

Four-loop Neutrino Model

Inspired by Diphoton Excess at 750 GeV

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Abstract

We propose a four-loop induced radiative neutrino mass model inspired by the diphoton excess at 750 GeV recently reported by ATLAS and CMS, in which a sizable diphoton excess is obtained via photon fusion introducing multi doubly-charged scalar bosons. Also we discuss the muon anomalous magnetic moment, and a dark matter candidate. The main process to explain the observed relic density relies on the final state of the new particle at 750 GeV. Finally we show the numerical results and obtain allowed region of several physical values in our model.

Keywords:

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I. INTRODUCTION

According to the recent announcements by ATLAS and CMS experiments, a new particle could exist at around 750 GeV by the observation of the diphoton invariant mass spectrum from the run-II data in 13 TeV [1, 2]. Subsequently a vast of paper along this line of issue has been arisen in Ref. [3–134]. One of these interpretations is to identify a scalar (or pseudoscalar) as the new particle (S), and the resonance occurs in the process; $pp \rightarrow S + X \rightarrow 2\gamma + X$, where X is the missing particle. This can be interpreted as the following 13 TeV data in terms of the production cross section of S and its branching ratio of two photons,

$$\mu_{\text{ATLAS}} = \sigma(2p \rightarrow S + X) \times BR(S \rightarrow 2\gamma) = (6.2^{+2.4}_{-2.0}) \text{ fb}, \quad (\text{I.1})$$

$$\mu_{\text{CMS}} = \sigma(2p \rightarrow S + X) \times BR(S \rightarrow 2\gamma) = (5.6 \pm 2.4) \text{ fb}, \quad (\text{I.2})$$

which is extremely large compared to the previous observations from the run-I data at 8 TeV [135, 136]. Also the ATLAS experiment group [1] reported $\Gamma_S = 45$ GeV that is the best fit value of the decay width of S to the two photons, and $\Gamma_S = 5.3$ GeV is given as the experimental resolution obtained by the analysis [14]. To achieve such a large signal strength, we have to enlarge the production cross section and (or) its branching ratio. One of the simplest ways to enhance the production cross section is to introduce a vector like exotic quark that couples to S , where such a quark induces the gluon fusion production of S that can be always dominant process [11]. On the other hand, one of the simplest ways to increase the branching ratio to photons is that S should couples to the isospin singlet bosons or fermions with nonzero electric charges, because main modes such as a pair of W^\pm bosons can be forbidden. However once one can reach the enough branching ratio to the two photons, (which is around ≈ 60 %), the dominant production cross section can also be arisen from the photon fusion process, which is proposed by, *i.e.*, Ref. [37]. This scenario is in favor of leptonic models, especially, radiative seesaw models, when such charged particles also interact with lepton sector. In this framework recent paper [126] has concluded that *the $\mathcal{O}(10^3 - 10^4)$ number of electrically charged bosons that propagate between S and two photons have to be introduced* as can be seen in Fig. 1,¹ in order to satisfy the condition of unitarity

¹ The diphoton excess is analyzed by rather general way, introducing arbitral number of doubly charged bosons with isospin singlet in this paper, although they fix a specific model in the neutrino sector. Hence

bound via processes such as $k^{\pm\pm}S \rightarrow k^{\pm\pm} \rightarrow k^{\pm\pm}S$ and $2k^{\pm\pm} \rightarrow S \rightarrow 2k^{\pm\pm}$. Therefore, the trilinear term μ_S proportional to $Sk^{\pm\pm}k^{\mp\mp}$ should be nearly equal or less than $m_S \approx 750$ GeV. The relevant potential per $k^{\pm\pm}$ to generate the diphoton anomaly is simply given by

$$\mathcal{V} = \mu_S S k^{++} k^{--} + m_k k^{++} k^{--} + \text{c.c.} \quad (\text{I.3})$$

Then the total cross section with $m_S = 750$ GeV at 13 TeV is given by [37]

$$\sigma_{\gamma\gamma}(\equiv \sigma(2p \rightarrow 2\gamma + X)) = \left(\frac{\Gamma_S}{45 \text{ GeV}} \right) \times BR^2(S \rightarrow 2\gamma) \times (73 - 162) \text{ fb.} \quad (\text{I.4})$$

In our case the cross section simplifies the following values due to $BR(S \rightarrow 2\gamma) \approx 60\%$,

$$(3.0 \text{ fb} \lesssim \sigma_{\gamma\gamma}(\Gamma_S = 5.3 \text{ GeV}) \lesssim 6.7 \text{ fb}) - (25.5 \text{ fb} \lesssim \sigma_{\gamma\gamma}(\Gamma_S = 45 \text{ GeV}) \lesssim 56.6 \text{ fb}), \quad (\text{I.5})$$

that satisfies the data in Eq. (I.2). Here we use the value $5.3 \text{ GeV} \lesssim \Gamma_S \lesssim 45 \text{ GeV}$ coming from the best fit value of ATLAS and the experimental resolution, and we find allowed regions in terms of $m_{k^{\pm\pm}}$ and μ_S to satisfy the decay width depending on the number of charged bosons N_{CB} as can be seen in Fig. 1.

