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Invisible Higgs decay width versus dark matter direct detection cross section in Higgs portal dark matter models

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The correlation between the invisible Higgs branching ratio ($B_h^{\rm inv}$) versus dark matter (DM) direct detection cross section ($\sigma_p^{\rm SI}$) in Higgs portal singlet fermion DM (SFDM) or vector DM (VDM) models is usually presented in the effective field theory (EFT) framework. In this paper, we derive the explicit expressions for this correlation within UV completions of SFDM and VDM models with Higgs portals, and we discuss the limitations of the EFT approach. We show that there are at least two additional hidden parameters in $\sigma_p^{\rm SI}$ in the UV completions: the singletlike scalar mass m_2 and its mixing angle α with the SM Higgs boson (h). In particular, if the singletlike scalar is lighter than the SM Higgs boson ($m_2 < m_h \cos\alpha/\sqrt{1+\cos^2\alpha}$), the collider bound becomes weaker than the one based on EFT.

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I. INTRODUCTION

As more data on the 125 GeV Higgs boson h are accumulated at the LHC, its invisible Higgs branching fraction $B_h^{\rm inv}$ is getting bounded from above. This bound can give some useful constraint on the Higgs coupling to the dark matter (DM) particle in some concrete DM models. In fact such attempts for Higgs portal DM models were made recently by both the ATLAS Collaboration and the CMS Collaboration [1,2]. Both collaborations announced that their measurements of the upper bounds on the $B_h^{\rm inv}$ can be translated into the upper bounds on $\sigma_p^{\rm SI}$ (the spin-independent cross section of the DM particle on the nucleon) in the Higgs portal DM models, which are much stronger than those obtained from DM direct detection experiments in the low DM mass region (i.e., $m_{\rm DM} \lesssim 10$ GeV). These analyses are based on the following model Lagrangians [3–6]:

$$\mathcal{L}_{\rm SSDM} = \frac{1}{2}\partial_\mu S\partial^\mu S - \frac{1}{2}m_S^2 S^2 - \frac{\lambda_S}{4!}S^4 - \frac{\lambda_{HS}}{2}S^2 H^\dagger H \qquad (1)$$

$$\mathcal{L}_{\rm SSDM} = \bar\psi(i\partial - m_\psi)\psi - \frac{\lambda_{\psi H}}{\Lambda}\bar\psi\psi H^\dagger H \qquad (2)$$

$$\mathcal{L}_{\rm VDM} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu - \frac{\lambda_{VH}}{2}V_\mu V^\mu H^\dagger H - \frac{\lambda_V}{4}(V_\mu V^\mu)^2. \qquad (3)$$

In all three cases, the DM phenomenology can be done with two parameters only, namely the DM mass and the DM coupling to the Higgs field. The latter parameter is strongly constrained by the upper bound on the invisible Higgs decay and can be translated into the upper bound on the spin-independent cross section of DM on the nucleon. This simple strategy has been adopted on numerous occasions.

The singlet scalar DM Lagrangian (1) is renormalizable, and the results based on it would be reliable [7]. We refer the reader to the existing literature [8] for the comprehensive analyses on this model without touching it in the following. On the other hand, the other two cases, i.e., singlet fermion DM (SFDM) and vector DM (VDM) have to be considered in better frameworks. Since we don't know the new physics scales related with DM, we cannot know *a priori* how good the effective field theory (EFT) approach would be. Also the mass for the VDM is given by hand, so that Lagrangians for both SFDM and VDM are not renormalizable and violate unitarity on some scale. In such cases, it is safer to consider simple UV completions of these two cases.

