fix to be the following values so as to maximize the muon $g - 2$:

$$O_{12} = 0.895 + 12.3i, \quad O_{23} = 1.88 + 0.52i, \quad O_{13} = 0.4 + 0.6i, \tag{22}$$

where $O_{12,23,13}$ are arbitral mixing matrix with complex values that are introduced in the neutrino sector [10,22]. Notice here that we also impose $|f| \lesssim \sqrt{4\pi}$ not to exceed the perturbative limit.

Fig. 4 represents various LFV processes and Δa_μ in terms of m_R, where $BR(\mu \to e\gamma)$, $BR(\tau \to e\gamma)$, $BR(\tau \to \mu\gamma)$, and Δa_μ are respectively colored by red, magenta, blue, and black. The black horizontal line shows the current upper limit of the experiment [33,34], while the green one does the future upper limit of the experiment [33,35]. Considering these bounds of $\mu \to e\gamma$, one finds that the current allowed mass range of $m_R \sim$ 4–20 TeV can be tested in the near future. Here the upper bounds of $BR(\tau \to e\gamma)$ and $BR(\tau \to \mu\gamma)$ are of the order 10^{-8}, which is safe for all the range. The maximum value of Δa_μ is about 10^{-12}, which is smaller than the experimental value by three order of magnitude.

[1] In case where the neutral component of H_5 is DM candidate, H_5 decays into SM-like Higgs pairs via λ_0, and its decay rate is given by $\frac{\lambda_0^2 v_7^2}{800\pi M_X}$. Then the required lower bound of λ_0 is of the order 10^{-19} so that its lifetime is longer than the age of Universe, where DM is estimated as 5 TeV [16].

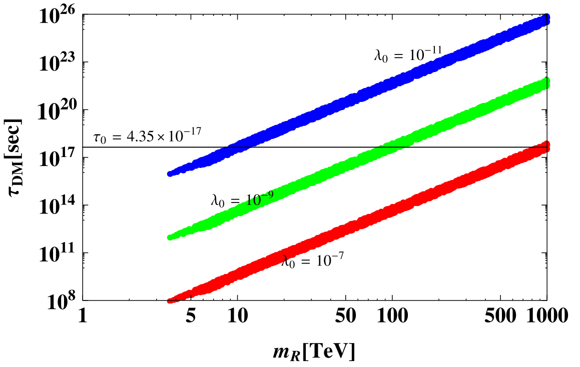

Fig. 5. The lifetime of DM in terms of m_R, where we fix $v_7 \approx 1.03$ GeV, and $\lambda_0 = (10^{-7}, 10^{-9}, 10^{-11})$ with (red, green, blue). The black horizontal line shows the current age of Universe τ_0.

Fig. 5 shows the lifetime of DM in terms of m_R, where we fix $v_7 \approx 1.03$ GeV, and $\lambda_0 = (10^{-7}, 10^{-9}, 10^{-11})$ with (red, green, blue). The black horizontal line shows the current age of Universe. The figure demonstrates as follows:

$$\lambda_0 = 10^{-7}: \ m_R \sim 1000 \text{ TeV}, \quad \lambda_0 = 10^{-9}: \ 100 \text{ TeV} \lesssim m_R,$$
$$\lambda_0 = 10^{-11}: \ 10 \text{ TeV} \lesssim m_R. \tag{23}$$

Collider Physics: Here let us briefly comments possible collider physics of our model. We have many new charged particles from $SU(2)_L$ multiplet scalars and fermions. Clear signal could be obtained from charged scalar bosons in H_7 and H_4, since they can decay into final states containing only SM particles where the components in these multiplets are given by

$$H_7 = (\phi_7^{++++}, \phi_7^{+++}, \phi_7^{++}, \phi_7^{+}, \phi_7^{0}, \phi_7^{\prime -}, \phi^{\prime --})^T, \tag{24}$$
$$H_4 = (\phi_4^{++}, \phi_4^{+}, \phi_4^{0}, \phi_4^{\prime -})^T. \tag{25}$$

