

Gamma ray emission in Fermi bubbles and Higgs portal dark matter

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It has been recently pointed out that the excess of the gamma ray spectrum in the Fermi bubbles at low latitude can be well explained by the annihilation of dark matter particles. The best-fit candidate corresponds to the annihilation of a dark matter with mass of around 62 GeV into $b\bar{b}$ with the cross section, $\sigma v \approx 3.3 \times 10^{-26} \text{ cm}^3/\text{s}$, or the annihilation of a dark matter with mass of around 10 GeV into a tau lepton pair with the cross section, $\sigma v \approx 5.6 \times 10^{-27} \text{ cm}^3/\text{s}$. We point out that the Higgs portal dark matter models are perfectly compatible with this interpretation of the dark matter annihilation, satisfying other phenomenological constraints. We also show that the parameter region which reproduces the best-fit values can be partly explored by the future direct dark matter search at the XENONIT.

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I. INTRODUCTION

Recently, the gamma ray bubbles found in the Fermi-LAT data, the so-called Fermi bubbles [1], have received a fair amount of attention, and their spectrum has been intensively studied. It has been pointed out in Ref. [2] that the gamma ray spectrum at the low latitude region shows an extra contribution in the energy range of $E \sim 1\text{--}4 \text{ GeV}$, while the spectrum at high latitude region can be reasonably explained by the inverse Compton scattering. It has been shown in Ref. [2] that the excess can originate from the annihilation of dark matter particles: a 10 GeV dark matter annihilating into a tau lepton pair with the cross section (times relative velocity) $\sigma v = 2 \times 10^{-27} \text{ cm}^3/\text{s}$ or a 50 GeV dark matter annihilating into quarks with the cross section $\sigma v = 8 \times 10^{-27} \text{ cm}^3/\text{s}$. Similarly and more recently, the authors of Ref. [3] have claimed that the excess is best fit by a 10 GeV dark matter annihilating into a pair of tau leptons with $\sigma v \approx 5.6 \times 10^{-27} \text{ cm}^3/\text{s}$ or a 62 GeV dark matter annihilating into $b\bar{b}$ with $\sigma v \approx 3.3 \times 10^{-26} \text{ cm}^3/\text{s}$. Interestingly, the magnitude of annihilation cross section favored by these analyses is close to the typical thermal annihilation cross section, $\sigma v \approx 3 \times 10^{-26} \text{ cm}^3/\text{s}$, for a weakly interacting massive particle dark matter to reproduce its correct thermal relic abundance of $\Omega_{\text{DM}} h^2 \approx 0.1$.

Besides the Fermi bubbles, the data of gamma rays from subhalos also show a similar spectrum shape consistent with the dark matter annihilation scenario: 8–10 GeV dark matter annihilating to tau leptons with $\sigma v \approx (1\text{--}2) \times 10^{-27} \text{ cm}^3/\text{s}$ or 30–60 GeV dark matter annihilating to

$b\bar{b}$ with $\sigma v \approx (5\text{--}10) \times 10^{-27} \text{ cm}^3/\text{s}$ [4]. See also [5,6] for similar discussions.

In this paper, we point out that the so-called Higgs portal dark matter scenario suits the interpretation of the dark matter annihilation for the gamma ray spectrum from the Fermi bubbles. We consider two simple Higgs portal dark matter models with a real scalar dark matter being singlet under the Standard Model (SM) gauge groups. The first model is one of the simplest extensions of the SM and we introduce the SM gauge singlet real scalar along with a Z_2 parity (for an incomplete list, see, e.g., [7–11]). The scalar dark matter with mass of around 60 GeV mainly annihilates into $b\bar{b}$ through the SM Higgs boson in the s channel. The other model is the Higgs portal dark matter realized in the two-Higgs-doublet extension of the SM. In this model, the scalar dark matter with mass of around 10 GeV mainly annihilates into a tau lepton pair through the Higgs bosons exchange in the s channel. We show that both of the models can account for the excess of the gamma ray spectrum from the Fermi bubbles, satisfying the cosmological condition for the observed relic abundance as well as the constraint from the current direct dark matter search experiments. See Ref. [12] for a supersymmetric model with a 10 GeV neutralino dark matter which can account for the Fermi bubble excess through the neutralino pair annihilation to tau leptons mediated by light scalar tau leptons. (See also, e.g., Ref. [13].)