In this letter, we point out that the claim by ATLAS and CMS based on the EFT is erroneous for SFDM and VDM cases, by working in renormalizable and unitary Higgs portal DM models proposed by the present authors [9–11]. In these two cases, there appears an additional SM singlet scalar, either from the renormalizable Yukawa couplings of the SFDM or from the remnant of the dark Higgs mechanism for generating the VDM mass. In each case, we derive the expressions for the $B_h^{\rm inv}$ and $\sigma_p^{\rm SI}$ and show that there are hidden variables in $\sigma_p^{\rm SI}$, namely, the mass of the second scalar boson (m_2), which is mostly singletlike, and the mixing angle α between the SM Higgs and the singlet scalar boson. If kinematically allowed, the heavier scalar boson can decay into a pair of lighter scalar bosons, so we have to consider the branching ratio for the nonstandard Higgs decays, $B_h(m_1)^{\rm non\,SM}$ with $m_1 = m_h \approx 125$ GeV being the mass of SM-like Higgs. Then we use the LHC bounds on $B_h^{\rm inv}$ to derive the bounds on $\sigma_p^{\rm SI}$ as functions of

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(m_2, α) and show when we recover the usual results presented by ATLAS and CMS, and when we do not. This exercise will not only be physically important but also will show good examples of the difference between the EFT and the full theory, and we will be able to understand clearly when the EFT can fail.

In the following, we do not address thermal relic density of DM since it is independent of the issues raised and resolved in this paper. It would be straightforward to include discussions on thermal relic density, which will be presented elsewhere [12].

II. RENORMALIZABLE SFDM MODEL

The simplest renormalizable Lagrangian for the Higgs portal SFDM model is given by [9,10,13]

$$\mathcal{L}_{\rm SFDM} = \bar{\psi}(i\partial - m_\psi - \lambda_\psi S)\psi - \mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \mu_S^3 S - \frac{\mu_S'}{3} S^3 - \frac{\lambda_S}{4} S^4. \tag{4}$$

We consider Dirac fermion DM in this paper. For the Majorana fermion DM case, we have to multiply the *invisible* decay rate of the Higgs boson by a factor of 1/2, and it results in a factor 2 larger $\sigma_p^{\rm SI}$ relative to the case of Dirac fermion DM. In general, the singlet scalar S can develop a nonzero vacuum expectation value, and we have to shift the field as $S(x) \to \langle S \rangle + s(x)$. Also, the SM Higgs will break the electroweak symmetry spontaneously. The detailed expressions for the relations among various parameters can be found in Ref. [9], to which we refer the reader for details.

After all, there are two scalar bosons, a mixture of the SM Higgs boson h and the singlet scalar s. The physical states are defined after the $SO(2)$ rotation:

$$H_1 = h\cos\alpha - s\sin\alpha,$$
$$H_2 = h\sin\alpha + s\cos\alpha.$$

Correspondingly, the masses of H_1 and H_2 are defined as $m_1 = m_h$ and m_2, respectively, and the same definition will be used for the case of VDM in the next section. Note that in the above equations there is a minus sign in one term which originates from the $SO(2)$ nature of the rotation matrix in the scalar sector. This minus sign plays an important role in the direct detection cross section of the DM scattering on the nucleon since the contributions of H_1 and H_2 to $\sigma_p^{\rm SI}$ interfere destructively [9]. This is a very generic phenomenon in both the SFDM case and the VDM case [9,11,14].

Now we give the explicit forms for the invisible branching fraction and the non-SM branching fraction of the SM Higgs boson, and the DM-proton scattering cross section within the renormalizable SFDM:

$$B_i^{\rm inv} = \frac{(1-\kappa_i(\alpha))\Gamma_i^{\rm inv}}{\kappa_i(\alpha)\Gamma_i^{\rm SM} + (1-\kappa_i(\alpha))\Gamma_i^{\rm inv} + \Gamma_i^{jj}} \tag{5}$$

$$B_i^{\rm non\,SM} = \frac{\Gamma_i^{jj}}{\kappa_i(\alpha)\Gamma_i^{\rm SM} + (1-\kappa_i(\alpha))\Gamma_i^{\rm inv} + \Gamma_i^{jj}} \tag{6}$$

$$\sigma_p^{\rm SI} = \frac{m_r^2}{\pi}\left(\frac{\lambda_\psi s_\alpha c_\alpha m_p}{v_H}\right)^2 \mathcal{F}(m_\psi, \{m_i\}, v) f_p^2, \tag{7}$$

