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Dark sector shining through 750 GeV dark Higgs boson at the LHC

P. Ko, Takaaki Nomura *

School of Physics, KIAS, Seoul 02455, Republic of Korea

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ABSTRACT

We consider a dark sector with $SU(3)_C \times U(1)_Y \times U(1)_X$ and three families of dark fermions that are chiral under dark $U(1)_X$ gauge symmetry, whereas scalar dark matter X is the SM singlet. $U(1)_X$ dark symmetry is spontaneously broken by nonzero VEV of dark Higgs field $\langle\Phi\rangle$, generating the masses of dark fermions and dark photon Z'. The resulting dark Higgs boson ϕ can be produced at the LHC by dark quark loop (involving 3 generations) and will decay into a pair of photon through charged dark fermion loop. Its decay width can be easily ~ 45 GeV due to its possible decays into a pair of dark photon, which is not strongly constrained by the current LHC searches $pp \to \phi \to Z'Z'$ followed by Z' decays into the SM fermion pairs. The scalar DM can achieve thermal relic density without conflict with direct detection bound or the invisible ϕ decay into a pair of DM.

1. Introduction

Recently both ATLAS and CMS Collaborations announced that there are some excess in the diphoton channel around $m_{\gamma\gamma} \approx$ 750 GeV [1,2]:

$$\sigma(pp \to \phi \to \gamma\gamma) = (6.2^{+2.4}_{-2.0})\ \text{fb} \quad (\text{ATLAS}) \tag{1}$$

$$= (5.6 \pm 2.4)\ \text{fb} \quad (\text{CMS}) \tag{2}$$

$$\Gamma_{\text{tot}}(\phi) \sim 45\ \text{GeV} \quad (\text{ATLAS}) \tag{3}$$

whereas the CMS data prefers a smaller decay width [2]. Furthermore, at Moriond 2016, ATLAS and CMS have reported that the local (global) significances of the diphoton excess are about $3.9(2.0)\sigma$ and $3.4(1.6)\sigma$, respectively, where CMS added 0.6 fb^{-1} new data to the 13 TeV analysis and combined with 8 TeV data [3,4].

This excess motivated a lot of phenomenological study on possible scenarii of new physics beyond the Standard Model (BSM) which include models related to DM physics [5–12,44,13–43], new gauge symmetry models [13,20,23,35,38–40,43,45–57] and other models [58–161]. It is not easy to generate a large enough width ~ 45 GeV with large $BR(\phi \to \gamma\gamma)$, maintaining relevant cross section of $\sigma(pp \to \phi \to \gamma\gamma) \sim O(10)$ fb and evading various collider search bounds.

In this letter, we solve these problems by introducing dark $\text{U}(1)_X$ gauge symmetry, dark photon Z', three generations of dark fermions with $SU(3)_C \times U(1)_Y$ charges and singlet scalar DM X. Dark photon Z' can decay into SM fermions via a small Z–Z' mixing. Dark fermions are assumed to be chiral under $\text{U}(1)_X$ dark gauge symmetry and get massive after spontaneous breaking of $\text{U}(1)_X$ by nonzero VEV of $\text{U}(1)_X$-charged complex scalar field Φ, and a new Higgs boson ϕ appears from Φ. This simple setup for dark matter is a viable DM scenario with interesting signatures at high energy colliders.

2. Model

Let us introduce a dark sector with new dark fermions which carry both the SM $SU(3)_C \times U(1)_Y$ quantum numbers and dark $\text{U}(1)_X$ gauge charges, and a SM singlet complex scalar field X as summarized in Table 1. In this model, every right-handed fermion f_R in the SM has its partner fermion F_L with nonzero dark charge in the dark sector. Then the $\overline{F}_L f_R$ operator becomes invariant under the SM gauge transformation. Its nonzero dark charge is canceled by the dark charge of scalar DM X in such a way that $\overline{F}_L f_R X$ becomes gauge invariant operator. And F_L becomes vectorlike un-

Table 1
Contents of new fermions and scalar fields and their charge assignments under the gauge symmetry $\text{SU(3)} \times \text{SU(2)}_L \times \text{U(1)}_Y \times \text{U(1)}_X$. We consider three families of dark fermions.

	Fermions								Scalar	
	E_L	E_R	N_L	N_R	U_L	U_R	D_L	D_R	Φ	X
SU(3)	**1**	**1**	**1**	**1**	**3**	**3**	**3**	**3**	**1**	**1**
SU(2)	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
$\text{U}(1)_Y$	-1	-1	0	0	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{-1}{3}$	$\frac{-1}{3}$	0	0
$\text{U}(1)_X$	a	$-b$	$-a$	b	$-a$	b	a	$-b$	$a+b$	a

* Corresponding author.
E-mail addresses: pko@kias.re.kr (P. Ko), nomura@kias.re.kr (T. Nomura).

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der the SM gauge group by introducing its chiral partner F_R. The model is very simple and free from gauge anomalies for arbitrary a and b. A novel feature of this model is that the new fermions F_L and F_R are *chiral* under dark $U(1)_X$ gauge symmetry so that they are massless before spontaneous symmetry breaking. And their effects on $\phi \to gg, \gamma\gamma$ through triangle diagram evades from the decoupling theorem as their mass becomes heavy.

The Yukawa interactions and the scalar potential including new fields in the dark sector are described by

$$\begin{aligned} L_{\rm Yukawa} &= y^E \bar{E}_L E_R \Phi + y^N \bar{N}_L N_R \Phi^\dagger + y^U \bar{U}_L U_R \Phi^\dagger \\ &\quad + y^D \bar{D}_L D_R \Phi + y^{Ee} \bar{E}_L e_R X + y^{Uu} \bar{U}_L u_R X^\dagger \\ &\quad + y^{Dd} \bar{D}_L d_R X + h.c., \end{aligned} \tag{4}$$

$$\begin{aligned} V &= \mu^2 H^\dagger H + \lambda (H^\dagger H)^2 + \mu_\Phi^2 \Phi^\dagger \Phi + \mu_X^2 X^\dagger X \\ &\quad + \lambda_\Phi (\Phi^\dagger \Phi)^2 + \lambda_X (X^\dagger X)^2 + \lambda_{H\Phi} (H^\dagger H)(\Phi^\dagger \Phi) \\ &\quad + \lambda_{HX} (H^\dagger H)(X^\dagger X) + \lambda_{X\Phi} (X^\dagger X)(\Phi^\dagger \Phi), \end{aligned} \tag{5}$$

where H denotes the SM Higgs field.[1] We have suppressed the generation indices on the SM and the dark fermions for simplicity. The Yukawa interactions provide mass terms for the dark fermions F, which decay through $F \to Xf$. X is the SM singlet and can be a good DM candidate. Note that there is an accidental Z_2 symmetry, $X \to -X$, $F_L \to -F_L$ and $F_R \to -F_R$ which make X stable at renormalizable level. There could be gauge invariant operators that break this accidental Z_2 symmetry: $X^\dagger \Phi^n$ and/or $X\Phi^n$ which would generate nonzero VEV for X after $U(1)_X$ symmetry breaking by nonzero $\langle \Phi \rangle \neq 0$. Gauge invariance requires that $\pm a/(a+b) = n$ to be an integer. We can forbid this type of operators by making a judicious choice of a, b so that $\pm a/(a+b)$ is not an integer. Or we can make n very large so that even if X develops a nonzero VEV, the lifetime of X becomes long enough ($\tau_X \gtrsim 10^{28}$ sec) to be a good DM candidate. This model can be considered as a generalization of the singlet portal extensions of the SM where dark matter lives in the dark sector [166], but the dark sector now contains dark fields which are charged under the SM gauge group as well as dark gauge group, unlike the earlier models [166].

