Higgs decay in Higgs portal dark matter models

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Abstract. In a so-called Higgs portal dark matter model, Higgs exchange processes are essential for both dark matter annihilation in the early Universe and direct search experiments. We study a scalar dark matter model with two Higgs doublets, and find that the possible maximal value for the branching ratio of the invisible decay of the Higgs boson can be significantly greater than that in the Higgs portal model with one Higgs doublet. Therefore, the search for the invisible decay of the Higgs boson at the CERN Large Hadron Collider and future collider experiments would provide useful information not only for the nature of dark matter but also for the structure of the Higgs sector even without directly detecting any extra scalar boson.

1. Introduction

Various astrophysical and cosmological observations provide evidence of the existence of dark matter (DM) [1]. The most interesting and promising candidate for DM is weakly interacting massive particles (WIMPs) whose relic abundance can be estimated in the standard thermal freeze out scenario without specifying the thermal history of the very early Universe. Among WIMP DM candidates, a class of models is categorized as “Higgs portal dark matter”, in which a DM particle interacts with Standard Model (SM) particles through only Higgs exchange processes. The minimal model was constructed by adding only one new $Z_2$ parity-odd real scalar field to the SM [2, 3]. A variety of such models has been proposed [4, 5, 6, 7, 8, 9]. Some of them are motivated in the context of radiative seesaw models [5, 7].

The Higgs sector is the last unknown piece of the SM of particle physics. Although the Weinberg-Salam model contains only one Higgs doublet, the Higgs sector might consist of multi-Higgs doublet fields. In fact, such multi-Higgs models are realized in various new physics models including supersymmetry. In Higgs portal DM models, the interactions between DM and SM particle is very sensitive not only to the size of DM-DM-Higgs boson coupling constants but also to the structure and nature of Higgs sector.

There are several approaches to explore the property of a WIMP DM candidate. One is WIMP direct detection through the elastic scattering of WIMP with target nuclei through nuclear recoil. Since these experiments with improved sensitivity have been carried out by many collaborations, the null results reported by EDELWEISS II [10], ZEPLIN II [11] and XENON [12, 13] give the stringent constraints on the scattering cross section between WIMP and a nucleon, while two suspicious events in CDMS-II [14] and an excess at low energy events...
in CoGeNT [15] were also reported. Higgs-boson-exchange processes mainly lead to scalar (in other words, spin-independent (SI)) couplings between nuclei and WIMP. Hence, the structure of a Higgs sector and its couplings with DM, namely again DM-DM-Higgs boson couplings, are crucial for direct DM searches.

Another approach to explore DM may be collider experiments, especially those at the Large Hadron Collider (LHC), where the signal of WIMP is expected to appear as a missing transverse momentum. Moreover, another signal is possible in Higgs portal DM models. That is the invisible decay of the Higgs boson due to DM-DM-Higgs couplings for the case that the DM mass is smaller than one half of the Higgs boson mass [16, 17]. In the minimal Higgs portal DM model, the upper bound is obtained for the branching ratio of the invisible decay from the CDMS II final results [18, 19, 20, 21].

We consider a $Z_2$-odd scalar Higgs portal DM scenario in the framework of multi-Higgs doublet models [22]. Such a scenario can appear, for example, in the effective theory of the three-loop-induced neutrino mass model [7], in which not only tiny neutrino masses but also DM as well as baryon asymmetry may be explained simultaneously by the TeV scale physics. The upper bound on the branching ratio of the Higgs boson invisible decay is evaluated in the model with two Higgs doublets and a real $Z_2$-odd singlet scalar field. In the analysis, a specific Yukawa interaction (the Type-X Yukawa interaction [8, 23, 24, 25]) is employed, which is used in Ref. [7] and is defined under the other (softly broken) discrete symmetry ($\tilde{Z}_2$) for avoiding flavor changing neutral current (FCNC). We also give a comment on the results assuming the other types of Yukawa interaction, such as so-called Type-II. We then discuss the difference of the upper bound from that in the minimal model with one Higgs doublet. We show exclusive features of scalar Higgs portal DM with multi-Higgs doublets.

