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

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Abstract

Due to the strong constrain from the LUX experiment, the scalar portal dark matter can not generally explain a gamma-ray excess in the galactic center by the annihilation of dark matter into $b\bar{b}$. 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 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 $\sigma v \rightarrow bb$ 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.

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I. 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 $<\sigma v>_{b\bar{b}} \approx 1.7 - 2.3 \times 10^{-26} \text{cm}^3/s$ [2], which is strikingly close to the thermal relic density value, $<\sigma v> \sim 10^{-26} \text{cm}^3/s$. 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 $<\sigma v>_{b\bar{b}}$, 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] consider the pseudoscalar mediator instead of a scalar, and Ref. [5] assume that the DM preferentially couples to b-quark. In addition, the 125 GeV Higgs can not be as the mediator since the large Higgs decay into DM is disfavored by the LHC Higgs signals. The excess of gamma-ray can be also fit by the 10 GeV DM annihilating to $\tau \bar{\tau}$ [6]. The various DM models have been proposed to explain the excess of gamma-ray [4, 5, 7, 8].

In this paper, with the motivation of eliminating the tension between $<\sigma v>_{b\bar{b}}$ 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) [9, 10], and focus on a simplified scenario: The mixing angle $\alpha$ equals to $\beta$, and the pseudoscalar and charged Higgs are very heavy. The heavy CP-even Higgs is the discovered 125 GeV Higgs boson [11], which has the same coupling to the gauge bosons and fermions as the SM Higgs. 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 show that the tension between $<\sigma v>_{SS \rightarrow b\bar{b}}$ 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.

Our work is organized as follows. In Sec. II we recapitulate the simplified aligned 2HDM with a scalar DM (S2HDM+D), and analyze the constraints from relevant experimental constraints. In Sec. III 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 Sec. IV.

II. SIMPLIFIED TWO-HIGGS-DOUBLET MODEL WITH A SCALAR DARK MATTER AND THE RELEVANT EXPERIMENTAL CONSTRAINTS

A. Model

We focus on an aligned 2HDM that allows both doublets to couple to the down-type quarks and charged leptons with aligned Yukawa matrices \([9, 10]\). Compared to the four traditional types of 2HDM, the model has two additional mixing angles \(\theta_d\) and \(\theta_l\) in the down-type quark and charged lepton Yukawa interactions. Table I 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 \(S\),

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

The linear and cubic terms of the scalar \(S\) are forbidden by a \(Z'\) symmetry \(S \rightarrow -S\). The DM mass is given from the Eq. (1), \(m_S^2 = m_0^2 + \frac{1}{2}\lambda_1v_0^2\cos^2\beta + \lambda_2v_0^2\sin^2\beta\) with \(v_0 \approx 246\) GeV. The DM interactions with the neutral Higgses are obtained,

\[
-\lambda_hv_0S^2h/2 = -(-\lambda_1\sin\alpha\cos\beta + \lambda_2\cos\alpha\sin\beta)v_0S^2h/2, \tag{2}
\]

\[
-\lambda_Hv_0S^2H/2 = -(\lambda_1\cos\alpha\cos\beta + \lambda_2\sin\alpha\sin\beta)v_0S^2H/2. \tag{3}
\]

Our previous paper shows detailedly the allowed ranges of \(\alpha\), \(\tan\beta\), \(\theta_d\), \(\theta_l\) 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 \([12]\). 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 enough heavy to avoid the constraints from the collider experiments and flavor observables. Further, the \(\delta\rho\) requires their masses to be almost degenerate. (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. 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 \(H \rightarrow hh\). The couplings
TABLE I: 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 \( \alpha \) parameterizes the mixing of two CP-even Higgses \( h \) and \( H \). \( \beta \) is defined as usual to be the ratio of the two vacuum expectation values (VEVs) from the two doublet Higgs fields \( \Phi_1 \) and \( \Phi_2 \).

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

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 our calculations, the involved free parameter of S2HDM+D are \( y_u \) (\( \tan \beta \)), \( y_d \) (\( \theta_d \)), \( y_l \) (\( \theta_l \)), \( m_h \), \( m_S \) and \( \lambda_h \). In order to generate the observed spectral shape of the gamma-ray excess, we fix \( m_S = 35 \) GeV and require \( <\sigma v>_{SS \rightarrow b\bar{b}} \) to be in the range of \( 1.7 - 2.3 \times 10^{-26} \text{cm}^3/\text{s} \). Following Ref. \[12\], since \( \tan \beta > 1 \) is favored by the constraints from \( \Delta m_{B_d} \) and \( \Delta m_{B_s} \), and the large \( \tan \beta \) is disfavored by the perturbativity, we take \( 0.2 < y_u < 1 \) (\( 1.0 < \tan \beta < 5.0 \)). 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 \( b\bar{b} \). \( \lambda_h \) and \( m_h \) are taken to be in the ranges of \( 0.0001-1.0 \) and \( 75-120 \) GeV, respectively.