The gauge symmetry is broken after H and Φ get non-zero VEVs:

$$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG^0) \end{pmatrix}, \quad \Phi = \frac{1}{\sqrt{2}}(v_\phi + \phi + iG_\phi), \tag{6}$$

where $G^\pm$, G^0 and G_ϕ are NG bosons which are absorbed by $W^\pm$, Z and Z' respectively. We shall call ϕ as dark Higgs boson, since it appears as a result of spontaneous breaking of dark $U(1)_X$ gauge symmetry.

We assume $\lambda_{H\Phi}$ is negligible and the mixing between SM Higgs boson h and ϕ is negligibly small which is consistent with the current Higgs data analysis [167]. Then the scalar VEVs are given approximately by

$$v \simeq \sqrt{\frac{-\mu^2}{\lambda}}, \quad v_\Phi \simeq \sqrt{\frac{-\mu_\Phi^2}{\lambda_\Phi}}. \tag{7}$$

The masses of new fermions are generated such that

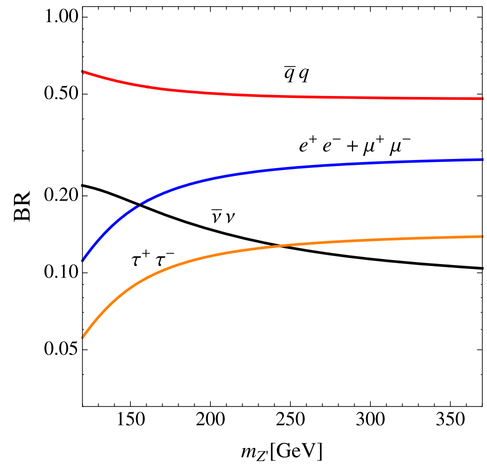

Fig. 1. Branching ratios of Z' as a function of $m_{Z'}$.

$$M_F = \frac{y^F}{\sqrt{2}} v_\Phi\,, \tag{8}$$

where $F = E, N, U$ and D.

We consider kinetic mixing of the $U(1)_Y$ and $U(1)_X$ gauge fields which are denoted respectively as $\tilde{B}_\mu$ and $\tilde{X}_\mu$;

$$\begin{aligned} \mathcal{L}_{\rm kin} &= -\frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} \\ &\quad - \frac{1}{4} (\tilde{B}_{\mu\nu}, \tilde{X}_{\mu\nu}) \begin{pmatrix} 1 & s_\chi \\ s_\chi & 1 \end{pmatrix} \begin{pmatrix} \tilde{B}^{\mu\nu} \\ \tilde{Z}'^{\mu\nu} \end{pmatrix}, \end{aligned} \tag{9}$$

where $s_\chi \equiv \sin\chi$. The kinetic terms are diagonalized by the following non-unitary transformation;

$$\begin{pmatrix} \tilde{B}_\mu \\ \tilde{X}_\mu \end{pmatrix} = \begin{pmatrix} 1 & -t_\chi \\ 0 & 1/t_\chi \end{pmatrix} \begin{pmatrix} B_\mu \\ X_\mu \end{pmatrix}, \tag{10}$$

where $t_\chi = \tan\chi$. After Φ and H develop non-zero VEVs, the mass matrix for neutral gauge field is approximately given by

$$\frac{1}{8} \begin{pmatrix} \tilde{Z} \\ X \end{pmatrix}^T \begin{pmatrix} (g^2 + g'^2) v^2 & t_\chi g' \sqrt{g^2 + g'^2} v^2 \\ t_\chi g' \sqrt{g^2 + g'^2} v^2 & 4(a+b)^2 g_X^2 v_\Phi^2 \end{pmatrix} \begin{pmatrix} \tilde{Z} \\ X \end{pmatrix}, \tag{11}$$

where $W^3_\mu = \cos\theta_W Z_\mu + \sin\theta_W A_\mu$ and $B_\mu = -\sin\theta_W + \cos\theta_W A_\mu$ are used. Assuming $\chi \ll 1$,[2] neutral gauge boson masses are

$$m_Z^2 \simeq \frac{1}{4}(g^2 + g'^2) v^2, \quad m_{Z'}^2 \simeq (a+b)^2 g_X^2 v_\Phi^2. \tag{12}$$

The mass eigenstates are given by

$$\begin{pmatrix} Z_\mu \\ Z'_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \tilde{Z}_\mu \\ X_\mu \end{pmatrix}, \tag{13}$$

and the small Z–Z' mixing angle is given by

$$\tan 2\theta \simeq \frac{g' \sqrt{g^2 + g'^2} v^2}{2(m_Z^2 - m_{Z'}^2)} t_\chi. \tag{14}$$

In Fig. 1, we show the branching ratios of Z' as a function of its mass. Here $q = u, d, s, c, b$, and $\nu\bar{\nu}$ includes all the three flavors. Note that Z' decays into the SM through the kinetic mixing so that $\Gamma(Z')/m_{Z'} \sim O(\chi^2) \lesssim 10^{-4}$. Therefore Z' would be a very narrow resonance.

[1] For $a = b = 1$, there appears an extra term $\Phi^\dagger X^2$ in the potential, which breaks $U(1)_X$ down to Z_2 subgroup after S develops nonzero VEV. Likewise, for $3a = (a+b)$, there appears an extra term $\Phi^\dagger X^3$, which breaks $U(1)_X$ down to Z_3 subgroup after S develops nonzero VEV. In this paper, we do not consider these possibilities, relegating the readers to Ref. [162] and Refs. [163–165] for Z_2 and Z_3 cases, respectively.

[2] The upper bound on the kinetic mixing is roughly $\lesssim 0.01$ in the dark photon mass range $m_{Z'} \lesssim 350$ GeV considered in this letter [168].

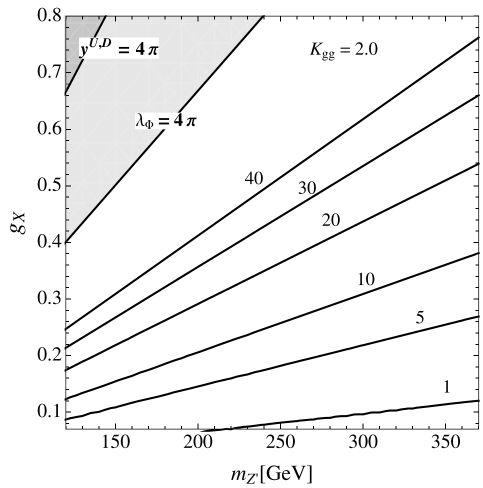

Fig. 2. The $\sigma(gg \to \phi)$ in unit of pb where 3 copy of fermions in Table 1 are applied and $a \simeq b \simeq 1$ with $a \neq b$ is adopted. We used parameter set as $\{M_{U,D}, M_{E,N}, m_X, \lambda_{X\Phi}\} = \{800\text{ GeV}, 400\text{ GeV}, 350\text{ GeV}, 0.075\}$. Gray (light gray) region indicate $y^{U,D}(\lambda_\Phi) > 4\pi$ using Eq. (15) and (16).