II. STANDARD MODEL HIGGS PORTAL SCALAR DARK MATTER

At first, we show that a gauge singlet scalar dark matter ϕ with the mass about 60 GeV has the desired property to account for the Fermi bubble excess. We only add a real scalar ϕ to the SM particle contents along with a Z_2 parity,

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under which the scalar is odd while the SM particles are even. The Lagrangian is given by

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}M_\phi^2\phi^2 - \frac{1}{2}c|\Phi|^2\phi^2 - \lambda_\phi\phi^4, \quad (1)$$

where Φ denotes the SM Higgs doublet field, and c is a dimensionless coupling constant. After the electroweak symmetry breaking, the dark matter mass is given by $m_\phi^2 = M_\phi^2 + cv^2/2$ with the Higgs vacuum expectation value (v), and the interaction terms between the scalar dark matter and the physical Higgs boson (h) are given by

$$\mathcal{L}_{\text{int}} = -\frac{c}{2}vh\phi^2 - \frac{c}{4}h^2\phi^2. \quad (2)$$

When $m_\phi < m_h/2$, the Higgs boson decays invisibly, $h \rightarrow \phi\phi$, through the coupling. From the LHC data, the branching ratio of the invisibly decaying Higgs boson is constrained (at 3σ) as $\text{BR}(h \rightarrow \phi\phi) \lesssim 0.35$ [14], which leads to an upper bound on the coupling constant c .

The thermal relic abundance of the dark matter is evaluated by solving the Boltzmann equation for the number density of ϕ :

$$\frac{dn}{dt} + 3Hn = -\langle\sigma v\rangle(n^2 - n_{\text{EQ}}^2), \quad (3)$$

with H and n_{EQ} being the Hubble parameter and the dark matter number density in thermal equilibrium, respectively [15]. With a good accuracy, the resultant thermal relic abundance is expressed as

$$\Omega_{\text{DM}}h^2 = \frac{1.1 \times 10^9 x_d \text{ GeV}^{-1}}{\sqrt{g_*} M_P \langle\sigma v\rangle}, \quad (4)$$

where $M_P = 1.22 \times 10^{19}$ GeV is the Planck mass, $\langle\sigma v\rangle$ is the thermal averaged product of the annihilation cross section and the relative velocity, g_* is the total number of relativistic degrees of freedom in the thermal bath, and $x_d = m_\phi/T_d$ with the decoupling temperature T_d . For the dark matter mass of around 60 GeV and the Higgs boson mass of around 125 GeV, the scalar dark matter dominantly annihilates to the $b\bar{b}$ final state through the Higgs boson exchange in the s channel.

For a given dark matter mass, we identify the value of the coupling constant (c) so as to reproduce the observed relic abundance $\Omega h^2 \approx 0.1$ [16,17]. Note that for a fixed parameter set, the thermal averaged cross section $\langle\sigma v\rangle$ determined by the condition of $\Omega h^2 \approx 0.1$ is in general different from the present annihilation cross section $(\sigma v)_0$ of the dark matter relevant to the indirect search for dark matter. Here $(\sigma v)_0$ is simply given by the limit of the vanishing relative velocity $v \rightarrow 0$, rather than taking the thermal average. This difference is noteworthy for the dark