This result could drastically changes the situation of any radiative seesaw models that include electrically charged bosons such as Zee-Babu model [137], which is the first proposal including the doubly charged boson, because the scale of neutrino masses must be enhanced by N_{CB} . To show this issue more clearly, let us consider the Zee-Babu model. The model has the following relevant terms per $k^{\pm\pm}$:

$$-\mathcal{L} \supset y_\ell \ell_L \Phi e_R + y_\ell \ell_L \Phi e_R + \bar{\ell}_L^c \ell_L h^+ + g \bar{e}_R^c e_R k^{++} + \mu h^+ h^+ k^{--} + \text{c.c.} \quad (\text{I.6})$$

Then the resulting neutrino mass has to be multiplied by N_{CB} , and can be estimated as

$$m_\nu \approx \frac{16 N_{CB}}{(4\pi)^4} \mu g^* (f m_\ell)^2 \times (\text{loop factor}) \lesssim \frac{\mathcal{O}(10^3 - 10^4)}{16\pi^4} \mu g^* f^2 \approx \mathcal{O}(1 - 10) \mu g^* f^2, \quad (\text{I.7})$$

where we have used $m_\ell = m_\tau \approx \mathcal{O}(1)$ GeV, and loop factor is order 1. It suggests that the neutrino mass scale is determined by the trilinear coupling μ and the Yukawa couplings, and N_{CB} that almost compensates the two loop suppression effect. Therefore the two loop neutrino mass scale is equivalent to the tree level scale. Applying this fact, we will discuss our radiative neutrino model at the four loop level in the next section, which could be equivalent to a typical two loop radiative model. Then we will conclude and discuss in Sec. III.

one can apply some results to any kind of leptonic models that include charged bosons with isospin singlet even when singly charged bosons.

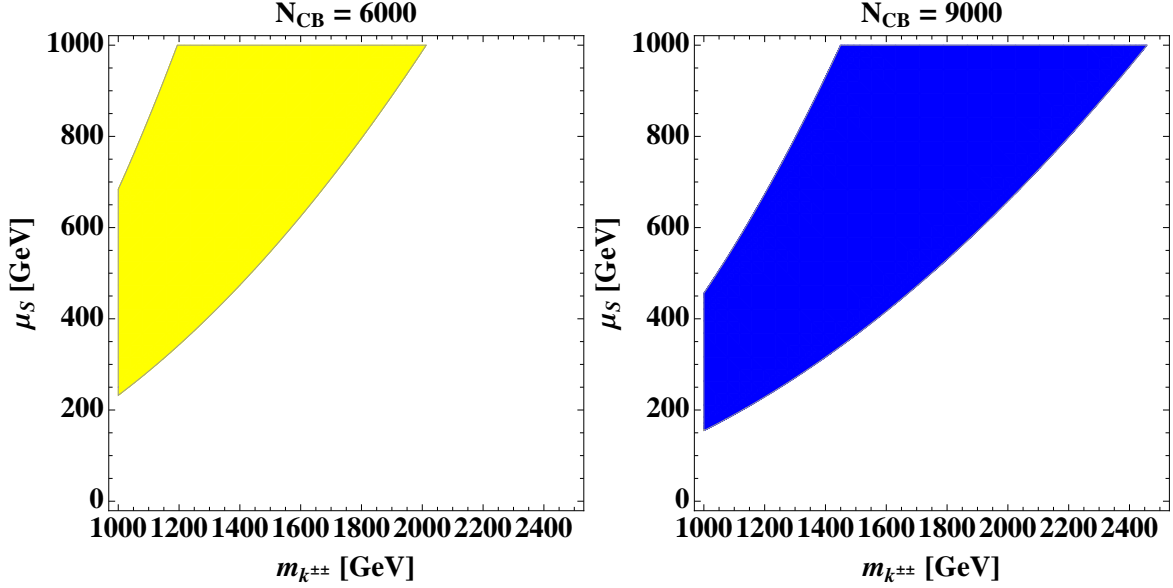


FIG. 1: The figures represent the allowed region between the mass of $k^{\pm\pm}$ and the trilinear term of μ_S to satisfy $5.3 \text{ GeV} \lesssim \Gamma_S \lesssim 45 \text{ GeV}$ coming from the experimental resolution and the best fit value of ATLAS respectively, where each of colored region (yellow for $N_{CB} = 6000$ and blue for $N_{CB} = 9000$) is allowed only and the upper line corresponds to $\Gamma_S = 45 \text{ GeV}$ and the lower line corresponds to $\Gamma_S = 5.3 \text{ GeV}$.

	Lepton Fields				Scalar Fields			
	L_L	e_R	E	N_R	Φ	S	h^+	k^{++}
$SU(2)_L$	2	1	1	1	2	1	1	1
$U(1)_Y$	-1	-1	-2	0	0	0	1	2
$U(1)$	ℓ	ℓ	3ℓ	$\frac{\ell}{3}$	0	$\frac{2\ell}{3}$	-2ℓ	$-\frac{10\ell}{3}$

TABLE I: Contents of fermion and scalar fields and their charge assignments under $SU(2)_L \times U(1)_Y \times U(1)$.

II. MODEL SETUP AND ANALYSIS

In this section, we explain our model with global $U(1)$ symmetry. The particle contents and their charges are shown in Tab. I. We add a vector-like exotic doubly charged fermion E , a Majorana fermion N_R , a singly charged scalar h^\pm , the N_{CB} number of doubly charged

scalars $k^{\pm\pm}$, and a neutral scalar S to the SM, where all these new fields are iso-spin singlet, and S is identified as a new scalar with 750 GeV mass. We assume that only the SM Higgs Φ and S have vacuum expectation values (VEVs), which are respectively symbolized by $v/\sqrt{2}$ and $v_S/\sqrt{2}$. The quantum number $\ell \neq 0$ of $U(1)$ symmetry is arbitrary, but its assignment for each field is unique to realize our four loop neutrino model.

