Galactic Center gamma ray excess from two Higgs doublet portal dark matter

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Abstract

We consider a simple extension of type-II two Higgs doublet model by introducing a real scalar being a candidate for the dark matter in the present Universe. The main annihilation mode of the dark matter particle with a mass of around $31 - 40$ GeV is into a $b\bar{b}$ pair, and this annihilation mode suitably explains the observed excess of the flux of gamma ray from the Galactic center. We identify the parameter region of the model which can fit the gamma ray excess and, at the same time, satisfy phenomenological constraints such as the observed dark matter relic density and the null results of the direct dark matter search experiments. Most of the parameter region is found to be within the search reach of the future direct dark matter detection experiments.

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I. INTRODUCTION

The Weakly Interacting Massive Particle (WIMP) is a primary candidate of the dark matter (DM) in the present Universe, and one of the major topics in particle physics and cosmology is to reveal the nature of the WIMP dark matter. Aiming for direct and indirect DM detections, there are many experiments in operation.

Over the past several years, many analysis have shown excesses of gamma ray flux from the Galactic center, and the interpretation with annihilating DM particles [1–5] has been considered for the origin of the gamma ray excess. Similarly, an excess of the gamma ray flux form the so-called Fermi bubble region [6] found in the Fermi-LAT data has been interpreted as a result of indirect dark matter particle detection [7, 8].

The previous studies for the gamma ray excess have shown that the excess can be fit a DM particle with a mass of around 10 GeV annihilating into a pair of tau leptons or a dark matter with $30 - 60$ GeV mass annihilating into a $b\bar{b}$ pair [2, 4, 5, 7, 8]. In addition, data of gamma rays from subhalos also show a similar spectrum shape, indicating the origin from such the dark matter particles [9]. Interestingly, the DM annihilation cross section to fit the data is found to be of the same order of a typical thermal annihilation cross section, $\sigma v \simeq 3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$, for the WIMP dark matter. For a natural realization of such DM particles, particle physics models have been proposed. For example, see Refs. [10–14] for light DM models in which a pair of DM particles annihilates into tau leptons.

However, a more recent analysis [15] has claimed that a dark matter particle with $31 - 40$ GeV mass provides an excellent fit for the gamma ray excess with the main annihilation mode into $b\bar{b}$ and its cross section $\sigma v = (1.4 - 2.0) \times 10^{-26}$ cm^3/s. Not only a fit with the annihilation mode into tau lepton pairs is no longer favored [15], but also the cross section of the tau lepton annihilation mode is severely constrained by the cosmic ray positron data [16] (see, however, Ref. [17]). Although a certain astrophysical source might be able to explain the excess [18, 19], the interpretation with annihilating DM particles is a very interesting possibility and along this direction, various particle models have been proposed recently. In the context of supersymmetric models, a neutralino DM in the Next-to-Minimal Supersymmetric Standard Model (NMSSM) [20–22], sneutrino [23] in the seesaw extended NMSSM [24] or sneutrino in a supersymmetric inverse seesaw model [25] plays a suitable role of the DM interpretation. For non-supersymmetric DM models, see, for example, Refs. [26–

37].

In this paper, we propose a model in a class of the so-called Higgs portal DM to explain the gamma ray excess, where a real scalar ϕ being singlet under the Standard Model (SM) gauge groups is introduced for a dark matter candidate, along with a Z_2 parity ensuring the stability of the scalar. In the simplest model, the real scalar is a unique field to be added to the SM particle contents (for an incomplete list, see, e.g., [38–42]). However, this minimal model is not suitable for explaining the gamma ray excess, because the desired DM mass range of $31 - 40$ GeV is excluded by the null results of the direct DM search experiments (see, for example, [42, 43]). Thus, we extend the Higgs sector to the two Higgs doublet model [44–47]. In fact, we have considered in our previous work [12] a Higgs portal DM in the context of type-X two Higgs doublet model, where a pair of DM particles mainly annihilates into tau leptons [1]. Motivated by the recent analysis in [15], we propose in this paper a Higgs portal DM with the $31 - 40$ GeV mass in the context of type-II two Higgs doublet model. In this case, a pair of the scalar DM particles mainly annihilates to a $b\bar{b}$ pair through the s-channel exchange of Higgs bosons with the type-II Yukawa couplings. We will identify a model parameter region which not only explains the gamma ray excess, but also be consistent with phenomenological constraints such as the observed DM relic abundance and the null results of the current direct DM search experiments. In addition, we will see that most of the identified parameter region can be covered by the search reach of future direct DM detection experiments.

