A light scalar dark matter extension of the type-II
two-Higgs-doublet model

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Abstract

We examine the type-II two-Higgs-doublet model with a light scalar dark matter ($S$) after imposing the constraints from the Higgs searches at the LHC and dark matter experiments. We first assume that both two CP-even Higgses ($h$ and $H$) are portals between the DM and SM sectors, and the CP-odd Higgs ($A$) and $H$ are heavier than 130 GeV. We find that the DM with a mass of $10 \sim 50$ GeV is disfavored by the joint constraints of the 125 GeV Higgs signal data, the relic density, XENON1T (2017), PandaX-II (2017) and the Fermi-LAT. Next, we consider a special scenario in which the heavy CP-even Higgs is taken as the 125 GeV Higgs. The light CP-even Higgs is the only portal between the DM and SM sectors, and the DM mass is slightly below Higgs resonance. We find that the signal data of the 125 GeV Higgs restrict $\tan \beta$ to be in the range of $1 \sim 1.5$ for $m_h < 62$ GeV. The $gg \rightarrow A \rightarrow hZ$ and $b\bar{b} \rightarrow h \rightarrow \tau^+\tau^-$ channels at the LHC can impose lower limits and upper limits on $\tan \beta$, respectively. For appropriate values of $\tan \beta$, $\lambda_h$ and $m_h$, the DM with a mass of $10 \sim 50$ GeV is allowed by the constraints of the Higgs searches at the LHC and dark matter experiments. For example, $\tan \beta$ is restricted to be in the range of $1.0 \sim 1.5$ for $10$ GeV $< m_s < 26$ GeV, and $\frac{m_h}{m_S} > 1.125$ is excluded for $30$ GeV $< m_S < 50$ GeV.

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I. INTRODUCTION

The weakly interacting massive particle (WIMP) is one popular candidate of dark matter (DM). The simplest WIMP-DM model is the standard model (SM) plus a real singlet scalar as DM [1]. In the model, the current experiments excluded the DM mass up to 330 GeV, except a small range near 63 GeV [2, 3]. Much of the region excluded in this model can be recovered if the Higgs sector is extended to the two-Higgs-doublet model (2HDM) [4] which contains two neutral CP-even Higgs bosons \( h \) and \( H \), one neutral pseudoscalar \( A \), and two charged Higgs \( H^\pm \) [3, 8–13]. Recently, Ref. [12] took the 125 GeV Higgs with wrong sign Yukawa coupling of the down-type quark as the only portal between the DM and SM sector, and found that the DM mass is allowed to be as low as 50 GeV for appropriate isospin-violating DM interactions with nucleons. The \( SS \rightarrow AA \) annihilation channel can play an important contribution to the relic density, but does not solve the tension between the DM relic density and the signal data of the 125 GeV Higgs, which leads that \( m_S < 50 \) GeV is excluded. Ref. [3] showed that if the heavy CP-even Higgs boson is the only portal, much of the region below 100 GeV are excluded.

In this paper, the question we want to answer is, which parameter space of the type-II 2HDM with a scalar DM is the DM with a mass below 50 GeV allowed in? We will consider joint constraints from the theory, the precision electroweak data, the flavor observables, the signal data of the 125 GeV Higgs, the searches for the additional Higgs at the LEP and LHC, the relic density, XENON1T (2017), PandaX-II (2017) and the Fermi-LAT searches for DM annihilation from dwarf spheroidal satellite galaxies (dSphs).

This paper is organized as follows. In Section II, we introduce some characteristic features of the type-II 2HDM with a scalar DM. In Section III we perform numerical calculations. In Section IV, we examine the allowed parameter space after imposing the relevant theoretical and experimental constraints. Finally, we draw our conclusion in Section V.
II. TYPE-II TWO-HIGGS-DOUBLET MODEL WITH A SCALAR DARK MATTER

A. Type-II two-Higgs-doublet model

In the type-II 2HDM with a scalar DM, the scalar potential includes two parts, $V_{2HDM} + V_S$, and they are the potential of type-II 2HDM and the potential of the DM sector, respectively. The $V_{2HDM}$ with a softly-broken discrete $Z_2$ symmetry is given by [14]

$$V_{2HDM} = m_{11}^2 (\Phi_1^\dagger \Phi_1) + m_{22}^2 (\Phi_2^\dagger \Phi_2) - \left[ m_{12}^2 (\Phi_1^\dagger \Phi_2 + h.c.) \right]$$
$$+ \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)$$
$$+ \left[ \frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2)^2 + h.c. \right].$$  \hspace{1cm} (1)

Here we focus on the case of the CP-conserving in which all $\lambda_i$ and $m_{12}^2$ are real. The two complex Higgs doublets have hypercharge $Y = 1$,

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

Where $v_1$ and $v_2$ are the electroweak vacuum expectation values (VEVs) with $v^2 = v_1^2 + v_2^2 = (246 \text{ GeV})^2$ and $\tan \beta = v_2/v_1$. After spontaneous electroweak symmetry breaking, the remaining five physical Higgs particles are two neutral CP-even $h$ and $H$, one neutral pseudoscalar $A$, and two charged scalars $H^\pm$.