We also find that Yukawa coupling of new dark fermions and λ_Φ can be written in terms of g_X and $m_{Z'}$;

$$y^F = \frac{\sqrt{2}(a+b)g_X M_F}{m'_Z}, \tag{15}$$

$$\lambda_\Phi = \frac{(a+b)^2 m_\phi^2 g_X^2}{2m_{Z'}^2}. \tag{16}$$

In our analysis, we require these couplings are perturbative as $y^F < 4\pi$ and $\lambda_\Phi < 4\pi$.

3. Phenomenology

3.1. 750 GeV diphoton excess

In this section, we analyze the production of ϕ and its decays at the LHC 13 TeV. The production of ϕ is through gluon fusion process where the relevant effective coupling is given by

$$\mathcal{L}_{\phi gg} = \frac{\alpha_s}{8\pi}\left(\sum_{F=U,D} \frac{(a+b)\sqrt{2}g_X}{m_{Z'}} A_{1/2}(\tau_F)\right)\phi G^{a\mu\nu}G^a_{\mu\nu}, \tag{17}$$

where $A_{1/2}(\tau) = 2\tau[1+(1-\tau)f(\tau)]$ with $f(\tau) = [\sin^{-1}(1/\sqrt{\tau})]$ for $\tau \geq 1$ and $\tau_F \equiv 4m_F^2/m_\phi^2$. We find that the effective coupling is described by $m_{Z'}$ and g_X since exotic fermion mass is given by VEV of Φ. Applying the effective coupling, the production cross section for the dark Higgs ϕ is calculated by use of CalcHEP [169] with CTEQ6L PDF [170]. Fig. 2 shows the cross section in the $m_{Z'}$–g_X plane using parameter setting $\{M_{U,D}, M_{E,N}, m_X, \lambda_{X\Phi}\} = \{800\text{ GeV}, 400\text{ GeV}, 350\text{ GeV}, 0.075\}$ as a reference and K-factor for gluon fusion as $K_{gg} = 2.0$. In the figure, we also indicate excluded parameter region which violate perturbative condition $y^{U,D} < 4\pi$ and $\lambda_\Phi < 4\pi$ derived from Eq. (15) and (16) respectively. Thus a sizable production cross section can be obtained in perturbative parameter region.

The partial decay widths for $\phi \to gg$ mode is derived by

$$\Gamma_{\phi\to gg} = \frac{\alpha_s^2 m_\phi^3}{32\pi^3}\left|\sum_{F=U,D}\frac{(a+b)g_X}{2m_{Z'}}A_{1/2}(\tau_F)\right|^2. \tag{18}$$

Similarly the partial decay width for $\phi \to \gamma\gamma$ is given via dark fermion loops such that

$$\Gamma_{\phi\to\gamma\gamma} = \frac{\alpha^2 m_\phi^3}{256\pi^3}\left|\sum_F N_c^F \frac{(a+b)g_X Q_F^2}{m_{Z'}}A_{1/2}(\tau_F)\right|^2, \tag{19}$$

where Q_F and N_c^F are electric charge and number of color of an exotic fermion F. The partial decay width for $\phi \to Z\gamma$ is also formulated by

$$\Gamma_{\phi\to Z\gamma} = \frac{m_\phi^3}{32\pi}\left|A_{Z\gamma}\right|^2\left(1-\frac{m_Z^2}{m_\phi^2}\right)^3, \tag{20}$$

$$A_{Z\gamma} = \frac{2\sqrt{2}\alpha s_W g_X}{\pi c_W} \times \sum_F \frac{N_c^F(a+b)Q_F^2}{m_{Z'}}[I_1(\tau_F,\lambda_F) - I_2(\tau_F,\lambda_F)],$$

where $\lambda_F = 4m_F^2/m_Z^2$ and the loop integrals are given as [171]:

$$I_1(x,y) = \frac{xy}{2(x-y)} + \frac{x^2y^2}{2(x-y)^2}[f(x)^2 - f(y)^2] + \frac{x^2 b}{(x-y)^2}[g(x)-g(y)],$$
$$I_2(x,y) = -\frac{xy}{2(x-y)}[f(x)^2 - f(y)^2],$$
$$g(t) = \sqrt{t-1}\sin^{-1}(1/\sqrt{t}). \tag{21}$$

On the other hand, the decay widths of ϕ into $Z'Z'$, X^*X and $\bar{F}F$ modes are given at tree level as

$$\Gamma_{\phi\to Z'Z'} = \frac{(a+b)^2 g_X^2 m_{Z'}^2}{32\pi m_\phi} \times \frac{m_\phi^4 - 4m_\phi^2 m_{Z'}^2 + 12m_{Z'}^4}{m_{Z'}^4}\sqrt{1-\frac{4m_{Z'}^2}{m_\phi^2}}, \tag{22}$$

$$\Gamma_{\phi\to X^*X} = \frac{\lambda_{X\Phi}^2 m_{Z'}^2}{16\pi(a+b)^2 g_X^2 m_\phi}\sqrt{1-\frac{4m_X^2}{m_\phi^2}}, \tag{23}$$

$$\Gamma_{\phi\to\bar{F}F} = \frac{g_X^2 M_F^2}{4\pi m_{Z'}^2} m_\phi \sqrt{1-\frac{4M_F^2}{m_{Z'}^2}}. \tag{24}$$

Fig. 3 shows the total decay width of ϕ in the $m_{Z'}$–g_X plane where the same parameter set as in Fig. 2 is used. The branching fractions of ϕ decay can be obtained by partial decay widths, which is shown as a function of g_X in Fig. 4 for $m_{Z'} = 300$ GeV with the above parameter setting. Finally Fig. 5 shows contours of $\sigma(gg \to \phi)BR(\phi \to \gamma\gamma)$ in the $m_{Z'}$–g_X plane. We therefore find that 3–10 fb cross section for diphoton mode can be obtained in the region of $g_X \simeq 0.2$–0.5 and $m_{Z'} < m_S/2$, simultaneously with a rather large decay width of ϕ: $\Gamma_{\text{tot}}(\phi) \approx 5$–$40$ GeV.

3.2. Dark matter phenomenology

The DM candidates of our model are X and N. We assume that the Higgs portal coupling $\lambda_{HX} = 0$ for simplicity, since this case is studied in great detail [172]. We also assume that the Yukawa couplings involving the DM X and SM fermions in Eq. (4) are small enough so that their contribution to thermal relic calculation is negligible. Then the dominant annihilation processes of DM in our model are $XX^*(N\bar{N}) \to Z'Z'$ assuming $m_{X,N} > m_{Z'}$. We have included the $t(u)$-channel processes mediated by virtual F exchange as well as the s-channel process mediated by ϕ exchange. Note that the Z'-exchanging processes are suppressed since interactions

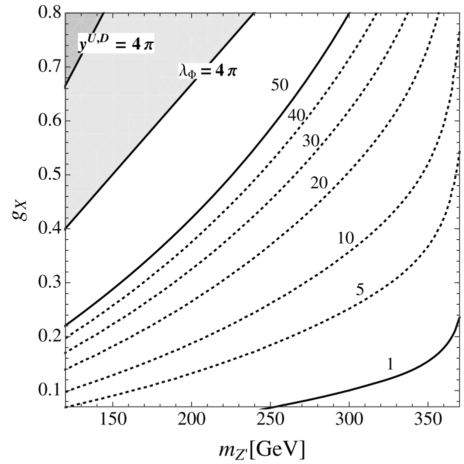

Fig. 3. The total decay width of ϕ in unit of GeV with same parameter setting as Fig. 2.

