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A simplified 2HDM with a scalar dark matter and the galactic center gamma-ray excess

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ABSTRACT

Due to the strong constraint from the LUX experiment, the scalar portal dark matter cannot generally explain a gamma-ray excess in the galactic center by the annihilation of dark matter to $b\bar{b}$. With the motivation of eliminating the tension, we add a scalar dark matter to the aligned two-Higgs-doublet model, and focus on a simplified scenario, which has two main characteristics: (i) The heavy CP-even Higgs is the discovered 125 GeV Higgs boson, which has the same couplings to the gauge bosons and fermions as the SM Higgs. (ii) Only the light CP-even Higgs mediates the dark matter interactions with SM particles, which have no couplings to *WW* and *ZZ*, but have the independent couplings to the up-type quarks, down-type quarks and charged leptons. We find that the tension between $\langle\sigma v\rangle_{SS\to b\bar{b}}$ and the constraint from LUX induced by the scalar portal dark matter can go away for the isospin-violating dark matter–nucleon coupling with $-1.0 < f^n/f^p < 0.7$, and the constraints from the Higgs search experiments and the relic density of Planck are also satisfied.

1. Introduction

Over the past several years, a gamma-ray excess at GeV energies around the galactic center has been identified in the Fermi-LAT data by several groups [1]. The recent study shows that the excess seems to be remarkably well described by an expected signal from 31–40 GeV dark matter (DM) annihilating dominantly to $b\bar{b}$ with a cross section $\langle\sigma v\rangle_{b\bar{b}} \simeq 1.7$–$2.3\times 10^{-26}$ cm^3/s [2], which is strikingly close to the thermal relic density value, $\langle\sigma v\rangle \sim 10^{-26}$ cm^3/s. Since the Higgs couplings to the fermions tend to be proportional to their masses, the Higgs portal DM is a simple scenario for DM model which explains the gamma-ray excess. However, to obtain such large $\langle\sigma v\rangle_{b\bar{b}}$, the model with the scalar portal DM will lead to a spin-independent cross section between DM and nucleon which is excluded by the LUX experiment [3]. Therefore, Ref. [4] considers the pseudoscalar mediator instead of a scalar, and Ref. [5] assume that the DM preferentially couples to b-quark. The measurements of the Higgs invisible width are quite imprecise, and the invisible branching fraction is required to be smaller than 0.55 from the CMS search for invisible decays of Higgs bosons in the vector boson fusion and associated ZH production modes [6]. However, from the analysis of the global fit to the Higgs signal strengths, the invisible branching fraction is required to be small than 0.1 at 68% C.L., see [7] and [8]. Therefore, it is challenging for the 125 GeV Higgs as the mediator since the large Higgs decay into DM is disfavored by the global fit to LHC Higgs signals. The excess of gamma-ray can be also fit by the 10 GeV DM annihilating to $\tau\bar{\tau}$ [9]. The various DM models have been proposed to explain the excess of gamma-ray [4,5,10,11].

In this paper, with the motivation of eliminating the tension between $\langle\sigma v\rangle_{b\bar{b}}$ and the LUX experiment induced by the scalar portal dark matter, we add a scalar DM (S) to the aligned two-Higgs-doublet model (2HDM) [12,13], and focus on a simplified scenario. Different from the SUSY models, the five Higgs masses in the 2HDM are theoretically independent. We assume that the pseudoscalar and charged Higgs are very heavy, and the heavy CP-even Higgs is the discovered 125 GeV Higgs boson [14]. The mixing angle α is equal to β, which leads to that the heavy CP-even Higgs has the same coupling to the gauge bosons and fermions as the SM Higgs. In addition, we assume that only the light CP-even Higgs mediates the DM interactions with SM particles, which have no couplings to *WW* and *ZZ*, but have the independent couplings to the up-type quarks, down-type quarks and charged leptons. We show that the tension between $\langle\sigma v\rangle_{SS\to b\bar{b}}$ and the constraints from the LUX induced by the scalar portal DM can go away for the isospin-violating S-nucleon coupling, and the constraints from the relic density of Planck, the Higgs search at the collider and the other relevant experiments are also satisfied.