where $\kappa_i(\alpha) = c_\alpha^2, s_\alpha^2$ for $i = 1, 2$. The decay rates of the Higgs particles are given by

$$\Gamma_i^{\rm SM} = \Gamma_h(m_i) \tag{8}$$

$$\Gamma_i^{\rm inv} = \frac{\lambda_\psi^2}{8\pi} m_i \left(1 - \frac{4m_\psi^2}{m_i^2}\right)^{3/2} \tag{9}$$

$$\Gamma_i^{jj} = \frac{1}{32\pi m_i}\lambda_{ijj}^2 \left(1 - \frac{4m_j^2}{m_i^2}\right)^{1/2}, \tag{10}$$

where λ_{ijj}'s are given by

$$\lambda_{122} = \lambda_{HS} v_H c_\alpha^3 + 2(3\lambda_H - \lambda_{HS}) v_H c_\alpha s_\alpha^2 - 2[\mu_S' + 3(\lambda_S - \lambda_{HS}) v_S] c_\alpha^2 s_\alpha - \lambda_{HS} v_S s_\alpha^3 \tag{11}$$

$$\lambda_{211} = \lambda_{HS} v_S c_\alpha^3 + 2(3\lambda_H - \lambda_{HS}) v_H c_\alpha^2 s_\alpha 2[\mu_S' + 3(\lambda_S - \lambda_{HS}) v_S] c_\alpha s_\alpha^2 + \lambda_{HS} v_H s_\alpha^3 \tag{12}$$

and the function $\mathcal{F}(m_\Psi, \{m_i\}, v)$ is given by

$$\mathcal{F} = \frac{1}{4m_\psi^2 v^2}\left[\sum_i \left(\frac{1}{m_i^2} - \frac{1}{4m_\psi^2 v^2 + m_i^2}\right) - \frac{2}{(m_2^2 - m_1^2)}\sum_i (-1)^{i-1} \ln\left(1 + \frac{4m_\psi^2 v^2}{m_i^2}\right)\right], \tag{13}$$

with v being the lab velocity of DM, $m_r \equiv m_\psi m_p/(m_\psi + m_p)$, and $f_p = \sum_{q=u,d,s} f_q + \frac{2}{9} f_Q$, with f_q being the hadronic matrix element and $f_Q = 1 - \sum_{q=u,d,s} f_q$. We take $f_p = 0.326$ from a lattice calculation [15]. Note that the channel "$h \to \phi\phi^* \to \phi b\bar{b}$" is also possible, and the associated decay rate is

$$\Gamma_{h\to\phi b\bar{b}} \sim \frac{(\lambda_{122}s_\alpha)^2}{3(2\pi)^5}\left(\frac{m_b}{m_h}\right)^2\frac{(m_h-m_\phi)^5}{m_h m_\phi^5}. \quad (14)$$

This is smaller than $\Gamma_h^{\rm SM}$ by many orders of magnitude and can be ignored safely.

Let us compare these results with those obtained in the EFT:

$$(B_h^{\rm inv})_{\rm EFT} = \frac{(\Gamma_h^{\rm inv})_{\rm EFT}}{\Gamma_h^{\rm SM}+(\Gamma_h^{\rm inv})_{\rm EFT}} \quad (15)$$

$$(\sigma_p^{\rm SI})_{\rm EFT} = \frac{m_r^2}{\pi}\left[\frac{\lambda_{\psi H}m_p}{\Lambda m_h^2}\right]^2 f_p^2, \quad (16)$$

where

$$(\Gamma_h^{\rm inv})_{\rm EFT} = \frac{1}{8\pi}\left(\frac{\lambda_{\psi H}v_H}{\Lambda}\right)^2 m_h\left(1-\frac{4m_\psi^2}{m_h^2}\right)^{3/2}. \quad (17)$$

