Fermi gamma ray line at 130 GeV from axion-mediated dark matter

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(Received 29 July 2012; published 2 November 2012)

We consider a singlet Dirac fermion with Peccei-Quinn (PQ) symmetry as dark matter. A singlet complex scalar is introduced to mediate between dark matter and the Standard Model through Higgs portal interaction and electroweak PQ anomalies. We show that a resonant annihilation of dark matter with axion mediation can explain the monochromatic photon line of the Fermi Large Area Telescope data at 130 GeV by anomaly interactions while the annihilation cross section with Higgs portal interaction is p-wave suppressed. We discuss the interplay between the direct detection of the fermion dark matter and the collider search of Higgs-like scalars. We also present an ultraviolet completion of the dark matter model into the Next-to-Minimal Supersymmetric Standard Model with PQ symmetry.

DOI: 10.1103/PhysRevD.86.103502 PACS numbers: 95.35.+d

I. INTRODUCTION

Dark matter (DM) is a dominant component of matter density in the Universe, occupying about five times larger than baryonic matter [1]. It is known that DM interacts with the Standard Model (SM) particles gravitationally, while the property of dark matter such as mass and other interactions has not been known. Weakly interacting massive particles have been a paradigm for cosmology, explaining the dark matter relic density by thermal freeze-out with weak-scale mass and weak interactions for dark matter. Thus, it is expected that weakly interacting massive particle is detectable in underground direct detection experiments [2]. Recently, from the direct production of dark matter, the LHC has provided a new constraint on dark matter models, in particular, from the limit on spin-dependent cross section of dark matter [3].

While DM direct searches have imposed strong limits on the direct detection cross section, indirect searches from the cosmic gamma ray such as the Fermi Large Area Telescope (LAT) [4] have reached the sensitivity of the gamma ray data from the Fermi LAT [8,9] has shown an indication for a gamma ray line at $E_{\gamma} = 130$ GeV at 4.6$\sigma$ local significance [9]. If the photon excess is explained by dark matter annihilating into a photon pair, the observations hint at a dark matter mass of $m_X = 129.8 \pm 2.4^{+13}_{-11}$ GeV and a partial annihilation cross section of $\langle \sigma v \rangle_{XX-\gamma\gamma} = (1.27 \pm 0.32^{+0.18}_{-0.28}) \times 10^{-27}$ cm$^3$ s$^{-1}$, or $\langle \sigma v \rangle_{XX-\gamma\gamma} = (2.27 \pm 0.57^{+0.32}_{-0.51}) \times 10^{-27}$ cm$^3$ s$^{-1}$, depending on the dark matter profile.1 The results are very interesting, although they need further confirmation for excluding the possibility of instrumental errors or unknown astrophysical backgrounds.

On the DM model building side, however, it is a non-trivial task to obtain such a large branching fraction into monochromatic photons from the annihilation of dark matter because the relevant annihilation channels are loop suppressed [11–21]. Furthermore, since the light SM degrees of freedom produced from the DM annihilation generate a continuum spectrum of gamma rays, one has to check if the continuum spectrum is consistent with the line spectrum. In this work, we propose a new dark matter model to explain the branching fraction into monochromatic photons as indicated by the Fermi LAT data [9] and discuss the gamma ray constraints in the model.

We consider a fermion dark matter which carries Peccei-Quinn (PQ) charge and couples to a complex scalar singlet. The complex scalar singlet does not couple to the SM directly. Instead, the real part of the complex scalar (CP-even scalar) mediates dark matter interactions to the SM Higgs boson by Higgs portal interaction, so does the imaginary part (the so-called axion in our model) to the SM electroweak gauge bosons by PQ anomalies. We show that the DM annihilation with axion mediation is a dominant channel in determining the relic density at freeze-out by a resonance effect, and it produces a monochromatic photon line by the DM annihilation into $\gamma \gamma$ or $Z\gamma$ with sizable branching fractions at present. On the other hand, the DM annihilation with CP-even scalar mediation can contribute to the total cross section at freeze-out comparably to the one with axion mediation while becoming $p$-wave suppressed at present. As a consequence, we show that there is a parameter space that explains the observed Fermi gamma ray line at $E_{\gamma} \approx 130$ GeV and satisfies all the phenomenological constraints such as gamma ray constraints, DM direct detection and the Higgs-like scalar search at the LHC, etc.

Although the introduction of extra DM annihilation coming from the CP-even singlet scalar reduces the

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1See also a different analysis of the Fermi LAT data [10].
gamma ray line to the central values as given in Ref. [9], extra contribution does not have to be sizable given the systematic and statistical errors of the DM annihilation cross section reported. In other words, the predicted gamma ray line of our model without CP-even scalar mediation is still consistent with DM annihilation into two photons (at about 2 sigma level with the Navarro-Frenk-White (NFW) dark matter profile [9]), so it is with DM annihilation into $Z\gamma$ for any dark matter profile. But, we have included the CP-even singlet sector in our DM discussion as it naturally appears in the PQ completion of the axionlike scalar.

The paper is organized as follows. First, we begin with a description of our model with PQ symmetric dark sector. Then, we present the results of the DM relic density and the production mechanism of gamma ray line and discuss the direct detection constraint on the model. We proceed to present an ultraviolet (UV) complete model for generating the electroweak anomalies by the electroweak PQ axion in the context of the Next-to-Minimal Supersymmetric Standard Model (NMSSM). Finally, a conclusion is drawn.

There are two appendices providing the details of the decay constant parameters $c_i$ depend on the anomalies generated by the axionlike scalar. If dark matter has a fixed mass as hinted by the tentative result from the Fermi LAT data, the dark matter coupling $\lambda_\chi$ is determined by the axion decay constant $v_a$. We take $v_a$ to be larger than the axion mass such that the anomaly loops with heavy fermions having masses of order $v_a$ are well approximated by the dimension-5 interactions between the axion and the SM electroweak gauge bosons.

The interactions of a complex scalar field $S = (s + ia)/\sqrt{2}$ containing $a$ as the imaginary part generates the DM mass and DM-axion coupling in the above action. When the anomalies with nonzero $c_i$ are generated by the couplings of the complex scalar $S$ to extra heavy fermions with SM charges, the axion mediates the dark matter interactions to the SM gauge bosons only through anomalies. We assume that our axion does not couple to colored fermions so it can be called the electroweak axion. Otherwise, the DM annihilation into a gluon pair would be too large to give a sizable branching fraction into photons. Since the anomaly interactions are model dependent, we treat them to be arbitrary parameters. We postpone the discussion on microscopic models to a later section.