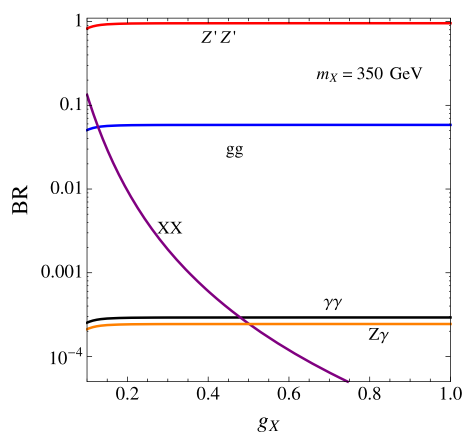

Fig. 4. Branching fraction for decay of ϕ.

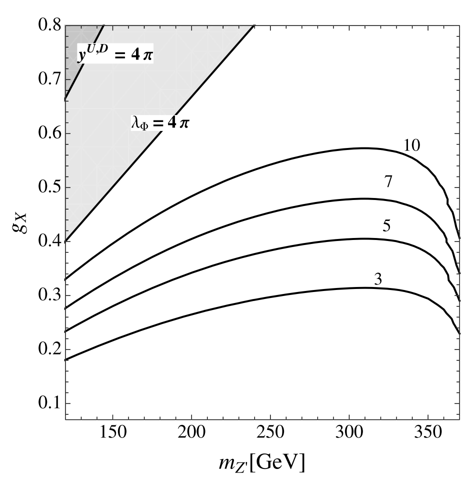

Fig. 5. The $\sigma(gg \to \phi)BR(\phi \to \gamma\gamma)$ in unit of fb with same parameter setting as Fig. 2.

between Z' and SM particles are small due to the small Z–Z' mixing we assume.

The thermal relic density is numerically estimated with `micrOMEGAs 4.1.5` [173] to solve the Boltzmann equation by implementing relevant interactions relevant for the DM pair annihilation processes. In calculating the relic density we assume $a \simeq b \simeq 1$ (but $a \neq b$). We find that the DM relic density is given dominantly

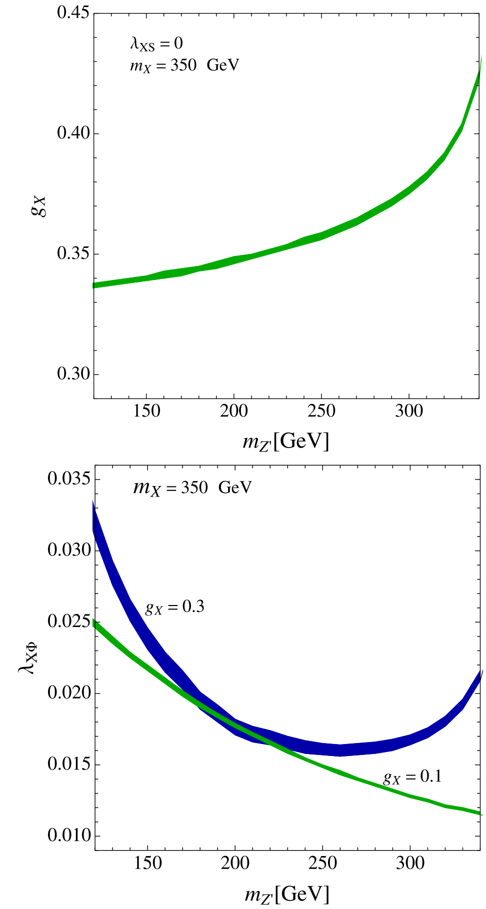

Fig. 6. The colored region in upper (lower) plot indicate parameter space in $m_{Z'}$–g_X ($m_{Z'}$–$\lambda_{X\Phi}$) plane which explain observed relic density of X where other parameters are indicated in the figures. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

by scalar DM X in the parameter region where one can explain the 750 GeV diphoton excess. It turns out that the relic density of N is small due to large Yukawa coupling y^N which makes the amplitude for the $\bar{N}N \to \phi \to Z'Z'$ process large. Thus the thermal relic density of scalar DM X is calculated with fixed parameter set of $\{M_{U,D}, M_{E,N}, m_X\} = \{800\text{ GeV}, 400\text{ GeV}, 350\text{ GeV}\}$ and by taking $\{g_X, \lambda_{X\Phi}, m_{Z'}\}$ as free parameters. We then search for the parameter region which gives the right thermal relic density, i.e. $\Omega h^2 = 0.1199 \pm 0.0027$ as reported by Planck Collaboration [174]. The upper figure in Fig. 6 shows the parameter region in the $(m_{Z'}, g_X)$ plane providing the observed relic density for $\lambda_{X\Phi} = 0$. On the other hand, the lower figure in Fig. 6 shows the corresponding parameter region in the $(m_{Z'}, \lambda_{X\Phi})$ plane for $g_X = 0.1$ and 0.3. We find that interference between $t(u)$-channel processes and ϕ exchanging s-channel process makes $\lambda_{X\Phi}$ dependence of the relic density nontrivial. For smaller $\lambda_{X\Phi}$ and g_X, small amount of Higgs portal coupling λ_{HX} can help us to achieve the correct thermal relic density.

In this model, DM–nucleon scattering occurs through h, ϕ and Z' exchanges. The amplitude for Z' exchange will be small since it involves Z–Z' mixing which can be sufficiently small. Also the Higgs contribution can be made small enough if we take a small λ_{HX}. For ϕ exchange, we have contribution to DM–nucleon scattering amplitude from ϕ–gluon–gluon coupling in Eq. (17) and ϕ–X–X coupling even if we suppress ϕ–h mixing. The relevant effective coupling is given by

$$\mathcal{L}_{XXGG} = \frac{\alpha_S}{4\pi}\left(\sum_{F=U,D}\frac{\lambda_{X\Phi}}{m_\phi^2}A_{1/2}(\tau_F)\right)X^\dagger X G^{a\mu\nu}G^a_{\mu\nu}$$
$$\equiv \frac{\alpha_S}{4\pi}C_g X^\dagger X G^{a\mu\nu}G^a_{\mu\nu}. \quad (25)$$

Then the spin-independent DM–nucleon scattering cross section is obtained as [175]

$$\sigma_{\rm SI} = \frac{m_N^2}{\pi(m_X+m_N)^2}f_N^2 \quad (26)$$
$$\frac{f_N}{m_N} = -\frac{2}{9}C_g f_{T_G}^{(N)} \quad (27)$$

where m_N is the nucleon mass and $f_{T_G}^{(N)}$ is the mass fraction of gluonic operators in the nucleon mass. For the numerical values for these parameters, we adopt values in Ref. [176]. We find that DM–nucleon scattering cross section is small as $\sigma_{\rm SI} \lesssim 10^{-48}$ cm^2 for the $\lambda_{X\Phi}$ providing the observed relic density in Fig. 6. Therefore it is difficult to observe the DM–nucleon scattering in direct detection experiment.