II.   TWO-HIGGS-DOUBLET PORTAL SCALAR DARK MATTER

We introduce a real SM gauge singlet scalar ϕ as the dark matter candidate along with the Z_2 parity by which the stability of the DM particle is guaranteed. The Higgs sector is extended to the so-called type-II two Higgs doublet model, where one Higgs doublet generates the mass of the SM up-type fermions while the other does for the SM down-type fermions, just like in the MSSM. In the type-II model, the Yukawa interaction is given by

$$\mathcal{L}_Y = -y_{\ell_i}\overline{L}^i\Phi_1\ell_R^i - y_{u_i}\overline{Q}^i\tilde{\Phi}_2 u_R^i - y_{d_i}\overline{Q}^i\Phi_1 d_R^i + \text{h.c.}, \tag{1}$$

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[1] This class of Higgs sector is motivated by a radiative generation of neutrino masses [48].

where Q^i (L^i) is the ordinary left-handed $SU(2)$ doublet quark (lepton) of the i-th generation, and u_R^i, d_R^i and e_R^i are the right-handed $SU(2)$ singlet up- and down-type quarks, and 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) and the scalar DM is given by

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

Electric charge neutral components of the two-Higgs doublets develop the vacuum expectation values, and we parametrize them as

$$
\Phi_1 = \begin{pmatrix} 0 \\ \frac{v_1+h_1}{\sqrt{2}} \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} 0 \\ \frac{v_2+h_2}{\sqrt{2}} \end{pmatrix},
\tag{3}
$$

where the vacuum expectation values are given by $v_1 = v\cos\beta$ and $v_2 = v\sin\beta$ with $v = 246$ GeV. The physical states h_1 and h_2 are diagonalized to the mass eigenstates (h and H) as

$$
\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}.
\tag{4}
$$

In this paper, we consider the case that the mixing angle α satisfies a condition $\sin(\beta-\alpha) = 1$, which is so-called the SM limit, so that the mass eigenstate h is the SM-like Higgs boson [2].

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

$$
\mathcal{L}_\sigma \supset -\frac{\sigma_1\cos\alpha\cos\beta + \sigma_2\sin\alpha\sin\beta}{2}vH\phi^2 - \frac{-\sigma_1\sin\alpha\cos\beta + \sigma_2\cos\alpha\sin\beta}{2}vh\phi^2.
\tag{5}
$$

The Yukawa interactions with quarks and leptons in Eq. (1) can then be written as

$$
\mathcal{L}_Y^{\text{Quarks}} \supset \frac{m_{u^i}\sin\alpha}{v\sin\beta}H\bar{u}^iu^i + \frac{m_{u^i}\cos\alpha}{v\sin\beta}h\bar{u}^iu^i + \frac{m_{d^i}\cos\alpha}{v\cos\beta}H\bar{d}^id^i - \frac{m_{d^i}\sin\alpha}{v\cos\beta}h\bar{d}^id^i,
\tag{6}
$$

$$
\mathcal{L}_Y^{\text{Leptons}} \supset \frac{m_{\ell^i}\cos\alpha}{v}\frac{1}{\cos\beta}H\bar{\ell}^i\ell^i - \frac{m_{\ell^i}\sin\alpha}{v}\frac{1}{\cos\beta}h\bar{\ell}^i\ell^i.
\tag{7}
$$

---

[2] In the following, we consider the extra Higgs boson mass to be $60 - 80$ GeV. The result of the Higgs boson search at the LEP [49] has severely constrained the coupling of such a light extra Higgs boson to Z-boson, which leads to $\cos^2(\beta - \alpha) \lesssim 0.01$. Thus, we take the SM limit, for simplicity.