For the PQ mechanism to work for solving the strong CP problem, the QCD anomalies must be generated by the invisible axion that couples to extra heavy quarks [22]. We note that the axionlike scalar $a$ gets a PQ-breaking mass $m_a^2$ from a higher dimensional interaction with a PQ-breaking scalar $\Phi$ containing the invisible axion with $\langle \Phi \rangle = F_a$: for $V = -\frac{1}{32\pi^2} \Phi^4 S^2 + \text{h.c.}$, we get $m_a^2 = \frac{F_a^2}{M_P}$. Thus, for $F_a \sim 10^{10}$ GeV, which is within the invisible axion window, $10^9 \text{GeV} < F_a < 10^{12}$ GeV, the Planck suppressed term generates a weak-scale mass for the axionlike scalar. Furthermore, the invisible axion can constitute the dark matter relic density too, but we assume that it is subdominant. On the other hand, if the soft PQ-breaking mass violates CP, a mixing between CP-even and -odd scalars could lead to too large branching fraction of the DM annihilation into the SM particles. In order for the axion to couple to the SM only by anomalies, we assume that the induced PQ-breaking mass does not violate CP.

After minimizing the potential in Eq. (2), the vacuum expectation values (VEVs) of the singlet and the Higgs doublet, $v_s$ and $v$, are determined as [24]

$$
\lambda_{\chi} = \lambda_{\chi} (S\tilde{\chi}P_L \chi + S^* \tilde{\chi}P_R \chi) + \sum_{i=1,2,3} \frac{c_i}{8\pi v_s} a F_{\mu\nu} \tilde{F}_{\mu\nu},
$$

where $\tilde{F}_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu\rho\sigma} F^{\rho\sigma}$, $v_s = \sqrt{2} \langle S \rangle$ is the axion decay constant and we need $|\lambda_{\chi}| \lesssim O(1)$ for a valid effective theory for dark matter with mass $M_\chi \equiv \lambda_{\chi} v_s / \sqrt{2}$, and the constant parameters $c_i$ depend on the anomalies generated by the axionlike scalar. If dark matter has a fixed mass as hinted by the tentative result from the Fermi LAT data, the dark matter coupling $\lambda_\chi$ is determined by the axion decay constant $v_a$. We take $v_a$ to be larger than the axion mass such that the anomaly loops with heavy fermions having masses of order $v_a$ are well approximated by the dimension-5 interactions between the axion and the SM electroweak gauge bosons.

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In the interesting region that explains the Fermi gamma line at 130 GeV from axion-... 

The conditions for a local minimum are \( \lambda_{HS}m_{H^2} - \lambda_H(m_S^2 - m_Z^2) > 0, \lambda_{HS}(m_S^2 - m_Z^2) - \lambda_Sm_H^2 > 0, \) and \( \lambda_S\lambda_H - \lambda_{HS} > 0. \) Expanding the scalar fields around the vacuum as \( S = (v_s + s + i\alpha)/\sqrt{2} \) and \( H^2 = (0, v + h)/\sqrt{2} \) in unitary gauge, the obtained mass matrix for CP-even scalars can be diagonalized by the field rotation,

\[
\begin{align*}
    s &= \cos\theta s + \sin\theta h, \\
    h &= -\sin\theta s + \cos\theta h,
\end{align*}
\]

with

\[
\tan 2\theta = \frac{2\lambda_{HS}v_s v}{\lambda_H v_S - \lambda_S v_H^2},
\]

and the mass eigenvalues are

\[
    m_{1,2}^2 = \lambda_H v_s^2 + \lambda_S v_H^2 + \sqrt{(\lambda_S v_H^2 - \lambda_H v_s^2)^2 + 4\lambda_{HS}^2 v_S^2 v_H^2}.
\]

Due to the singlet-Higgs mixing, the real scalar also mediates the dark matter interactions to the SM particles as the Higgs boson does. The axion mass is just given by the PQ-breaking mass as \( m_a = m_S. \) In our model, we can trade four independent Lagrangian parameters in the CP-even scalar sector to four physical parameters by Eqs. (4)–(8): \( v_s, m_{1,2} \) and the mixing angle \( \theta. \)

III. DARK MATTER CONSTRAINT AND FERMI GAMMA RAY LINE

In this section, we consider the constraint coming from the DM relic density in our model and show how a monochromatic photon line is produced by DM annihilation as observed by the Fermi LAT. We also discuss the interplay between DM direct detection and Higgs search at the LHC in the interesting region that explains the Fermi gamma ray line.

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A. Dark matter annihilation cross section

Dark matter annihilates into a SM pair through both the axion and the real scalar partner of the axion. There are four channels with s-channel axion in our model as shown in Fig. 1: \( \tilde{\chi}\chi \rightarrow a \rightarrow \gamma\gamma, Z\gamma, ZZ, W^+W^- \). All the channels are s-wave so their annihilation cross sections are little changed since the freeze-out. The first two channels lead to monochromatic gamma lines from dark matter annihilation. If the branching fraction of the first two channels is sizable and DM annihilation occurs due to the resonance at \( m_a \sim 2M_X \), it is possible to explain the tentative gamma ray line observed at Fermi LAT with the cross section required to explain the dark matter relic density. We denote the annihilation cross section coming from axion mediation by \( \sigma(v)_a. \)

On the other hand, dark matter can also annihilate by the mixing between the CP-even singlet scalar and the Higgs boson. If kinematically allowed, there are four channels with s-channel CP-even scalar annihilating into the SM particles as shown in Fig. 1: \( \tilde{\chi}\chi \rightarrow s \rightarrow \bar{f}f, ZZ, W^+W^-, hh \). As shown in Appendix B, all the channels are p-wave suppressed. So, even if they can be relevant for generating the correct relic density at freeze-out, they become suppressed at later time. We denote the annihilation cross section coming from CP-even scalar mediation by \( \sigma(v)_s. \)

Moreover, singlet self-interaction and/or Higgs portal interaction could lead to extra annihilation channels at tree level: \( \tilde{\chi}\chi \rightarrow ss, sh, hh, aa, as \) in the interaction basis. All the additional channels except \( \tilde{\chi}\chi \rightarrow as \) are p-wave suppressed. In particular, the first three channels into CP-even scalars can be comparable to the loop-induced channels with axion mediation at freeze-out while they do not affect the branching fraction of the annihilation cross section into monochromatic photons. On the other hand, the \( \tilde{\chi}\chi \rightarrow aa \) channel is kinematically forbidden even at freeze-out, close to \( m_a = 2M_X \) that we are interested in for the gamma ray line. The \( \tilde{\chi}\chi \rightarrow as \) channel is s-wave so the cascade annihilation of the CP-even scalar into the SM particles could produce too many intense secondary photons [5]. So, we forbid the \( \tilde{\chi}\chi \rightarrow as \) channel kinematically by taking \( m_a + m_{1,2} > 2M_X \) and search the parameter space that is compatible with the relic density. Therefore, the total annihilation cross section is given approximately by the

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3Recently, even a small singlet-Higgs mixing can lead to a sizable threshold correction to the Higgs quartic coupling at tree level, solving the vacuum instability problem of the Higgs mass lighter than 130 GeV in the SM [25].