**B. 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 \[13\],

\[
\sigma_p(n) = \frac{\mu_{p(n)}^2}{4\pi m_S^2} \left[ f^{p(n)} \right]^2, \quad (4)
\]

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

\[
f^{p(n)} = \sum_{q=u,d,s} f^{p(n)}_q C_{Sq} \frac{m_{p(n)}}{m_q} + \frac{2}{27} f^{p(n)}_g \sum_{q=c,b,t} C_{Sq} \frac{m_{p(n)}}{m_q}, \quad (5)
\]
with $C_{Sq} = \frac{\lambda y_q}{m_h}$. Following the recent study \cite{14}, we take

$$f_u^{(p)} \approx 0.0208, \quad f_d^{(p)} \approx 0.0399, \quad f_s^{(p)} \approx 0.0430, \quad f_g^{(p)} \approx 0.8963,$$

$$f_u^{(n)} \approx 0.0188, \quad f_d^{(n)} \approx 0.0440, \quad f_s^{(n)} \approx 0.0430, \quad f_g^{(n)} \approx 0.8942. \quad (6)$$

The recent data on the direct DM search from LUX put the most stringent constraint on the cross section \cite{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 \cite{15}, especially for $f_n/f_p \approx -0.7$. Results of direct detection experiments are often quoted in terms of "normalized-to-nucleon cross section", which is given by \cite{16}

$$\frac{\sigma_p}{\sigma_N^Z} = \frac{\sum_i \eta_i \mu^2_i A_i^2}{\sum_i \eta_i \mu^2_i [Z + (A_i - Z)f_n/f_p]^2}, \quad (7)$$

$\sigma_N^Z$ 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. $\eta_i$ is the natural abundance of the i-th isotope.

C. Relic density, indirect detection and collider constraints

In the parameter space taken in the S2HDM+D, the main annihilation processes include $SS \rightarrow q\bar{q}$ and $SS \rightarrow gg$ which proceed via an s-channel $h$ exchange. For the absolute value of $y_d$ is much less than $y_u$, $SS \rightarrow gg$ and $SS \rightarrow c\bar{c}$ annihilation processes can dominate over $SS \rightarrow b\bar{b}$. We employ micrOMEGAs-3.6.9.2 \cite{17} 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 $\Omega_c h^2 = 0.1199 \pm 0.0027$ \cite{18}, and we require S2HDM+D to explain the experimental data within $2\sigma$ 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 \cite{19} is used to implement the exclusion constraints from the Higgses searches at LEP, Tevatron and LHC at 95% confidence level.

The ATLAS \cite{20} and CMS \cite{21} 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+$E_T$ 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 \[20–22\].

III. 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 $<\sigma v >_{SS\rightarrow \bar{b}b}$ versus $f^n/f^p$ and $\sigma_p$ versus $f^n/f^p$, respectively. The left panel shows that, for $-1 < f^n/f^p < 0.7$, $<\sigma v >_{SS\rightarrow \bar{b}b}$ can be in the range of $1.7 - 2.3 \times 10^{-26} cm^3/s$ while $\sigma_p$ is below the upper bound from the LUX experiment. For $f^n/f^p$ is very close to 1.0, $<\sigma v >_{SS\rightarrow \bar{b}b}$ 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 $\sigma_p$ decreases as $f^n/f^p$ varies from 1.0 to -1.0, and $\sigma_p$ is smaller than the upper bound of LUX by several orders of magnitude for $f^n/f^p$ is around -0.7.
FIG. 2: The scatter plots of surviving samples projected on the planes of $<\sigma v>_{SS\rightarrow b\bar{b}}$ versus $f^n/f^p$ and $\sigma_p$ versus $f^n/f^p$. The two horizontal lines in the left panel denote $<\sigma v>_{SS\rightarrow b\bar{b}}=1.7\times10^{-26}\text{cm}^3/\text{s}$ and $2.3\times10^{-26}\text{cm}^3/\text{s}$.

In Fig. 3 we project the surviving samples on the planes of $\lambda_h$ versus $m_h$, $\lambda_h$ 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 $\lambda_h$ 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 $\lambda_h$ is visibly enhanced for the large $m_h$, such as $m_h = 120\text{ GeV}$. For $m_h/2$ approaches to $m_S$ (35 GeV), $\lambda_h$ 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 $\lambda_h$ 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 $b\bar{b}$.

IV. CONCLUSION

In this note, we add a scalar DM to the aligned 2HDM, 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 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 $<\sigma v>_{S\rightarrow b\bar{b}}$ 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 $\lambda_h$, $m_h$, $y_u$ and $y_d$.

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