



# Natural explanation for 130 GeV photon line within vector boson dark matter model

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## ABSTRACT

We present a dark matter model for explaining the observed 130 GeV photon line from the galaxy center. The dark matter candidate is a vector boson of mass  $m_V$  with a dimensionless coupling to the photon and Z boson. The model predicts a double line photon spectrum at energies equal to  $m_V$  and  $m_V(1 - m_Z^2/4m_V^2)$  originating from the dark matter annihilation. The same coupling leads to a mono-photon plus missing energy signal at the LHC. The entire perturbative parameter space can be probed by the 14 TeV LHC run. The model has also a good prospect of being probed by direct dark matter searches as well as the measurement of the rates of  $h \rightarrow \gamma\gamma$  and  $h \rightarrow Z\gamma$  at the LHC.

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## 0. Introduction

Recently a monochromatic photon line at 130 GeV has been found in the Fermi-LAT data in the vicinity of the galactic center [1,2]. A possible explanation for this line can be the annihilation of a Dark Matter (DM) pair of mass 130 GeV directly to a photon pair with cross section equal to  $10^{-37}$  cm<sup>2</sup>. Extensive studies have been carried out in the literature to explain this line [3,4]. In these models, the DM is taken to be either a scalar or a fermion so the annihilation to a photon pair cannot take place at a tree level with renormalizable couplings. If the charged particles propagating in the loop are light enough, their direct production via DM annihilation typically exceeds the bounds [5].

However, within Vector Dark Matter (VDM) models novel features appear. Such VDM models have recently received attention in the literature [6,7]. Here, we show that the vector boson DM candidate has a unique advantage for explaining the 130 GeV photon line because unlike a neutral scalar or spinor, a neutral vector boson can directly couple to photon through a large unsuppressed dimensionless gauge invariant coupling. In this Letter, we introduce a simple model that explains the 130 GeV line. The model predicts accessible new signals for the LHC and can explain the slight excess of  $Br(h \rightarrow \gamma\gamma)$ . In Section 1, we introduce the model and

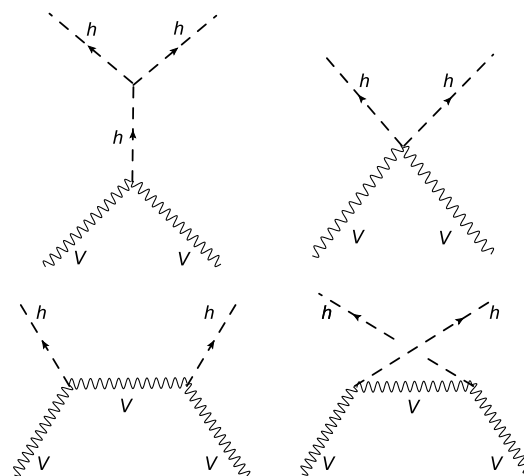


Fig. 1. Annihilation of the  $V$  pair to a Higgs pair via  $\lambda_1$  coupling.

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discuss the direct and indirect DM searches within this model. In Section 2, we compute the contribution to the Higgs decay to a photon pair. In Section 3, we discuss the potential signal at colliders. Results are summarized in Section 4.

## 1. The model

The model adds only a pair of neutral vector bosons  $V$  and  $V'$  with masses  $m_V < m_{V'}$  to the Standard Model (SM). We impose

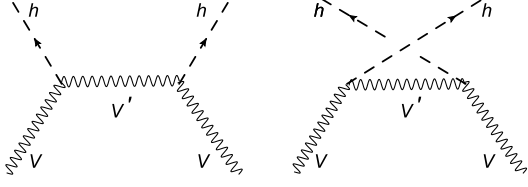


Fig. 2. Annihilation of the  $V$  pair to a Higgs pair via the  $\lambda_3$  coupling.

a  $Z_2$  symmetry under which only  $V$  and  $V'$  are odd so  $V$  is stable and therefore a potentially suitable dark matter candidate. To avoid negative norm modes, we take their kinetic terms to be of antisymmetric form: i.e.,  $-[V_{\mu\nu}V^{\mu\nu} + V'_{\mu\nu}V'^{\mu\nu}]/4$  where  $V_{\mu\nu}^{(\prime)} \equiv \partial_\mu V_\nu^{(\prime)} - \partial_\nu V_\mu^{(\prime)}$ . In a general basis, the mass terms are

$$\frac{m_1^2}{2} V \cdot V + \frac{m_2^2}{2} V' \cdot V' + m_3^2 V \cdot V' \quad (1)$$

and the dimensionless gauge and  $Z_2$  invariant couplings to the Higgs are

$$\frac{\lambda_1}{2} |H|^2 V_\mu V^\mu + \frac{\lambda_2}{2} |H|^2 V'_\mu V'^\mu + \lambda_3 |H|^2 V'_\mu V^\mu. \quad (2)$$