3.3. Muon $(g-2)_\mu$

It is interesting to note that this model can also solve the muon $(g-2)_\mu$ through the dark muon and dark matter loop. For $m_X =$ 350 GeV and $m_{E_i} = 400$ GeV, we can account for the deficit in the $a_\mu = 8\times 10^{-10}$ if $y^{E_i\mu} \sim 2$–3 assuming the universal $y^{E_i\mu}$ and m_{E_i}. If we assume flavor conserving Yukawa, $y \sim 5$ is needed. For such a large Yukawa coupling, however, we have large cross section for DM annihilation into lepton pair through the t-channel exchange of E_i. Therefore when the muon $(g-2)_\mu$ is explained by the dark leptons within our model, the thermal relic density of X is too small and we need another component of DM. Therefore we don't consider this possibility any more in this letter.

3.4. Stability of the potential

Here we briefly discuss the stability of the scalar potential. The one-loop beta functions of the Yukawa coupling y^F and λ_ϕ are given by [128]

$$\beta_{y^F} = y^F\left[3(2N_c^F+1)(y^F)^2 - \frac{18}{5}Q_F^2 g_1^2 - 8g_3^2\right], \quad (28)$$
$$\beta_{\lambda_\Phi} = 8\lambda_\Phi\sum_F N_c^F(y^F)^2 + 18\lambda_\Phi^2 - 8\sum_F N_c^F(y^F)^4 \quad (29)$$

where $g_{1(3)}$ are gauge couplings for SU(1)$_Y$(SU(3)) and the $\overline{\rm MS}$ scheme is applied. As a rough estimation, we ignore the running of gauge couplings in the energy range of $O(1)$ TeV to $O(10)$ TeV since the moderate running of gauge couplings in the RHS of Eq. (28) does not make significant changes for the running behavior of y^F and λ_Φ. In Fig. 7, we show the renormalization group running of λ_Φ where we took $\lambda_\Phi = \{1.3, 1.4, 1.5\}$ as reference points at $\mu = 1$ TeV and assumed universal Yukawa couplings $y^F = 1.2$ at the same μ for simplicity. We thus find that λ_Φ cannot be too small or too large to stabilize the potential. Also relative magnitude between y^F and λ_Φ changes the running property significantly, which can be tuned by changing U(1)$_X$ charge of Φ, $a+b$, according to Eq. (15) and (16). By tuning the parameters, the stability of the potential can be achieved up to ~ 10 TeV. The complete analysis is beyond the scope of this letter and we left it as future work.

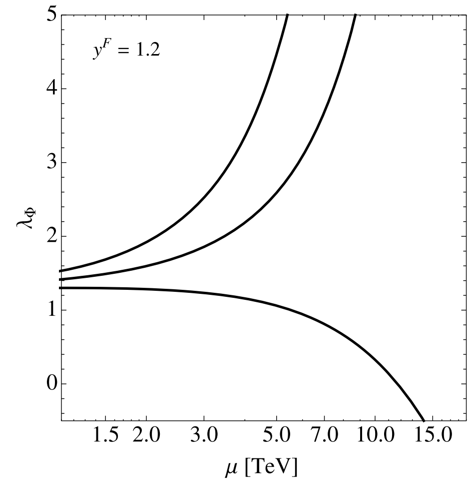

Fig. 7. The running of λ_Φ according to Eq. (28) and (29) where we adopted $y^F = 1.2$ and $\lambda_\Phi = \{1.3, 1.4, 1.5\}$ at $\mu = 1$ TeV as reference points.

3.5. Future tests of this model

The model presented in this letter can be tested at the upcoming LHC experiments by searching for a pair of dark photons around $m_{Z'Z'} \sim 750$ GeV in the following channels:

$$pp \to \phi \to Z'Z'$$
$$Z'Z' \to 4j\,,\, 2j+ll\,,\, 2j+\not{E}_T,\, 4l\,,\, 2l+\not{E}_T\,,$$

where $\not{E}_T$ is from $\nu\bar{\nu}$ pair. Note that the total decay width of dark photon Z' should be very narrow, $\Gamma_{\rm tot}(Z')/m_{Z'} \lesssim 10^{-4}$. If the current ATLAS result on $\Gamma_\phi \sim 45$ GeV is confirmed in the future, our model predicts that the main decay channel of dark Higgs ϕ should be a pair of dark photon, with a large cross section, $\sigma(\phi \to Z'Z') \approx O(5$–$40)$ pb (see Fig. 1) at the LHC@$\sqrt{s} = 13$ TeV. Therefore a dedicated search for dark photon pair could confirm or exclude our model.

Our model also opens widely a new window for DM model building, especially the Higgs portal DM. By assuming that the dark sector matter fields carry nonzero SM charges, the collider signatures become richer and also the Higgs signal strength can be different from the usual Higgs portal DM models in the presence of the mixing between the dark Higgs and the SM Higgs bosons. Our model can satisfy all the constraints from (in)direct search bounds as well as DM searches at colliders.

4. Conclusion

In this letter, we proposed a new dark matter model with 3 generations of dark fermions that are chiral under new dark U(1)$_X$ gauge symmetry. Both dark photon and the dark fermions get their masses entirely from spontaneous breaking of dark U(1)$_X$ gauge symmetry from the nonzero VEV of Φ, and dark Higgs boson ϕ appears as a result. Then the diphoton excess at 750 GeV is identified as the dark Higgs boson from U(1)$_X$ symmetry breaking. The main decay mode of ϕ is a pair of dark photon ($\phi \to Z'Z'$) and could be probed at the LHC by searching for $4j$, $2j+ll$, $2j+\not{E}_T$, $4l$, $2l+\not{E}_T$. It is remained to be seen if the 750 GeV diphoton excess survives in the future data accumulation. If it does, the model presented in this letter would be an interesting possibility without conflict with the known experimental constraints even for large decay width of ϕ. In particular the production and the decay of the dark Higgs boson ϕ involves dark fermions in the triangle loops, opening a new window to the dark sector.