The relevant Lagrangian and Higgs potential under these symmetries per $k^{\pm\pm}$ are given by

$$-\mathcal{L}_Y \supset y_\ell \bar{L}_L \Phi e_R + f \bar{L}_L^c i\tau_2 L_L h^+ + g \bar{E}_L e_R h^- + h \bar{N}_R E_R^c k^{--} + \frac{y_N}{2} S^* \bar{N}_R^c N_R + M_E \bar{E}_L E_R - \lambda_{hk} S^* h^- h^- k^{++} - \lambda_{Sk} |S|^2 k^{++} k^{--} + \text{h.c.}, \quad (\text{II.1})$$

where τ_2 is a second component of the Pauli matrix. After the global $U(1)$ spontaneous breaking of S , we obtain trilinear terms as well as the Majorana masses as follows:

$$-\mathcal{L}_Y \supset \frac{M_N}{2} \bar{N}_R^c N_R - \mu h^- h^- k^{++} - \mu_S S k^{++} k^{--} + \text{h.c.}, \quad (\text{II.2})$$

where $M_N \equiv y_N v_S/\sqrt{2}$, $\mu \equiv \lambda_{hk} v_S/\sqrt{2}$, and $\mu_S \equiv \lambda_{Sk} v_S/\sqrt{2}$. The first term of \mathcal{L}_Y generates the SM charged-lepton masses $m_\ell \equiv y_\ell v/\sqrt{2}$ after the electroweak spontaneous breaking of Φ . We work on the basis where all the coefficients are real and positive for simplicity. The isospin doublet scalar field can be parameterized as $\Phi = [w^+, \frac{v+\phi+iz}{\sqrt{2}}]^T$ where $v \simeq 246$ GeV is VEV of the Higgs doublet, and w^\pm and z are respectively absorbed by the longitudinal component of W and Z boson. The isospin singlet scalar field can be parameterized as $S = \frac{v_S+s}{\sqrt{2}} e^{iG/v_S}$. Here we assume ϕ is the SM Higgs, therefore we neglect the mixing between ϕ and s for simplicity. We also assume that the lightest Majorana fermion $N_R|_{\text{lightest}} = X$ does not couple to E_R and $k^{\pm\pm}$ in the fourth term of \mathcal{L}_Y and does not mix with other N_R so that it can be stable and a DM candidate. Such a situation for DM can easily be realized by imposing additional Z_2 odd assignment.

Neutrino mass matrix:

Then the leading contribution to the active neutrino masses m_ν is given at four-loop level as shown in Figure 2, and we can respectively estimate the order of masses as follows:

$$m_\nu = m_\nu^I + m_\nu^{II} + m_\nu^{III} + m_\nu^{IV}, \quad (\text{II.3})$$

$$m_\nu^I \approx \frac{[N_{CB} \mu m_\ell M_E f g^* h]^2}{(4\pi)^8 M_{\text{max}}^4 M_N} G_I(x_\ell, x_E, x_h, x_k), \quad (\text{II.4})$$

$$m_\nu^i \approx \frac{N_{CB}^2 M_R [\mu m_\ell M_E f g^* h]^2}{(4\pi)^8 M_{\text{max}}^6} G_i(x_\ell, x_E, x_h, x_k, x_N), \quad (i = II - IV), \quad (\text{II.5})$$

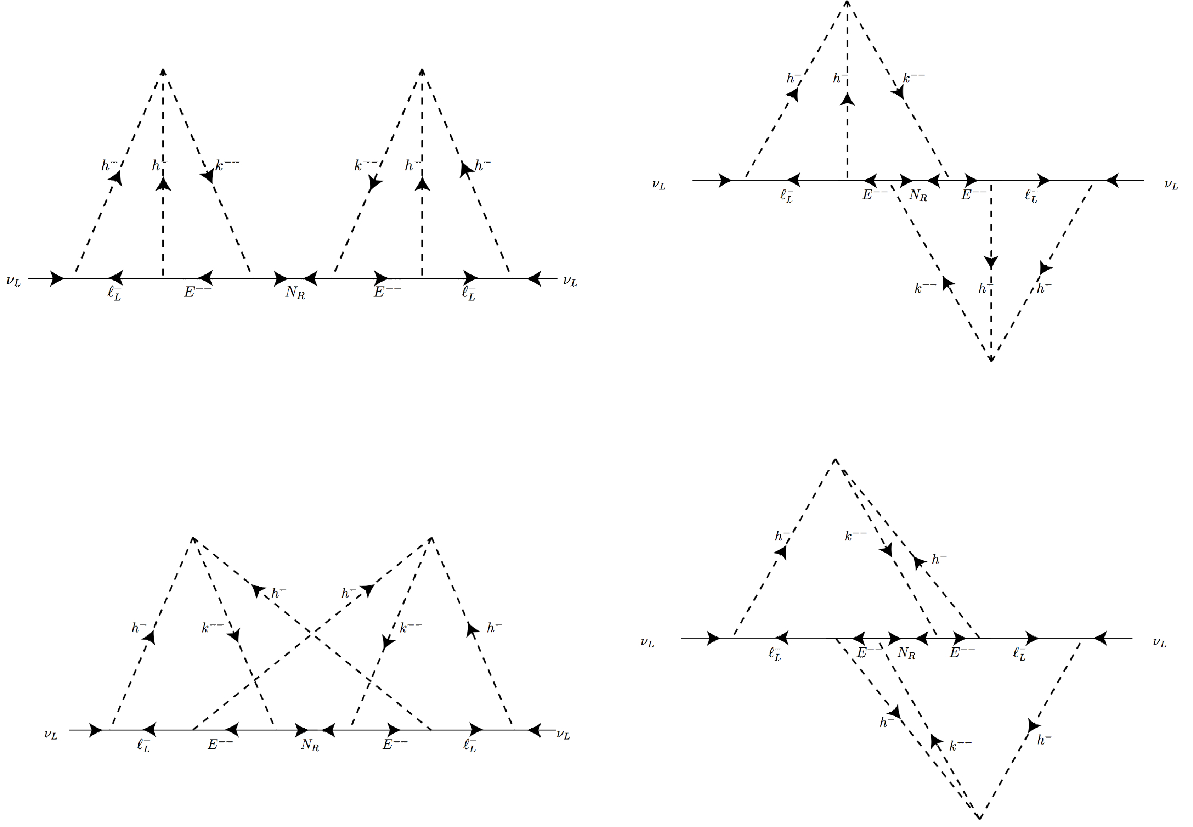


FIG. 2: Neutrino masses at the one-loop level.