Without loss of generality we can go to a basis in which  $V$  and  $V'$  are mass eigenstates with masses  $m_V^2$  and  $m_{V'}^2$ . Notice that in this basis  $\lambda_3$  can be nonzero but  $\lambda_3 v_h^2/2 + m_3^2 = 0$ . Although the  $\lambda_i$  couplings are dimensionless, if  $V_\mu$  are not gauge bosons, they will be non-renormalizable [8]. We can promote  $V_\mu$  and  $V'_\mu$  to gauge bosons of two new  $U(1)$  gauge symmetries as prescribed in the Stückelberg mechanism, by replacing  $V_\mu$  and  $V'_\mu$  in these terms as well as in mass terms with  $\partial_\mu \theta_V - V_\mu$  and  $\partial_\mu \theta_{V'} - V'_\mu$ . We will work in a gauge that the Stückelberg fields  $\theta_V$  and  $\theta_{V'}$  are eaten by the longitudinal components of  $V$  and  $V'$ . For the purpose of this Letter, it is enough to take  $\lambda_i$  Wilsonian effective couplings below some cut-off  $\Lambda$ . The new vector boson can have quartic couplings with each other but these couplings are not relevant for our discussion. Notice that  $\lambda_i$  should be real to guarantee the Hermiticity of the potential; however, because of the presence of quartic vector boson coupling, we do not know a priori their sign.

The  $\lambda_1$  and  $\lambda_3$  couplings give rise to annihilation of the  $V$  pair (see Figs. 1, 2). Setting  $\lambda_3 = 0$ , we find

$$\begin{aligned} \langle \sigma(VV \rightarrow hh) v_{rel} \rangle &= \frac{\lambda_1^2 \sqrt{m_V^2 - m_h^2}}{576\pi m_V^3} \\ &\times \left\{ \frac{[(4m_V^2 - m_h^2)(m_V^2 + 2\lambda_1 v_h^2) - \frac{3}{2} \tan \theta_W m_V^2 m_h^2]^2}{m_V^4 (m_H^2 - 4m_V^2)^2} \right. \\ &\left. + 2 \left[ 1 + \frac{2\lambda_1 v_h^2}{2m_V^2 - m_h^2} + \frac{3 \tan \theta_W m_h^2}{2(-4m_V^2 + m_h^2)} \right]^2 \right\}. \quad (3) \end{aligned}$$

The vacuum expectation value of Higgs is denoted by  $v_h = 246$  GeV. Moreover, like other Higgs portal models, the  $\lambda_1$  coupling gives rise to the annihilation of the  $V$  pair via an  $s$ -channel Higgs exchange diagram with cross section

$$\langle \sigma(VV \rightarrow f\bar{f}) v_{rel} \rangle = \frac{\lambda_1^2 v_h^2 \Gamma(h^* \rightarrow f\bar{f})}{3m_V (4m_V^2 - m_h^2)^2},$$

where  $f\bar{f}$  can be  $W^+W^-$ ,  $ZZ$ ,  $b\bar{b}$  and etc.  $\Gamma(h^* \rightarrow f\bar{f})$  is the decay rate of a hypothetical SM-like Higgs ( $h^*$ ) with a mass equal to  $2m_V$  to  $f\bar{f}$ . To account for the observed dark matter abundance

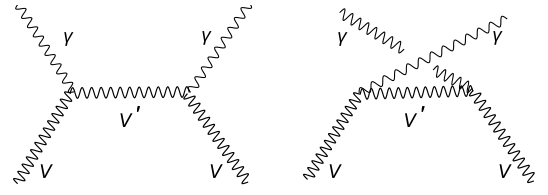


Fig. 3. Annihilation of the  $V$  pair to a photon pair.