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References

[1] The ATLAS Collaboration, ATLAS-CONF-2015-081.
[2] CMS Collaboration, CMS-PAS-EXO-15-004.
[3] The ATLAS Collaboration, ATLAS-CONF-2016-018.
[4] CMS Collaboration, CMS-PAS-EXO-16-018.
[5] Y. Mambrini, G. Arcadi, A. Djouadi, Phys. Lett. B 755 (2016) 426, arXiv:1512.04913 [hep-ph].
[6] M. Backovic, A. Mariotti, D. Redigolo, J. High Energy Phys. 1603 (2016) 157, arXiv:1512.04917 [hep-ph].
[7] R. Franceschini, et al., J. High Energy Phys. 1603 (2016) 144, arXiv:1512.04933 [hep-ph].
[8] J. Ellis, S.A.R. Ellis, J. Quevillon, V. Sanz, T. You, J. High Energy Phys. 1603 (2016) 176, arXiv:1512.05327 [hep-ph].
[9] B. Dutta, Y. Gao, T. Ghosh, I. Gogoladze, T. Li, Phys. Rev. D 93 (5) (2016) 055032, arXiv:1512.05439 [hep-ph].
[10] J.M. No, V. Sanz, J. Setford, arXiv:1512.05700 [hep-ph].
[11] W. Chao, R. Huo, J.H. Yu, arXiv:1512.05738 [hep-ph].
[12] L. Bian, N. Chen, D. Liu, J. Shu, arXiv:1512.05759 [hep-ph].
[13] W. Chao, arXiv:1512.06297 [hep-ph].
[14] C. Han, H.M. Lee, M. Park, V. Sanz, Phys. Lett. B 755 (2016) 371, arXiv:1512.06376 [hep-ph].
[15] X.J. Bi, Q.F. Xiang, P.F. Yin, Z.H. Yu, arXiv:1512.06787 [hep-ph].
[16] W.S. Cho, D. Kim, K. Kong, S.H. Lim, K.T. Matchev, J.C. Park, M. Park, arXiv:1512.06824 [hep-ph].
[17] J.M. Cline, Z. Liu, arXiv:1512.06827 [hep-ph].
[18] M. Bauer, M. Neubert, arXiv:1512.06828 [hep-ph].
[19] D. Barducci, A. Goudelis, S. Kulkarni, D. Sengupta, arXiv:1512.06842 [hep-ph].
[20] U. Kumar Dey, S. Mohanty, G. Tomar, Phys. Lett. B 756 (2016) 384, arXiv:1512.07212 [hep-ph].
[21] P.S.B. Dev, D. Teresi, arXiv:1512.07243 [hep-ph].
[22] S. Moretti, K. Yagyu, Phys. Rev. D 93 (5) (2016) 055043, arXiv:1512.07462 [hep-ph].
[23] K.M. Patel, P. Sharma, arXiv:1512.07468 [hep-ph].
[24] H. Davoudiasl, C. Zhang, Phys. Rev. D 93 (5) (2016) 055006, arXiv:1512.07672 [hep-ph].
[25] H. Han, S. Wang, S. Zheng, arXiv:1512.07992 [hep-ph].
[26] J.C. Park, S.C. Park, arXiv:1512.08117 [hep-ph].
[27] G. Li, Y.n. Mao, Y.L. Tang, C. Zhang, Y. Zhou, S.h. Zhu, arXiv:1512.08255 [hep-ph].
[28] W. Chao, arXiv:1512.08484 [hep-ph].
[29] C.W. Chiang, M. Ibe, T.T. Yanagida, arXiv:1512.08895 [hep-ph].
[30] X.J. Huang, W.H. Zhang, Y.F. Zhou, arXiv:1512.08992 [hep-ph].
[31] S. Kanemura, K. Nishiwaki, H. Okada, Y. Orikasa, S.C. Park, R. Watanabe, arXiv:1512.09048 [hep-ph].
[32] A.E.C. Hernandez, arXiv:1512.09092 [hep-ph].
[33] K. Kaneta, S. Kang, H.S. Lee, arXiv:1512.09129 [hep-ph].
[34] T. Nomura, H. Okada, Phys. Lett. B 755 (2016) 306, arXiv:1601.00386 [hep-ph].
[35] P. Ko, Y. Omura, C. Yu, arXiv:1601.00586 [hep-ph].
[36] K. Ghorbani, H. Ghorbani, arXiv:1601.00602 [hep-ph].
[37] D. Palle, arXiv:1601.00618 [physics.gen-ph].
[38] T. Modak, S. Sadhukhan, R. Srivastava, Phys. Lett. B 756 (2016) 405, arXiv:1601.00836 [hep-ph].
[39] F.F. Deppisch, C. Hati, S. Patra, P. Pritimita, U. Sarkar, arXiv:1601.00952 [hep-ph].
[40] A. Berlin, Phys. Rev. D 93 (5) (2016) 055015, arXiv:1601.01381 [hep-ph].
[41] S. Bhattacharya, S. Patra, N. Sahoo, N. Sahu, arXiv:1601.01569 [hep-ph].
[42] F. D'Eramo, J. de Vries, P. Panci, arXiv:1601.01571 [hep-ph].
[43] D. Borah, S. Patra, S. Sahoo, arXiv:1601.01828 [hep-ph].
[44] Y. Bai, J. Berger, R. Lu, arXiv:1512.05779 [hep-ph].
[45] R. Martinez, F. Ochoa, C.F. Sierra, arXiv:1512.05617 [hep-ph].
[46] S. Chang, Phys. Rev. D 93 (5) (2016) 055016, arXiv:1512.06426 [hep-ph].
[47] T.F. Feng, X.Q. Li, H.B. Zhang, S.M. Zhao, arXiv:1512.06696 [hep-ph].
[48] S.M. Boucenna, S. Morisi, A. Vicente, arXiv:1512.06878 [hep-ph].
[49] A.E.C. Hernandez, I. Nisandzic, arXiv:1512.07165 [hep-ph].
[50] G.M. Pelaggi, A. Strumia, E. Vigiani, J. High Energy Phys. 1603 (2016) 025, arXiv:1512.07225 [hep-ph].
[51] J. de Blas, J. Santiago, R. Vega-Morales, arXiv:1512.07229 [hep-ph].
[52] W.C. Huang, Y.L.S. Tsai, T.C. Yuan, arXiv:1512.07268 [hep-ph].
[53] K. Das, S.K. Rai, arXiv:1512.07789 [hep-ph].
[54] Q.H. Cao, Y. Liu, K.P. Xie, B. Yan, D.M. Zhang, arXiv:1512.08441 [hep-ph].
[55] Y. Jiang, Y.Y. Li, T. Liu, arXiv:1512.09127 [hep-ph].