The quadruply charged scalar is particularly interesting since it is specific in our model and would provide sizable production cross section. We thus focus on $\phi_7^{\pm\pm\pm\pm}$ signal in our model.[2] The quadruply charged scalar can be pair produced by Drell-Yan(DY) process, $q\bar{q} \to Z/\gamma \to \phi_7^{++++}\phi_7^{----}$, and by photon fusion (PF) process $\gamma\gamma \to \phi_7^{++++}\phi_7^{----}$ [39–41]. We estimate the cross section using MADGRAPH/MADEVENT 5 [42], where the necessary Feynman rules and relevant parameters of the model are implemented by use of FeynRules 2.0 [43] and the NNPDF23LO1 PDF [44] is adopted. In Fig. 6 we show the cross section for the quadruply charged scalar production process $pp \to \phi_7^{++++}\phi_7^{----}$ at the LHC 14 TeV, where dashed line indicates the cross section from only Drell-Yan process and solid line corresponds to the cross section including both Drell-Yan and photon fusion processes. We thus find that the cross section is highly enhanced including PF process due to large electric charge of the scalar boson. Thus sizable number of $\phi_7^{\pm\pm\pm\pm}$ pair can be produced at the LHC 14 TeV if its mass is $\mathcal{O}(1)$ TeV, with sufficiently large integrated luminosity. Produced $\phi_7^{\pm\pm\pm\pm}$ mainly decays into $\phi_4^{\pm\pm}\phi_4^{\pm\pm}$ via $H_4^T \tilde{H}_7 H_4$ interactions in the scalar potential since components in H_7 have degenerate mass. Then $\phi_4^{\pm\pm}$ decays into $W^\pm W^\pm$ via $(D_\mu H_4)^\dagger (D^\mu H_4)$ term. We thus obtain multi W boson signal from

2 Collider phenomenology of charged scalars from quartet is discussed in refs. [13,36–38].

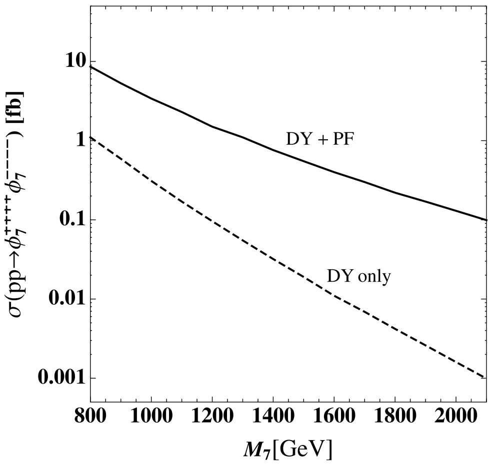

Fig. 6. Cross section for $pp \to \phi_7^{++++}\phi_7^{----}$ at the LHC 14 TeV where dashed line indicate the cross section from only Drell-Yan process and solid line corresponds to the cross section including both Drell-Yan and photon fusion processes.

quadruply charged scalar boson production. Mass reconstruction from multi W boson final state is not trivial and detailed analysis is beyond the scope of this paper.

In addition to the charged scalar bosons, we consider production of exotic charged fermions at the LHC. The quadruplet fermion ψ^a is written by

$$\psi^a = (\psi^0, \psi^-, \psi^{--}, \psi^{---})^a \tag{26}$$

where the subscript indicates electric charge of components. As in the scalar sector, we focus on the component with the highest electric charge that is $\psi^{\pm\pm\pm}$ in the multiplet. Pair production of $\psi^{\pm\pm\pm}$ is estimated by MADGRAPH/MADEVENT 5 as in the charged scalar case where we consider both DY- and PF-processes. The production cross section is shown In Fig. 7 where the dashed and solid lines correspond to values from only DY process and from sum of both processes as in the scalar case. We obtain cross section $\sigma \sim 0.03$ fb for $M_\psi \sim 2.4$ TeV which is motivated by DM relic density. In that case we can obtain $\sim 10(100)$ events for integrated luminosity of 300(3000) fb. Charged fermions in ψ^a decay as $\psi^n \to \psi^{n\pm1} W^{\mp *}$ where n indicates electric charge and W boson is off-shell since the mass differences between components are radiatively induced and its value is around 350 MeV [16]; exotic fermions cannot decay via $\bar{L} H_5 \psi$ coupling since H_5 is heavier than ψ. Thus $\psi^{\pm\pm\pm}$ production gives signature of light mesons with missing transverse momentum through decay chain of $\psi^{\pm\pm\pm} \to W^{\pm *}\psi^{\pm\pm}(\to W^{\pm *}\psi^{\pm}(\to W^{\pm *}\psi^0))$ where ψ^0 is DM. Furthermore we would have displaced vertex signature since decay length of charged fermions is long as $\mathcal{O}(1)$ cm [16] for quadruplet fermion. Therefore analysis of displaced vertex will be important to test our scenario.