where the left-top side of figure corresponds to m_ν^I , the right-top side of figure corresponds to m_ν^{II} , the left-bottom side of figure corresponds to m_ν^{III} , the right-bottom side of figure corresponds to m_ν^{IV} , and we define $x_i \equiv (m_i/M_{\max})^2$ and $M_{\max} = \text{Max}[M_E, m_h, m_k, M_N]$. G_I consists of two pairs of the Zee-Babu like two-loop function. Obviously m_ν^I can be greater than m_ν^{II-IV} under the condition $G_I \approx G_i$, since the ratio is given by

$$\frac{m_\nu^I}{m_\nu^{II-IV}} \approx \left(\frac{M_{\max}}{M_N} \right)^2 \gg 1. \quad (\text{II.6})$$

Hence we can approximate the neutrino masses as

$$m_\nu = m_\nu^I \approx \frac{[N_{CB} \mu m_\ell M_E f g^* h]^2}{(4\pi)^8 M_{\max}^4 M_N}, \quad (\text{II.7})$$

where we take $G_I = \mathcal{O}(1)$, and m_ν should be $0.001 \text{ eV} \lesssim m_\nu \lesssim 0.1 \text{ eV}$ from the neutrino oscillation data [138].

Muon anomalous magnetic moment:

The muon anomalous magnetic moment (muon $g - 2$) has been measured at Brookhaven National Laboratory that suggests there is a discrepancy between the experimental data and the prediction in the SM. The difference $\Delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM}}$ is respectively calculated in Ref. [139] and Ref. [140] as

$$\Delta a_\mu = (29.0 \pm 9.0) \times 10^{-10}, \quad \Delta a_\mu = (33.5 \pm 8.2) \times 10^{-10}. \quad (\text{II.8})$$

The above results given in Eq. (II.8) correspond to 3.2σ and 4.1σ deviations, respectively. Our formula of muon $g - 2$ is given by

$$\Delta a_\mu \approx \frac{N_{CB} m_\mu^2}{(4\pi)^2} \left[(g^* g)_{22} F(E, h) - \frac{(f^* f)_{22}}{m_{h^\pm}^2} \right], \quad (\text{II.9})$$

$$F(E, h) \approx \frac{4M_E^6 - 9M_E^4 m_{h^\pm}^2 + 5m_{h^\pm}^6 + 6M_E^2 (M_E^2 - 2m_{h^\pm}^2) m_{h^\pm}^2 \ln \left[\frac{m_{h^\pm}^2}{M_E^2} \right]}{12(M_E^2 - m_{h^\pm}^2)^4}. \quad (\text{II.10})$$

Dark matter:

Assuming the lightest Majorana particle of N_R as our DM candidate, which is denoted by X , we find the dominant mode to explain the observed relic density $\Omega h^2 \approx 0.12$ [141]. Our dominant non-relativistic cross section comes from $2X \rightarrow 2s$ with t - and u -channels ², and its formula is given by

$$\sigma v_{\text{rel}} \approx \frac{M_X^6}{3\pi v_S^4} \sqrt{1 - \frac{m_S^2}{M_X^2}} (41M_X^4 - 38M_X^2 m_S^2 + 9m_S^4) v_{\text{rel}}^2 \equiv b v_{\text{rel}}^2. \quad (\text{II.11})$$

Then the relic density is formulated by

$$\Omega h^2 \approx \frac{1.07 \times 10^9}{6\sqrt{g_*} M_P \int_{x_f}^{\infty} \frac{b}{x^3}}, \quad (\text{II.12})$$

where $M_P \approx 1.22 \times 10^{19}$ GeV is the Planck mass, $g_* \approx 100$ is the total number of effective relativistic degrees of freedom at the time of freeze-out, and $x_F \approx 25$. In our numerical analysis below, we set the allowed region to be

$$0.11 \lesssim \Omega h^2 \lesssim 0.13, \quad (\text{II.13})$$

where mass relation $M_X < \{M_E, m_{h^\pm}, m_{k^\pm\pm}\}$ is expected to stabilize DM.

Numerical results:

² Even when there is N_{CB} enhancement for the processes of $\gamma\gamma$ or γZ final state modes, these cross sections are still subdominant.

Now we randomly select values of the twelve parameters within the corresponding ranges

$$\begin{aligned}
v_S &\in [2 \text{ TeV}, 3 \text{ TeV}], & \mu = \mu_S &\in [0, 1][\text{TeV}], & M_X &\in [m_S, v_S], \\
m_{k^{\pm\pm}} &\in [M_X, 5 \text{ TeV}], & M_E = M_N = m_{h^\pm} &\in [M_X, 10 \text{ TeV}], \\
m_\ell &\in [m_e, m_\tau], & f = g = h &\in [-1, 1],
\end{aligned} \tag{II.14}$$

to reproduce the neutrino mass scale $0.001 \text{ eV} \lesssim m_\nu \lesssim 0.1 \text{ eV}$, the anomalous magnetic moment $2.0 \times 10^{-9} \lesssim \Delta a_\mu \lesssim 4.2 \times 10^{-9}$ in Eq. (II.8), the measured relic density $0.11 \lesssim \Omega h^2 \lesssim 0.13$ in Eq. (II.13), and the decay rate to the two photons of the doubly charged bosons $k^{\pm\pm}$ observed by the 750 GeV diphoton excess $5.3 \text{ GeV} \lesssim \Gamma_S \lesssim 45 \text{ GeV}$ in Eq. (I.5). Here we fix $N_{CB} = [6000, 9000]$, $m_S = 750 \text{ GeV}$ is the new particle, $m_e = 0.51 \text{ MeV}$ is the electron mass, and $m_\tau = 1.776 \text{ GeV}$ is the tauon mass. Then we have obtained the following constrained parameters with five millions random sampling points:

$N_{CB} = 6000$:

$$\begin{aligned}
v_S &\in [2, 2.8] [\text{TeV}], & \mu_S &\in [0.3, 1][\text{TeV}], & M_X &\in [0.8, 1.8] [\text{TeV}], \\
m_{k^{\pm\pm}} &\in [0.9, 2] [\text{TeV}], & M_E &\in [M_X, 6 \text{ TeV}], & m_{h^\pm} &\in [M_X, 8 \text{ TeV}], \\
|f| = |g| &\in [0.5, 1],
\end{aligned} \tag{II.15}$$

$N_{CB} = 9000$:

$$\begin{aligned}
\mu_S &\in [0.2, 1][\text{TeV}], & M_X &\in [0.8, 2.1] [\text{TeV}], \\
m_{k^{\pm\pm}} &\in [1.0, 2.5] [\text{TeV}], & M_E &\in [M_X, 8 \text{ TeV}], & m_{h^\pm} &\in [M_X, 9 \text{ TeV}], \\
|f| = |g| &\in [0.5, 1].
\end{aligned} \tag{II.16}$$

These above results suggest that $N_{CB} = 9000$ gives larger number of solutions than those of $N_{CB} = 6000$, that is expected from Fig. 1. Also both the allowed regions of $m_{k^{\pm\pm}}$ and μ_S directly reflect the results of this figures. The Yukawa couplings of f and g needs rather large values that are required to satisfy muon anomalous magnetic moment. It is worth mentioning that there exist lepton flavor violating processes (LFVs) whenever we have the contributions of the muon $g - 2$ as discussed in Eq. (II.9), although serious analysis is beyond our scope due to the very complicated neutrino sector. These processes provide some constraints such as Yukawas (f and g in our case) and/or the mediating particles ($m_{k^{\pm\pm}}$, m_{h^\pm} , M_N , and M_E in our case). Even when our Yukawa couplings f and g are relatively large, we expect that

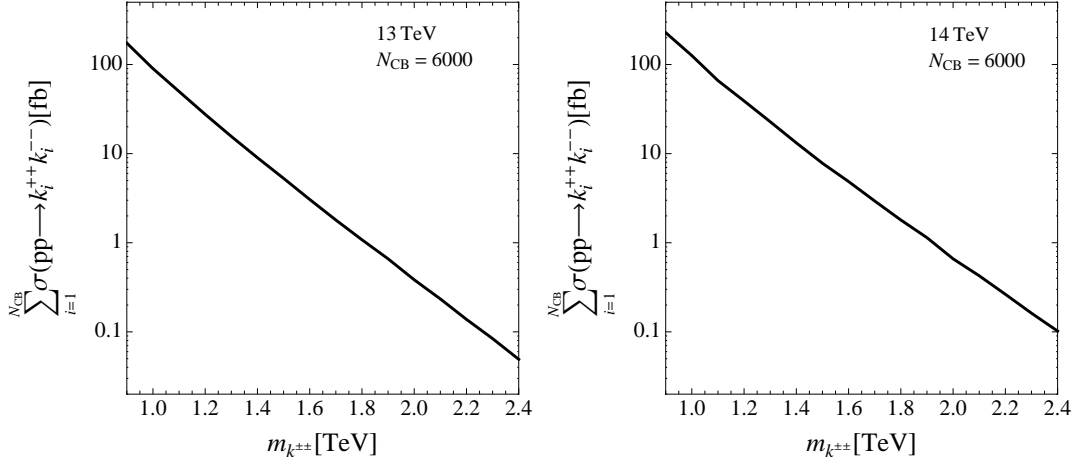


FIG. 3: Sum of cross sections for doubly charged scalar production $pp \rightarrow \gamma^*/Z^* \rightarrow k_i^{++}k_i^{--}$ at the LHC 13(14) TeV.

LFVs could be suppressed by the mediating particles; $m_{k^{\pm\pm}}$, m_{h^\pm} , M_N , M_E , all of which are $\mathcal{O}(1)$ TeV.

We also estimate the cross section of doubly charged scalar production, i.e. $pp \rightarrow \gamma^*/Z^* \rightarrow k^{++}k^{--}$. Although each pair production cross section is small the sum of the cross section for N_{CB} pair can be sizable. The production cross section is numerically estimated by CalcHEP [142] implementing relevant interactions and using CTEQ6L PDF [143]. The left(right) plots in Fig. 3 show the sum of the $k^{++}k^{--}$ production cross section at the LHC 13(14) TeV applying $N_{CB} = 6000$. Note that the total cross section is simply $N_{CB} \times$ (each $k^{++}k^{--}$ production cross section). We thus find that the doubly charged scalar could be produced at the LHC run-II with $\mathcal{O}(100)$ fb cross section when $m_{k^{\pm\pm}} \sim 1$ TeV. The doubly charged scalar then decays as $k^{\pm\pm} \rightarrow h^\pm h^\pm \rightarrow \ell^\pm \ell^\pm \nu \bar{\nu}$ where $\ell = e, \mu$ and τ . Therefore the signal of the $k^{++}k^{--}$ pair is four charged lepton plus missing transverse energy.

III. CONCLUSIONS AND DISCUSSIONS

We have proposed a four-loop induced radiative neutrino mass model inspired by the diphoton excess at 750 GeV recently reported by ATLAS and CMS, in which a sizable diphoton excess is obtained via photon fusion introducing multi doubly-charged scalar bosons. The

sizable neutrino mass scale has been obtained due to the enhancement of the number of doubly charged bosons N_{CB} . Also we have discussed the muon anomalous magnetic moment, and a dark matter candidate of the lightest fermion X , and we have found that the main process to explain the correct relic density relies on the final state of the new particle at 750 GeV through the t - and u -channels. Finally we have shown the numerical results and have obtained allowed region of several physical values in our model, as can be seen in Eqs (II.15) for $N_{CB} = 6000$ and Eqs (II.16) for $N_{CB} = 9000$ respectively. The doubly charged scalar production cross section has been numerically estimated. Then we have found that sum of the pair production cross section can be as large as $O(100)$ fb for $m_{k^{\pm\pm}} \sim 1$ TeV. Therefore our model could be tested at the LHC run-II by searching for the signal of four charged lepton plus missing transverse energy which is obtained as $k^{++}k^{--} \rightarrow h^+h^+h^-h^- \rightarrow \ell^+\ell^+\ell^-\ell^- + 4\nu$. Further analysis of the signal is left as future work.