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Note that Refs. [15,16] study the constraint on the Type-II and Type-III 2HDMs with a scalar DM from the direct detection experiments. In Ref. [17], a scalar DM is added to the Higgs triple model, which gives a valid explanation for 130 gamma-ray line signal and the enhancement of LHC diphoton Higgs signal [18].

Our work is organized as follows. In Section 2 we recapitulate the simplified aligned 2HDM with a scalar DM (S2HDM+D), and analyze the constraints from relevant experimental constraints. In Section 3 we give the numerical results, and show that the scalar portal DM in our model can explain the gamma-ray excess. Finally, we give our conclusion in Section 4.

2. Simplified two-Higgs-doublet model with a scalar dark matter and the relevant experimental constraints

2.1. Model

The general Higgs potential is written as [19]

$$\begin{aligned} V = {} & m_{11}^2(\Phi_1^\dagger\Phi_1) + m_{22}^2(\Phi_2^\dagger\Phi_2) - \left[m_{12}^2(\Phi_1^\dagger\Phi_2 + \text{h.c.})\right] \\ & + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) \\ & + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ & + \left[\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right] + \left[\lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \text{h.c.}\right] \\ & + \left[\lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + \text{h.c.}\right]. \end{aligned} \tag{1}$$

For the CP-conserving case, all λ_i and m_{12}^2 are real. After the electroweak $SU(2)\times U(1)$ symmetry is spontaneously broken down to $U(1)_{EM}$,

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \phi_1^0 + ia_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \phi_2^0 + ia_2) \end{pmatrix}. \tag{2}$$

The mass eigenstates of the five physical scalars can be written as:

$$\begin{aligned} \begin{pmatrix} H \\ h \end{pmatrix} &= \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix}\begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix}, \\ A &= -G_1\sin\beta + G_2\cos\beta, \\ H^\pm &= -\phi_1^\pm\sin\beta + \phi_2^\pm\cos\beta, \end{aligned} \tag{3}$$

where $\tan\beta \equiv v_2/v_1$ and $v = \sqrt{v_1^2+v_2^2} \simeq 246$ GeV. Their masses are given as [20]

$$\begin{aligned} m_A^2 &= \frac{m_{12}^2}{\sin\beta\cos\beta} - \frac{v^2}{2}(2\lambda_5 + \lambda_6\cot\beta + \lambda_7\tan\beta), \\ m_{H^\pm}^2 &= m_A^2 + \frac{v^2}{2}(\lambda_5 - \lambda_4), \\ m_{H,h}^2 &= \frac{1}{2}\left[M_{11}^2 + M_{22}^2 \pm \sqrt{(M_{11}^2 - M_{22}^2)^2 + 4(M_{12}^2)^2}\right], \end{aligned} \tag{4}$$

with

$$M^2 = m_A^2\begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} + v^2 B^2, \tag{5}$$

where

$$B^2 = \begin{pmatrix} \lambda_1 c_\beta^2 + 2\lambda_6 s_\beta c_\beta + \lambda_5 s_\beta^2 & (\lambda_3+\lambda_4)s_\beta c_\beta + \lambda_6 c_\beta^2 + \lambda_7 s_\beta^2 \\ (\lambda_3+\lambda_4)s_\beta c_\beta + \lambda_6 c_\beta^2 + \lambda_7 s_\beta^2 & \lambda_2 s_\beta^2 + 2\lambda_7 s_\beta c_\beta + \lambda_5 c_\beta^2 \end{pmatrix}. \tag{6}$$

Table 1
The tree-level couplings of the neutral Higgs bosons with respect to those of the SM Higgs boson. u, d and l denote the up-type quarks, down-type quarks and the charged leptons, respectively. The angle α parameterizes the mixing of two CP-even Higgses h and H.