In the type II 2HDM, the up-type fermions obtain masses from only $\Phi_2$ field, and the down-type fermions from $\Phi_1$ field [15, 16]. The Yukawa interactions are given by

$$-\mathcal{L} = Y_{u2} \bar{Q}_L \tilde{\Phi}_2 u_R + Y_{d1} \bar{Q}_L \Phi_1 d_R + Y_{e1} \bar{L}_L \Phi_1 e_R + h.c.,$$  \hspace{1cm} (3)

where $Q^T_L = (u_L, d_L)$, $L^T_L = (\nu_L, l_L)$, $\Phi_{1,2} = i\sigma_2 \Phi_{1,2}^*$, and $Y_{u2}, Y_{d1}$ and $Y_{e1}$ are $3 \times 3$ matrices in family space.

The Yukawa couplings of the neutral Higgs bosons normalized to the SM are given by

$$y_V^h = \sin(\beta - \alpha), \quad y_f^h = \left[ \sin(\beta - \alpha) + \cos(\beta - \alpha)\kappa_f \right],$$
$$y_V^H = \cos(\beta - \alpha), \quad y_f^H = \left[ \cos(\beta - \alpha) - \sin(\beta - \alpha)\kappa_f \right],$$
$$y_V^A = 0, \quad y_f^A = -i\kappa_f \text{ (for u)}, \quad y_f^A = i\kappa_f \text{ (for d, } \ell),$$

with $\kappa_d = \kappa_\ell \equiv -\tan \beta, \quad \kappa_u \equiv 1/\tan \beta$, \hspace{1cm} (4)
where $\alpha$ is the mixing angle of the two CP-even Higgs bosons, and $V$ denotes $Z$ or $W$.

**B. A scalar dark matter**

Now we add a real singlet scalar $S$ to the type-II 2HDM, and the potential containing the $S$ field is written as

$$V_S = \frac{1}{2} S^2 (\kappa_1 \Phi_1^\dagger \Phi_1 + \kappa_2 \Phi_2^\dagger \Phi_2) + \frac{m_0^2}{2} S^2 + \frac{\lambda_S}{4!} S^4.$$  \hspace{1cm} (5)

The linear and cubic terms of the $S$ field are forbidden by a $Z_2'$ symmetry, under which $S \rightarrow -S$. The $S$ is a possible DM candidate provided it does not acquire a VEV. We can obtain the DM mass and the cubic interactions with the neutral Higgses from the Eq. (5),

$$m_S^2 = m_0^2 + \frac{1}{2} \kappa_1 v^2 \cos^2 \beta + \frac{1}{2} \kappa_2 v^2 \sin^2 \beta,$$

$$-\lambda_h v S^2 h/2 \equiv -(-\kappa_1 \sin \alpha \cos \beta + \kappa_2 \cos \alpha \sin \beta) v S^2 h/2,$$

$$-\lambda_H v S^2 H/2 \equiv -(\kappa_1 \cos \alpha \cos \beta + \kappa_2 \sin \alpha \sin \beta) v S^2 H/2. \hspace{1cm} (6)$$

**III. NUMERICAL CALCULATIONS**

In this paper, we discuss two different scenarios:

**Case A:** The light CP-even Higgs boson $h$ is taken as the 125 GeV Higgs, $m_h = 125$ GeV, and $H$ and $A$ are heavier than 130 GeV. Both $h$ and $H$ are the portals between the DM and SM sectors, and contribute to the DM interactions with SM particles.

**Case B:** The heavy CP-even Higgs boson $H$ is taken as the 125 GeV Higgs, $m_H = 125$ GeV. The light CP-even Higgs $h$ is the only portal between the DM and SM sectors, namely fixing $\lambda_H = 0$. Thus, the invisible decay mode $H \rightarrow SS$ is absent, and does not bring troubles to the signal data of the 125 GeV Higgs. The DM mass is slightly below Higgs resonance, $m_S/2 = (1.0 \sim 1.2) \times m_S$. In the calculation of the thermal averaged cross section, the kinetic energy of the DM is non negligible in the early universe, and as a result the resonant condition in the DM pair-annihilation can be met for $m_S$ slightly smaller than $m_h/2$. The temperature at the present time is much lower compared to the freeze-out temperature, and the velocity of DM is much smaller than that in the early universe. Therefore, the resonant condition for the today DM pair-annihilation is hardly satisfied for $m_S$ slightly smaller than $m_h/2$. 

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In our calculations, to implement the constraints from the Higgs searches at the LHC, we need employ SusHi \cite{17} to compute cross sections of Higgs in the gluon fusion and $b\bar{b}$-associated production at NNLO in QCD. Results of SusHi might not be reasonable for a small Higgs mass. Therefore, we take $m_h > 20 \text{ GeV}$, which determines the DM mass to be larger than 10 GeV in the Case B. The measurement of the branching fraction of $b \to s\gamma$ imposed the strongest lower limit on the charged Higgs mass of type-II 2HDM, $m_{H^\pm} > 580 \text{ GeV}$ \cite{18}. The $S$, $T$ and $U$ oblique parameters give the stringent constraints on the mass spectrum of Higgses of type II 2HDM \cite{19,21}. One of $m_A$ and $m_H$ is around 600 GeV, and another is allowed to have a wide mass range including low mass \cite{19}. Therefore, to allow $h$ to be light enough we fix $m_A = 600 \text{ GeV}$ in the Case B.