within the thermal production scenario [9], the total DM pair annihilation cross section should be equal to 1 pb. Setting the sum of cross sections of these modes equal to 1 pb and  $m_V = 130$  GeV, we find  $\lambda_1 = 0.09$ . Notice that the total annihilation cross section falls well below the  $10^{-25}$  cm<sup>3</sup>/s bound from Fermi-LAT continuum gamma-ray constraint [10] as well as the bounds from the PAMELA constraint on the anti-proton flux [11]. More data from Fermi-LAT and AMS02 may make it possible to probe the model in future. The  $\lambda_3$  coupling also gives rise to annihilation to a Higgs pair via a  $t$ - and  $u$ -channel  $V'$  exchange (see Fig. 2). Fixing  $\lambda_1 = 0$ , we find

$$\begin{aligned} \langle \sigma(VV \rightarrow hh) v_{rel} \rangle &= \frac{\lambda_3^4 v_h^4 \sqrt{m_V^2 - m_h^2}}{144\pi m_V^3} \\ &\times \left\{ \frac{1}{m_{V'}^4} + \frac{2}{(m_V^2 - m_h^2 + m_{V'}^2)^2} \right\}. \quad (4) \end{aligned}$$

Taking  $\sigma(VV \rightarrow hh) = 1$  pb, for  $\lambda_1 = 0$  and  $m_V = 130$  GeV, we find  $\lambda_3 \simeq 0.4(m_V/300 \text{ GeV})$ . Notice that for  $\lambda_1 = 0$  and  $m_{V'} > O(3 \text{ TeV})$  the required  $\lambda_3$  enters the non-perturbative regime.

The symmetries of the model also allow the presence of the following terms<sup>1</sup>:

$$g_V B^{\mu\nu} V_\mu V'_\nu + g'_V \epsilon^{\mu\nu\alpha\beta} B_{\mu\nu} V_\alpha V'_\beta, \quad (5)$$

where  $B^{\mu\nu}$  is the field strength associated with the hypercharge gauge boson:  $B_{\mu\nu} = \cos \theta_W F_{\mu\nu} - \sin \theta_W Z_{\mu\nu}$ . Again although  $g_V$  and  $g'_V$  are dimensionless, if  $V_\mu$  and  $V'_\mu$  are not promoted to gauge bosons, these couplings will be non-renormalizable [14]. Again using the Stückelberg mechanism, these terms can be made gauge invariant. The  $g'_V$  coupling is the familiar “generalized Chern–Simons” term [13] which can arise by integrating out heavy chiral fermions charged both under the hypercharge and the new  $U(1)$  gauge symmetries. The  $g'_V$  coupling can be large contrary to the non-decoupling theorem [14]. A similar term has also been employed in [3] to explain the 130 GeV line. In the following, we study the phenomenology of these two terms.

The  $g_V$  and  $g'_V$  couplings respectively lead to (see Fig. 3)

$$\langle \sigma(V + V \rightarrow \gamma\gamma) v_{rel} \rangle = \frac{g_V'^4 \cos^4 \theta_W}{9\pi} \frac{R(x)}{m_V^2 x^2 (1+x)^2}$$

in which  $x = (m_{V'}/m_V)^2$ . For the contribution from the  $g_V$  coupling,  $R(x) = (2 + 8x + 9x^2)/8$  and for that from the  $g'_V$  coupling,  $R(x) = 2(2 + x^2)$ . These couplings also induce annihilation to a  $Z\gamma$  pair as follows

$$\langle \sigma(V + V \rightarrow \gamma Z) v_{rel} \rangle = \frac{g_V'^4 \sin^2 2\theta_W (4y - 1)^3 f^{(\prime)}(y, y')}{9\pi 2^{12} m_V^2 y^4 y'^2 (1 - 2y - 2y')^2}$$

where

<sup>1</sup> When revising the present Letter, Ref. [12] appeared which has some overlap with our work.

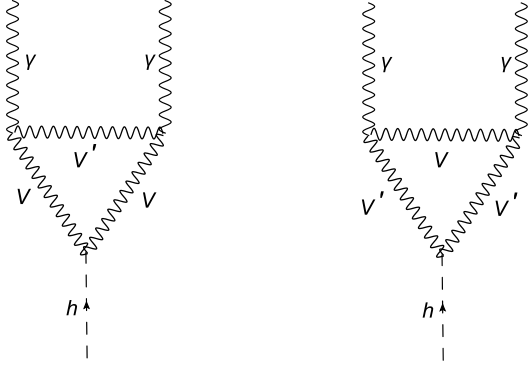


Fig. 4. Diagrams of Higgs decay to a photon pair via the  $\lambda_1$  and  $\lambda_2$  couplings.