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- [1] The ATLAS collaboration, ATLAS-CONF-2015-081.
 - [2] CMS Collaboration [CMS Collaboration], collisions at 13TeV,” CMS-PAS-EXO-15-004.
 - [3] K. Harigaya and Y. Nomura, arXiv:1512.04850 [hep-ph].
 - [4] Y. Mambrini, G. Arcadi and A. Djouadi, arXiv:1512.04913 [hep-ph].
 - [5] M. Backovic, A. Mariotti and D. Redigolo, arXiv:1512.04917 [hep-ph].
 - [6] A. Angelescu, A. Djouadi and G. Moreau, arXiv:1512.04921 [hep-ph].
 - [7] Y. Nakai, R. Sato and K. Tobioka, arXiv:1512.04924 [hep-ph].
 - [8] S. Knapen, T. Melia, M. Papucci and K. Zurek, arXiv:1512.04928 [hep-ph].
 - [9] D. Buttazzo, A. Greljo and D. Marzocca, arXiv:1512.04929 [hep-ph].
 - [10] A. Pilaftsis, arXiv:1512.04931 [hep-ph].

- [11] R. Franceschini *et al.*, arXiv:1512.04933 [hep-ph].
- [12] S. Di Chiara, L. Marzola and M. Raidal, arXiv:1512.04939 [hep-ph].
- [13] T. Higaki, K. S. Jeong, N. Kitajima and F. Takahashi, arXiv:1512.05295 [hep-ph].
- [14] S. D. McDermott, P. Meade and H. Ramani, arXiv:1512.05326 [hep-ph].
- [15] J. Ellis, S. A. R. Ellis, J. Quevillon, V. Sanz and T. You, arXiv:1512.05327 [hep-ph].
- [16] M. Low, A. Tesi and L. T. Wang, arXiv:1512.05328 [hep-ph].
- [17] B. Bellazzini, R. Franceschini, F. Sala and J. Serra, arXiv:1512.05330 [hep-ph].
- [18] R. S. Gupta, S. Jager, Y. Kats, G. Perez and E. Stamou, arXiv:1512.05332 [hep-ph].
- [19] C. Petersson and R. Torre, arXiv:1512.05333 [hep-ph].
- [20] E. Molinaro, F. Sannino and N. Vignaroli, arXiv:1512.05334 [hep-ph].
- [21] B. Dutta, Y. Gao, T. Ghosh, I. Gogoladze and T. Li, arXiv:1512.05439 [hep-ph].
- [22] Q. H. Cao, Y. Liu, K. P. Xie, B. Yan and D. M. Zhang, arXiv:1512.05542 [hep-ph].
- [23] S. Matsuzaki and K. Yamawaki, arXiv:1512.05564 [hep-ph].
- [24] A. Kobakhidze, F. Wang, L. Wu, J. M. Yang and M. Zhang, arXiv:1512.05585 [hep-ph].
- [25] R. Martinez, F. Ochoa and C. F. Sierra, arXiv:1512.05617 [hep-ph].
- [26] P. Cox, A. D. Medina, T. S. Ray and A. Spray, arXiv:1512.05618 [hep-ph].
- [27] D. Becirevic, E. Bertuzzo, O. Sumensari and R. Z. Funchal, arXiv:1512.05623 [hep-ph].
- [28] J. M. No, V. Sanz and J. Setford, arXiv:1512.05700 [hep-ph].
- [29] S. V. Demidov and D. S. Gorbunov, arXiv:1512.05723 [hep-ph].
- [30] W. Chao, R. Huo and J. H. Yu, arXiv:1512.05738 [hep-ph].
- [31] S. Fichet, G. von Gersdorff and C. Royon, arXiv:1512.05751 [hep-ph].
- [32] D. Curtin and C. B. Verhaaren, arXiv:1512.05753 [hep-ph].
- [33] L. Bian, N. Chen, D. Liu and J. Shu, arXiv:1512.05759 [hep-ph].
- [34] J. Chakraborty, A. Choudhury, P. Ghosh, S. Mondal and T. Srivastava, arXiv:1512.05767 [hep-ph].
- [35] A. Ahmed, B. M. Dillon, B. Grzadkowski, J. F. Gunion and Y. Jiang, arXiv:1512.05771 [hep-ph].
- [36] P. Agrawal, J. Fan, B. Heidenreich, M. Reece and M. Strassler, arXiv:1512.05775 [hep-ph].
- [37] C. Csaki, J. Hubisz and J. Terning, arXiv:1512.05776 [hep-ph].
- [38] A. Falkowski, O. Slone and T. Volansky, arXiv:1512.05777 [hep-ph].
- [39] D. Aloni, K. Blum, A. Dery, A. Efrati and Y. Nir, arXiv:1512.05778 [hep-ph].