In our calculations, we consider the following observables and constraints:

(1) Theoretical constraints. The scalar potential of the model contains the potential type-II 2HDM and the potential of the DM sector. The vacuum stability, perturbativity, and tree-level unitarity impose constraints on the relevant parameters, which are discussed in detail in Refs. \cite{3,9}. Here we employ the formulas in \cite{3,9} to implement the theoretical constraints. Compared to Refs. \cite{3,9}, there are additional factors of $\frac{1}{2}$ in the $\kappa_1$ term and the $\kappa_2$ term of this paper.

(2) The oblique parameters. The $S$, $T$, $U$ parameters can impose strong constraints on the mass spectrum of Higgses of 2HDM. The 2HDMC \cite{22} is employed to implement the constraints from the oblique parameters ($S$, $T$, $U$).

(3) The flavor observables and $R_b$. SuperIso-3.4 \cite{23} is employed to consider the constraint of $B \to X_s\gamma$, and $\Delta m_{B_s}$ is calculated following the formulas in \cite{24}. Besides, we perform the constraints of bottom quarks produced in $Z$ decays, $R_b$, which is calculated using the formulas in \cite{25,26}.

(4) The global fit to the signal data of the 125 GeV Higgs. Because the 125 GeV Higgs couplings with the SM particles in this model can be modified compared to the SM, the SM-like decay modes will be corrected. In the Case A, $h$ is the 125 GeV Higgs, and the invisible decay $h \to SS$ is kinematically allowed, which will be strongly constrained by the experimental data of the 125 GeV Higgs. In the Case B, $H$ is the 125 GeV Higgs, and the invisible decay $H \to SS$ is absent since the coupling $HSS$ is taken as zero.
However, the decay $H \rightarrow hh$ is kinematically allowed for $m_h < 62.5$ GeV. We perform the $\chi^2$ calculation for the signal strengths of the 125 GeV Higgs in the $\mu_{ggF+ttH}(Y)$ and $\mu_{VBF+Vh}(Y)$ with $Y$ denoting the decay mode $\gamma\gamma$, $ZZ$, $WW$, $\tau^+\tau^-$ and $b\bar{b}$,

$$
\chi^2(Y) = \left( \begin{array}{c}
\mu_{ggH+ttH}(Y) - \hat{\mu}_{ggH+ttH}(Y) \\
\mu_{VBF+VH}(Y) - \hat{\mu}_{VBF+VH}(Y)
\end{array} \right)^T \left( \begin{array}{cc}
a_Y & b_Y \\
b_Y & c_Y
\end{array} \right) \left( \begin{array}{c}
\mu_{ggH+ttH}(Y) - \hat{\mu}_{ggH+ttH}(Y) \\
\mu_{VBF+VH}(Y) - \hat{\mu}_{VBF+VH}(Y)
\end{array} \right).
$$

(7)

$\hat{\mu}_{ggH+ttH}(Y)$ and $\hat{\mu}_{VBF+VH}(Y)$ are the data best-fit values and $a_Y$, $b_Y$ and $c_Y$ are the parameters of the ellipse, which are given by the combined ATLAS and CMS experiments [27]. We pay particular attention to the surviving samples with $\chi^2 - \chi^2_{\text{min}} \leq 6.18$, where $\chi^2_{\text{min}}$ denotes the minimum of $\chi^2$. These samples correspond to be within the 2\(\sigma\) range in any two-dimension plane of the model parameters when explaining the Higgs data.

In addition, the ATLAS and CMS reported the upper limits on the branching ratio of invisible decay of the 125 GeV Higgs. In our calculation we impose the constraints, $\text{Br}(h \rightarrow SS) < 0.34$ [27].

(5) The non-observation of additional Higgs bosons. We employ HiggsBounds [65, 66] to implement the exclusion constraints from the searches for the neutral and charged Higgs at the LEP at 95\(\%\) confidence level. Especially for the Case B, the searches for a light Higgs at the LEP can impose stringent constraints on the parameter space.