$$f(y, y') = 32y^4 + y'^2 + 16y^3(8y' - 3) + 6y^2(24y'^2 - 16y' + 3) + y(8y'^2 - 8y' + 1)$$

and

$$f'(y, y') = 1/2 + 64y^4 + 32y'^2 - 64y^3(1 + 16y') + 4y(64y'^2 - 1) + 16y^2(1 + 16y' + 160y'^2),$$

in which  $y = (m_V/m_Z)^2$  and  $y' = (m_{V'}/m_Z)^2$ . We therefore expect two photon lines: one photon line at  $m_V$  and another at  $m_V(1 - m_Z^2/4m_V^2)$  with an intensity suppressed by  $\sigma(V + V \rightarrow \gamma Z)/[2\sigma(V + V \rightarrow \gamma\gamma)] < (\tan^2\theta_W) = 0.3$  irrespective of the ratio  $g_V/g_{V'}$ . In fact, the observation favors double line structure over a single line [2]; however, more data is required to resolve such a double line feature [15]. From now on, we take  $m_V = 130$  GeV and  $\sigma(V + V \rightarrow \gamma\gamma) = 10^{-37}$  cm<sup>2</sup>. For  $m_{V'} \geq 300$  GeV, this yields  $g_V \simeq 0.27(m_{V'}/300$  GeV) for the  $g_V$ -dominated range and  $g_{V'} \simeq 0.24(m_{V'}/300$  GeV) for the  $g_{V'}$ -dominated range. As long as  $m_{V'} < a$  few TeV, the required values of  $g_V$  and  $g_{V'}$  will remain in the perturbative regime.

Through the  $\lambda_1$  coupling, the dark matter interacts with nuclei with cross section of

$$\sigma_{SI}(V + N \rightarrow V + N) = \frac{\lambda_1^2 f^2 m_N^2 m_r^2}{4\pi m_V^2 m_h^4}$$

where  $m_N$  is the mass of a nucleon and  $m_r = m_N m_V / (m_V + m_N)$  is the reduced mass for the collision.  $f$  parameterizes the nuclear matrix element ( $0.14 < f < 0.66$ ) [16]. Taking  $\lambda_1 = 0.09$ , we find  $\sigma = 4.4 \times 10^{-45} (f/0.27)^2$  cm<sup>2</sup>. This means under the condition that  $\lambda_1$  is the main contributor to the DM annihilation, the present bound from XENON100 [17] practically rules out  $f > 0.27$ . However for  $\lambda_1 \ll \lambda_3 \simeq 0.5(m_{V'}/300$  GeV), we do not expect an observable effect in the direct searches. If the mass splitting between  $V$  and  $V'$  is smaller than  $O(100$  keV), the DM can interact inelastically with the  $g_V$  and  $g_{V'}$  couplings through a  $t$ -channel photon exchange. Small splitting can be justified by an approximate  $V \leftrightarrow V'$  symmetry. We do not however consider such a limit so the main interaction will be via the Higgs portal channel.

## 2. Higgs decay to a photon pair

The  $\lambda_1$  and  $\lambda_2$  couplings contribute to  $h \rightarrow \gamma\gamma$  via triangle diagrams within which  $V$  and  $V'$  propagate (see Fig. 4). For the  $g_V$  and  $g_{V'}$  couplings, the leading-log contribution of  $\lambda_1$  to the decay amplitude is

$$M(h \rightarrow \gamma\gamma) = g_V^{(2)} \frac{V_h \lambda_1 \cos^2\theta_W}{8\pi^2} g(x, z) \log \frac{\Lambda^2}{m_{V'}^2}, \quad (6)$$

where for the  $g_V$  contribution  $g(x, z) \equiv (13z - 5z^2/8 + z/x - 3x^2)$  while for the  $g_{V'}$  contribution,  $g(x, z) \equiv (13z - 5z^2/16 + z/2x - 6x^2)$ . In both cases,  $z = (m_H/m_V)^2$  and  $x = (m_{V'}/m_V)^2$ . Replacing  $\lambda_1 \rightarrow \lambda_2$  and  $m_V \leftrightarrow m_{V'}$ , we obtain the contribution of  $\lambda_2$ . These amplitudes have to be summed up with the SM triangle diagrams within which top quark and  $W$  boson propagate. Notice that our result is ultra-violet divergent. This is because  $g_V$  and  $\lambda_1$ , despite being dimensionless, are non-renormalizable [8]. For  $\lambda_1 \log \Lambda^2/m_{V'}^2 \sim 1$ , the contribution of  $\lambda_1$  will be comparable to that in the SM. The observed slight excess [18] can be attributed to this effect. Notice that if the excess is confirmed, the sign of  $\lambda_1$  can also be determined. If further data rules out the excess, a bound on  $\lambda_1 \log \Lambda^2/m_{V'}^2$  can be derived which for the value of  $\lambda_1$  found in previous section ( $\lambda_1 = 0.09$ ) can be interpreted as an upper bound on  $\Lambda$ . That is the scale of new physics giving rise to the effective  $g_V$  coupling can be constrained. In case that  $\lambda_3$  is the main contributor to the dark matter annihilation, the effect of  $\lambda_1$  can be arbitrarily small. As discussed, these two possibilities can be distinguished by direct dark matter searches.