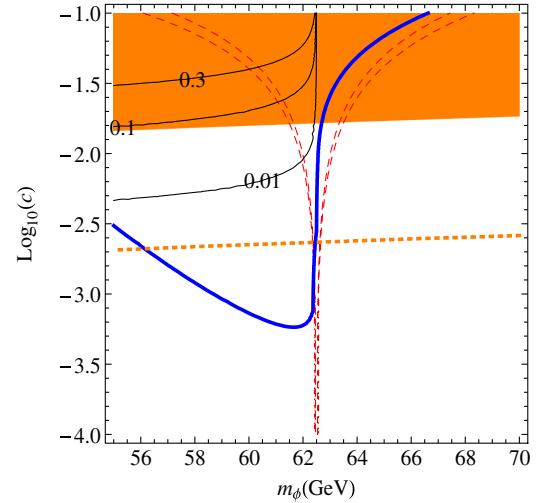


FIG. 1 (color online). Various constraints and prediction: $\Omega h^2 = 0.1$ (thick blue line), $2.81 \times 10^{-26} \leq (\sigma v)_0 \leq 3.99 \times 10^{-26}$ cm³/s (dashed red lines) claimed in Ref. [3], and the contours corresponding to $\text{BR}(h \rightarrow \phi\phi) = 0.01, 0.1, \text{ and } 0.3$ (solid gray line). The shaded region is excluded by the direct dark matter search at XENON100(2012) [18], and the future expected sensitivity 4×10^{-47} cm² by the XENON1T experiment [19] is depicted by the horizontal dotted line. Here, we have fixed $m_h = 125$ GeV.

matter mass being close to the Higgs resonance pole in its annihilation process, $m_\phi \approx m_h/2$.

In Fig. 1, we show the thick blue line along which $\Omega h^2 = 0.1$ is satisfied. The region inside the dashed red lines corresponds to the dark matter annihilation cross section to the $b\bar{b}$ final state at the present Universe in the range of $2.81 \times 10^{-26} \leq (\sigma v)_0 \leq 3.99 \times 10^{-26}$ cm³/s. Recently it has been pointed out in Ref. [3] that this range of the annihilation cross section gives the best fit for the gamma ray spectrum from the Fermi bubbles for the dark matter mass in the range of $56.9 \leq m_{\text{DM}} \leq 68.7$ GeV. We have found in Fig. 1 that the best fit for the gamma ray spectrum from the Fermi bubbles and the observed relic abundance are simultaneously realized by $c \approx 10^{-3}$ and $m_\phi \approx 62.5$ GeV. In the figure, the contours for the branching ratio of the Higgs invisible decay [$\text{BR}(h \rightarrow \phi\phi) = 0.01, 0.1, \text{ and } 0.3$] are also shown. The shaded region is excluded by the null result of the direct dark matter search at the XENON100 [18] while the horizontal dotted line denotes the future reach by the XENON1T experiment [19].

III. TWO-HIGGS-DOUBLET PORTAL SCALAR DARK MATTER

Next let us consider the Higgs portal dark matter realized in the two-Higgs-doublet extension of the SM, namely, the so-called type-X two-Higgs-doublet model (THDM). This type of THDM has been extensively studied from the viewpoint of, especially, nonvanishing neutrino mass [20], and the results from dark matter direct [21] or indirect [22]

searches. In this model, a scalar dark matter with mass of around 10 GeV annihilates mainly into a tau lepton pair.

In the type-X model, the Yukawa interaction is given by

$$\mathcal{L}_Y = -y_{\ell_i} \bar{L}^i \Phi_1 \ell_R^i - y_{u_i} \bar{Q}^i \tilde{\Phi}_2 u_R^i - y_{d_i} \bar{Q}^i \Phi_2 d_R^i + \text{H.c.}, \quad (5)$$

where Q^i (L^i) is the ordinary left-handed quark (lepton) in the i th generation, and u_R^i and d_R^i (e_R^i) are the right-handed SU(2) singlet up- and down-type quarks (charged leptons), respectively. Here, we have neglected the flavor mixing, for simplicity. The scalar potential for the two-Higgs doublets (Φ_1 and Φ_2) is given by

$$\begin{aligned} V = & -\mu_1^2 |\Phi_1|^2 - \mu_2^2 |\Phi_2|^2 - (\mu_{12}^2 \Phi_1^\dagger \Phi_2 + \text{H.c.}) \\ & + \lambda_1 |\Phi_1|^4 + \lambda_2 |\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 |\Phi_1^\dagger \Phi_2|^2 \\ & + \left\{ \frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2)^2 + \text{H.c.} \right\} \\ & + \frac{1}{2} \mu_\phi^2 \phi^2 + \lambda_\eta \phi^4 + (\sigma_1 |\Phi_1|^2 + \sigma_2 |\Phi_2|^2) \frac{\phi^2}{2}. \quad (6) \end{aligned}$$