- [40] Y. Bai, J. Berger and R. Lu, arXiv:1512.05779 [hep-ph].
- [41] E. Gabrielli, K. Kannike, B. Mele, M. Raidal, C. Spethmann and H. Veermae, arXiv:1512.05961 [hep-ph].
- [42] R. Benbrik, C. H. Chen and T. Nomura, arXiv:1512.06028 [hep-ph].
- [43] J. S. Kim, J. Reuter, K. Rolbiecki and R. R. de Austri, arXiv:1512.06083 [hep-ph].
- [44] A. Alves, A. G. Dias and K. Sinha, arXiv:1512.06091 [hep-ph].
- [45] E. Megias, O. Pujolas and M. Quiros, arXiv:1512.06106 [hep-ph].
- [46] L. M. Carpenter, R. Colburn and J. Goodman, arXiv:1512.06107 [hep-ph].
- [47] J. Bernon and C. Smith, arXiv:1512.06113 [hep-ph].
- [48] W. Chao, arXiv:1512.06297 [hep-ph].
- [49] M. T. Arun and P. Saha, arXiv:1512.06335 [hep-ph].
- [50] C. Han, H. M. Lee, M. Park and V. Sanz, arXiv:1512.06376 [hep-ph].
- [51] S. Chang, arXiv:1512.06426 [hep-ph].
- [52] I. Chakraborty and A. Kundu, arXiv:1512.06508 [hep-ph].
- [53] R. Ding, L. Huang, T. Li and B. Zhu, arXiv:1512.06560 [hep-ph].
- [54] H. Han, S. Wang and S. Zheng, arXiv:1512.06562 [hep-ph].
- [55] X. F. Han and L. Wang, arXiv:1512.06587 [hep-ph].
- [56] M. x. Luo, K. Wang, T. Xu, L. Zhang and G. Zhu, arXiv:1512.06670 [hep-ph].
- [57] J. Chang, K. Cheung and C. T. Lu, arXiv:1512.06671 [hep-ph].
- [58] D. Bardhan, D. Bhatia, A. Chakraborty, U. Maitra, S. Raychaudhuri and T. Samui, arXiv:1512.06674 [hep-ph].
- [59] T. F. Feng, X. Q. Li, H. B. Zhang and S. M. Zhao, arXiv:1512.06696 [hep-ph].
- [60] O. Antipin, M. Mojaza and F. Sannino, arXiv:1512.06708 [hep-ph].
- [61] F. Wang, L. Wu, J. M. Yang and M. Zhang, arXiv:1512.06715 [hep-ph].
- [62] J. Cao, C. Han, L. Shang, W. Su, J. M. Yang and Y. Zhang, arXiv:1512.06728 [hep-ph].
- [63] F. P. Huang, C. S. Li, Z. L. Liu and Y. Wang, arXiv:1512.06732 [hep-ph].
- [64] W. Liao and H. q. Zheng, arXiv:1512.06741 [hep-ph].
- [65] J. J. Heckman, arXiv:1512.06773 [hep-ph].
- [66] M. Dhuria and G. Goswami, arXiv:1512.06782 [hep-ph].
- [67] X. J. Bi, Q. F. Xiang, P. F. Yin and Z. H. Yu, arXiv:1512.06787 [hep-ph].
- [68] J. S. Kim, K. Rolbiecki and R. R. de Austri, arXiv:1512.06797 [hep-ph].

- [69] L. Berthier, J. M. Cline, W. Shepherd and M. Trott, arXiv:1512.06799 [hep-ph].
- [70] W. S. Cho, D. Kim, K. Kong, S. H. Lim, K. T. Matchev, J. C. Park and M. Park, arXiv:1512.06824 [hep-ph].
- [71] J. M. Cline and Z. Liu, arXiv:1512.06827 [hep-ph].
- [72] M. Bauer and M. Neubert, arXiv:1512.06828 [hep-ph].
- [73] M. Chala, M. Duerr, F. Kahlhoefer and K. Schmidt-Hoberg, arXiv:1512.06833 [hep-ph].
- [74] D. Barducci, A. Goudelis, S. Kulkarni and D. Sengupta, arXiv:1512.06842 [hep-ph].
- [75] S. M. Boucenna, S. Morisi and A. Vicente, arXiv:1512.06878 [hep-ph].
- [76] C. W. Murphy, arXiv:1512.06976 [hep-ph].
- [77] A. E. C. Hernandez and I. Nisandzic, arXiv:1512.07165 [hep-ph].
- [78] U. K. Dey, S. Mohanty and G. Tomar, arXiv:1512.07212 [hep-ph].
- [79] G. M. Pelaggi, A. Strumia and E. Vigiani, arXiv:1512.07225 [hep-ph].
- [80] J. de Blas, J. Santiago and R. Vega-Morales, arXiv:1512.07229 [hep-ph].
- [81] A. Belyaev, G. Cacciapaglia, H. Cai, T. Flacke, A. Parolini and H. Serodio, arXiv:1512.07242 [hep-ph].
- [82] P. S. B. Dev and D. Teresi, arXiv:1512.07243 [hep-ph].
- [83] W. C. Huang, Y. L. S. Tsai and T. C. Yuan, arXiv:1512.07268 [hep-ph].
- [84] S. Moretti and K. Yagyu, arXiv:1512.07462 [hep-ph].
- [85] K. M. Patel and P. Sharma, arXiv:1512.07468 [hep-ph].
- [86] M. Badziak, arXiv:1512.07497 [hep-ph].
- [87] S. Chakraborty, A. Chakraborty and S. Raychaudhuri, arXiv:1512.07527 [hep-ph].
- [88] Q. H. Cao, S. L. Chen and P. H. Gu, arXiv:1512.07541 [hep-ph].
- [89] W. Altmannshofer, J. Galloway, S. Gori, A. L. Kagan, A. Martin and J. Zupan, arXiv:1512.07616 [hep-ph].
- [90] M. Cvetič, J. Halverson and P. Langacker, arXiv:1512.07622 [hep-ph].
- [91] J. Gu and Z. Liu, arXiv:1512.07624 [hep-ph].
- [92] B. C. Allanach, P. S. B. Dev, S. A. Renner and K. Sakurai, arXiv:1512.07645 [hep-ph].
- [93] H. Davoudiasl and C. Zhang, arXiv:1512.07672 [hep-ph].
- [94] N. Craig, P. Draper, C. Kilic and S. Thomas, arXiv:1512.07733 [hep-ph].
- [95] K. Das and S. K. Rai, arXiv:1512.07789 [hep-ph].
- [96] K. Cheung, P. Ko, J. S. Lee, J. Park and P. Y. Tseng, arXiv:1512.07853 [hep-ph].

