

Invisible Higgs Decay Width vs. 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^{inv}) vs. dark matter (DM) direct detection (σ_p^{SI}) in Higgs portal DM models is usually presented in the effective field theory (EFT) framework. This is fine for singlet scalar DM, but not in the singlet fermion DM (SFDM) or vector DM (VDM) models. In this paper, we derive the explicit expressions for this correlation within UV completions of SFDM and VDM models with Higgs portals, and discuss the limitation of the EFT approach. We show that there are at least two additional hidden parameter in σ_p^{SI} in the UV completions: the singlet-like scalar mass m_2 and its mixing angle α with the SM Higgs boson (h). In particular, if the singlet-like 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.

INTRODUCTION

As more data on the 126 GeV Higgs boson H are accumulated at the LHC, its invisible Higgs branching fraction B_h^{inv} is getting bounded from above. This bound can give some useful constraint on the Higgs coupling to the DM particle in some concrete DM models. In fact such attempts for Higgs portal DM models were made recently by both ATLAS and CMS Collaborations [1, 2].

Both Collaborations announced that their measurements of the upper bounds on the B_h^{inv} can be translated into the upper bounds on σ_p (spin-independent cross section of DM particle on 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., $m_{\text{DM}} \lesssim 10$ GeV). These analyses are based on the following model Lagrangians [3–6]:

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

$$\mathcal{L}_{\text{SFDM}} = \bar{\psi}(i\partial - m_\psi)\psi - \frac{\lambda_{\psi H}}{\Lambda} \bar{\psi}\psi H^\dagger H \quad (2)$$

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

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 nucleon. This simple strategy has been adopted numerously.

The SSDM Lagrangian (1) is renormalizable, and the results based on it would be reliable [26]. We refer to the comprehensive analyses on this model to the existing literature [7] without touching it in the following. On the other hand, the other two cases for SFDM and 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 EFT approach would be. Also the mass for the VDM is given by hand, so that both Lagrangians for SFDM and VDM are not renormalizable and violate unitarity at 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 [8, 9, 18]. 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 dark Higgs mechanism for generating the VDM mass. In each case, we derive the expressions for the B_h^{inv} and σ_p^{SI} , and show that there are hidden variables in σ_p^{SI} , namely the mass of the 2nd scalar boson which is mostly singlet-like, 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, $B_h(m_h = 125)^{\text{nonSM}}$. Then

we use the LHC bounds on B_h^{inv} to derive the bounds on σ_p^{SI} as functions of (m_2, α) , and show when we recover the usual results presented by ATLAS and CMS, and when we do not. This exercise will be not only physically important, but also make good examples about the difference between the EFT and the full theory, and we would 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 the discussions on thermal relic density, which would be presented elsewhere [11].

RENORMALIZABLE SFDM MODEL

The simplest renormalizable Lagrangian for the Higgs portal SFDM model is given by [8, 9] [27]

$$\begin{aligned} \mathcal{L}_{\text{SFDM}} = & \bar{\psi}(i\partial - m_\psi - \lambda_\psi S) - \mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H \\ & + \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \mu'_S S - \frac{\mu'_S}{3} S^3 - \frac{\lambda_S}{4} S^4. \end{aligned} \quad (4)$$

We consider Dirac fermion DM in this paper. For the Majorana fermion DM case, we have to multiply a factor 1/2 to the *invisible* decay rate of Higgses, and it results in a factor 2 larger σ_p^{SI} relative to the case of Dirac fermion DM. In general, the singlet scalar S can develop a nonzero VEV, and we have to shift the field as $S(x) \rightarrow \langle S \rangle + s(x)$. Also the SM Higgs will break the EWSB spontaneously. The detailed expressions for the relations among various parameters can be found in Ref. [8], to which we refer the 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:

$$\begin{aligned} H_1 &= h \cos \alpha - s \sin \alpha, \\ H_2 &= h \sin \alpha + s \cos \alpha. \end{aligned}$$

Note that there is a minus sign in one term which originates from $SO(2)$ 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 nucleon, since the contributions of H_1 and H_2 to σ_p interferes destructively [8]. This is a very generic phenomenon in both SFDM and VDM cases [8, 18] [28].