4Dirac fermion dark matter with a CP-even singlet scalar mediation was previously considered [26].
addition of the axion-mediated and scalar-mediated cross sections at freeze-out,

$$\langle \sigma v \rangle_{\text{IR}} \approx \langle \sigma v \rangle_{\alpha} + \langle \sigma v \rangle_{\beta}.$$ (9)

Then, from the velocity times cross section of dark matter annihilation, \(\sigma v = a + b v^2\), the dark matter relic density is given by

$$\Omega_{\chi} h^2 = \frac{2.09 \times 10^8 \text{ GeV}^{-1}}{M_{\text{IR}} \sqrt{g_{\ast}(x_F)} (a/x_F + 3b/x_F^2)},$$ (10)

where the freeze-out temperature gives \(x_F = M_\chi / T_F \approx 20\) and \(g_{\ast}(x_F)\) is the number of the effective relativistic degrees of freedom entering in the entropy density. The DM relic density measured by Wilkinson microwave anisotropy probe (WMAP) is \(\Omega_{\text{DM}} h^2 = 0.1123 \pm 0.0035\) at 68% C.L. [1].

In Fig. 2, on the \(m_\alpha - m_2\) mass plane, for the fixed DM mass to \(M_\chi = 130\) GeV or 145 GeV, we show the parameter space satisfying the WMAP bound on the relic density at 3\(\sigma\) and the branching fraction of the DM annihilation into a photon pair within 8% or into \(Z\) within 8–13% at present. We have used FeynRules [27] and micrOMEGAs [28] for the numerical analysis. There are four separate lines satisfying the relic density. Each pair of lines parallel to the \(m_\alpha\) axis gets close to the axion resonance due to a small decay width of the axion. The necessary tuning for the axion resonance to produce the correct relic density within the WMAP \(3\sigma\) band is \(\delta m_\alpha / m_\alpha \approx 0.008\) for \(m_\alpha = m_\alpha^0 + \delta m_\alpha\), that is, \(\delta m_\alpha \approx 2\) GeV for \(m_\alpha^0 = 2m_\chi = 260\) GeV. Each pair of lines parallel to the \(m_\alpha\) axis are separated wider from each other due to a larger decay width of the \(CP\)-even scalars. We note that there is a parameter space in red in both figures where the gamma ray line at 130 GeV can be obtained with the observed intensity as will be discussed in more detail later.

**B. Gamma ray line spectra and differential flux of photons**

The spectrum of the \(\gamma\gamma\) line is a delta function at \(M_\chi\). On the other hand, the photon spectrum per annihilation with the process \(\tilde{\chi}\chi \rightarrow Z\gamma\) depends on the mass and width of the \(Z\) boson as follows [16]:

$$\frac{dN_\gamma}{dE_\gamma} = \frac{4M_\chi M_Z \Gamma_Z}{f_1 f_2},$$ (11)

where \(\Gamma_Z\) is the decay width of the \(Z\) boson and

$$f_1 = \tan^{-1} \left( \frac{M_Z}{\Gamma_Z} \right) + \tan^{-1} \left( \frac{4M_\chi^2 - M_Z^2}{M_Z \Gamma_Z} \right),$$ (12)

$$f_2 = (4M_\chi^2 - 4M_\chi E_\gamma - M_Z^2)^2 + \Gamma_Z^2 M_Z^2.$$ (13)

The differential photon flux produced by dark matter annihilation and integrated over the region of angular size \(\Delta \Omega\) is computed as [16]

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{1}{4\pi} \frac{r_s \rho_0^2}{4M_\chi^2} \frac{dN_\gamma}{dE_\gamma} J \Delta \Omega,$$ (14)

with

![Image](103502-4)
\[ \frac{dN_{\gamma}}{dE_{\gamma}} = 2\pi\langle\sigma v\rangle_{\gamma\gamma}\delta(E_{\gamma} - M_\chi) + \langle\sigma v\rangle_{Z\gamma}\frac{dN_{\gamma}}{dE_{\gamma}}, \]  
(15)

\[ j = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} J(\psi) = \int_{\Delta\Omega} \frac{d\Omega}{\rho} \left( \frac{\rho(r,\psi)}{\rho_0} \right)^2. \]  
(16)

Here, we note that \( \rho(\vec{x}) \), \( \rho_0 = 0.3 \) GeV/cm\(^3\) and \( r_0 = 8.5 \) kpc denote the dark matter density at a location \( \vec{x} \) with respect to the galactic center (GC), its value at the Solar System and the distance between the Sun and the GC. The coordinate \( s \) spans along the line of sight, making an angle \( \psi \) with the direction of the GC. In order to compare to the spectrum observed by Fermi LAT, we should take into account a 10\% energy resolution so we can replace the actual spectrum by a Gaussian distribution function centered at the photon energy.

There are models for the dark matter density distribution in our Galaxy. The NFW profile is often used for indirect searches,

\[ \rho_{\text{NFW}}(r) = \frac{\rho_s}{r_s(1 + r/r_s)^2}. \]  
(17)

On very small scales, the optimal fit to simulated DM halos is provided by the Einasto profile,

\[ \rho(r) = \rho_0 \exp \left[ -2 \alpha \left( \frac{r}{R} \right)^\alpha - 1 \right] \].  
(18)

where \( \alpha = 0.17 \) and \( R = 20 \) kpc. The Einasto profile is shallower than NFW at very small radii.

### C. Monochromatic gamma ray from fermion dark matte

In this subsection, we consider the annihilation of the fermion dark matter with axion mediation and show that the monochromatic photons with sizable branching fraction can be produced.

Suppose that the gamma ray line at \( E_\gamma = 130 \) GeV hinted by the recent analysis \[9\] is explained by dark matter with \( M_\chi = 13 \) GeV annihilating into two photons. Then, there is another peak at \( E_\gamma = M_\chi(1 - \frac{m_\chi^2}{4M_\chi^2}) \approx 114 \) GeV. On the other hand, if the observed gamma ray line is explained by the DM annihilation into one photon, we need to choose the dark matter mass to \( M_\chi = 145 \) GeV, and another peak coming from the DM annihilation into two photons is at \( E_\gamma = 145 \) GeV.