Recent analyses of LHC experiments impose a bound [1,2] on the branching fraction of SM-like Higgs decay to invisible particles as [2]

$$B_h^{\rm inv} < 0.51 \quad \text{at 95\% CL} \quad (18)$$

(see also Ref. [16] for a more involved analysis in the presence of an extra singletlike scalar boson that mixes with the SM Higgs boson). In the renormalizable model described by Eq. (4), the LHC bound on $B_h^{\rm inv}$ can be translated directly to a constraint on $\sigma_p^{\rm SI}$ by the relation

$$\sigma_p^{\rm SI} = c_\alpha^4 m_h^4 \mathcal{F}(m_\psi,\{m_i\},v) \times \frac{B_h^{\rm inv}\Gamma_h^{\rm SM}}{(1-B_h^{\rm inv})}\frac{8m_r^2}{m_h^5\beta_\psi^3}\left(\frac{m_p}{v_H}\right)^2 f_p^2, \quad (19)$$

where $\beta_\psi = \sqrt{1-4m_\psi^2/m_h^2}$. Here we set $B_1^{\rm non\,SM}=0$ for simplicity and denote $B_1^{\rm inv}$ as $B_h^{\rm inv}$. On the other hand, in the EFT described by Eq. (2) with $(B_h^{\rm inv})_{\rm EFT}\to B_h^{\rm inv}$, one finds

$$(\sigma_p^{\rm SI})_{\rm EFT} = \frac{B_h^{\rm inv}\Gamma_h^{\rm SM}}{1-B_h^{\rm inv}}\frac{8m_r^2}{m_h^5\beta_\psi^3}\left(\frac{m_p}{v_H}\right)^2 f_p^2, \quad (20)$$

which was used in the analyses of ATLAS [1] and CMS [2]. Now it is clear from Eqs. (19) and (20) that, contrary to $(\sigma_p^{\rm SI})_{\rm EFT}$ of EFT, $\sigma_p^{\rm SI}$ of a full theory of Eq. (4) has additional factors, $c_\alpha^4 m_h^4\mathcal{F}$, which involve two extra parameters, (α, m_2). Note that, in the limit of small α and $m_2 \gg m_1$, $\cos\alpha \simeq 1$ and we can drop the $1/m_2^2$ term in the $\sigma_p^{\rm SI}$; Eq. (19) for $\sigma_p^{\rm SI}$ approaches Eq. (20) for $(\sigma_p^{\rm SI})_{\rm EFT}$. However, if one of these two assumptions is not valid, one cannot make a definitive prediction for the $\sigma_p^{\rm SI}$. Therefore the

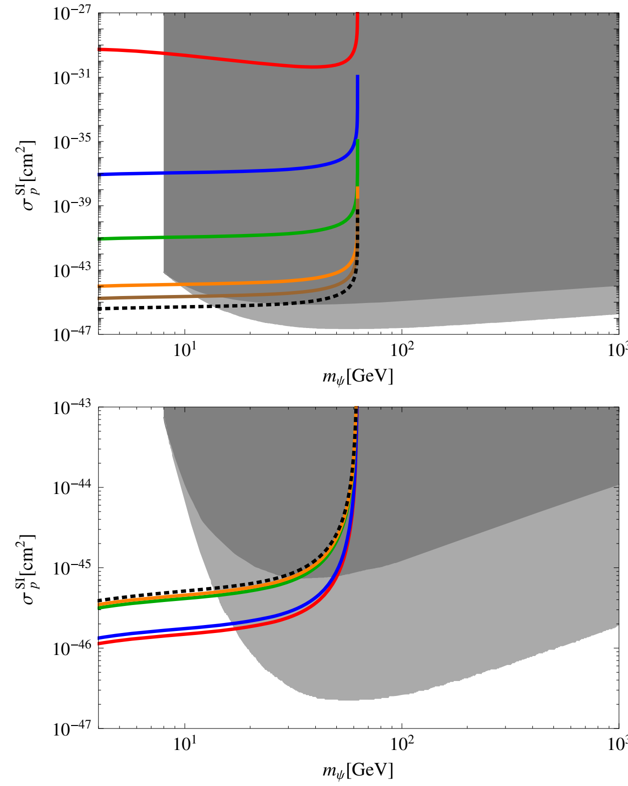

FIG. 1 (color online). $\sigma_p^{\rm SI}$ as a function of the mass of dark matter for SFDM for a mixing angle $\alpha = 0.2$. (Upper panel) $m_2 = 10^{-2}, 1, 10, 50, 70$ GeV for solid lines from top to bottom. (Lower panel) $m_2 = 100, 200, 500, 1000$ GeV for dashed lines from bottom to top. The black dashed lines are EFT predictions. Dark-gray and gray regions are the exclusion regions of LUX [17] and projected XENON1T (gray) [18].