The invisible and the non-SM branching fractions of Higgs decay and the DM-proton scattering cross section within the renormalizable SFDM model are given as follows:

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

$$B_i^{\text{nonSM}} = \frac{\Gamma_i^{\text{jj}}}{\kappa_i(\alpha) \Gamma_i^{\text{SM}} + (1 - \kappa_i(\alpha)) \Gamma_i^{\text{inv}} + \Gamma_i^{\text{jj}}} \quad (6)$$

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

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

$$\Gamma_i^{\text{SM}} = \Gamma_h(m_i) \quad (8)$$

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

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

with λ_{ijj} which is given by

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

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

and

$$\begin{aligned} \mathcal{F} = & \frac{1}{4m_\psi^2 v^2} \left[\sum_i \left(\frac{1}{m_i^2} - \frac{1}{4m_\psi^2 v^2 + m_i^2} \right) \right. \\ & \left. - \frac{2}{(m_2^2 - m_1^2)} \sum_i (-1)^{i-1} \ln \left(1 + \frac{4m_\psi^2 v^2}{m_i^2} \right) \right] \end{aligned} \quad (13)$$

with v being the lab velocity of DM, and $m_r \equiv m_\psi m_p / (m_\psi + m_p)$ 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 the $f_p = 0.326$ from a lattice calculation [12]. Note that the channel, “ $h \rightarrow \phi\phi^* \rightarrow \phi b \bar{b}$ ” is also possible, and the associated decay rate is

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

This is smaller than Γ_h^{SM} by many orders of magnitude, and can be ignored safely.

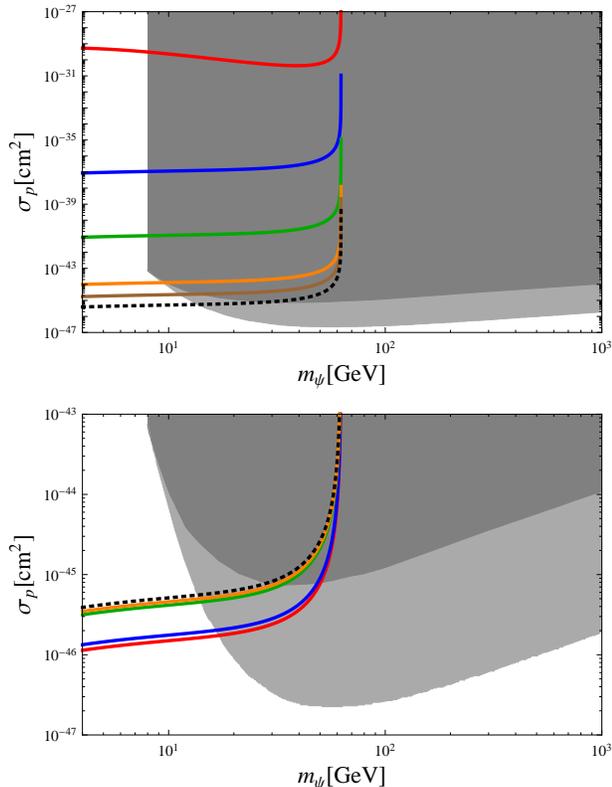


FIG. 1: σ_p^{SI} as a function of the mass of dark matter for SFDM for a mixing angle $\alpha = 0.2$. Upper panel: $m_2 = 10^{-2}, 1, 10, 50, 70$ GeV for solid lines from top to bottom. Lower panel: $m_2 = 100, 200, 500, 1000$ GeV for dashed lines from bottom to top. The black dotted line is EFT prediction. Dark-gray and gray region are the exclusion regions of LUX [15] and projected XENON1T (gray) [16].

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

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

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

where

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

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

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

(see also Ref. [13] for more involved analysis in the presence of extra singlet-like scalar boson that mixes with the SM Higgs boson). In the renormalizable model described by Eq. (4), the LHC bound on B_h^{inv} can be translated directly to a constraint on σ_p^{SI} by the relation,

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

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

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

which was used in the analysis's of ATLAS [1] and CMS [2]. Now it is clear from Eqs. (19) and (20) that, contrary to $(\sigma_p^{\text{SI}})_{\text{EFT}}$ of EFT, σ_p^{SI} of a full theory of Eq. (4) has additional factors, $c_\alpha^4 m_h^4 \mathcal{F}$, which involves two extra parameters, (α, m_2) . Note that, in the limit α is very small so that we can make $\cos \alpha \simeq 1$, and $m_2 \gg m_1$ so that we can drop $1/m_2^2$ term in the σ_p^{SI} , Eq. (19) for σ_p^{SI} approaches to Eq. (20) for $(\sigma_p^{\text{SI}})_{\text{EFT}}$. However, if one of these two assumptions is not valid, one cannot make a definitive prediction for the σ_p^{SI} . Therefore the bounds on the σ_p^{SI} derived by the ATLAS and the CMS Collaborations should be taken with caution. Basically one cannot make model-independent connections between $B_h^{\text{inv}} (= B_1^{\text{inv}})$ and σ_p^{SI} in the Higgs portal SFDM model. This is clearly shown in Fig. 1 where colored solid lines represent the LHC bound on σ_p^{SI} of Eq. (7) for various values for m_2 . The bound on $(\sigma_p^{\text{SI}})_{\text{EFT}}$ 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]. Especially, for $m_2 \lesssim m_h c_\alpha / \sqrt{12.3 + c_\alpha^2}$, it can not win the direct detection bound for $m_\psi \gtrsim 8$ GeV.