The ratio of the annihilation cross sections into \( Z\gamma \) and \( \gamma\gamma \) in our model is determined by

\[ r = \frac{\langle\sigma v\rangle_{Z\gamma}}{\langle\sigma v\rangle_{\gamma\gamma}} = \frac{(c_2\alpha_2 - c_1\alpha_1)^2\sin^2(2\theta_w)\left(1 - \frac{M_\chi^2}{4M_\chi^2}\right)^3}{2(c_1\alpha_1\cos^2\theta_w + c_2\alpha_2\sin^2\theta_w)} \]  
(19)

For \( c_1 = c_2 \), which is the case where two Higgsinos generate electroweak anomalies in the NMSSM as will be discussed in the later section, the above ratio becomes \( r \approx 0.54 \) for \( M_\chi = 130 \) GeV. Then, the intensity of the one-photon line coming from \( Z\gamma \) is 0.27 times that of the two-photon line. Although the one-photon peak may be resolved from the two-photon peak separated by 16 GeV, the suppressed one-photon line may not be significant due the background while the two-photon line can explain the observed Fermi gamma ray line.\[5\] On the other hand, for \( c_1 = 0.2c_2 \), the cross section ratio becomes \( r \approx 2.9 \) for \( M_\chi = 145 \) GeV. Then, the intensity of the two-photon line coming from \( \gamma\gamma \) is 0.69 times that of the one-photon line. But in this case, the one-photon line fits the Fermi gamma ray line worse than the case with two-photon line dominance \[29\].

In order to explain the observed Fermi gamma ray line by dark matter annihilation, one needs the cross section of dark matter annihilating into a pair of monochromatic photons to be \( \langle\sigma v\rangle_{\gamma\gamma} = (1.27 \pm 0.32^{+0.18}_{-0.28}) \times 10^{-27} \) cm\(^3\) s\(^{-1}\) for the Einasto profile and \( \langle\sigma v\rangle_{\gamma\gamma} = (2.27 \pm 0.57^{+0.32}_{-0.51}) \times 10^{-27} \) cm\(^3\) s\(^{-1}\) for the NFW profile; that is, \( \text{Br}(\tilde{\chi}\chi \to \gamma\gamma) \approx 4\% \) for thermal dark matter \[9\].

In our model, the DM annihilation with axion mediation is \( s\)-wave so it alone would have produced a more intense gamma ray line than observed because the branching fraction into photons is rather large, as shown in Fig. 3. But, the DM annihilation channels with \( CP\)-even scalar mediation can give a sizable contribution to the total cross section at freeze-out while they do not affect the branching fraction into photons at present because of a \( p\)-wave suppression. Thus, as \( \langle\sigma v\rangle_s = 0 \) at zero temperature, the present total annihilation cross sections is less than the one at freeze-out so we can reduce the partial annihilation cross section into photons. We can write the partial cross sections at present in terms of the total annihilation cross section at freeze-out,

\[ \langle\sigma v\rangle_{XY} \equiv \frac{\text{Br}(\tilde{\chi}\chi \to XY)}{\langle\sigma v\rangle_{\chi\chi}}. \]

\[ \text{Br}(\tilde{\chi}\chi \to XY) \equiv \frac{\langle\sigma v\rangle_{XY}}{\langle\sigma v\rangle_{\chi\chi}}. \]

We plot the present partial annihilation cross sections with respect to the ratio of scalar-mediated to axion-mediated cross sections at freeze-out in Fig. 4. For \( c_1 = c_2 \), the DM annihilation into two photons is dominant to explain the Fermi LAT peak and we get \( \text{Br}(\tilde{\chi}\chi \to \gamma\gamma) = 0.14 \). In this case, we need the annihilation cross section with \( CP\)-even...
scalar mediation at freeze-out to be $\langle \sigma v \rangle_s / \langle \sigma v \rangle_a = 0.8 - 2.3$ for $\langle \sigma v \rangle_{\gamma\gamma} = (10^{-27} \text{ cm}^3 \text{ s}^{-1}) = 1.27 - 2.27$. On the other hand, for $c_1 = 0.2 c_2$, the DM annihilation into one photon can explain the Fermi LAT peak and we get $\text{Br}(\bar{\chi} \chi \rightarrow Z\gamma) = 0.13$. So, we need a smaller annihilation cross section with $CP$-even scalar mediation as compared to the case with two photons: $\langle \sigma v \rangle_s / \langle \sigma v \rangle_a = 0 - 0.54$ for $\langle \sigma v \rangle_{Z\gamma} = (10^{-27} \text{ cm}^3 \text{ s}^{-1}) = 2.54 - 3.9$.

We note that the partial cross section into $WW$ is the largest, being about five times larger than the one for the dominant photon channel. But, it satisfies the current limit of about $10^{-25} \text{ cm}^3 \text{ s}^{-1}$, coming from the gamma ray emission of dwarf spheroidal galaxies observed by the Fermi LAT [5]. Furthermore, PAMELA has measured the spectrum of cosmic antiproton flux below 180 GeV, which is consistent with the background [30]. In our model, the antiproton flux coming from the hadronic decays of $WW$, $ZZ$ with the annihilation cross sections of about 60 and 20%, respectively, is well below the measured one by one or two orders of magnitude [31].

FIG. 3 (color online). Branching fraction of the partial cross sections for DM annihilations with axion mediation vs $c_1/c_2$. Dark matter mass is fixed to give the dominant photon line.

FIG. 4 (color online). Partial annihilation cross sections vs ratio of $CP$-even scalar to axion-mediated cross sections at freeze-out. Dark matter mass is fixed to give the dominant photon line. Left: $WW$, $ZZ$, $\gamma\gamma$, $Z\gamma$ from top to bottom. Right: $WW$, $ZZ$, $Z\gamma$, $\gamma\gamma$ from top to bottom.
dependent cross section with axion exchange is velocity coupling, is given by the sum of the light quarks (lower shaded) region is excluded by XENON 100 T and dark gray region (upper darker-shaded) is disfavored by the electroweak precision data.