Electric charge neutral components of the two-Higgs doublets develop the vacuum expectation values as

$$\Phi_1 = \begin{pmatrix} 0 \\ \frac{v_1 + h_1}{\sqrt{2}} \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} 0 \\ \frac{v_2 + h_2}{\sqrt{2}} \end{pmatrix}, \quad (7)$$

where $v^2 = v_1^2 + v_2^2 = (246 \text{ GeV})^2$, and we introduce the usual parametrization, $\tan \beta = v_2/v_1$. The physical states (h_1 and h_2) are diagonalized to the mass eigenstates (h and H) as

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}. \quad (8)$$

When the mixing angle α satisfies the condition $\sin(\beta - \alpha) \approx 1$, the mass eigenstate h is the SM-like Higgs boson.

In terms of the mass eigenstates, the (3-point) interactions of the scalar dark matter with the Higgs bosons are given by

$$\begin{aligned} \mathcal{L}_\sigma \supset & -\frac{\sigma_1 \cos \alpha \cos \beta + \sigma_2 \sin \alpha \sin \beta}{2} v H \phi^2 \\ & -\frac{-\sigma_1 \sin \alpha \cos \beta + \sigma_2 \cos \alpha \sin \beta}{2} v h \phi^2. \quad (9) \end{aligned}$$

The Yukawa interactions with quarks and leptons in Eq. (5) can then be written as

$$\begin{aligned} \mathcal{L}_Y^{\text{Quarks}} \supset & -\frac{m_{u^i} \sin \alpha}{v \sin \beta} H \bar{u}^i u^i - \frac{m_{u^i} \cos \alpha}{v \sin \beta} h \bar{u}^i u^i \\ & -\frac{m_{d^i} \sin \alpha}{v \sin \beta} H \bar{d}^i d^i - \frac{m_{d^i} \cos \alpha}{v \sin \beta} h \bar{d}^i d^i, \quad (10) \end{aligned}$$

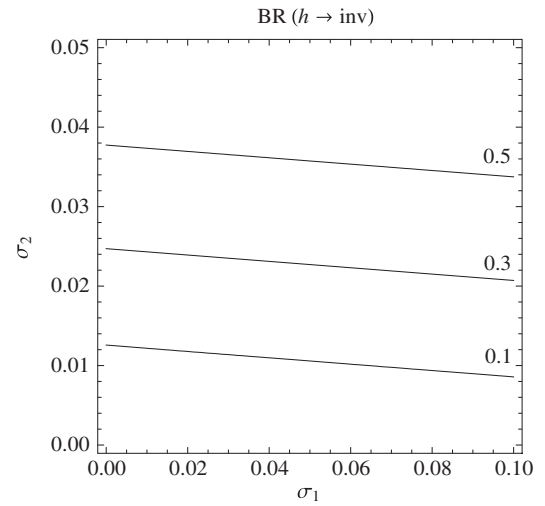


FIG. 2. Contours of the invisible decay branching ratio of the SM-like Higgs boson, $\text{BR}(h \rightarrow \phi\phi) = 0.1, 0.3, \text{ and } 0.5$, respectively. We have taken $\tan \beta = 5$, $\sin(\beta - \alpha) = 1$, and $m_\phi = 10 \text{ GeV}$.

$$\mathcal{L}_Y^{\text{Leptons}} \supset -\frac{m_{\ell^i} \cos \alpha}{v \cos \beta} H \bar{\ell}^i \ell^i + \frac{m_{\ell^i} \sin \alpha}{v \cos \beta} h \bar{\ell}^i \ell^i. \quad (11)$$