RENORMALIZABLE VDM MODEL

The simplest renormalizable Lagrangian for the Higgs portal VDM model is given by [14, 18]

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

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

$$D_\mu\Phi \equiv (\partial_\mu + ig_X Q_\Phi V_\mu)\Phi$$

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

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

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

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

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

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

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

$$\begin{aligned} (B_h^{\text{inv}})_{\text{EFT}} &= \frac{\lambda_{VH}^2 v_H^2 m_h^3}{128\pi m_V^4} \times \\ &\left(1 - \frac{4m_V^2}{m_h^2} + 12\frac{m_V^4}{m_h^4}\right) \left(1 - \frac{4m_V^2}{m_h^2}\right)^{1/2} \end{aligned} \quad (23)$$

and the VDM-nucleon scattering cross section is

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

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

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

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

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

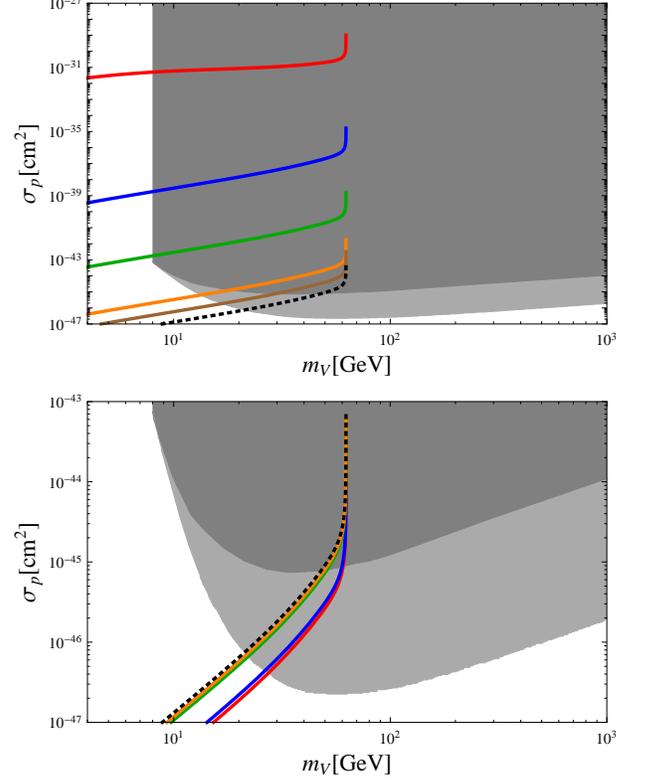


FIG. 2: σ_p^{SI} as a function of the mass of dark matter for SVDM for a mixing angle $\alpha = 0.2$. Same color and line scheme as Fig. 1.

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

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 for the singlet-like second scalar boson H_2 . It could be either lighter or heavier than the observed Higgs boson. Since the observed 125 GeV Higgs boson has a sig-

nal strength ~ 1 , the other one has the signal strength $\lesssim 0.1$. Therefore it would require dedicated searches for this singlet-like 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 [17–23]. In case this second scalar is light, it could solve some puzzles in the CDM paradigm, such as core cusp problem, missing satellite problem or too-big-to-fail problem [22, 23]. And it can help the Higgs inflation work [24] in light of the recent BICEP2 results with large tensor-to-scalar ratio $r = 0.2^{+0.07}_{-0.05}$. Therefore it would be very important to search for the singlet-like 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 an ample room for the 2nd scalar remaining undiscovered at colliders unfortunately. It would be a tough question how to probe the region below $\alpha \lesssim 10^{-3}$ in the future terrestrial experiments (for example, see [25] 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 nucleon. One can not say that the former gives stronger bound for 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 σ_{SI} for low m_{DM} , regardless of collider bounds. Collider bounds can never replace the DM direct search bounds in a model independent way, unlike many such claims.