FIG. 5 (color online). Parameter space of the mixing angle of $CP$-even scalars vs the mass of singletlike $CP$-even scalar. The region consistent with WMAP 3σ band of the relic density is bounded by blue dotted lines while the blue solid line is the central value within 3σ. Left: Parameter space of the present partial annihilation cross section into a photon pair within 4–8% (red region bounded by red solid lines, lower shaded region bounded by solid lines) and less than 4% (pink, the rest of lower shaded region) and $c_1 = c_2 = 1$. Right: Parameter space of the present partial annihilation cross section into $Z\gamma$ within 8–13% (red region bounded by red solid lines, bulk shaded region) and $c_1 = 0.2$, $c_2 = 1$. The mass of the Higgs-like scalar is chosen to $m_1 = 125$ GeV. In both figures, gray (upper shaded) region is excluded by XENON 100 T and dark gray region (upper darker-shaded) is disfavored by the electroweak precision data.

IV. DIRECT DETECTION AND LHC HIGGS SEARCH

As discussed in the previous section, although the DM annihilation with axion mediation gives a sizable branching fraction of the annihilation cross section into monochromatic photon(s), the level of the gamma ray line excess of the Fermi LAT data requires a sizable contribution of the $CP$-even scalar mediation to the total annihilation cross section at freeze-out. This is achieved by a sizable mixing between the $CP$-even scalar singlet and the Higgs boson. Then, the same mixing parameter determines the direct detection cross section of dark matter.

From the scattering process with the fermion dark matter, the spin-independent cross section for dark matter with nuclei is at tree level given by

$$\sigma_{X-N}^{SI} = |\lambda_X|^2 \sin^2(2\theta) \cdot \frac{m_N^2 f_N^2}{8 \pi} \left( \frac{m_N}{m_1} \right)^2 \left( \frac{1}{m_1^2} - \frac{1}{m_2^2} \right)^2,$$

where $m_r = m_N M_X / (m_N + M_X)$ is the reduced mass, $m_N$ is the nucleon mass, $f_N$, parametrizing the Higgs-nucleon coupling, is given by the sum of the light quarks ($f_L$) and heavy quarks ($f_H$) as $f_N = \sum f_L + 3 \times \frac{2}{3} f_H$ [32], and $m_{1,2}$ are physical $CP$-even scalar masses given in Eq. (8). For instance, the direct detection bound is $\sigma_{X-N}^{SI} \lesssim 10^{-8}$ pb for $M_X = 130$ GeV [2]. We note that the spin-dependent cross section with axion exchange is velocity suppressed so the bounds coming from IceCube [33] and Super-Kamiokande [34] do not constrain our model.

On the left plot of Fig. 5, in the parameter space of the mixing angle and the mass of the singletlike $CP$-even scalar, for $M_X = 130$ GeV, we considered the WMAP 3σ band for the relic density and the branching fraction of the annihilation cross section into a photon pair less than 8%, and also show the limits from DM direct detection as well as the electroweak precision data at 95% C.L. [24,35]. We have also shown the case with $M_X = 145$ GeV on the right plot of Fig. 5 where both the WMAP bound and the gamma ray line are obtained in all the parameter space away from the $CP$-even scalar resonance at $m_2 \sim 2 M_X$, and the direct detection bound is little changed as compared to the case $M_X = 130$ GeV. We can see that there is a parameter space with the mixing angle smaller than about 0.4–0.5 that explains the Fermi gamma ray line at $E_\gamma = 130$ GeV and is compatible with all the phenomenological constraints. As shown in both plots of Fig. 5, the region below $m_2 \sim 180$ GeV is not constrained by direct detection because there is a cancellation effect in the scattering cross section due to the opposite signs in the amplitudes with $CP$-even scalars. In the range of the singletlike $CP$-even scalar masses away from the cancellation zone, the mixing angle is constrained to be smaller than about $\theta = 0.4$ by DM direct detection. We note that the electroweak precision data does not give a stronger bound that the direct detection in the region with the correct relic density and the Fermi...
gamma ray line. But, the former gives a stronger bound than the latter for $m_2 \approx 260$ GeV and $m_2 \approx 350$ GeV.

We note that if the singletlike $CP$-even scalar gets mass outside the range $122$ GeV $< m_2 < 128$ GeV, and there is no additional decay mode other than the ones of the SM Higgs boson, the LEP and LHC limits on the Higgs-like couplings will apply. The LEP restricts the Higgs-like Higgs boson, the LEP and LHC limits on the Higgs-like no additional decay mode other than the ones of the SM symmetry.

Breaking sector breaks PQ symmetry while it respects discrete R

Higgs-like coupling to the

couplings will apply. The LEP restricts the Higgs-like Higgs boson, the LEP and LHC limits on the Higgs-like no additional decay mode other than the ones of the SM symmetry.

In this section, we consider the interaction terms between the axionlike scalar and the coupling to the

couplings will apply. The LEP restricts the Higgs-like Higgs boson, the LEP and LHC limits on the Higgs-like no additional decay mode other than the ones of the SM symmetry.

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TABLE I. PQ and $Z_4^R$ charges. Right-handed neutrinos $N$ are also included for neutrino masses.

<table>
<thead>
<tr>
<th>$Q$, $L$</th>
<th>$U$, $N$</th>
<th>$D$, $E$</th>
<th>$H_u$</th>
<th>$H_d$</th>
<th>$S$</th>
<th>$\chi_1$</th>
<th>$\chi_2$</th>
<th>$X$</th>
<th>$Y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PQ</td>
<td>$q_1$</td>
<td>0</td>
<td>$-q_1 + q_2$</td>
<td>$-q_1$</td>
<td>$-q_2$</td>
<td>$q_1 + q_2$</td>
<td>$q_X$</td>
<td>$-q_X = q_1 - q_2$</td>
<td>$q_X$</td>
</tr>
<tr>
<td>$Z_4^R$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>
Here, we have introduced the R-symmetry breaking\(^7\) in terms of a constant superpotential \( W_0 \). After the saxion is stabilized, the above superpotential leads to nonzero \( F \)-terms, \( F_X = \mu_1^2 e^{-q_S A} \) and \( F_Y = W_0 \mu_2^2 e^{-q_I A} \). Therefore, the SUSY-breaking sector also breaks PQ symmetry after the scalar partner of the saxion multiplet is stabilized [41]. Henceforth we take two \( F \)-terms to be comparable. Furthermore, we can write the PQ and R invariant effective interactions composed of the invisible axion and SUSY-breaking fields as follows:

\[
\int d^4 \theta \frac{\alpha}{2M} Y^I S^2 + \int d^2 \theta a X e^{-(q_S - q_I)A} H_u H_d^c
\]

\[
+ \int d^2 \frac{b}{M} Y^I X e^{-(q_S - q_I)A} S + \text{H.c.},
\]

with \( M \) being the messenger scale. The first term corresponds to a supersymmetric singlet mass term of order scalar soft mass from nonzero \( F_Y \) term as follows:

\[
\Delta W_{vis} = \frac{1}{2} \mu_S S^2, \quad \mu_S = \alpha F_Y^1 M.
\]