In the following analysis, we fix the mixing angle to give $\sin(\beta - \alpha) = 1$. Then, the coupling between the non-SM-like Higgs (H) and the lepton is enhanced for $\tan \beta > 1$, while the SM couplings between the Higgs boson and the quarks remain the same as the SM ones. From now on, we take $\tan \beta = 5$ as a reference value. In addition, we fix model parameters to make the charged and CP -odd Higgs bosons heavy enough to be consistent with the current experimental lower bound and not to be involved in our analysis of the dark matter.¹

We first calculate the invisible decay width of the SM-like Higgs boson into a pair of the scalar dark matters through the interactions in Eq. (9).² The branching ratio of the invisible decay $\text{BR}(h \rightarrow \phi\phi)$ is shown in Fig. 2. We have found that the bound from the LHC data, $\text{BR}(h \rightarrow \phi\phi) \lesssim 0.35$ [14], is satisfied for $\sigma_2 \lesssim 0.02$, almost independently of σ_1 .

¹In the following, we will find the results that the non-SM-like Higgs boson mass $\lesssim 30 \text{ GeV}$, and hence the mass splitting between this Higgs boson and the charged and CP -odd Higgs bosons is large. We can check that even with the large mass splitting, our model is consistent with the electroweak precision tests when the charged and CP -odd Higgs bosons are well degenerate. Our model has enough freedom of free parameters to realize such a mass spectrum, keeping our results for dark matter physics intact.

²As we will see in the following, the Higgs boson H is light and the SM-like Higgs boson also decays to a pair of the H bosons. Since many free parameters are involved in the decay process (see the Appendix), we simply assume a negligible partial decay width for it in this paper.

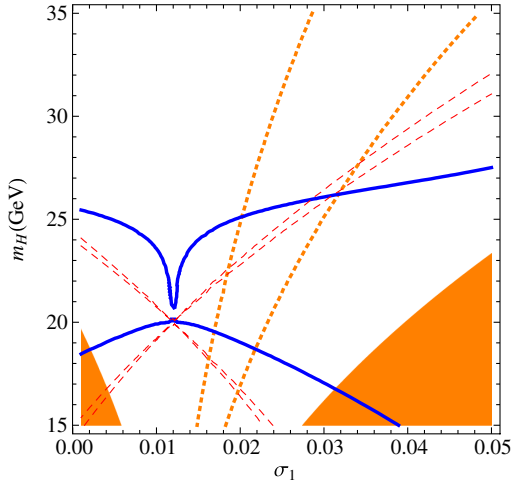


FIG. 3 (color online). Contours for $\Omega h^2 = 0.1$ (thick blue line) and $2.81 \times 10^{-26} \leq (\sigma v)_0 \leq 3.99 \times 10^{-26} \text{ cm}^3/\text{s}$ (dashed red lines) claimed in Ref. [3]. The shaded regions are excluded by the direct dark matter search by the XENON100(2012) experiment [18], and the expected future sensitivity $5 \times 10^{-45} \text{ cm}^2$ by the XENON1T experiment [19] are depicted as the dotted lines. In this analysis, we have fixed $\sigma_2 = 0.012$ and $m_\phi = 10 \text{ GeV}$.

Now we calculate the annihilation cross section of the scalar dark matter dominated by the s -channel Higgs bosons (h and H) exchange. We evaluate the cross section as a function of the coupling σ_1 and the non-SM-like Higgs boson mass m_H with a fixed value for $\sigma_2 < 0.02$. For the dark matter with $m_\phi = 10 \text{ GeV}$, the annihilation mode into a tau lepton pair through the H -boson exchange dominates for suitable values of σ_1 and m_H .