	VV (WW, ZZ)	$u\bar{u}$	$d\bar{d}$	$l\bar{l}$
h	$\sin(\beta-\alpha)$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin(\alpha-\theta_d)}{\cos(\beta-\theta_d)}$	$-\frac{\sin(\alpha-\theta_l)}{\cos(\beta-\theta_l)}$
H	$\cos(\beta-\alpha)$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos(\alpha-\theta_d)}{\cos(\beta-\theta_d)}$	$\frac{\cos(\alpha-\theta_l)}{\cos(\beta-\theta_l)}$

The heavy CP-even Higgs (H) and the light CP-even Higgs (h) can be respectively taken as the 125 GeV Higgs. In the physical basis, m_h, m_H, m_A, $m_{H^\pm}$, m_{12}^2, $\sin(\beta-\alpha)$, $\tan\beta$, λ_6 and λ_7 are taken as the free input parameters. From that point of view, the Higgs masses are independent on the dimensional constant m_{12}^2. The Higgs spectrum in the minimal supersymmetric standard model (MSSM) can decouple to the five Higgses in 2HDM. To solve some problems such as unnaturalness of μ parameter in MSSM, the next-to-minimal supersymmetric standard model (NMSSM) [21] extends the MSSM by introducing a gauge singlet superfield S with the Z_3-invariant superpotential given by $W_F + \lambda\hat{H}_u\cdot\hat{H}_d\hat{S} + \kappa\hat{S}^3/3$. As a result, the NMSSM predicts one more CP-even Higgs boson and one more CP-odd Higgs boson in addition to the five Higgses. For $\lambda = 0$ and $\kappa = 0$, the Higgs spectrum in NMSSM can decouple to MSSM.

In the aligned 2HDM, the two complex scalar doublets couple to the down-type quarks and charged leptons with aligned Yukawa matrices [12,13]. The Yukawa interactions can be given by

$$\begin{aligned} -\mathcal{L} = {} & y_u\overline{Q}_L\tilde{\Phi}_2 u_R + y_d\overline{Q}_L(\cos\theta_d\Phi_1 + \sin\theta_d\Phi_2)d_R \\ & + y_l\bar{l}_L(\cos\theta_l\Phi_1 + \sin\theta_l\Phi_2)e_R + \text{h.c.}, \end{aligned} \tag{7}$$

where $Q^T = (u_L, d_L)$, $L^T = (\nu_L, l_L)$, and $\tilde{\Phi}_2 = i\tau_2\Phi_2^*$. y_u, y_d and y_ℓ are 3×3 matrices in family space. θ_d and θ_l parameterize the two Higgs doublets couplings to down-type quarks and charged leptons, respectively. Where a freedom is used to redefine the two linear combinations of Φ_1 and Φ_2 to eliminate the coupling of the up-type quarks to Φ_1 [13]. Table 1 shows the couplings of two CP-even Higgs bosons with respect to the SM Higgs boson.

Now we introduce the renormalizable Lagrangian of the real single scalar S,

$$\mathcal{L}_S = -\frac{1}{2}S^2(\lambda_1\Phi_1^\dagger\Phi_1 + \lambda_2\Phi_2^\dagger\Phi_2) - \frac{m_0^2}{2}S^2 - \frac{\lambda_S}{4!}S^4. \tag{8}$$

The linear and cubic terms of the scalar S are forbidden by a Z_2' symmetry $S\to -S$. The DM mass and the interactions with the neutral Higgses are obtained from Eq. (8),

$$\begin{aligned} m_S^2 &= m_0^2 + \frac{1}{2}\lambda_1 v^2\cos^2\beta + \frac{1}{2}\lambda_2 v^2\sin^2\beta, \\ -\lambda_h v S^2 h/2 &\equiv -(-\lambda_1\sin\alpha\cos\beta + \lambda_2\cos\alpha\sin\beta)vS^2h/2, \\ -\lambda_H v S^2 H/2 &\equiv -(\lambda_1\cos\alpha\cos\beta + \lambda_2\sin\alpha\sin\beta)vS^2H/2. \end{aligned} \tag{9}$$