- [97] J. Liu, X. P. Wang and W. Xue, arXiv:1512.07885 [hep-ph].
- [98] J. Zhang and S. Zhou, arXiv:1512.07889 [hep-ph].
- [99] J. A. Casas, J. R. Espinosa and J. M. Moreno, arXiv:1512.07895 [hep-ph].
- [100] L. J. Hall, K. Harigaya and Y. Nomura, arXiv:1512.07904 [hep-ph].
- [101] H. Han, S. Wang and S. Zheng, arXiv:1512.07992 [hep-ph].
- [102] J. C. Park and S. C. Park, arXiv:1512.08117 [hep-ph].
- [103] A. Salvio and A. Mazumdar, arXiv:1512.08184 [hep-ph].
- [104] D. Chway, R. Dermisek, T. H. Jung and H. D. Kim, arXiv:1512.08221 [hep-ph].
- [105] G. Li, Y. n. Mao, Y. L. Tang, C. Zhang, Y. Zhou and S. h. Zhu, arXiv:1512.08255 [hep-ph].
- [106] M. Son and A. Urbano, arXiv:1512.08307 [hep-ph].
- [107] Y. L. Tang and S. h. Zhu, arXiv:1512.08323 [hep-ph].
- [108] H. An, C. Cheung and Y. Zhang, arXiv:1512.08378 [hep-ph].
- [109] J. Cao, F. Wang and Y. Zhang, arXiv:1512.08392 [hep-ph].
- [110] F. Wang, W. Wang, L. Wu, J. M. Yang and M. Zhang, arXiv:1512.08434 [hep-ph].
- [111] C. Cai, Z. H. Yu and H. H. Zhang, arXiv:1512.08440 [hep-ph].
- [112] Q. H. Cao, Y. Liu, K. P. Xie, B. Yan and D. M. Zhang, arXiv:1512.08441 [hep-ph].
- [113] J. E. Kim, arXiv:1512.08467 [hep-ph].
- [114] J. Gao, H. Zhang and H. X. Zhu, arXiv:1512.08478 [hep-ph].
- [115] W. Chao, arXiv:1512.08484 [hep-ph].
- [116] X. J. Bi *et al.*, arXiv:1512.08497 [hep-ph].
- [117] F. Goertz, J. F. Kamenik, A. Katz and M. Nardecchia, arXiv:1512.08500 [hep-ph].
- [118] L. A. Anchordoqui, I. Antoniadis, H. Goldberg, X. Huang, D. Lust and T. R. Taylor, arXiv:1512.08502 [hep-ph].
- [119] P. S. B. Dev, R. N. Mohapatra and Y. Zhang, arXiv:1512.08507 [hep-ph].
- [120] N. Bizot, S. Davidson, M. Frigerio and J.-L. Kneur, arXiv:1512.08508 [hep-ph].
- [121] L. E. Ibanez and V. Martin-Lozano, arXiv:1512.08777 [hep-ph].
- [122] C. W. Chiang, M. Ibe and T. T. Yanagida, arXiv:1512.08895 [hep-ph].
- [123] S. K. Kang and J. Song, arXiv:1512.08963 [hep-ph].
- [124] Y. Hamada, T. Noumi, S. Sun and G. Shiu, arXiv:1512.08984 [hep-ph].
- [125] X. J. Huang, W. H. Zhang and Y. F. Zhou, arXiv:1512.08992 [hep-ph].
- [126] S. Kanemura, K. Nishiwaki, H. Okada, Y. Orikasa, S. C. Park and R. Watanabe,

- arXiv:1512.09048 [hep-ph].
- [127] S. Kanemura, N. Machida, S. Odori and T. Shindou, arXiv:1512.09053 [hep-ph].
- [128] I. Low and J. Lykken, arXiv:1512.09089 [hep-ph].
- [129] A. E. C. Hernandez, arXiv:1512.09092 [hep-ph].
- [130] Y. Jiang, Y. Y. Li and T. Liu, arXiv:1512.09127 [hep-ph].
- [131] K. Kaneta, S. Kang and H. S. Lee, arXiv:1512.09129 [hep-ph].
- [132] L. Marzola, A. Racioppi, M. Raidal, F. R. Urban and H. Veermae, arXiv:1512.09136 [hep-ph].
- [133] E. Ma, arXiv:1512.09159 [hep-ph].
- [134] A. Dasgupta, M. Mitra and D. Borah, arXiv:1512.09202 [hep-ph].
- [135] G. Aad *et al.* [ATLAS Collaboration], Phys. Rev. D **92**, no. 3, 032004 (2015) doi:10.1103/PhysRevD.92.032004 [arXiv:1504.05511 [hep-ex]].
- [136] CMS Collaboration [CMS Collaboration], CMS-PAS-HIG-14-006. arXiv:1512.05776 [hep-ph].
- [137] A. Zee, Nucl. Phys. B **264**, 99 (1986); K. S. Babu, Phys. Lett. B **203**, 132 (1988).
- [138] K.A. Olive et al. (Particle Data Group), Chin. Phys. C, **38**, 090001 (2014).
- [139] F. Jegerlehner and A. Nyffeler, Phys. Rept. **477**, 1 (2009) [arXiv:0902.3360 [hep-ph]].
- [140] M. Benayoun, P. David, L. Delbuono and F. Jegerlehner, Eur. Phys. J. C **72**, 1848 (2012) [arXiv:1106.1315 [hep-ph]].
- [141] P. A. R. Ade *et al.* [Planck Collaboration], Astron. Astrophys. (2014) [arXiv:1303.5076 [astro-ph.CO]].
- [142] A. Belyaev, N. D. Christensen and A. Pukhov, Comput. Phys. Commun. **184**, 1729 (2013) [arXiv:1207.6082 [hep-ph]].
- [143] P. M. Nadolsky, H. L. Lai, Q. H. Cao, J. Huston, J. Pumplin, D. Stump, W. K. Tung and C.-P. Yuan, Phys. Rev. D **78**, 013004 (2008) [arXiv:0802.0007 [hep-ph]].