[56] A. Dasgupta, M. Mitra, D. Borah, arXiv:1512.09202 [hep-ph].
[57] A. Karozas, S.F. King, G.K. Leontaris, A.K. Meadowcroft, arXiv:1601.00640 [hep-ph].
[58] K. Harigaya, Y. Nomura, Phys. Lett. B 754 (2016) 151, arXiv:1512.04850 [hep-ph].
[59] A. Angelescu, A. Djouadi, G. Moreau, Phys. Lett. B 756 (2016) 126, arXiv:1512.04921 [hep-ph].
[60] Y. Nakai, R. Sato, K. Tobioka, arXiv:1512.04924 [hep-ph].
[61] S. Knapen, T. Melia, M. Papucci, K. Zurek, arXiv:1512.04928 [hep-ph].
[62] D. Buttazzo, A. Greljo, D. Marzocca, Eur. Phys. J. C 76 (3) (2016) 116, arXiv:1512.04929 [hep-ph].
[63] A. Pilaftsis, Phys. Rev. D 93 (1) (2016) 015017, arXiv:1512.04931 [hep-ph].
[64] S. Di Chiara, L. Marzola, M. Raidal, arXiv:1512.04939 [hep-ph].
[65] T. Higaki, K.S. Jeong, N. Kitajima, F. Takahashi, Phys. Lett. B 755 (2016) 13, arXiv:1512.05295 [hep-ph].
[66] S.D. McDermott, P. Meade, H. Ramani, Phys. Lett. B 755 (2016) 353, arXiv:1512.05326 [hep-ph].
[67] M. Low, A. Tesi, L.T. Wang, J. High Energy Phys. 1603 (2016) 108, arXiv:1512.05328 [hep-ph].
[68] B. Bellazzini, R. Franceschini, F. Sala, J. Serra, arXiv:1512.05330 [hep-ph].
[69] R.S. Gupta, S. Jager, Y. Kats, G. Perez, E. Stamou, arXiv:1512.05332 [hep-ph].
[70] C. Petersson, R. Torre, arXiv:1512.05333 [hep-ph].
[71] E. Molinaro, F. Sannino, N. Vignaroli, arXiv:1512.05334 [hep-ph].
[72] Q.H. Cao, Y. Liu, K.P. Xie, B. Yan, D.M. Zhang, arXiv:1512.05542 [hep-ph].
[73] S. Matsuzaki, K. Yamawaki, arXiv:1512.05564 [hep-ph].
[74] A. Kobakhidze, F. Wang, L. Wu, J.M. Yang, M. Zhang, arXiv:1512.05585 [hep-ph].
[75] P. Cox, A.D. Medina, T.S. Ray, A. Spray, arXiv:1512.05618 [hep-ph].
[76] D. Becirevic, E. Bertuzzo, O. Sumensari, R.Z. Funchal, arXiv:1512.05623 [hep-ph].
[77] S.V. Demidov, D.S. Gorbunov, arXiv:1512.05723 [hep-ph].
[78] S. Fichet, G. von Gersdorff, C. Royon, arXiv:1512.05751 [hep-ph].
[79] D. Curtin, C.B. Verhaaren, Phys. Rev. D 93 (5) (2016) 055011, arXiv:1512.05753 [hep-ph].
[80] J. Chakrabortty, A. Choudhury, P. Ghosh, S. Mondal, T. Srivastava, arXiv:1512.05767 [hep-ph].
[81] A. Ahmed, B.M. Dillon, B. Grzadkowski, J.F. Gunion, Y. Jiang, arXiv:1512.05771 [hep-ph].
[82] P. Agrawal, J. Fan, B. Heidenreich, M. Reece, M. Strassler, arXiv:1512.05775 [hep-ph].
[83] C. Csaki, J. Hubisz, J. Terning, Phys. Rev. D 93 (3) (2016) 035002, arXiv:1512.05776 [hep-ph].
[84] A. Falkowski, O. Slone, T. Volansky, J. High Energy Phys. 1602 (2016) 152, arXiv:1512.05777 [hep-ph].
[85] D. Aloni, K. Blum, A. Dery, A. Efrati, Y. Nir, arXiv:1512.05778 [hep-ph].
[86] E. Gabrielli, K. Kannike, B. Mele, M. Raidal, C. Spethmann, H. Veermae, Phys. Lett. B 756 (2016) 36, arXiv:1512.05961 [hep-ph].
[87] R. Benbrik, C.H. Chen, T. Nomura, Phys. Rev. D 93 (5) (2016) 055034, arXiv:1512.06028 [hep-ph].
[88] J.S. Kim, J. Reuter, K. Rolbiecki, R. Ruiz de Austri, Phys. Lett. B 755 (2016) 403, arXiv:1512.06083 [hep-ph].
[89] A. Alves, A.G. Dias, K. Sinha, Phys. Lett. B 757 (2016) 39, arXiv:1512.06091 [hep-ph].
[90] E. Megias, O. Pujolas, M. Quiros, arXiv:1512.06106 [hep-ph].
[91] L.M. Carpenter, R. Colburn, J. Goodman, arXiv:1512.06107 [hep-ph].
[92] J. Bernon, C. Smith, arXiv:1512.06113 [hep-ph].
[93] M.T. Arun, P. Saha, arXiv:1512.06335 [hep-ph].
[94] I. Chakraborty, A. Kundu, Phys. Rev. D 93 (5) (2016) 055003, arXiv:1512.06508 [hep-ph].
[95] R. Ding, L. Huang, T. Li, B. Zhu, arXiv:1512.06560 [hep-ph].
[96] H. Han, S. Wang, S. Zheng, arXiv:1512.06562 [hep-ph].
[97] X.F. Han, L. Wang, Phys. Rev. D 93 (5) (2016) 055027, arXiv:1512.06587 [hep-ph].
[98] M.x. Luo, K. Wang, T. Xu, L. Zhang, G. Zhu, Phys. Rev. D 93 (5) (2016) 055042, arXiv:1512.06670 [hep-ph].
[99] J. Chang, K. Cheung, C.T. Lu, Phys. Rev. D 93 (2016) 075013, arXiv:1512.06671 [hep-ph].
[100] D. Bardhan, D. Bhatia, A. Chakraborty, U. Maitra, S. Raychaudhuri, T. Samui, arXiv:1512.06674 [hep-ph].
[101] O. Antipin, M. Mojaza, F. Sannino, arXiv:1512.06708 [hep-ph].
[102] F. Wang, L. Wu, J.M. Yang, M. Zhang, arXiv:1512.06715 [hep-ph].
[103] J. Cao, C. Han, L. Shang, W. Su, J.M. Yang, Y. Zhang, Phys. Lett. B 755 (2016) 456, arXiv:1512.06728 [hep-ph].