Our previous paper shows detailedly the allowed ranges of α, $\tan\beta$, θ_d, θ_l and the charged and neutral Higgses in the aligned 2HDM by the theoretical constraints from vacuum stability, unitarity and perturbativity as well as the experimental constraints from the electroweak precision data, flavor observables and the Higgs searches [22]. In this paper, we focus on a simplified scenario: (i) The heavy CP-even Higgs (H) is the discovered 125 GeV Higgs. The masses of pseudoscalar and charged Higgs are assumed to be heavy enough to avoid the constraints from the collider experiments and flavor observables. Further, the electroweak parameter ρ ($\equiv M_W/(M_Z\cos_{\theta_W})$) requires their masses to be almost degenerate [22]. (ii) $\alpha = \beta$ and $\lambda_H = 0$. As the 125 GeV Higgs, the heavy CP-even Higgs has the same couplings to the gauge bosons and fermions as the SM Higgs. $\lambda_H = 0$ forbids the heavy Higgs decaying to dark matter. As a result, the heavy Higgs as the 125 GeV Higgs can fit the Higgs signals well. Only the light CP-even Higgs h mediates the DM interactions with the SM particles. Its mass is larger than 62.5 GeV to forbid the decay $H \to hh$. The couplings to WW and ZZ vanish, and ones to fermions normalized to SM are $y_u = 1/\tan\beta$ for the up-type quarks, $y_d = -\tan(\beta - \theta_d)$ for the down-type quarks and $y_l = -\tan(\beta - \theta_l)$ for the charged leptons. In addition, from Eq. (9), we can obtain $m_S = m_0$ for $\alpha = \beta$ and $\lambda_H = 0$.

In our calculations, the involved free parameter of S2HDM+D are y_u ($\tan\beta$), y_d (θ_d), y_l (θ_l), m_h, m_S and λ_h. In order to generate the observed spectral shape of the gamma-ray excess, we fix $m_S = 35$ GeV and require $\langle\sigma v\rangle_{SS\to b\bar{b}}$ to be in the range of 1.7–2.3 $\times 10^{-26}$ cm^3/s. In 2HDMs, the charged Higgs can give the additional contributions to the low energy flavor observable Δm_{B_d} and Δm_{B_s}. The experimental constraints of Δm_{B_d} and Δm_{B_s} favor $\tan\beta > 1$ since the coupling $H^+\bar{t}b$ is proportional to $1/\tan\beta$ [22]. In addition, the perturbative of Higgs potential disfavors the large $\tan\beta$ for the absence of the soft-breaking term [23]. Therefore, we take $0.2 < y_u < 1.0$ ($1.0 < \tan\beta < 5.0$). For such $\tan\beta$ ($\alpha = \beta$), both y_d ($-\tan(\beta - \theta_d)$) and y_l ($-\tan(\beta - \theta_l)$) are allowed to be in the range of -1.0 and 0.5. Here we take $-1.0 < y_d < -0.2$ which has opposite sign to y_u, and favors to obtain an isospin-violating S-nucleon coupling. For simplicity, we take $y_l = 0$ to favor S to annihilate dominantly to $b\bar{b}$. λ_h and m_h are taken to be in the ranges of 0.0001–1.0 and 75–120 GeV, respectively.

2.2. The spin-independent cross section between S and nucleon

In this model, the elastic scattering of S on a nucleon receives the contributions from the h exchange diagrams, which is given as [24],

$$\sigma_{p(n)} = \frac{\mu^2_{p(n)}}{4\pi m_S^2}\left[f^{p(n)}\right]^2, \tag{10}$$

where $\mu_{p(n)} = \frac{m_S m_{p(n)}}{m_S + m_{p(n)}}$,

$$f^{p(n)} = \sum_{q=u,d,s} f_q^{p(n)} \mathcal{C}_{Sq} \frac{m_{p(n)}}{m_q} + \frac{2}{27} f_g^{p(n)} \sum_{q=c,b,t} \mathcal{C}_{Sq} \frac{m_{p(n)}}{m_q}, \tag{11}$$

with $\mathcal{C}_{Sq} = \frac{\lambda_h m_q}{m_h^2} y_q$. Following the recent study [25], we take

$$\begin{aligned} &f_u^{(p)} \approx 0.0208, \quad f_d^{(p)} \approx 0.0399, \quad f_s^{(p)} \approx 0.0430, \\ &f_g^{(p)} \approx 0.8963, \quad f_u^{(n)} \approx 0.0188, \quad f_d^{(n)} \approx 0.0440, \\ &f_s^{(n)} \approx 0.0430, \quad f_g^{(n)} \approx 0.8942. \end{aligned} \tag{12}$$

