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 nontrivial terms in the Higgs potential. 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 large hadron collider.

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I. 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 frequently be realized by imposing additional symmetry such as $Z_2$ symmetry \cite{1-4} and/or $U(1)$ symmetry \cite{5-7}, which also play an role in stabilizing the DM. On the other hand, once we introduce multiplet fields such as quartet \cite{8, 9}, quintet \cite{10, 11}, septet fields \cite{12-14} under $SU(2)_L$ gauge group, we sometimes can evade imposing additional symmetries \cite{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.

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 \cite{17}. 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 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. II, we review our model and formulate the Higgs sector, neutral fermion sector including active neutrinos. Then we discuss the RGE
II. MODEL SETUP AND CONSTRAINTS

In this section we formulate our model. As for the fermion sector, we introduce three families of vector fermions $\psi$ 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 ($H_7$) 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 as $H_2$, 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 spontaneously electroweak symmetry breaking. All the field contents and their assignments are summarized in Table I where the quark sector is exactly the same as the SM. The renormalizable Yukawa Lagrangian under these symmetries is given by

$$-\mathcal{L}_\ell = y_{\ell a a} \bar{L}_a^\alpha H_2 e_R^\alpha + f_{ab} [\bar{L}_a^\alpha H_5 (\psi^c_R)^b] + g_{L a a} [(\bar{\psi}_L^c)^a H_7 \psi_L^a] + g_{R a a} [(\bar{\psi}_R^c)^a H_7 \psi_R^a] + M_{D a a} \bar{\psi}_R^a \psi_L^a + \text{h.c.},$$

(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 $y_\ell$ 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 $\psi$ so that the source of lepton

| Field | $L_L^a$ | $e_R^a$ | $\psi^a$ | $H_2$ | $H_4$ | $H_5$ | $H_7$ |
|-------|---------|---------|---------|-------|-------|-------|-------|
| $SU(2)_L$ | 2 | 1 | 4 | 2 | 4 | 5 | 7 |
| $U(1)_Y$ | $-1/2$ | -1 | 1/2 | 1/2 | 0 | 1 |

TABLE I: 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 $SU(3)_C$. of the $SU(2)_L$ gauge coupling, LFVs, muon $g-2$, and our DM candidate. In Sec. III, we explore the allowed region to satisfy all the constraints, and discuss production of our new fields (especially charged bosons) at he LHC. In Sec. IV, we devote the summary of our results and the conclusion.
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.

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

$$
\mathcal{V} = -M_2^2 H_2^2 + M_4^2 H_4^2 H_2 + M_7^2 H_7^2 H_7 + \lambda_H (H_2^2 H_2)^2 \\
+ \mu_H^2 (H_5^2) + \mu_1 (H_2 H_4 H_5) + \mu_2 (H_4^2 H_7 H_4) + \lambda_0 (H_2^2 H_2 H_5 H_7^2) \\
+ \lambda_1 (H_2 H_4 H_5 H_7) + \lambda_2 (H_4^2 H_2 H_7^2 H_2) + \text{h.c.} + V_{\text{tri}},
$$

(2)

where $V_{\text{tri}}$ 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:

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

(3)

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

$$
v_2 = \frac{3}{8} \left( \frac{\lambda_2}{\lambda_H} v_4 + \sqrt{\frac{\lambda_2^2 v_4^2}{\lambda_H^2} + \frac{64 M_2^2}{9 \lambda_H}} \right), \quad v_4 = \frac{5 v_2^2 \lambda_2}{2 \sqrt{3} (10 M_4^2 + \sqrt{30} \mu_2)}, \quad v_7 = -\sqrt{\frac{3}{10}} \frac{v_2^2 \mu_2}{2 M_7^2},
$$

(4)

where we have ignored contributions from terms in $V_{\text{tri}}$ 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 $\rho$ parameter, which is given by the following relation at tree level:

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

(5)

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

### A. Neutral fermion masses

**Heavier neutral sector:** After the spontaneously electroweak symmetry breaking, extra neutral fermion mass matrix in basis of $\Psi^0_R \equiv (\psi^0_R, \psi^0_L)^T$ is given by

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

(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 to be $\mu_{L/R} \ll M_D$, the mixing is expected to be maximal. Thus, we formulate the eigenstates in terms of the flavor eigenstate as follows:

$$\psi^0_R = \frac{i}{\sqrt{2}} \psi^c_2 - \frac{i}{\sqrt{2}} \psi^e_2, \quad \psi^0_L = \frac{1}{\sqrt{2}} \psi^c_1 + \frac{1}{\sqrt{2}} \psi^e_1,$$

where $\psi^c_2$ and $\psi^e_2$ represent the mass eigenstates, and their masses are respectively given by $M_a \equiv M_D - (\mu_R + \mu_L)/2 \quad (a=1-3)$ and $M_b \equiv M_D + (\mu_R + \mu_L)/2 \quad (b=4-6)$.