Since we have set $\sin(\beta - \alpha) = 1$, the coupling between the non-SM-like Higgs (H) and down-type quarks (charged leptons) are enhanced for $\tan\beta > 1$ and those between H and up-type quarks are suppressed by $1/\tan\beta$, [3] while the Yukawa couplings between the SM-like-Higgs boson h and the SM fermions remain the same as those in the SM. For simplicity, we fix other model parameters so as to make the charged and CP-odd Higgs bosons heavy enough to be consistent with their current experimental mass bound and to be decoupled from our analysis of the dark matter physics.

We first calculate the invisible decay width of the SM-like Higgs boson into a pair of the scalar DMs through the interactions in Eq. (5). [4] Fig. 1 shows the branching ratio of this invisible decay $\mathrm{BR}(h \to \phi\phi)$ for the DM mass $m_\phi = 30$ GeV and $\tan\beta = 10$. We have found that the upper bound from the LHC data, $\mathrm{BR}(h \to \phi\phi) \lesssim 0.35$ [50], is satisfied for $\sigma_2 \lesssim 0.03$, almost independently of σ_1.

Next, we estimate the thermal relic abundance of the real scalar DM by solving the Boltzmann equation:

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle (n^2 - n_{\mathrm{EQ}}^2), \tag{8}$$

where H and n_{EQ} are the Hubble parameter and the DM number density in thermal equilibrium, respectively [51]. The resultant thermal relic abundance is approximated as

$$\Omega_{\mathrm{DM}} h^2 = \frac{1.1 \times 10^9 (m_\phi / T_d) \,\mathrm{GeV}^{-1}}{\sqrt{g_*} M_P \langle \sigma v \rangle}, \tag{9}$$

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 T_d is the decoupling temperature.

The present annihilation cross section $(\sigma v)_0$ of the DM particle, which is relevant for the indirect detection of dark matter, is given by its s-wave component of the annihilation cross section, in other words, by the limit of $v \to 0$. Note that, in general, the thermal averaged cross section $\langle \sigma v \rangle$ determined by the condition of $\Omega h^2 \simeq 0.1$ [52, 53] is not the same as the present annihilation cross section $(\sigma v)_0$. This difference becomes significant for two cases.

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[3] This leads to a suppression of the non-SM-like Higgs boson production through the gluon fusion at the LHC. Even if non-SM-like Higgs bosons are produced, each H mainly decays to a $b\bar{b}$ pair, and this decay mode is challenging to observe at the LHC.

[4] As we will see in the following, the non-SM-like Higgs boson H is light, and the SM-like Higgs boson can decay to a pair of the H bosons. To simplify our analysis, we fix free parameters in the scalar potential to suppress this decay rate.
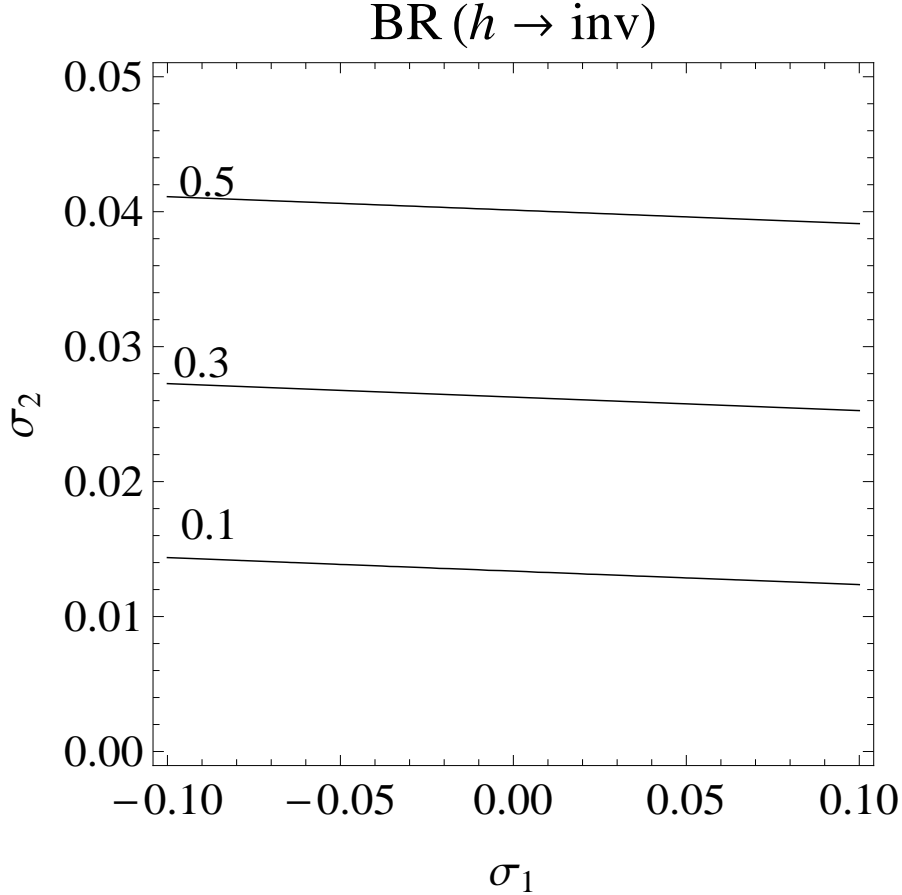
FIG. 1: Contours of the invisible decay branching ratio of the SM-like Higgs boson, $\mathrm{BR}(h \to \phi\phi) = $ 0.1, 0.3, and 0.5, respectively. We have taken the DM mass $m_\phi = 40$ GeV and $\tan\beta = 10$.