Figure 3 shows the results for $\sigma_2 = 0.012$. The thick blue line corresponds to the parameter set which reproduces the thermal relic abundance of the scalar dark matter $\Omega h^2 = 0.1$, while the parameters between the two dashed red lines provide the annihilation cross section, $2.81 \times 10^{-26} \leq (\sigma v)_0 \leq 3.99 \times 10^{-26} \text{ cm}^3/\text{s}$ [3]. The shaded regions are excluded by the direct dark matter search at the XENON100(2012) [18], and the expected sensitivity by the XENON1T experiment [19] is depicted by two dotted lines. We can see that near the resonance pole $m_\phi = m_H/2$, the conditions for the thermal relic abundance and the best-fit annihilation cross section into a tau pair claimed in Ref. [3] are simultaneously satisfied for

$$\begin{aligned} \sigma_1 &\approx 0.03, \\ m_H &\approx 26 \text{ GeV}. \end{aligned} \quad (12)$$

This region is found to be close to the sensitivity of the direct dark matter search expected by the XENON1T experiment. Results for the same analysis but with $\sigma_2 = 0$ are depicted in Fig. 4. In this case, we have found the solution for

$$\begin{aligned} \sigma_1 &\approx 0.018, \\ m_H &\approx 26 \text{ GeV}. \end{aligned} \quad (13)$$

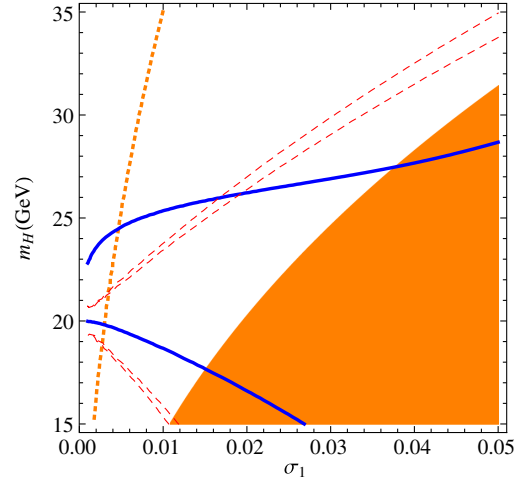


FIG. 4 (color online). Same as Fig. 3 but for $\sigma_2 = 0$.

Interestingly, this parameter region can be tested by the XENON1T experiment in the future.

IV. SUMMARY

We have shown that a Higgs portal dark matter particle annihilating into $b\bar{b}$ or $\tau^+\tau^-$ through the s -channel exchange of Higgs boson(s) very well suits the dark matter interpretation in explaining the excess of the gamma ray spectrum from the Fermi bubbles at low latitude, observed by the Fermi-LAT. In the simplest Higgs portal dark matter model (“SM plus ϕ ” model), we have identified a model-parameter region ($c \approx 10^{-3}$ and $m_\phi \approx 62.5 \text{ GeV}$) which can simultaneously satisfy the correct thermal relic abundance and the best-fit value of the dark matter annihilation cross section to explain the gamma ray excess [3]. Very interestingly, the mass we have found is almost the best-fit value claimed in Ref. [3]. In our analysis, we see that the parameter region appears near the SM Higgs resonance point ($m_\phi \sim m_h/2$), and therefore a suitable dark matter mass is almost fixed by the SM Higgs boson mass. The SM Higgs boson is finally discovered with a mass of around $m_h = 125\text{--}126 \text{ GeV}$. It is another interesting point that in the simplest Higgs portal dark matter model, the observed Higgs boson mass is compatible with the dark matter interpretation for the gamma ray excess in the Fermi bubbles. We have also considered the Higgs portal dark matter model realized in the two-Higgs-doublet extension of the SM (“type-X THDM plus ϕ ” model). In this case, a scalar dark matter with $m_\phi = 10 \text{ GeV}$ dominantly annihilates into a pair of tau leptons. We have identified a parameter region which reproduces the best-fit region corresponding to the dark matter annihilation into a tau lepton pair [3], as well as the observed thermal relic abundance. We have found that the parameter region is partly covered by the expected sensitivity of the direct dark matter search at the XENON1T.

Finally, analysis in Refs. [2,3] has been done by assuming a 100% annihilation fraction for a selected annihilation mode. However, for a given concrete particle model, there are various annihilation modes in general. It should be worth performing more detailed analysis for the gamma ray spectrum based on a concrete model with a realistic annihilation fraction to various final states. The Higgs portal dark matter scenario presented in this paper can be a good benchmark for the analysis.