2. Model

We consider the model with two Higgs doublet fields $\Phi_1$ and $\Phi_2$ and one real singlet scalar field $\eta$. A discrete $Z_2$ parity is introduced in the model, and the odd charge is assigned for $\eta$ to guarantee the stability as a candidate of DM. The scalar potential is given by

$$V = \frac{1}{2} \mu^2 \eta^2 + \lambda \eta^4 + \sum_{i=1,2} \sigma_i |\Phi_i|^2 \eta^2 + V(\Phi_1, \Phi_2),$$

where $\mu^2$ is the invariant squared mass of $\eta$, and $V(\Phi_1, \Phi_2)$ is the potential of the two Higgs doublet model. We neglect the CP violating phase, so that all the coupling constants are real. After electroweak symmetry breaking, neutral components in the Higgs doublets are parametrized as

$$\phi^0_i = \frac{1}{\sqrt{2}}(v_i + h_i + iz_i), \quad (i = 1, 2),$$

where $v_i$ are the vacuum expectation values (VEVs) that satisfy $v_1^2 + v_2^2 = v^2 \approx (246 \text{ GeV})^2$ and $\tan \beta = v_2/v_1$. The mass matrix for $h_1$ and $h_2$ is diagonalized by introducing the mixing angle $\alpha$, and two CP-even states $h$ and $H$ are the mass eigenstates of the CP-even bosons. The CP-odd scalar bosons $z_1$ and $z_2$ mix with each other, and become the CP-odd Higgs $A$ and the longitudinal mode of the $Z$ boson. In total, from $\Phi_1$ and $\Phi_2$ five physical states appear; i.e., two CP-even ($h, H$), one CP-odd ($A$), and charged ($H^\pm$) scalar bosons.

In the limit of $\sin(\beta - \alpha) = 1$, $h$ is the SM-like Higgs boson; i.e., all the coupling constants with SM fields coincide with those of the SM Higgs boson at the tree level [26]. On the other hand, $H$ does not receive the VEV and does not couple to the weak gauge bosons in this limit. Throughout this work, for simplicity, we always take this limit (the SM-like limit) where the mass of the SM-like Higgs boson $h$ is bounded from below ($m_h > 114 \text{ GeV}$) from the LEP
Table 1. The mixing factors in Yukawa interactions in Eq. 3

| Type    | $\xi_u^a$ | $\xi_d^a$ | $\xi_e^a$ | $\xi_H$ | $\xi_u^d$ | $\xi_d^d$ | $\xi_e^d$ |
|---------|-----------|-----------|-----------|---------|-----------|-----------|-----------|
| Type-I  | $c_\alpha/s_\beta$ | $c_\alpha/s_\beta$ | $s_\alpha/s_\beta$ | $s_\alpha/s_\beta$ | $s_\alpha/s_\beta$ | $\cot \beta$ | $-\cot \beta$ |
| Type-II | $c_\alpha/s_\beta$ | $-s_\alpha/c_\beta$ | $s_\alpha/s_\beta$ | $c_\alpha/c_\beta$ | $c_\alpha/c_\beta$ | $\cot \beta$ | $\tan \beta$ |
| Type-X  | $c_\alpha/s_\beta$ | $c_\alpha/s_\beta$ | $-s_\alpha/c_\beta$ | $s_\alpha/s_\beta$ | $c_\alpha/c_\beta$ | $\cot \beta$ | $-\cot \beta$ |
| Type-Y  | $c_\alpha/s_\beta$ | $-s_\alpha/c_\beta$ | $c_\alpha/s_\beta$ | $c_\alpha/c_\beta$ | $s_\alpha/s_\beta$ | $\cot \beta$ | $\tan \beta$ |

experiment while that of $H$ can be lower than 100 GeV because of no coupling to the weak gauge bosons.