At the LHC, the ATLAS and CMS have searched for an additional scalar via its decay into various SM channels and some exotic decays. For $gg \rightarrow A$ production in type-II 2HDM, the contributions of $b$-quark loop interfere destructively with those of top quark loop. The cross section decreases with an increasing of $\tan\beta$, reaches the minimum value for the moderate value of $\tan\beta$, and is dominated by the $b$-quark loop for enough large value of $\tan\beta$. The cross section of the CP-even Higgs in the gluon fusion depends on $\sin(\beta - \alpha)$ in addition to the Higgs mass and $\tan\beta$. We use SusHi [17] to compute cross sections for Higgs in the gluon fusion and $b\bar{b}$-associated production at NNLO in QCD. A complete list of the searches for additional Higgs considered by us is summarized in Table I and Table II where some channels are taken from Ref.
| Channel                                      | Experiment | Mass range (GeV) | Luminosity |
|----------------------------------------------|------------|------------------|------------|
| \( gg/b \bar{b} \rightarrow \phi'/A \rightarrow \tau^+\tau^- \) | ATLAS 8 TeV [28] | 90-1000          | 19.5-20.3 fb\(^{-1}\) |
| \( gg/b \bar{b} \rightarrow \phi'/A \rightarrow \tau^+\tau^- \) | CMS 8 TeV [29] | 90-1000          | 19.7 fb\(^{-1}\) |
| \( gg/b \bar{b} \rightarrow \phi'/A \rightarrow \tau^+\tau^- \) | ATLAS 13 TeV [30] | 200-1200         | 13.3 fb\(^{-1}\) |
| \( gg \rightarrow \phi'/A \rightarrow \tau^+\tau^- \) | CMS 13 TeV [31] | 90-3200          | 12.9 fb\(^{-1}\) |
| \( b \bar{b} \rightarrow \phi'/A \rightarrow \tau^+\tau^- \) | CMS 13 TeV [32] | 200-2250         | 36.1 fb\(^{-1}\) |
| \( b \bar{b} \rightarrow \phi'/A \rightarrow \mu^+\mu^- \) | CMS 8 TeV [34] | 25-60            | 19.7 fb\(^{-1}\) |
| \( pp \rightarrow \phi'/A \rightarrow \gamma\gamma \) | ATLAS 13 TeV [35] | 200-2400         | 15.4 fb\(^{-1}\) |
| \( gg \rightarrow \phi'/A \rightarrow \gamma\gamma \) | CMS 8+13 TeV [36] | 500-4000         | 12.9 fb\(^{-1}\) |
| \( gg \rightarrow \phi'/A \rightarrow \gamma\gamma + t\bar{t}\phi'/A (\phi'/A \rightarrow \gamma\gamma) \) | CMS 8 TeV [37] | 80-110           | 19.7 fb\(^{-1}\) |
| \( gg \rightarrow \phi'/A \rightarrow \gamma\gamma + t\bar{t}\phi'/A (\phi'/A \rightarrow \gamma\gamma) \) | CMS 13 TeV [37] | 70-110           | 35.9 fb\(^{-1}\) |
| \( VV \rightarrow \phi' \rightarrow \gamma\gamma + V\phi' (\phi' \rightarrow \gamma\gamma) \) | CMS 8 TeV [37] | 80-110           | 19.7 fb\(^{-1}\) |
| \( VV \rightarrow \phi' \rightarrow \gamma\gamma + V\phi' (\phi' \rightarrow \gamma\gamma) \) | CMS 13 TeV [37] | 70-110           | 35.9 fb\(^{-1}\) |
| \( gg/VV \rightarrow \phi' \rightarrow W^+W^- \) | ATLAS 8 TeV [38] | 300-1500         | 20.3 fb\(^{-1}\) |
| \( gg/VV \rightarrow \phi' \rightarrow W^+W^- (\ell\nu\ell\nu) \) | ATLAS 13 TeV [39] | 300-3000         | 13.2 fb\(^{-1}\) |
| \( gg \rightarrow \phi' \rightarrow W^+W^- (\ell\nuqq) \) | ATLAS 13 TeV [40] | 500-3000         | 13.2 fb\(^{-1}\) |
| \( gg/VV \rightarrow \phi' \rightarrow W^+W^- (\ell\nuqq) \) | ATLAS 13 TeV [41] | 200-3000         | 36.1 fb\(^{-1}\) |
| \( gg/VV \rightarrow \phi' \rightarrow W^+W^- (e\nu\mu\nu) \) | ATLAS 13 TeV [42] | 200-3000         | 36.1 fb\(^{-1}\) |
| \( gg/VV \rightarrow \phi' \rightarrow ZZ \) | ATLAS 8 TeV [43] | 160-1000         | 20.3 fb\(^{-1}\) |
| \( gg \rightarrow \phi' \rightarrow ZZ(\ell\ell\nu\nu) \) | ATLAS 13 TeV [44] | 300-1000         | 13.3 fb\(^{-1}\) |
| \( gg \rightarrow \phi' \rightarrow ZZ(\nu\nu\nu\nu) \) | ATLAS 13 TeV [45] | 300-3000         | 13.2 fb\(^{-1}\) |
| \( gg/VV \rightarrow \phi' \rightarrow ZZ(\ell\ell\nu\nu) \) | ATLAS 13 TeV [45] | 300-3000         | 13.2 fb\(^{-1}\) |
| \( gg/VV \rightarrow \phi' \rightarrow ZZ(\ell\ell\ell\ell) \) | ATLAS 13 TeV [46] | 200-3000         | 14.8 fb\(^{-1}\) |
| \( gg/VV \rightarrow \phi' \rightarrow ZZ(\ell\ell\ell\ell) \) | ATLAS 13 TeV [47] | 200-2000         | 36.1 fb\(^{-1}\) |
| \( gg/VV \rightarrow \phi' \rightarrow ZZ(\nu\nu\nu\nu + \ell\ell\ell\ell) \) | ATLAS 13 TeV [48] | 300-5000         | 36.1 fb\(^{-1}\) |