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APPENDIX: TYPE-X TWO-HIGGS-DOUBLET MODEL

1. Decay width of Higgs bosons

a. Invisible decay width

$$\Gamma_h^{(\text{inv})} = (-\sigma_1 \sin \alpha \cos \beta + \sigma_2 \cos \alpha \sin \beta)^2 \times \frac{v^2}{32\pi m_h} \sqrt{1 - \frac{4m_\phi^2}{m_h^2}}, \quad (\text{A1})$$

$$\Gamma_H^{(\text{inv})} = (\sigma_1 \cos \alpha \cos \beta + \sigma_2 \sin \alpha \sin \beta)^2 \times \frac{v^2}{32\pi m_H} \sqrt{1 - \frac{4m_\phi^2}{m_H^2}}. \quad (\text{A2})$$

b. Total decay width

$$\Gamma_h \approx \sin^2(\beta - \alpha) \Gamma(h_{\text{SM}} \rightarrow VV) + \left(\frac{\cos \alpha}{\sin \beta}\right)^2 \Gamma(h_{\text{SM}} \rightarrow q\bar{q}) + \left(\frac{\sin \alpha}{\cos \beta}\right)^2 \Gamma(h_{\text{SM}} \rightarrow \tau\bar{\tau}) + \Gamma_h^{(\text{inv})} + \Gamma(h \rightarrow HH), \quad (\text{A3})$$

$$\Gamma_H \approx \cos^2(\beta - \alpha) \Gamma(h_{\text{SM}} \rightarrow VV) + \left(\frac{\sin \alpha}{\sin \beta}\right)^2 \Gamma(h_{\text{SM}} \rightarrow q\bar{q}) + \left(\frac{\cos \alpha}{\cos \beta}\right)^2 \Gamma(h_{\text{SM}} \rightarrow \tau\bar{\tau}) + \Gamma_H^{(\text{inv})}, \quad (\text{A4})$$

with

$$\Gamma(h \rightarrow HH) = (\sin \alpha \sin \beta (\cos 2\alpha (-6\lambda_1 + 3\lambda) - 6\lambda_1 + \lambda) - \cos \alpha \cos \beta (\cos 2\alpha (6\lambda_2 - 3\lambda) - 6\lambda_2 + \lambda))^2 \times \frac{v^2}{128\pi m_h} \sqrt{1 - \frac{4m_H^2}{m_h^2}}, \quad (\text{A5})$$

$$\lambda = \lambda_3 + \lambda_4 + \lambda_5. \quad (\text{A6})$$

2. Dark matter annihilation cross section

$$w(s) \equiv \frac{1}{4} \int |\overline{\mathcal{M}}|^2 d\text{LIPS}, \quad (\text{A7})$$

$$|\overline{\mathcal{M}}(\phi\phi \rightarrow b\bar{b})|^2 = 3 \left| \frac{(-\sigma_1 \sin \alpha \cos \beta + \sigma_2 \cos \alpha \sin \beta) \cos \alpha}{s - m_b^2 + im_b \Gamma_b} \frac{\cos \alpha}{\sin \beta} + \frac{(\sigma_1 \cos \alpha \cos \beta + \sigma_2 \sin \alpha \sin \beta) \sin \alpha}{s - m_H^2 + im_H \Gamma_H} \frac{\sin \alpha}{\sin \beta} \right|^2 \times m_b^2 (s - 4m_b^2), \quad (\text{A8})$$

$$|\overline{\mathcal{M}}(\phi\phi \rightarrow \tau\bar{\tau})|^2 = \left| \frac{(-\sigma_1 \sin \alpha \cos \beta + \sigma_2 \cos \alpha \sin \beta) \sin \alpha}{s - m_\tau^2 + im_\tau \Gamma_\tau} \frac{\sin \alpha}{\cos \beta} - \frac{(\sigma_1 \cos \alpha \cos \beta + \sigma_2 \sin \alpha \sin \beta) \cos \alpha}{s - m_H^2 + im_H \Gamma_H} \frac{\cos \alpha}{\cos \beta} \right|^2 \times m_\tau^2 (s - 4m_\tau^2). \quad (\text{A9})$$

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