Multi-Higgs doublet models in general suffer from dangerous FCNC. To avoid FCNC, we impose a softly broken discrete symmetry $\tilde{Z}_2$ under the transformation $\Phi_1 \rightarrow \Phi_1$ and $\Phi_2 \rightarrow -\Phi_2$. The Yukawa interactions are expressed in terms of mass eigenstates of the Higgs bosons as

$$\mathcal{L}^{\text{THDM}}_{\text{Yukawa}} = -\sum_{f=u,d,\ell} \left( \frac{m_f}{v} \xi_{f}^u \bar{f} h + \frac{m_f}{v} \xi_{f}^d \bar{f} H - i \frac{m_f}{v} \xi_{f}^e \bar{f} A \right) - \left\{ \sqrt{2} v \xi^u_{\nu} P_L + v \xi^d_{\nu} P_R \right\} H^+ + \mathcal{H.C.} \right), \quad (3)$$

where $P_{L/R}$ are projection operators for left-/right-handed fermions, and the factors $\xi_{\nu}^f$ are listed in TABLE 1. There are four ways of charge assignment under this $\tilde{Z}_2$ parity, thus correspondingly four independent types of Yukawa interaction are possible [27, 28]. The typical example of so-called Type-II Yukawa interactions is that of the minimal supersymmetric standard model. The Type-X Yukawa interaction [8, 23, 24, 25], where one of the Higgs doublets couples to only quarks and the other does to only leptons, is adopted in the model for radiative generation of tiny neutrino masses with including the scalar DM proposed in Ref. [7], whose Higgs sector contains two Higgs doublets and a DM candidate $Z_2$-odd singlet scalar field as well as some heavier particles. Therefore, our present model given in Eq. (1) can be regarded as the effective theory of the model in Ref. [7]. We mainly study the model with the Type-X Yukawa interaction, and then give a short comment on the cases of the other types for Yukawa interactions.

Even in the SM-like limit, the total decay width of the SM-like Higgs boson $h$ in our model can drastically change from the SM value when $m_\eta < m_h/2$ because of the additional invisible $h \rightarrow \eta \eta$ decay. The total width of $h$ is given by

$$\Gamma_{\text{tot}} = \Gamma_{\text{vis}} + \Gamma_{\text{inv}}, \quad (4)$$

where $\Gamma_{\text{vis}}$ denotes the width for Higgs boson decays into SM particle contents. In the SM-like limit, $\Gamma_{\text{vis}}$ in our model coincides with that in the SM at the lowest order. The invisible decay width $\Gamma_{\text{inv}}$ of the SM-like Higgs boson is computed as

$$\Gamma_{\text{inv}}(h \rightarrow \eta \eta) = \frac{v^2}{32 \pi m_h} \sqrt{1 - \frac{4 m_\eta^2}{m_h^2}} \left| -\sigma_1 \sin \alpha \cos \beta + \sigma_2 \cos \alpha \sin \beta \right|^2. \quad (5)$$

The corresponding formula in the minimal Higgs portal DM model with a scalar doublet $\Phi$ and a real scalar field $\eta$ is obtained from Eq. (5) by replacing $(-\sigma_1 \sin \alpha \cos \beta + \sigma_2 \cos \alpha \sin \beta)$ by $2 \sigma_m$ when the DM-Higgs coupling is given by

$$\mathcal{L}_{\text{int}} = \cdots - \sigma_m \eta^2 |\Phi|^2 \cdots. \quad (6)$$

The branching ratio for the invisible decay is given by

$$B_{\text{inv}}(h \rightarrow \eta \eta) \equiv \frac{\Gamma_{\text{inv}}}{\Gamma_{\text{tot}}}. \quad (7)$$
3. The invisible decay branching ratio

3.1. Astrophysical and cosmological constraints

Before we consider the invisible decay branching ratio of the SM-like Higgs boson $h$, we summarize the constraints on the $h\eta\eta$ coupling $\sigma_i$.