bounds on the $\sigma_p^{\rm SI}$ derived by the ATLAS and CMS collaborations should be taken with caution. Basically one cannot make model-independent connections between $B_h^{\rm inv}(=B_1^{\rm inv})$ and $\sigma_p^{\rm SI}$ in the Higgs portal SFDM model. This is clearly shown in Fig. 1, where colored solid lines represent the LHC bound on $\sigma_p^{\rm SI}$ of Eq. (7) for various values for m_2. The bound on $(\sigma_p^{\rm SI})_{\rm EFT}$ of Eq. (16) was also depicted for comparison. Note that, for low m_ψ if $m_2 < m_h c_\alpha/\sqrt{1+c_\alpha^2}$, the LHC bound becomes weaker than the claims made in [1,2]. In particular, for $m_2 \lesssim m_h c_\alpha/\sqrt{12.3+c_\alpha^2}$, it cannot beat the direct detection bound for $m_\psi \gtrsim 8$ GeV. FIG. 1, where $\sigma_p^{\rm SI}$ of Eq. (19) and $(\sigma_p^{\rm SI})_{\rm EFT}$ of Eq. (20) in the SFDM scenario are depicted for comparison, shows clearly this discrepancy caused by the different dependence on α and m_2.

III. RENORMALIZABLE VDM MODEL

The simplest renormalizable Lagrangian for the Higgs portal VDM model is given by [11,19]

$$\mathcal{L}_{\rm VDM} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + D_\mu\Phi^\dagger D^\mu\Phi - \lambda_\Phi\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right)^2 - \lambda_{\Phi H}\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right)\left(H^\dagger H - \frac{v_H^2}{2}\right), \tag{21}$$

where Φ is the dark Higgs field which generates nonzero mass for the VDM through spontaneous $U(1)_X$ breaking, and

$$D_\mu\Phi \equiv (\partial_\mu + i g_X Q_\Phi V_\mu)\Phi.$$

After the $U(1)_X$ breaking, we shift the field Φ_X as follows:

$$\Phi \to \frac{1}{\sqrt{2}}(v_\Phi + \phi(x)).$$

where the field $\phi(x)$ is a SM singlet scalar similar to the singlet scalar in the SFDM case. Again, there are two scalar bosons which are mixtures of h and ϕ.

The invisible and the non-SM branching fractions of the Higgs decay are of the same forms as Eqs. (5) and (6), but with

$$\Gamma_i^{\rm inv} = \frac{g_X^2}{32\pi}\frac{m_i^3}{m_V^2}\left(1 - \frac{4m_V^2}{m_i^2} + 12\frac{m_V^4}{m_i^4}\right)\left(1 - \frac{4m_V^2}{m_i^2}\right)^{1/2}, \tag{22}$$

where m_V is the mass of VDM, and Γ_i^{jj} with $\mu_P' = 0$. The spin-independent cross section of VDM to the proton is also the same as the one in Eq. (7), with λ_ψ and m_ψ replaced by g_X and m_V, respectively.

Again, let us compare these results with those in the EFT: $(B_h^{\rm inv})_{\rm EFT}$ is of the same form as Eq. (15), with

$$(\Gamma_h^{\rm inv})_{\rm EFT} = \frac{\lambda_{VH}^2}{128\pi}\frac{v_H^2 m_h^3}{m_V^4} \times \left(1 - \frac{4m_V^2}{m_h^2} + 12\frac{m_V^4}{m_h^4}\right)\left(1 - \frac{4m_V^2}{m_h^2}\right)^{1/2}, \tag{23}$$

and the VDM-nucleon scattering cross section is

$$(\sigma_p^{\rm SI})_{\rm EFT} = \frac{m_r^2}{\pi}\left[\frac{\lambda_{VH} m_p}{2m_V m_h^2}\right]^2 f_p^2. \tag{24}$$