**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 part 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

$$m_\nu = \sum_{\alpha=1}^6 f_i M_{\alpha ij}^T \frac{C_{T\alpha}}{8(4\pi)^2} \left[ r_\alpha^R \ln r_\alpha^R - r_\alpha^I \ln r_\alpha^I \right],$$

where $r_\alpha^R/I \equiv \frac{m_\nu^2}{M_{\alpha ij}}$. Neutrino mass eigenvalues ($D_\nu$) are given by $D_\nu = U_{MNS} m_\nu U_{MNS}^T$, where $U_{MNS}$ is the MNS matrix. Once we define $m_\nu \equiv f M f^T$, one can rewrite $f$ in terms of the other parameters [19, 20] as follows:

$$f_{ik} = \sum_{\alpha=1}^6 U_{ij}^T D_{\alpha j} O_{\alpha k} \sqrt{M_{\alpha ij}} V_{\alpha k},$$

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

**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, 21]

$$\Delta b_{g_2}^f = \frac{10}{3}, \quad \Delta b_{g_2}^b = \frac{43}{3}.$$ (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 $\mu = O(1)$ PeV in case of $m_{th} = 0.5$ TeV, while the blue is relevant up to the mass scale $\mu = O(10)$ PeV in case of $m_{th} = 5$ TeV.

**Lepton flavor violations (LFVs)**: LFV decays $\ell_i \to \ell_j \gamma$ arise from the term $f$ at one-loop level, and its form can be given by [22, 23]

$$\text{BR}(\ell_i \to \ell_j \gamma) = \frac{48\pi^3 a_{em} C_{ij}}{G_F^2 m_{\ell_i}^2} \left( |a_{R ij}|^2 + |a_{L ij}|^2 \right),$$ (11)
FIG. 1: The diagram inducing active neutrino mass.

\[ H_5 \]

\[ \nu_L \quad \psi_i \quad \psi_i \quad \nu_L \]

FIG. 2: The running of \( g_2 \) in terms of a reference energy of \( \mu \), where the red line corresponds to \( m_{th} = 0.5 \text{ TeV} \), while the blue one does \( m_{th} = 5 \text{ TeV} \).

where

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

and

\[
G(m_\alpha, m_b) \equiv \int_0^1 dx \int_0^{1-x} dy \frac{xy}{(x^2-x)m_{\ell_i}^2 + x m_\alpha^2 + (1-x)m_b^2}, \tag{13}
\]
where \( a_L = a_R(m_{\ell_i} \to m_{\ell_j}) \).

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

\[
\Delta a_\mu \approx -m_\mu [a_{L\mu\mu} + a_{R\mu\mu}] = -2m_\mu a_{L\mu\mu},
\]

(14)

where \( a_{L\mu\mu} = a_{R\mu\mu} \) has been applied and we use the allowed range of \( \Delta a_\mu = (26.1 \pm 8.0) \times 10^{-10} \) in our numerical analysis below.

*Dark matter candidate*: In our case, the lightest neutral fermions 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 \[24\]. Then the typical order of spin independent cross section for DM-nucleon scattering via Z-portal is at around \( 1.6 \times 10^{-45} \) cm\(^2\) \[16\] for \( M_{DM} \approx 2.4 \) TeV, which marginally satisfies the current experimental data of direct detection searches such as LUX \[25\], XENON1T \[26\], and PandaX-II \[27\]; 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 \( 4.35 \times 10^{17} \) second. The main decay channel arises from \( f \) and \( \lambda_0 \), 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

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

(15)

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 $|f_{1a}|$.  

III. 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 $m_I = 1.1m_R$. These assumptions are reasonable in the aspect of oblique parameters in the multiplet fields [18]. Also we fix to be the following values so as to maximize the muon $g-2$:

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

where $O_{12,23,13}$ are arbitral mixing matrix with complex values that are introduced in the neutrino sector [10, 20]. Notice here that we also impose $|f| \lesssim \sqrt{4\pi}$ not to exceed the perturbative limit.

Fig. 3 represents various LFV processes and $\Delta a_\mu$ in terms of $m_R$, where $BR(\mu \to e\gamma)$, $BR(\tau \to e\gamma)$, $BR(\tau \to \mu\gamma)$, and $\Delta a_\mu$ are respectively colored by red, magenta, blue, and black. The black horizontal line shows the current upper limit of the experiment [28, 29], while the green one does the future upper limit of the experiment [28, 30]. Considering these bounds of $\mu \to e\gamma$, one finds that the current allowed mass range of $m_R \sim 4\text{-}20$ 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 $\Delta a_\mu$ is about $10^{-12}$, which is smaller than the experimental value by three order of magnitude.