One is that the DM annihilation cross section has a sizable p-wave contribution, and the other is that a dark matter mass is close to a resonance pole of mediators in the annihilation process. In fact, the latter is our case.

A pair of the scalar dark matters with the mass $m_\phi = 31-40$ GeV dominantly annihilates into $b\bar{b}$ through the s-channel exchange of the Higgs bosons (h and H). The cross section is enhanced by the H boson exchange when $m_H \sim 2m_\phi$. We evaluate the cross section as a function of the coupling σ_1 and the non-SM-like Higgs boson mass m_H with fixed values for σ_2. Figs. 2 and 3 show the results for $m_\phi = 40$ and 30 GeV for $tan\beta = 50, 40, 30$ with $\sigma_2 = 0.02$, which corresponds to a relatively large invisible decay rate of h, $\mathrm{BR}(h \to \phi\phi) \sim$ 0.2. Along the thick blue line, the observed DM relic density $\Omega h^2 = 0.1$ is reproduced, while two dashed lines correspond to the parameters to yield the present DM annihilation cross

sections, $(\sigma v)_0 = 1.4$ and 2.0, respectively, in unit of 10^{-26} cm^3/s . The parameters in the overlapping region of the thick solid line and the region between the two dashed lines well fit the gamma ray excess and, at the same time, reproduce the observed relic abundance. We also calculate the cross section of DM elastic scattering off nuclei, which is constrained by the null results of the current direct DM detection experiments. The shaded regions are excluded by the LUX (2014) experiment [54], and the expected sensitivity in the future direct DM search experiments, for example, XENON1T experiment [55] is depicted by two thin lines. We find that there is no solution for $\tan\beta \lesssim 30$.
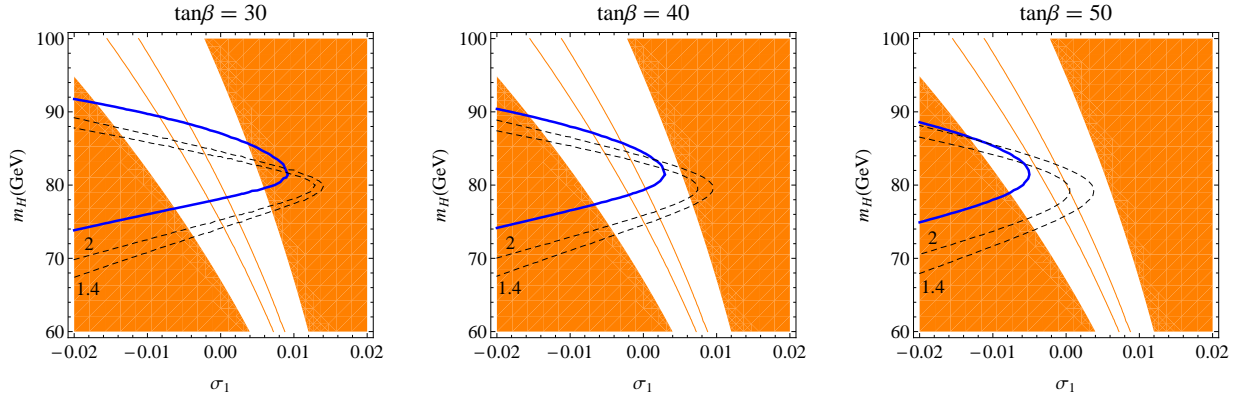