In the renormalizable model of Eq. (21), the LHC bound on $B_h^{\rm inv}$ can be translated directly to a constraint on $\sigma_p^{\rm SI}$ by the relation

$$\sigma_p^{\rm SI} = c_\alpha^4 m_h^4 \mathcal{F}(m_V, \{m_i\}, v) \times \frac{B_h^{\rm inv}\Gamma_h^{\rm SM}}{(1 - B_h^{\rm inv})}\frac{32 m_r^2 m_V^2 (m_p/v_H)^2 f_p^2}{m_h^7 \beta_V\left(1 - \frac{4m_V^2}{m_h^2} + 12\frac{m_V^4}{m_h^4}\right)}, \tag{25}$$

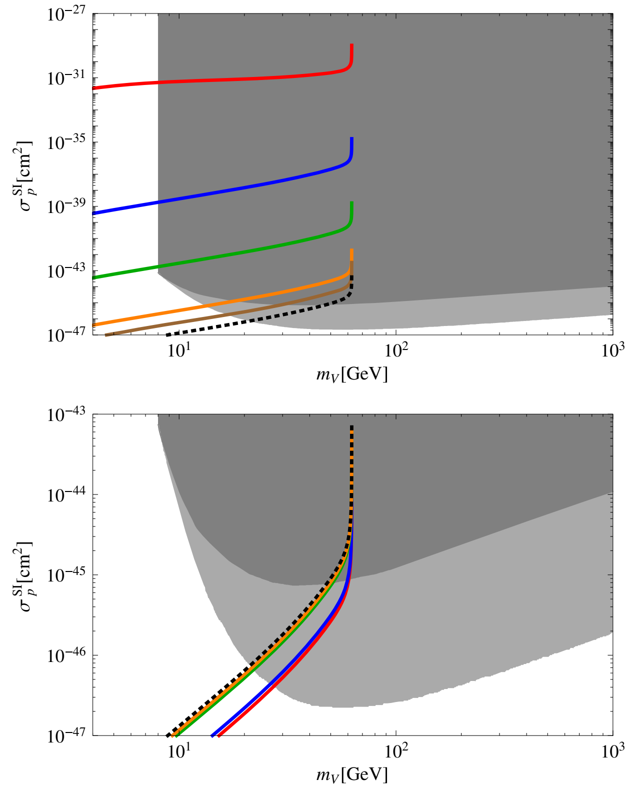

FIG. 2 (color online). $\sigma_p^{\rm SI}$ as a function of the mass of dark matter for VDM for a mixing angle $\alpha = 0.2$. The same color and line scheme as Fig. 1.

where $\beta_V = \sqrt{1 - 4m_V^2/m_h^2}$. On the other hand, in the EFT of Eq. (3) one finds

$$(\sigma_p^{\rm SI})_{\rm EFT} = \frac{B_h^{\rm inv}\Gamma_h^{\rm SM}}{1 - B_h^{\rm inv}}\frac{32 m_r^2 m_V^2 (m_p/v_H)^2 f_p^2}{m_h^7 \beta_V(1 - \frac{4m_V^2}{m_h^2} + 12\frac{m_V^4}{m_h^4})}, \tag{26}$$

which is used in the analyses of ATLAS [1] and CMS [2]. Note again that $\sigma_p^{\rm SI}$ of Eq. (25) has additional factors involving $(\alpha,\ m_2)$, compared to $(\sigma_p^{\rm SI})_{\rm EFT}$ of Eq. (26). Therefore, similar to the case of SFDM, one cannot make model-independent connections between $B_h^{\rm inv}$ and $\sigma_p^{\rm SI}$ in the Higgs portal VDM model. FIG. 2, where $\sigma_p^{\rm SI}$ of Eq. (25) and $(\sigma_p^{\rm SI})_{\rm EFT}$ of Eq. (26) in the VDM scenario are depicted for comparison, shows clearly this discrepancy caused by the different dependence on α and m_2.