**TABLE I:** The upper limits at 95% C.L. on the production cross-section times branching ratio of \( \tau^+\tau^- \), \( \mu^+\mu^- \), \( \gamma\gamma \), \( WW \) and \( ZZ \) considered in the \( \phi' \) and \( A \) searches at the LHC. Here \( \phi' \) denotes the non-SM-like CP-even Higgs in 2HDM.
| Channel                                      | Experiment               | Mass range (GeV) | Luminosity |
|---------------------------------------------|--------------------------|------------------|------------|
| $gg \to \phi' \to \phi_s \phi_s \to (\gamma \gamma)(b\bar{b})$ | CMS 8 TeV [49]           | 250-1100         | 19.7 fb$^{-1}$ |
| $gg \to \phi' \to \phi_s \phi_s \to (b\bar{b})(b\bar{b})$ | CMS 8 TeV [50]           | 250-1100         | 17.9 fb$^{-1}$ |
| $gg \to \phi' \to \phi_s \phi_s \to (b\bar{b})(\tau^+ \tau^-)$ | CMS 8 TeV [51]           | 260-350          | 19.7 fb$^{-1}$ |
| $gg \to \phi' \to \phi_s \phi_s \to (\gamma \gamma)(b\bar{b})$ | ATLAS 13 TeV [52]        | 275-400          | 3.2 fb$^{-1}$  |
| $gg \to \phi' \to \phi_s \phi_s \to (\gamma \gamma)(b\bar{b})$ | CMS 13 TeV [53]          | 250-900          | 2.7 fb$^{-1}$  |
| $gg \to \phi' \to \phi_s \phi_s \to b\bar{b}b\bar{b}$ | ATLAS 13 TeV [54]        | 300-3000         | 13.3 fb$^{-1}$ |
| $gg \to \phi' \to \phi_s \phi_s \to (b\bar{b})(\tau^+ \tau^-)$ | CMS 13 TeV [55]          | 250-900          | 12.9 fb$^{-1}$ |
| $gg \to \phi' \to \phi_s \phi_s \to b\bar{b}b\bar{b}$ | CMS 13 TeV [56]          | 750-3000         | 35.9 fb$^{-1}$ |
| $gg \to \phi' \to \phi_s \phi_s \to (b\bar{b})(\tau^+ \tau^-)$ | CMS 13 TeV [57]          | 250-900          | 35.9 fb$^{-1}$ |
| $gg \to \phi' \to \phi_s \phi_s \to (WW^*)(\gamma \gamma)$ | ATLAS 13 TeV [57]        | 260-500          | 13.3 fb$^{-1}$ |
| $gg \to A \to \phi_s Z \to (\tau^+ \tau^-) (\ell \ell)$ | CMS 8 TeV [51]           | 220-350          | 19.7 fb$^{-1}$ |
| $gg \to A \to \phi_s Z \to (b\bar{b})(\ell \ell)$ | CMS 8 TeV [58]           | 225-600          | 19.7 fb$^{-1}$ |
| $gg \to A \to \phi_s Z \to (\tau^+ \tau^-) Z$ | ATLAS 8 TeV [59]         | 220-1000         | 20.3 fb$^{-1}$ |
| $gg \to A \to \phi_s Z \to (b\bar{b}) Z$ | ATLAS 8 TeV [59]         | 220-1000         | 20.3 fb$^{-1}$ |
| $gg/b\bar{b} \to A \to \phi_s Z \to (b\bar{b}) Z$ | ATLAS 13 TeV [60]        | 200-2000         | 3.2 fb$^{-1}$  |
| $gg/b\bar{b} \to A \to \phi_s Z \to (b\bar{b}) Z$ | ATLAS 13 TeV [61]        | 200-2000         | 36.1 fb$^{-1}$ |
| $gg \to \phi' A \to \phi' \phi\phi' \to \tau^+ \tau^- \tau^+ \tau^-$ | ATLAS 8 TeV [62]         | 4-50             | 20.3 fb$^{-1}$ |
| $pp \to \phi_s A \to \phi' \phi' \to \tau^+ \tau^- \tau^+ \tau^-$ | CMS 8 TeV [63]           | 5-15             | 19.7 fb$^{-1}$ |
| $pp \to \phi_s A \to \phi' \phi' \to (\mu^+ \mu^-)(b\bar{b})$ | CMS 8 TeV [63]           | 25-62.5          | 19.7 fb$^{-1}$ |
| $pp \to \phi_s A \to \phi' \phi' \to (\mu^+ \mu^-)(\tau^+ \tau^-)$ | CMS 8 TeV [63]           | 15-62.5          | 19.7 fb$^{-1}$ |
| $gg \to A(\phi') \to \phi'(A) Z \to (b\bar{b})(\ell \ell)$ | CMS 8 TeV [64]           | 40-1000          | 19.8 fb$^{-1}$ |
| $gg \to A(\phi') \to \phi'(A) Z \to (\tau^+ \tau^-)(\ell \ell)$ | CMS 8 TeV [64]           | 20-1000          | 19.8 fb$^{-1}$ |

TABLE II: The upper limits at 95% C.L. on the production cross-section times branching ratio for the channels of Higgs-pair and a Higgs production in association with $Z$ at the LHC. Here $\phi'$ and $\phi_s$ denote the non-SM-like CP-even Higgs and the 125 GeV Higgs in the 2HDM, respectively.