Fig. 4 shows the lifetime of DM in terms of $m_R$, where we fix $\nu_7 \approx 1.03$ 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:

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

(17)

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1 In case where the neutral component of $H_5$ is DM candidate, $H_5$ decays into SM-like Higgs pairs via $\lambda_0$, and its decay rate is given by $\frac{\lambda_0^2 v^2}{800\pi M_{H^\pm}}$. Then the required lower bound of $\lambda_0$ is of the order $10^{-19}$ so that its lifetime is longer than the age of Universe, where DM is estimated as 5 TeV [10].
FIG. 3: Various LFV processes and $\Delta a_\mu$ in terms of $m_R$, where $BR(\mu \rightarrow e\gamma)$, $BR(\tau \rightarrow e\gamma)$, $BR(\tau \rightarrow \mu\gamma)$, and $\Delta a_\mu$ are respectively colored by red, magenta, blue, and black. The black horizontal line shows the current upper limit of the experiment [28, 29], while the green one does the future upper limit of the experiment [28, 30].

Collider Physics: Here let us briefly comment 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

$$H_7 = (\phi_7^{++}, \phi_7^{++}, \phi_7^{++}, \phi_7^0, \phi_7^{-}, \phi_7^{-})^T,$$

$$H_4 = (\phi_4^{++}, \phi_4^{+}, \phi_4^0, \phi_4^-)^T.$$  

(18)  

(19)

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 $\phi_7^{++}$ signal in our model. The quadruply charged scalar can be pair produced by Drell-Yang(DY) process, $q\bar{q} \rightarrow Z/\gamma \rightarrow \phi_7^{++}\phi_7^{-}$, and by photon fusion(PF) process $\gamma\gamma \rightarrow \phi_7^{++}\phi_7^{-}$ [34–36]. We estimate the cross section using MADGRAPH/MADEVENT 5 [37], where the necessary Feynman rules and relevant parameters of the model are implemented by use of FeynRules 2.0 [38] and the NNPDF23LO1 PDF [39] is adopted. In Fig. 5 we show the cross section for the quadruply charged scalar production process $pp \rightarrow \phi_7^{++}\phi_7^{-}$ at the LHC 14 TeV, where dashed

2 Collider phenomenology of charged scalars from quartet is discussed in refs. [13, 31–33].
FIG. 4: 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 $\tau_0$.

The solid line indicates the cross section from only Drell-Yang process and solid line corresponds to the cross section including both Drell-Yang 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 $O(1)$ 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 $H_4^T\tilde{H}_7H_4$ 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 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.

IV. 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 our cut-off energy that does makes our theory stay within the
FIG. 5: Cross section for $pp \rightarrow \phi_7^{+++} \phi_7^{-+}$ at the LHC 14 TeV where dashed line indicate the cross section from only Drell-Yang process and solid line corresponds to the cross section including both Drell-Yang and photon fusion processes.

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 $\mu \rightarrow e\gamma$ at the range of $3.2 \text{ TeV} \lesssim m_R \lesssim 11 \text{ TeV}$. 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 $H_7$. 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 $\phi_7^{+++-}$. Then possible signal of $\phi_7^{+++-}$ comes from decay chain of $\phi_7^{+++-} \rightarrow \phi_4^{\pm} \phi_4^{\pm} \rightarrow 4W^\pm$ 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.