IV. IMPLICATIONS FOR DM SEARCH AND COLLIDER EXPERIMENTS

From our arguments based on the renormalizable and unitary model Lagrangians, it is clear that one has to seek the singletlike second scalar boson H_2. It could either be lighter or heavier than the observed Higgs boson. Since the observed 125 GeV Higgs boson has a signal strength ~ 1, the other scalar boson has the signal strength $\lesssim 0.1$. Therefore it would require dedicated searches for this singletlike scalar boson at the LHC. In fact this second scalar boson is almost ubiquitous in hidden sector DM models, where DM is stabilized or long lived due to dark gauge symmetries [11,20–25]. In a case in which this second scalar is light, it could solve some puzzles in the CDM paradigm, such as the core cusp problem, the missing satellite problem, or the too-big-to-fail problem [24,25]. And it can help the Higgs inflation work [26] in light of the recent BICEP2 results with the large tensor-to-scalar ratio $r = 0.2^{+0.07}_{-0.05}$. Therefore it would be very important to search for the singletlike second scalar boson at the LHC and elsewhere, in order to test the idea of dark gauge symmetry stabilizing the DM of the Universe. Since the ILC can probe α down to a few $\times\, 10^{-3}$ only, there would be ample room for the second scalar to remain undiscovered at colliders, unfortunately. It would be a tough question to determine how to probe the region below $\alpha \lesssim 10^{-3}$ in future terrestrial experiments (for example, see Ref. [27] for a recent study).

The second point is that there is no unique correlation between the LHC data on the Higgs invisible branching ratio and the spin-independent cross section of Higgs portal DM on the nucleon. One cannot say that the former gives a stronger bound for the low DM mass region compared with the latter, which is very clear from the plots we have shown. Therefore it is important for the direct detection experiments to improve the upper bound on $\sigma_p^{\rm SI}$ for low $m_{\rm DM}$, regardless of collider bounds. Collider bounds can never replace the DM direct search bounds in a model independent way, despite many such claims.

V. CONCLUSION

In this letter, we have demonstrated that the effective theory approach in dark matter physics could lead to erroneous or misleading results. For the Higgs portal SFDM and VDM, there are at least two more important parameters, the mass m_2 of the second scalar, which is mostly a SM singlet, and the mixing angle α between the SM Higgs boson and the second scalar boson:

$$\sigma_p^{\rm SI} = (\sigma_p^{\rm SI})_{\rm EFT} c_\alpha^4 m_h^4 \mathcal{F}(m_{\rm DM}, \{m_i\}, v) \tag{27}$$

$$\simeq (\sigma_p^{\rm SI})_{\rm EFT} c_\alpha^4 \left(1 - \frac{m_h^2}{m_2^2}\right)^2, \tag{28}$$

where the function $\mathcal{F}$ is defined in Eq. (13) and $m_1 = m_h = 125$ GeV. The second equation is obtained when the momentum of DM is negligible relative to both masses of Higgs bosons. The usual EFT approach applies only for the case $m_2 = m_h c_\alpha / \sqrt{1 + c_\alpha^2}$ or $m_2 \to \infty$ with $\alpha \to 0$. For the finite m_2, there is a generic cancellation between the H_1 and H_2 contributions due to the orthogonal nature of the rotation matrix from interaction to mass eigenstates of two scalar bosons. The resulting bound on $\sigma_p^{\rm SI}$ becomes even stronger if $m_2 > m_1 = 125$ GeV. On the other hand, for a light second Higgs ($m_2 < m_h c_\alpha / \sqrt{1 + c_\alpha^2}$), the LHC bound derived from the invisible Higgs decay width is weaker than the claims made in both the ATLAS Collaboration and the CMS Collaboration. In particular, for $m_2 \lesssim m_h c_\alpha / \sqrt{12.3 + c_\alpha^2}$, it cannot compete with the DM direct search bounds from XENON100, CDMS, and LUX, which is the main conclusion of this paper. Both the LHC search for the singletlike second scalar boson and the DM direct search experiments are important to be continued, and they will be complementary with each other.

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