For the relations $f_q^{(p)} = f_q^{(n)}$ and $f_g^{(p)} = f_g^{(n)}$ are satisfied, the S-nucleon coupling is always isospin-conserved. Conversely, the S-nucleon coupling is violated for the relations are not satisfied, as shown in Eq. (12). However, the Higgs couplings to the quarks (y_d and y_u) need fine-tuning in order to obtain the large violating, such as $f^n/f^p = -0.7$. The recent data on the direct DM search from LUX put the most stringent constraint on the cross section [3]. For the isospin-violating S-nucleon coupling, the scattering rate with the target can be suppressed, thus weakening the constrains from LUX and XENON100 [26], especially for $f_n/f_p \simeq -0.7$. Results of direct detection experiments are often quoted in terms of "normalized-to-nucleon cross section", which is given by [27]

$$\frac{\sigma_p}{\sigma_N^Z} = \frac{\sum_i \eta_i \mu_{A_i}^2 A_i^2}{\sum_i \eta_i \mu_{A_i}^2 [Z + (A_i - Z) f_n/f_p]^2}, \tag{13}$$

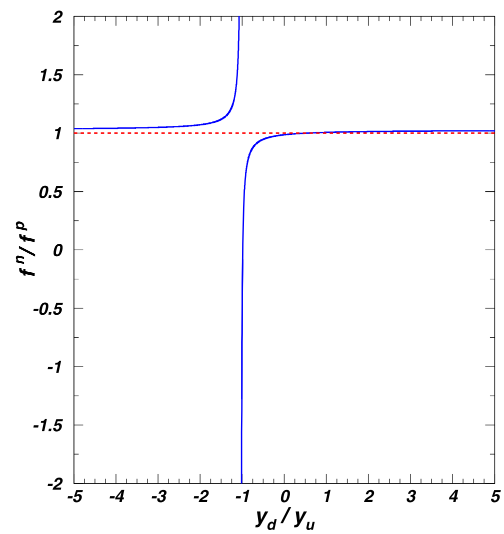

Fig. 1. f^n/f^p versus y_d/y_u.

σ_N^Z is the typically-derived DM-nucleon cross section from scattering off nuclei with atomic number Z, assuming isospin conservation and the isotope abundances found in nature. η_i is the natural abundance of the i-th isotope.

2.3. Relic density, indirect detection and collider constraints

In the parameter space taken in the S2HDM+D, the main annihilation processes include $SS \to q\bar{q}$ and $SS \to gg$ which proceed via an s-channel h exchange. For the absolute value of y_d is much less than y_u, $SS \to gg$ and $SS \to c\bar{c}$ annihilation processes can dominate over $SS \to b\bar{b}$. We employ micrOMEGAs-3.6.9.2 [28] to calculate the relic density and the today pair-annihilation cross sections of DM in the inner galaxy. The Planck Collaboration released its relic density as $\Omega_c h^2 \pm \sigma = 0.1199 \pm 0.0027$ [29], and we require S2HDM+D to explain the experimental data within 2σ range.

The heavy CP-even Higgs has the same couplings as SM Higgs, which can fit the Higgs signals at the LHC well. There is no couplings to WW, ZZ and leptons for the light CP-even Higgs, which favors it not to be detected at the collider. HiggsBounds-4.1.1 [30] is used to implement the exclusion constraints from the Higgses searches at LEP, Tevatron and LHC at 95% confidence level.

The ATLAS [31] and CMS [32] Collaborations have published monojet search results, which can be used to place constraints on the DM-nucleon scattering cross section. For the scalar portal DM, the DM interactions with the light quarks are proportional to quark mass, leading to suppressing the monojet + $\not{E}_T$ signal sizably. Therefore, the current monojet searches for DM at the LHC appears to provide no stronger constraints on the S2HDM+D than the direct detection from the LUX experiment [31–33].