With similar diagrams we predict a contribution to  $H \rightarrow Z\gamma$ . Since in this model the new particles are heavier than  $m_h$ , the Higgs cannot have invisible decay modes.

## 3. Direct production at the colliders

A pair of  $V$  and  $V'$  can be produced by the annihilation of a fermion ( $f$ ) and antifermion ( $\bar{f}$ ) pair via a  $s$ -channel photon exchange,

$$\sigma(f\bar{f} \rightarrow VV') = \frac{g_V^{(2)2} (eQ_f \cos\theta_W)^2}{12\pi N_c E_{cm}^6 m_V^2 m_{V'}^2} \mathcal{K} \mathcal{S}(E_{cm}, m_V, m_{V'}) \quad (7)$$

where  $\mathcal{K} = \sqrt{(E_{cm}^2 + m_V^2 - m_{V'}^2)^2 - 4m_V^2 E_{cm}^2}$ . For the  $g_V$  contribution, we obtain

$$\mathcal{S}(E_{cm}, m_V, m_{V'}) = [E_{cm}^2 + 2(m_V^2 + m_{V'}^2)][(E_{cm} - m_{V'})^2 - m_V^2] \times [(E_{cm} + m_{V'})^2 - m_V^2]$$

while for the  $g_{V'}$  coupling

$$\mathcal{S}(E_{cm}, m_V, m_{V'}) = [E_{cm}^4 + (m_V^2 - m_{V'}^2)^2](m_V^2 + m_{V'}^2) - 2E_{cm}^2(m_V^4 - 4m_V^2 m_{V'}^2 + m_{V'}^4).$$

Notice that the behavior of the cross section for  $E_{cm} \rightarrow \infty$  violates unitarity. This is because  $g_V$  and  $g_{V'}$  are effective couplings below  $\Lambda$ . There is also a subdominant contribution from  $g\bar{g} \rightarrow h^* \rightarrow VV'$  which can be neglected relative to  $f\bar{f} \rightarrow \gamma^* \rightarrow VV'$ . The energy of center in the LEP experiment was too low to allow the production of  $V$  and  $V'$  pair. However, in the LHC, the  $V$  and  $V'$  pair can be produced as long as we are in the perturbative regime; i.e., as long as  $m_{V'} < \text{few TeV}$ .

Regardless of the mass range,  $V'$  can decay to a photon and  $V$ . For  $g_{V'} = 0$  and nonzero  $g_V$

$$\Gamma(V' \rightarrow V + \gamma) = \frac{g_V^2 \cos^2\theta_W}{96\pi} \frac{(m_{V'}^2 - m_V^2)^3 (m_{V'}^2 + m_V^2)}{m_V^2 m_{V'}^5}.$$

For  $g_V = 0$  and nonzero  $g_{V'}$ ,  $g_V^2/96$  has to be replaced with  $g_{V'}^2/24$ . For both  $g_V$  and  $g_{V'}$  regimes, the signature of the  $V + V'$  production at the LHC will therefore be an energetic mono-photon plus missing energy which has only low background [19] and therefore enjoys a good discovery chance. There is also a decay mode to  $V + Z$  suppressed by  $\tan^2\theta_W$ . If the kinematics allows  $V'$  can decay to  $V + H$ ,  $V + W^- + W^+$  and  $V + 2H$ ; however, the decay