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[1] E. Ma, Phys. Rev. D 73, 077301 (2006) [hep-ph/0601225].
[2] L. M. Krauss, S. Nasri and M. Trodden, Phys. Rev. D 67, 085002 (2003) [arXiv:hep-ph/0210389].
[3] M. Aoki, S. Kanemura and O. Seto, Phys. Rev. Lett. 102, 051805 (2009) [arXiv:0807.0361].
[4] M. Gustafsson, J. M. No and M. A. Rivera, Phys. Rev. Lett. 110, no. 21, 211802 (2013) Erratum: [Phys. Rev. Lett. 112, no. 25, 259902 (2014)] [arXiv:1212.4806 [hep-ph]].
[5] H. Okada and T. Toma, Phys. Rev. D 86, 033011 (2012) [arXiv:1207.0864 [hep-ph]].
[6] Y. Kajiyama, H. Okada and K. Yagyu, Nucl. Phys. B 874, 198 (2013) [arXiv:1303.3463 [hep-ph]].
[7] Y. Kajiyama, H. Okada and T. Toma, Phys. Rev. D 88, no. 1, 015029 (2013) [arXiv:1303.7356 [hep-ph]].
[8] T. Nomura and H. Okada, arXiv:1809.06039 [hep-ph].
[9] T. Nomura and H. Okada, arXiv:1806.07182 [hep-ph].
[10] T. Nomura and H. Okada, arXiv:1808.05476 [hep-ph].
[11] T. Nomura and H. Okada, Phys. Lett. B 783, 381 (2018) [arXiv:1805.03942 [hep-ph]].
[12] T. Nomura and H. Okada, arXiv:1807.04555 [hep-ph].
[13] T. Nomura and H. Okada, Phys. Rev. D 96, no. 9, 095017 (2017) [arXiv:1708.03204 [hep-ph]].
[14] T. Nomura, H. Okada and Y. Orikasa, Phys. Rev. D 94, no. 5, 055012 (2016) [arXiv:1605.02601 [hep-ph]].
[15] G. Anamiati, O. Castillo-Felisola, R. M. Fonseca, J. C. Helo and M. Hirsch, arXiv:1806.07264 [hep-ph].
[16] M. Cirelli, N. Fornengo and A. Strumia, Nucl. Phys. B 753, 178 (2006) [hep-ph/0512090].
[17] H. Okada, N. Okada and Y. Orikasa, Phys. Rev. D 93, no. 7, 073006 (2016) [arXiv:1504.01204 [hep-ph]].
[18] C. Patrignani et al. [Particle Data Group], Chin. Phys. C 40, no. 10, 100001 (2016).
[19] J. A. Casas and A. Ibarra, Nucl. Phys. B 618, 171 (2001) [hep-ph/0103065].
[20] C. W. Chiang, H. Okada and E. Senaha, Phys. Rev. D 96, no. 1, 015002 (2017) [arXiv:1703.09153 [hep-ph]].
[21] S. Kanemura, K. Nishiwaki, H. Okada, Y. Orikasa, S. C. Park and R. Watanabe, PTEP 2016, no. 12, 123B04 (2016) [arXiv:1512.09048 [hep-ph]].
[22] M. Lindner, M. Platscher and F. S. Queiroz, Phys. Rept. 731, 1 (2018) [arXiv:1610.06587 [hep-ph]].
[23] S. Baek, T. Nomura and H. Okada, Phys. Lett. B 759, 91 (2016) [arXiv:1604.03738 [hep-ph]].
[24] M. Cirelli, A. Strumia and M. Tamburini, Nucl. Phys. B 787, 152 (2007) [arXiv:0706.4071 [hep-ph]].
[25] D. S. Akerib et al. [LUX Collaboration], Phys. Rev. Lett. 118, no. 2, 021303 (2017) [arXiv:1608.07648 [astro-ph.CO]].
[26] E. Aprile et al. [XENON Collaboration], Phys. Rev. Lett. 119, no. 18, 181301 (2017) [arXiv:1705.06655 [astro-ph.CO]].
[27] X. Cui et al. [PandaX-II Collaboration], Phys. Rev. Lett. 119, no. 18, 181302 (2017) [arXiv:1708.06917 [astro-ph.CO]].
[28] Y. Cai, J. Herrero-Garcia, M. A. Schmidt, A. Vicente and R. R. Volkas, Front. in Phys. 5, 63 (2017) [arXiv:1706.08524 [hep-ph]].
[29] A. M. Baldini et al. [MEG Collaboration], Eur. Phys. J. C 76, no. 8, 434 (2016) [arXiv:1605.05081 [hep-ex]].
[30] A. M. Baldini et al., arXiv:1301.7225 [physics.ins-det].
[31] F. del Águila, M. Chala, A. Santamaria and J. Wudka, Phys. Lett. B 725, 310 (2013) [arXiv:1305.3904 [hep-ph]].
[32] F. del Águila and M. Chala, JHEP 1403, 027 (2014) arXiv:1311.1510 [hep-ph].
[33] M. Chala, C. Krause and G. Nardini, arXiv:1802.02168 [hep-ph].
[34] K. S. Babu and S. Jana, Phys. Rev. D 95, no. 5, 055020 (2017) [arXiv:1612.09224 [hep-ph]].

[35] K. Ghosh, S. Jana and S. Nandi, JHEP 1803, 180 (2018) [arXiv:1705.01121 [hep-ph]].

[36] T. Ghosh, S. Jana and S. Nandi, Phys. Rev. D 97, no. 11, 115037 (2018) [arXiv:1802.09251 [hep-ph]].

[37] J. Alwall et al., JHEP 1407, 079 (2014) [arXiv:1405.0301 [hep-ph]].

[38] A. Alloul, N. D. Christensen, C. Degrande, C. Duhr and B. Fuks, Comput. Phys. Commun. 185, 2250 (2014) [arXiv:1310.1921 [hep-ph]].

[39] C. S. Deans [NNPDF Collaboration], arXiv:1304.2781 [hep-ph].