3. Results and discussions

Since the hadronic quantities in the spin independent S-nucleon scattering are fixed, f^n/f^p only depends on the normalized factors of Yukawa couplings, y_u and y_d. Fig. 1 shows f^n/f^p versus y_d/y_u. We find that f^n/f^p is very sensitive to y_d/y_u for y_d/y_u is around -1.0, and very close to 1.0 for $y_d/y_u > 0$. In the following discussions, we will focus on the surviving samples with $-1.0 < f^n/f^p < 1.0$ where the constraint from the LUX experiment can be weakened. f^n/f^p in such range favors $y_d/y_u < 0$, which is the reason why we choose y_d to have opposite sign to y_u.

In Fig. 2, we project the surviving samples on the planes of $\langle\sigma v\rangle_{SS\to b\bar{b}}$ versus f^n/f^p and σ_p versus f^n/f^p, respectively.

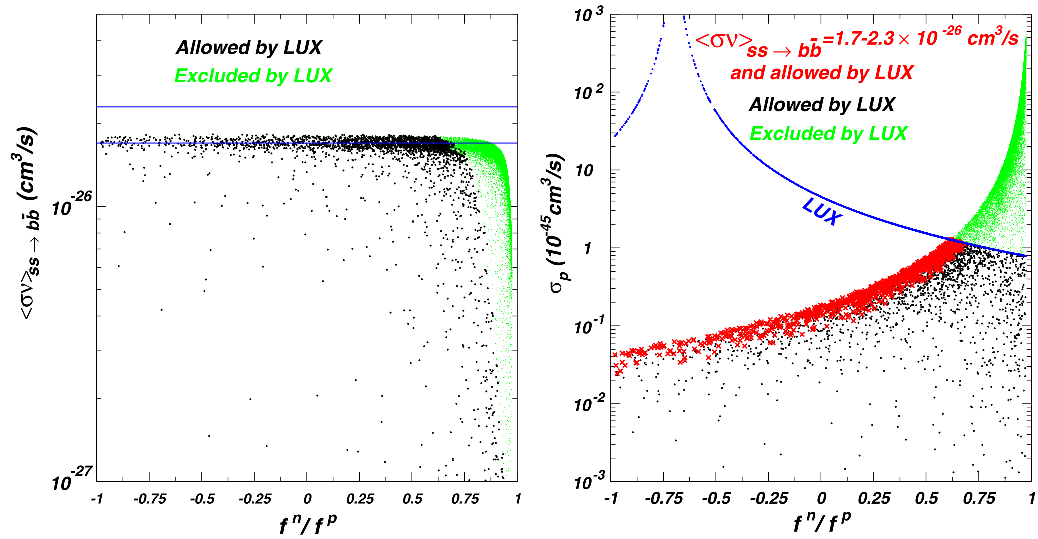

Fig. 2. The scatter plots of surviving samples projected on the planes of $\langle\sigma v\rangle_{SS\to b\bar{b}}$ versus f^n/f^p and σ_p versus f^n/f^p. The two horizontal lines in the left panel denote $\langle\sigma v\rangle_{SS\to b\bar{b}} = 1.7\times 10^{-26}$ cm^3/s and 2.3×10^{-26} cm^3/s.