Refs. 68, 69 show that the LHC searches for the charged Higgs fail to constrain the model for $m_{H^\pm} > 500$ GeV. Therefore, the searches channels of the charged Higgs are not included in this paper.
The DM observables. We use micrOMEGAs [70] to calculate the relic density and today DM pair-annihilation. The model file is generated by FeynRules [71]. For 10 GeV < m_S < 50 GeV, the DM will annihilate into \( \bar{b}b \) dominantly in this model.

In this model, the elastic scattering of \( S \) on a nucleon receives the contributions of the process with \( t- \) channel exchange of \( h \) and \( H \) in the Case A, and only \( h \) exchange in the Case B. If both \( h \) and \( H \) contribute to the DM interactions with nucleons, the spin-independent cross section is given by [72],

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

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

\[
f_{p(n)}^p = \sum_{q=u,d,s} f_q^p C_{Sq} m_{p(n)} m_q + \frac{2}{27} f_g^p \sum_{q=c,b,t} C_{Sq} m_{p(n)} m_q,
\]

with \( C_{Sq} = \frac{\lambda_h}{m_h^2} m_q y_h^H + \frac{\lambda_H}{m_H^2} m_q y_H^H \). The values of the form factors \( f_q^{p,n} \) and \( f_g^{p,n} \) are extracted from micrOMEGAs [70].

Recently, the Planck collaboration reported the density of cold DM in the universe, \( \Omega_c h^2 = 0.1198 \pm 0.0015 \) [73]. The PandaX-II (2017) and the XENON1T (2017) respectively impose the strongest constraints on the spin-independent DM-nucleon cross section for \( m_S > 100 \) GeV and \( m_S < 60 \) GeV [74, 75]. The upper limits of PandaX-II (2017) are nearly the same as those of XENON1T (2017) for the DM with a mass of \( 60 \sim 100 \) GeV. The Fermi-LAT searches for the DM annihilation from dSphs gave the upper limits on the averaged cross sections of the DM annihilation to \( e^+e^- \), \( \mu^+\mu^- \), \( \tau^+\tau^- \), \( u\bar{u} \), \( b\bar{b} \), and \( WW \) [76].

IV. RESULTS AND DISCUSSIONS

A. Case A

In Fig. 1 we show \( \lambda_H \) and \( \lambda_h \) in the Case A allowed by the constraints of theory, the oblique parameters, the signal data of the 125 GeV Higgs, the flavor observables, \( R_b \), and the exclusion limits from searches for Higgs at LEP. The left panel shows that the vacuum stability, perturbativity, unitarity and the oblique parameters impose upper and lower limits
FIG. 1: In the Case A, the surviving samples projected on the planes of $\lambda_H$ versus $\lambda_h$ and $\lambda_h$ versus $m_S$. All the samples are allowed by the constraints from the vacuum stability, perturbativity, unitarity and the oblique parameters. The pluses (red) are also allowed by the joint constraints from the signal data of the 125 GeV Higgs, the flavor observables, $R_b$, and the exclusion limits from searches for Higgs at LEP.

on $\lambda_H$, $-5 < \lambda_H < 7$. Because the invisible decay $h \to SS$ is kinematically allowed, the signal data of the 125 GeV Higgs impose strong upper limits on $|\lambda_h|$, $|\lambda_h| < 0.017$ ($0.022$) for $m_S= 10$ (50) GeV.

In Fig. 2 we project the surviving samples on the planes of $\tan\beta$ versus $m_H$ and $\lambda_H$ versus $m_H$ after imposing the constraints of "pre-LHC" (denoting the theory, the oblique parameters, the flavor observables, $R_b$, and the exclusion limits from searches for Higgs at LEP), the signal data of the 125 GeV Higgs, the relic density, XENON1T (2017), and PandaX-II (2017). Because the signal data of the 125 GeV Higgs impose the strong upper limits on $|\lambda_h|$, the DM interactions mediated by $H$ play a key role in the relic density. From Fig. 2 we find that the model can give the correct relic density for the heavy CP-even Higgs mass up to 700 GeV. With an increase of $m_H$, $\lambda_H$ and $\tan\beta$ is favored to have large values, which can enhance the couplings of $HSS$ and $Hb\bar{b}$. This is because the $H$-mediated annihilation amplitude is suppressed by its large mass, and the $H$ couplings to the DM and the SM particles are required to be large enough to obtain the correct annihilation rate. Most of the parameter space are excluded by the PandaX-II (2017) and the XENON1T (2017), and only the narrow regions of $M_H < 400$ GeV and $\tan\beta$ around 1.0 are allowed.
FIG. 2: In the Case A, the surviving samples projected on the planes of $\tan \beta$ versus $m_H$ and $\lambda_H$ versus $m_H$. All the samples are allowed by the constraints of "pre-LHC" and the signal data of the 125 GeV Higgs. Also the inverted triangles (sky blue) are allowed by the relic density, and the crosses (black) are allowed by the relic density, the XENON1T (2017), and PandaX-II (2017).