4. Summary and discussions

We have proposed an one-loop neutrino mass model, introducing large multiplet fields under $SU(2)_L$. The inert boson is achieved by nontrivial cancellations among quadratic terms. We have also considered the RGE for g_2, the LFVs, muon $g-2$, and fermionic DM candidate, and shown allowed region to satisfy all the constraints as we have discussed above. RGE of g_2 determines

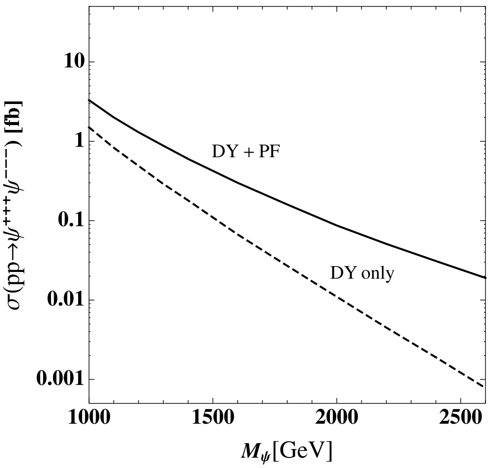

Fig. 7. Cross section for $pp \to \psi^{+++}\psi^{---}$ at the LHC 14 TeV where dashed line indicate the cross section from only Drell-Yan process and solid line corresponds to the cross section including both Drell-Yan and photon fusion processes.

our cut-off energy that does makes our theory stay within the order 10 PeV scale, therefore our model could totally be tested by current or near future experiments. Due to the multiplet fields, we have positive value of muon $g-2$, but find its maximum value to be of the order 10^{-12} that is smaller than the sizable value by three order of magnitude. For the LFVs, the most promising mode to be tested in the current and future experiments is $\mu \to e\gamma$ at the range of 3.2 TeV $\lesssim m_R \lesssim$ 11 TeV. We have also discussed possible decay mode of our DM candidate and some parameters are constrained requiring DM to be stable on cosmological time scale. Notice that the decay of DM is one feature of our model and we would discriminate our model from models with absolutely stable DM by searching for signal of the DM decay. Finally, we have analyzed the collider physics, focussing on multi-charged scalar bosons H_4 and H_7, and triply charged fermion $\psi^{\pm\pm\pm}$ in exotic fermion sector. For scalar sector, we find that sizable production cross section for quadruply charged scalar pair can be obtained adding the photon fusion process that is enhanced by large electric charge of $\phi_7^{\pm\pm\pm\pm}$. Then possible signal of $\phi_7^{\pm\pm\pm\pm}$ comes from decay chain of $\phi_7^{\pm\pm\pm\pm} \to \phi_4^{\pm\pm}\phi_4^{\pm\pm} \to 4W^\pm$ which would provide multi-lepton plus jets at the detector. We expect sizable number of events with sufficiently large integrated luminosity to detect them at the LHC 14 TeV where the detailed analysis of the signal and background is left in future works. For exotic fermion sector, we have also find sizable production cross section for triply charged fermion pair. The triply charged fermion decay gives signature of light mesons with missing transverse momentum through decay chain of $\psi^{\pm\pm\pm} \to W^{\pm *}\psi^{\pm\pm}(\to W^{\pm *}\psi^{\pm}(\to W^{\pm *}\psi^0))$ where ψ^0 is DM. In addition, would have displaced vertex signature since decay length of charged fermions is long as $\mathcal{O}(1)$ cm for components in quadruplet fermion, and thus analysis of displaced vertex will be important to test our scenario.

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