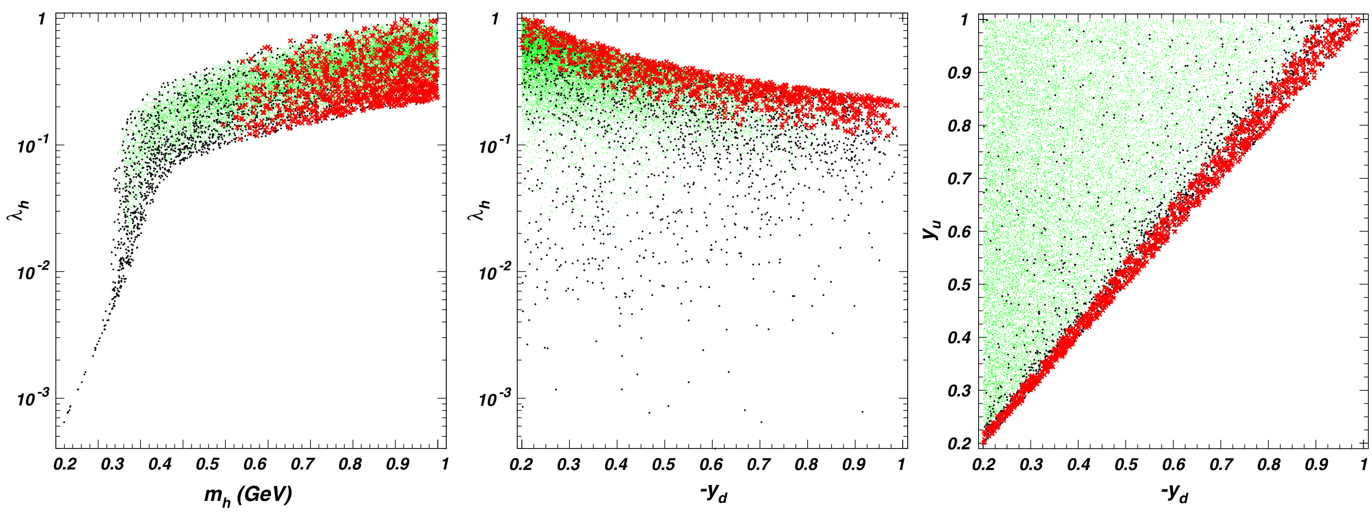

Fig. 3. Same as Fig. 2, but projected on the planes of λ_h versus m_h, λ_h versus $-y_d$, and y_u versus $-y_d$, respectively.

The left panel shows that, for $-1 < f^n/f^p < 0.7$, $\langle\sigma v\rangle_{SS\to b\bar{b}}$ can be in the range of 1.7–2.3×10^{-26} cm^3/s while σ_p is below the upper bound from the LUX experiment. For f^n/f^p is very close to 1.0, $\langle\sigma v\rangle_{SS\to b\bar{b}}$ as low as 10^{-27} cm^3/s is still not allowed by the LUX constraint. The right panel shows that the maximal value of σ_p decreases as f^n/f^p varies from 1.0 to -1.0, and σ_p is smaller than the upper bound of LUX by several orders of magnitude for f^n/f^p is around -0.7.

In Fig. 3, we project the surviving samples on the planes of λ_h versus m_h, λ_h versus $-y_d$, and y_u versus $-y_d$, respectively. For the surviving samples which can explain the gamma-ray excess validly: The middle panel shows the lower bound of λ_h is 0.1 for $-y_d = 1.0$, and enhanced to 0.6 as $-y_d$ decreases to 0.2. The left panel shows the lower bound of λ_h is visibly enhanced for the large m_h, such as $m_h = 120$ GeV. For $m_h/2$ approaches to m_S (35 GeV), λ_h can be much smaller than 0.1 to achieve the correct relic abundance since the integral in the calculation of thermal average can be dominated by the resonance at $s = m_h^2$ even if m_S is below $m_h/2$. However, such small λ_h will suppress sizably the scattering of DM off nuclei and even the today pair-annihilation of DM into $b\bar{b}$ which leads to fail to explain the gamma-ray excess. The right panel shows that y_d/y_u is required to be around -1.0 where f^n/f^p is in the range of -1.0 and 0.7 (see Fig. 1 and Fig. 2), and DM annihilates dominantly into $b\bar{b}$.

4. Conclusion

In this note, we add a scalar DM to the aligned 2HDM, and focus on a simplified scenario, which very economically implements the following two characteristics: (i) The heavy CP-even Higgs is the discovered 125 GeV Higgs boson, which has the same couplings to the gauge bosons and fermions as the SM Higgs. (ii) Only the light CP-even Higgs mediates the DM interactions with SM particles, which has no couplings to *WW* and *ZZ*, but the independent couplings to the up-type quarks, down-type quarks and charged leptons. We find that the tension between $\langle\sigma v\rangle_{SS\to b\bar{b}}$ and the constraint from LUX induced by the scalar portal DM can go away for the isospin-violating S-nucleon coupling, $-1.0 < f^n/f^p < 0.7$. Being consistent with the constraints from the relic density of Planck, the direct detection of LUX, the Higgs searches at the collider and the other relevant experiments, the model can give a valid explanation for the galactic center gamma-ray excess in the proper ranges of λ_h, m_h, y_u and y_d.

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