For $\tan \beta$ around 1 and $|\sin(\beta - \alpha)|$ close to 1, $y_d^H / y_u^H$ approaches -1. For such a case, the DM interactions with nucleons mediated by $H$ can have a large isospin violation, which can weaken the bounds of the PandaX-II and the XENON1T sizably. Because $\tan \beta$ is restricted to be around 1.0, an appropriate value of $\lambda_H$ is required to obtain the correct relic density, such as $|\lambda_H| \sim 1.8$ for $m_H = 300$ GeV, as shown in the right panel.

The Fig. 3 shows that the limits of the Fermi-LAT searches for DM annihilation from dSphs exclude the whole region of $10 \text{ GeV} < m_S < 50 \text{ GeV}$, including the parameter space surviving from the PandaX-II (2017) and the XENON1T (2017) bounds. With the decreasing of $m_S$, the values of the today DM pair-annihilation into $b\bar{b}$ in this model exceed the Fermi-LAT upper limits sizably.

B. Case B

Now we discuss the Case B in which the heavy CP-even Higgs is the 125 GeV Higgs. In Fig. 4 we project the surviving samples on the planes of $\tan \beta$ versus $m_h$ and $\sin(\beta - \alpha)$ versus $m_h$ after imposing the constraints of "pre-LHC", the signal data of the 125 GeV Higgs, the searches for the additional Higgs at LHC, the DM relic density, XENON1T
FIG. 3: In the Case A, the surviving samples projected on the planes of $<\sigma v>_{SS\rightarrow b\bar{b}}$ versus $m_S$. The meanings of the inverted triangles (sky blue) and crosses (black) are the same as Fig. 2.

(2017), PandaX-II (2017), and the Fermi-LAT searches for DM annihilation from dSphs. The left panel shows that the signal data of the 125 GeV Higgs restrict tan $\beta$ to be in the range of $1 \sim 1.5$ for $m_h < 62$ GeV. For such range of $m_h$, the decay $H \rightarrow hh$ is kinematically open, and enhance the total width of the 125 GeV Higgs. Since the width of $H \rightarrow hh$ is strongly constrained, the searches for a light Higgs via $H \rightarrow hh$ channels at the LHC fail to impose constraints on the parameter space. The right panel shows that sin($\beta - \alpha$) is imposed a lower bound for a given value of $m_h$. This is because the $hZZ$ coupling is proportional to sin($\beta - \alpha$), and a large absolute value of sin($\beta - \alpha$) is excluded by the searches for a light Higgs via $e^+e^- \rightarrow Zh$ at the LEP.

The left panel of Fig. 4 shows that the $gg \rightarrow A \rightarrow hZ$ channels at the LHC impose lower bounds on tan $\beta$ for $53$ GeV $< m_h < 120$ GeV with $m_A$ being taken as 600 GeV, such as tan $\beta > 1.3$ for $m_h = 55$ GeV, tan $\beta > 2.3$ for $m_h = 70$ GeV, and tan $\beta > 2.7$ for $m_h = 110$ GeV. The $AhZ$ coupling is proportional to cos($\beta - \alpha$) and as a result the decay $A \rightarrow hZ$ is not suppressed by sin($\beta - \alpha$). However, the cross section of $gg \rightarrow A$ will sizably decrease with an increasing of tan $\beta$. The $b\bar{b} \rightarrow h \rightarrow \tau^+\tau^-$ channels impose upper limits on tan $\beta$, and tan $\beta > 10$ is excluded for both $m_h < 80$ GeV and $m_h > 90$ GeV. In the range of 80 GeV $< m_h < 90$ GeV, there is no available experimental data of $b\bar{b} \rightarrow h \rightarrow \tau^+\tau^-$ from the ATLAS and CMS.
FIG. 4: In the Case B, the surviving samples projected on the planes of $\tan \beta$ versus $m_h$ and $\sin(\beta - \alpha)$ versus $m_h$. All the samples are allowed by the constraints of "pre-LHC" and the signal data of the 125 GeV Higgs. The pluses (pink) and the triangles (royal blue) are respectively excluded by the $h \rightarrow \tau^+\tau^-$ and $A \rightarrow hZ$ channels at the LHC, and the other points are allowed by the two channels. The circles (red) are also allowed by the constraints of the relic density, XENON1T (2017), PandaX-II (2017) and the Fermi-LAT.

Fig. 4 shows that a narrow region of $m_h$ around 60 GeV and $m_A = 600$ GeV is excluded by the joint constraints of the 125 GeV Higgs signal data and the $gg \rightarrow A \rightarrow hZ$ channels at the LHC. In the other region of $m_h$, the DM with a mass of $10 \sim 50$ GeV is allowed by the constraints of the relic density, XENON1T (2017), PandaX-II (2017), and the Fermi-LAT searches for DM annihilation from dSphs. Certainly, the DM coupling with $h$ will play an important role.