This supersymmetric singlet field is crucial to make the extra singlet fermion heavier than the Dirac fermion dark matter. On the other hand, from Eq. (25), the second term generates a \( B \)-term for Higgs doublets while the third term generates a singlet linear soft mass term. We note that the soft trilinear term is also generated by SUSY-breaking with \( \int d^2 \theta \frac{\alpha}{2M} Ye^{-(q_S - q_I)A} SH_u H_d^c \), but they are suppressed as compared to soft scalar masses of order \( |F_Y| \sim |F_X| \) because the SUSY-breaking fields carry nonzero PQ charges. Nonetheless, gravity mediation can generate soft mass terms of order gravitino mass corresponding to all the terms present allowed in the superpotential. Therefore, we get the soft SUSY-breaking terms as follows:

\[
-L_{\text{soft}} = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2
\]

\[
+ m_{\chi_1}^2 |\chi_1|^2 + m_{\chi_2}^2 |\chi_2|^2 + \left( \frac{1}{2} B_S \mu_S S^2 + \text{H.c.} \right) + (\lambda_h A_h S H_u H_d + \lambda_A A_S \chi_1 \chi_2 + B_S \mu H_u H_d + \lambda_A \mu_S \chi_1 \chi_2 + B_S m_S^2 S + \text{H.c.}),
\]

where \( \lambda_h \) is of order gravitino mass and

\[
B_S \mu \sim B_{\chi} \mu \sim a F_X e^{-(q_S - q_I)A},
\]

\[
B_S m_S \sim b \frac{F_Y}{M} F_X e^{-(q_S - q_I)A}.
\]

\[
7\text{A possible domain-wall problem could arise after R-symmetry breaking of order }10^{14} \text{ GeV related to } W_0 \text{ in gravity mediation, but it depends on the reheating temperature coming from the gravitino problem, which is about }10^9 \text{ GeV, is satisfied, there is no domain wall produced after inflation along the line of discussion in Refs. [39,40].}
\]

If the above \( B \)-terms are of order the soft scalar mass, for \( |F_X| \sim |F_Y| \), we need

\[
a \sim b \sim \frac{|F_X|}{M^2}
\]

PQ-breaking linear soft mass for the singlet stabilizes the singlet at a nonzero VEV and gives the \( S \) axion a nonzero mass. The minimization of the potential leads to [42]

\[
\sin 2 \beta = \frac{B_S \mu + (2 \lambda_h + \lambda_h \mu_S)(s)}{m_H^2 + m_H^2 + 2 \mu_{\text{eff}}^2 + \lambda_h v^2},
\]

\[
\mu_{\text{eff}} = \lambda_h \langle s \rangle,
\]

\[
\langle s \rangle = \frac{\lambda_h v u_d (A_h + 2 \mu_S) - B_S m^2}{m_S^2 + B_S \mu_S + \mu_S^2 + \lambda_h v^2}.
\]

The scalar potential in NMSSM is more predictive because the Higgs quartic coupling is given by the gauge coupling and there is no singlet self-coupling. However, as in the toy model, a mixing between \( CP \)-even Higgs and singlet is possible due to the singlet coupling to the Higgs doublets.

The \( A \)-term in Eq. (27) and the \( \Delta \)-term for the \( S \) from the superpotential, \( W_{vis} + \Delta W_{vis} \), can mix between the pseudoscalar Higgs and the \( S \) axion, so the tree-level DM annihilation into a pair of SM particles through the mixing could be large. Thus, in order to explain the gamma ray line with the correct relic density, the mixing between the pseudoscalar Higgs and the \( S \) axion should be suppressed. From the gamma ray constraint that the extra tree-level axion mediation through the mixing is smaller than the one-loop induced counterpart, if the Higgs pseudoscalar and \( S \) axion masses, i.e., \( m_A \) and \( m_s \), are comparable, we need to impose the soft mass parameter as

\[
|A_h - \mu_S| \lesssim \sqrt{\frac{g_2 M_X}{32 \pi^2 v_s (m_A + M_X)}} \approx \sqrt{\frac{g_2 M_X}{96 \pi^2 v_s}} \approx 0.01.
\]

If the pseudoscalar Higgs mass is much larger than the \( S \) axion mass, the amount of a tuning on \( |A_h - \mu_S| \) is reduced by a factor of \( \frac{m_A}{m_s} \). Then, the \( S \) axion couples dominantly to the electroweak gauge bosons in the SM through the anomalies, playing a role of the mediator between dark matter and the SM. Ignoring the mixing of pseudoscalars for \( A_h = \mu_S \), we obtain the pseudoscalar masses as [42]

\[
m_A^2 = \frac{2(B_S \mu + A_h \langle s \rangle + \lambda_h \mu_S)}{\sin 2 \beta},
\]

\[
m_s^2 = \frac{1}{\langle s \rangle} (\lambda(A_h + \mu_S) v u_d - B_S m^2) - 2 B_S \mu_S.
\]

We note that there are extra fields from the dark matter and messenger sectors in the supersymmetric models as compared to the toy model in Sec. II: an extra Higgs doublet, the scalar partners of Dirac fermion dark matter and the fermionic partner of the \( S \) singlet. But, the scalar...
partners of Dirac dark matter are not relevant for PQ and electroweak symmetry breaking. Furthermore, the extra singlet superparticles can be heavier than dark matter with mass $M_s$ so the additional annihilation channels into a singlet pair can be kinematically suppressed. Moreover, since the extra CP-even Higgs is heavier than the SM-like Higgs, the DM annihilation cross section is determined dominantly by the mediation channels with the $S$ axion and lighter CP-even scalars as discussed in our toy model in Sec. II.

VI. CONCLUSION

We have considered a Dirac singlet fermion as dark matter that communicates with the SM by a complex scalar close to the resonance, $s_V$, that the axion mediates dark matter interactions. Bosons are generated by anomalies in the presence of extra partners of Dirac dark matter are not relevant for PQ and electroweak symmetry breaking. Furthermore, the extra singlet superparticles can be heavier than dark matter with mass $M_s$ so the additional annihilation channels into a singlet pair can be kinematically suppressed. Moreover, since the extra CP-even Higgs is heavier than the SM-like Higgs, the DM annihilation cross section is determined dominantly by the mediation channels with the $S$ axion and lighter CP-even scalars as discussed in our toy model in Sec. II.