One is the cosmological DM abundance determined by thermal freeze out. The relic mass density is evaluated as

$$\Omega_\chi h^2 = 1.1 \times 10^9 \frac{m_\chi/T_\chi}{\sqrt{g_*}M_P}\langle\sigma v\rangle\text{GeV}^{-1},$$

with the Planck mass $M_P$, the total number of relativistic degrees of freedom in the thermal bath $g_*$, and the decoupling temperature $T_\chi$. For the Type-X Yukawa interaction, the processes of $\eta\eta \to b\bar{b}$ and $\eta\eta \to \tau^+\tau^-$ are dominant when $m_\eta < m_W$, and the thermal averaged product of annihilation cross section and relative velocity is evaluated as [7]

$$\langle\sigma v\rangle \simeq \frac{s}{16\pi m_\eta^2} \left[3m_b^2\left| \frac{-\sigma_1 \sin \alpha \cos \beta + \sigma_2 \cos \alpha \sin \beta}{s - m_h^2 + im_h\Gamma^H_{tot}} \right|^2 \right. + \frac{\sigma_1 \cos \alpha \cos \beta + \sigma_2 \sin \alpha \sin \beta}{s - m_h^2 + im_h\Gamma^H_{tot}} \left(\frac{\sin \alpha}{\sin \beta}\right)^2 ] + m_f^2 \left| \frac{-\sigma_1 \sin \alpha \cos \beta + \sigma_2 \cos \alpha \sin \beta}{s - m_h^2 + im_h\Gamma^H_{tot}} \right|^2 \right\|_{s=4m_\eta^2},$$

where $\Gamma^H_{tot}$ is the total width of $H$. In the minimal Higgs portal DM model, it is given as $\langle\sigma v\rangle \sim 3s/(4\pi m_\eta^2)|\sigma_m/(s - m_h^2 + im_h\Gamma^H_{tot})|^2$ with $s \simeq 4m_\eta^2$. Too large (small) coupling constants $\sigma_i$ correspond to the over-annihilation (over-abundance) of DM. We evaluate the consistent parameter region of the $h\eta\eta$ coupling and DM mass.

The other is from the direct DM search, because the DM proton scattering is induced by only the $t$-channel Higgs bosons exchange in the Higgs portal models and its strength is proportional to the square of the $h\eta\eta$ coupling $\sigma_i$s. The DM SI cross section for a proton is given by

$$\sigma_p^{SI} = \frac{m_p^2}{\pi(m_\eta + m_p)^2}f_p^2,$$

with

$$f_p = \left( \sum_q f^{(p)}_T q + \frac{2}{27} \sum_q f^{(p)}_{TG} q \right) \frac{f_q}{m_q},$$

where $m_p$ is the proton mass, $f_p$ is the effective coupling with proton and $f^{(p)}_q$ is the hadronic matrix elements. The effective coupling of DM particle with a quark $f_q$ depends on models. In the model in Eq. (1) with the Type-X Yukawa coupling, this is calculated at the tree level as

$$\frac{f_q}{m_q} = \left( \frac{-\sigma_1 \sin \alpha \cos \beta + \sigma_2 \cos \alpha \sin \beta}{2m_h^2} \cos \alpha \frac{\sin \beta}{\sin \beta} \right) + \left( \frac{\sigma_1 \cos \alpha \cos \beta + \sigma_2 \sin \alpha \sin \beta}{2m_h^2} \sin \alpha \frac{\sin \beta}{\sin \beta} \right).$$

In the minimal Higgs portal DM model, it is given by $f_q/m_q = \sigma_m/m_h^2$. 


The constraint on the decay branching ratio $B_{\text{inv}}(h \to \eta \eta)$ for the invisible decay of the SM-like Higgs boson into a DM pair from the CDMS II results and the XENON 10 results. [Right] The thermal abundance $\Omega_\eta h^2$ of DM as a function of the DM mass with $\sigma = 0.076$.