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 2nd scalar which is mostly a SM singlet, and the mixing angle α between the SM Higgs boson and the 2nd scalar boson:

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

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

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 Higgses. The usual EFT approach applies only for the case $m_2 = m_h c_\alpha / \sqrt{1 + c_\alpha^2}$ or $m_2 \rightarrow \infty$ with $\alpha \rightarrow 0$. For the finite m_2 , there is a generic cancellation between H_1 and H_2 contribution due to the orthogonal nature of the rotation matrix from interaction

to mass eigenstates of two scalar bosons. The resulting bound on σ_{SI} becomes even stronger if $m_2 > m_1 = 125$ GeV. On the other hand, for a light 2nd 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 ATLAS and CMS collaborations. Especially, for $m_2 \lesssim m_h c_\alpha / \sqrt{12.3 + c_\alpha^2}$, it can not compete with the DM direct search bounds from XENON100, CDMS and LUX, which is the main conclusion of this paper. Both LHC search for the singlet-like 2nd scalar boson and the DM direct search experiments are important to be continued, and will be complementary with each other.

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- [1] G. Aad *et al.* [ATLAS Collaboration], arXiv:1402.3244 [hep-ex].
- [2] S. Chatrchyan *et al.* [CMS Collaboration], arXiv:1404.1344 [hep-ex].
- [3] V. Silveira and A. Zee, Phys. Lett. B **161**, 136 (1985).
- [4] C. P. Burgess, M. Pospelov and T. ter Veldhuis, Nucl. Phys. B **619**, 709 (2001) [hep-ph/0011335].
- [5] A. Djouadi, O. Lebedev, Y. Mambrini and J. Quevillon, Phys. Lett. B **709**, 65 (2012) [arXiv:1112.3299 [hep-ph]].
- [6] A. Djouadi, A. Falkowski, Y. Mambrini and J. Quevillon, Eur. Phys. J. C **73**, 2455 (2013) [arXiv:1205.3169 [hep-ph]].
- [7] K. Cheung, Y.-L. S. Tsai, P.-Y. Tseng, T.-C. Yuan and A. Zee, JCAP **1210**, 042 (2012) [arXiv:1207.4930 [hep-ph]]; J. M. Cline, K. Kainulainen, P. Scott and C. Weniger, Phys. Rev. D **88**, 055025 (2013) [arXiv:1306.4710 [hep-ph]].
- [8] S. Baek, P. Ko and W.-I. Park, JHEP **1202**, 047 (2012) [arXiv:1112.1847 [hep-ph]].
- [9] S. Baek, P. Ko, W.-I. Park and E. Senaha, JHEP **1211**, 116 (2012) [arXiv:1209.4163 [hep-ph]].
- [10] S. Baek, P. Ko, W.-I. Park and E. Senaha, JHEP **1305**, 036 (2013) [arXiv:1212.2131 [hep-ph]].
- [11] Work in preparation.
- [12] R. D. Young and A. W. Thomas, Phys. Rev. D **81**, 014503 (2010) [arXiv:0901.3310 [hep-lat]].
- [13] S. Choi, S. Jung and P. Ko, JHEP **1310**, 225 (2013) [arXiv:1307.3948].
- [14] Y. Farzan and A. R. Akbarieh, JCAP **1210**, 026 (2012) [arXiv:1207.4272 [hep-ph]].
- [15] D. S. Akerib *et al.* [LUX Collaboration], arXiv:1310.8214 [astro-ph.CO].

- [16] E. Aprile [XENON1T Collaboration], arXiv:1206.6288 [astro-ph.IM].
- [17] T. Hur and P. Ko, Phys. Rev. Lett. **106**, 141802 (2011) [arXiv:1103.2571 [hep-ph]].
- [18] S. Baek, P. Ko, W. -I. Park and E. Senaha, JHEP **1305**, 036 (2013) [arXiv:1212.2131 [hep-ph]].
- [19] S. Baek, P. Ko and W. -I. Park, JHEP **1307**, 013 (2013) [arXiv:1303.4280 [hep-ph]].
- [20] S. Baek, P. Ko and W. -I. Park, arXiv:1311.1035 [hep-ph].
- [21] S. Baek, P. Ko, W. -I. Park and Y. Tang, arXiv:1402.2115 [hep-ph].
- [22] P. Ko and Y. Tang, arXiv:1402.6449 [hep-ph].
- [23] P. Ko and Y. Tang, arXiv:1404.0236 [hep-ph].
- [24] P. Ko and W. -I. Park, arXiv:1405.1635 [hep-ph].
- [25] M. R. Buckley, V. Halyo and P. Lujan, arXiv:1405.2082 [hep-ph].
- [26] There is an issue on the stability of DM using discrete Z_2 symmetry, which is beyond the scope this letter.
- [27] One can consider another type of UV completion by introducing a new electroweak lepton doublet with the same quantum number as the SM Higgs doublet. The model is not a Higgs portal DM model, but is interesting in its own. Detailed study of this model will be presented in a separate publication.
- [28] This phenomenon is similar to the GIM mechanism in the quark flavor physics.