VI. CONCLUSION

We have considered a Dirac singlet fermion as dark matter that communicates with the SM by a complex scalar mediator. Identifying a $U(1)$ global symmetry in the dark sector with PQ symmetry, a spontaneous breakdown of PQ symmetry at high scale generates a soft PQ-breaking mass of weak scale for the axion part of the complex scalar in a CP-invariant fashion. After the complex scalar gets a VEV, the effective axion interactions to the electroweak gauge bosons are generated by anomalies in the presence of extra heavy fermions with axion coupling. This opens up a possibility that the axion mediates dark matter interactions close to the resonance, $m_a \sim 2M_s$, such that dark matter annihilates into $\gamma\gamma$ and $Z\gamma$ with sizable branching fractions while reproducing the relic density. If the Fermi gamma ray line is confirmed, there will be interesting signatures to be pursued for DM direct detection and Higgs-like scalar searches below 300 GeV at the LHC in the near future.

We also have presented an ultraviolet complete model that accommodates the axion coupling to the electroweak gauge bosons naturally by the singlet coupling to Higgsinos in the NMSSM with PQ symmetry. The SUSY extension relies on the specific PQ-breaking soft mass terms in the NMSSM that are obtained in the presence of a discrete R symmetry. It would be worthwhile to investigate the implications of the gamma ray line on the Higgs boson and SUSY searches in this context.

ACKNOWLEDGMENTS

We would like to thank Marco Cirelli and Geraldine Servant for discussions. The implementation of our model with FeynRules became possible thanks to the help of Neil D. Christensen and Claude Duhr and through the MC4BSM 2012 workshop. The work of H. M. L. and M. H. P. is partially supported by a CERN-Korean fellowship. W. I. P. is supported in part by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology Grant No. 2012-0003102.

APPENDIX A: DECAY RATES

In the presence of the anomaly interactions between the axion and the electroweak gauge bosons, $c_{V_1V_2} \mathcal{A}_{\mu\nu\rho\sigma}$, $F_{V_1}^\mu F_{V_2}^{\mu\nu}$, the decay rate for $a \rightarrow V_1V_2$ with two gauge bosons, $V_1$ and $V_2$, having masses $M_1$ and $M_2$, respectively, is

$$\Gamma(a \rightarrow V_1V_2) = \frac{m_a^3}{2\pi} s_V [c_{V_1V_2} \mathcal{A}_{\mu\nu\rho\sigma}] \left( 1 - \frac{(M_1 + M_2)^2}{m_a^2} \right)^{3/2} \left( 1 - \frac{(M_1 - M_2)^2}{m_a^2} \right)^{3/2},$$

(A1)

with $s_V$ being the symmetry factor for the final states, for instance, $s_V = N!$ for $N$ identical final states. Furthermore, if the axion mass is larger than twice the dark matter mass, the axion can decay into a dark matter pair. Then, the total decay rate of the axion is given by

$$\Gamma_a = \Gamma_a(\gamma\gamma) + \Gamma_a(Z\gamma) + \Gamma_a(ZZ) + \Gamma_a(WW) + \Gamma_a(\tilde{\chi}\tilde{\chi}).$$

(A2)

where

$$\Gamma_a(\gamma\gamma) = \frac{m_a^3}{\pi} |c_{\gamma\gamma}|^2,$$

(A3)

$$\Gamma_a(Z\gamma) = \frac{m_a^3}{2\pi} |c_{Z\gamma}|^2 \left( 1 - \frac{M_Z^2}{m_a^2} \right)^{3/2},$$

(A4)

$$\Gamma_a(ZZ) = \frac{m_a^3}{\pi} |c_{ZZ}|^2 \left( 1 - \frac{4M_Z^2}{m_a^2} \right)^{3/2},$$

(A5)

$$\Gamma_a(WW) = \frac{m_a^3}{2\pi} |c_{WW}|^2 \left( 1 - \frac{4M_W^2}{m_a^2} \right)^{3/2},$$

(A6)

$$\Gamma_a(\tilde{\chi}\tilde{\chi}) = \frac{|\lambda_{\chi\chi}|^2}{16\pi m_a} \left( 1 - \frac{4m_{\tilde{\chi}}^2}{m_a^2} \right)^{1/2}.$$ 

(A7)

Here, the anomaly couplings are related to the original parameters in Eq. (1) as

$$c_{\gamma\gamma} = \frac{1}{16\pi v_s} (c_1 \alpha_1 \cos^2 \theta_w + c_2 \alpha_2 \sin^2 \theta_w),$$

(A8)

$$c_{Z\gamma} = \frac{1}{16\pi v_s} (c_2 \alpha_2 - c_1 \alpha_1) \sin(2\theta_w),$$

(A9)

$$c_{ZZ} = \frac{1}{16\pi v_s} (c_2 \alpha_2 \cos^2 \theta_w + c_1 \alpha_1 \sin^2 \theta_w),$$

(A10)

$$c_{WW} = \frac{c_2 \alpha_2}{8\pi v_s}.$$

(A11)

We also consider the decay rates of CP-even scalars. They can decay into the SM particles due to the mixing with the Higgs boson as the SM Higgs does. Each partial decay width of the CP-even scalars into a SM particle pair
FERMI GAMMA RAY LINE AT 130 GeV FROM AXION- ... is obtained from the one of the SM Higgs multiplied by \(\sin^2 \theta\) for \(\tilde{s}\) and \(\cos^2 \theta\) for \(\tilde{h}\). If kinematically allowed, the heavier \(CP\)-even scalar \(\tilde{s}\) can decay into a pair of the lighter \(CP\)-even scalar \(\tilde{h}\) and the \(CP\)-even scalars can decay into a dark matter pair by the direct coupling. So, the decay rates for the possible additional decay modes are

\[
\Gamma(\tilde{s} \rightarrow \tilde{h} \tilde{h}) = \frac{\lambda_{\tilde{s}\tilde{h}\tilde{h}}^2}{8 \pi m_2} \sqrt{1 - \frac{4m_2^2}{m_s^2}}, \quad (A12)
\]

\[
\Gamma(\tilde{s} \rightarrow \chi \chi) = \frac{|\lambda_s|^2 m_2}{16 \pi} \cos^2 \theta \left(1 - \frac{4m_s^2}{m_s^2}\right)^{3/2}, \quad (A13)
\]

\[
\Gamma(\tilde{h} \rightarrow \chi \chi) = \frac{|\lambda_h|^2 m_1}{16 \pi} \sin^2 \theta \left(1 - \frac{4m_h^2}{m_h^2}\right)^{3/2}. \quad (A14)
\]