### 3.2. The invisible decay branching ratio

Now we consider the invisible decay branching ratio of the SM-like Higgs boson $h$. We examine the upper bound on $B_{\text{inv}}(h \to \eta \eta)$ from the CDMS II and the XENON 10 for some parameter sets in the case of the Type-X interaction. As stated, we work in the SM-like limit $\sin(\beta - \alpha) = 1$. We use the average of the coupling constants $\sigma \equiv (\sigma_1 + \sigma_2)/2$ to show the typical scale of couplings and the difference $\Delta \sigma \equiv \sigma_1 - \sigma_2$ to see the effect of the difference instead of $\sigma_1$ and $\sigma_2$. The mass of the SM-like Higgs boson $h$ is set to be $m_h = 120$ GeV. The other input parameters are commonly taken as $m_H = 90$ GeV and $\Delta \sigma = 0.02$. These parameter sets are not excluded by the current data. We here only show the results of the case $\tan \beta = 1$. One may find a case of another choice of $\tan \beta$ in Ref. [22].

The left panel of Fig. 1 shows the constraint on the Higgs invisible decay branching ratio from direct DM searches in the model with the Type-X Yukawa interaction and $\sin(\beta - \alpha) = 1$ for $(m_h, m_H, \Delta \sigma, \tan \beta) = (120$ GeV, 90 GeV, 0.02, 1). The upper bound on $B_{\text{inv}}(h \to \eta \eta)$ does not depend on the DM mass much and about $B_{\text{inv}}(h \to \eta \eta) \sim 0.8$ is allowed for $m_\eta \lesssim 50$ GeV, while the bound becomes stringent for $m_\eta > 55$ GeV. Around $m_\eta \simeq 43$ GeV (near the $H$-resonance), we can obtain the maximal value of $B_{\text{inv}}(h \to \eta \eta) \simeq 0.8$ which corresponds to $\sigma \simeq 0.076$ through Eqs. (5) and (7). The right figure shows the point $(m_\eta, \sigma) \simeq (43$ GeV, 0.076) with the same other parameters indeed satisfies the WMAP constraint $\Omega_\eta h^2 \simeq 0.1$.

We have found that various parameter sets satisfy $\Omega_\eta h^2 \simeq 0.1$ and the bound from the direct DM searches. For instance, with the above parameter set,

$$B_{\text{inv}}(h \to \eta \eta) = 0.8,$$

(13)

can be realized for $m_h = 120$ GeV and $m_\eta \simeq 43$ GeV around the edge of the resonance of $H$. On the other hand, in the model with the minimal Higgs portal DM model, we obtain

$$B_{\text{inv}}(h \to \eta \eta) \lesssim 0.63,$$

(14)

for the same value of $m_h$ but for $m_\eta \simeq 55$ GeV (near the $h$ resonance) in the same calculation manner. Therefore, if $B_{\text{inv}}(h \to \eta \eta) \gg 0.63$ will be measured at the LHC, it will indicate a non-minimal Higgs sector in the Higgs portal DM scenario even when no extra Higgs boson will be found there yet. Here, we note that our result of the upper bound of $B_{\text{inv}}(h \to \eta \eta)$ in the minimal Higgs portal DM model is somewhat smaller than those reported in Refs. [18] and [19].
The difference between ours and theirs mainly comes from the different choice for the values of the hadronic matrix elements. We have consistently used the values in Ref. [29].

At the International Linear Collider (ILC), invisible decays of the SM-like Higgs boson can be tested when $B_{\text{inv}}(h \to \eta \eta) > 0.25$ [30]. As compared to the case of the minimal Higgs portal DM model, in the two Higgs doublet model it is still allowed to have a larger value of the invisible decay branching ratio such as 0.8 or even larger. Although the Type-X Yukawa interaction has been used in our analysis of the invisible decay branching ratio, this main results and its physics behind is independent of the type of Yukawa interaction. Thus, we conclude that precise determination of the invisible decay branching ratio at the LHC or future collider experiments would give useful information not only for the nature of dark matter but also for the structure of the Higgs sector even without detecting any extra scalar boson directly.

4. Summary

We studied the branching ratio of the Higgs invisible decay in the model with two Higgs doublets and one scalar singlet DM field, mainly assuming the Type-X Yukawa coupling. We could rewrite the latest CDMS II and XENON 10 excluded region into an upper bound of Higgs invisible decay for a given parameter set.