In Fig. 5, we project the surviving samples on the planes of $\tan \beta$ versus $m_S$, $\lambda_h$ versus $m_S$, and $\frac{m_h}{2m_S}$ versus $m_S$. From Fig. 5, we find that for appropriate values of $\tan \beta$, $\lambda_h$ and $m_h$, the DM with a mass of $10 \sim 50$ GeV is allowed by the constraints of "pre-LHC", the signal data of the 125 GeV Higgs, the searches for the additional Higgs at LHC, the DM relic density, XENON1T (2017), PandaX-II (2017), and the Fermi-LAT. The right panel shows that the XENON1T (2017) and PandaX-II (2017) exclude the region of $\frac{m_h}{2m_S} > 1.125$ and $30$ GeV $< m_S < 50$ GeV. In such range, the kinetic energy of DM in the early universe can not offset the splitting of $m_h$ and $2m_S$, and the resonant condition in the DM pair-annihilation is not met. Therefore, a large $hSS$ coupling is required to obtain the correct relic density,
FIG. 5: In the Case B, the surviving samples projected on the planes of $\tan \beta$ versus $m_S$, $\lambda_h$ versus $m_S$, and $\frac{m_h}{2m_S}$ versus $m_S$. All the samples are allowed by the constraints of “pre-LHC”, the signal data of the 125 GeV Higgs, and the relic density. Also the crosses (black) are allowed by the XENON1T (2017) and PandaX-II (2017), and the circles (red) are allowed by the XENON1T (2017), PandaX-II (2017), and the Fermi-LAT.

and leads the spin-independent DM-nucleon cross section to exceed the upper limits of the XENON1T (2017) and PandaX-II (2017). Several points with $\frac{m_h}{2m_S}$ very close to 1.0 are allowed by the XENON1T (2017) and PandaX-II (2017), but excluded by the Fermi-LAT limits. This is because the resonant condition for the today DM pair-annihilation is also satisfied for $\frac{m_h}{2m_S}$ very close to 1.0. The left panel shows that $\tan \beta$ is restricted to be in the range of $1.0 \sim 1.5$ for $10 \text{ GeV} < m_s < 26 \text{ GeV}$. The middle panel shows that $| \lambda_h |$ is allowed to be as low as $10^{-5}$ due to the $h$ resonance contributions to the DM pair-annihilation.

In Fig. 6 we project the surviving samples on the planes of $Br(h \rightarrow SS)$ versus $m_h$ and $Br(h \rightarrow SS)$ versus $\frac{m_h}{2m_S}$. Fig. 6 shows that in the parameter space allowed by the XENON1T (2017), PandaX-II (2017), and the Fermi-LAT, $Br(h \rightarrow SS)$ is smaller than 3% for $m_S < 60 \text{ GeV}$ and smaller than 0.2% for $60 \text{ GeV} < m_S < 120 \text{ GeV}$. The current searches for the DM at the LHC do not impose the constraints on the parameter space.

V. CONCLUSION

The type-II 2HDM with a scalar DM provides a WIMP-DM candidate economically. Recent some studies do not find the parameter space of the DM with a mass below 50 GeV in the model. In this paper, we examine the DM with a mass below 50 GeV in the model.
after imposing the constraints from the Higgs searches at the LHC and the DM experiments.

We first discuss a general scenario in which both two CP-even Higgses ($h$ and $H$) are portals between the DM and SM sectors, and the CP-odd Higgs ($A$) and $H$ are heavier than 130 GeV. We find that the DM with a mass of $10 \sim 50$ GeV is disfavored by the joint constraints of the 125 GeV Higgs signal data, the relic density, XENON1T (2017), PandaX-II (2017) and the Fermi-LAT.

Next, we consider a special scenario in which the heavy CP-even Higgs is taken as the 125 GeV Higgs, and the light CP-even Higgs is the only portal between the DM and SM sectors. The DM mass is slightly below Higgs resonance, $m_h/2 = (1.0 \sim 1.2) \times m_S$. We find that the signal data of the 125 GeV Higgs restrict $\tan \beta$ to be in the range of $1 \sim 1.5$ for $m_h < 62$ GeV. The $gg \rightarrow A \rightarrow hZ$ channel at the LHC give the lower bounds on $\tan \beta$ for 53 GeV $< m_h < 120$ GeV and $m_A = 600$ GeV. The $b\bar{b} \rightarrow h \rightarrow \tau^+\tau^-$ channels impose the upper limits on $\tan \beta$, and $\tan \beta > 10$ is excluded for both $m_h < 80$ GeV and $m_h > 90$ GeV. For the appropriate values of $\tan \beta$, $\lambda_h$ and $m_h$, the DM with a mass of $10 \sim 50$ GeV is allowed by the constraints of ”pre-LHC”, the signal data of the 125 GeV Higgs, the searches for the additional Higgs at LHC, the DM relic density, XENON1T (2017), PandaX-II (2017), and the Fermi-LAT. For example, $\tan \beta$ is restricted to be in the range of $1.0 \sim 1.5$ for 10 GeV $< m_s < 26$ GeV, and $m_h/2m_S > 1.125$ is excluded for 30 GeV $< m_S < 50$ GeV.
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