**APPENDIX B: DARK MATTER ANNHIILATION CROSS SECTION**

First, due to the dark matter coupling to the axion and the axion anomaly interactions, the cross section times relative velocity for \(\tilde{\chi} \chi \rightarrow V_1 V_2\) is given by

\[
\sigma_{v_1 v_2} = \frac{1}{32 \pi} |s|^2 [\lambda_{\chi V_1}^2 |c_{v_1}]^2 \frac{s^2}{(s-m_a^2)^2 + m_a^2 \Gamma_a^2} \times \left(1 - \frac{(M_1 + M_2)^2}{s}\right)^{3/2} \times \left(1 - \frac{(M_1 - M_2)^2}{s}\right)^{3/2}, \quad (B1)
\]

with \(s\) being the center of momentum squared. Then, the velocity averaged cross section for dark matter annihilation with axion mediation is

\[
\langle \sigma v \rangle_a = \langle \sigma v \rangle_{\gamma \gamma} + \langle \sigma v \rangle_{Z \gamma} + \langle \sigma v \rangle_{ZZ} + \langle \sigma v \rangle_{WW}, \quad (B2)
\]

where

\[
\langle \sigma v \rangle_{\gamma \gamma} = \frac{1}{16 \pi} |\lambda_{\chi V_1}^2| |c_{v_1}|^2 \frac{16M_X^4}{(4M_X^2 - m_a^2)^2 + m_a^2 \Gamma_a^2}, \quad (B3)
\]

\[
\langle \sigma v \rangle_{Z \gamma} = \frac{1}{32 \pi} |\lambda_{\chi V_1}^2| |c_{Z V_1}|^2 \frac{16M_X^4}{(4M_X^2 - m_a^2)^2 + m_a^2 \Gamma_a^2} \times \left(1 - \frac{M_2^2}{4M_X^2}\right)^{3}, \quad (B4)
\]

\[
\langle \sigma v \rangle_{ZZ} = \frac{1}{16 \pi} |\lambda_{\chi V_1}^2| |c_{Z Z}|^2 \frac{16M_X^4}{(4M_X^2 - m_a^2)^2 + m_a^2 \Gamma_a^2} \times \left(1 - \frac{M_2^2}{M_X^2}\right)^{3/2}, \quad (B5)
\]

Second, dark matter can also annihilate into a SM particle pair by the Higgs portal interaction to the real scalar partner of the axion. The DM annihilations through the \(CP\)-even scalars are \(p\)-wave suppressed unlike the counterpart of axion mediation as shown below. The dominant annihilation cross section coming from the \(CP\)-even scalar interaction is composed of

\[
\langle \sigma v \rangle_s = \langle \sigma v \rangle_{jj} + \langle \sigma v \rangle_{WW} + \langle \sigma v \rangle_{ZZ} + \langle \sigma v \rangle_{\tilde{h}\tilde{h}}, \quad (B7)
\]

The partial annihilation cross section into a SM fermion pair is

\[
\langle \sigma v \rangle_{jj} = \frac{3N_c |\lambda_{\chi V_1}^2| m_s^2 \sin^2(2\theta)}{32 \pi v^2} P_1 P_2 M_2^2 (m_1^2 - m_2^2)^2
\]

\[
+ (m_1 \Gamma_1 - m_2 \Gamma_2)^2 \left(1 - \frac{M_2^2}{M_X^2}\right)^{3/2} \frac{T}{M_X}, \quad (B8)
\]

with \(T\) being the temperature of the universe and \(P_i = [(4M_X^2 - m_i^2)^2 + m_i^2 \Gamma_i^2]^{-1}\) \((i = 1, 2)\). From the gauge-Higgs interactions, \(c_{V^\mu V^\nu}^\mu\) with

\[
c_w = -\frac{M_W^2}{v}, \quad c_Z = -\frac{M_Z^2}{v}, \quad (B9)
\]

the annihilation cross section into a gauge boson pair is similarly obtained as follows:

\[
\langle \sigma v \rangle_{VV} = \frac{3|\lambda_{\chi V_1}^2|^2 c_w^2 \sin^2(2\theta)}{32 \pi M_V^2} P_1 P_2 M_2^4 (m_1^2 - m_2^2)^2
\]

\[
+ (m_1 \Gamma_1 - m_2 \Gamma_2)^2 \left(1 - \frac{M_2^2}{M_X^2}\right) + \frac{3}{4} M_V^4 \left(1 - \frac{M_2^2}{M_X^2}\right)^{1/2} \frac{T}{M_X}, \quad (B10)
\]

with \(s_V\) being the symmetry factor. Finally, from the interactions between \(CP\)-even scalars, \(\frac{1}{2} a_1 \tilde{h}^3 + \frac{1}{2} a_2 \tilde{s}^2 \tilde{h}\), the annihilation cross section into a Higgs-like pair is

\[
\langle \sigma v \rangle_{\tilde{h}\tilde{h}} = \frac{1}{16 \pi} |\lambda_{\chi V_1}^2|^2 \sin^4 \theta M_X^4 \left(9M_X^2 - 8M_X^2 m_1^2 + 2m_1^4\right)
\]

\[
\left(1 - \frac{m_1^2}{M_X^2}\right)^{1/2} \frac{T}{M_X} (A_{tt} + A_{ts} + A_{ss}), \quad (B11)
\]

where

\[
A_{tt} = \frac{|\lambda_{\chi V_1}^2|^2 \sin^4 \theta M_X^2 (9M_X^2 - 8M_X^2 m_1^2 + 2m_1^4)}{(2M_X^2 - m_1^2)^4}, \quad (B12)
\]
\[ A_{ts} = \frac{\sin^2 \theta M_\chi (5M_\chi^2 - 2m_f^2)}{\sqrt{2}(2M_\chi^2 - m_f^2)^2} \times \sum_{i=1,2} P_i \text{Re}[\lambda_\chi i^4](4M_\chi^2 - m_f^2), \]  

(B13)  

\[ A_{ss} = \frac{3}{8} \left( \sum_{i=1,2} P_i |\bar{a}_i|^2 + 2P_1 P_2 \text{Re}[\bar{a}_1 \bar{a}_2^*][(4M_\chi^2 - m_f^2) \times (4M_\chi^2 - m_1^2) + m_1 m_2 \Gamma_1 \Gamma_2] \right). \]  

(B14)  

with  

\[ \bar{a}_1 = \frac{3m_f^2}{\nu_+ \nu_-} (\nu_+ \cos^3 \theta + \nu_- \sin^3 \theta) \sin \theta, \]  

(B15)  

\[ \bar{a}_2 = \frac{\sin(2\theta)(2m_f^2 + m_1^2)}{2\nu_+ \nu_-} (\nu_+ \sin \theta - \nu_- \cos \theta) \cos \theta. \]  

(B16)