As compared to the case of the minimal Higgs portal DM model, in the two Higgs doublet portal DM model it is still allowed to have a larger value of the invisible decay branching ratio such as 0.8 or even larger. Although the Type-X Yukawa interaction has been used in our analysis of the invisible decay branching ratio, this main results and its physics behind is independent of the type of Yukawa interaction. Thus, we conclude that precise determination of the invisible decay branching ratio at the LHC or future collider experiments would give useful information not only for the nature of dark matter but also for the structure of the Higgs sector even without detecting any extra scalar boson directly.

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References

[1] e.g., Spergel D N et al. [WMAP Collaboration] 2007 *Astrophys. J. Suppl.* 170 377
[2] McDonald J 1994 *Phys. Rev.* D 50 3637
[3] Burgess C P, Pospelov M and ter Veldhuis T 2001 *Nucl. Phys.* B 619 709
[4] Deshpande N G and Ma E 1978 *Phys. Rev.* D 18 2574
[5] Ma E 2006 *Phys. Rev.* D 73 077301
[6] Barbieri R, Hall L J and Rychkov V S 2006 *Phys. Rev.* D 74 015007
[7] Aoki M, Kanemura S and Seto O 2009 *Phys. Rev. Lett.* 102 051805 and *Phys. Rev.* D 80 033007
[8] Goh H S, Hall L J and Kumar P 2009 *J. High Energy Phys.* JHEP05(2009)097
[9] Okada N and Seto O 2010 *Phys. Rev.* D 82 023507
[10] Broniatowski A et al. 2009 *Phys. Lett.* B 681 305
[11] Lebedenko V N et al. 2009 *Phys. Rev.* D 80 052010
[12] Angle J et al. [XENON10 Collaboration] 2008 *Phys. Rev. Lett.* 101 091301
[13] Aprile E et al. [XENON100 Collaboration] 2010 *Phys. Rev. Lett.* 105 131302
[14] Ahmed Z et al. [The CDMS Collaboration] 2010 *Science* 327 1619
[15] Aalseth C E et al. [CoGeNT collaboration] 2011 *Phys. Rev. Lett.* 106 131301
[16] Bento M C, Bertolami O, Rosenfeld R and Teodoro L 2000 *Phys. Rev.* D 62 041302
[17] Bento M C, Bertolami O and Rosenfeld R 2001 *Phys. Lett.* B 518 276
[18] He X G, Li T, Li X Q, T andean J and Tsai H C 2010 *Phys. Lett.* B 688 332
[19] Farina M, Pappadopulo D and Strumia A 2010 *Phys. Lett.* B 688 329
[20] Kadastik M, Kamion K, Racioppi A and Raidal M 2010 *Phys. Lett.* B 694 242
[21] Cheung K and Yuan T C 2010 *Phys. Lett.* B 685 182
[22] Aoki M, Kanemura S and Seto O 2010 *Phys. Lett.* B 685 313
[23] Aoki M, Kanemura S, Tsumura K and Yagyu K 2009 *Phys. Rev.* D 80 015017
[24] Su S and Thomas B 2009 *Phys. Rev.* D 79 095014
[25] Logan H E and MacLennan D 2009 *Phys. Rev.* D 79 115022
[26] Gunion J F and Haber H E 2003 *Phys. Rev.* D 67 075019
[27] Barger V D, Hewett J L and Phillips R J N 1990 *Phys. Rev.* D 41 3421
[28] Grossman Y 1994 *Nucl. Phys.* B 426 355
[29] Ellis J R, Olive K A and Savage C 2008 *Phys. Rev.* D 77 065026
[30] Warsinsky M [ATLAS Collaboration] 2008 *J. Phys.: Conf. Series* 110 072046
[31] Schumacher M 2003 *Report No.* LC-PHSM-2003-096.
[32] Belyaev A, Guedes R, Moretti S and Santos R 2010 *J. High Energy Phys.* JHEP07(2010)051