[104] F.P. Huang, C.S. Li, Z.L. Liu, Y. Wang, arXiv:1512.06732 [hep-ph].
[105] W. Liao, H.q. Zheng, arXiv:1512.06741 [hep-ph].
[106] J.J. Heckman, Nucl. Phys. B 906 (2016) 231, arXiv:1512.06773 [hep-ph].
[107] M. Dhuria, G. Goswami, arXiv:1512.06782 [hep-ph].
[108] J.S. Kim, K. Rolbiecki, R.R. de Austri, arXiv:1512.06797 [hep-ph].
[109] L. Berthier, J.M. Cline, W. Shepherd, M. Trott, arXiv:1512.06799 [hep-ph].
[110] M. Chala, M. Duerr, F. Kahlhoefer, K. Schmidt-Hoberg, Phys. Lett. B 755 (2016) 145, arXiv:1512.06833 [hep-ph].
[111] C.W. Murphy, arXiv:1512.06976 [hep-ph].
[112] A. Belyaev, G. Cacciapaglia, H. Cai, T. Flacke, A. Parolini, H. Serodio, arXiv:1512.07242 [hep-ph].
[113] M. Badziak, arXiv:1512.07497 [hep-ph].
[114] S. Chakraborty, A. Chakraborty, S. Raychaudhuri, arXiv:1512.07527 [hep-ph].
[115] Q.H. Cao, S.L. Chen, P.H. Gu, arXiv:1512.07541 [hep-ph].
[116] W. Altmannshofer, J. Galloway, S. Gori, A.L. Kagan, A. Martin, J. Zupan, arXiv:1512.07616 [hep-ph].
[117] M. Cvetic, J. Halverson, P. Langacker, arXiv:1512.07622 [hep-ph].
[118] J. Gu, Z. Liu, Phys. Rev. D 93 (2016) 075006, arXiv:1512.07624 [hep-ph].
[119] B.C. Allanach, P.S.B. Dev, S.A. Renner, K. Sakurai, arXiv:1512.07645 [hep-ph].
[120] N. Craig, P. Draper, C. Kilic, S. Thomas, arXiv:1512.07733 [hep-ph].
[121] K. Cheung, P. Ko, J.S. Lee, J. Park, P.Y. Tseng, arXiv:1512.07853 [hep-ph].
[122] J. Liu, X.P. Wang, W. Xue, arXiv:1512.07885 [hep-ph].
[123] J. Zhang, S. Zhou, arXiv:1512.07889 [hep-ph].
[124] J.A. Casas, J.R. Espinosa, J.M. Moreno, arXiv:1512.07895 [hep-ph].
[125] L.J. Hall, K. Harigaya, Y. Nomura, J. High Energy Phys. 1603 (2016) 017, arXiv:1512.07904 [hep-ph].
[126] A. Salvio, A. Mazumdar, Phys. Lett. B 755 (2016) 469, arXiv:1512.08184 [hep-ph].
[127] D. Chway, R. Dermisek, T.H. Jung, H.D. Kim, arXiv:1512.08221 [hep-ph].
[128] M. Son, A. Urbano, arXiv:1512.08307 [hep-ph].
[129] Y.L. Tang, S.h. Zhu, arXiv:1512.08323 [hep-ph].
[130] H. An, C. Cheung, Y. Zhang, arXiv:1512.08378 [hep-ph].
[131] J. Cao, F. Wang, Y. Zhang, arXiv:1512.08392 [hep-ph].
[132] F. Wang, W. Wang, L. Wu, J.M. Yang, M. Zhang, arXiv:1512.08434 [hep-ph].
[133] C. Cai, Z.H. Yu, H.H. Zhang, arXiv:1512.08440 [hep-ph].
[134] J.E. Kim, Phys. Lett. B 755 (2016) 190, arXiv:1512.08467 [hep-ph].
[135] J. Gao, H. Zhang, H.X. Zhu, arXiv:1512.08478 [hep-ph].
[136] X.J. Bi, et al., arXiv:1512.08497 [hep-ph].
[137] F. Goertz, J.F. Kamenik, A. Katz, M. Nardecchia, arXiv:1512.08500 [hep-ph].
[138] L.A. Anchordoqui, I. Antoniadis, H. Goldberg, X. Huang, D. Lust, T.R. Taylor, Phys. Lett. B 755 (2016) 312, arXiv:1512.08502 [hep-ph].
[139] P.S.B. Dev, R.N. Mohapatra, Y. Zhang, J. High Energy Phys. 1602 (2016) 186, arXiv:1512.08507 [hep-ph].
[140] N. Bizot, S. Davidson, M. Frigerio, J.-L. Kneur, J. High Energy Phys. 1603 (2016) 073, arXiv:1512.08508 [hep-ph].
[141] L.E. Ibanez, V. Martin-Lozano, arXiv:1512.08777 [hep-ph].
[142] S.K. Kang, J. Song, arXiv:1512.08963 [hep-ph].
[143] Y. Hamada, T. Noumi, S. Sun, G. Shiu, arXiv:1512.08984 [hep-ph].
[144] S. Kanemura, N. Machida, S. Odori, T. Shindou, arXiv:1512.09053 [hep-ph].
[145] I. Low, J. Lykken, arXiv:1512.09089 [hep-ph].
[146] L. Marzola, A. Racioppi, M. Raidal, F.R. Urban, H. Veermae, J. High Energy Phys. 1603 (2016) 190, arXiv:1512.09136 [hep-ph].
[147] E. Ma, arXiv:1512.09159 [hep-ph].
[148] S. Jung, J. Song, Y.W. Yoon, arXiv:1601.00006 [hep-ph].
[149] C.T. Potter, arXiv:1601.00240 [hep-ph].
[150] E. Palti, arXiv:1601.00285 [hep-ph].
[151] X.F. Han, L. Wang, L. Wu, J.M. Yang, M. Zhang, Phys. Lett. B 756 (2016) 309, arXiv:1601.00534 [hep-ph].
[152] U. Danielsson, R. Enberg, G. Ingelman, T. Mandal, arXiv:1601.00624 [hep-ph].
[153] W. Chao, arXiv:1601.00633 [hep-ph].
[154] C. Csaki, J. Hubisz, S. Lombardo, J. Terning, arXiv:1601.00638 [hep-ph].
[155] A.E.C. Hernandez, I.d.M. Varzielas, E. Schumacher, arXiv:1601.00661 [hep-ph].
[156] B. Dutta, Y. Gao, T. Ghosh, I. Gogoladze, T. Li, Q. Shafi, J.W. Walker, arXiv:1601.00866 [hep-ph].
[157] H. Ito, T. Moroi, Y. Takaesu, Phys. Lett. B 756 (2016) 147, arXiv:1601.01144 [hep-ph].
[158] H. Zhang, arXiv:1601.01355 [hep-ph].
[159] I. Sahin, arXiv:1601.01676 [hep-ph].
[160] S. Fichet, G. von Gersdorff, C. Royon, arXiv:1601.01712 [hep-ph].
[161] D. Stolarski, R. Vega-Morales, Phys. Rev. D 93 (5) (2016) 055008, arXiv:1601.02004 [hep-ph].
[162] S. Baek, P. Ko, W.I. Park, Phys. Lett. B 747 (2015) 255, arXiv:1407.6588 [hep-ph].
[163] P. Ko, Y. Tang, J. Cosmol. Astropart. Phys. 1405 (2014) 047, arXiv:1402.6449.
[164] P. Ko, Y. Tang, J. Cosmol. Astropart. Phys. 1501 (2015) 023, arXiv:1407.5492 [hep-ph].
[165] J. Guo, Z. Kang, P. Ko, Y. Orikasa, Phys. Rev. D 91 (11) (2015) 115017, arXiv:1502.00508 [hep-ph].
[166] S. Baek, P. Ko, W.I. Park, J. High Energy Phys. 1307 (2013) 013, arXiv:1303.4280 [hep-ph].
[167] S. Choi, S. Jung, P. Ko, J. High Energy Phys. 1310 (2013) 225, arXiv:1307.3948 [hep-ph];
K. Cheung, P. Ko, J.S. Lee, P.Y. Tseng, J. High Energy Phys. 1510 (2015) 057, arXiv:1507.06158 [hep-ph];
K. Cheung, P. Ko, J.S. Lee, J. Park, P.Y. Tseng, arXiv:1512.07853 [hep-ph].
[168] J. Jaeckel, M. Jankowiak, M. Spannowsky, Phys. Dark Universe 2 (2013) 111, arXiv:1212.3620 [hep-ph].
[169] A. Belyaev, N.D. Christensen, A. Pukhov, Comput. Phys. Commun. 184 (2013) 1729, arXiv:1207.6082 [hep-ph].
[170] P.M. Nadolsky, H.L. Lai, Q.H. Cao, J. Huston, J. Pumplin, D. Stump, W.K. Tung, C.-P. Yuan, Phys. Rev. D 78 (2008) 013004, arXiv:0802.0007 [hep-ph].
[171] J.F. Gunion, H.E. Haber, G.L. Kane, S. Dawson, Front. Phys. 80 (2000) 1.
[172] J.M. Cline, K. Kainulainen, P. Scott, C. Weniger, Phys. Rev. D 88 (2013) 055025, arXiv:1306.4710 [hep-ph];
J.M. Cline, K. Kainulainen, P. Scott, C. Weniger, Phys. Rev. D 92 (3) (2015) 039906, Erratum.
[173] G. Belanger, F. Boudjema, A. Pukhov, A. Semenov, arXiv:1407.6129 [hep-ph].
[174] P.A.R. Ade, et al., Planck Collaboration, Astron. Astrophys. (2014), arXiv:1303.5076 [astro-ph.CO].
[175] F. Giacchino, A. Ibarra, L.L. Honorez, M.H.G. Tytgat, S. Wild, J. Cosmol. Astropart. Phys. 1602 (02) (2016) 002, arXiv:1511.04452 [hep-ph].
[176] J. Hisano, R. Nagai, N. Nagata, J. High Energy Phys. 1505 (2015) 037, arXiv:1502.02244 [hep-ph].