into  $V + \gamma$  will dominate. Using the parton distribution functions in [20], we have calculated  $\sigma(pp \rightarrow VV')$  and have found that for  $\sqrt{s} = 7$  TeV and  $m_{V'} = 200$  GeV and for the value of  $g_V = 0.19$  that induces the desired 130 line intensity,  $\sigma(p + p \rightarrow V + V') = 50$  fb which seems to be already excluded by the 7 TeV run of the LHC [19]. Thus, for  $g'_V = 0$ ,  $m_{V'}$  should be larger than 200 GeV. For  $m_{V'} < 500$  GeV and  $g'_V = 0.4(m_{V'}/500 \text{ GeV})$ , the cross section  $\sigma(p + p \rightarrow V + V')$  is larger than 50 fb so  $m_{V'}$  should be larger than 500 GeV. However, to draw a conclusive result a dedicated analysis with customized cuts is necessary. Taking  $\sqrt{s} = 8$  TeV (14 TeV) and  $m_{V'} = 1.5$  TeV and therefore  $g_V = 1.35$ , we have found  $\sigma(p + p \rightarrow V + V') = 0.5$  fb (90 fb). Similarly, for the case of  $g'_V$  contribution with  $g'_V = 1.16$  and  $m_{V'} = 1.5$  TeV, we have found  $\sigma(p + p \rightarrow V + V') = 2$  fb (60 fb). Thus, the LHC can probe almost the whole perturbative regime. Pairs of  $V + V'$  can be produced via  $gg \rightarrow h^* \rightarrow VV$  at the LHC. For  $\lambda_1 = 0.09$ , we have found the cross section to be 0.25 fb (0.8 fb) for 8 TeV (14 TeV) c.o.m energy.

#### 4. Conclusions

We have presented a model within which dark matter is composed of a new vector boson ( $V$ ) of mass 130 GeV such that through its annihilation the observed 130 GeV photon line from the galaxy center can be explained. The model also contains another vector boson ( $V'$ ) which together they can couple to the antisymmetric field strengths of the photon and  $Z$  boson. As shown in Eq. (5), two types of couplings are possible. Both these couplings lead to the annihilation of dark matter pair to two monochromatic lines: one line at 130 GeV and the other with an intensity suppressed relative to the first one by  $\sigma(VV \rightarrow \gamma Z)/[2\sigma(VV \rightarrow \gamma\gamma)] < 0.3$  at 114 GeV. Thus, by searching for such double line feature the model can be tested.  $V'$  has to have a mass smaller than a few TeV to account for the 130 GeV line in the perturbative regime. The same coupling can also lead to  $V + V'$  pair production at the LHC which will appear as mono-photon plus missing energy signal. For a given  $V'$  mass, the production rate is fixed. The present data seems to already rule out light  $V'$ . The entire perturbative region with  $m_{V'} < 1.5$  TeV can be probed by the 14 TeV run of the LHC so this model is testable with this method, too.

Within this model the dark matter pair mainly annihilates to a Higgs pair with a cross section equal to 1 pb to account for the observed dark matter abundance within the thermal dark matter scenario. This annihilation can take place with either  $\lambda_1$  coupling or the  $\lambda_3$  coupling defined in Eq. (2). If  $\lambda_1$  is responsible for this annihilation, we expect an observable effect in near future in direct searches for dark matter. In fact, the present bound on dark matter-nucleon scattering cross section can be accommodated only with small form factor.  $\lambda_1$  can also explain the small excess observed in  $h \rightarrow \gamma\gamma$ . It can also contribute to  $h \rightarrow Z\gamma$ . These observations can fix the sign of  $\lambda_1$ . However, if  $\lambda_1 \ll \lambda_3$ , such effects in the Higgs decay as well as direct dark matter searches disappear.

The couplings that lead to dark matter pair annihilation to the Higgs pair and  $\gamma\gamma$  pair are all dimensionless. Nonetheless, if the vector bosons are not gauge bosons, they will be non-renormalizable leading to ultra-violet infinities and violation of unitarity. Thus, these couplings are only effective at low energies. However, as shown in [14], the “generalized Chern–Simons coupling”,  $g'_V$  can be large. Using the Stückelberg mechanism, these vector bosons can be made  $U(1)$  gauge bosons, removing the cut-off dependence of  $h \rightarrow \gamma\gamma$  and violation of unitarity in the  $V + V'$  production at large center of mass energies.

If further data confirms the existence of the  $\gamma$  line at 130 GeV, our model can provide a testable explanation with rich phenomenology. If however this line disappears with further data still the model has interesting features worth exploration. Absence of any line would set an upper bound on  $g_V$  and  $g'_V$ . If a photon line at a different energy appears, our model with  $m_V$  equal to the energy of the new line can provide an explanation.

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