FIG. 2: Contours of $\Omega h^2 = 0.1$ (thick blue line) and $(\sigma v)_0$ in the unit of 10^{-26} cm^3/s (dashed lines) for $m_{\mathrm{DM}} = 40$ GeV and $\sigma_2 = 0.02$. $\tan\beta$ is taken to be 30, 40, 50 from left to right. The shaded regions are excluded by the direct dark matter search by the LUX experiment (2014) [54], and the expected future sensitivity 3×10^{-47} cm^2 by the XENON1T experiment [55] are depicted as the thin lines.
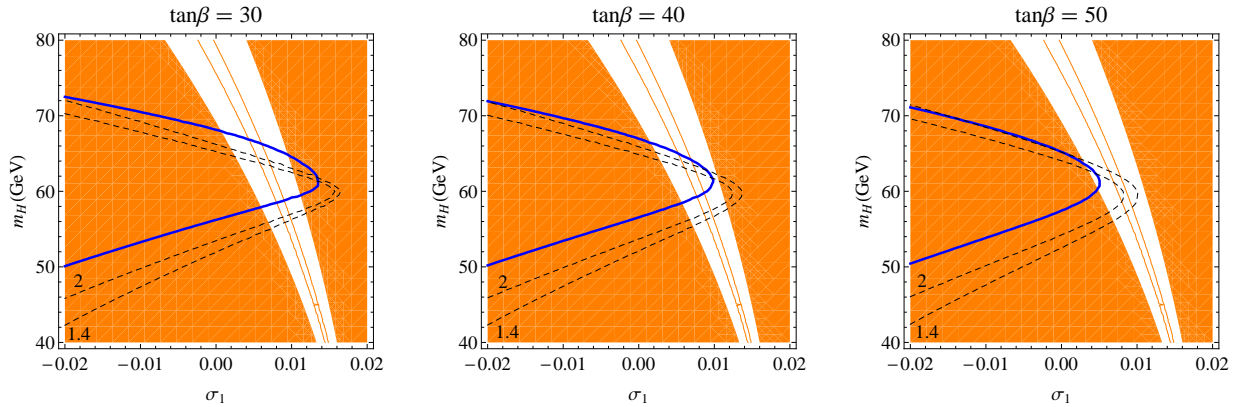

FIG. 3: Same as Fig. 2 but for $m_{\mathrm{DM}} = 30$ GeV.

Fig. 4 shows the results for $\sigma_2 = 0$, which corresponds to a negligible invisible decay
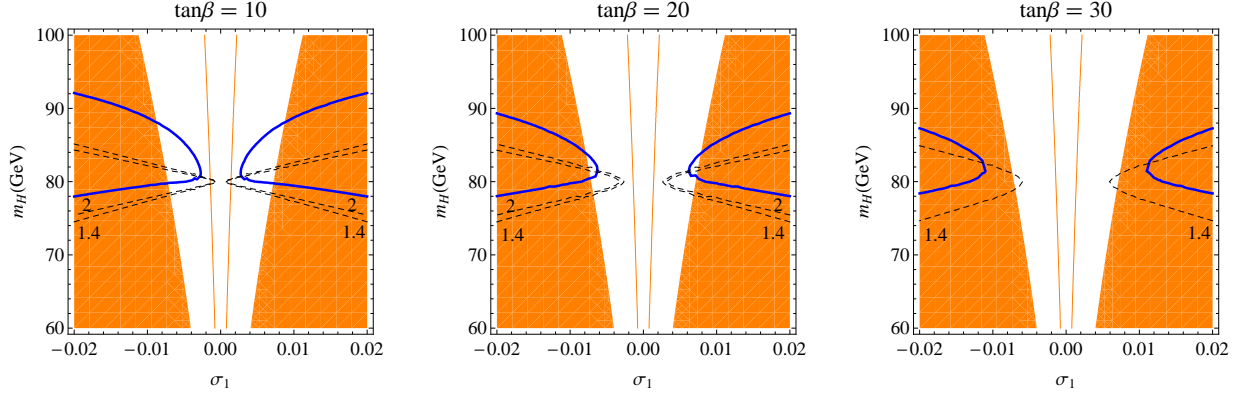
FIG. 4: Same as Fig. 2 but for $\sigma_2 = 0$. $\tan\beta$ is taken to be $10, 20, 30$ from left to right.

rate of h. We see that the results for a large $\tan\beta \gtrsim 30$ is already excluded by the LUX experiment. Currently allowed parameter region will be covered by the future direct DM detection experiments.

From above results, we find a correlation between σ_2 (in other words, the invisible decay rate of the SM-like Higgs boson h) and $\tan\beta$ in order to find viable parameter regions. Namely, a larger value of σ_2 requires a larger $\tan\beta$ value. In fact, with $\sigma_2 = 0.02$, the large present DM annihilation cross section is obtained for $40 \lesssim \tan\beta \lesssim 50$, as seen in Figs. 2 and 3. On the other hand, for $\sigma_2 = 0.00$, a smaller $\tan\beta \lesssim 20$ is needed to avoid the direct DM search bound, as shown in Fig. 4. We see in Fig. 5 that the $\tan\beta = 30$ case becomes available for a middle size of σ_2.

III. SUMMARY

Motivated by the gamma ray excess from the Galactic center and its interpretation with annihilating dark matter particles, we propose a Higgs portal DM scenario in the context of type-II two Higgs doublet model. This model can account for the gamma ray excess through its main annihilation mode into a pair of $b\bar{b}$ quarks through the s-channel exchange of the non-SM-like Higgs boson with the type-II Yukawa coupling. We have identified the model parameter region which can explain the gamma ray excess and, at the same time, satisfy the phenomenological constraints on the relic dark matter abundance and the elastic scattering cross section of the DM particle off nuclei, as well as the invisible decay rate of the SM-like Higgs boson into a pair of the DM particles. Most of the identified parameter region can be tested by the future direct dark matter detection experiments. In addition, the search for
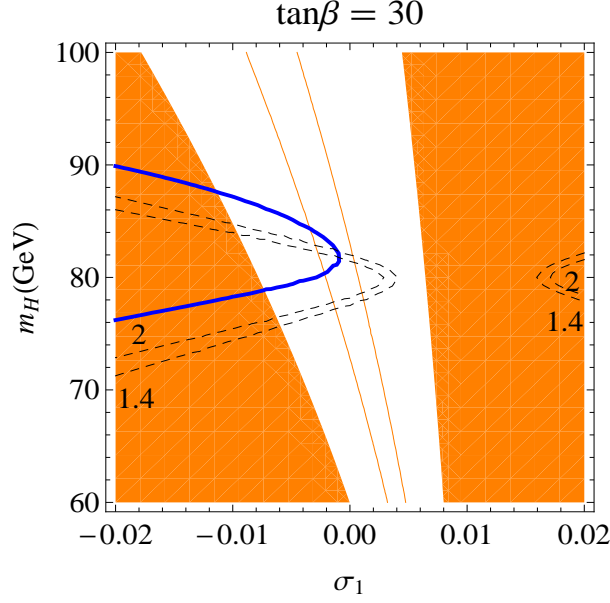
FIG. 5: Same as Fig. 2 but for $\tan\beta = 30$ and $\sigma_2 = 0.01$.

the invisible decay process of the SM-like Higgs boson and the non-SM-like Higgs boson at future collider experiments is complementary to the direct DM search.

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