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

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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 CP -even Higgses (h and H) are portals between the dark matter and standard model (SM) sectors, and the CP -odd Higgs (A) and H are heavier than 130 GeV. We find that the dark matter with a mass of 10–50 GeV is disfavored by the joint constraints of the 125 GeV Higgs signal data, the relic density, XENON1T (2018), and 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 dark matter and SM sectors, and the dark matter mass is slightly below the Higgs resonance. We find that the signal data of the 125 GeV Higgs restrict $\tan\beta$ to be in the range of 1–1.5 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 $\tan\beta$, λ_h , and m_h , the dark matter with a mass of 10–50 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 1.0–1.5 for $10 \text{ GeV} < m_s < 28 \text{ GeV}$, and $\frac{m_h}{2m_s} > 1.12$ is excluded for $30 \text{ GeV} < m_s < 50 \text{ GeV}$.

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I. INTRODUCTION

A weakly interacting massive particle (WIMP) is one of the most popular dark matter (DM) candidates. The simplest WIMP-DM model is the standard model (SM) plus a real singlet scalar as DM [1]. In the model, the current experiments exclude a DM mass up to 330 GeV, except for a small range near 63 GeV [2,3]. Much of the region 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 $H^\pm$.

The type-II 2HDM with a singlet scalar as DM has been widely explored [3,5–13]. Recently, the authors of Ref. [3] showed that in such a model, much of the DM mass region below 100 GeV is excluded if the heavy CP -even Higgs boson is the only portal between the DM and SM sectors. The authors of Ref. [12] took the 125 GeV Higgs with a wrong-sign Yukawa coupling of the down-type quark as the only portal, and found that the DM mass is allowed to be as low as 50 GeV for appropriate isospin-violating DM interactions with nucleons. Because of the tension between

the DM relic density and the invisible decay of the 125 GeV Higgs, a DM mass below 50 GeV is excluded. As the DM mass increases from 50 to 62.5 GeV, the width of the invisible decay becomes small due to phase-space suppression. Meanwhile DM pair annihilation approaches the resonant condition ($2m_{\text{DM}} \sim 125 \text{ GeV}$). As a result, the tension is automatically relaxed. In this paper, we manage to find some parameter spaces where DM with a mass below 50 GeV is allowed by the relic density and the invisible decay of the 125 GeV Higgs. Also we will consider joint constraints from theory, precision electroweak data, flavor observables, the signal data of the 125 GeV Higgs, the searches for the additional Higgses at LEP and the LHC, XENON1T (2018), and the Fermi-LAT searches for DM annihilation from dwarf spheroidal satellite galaxies (dSphs).

This paper is organized as follows. In Sec. II, we introduce some characteristic features of the type-II 2HDM with scalar DM. In Sec. III, we perform numerical calculations. In Sec. IV, we examine the allowed parameter space after imposing the relevant theoretical and experimental constraints. Finally, we draw our conclusions in Sec. V.

II. TYPE-II TWO-HIGGS-DOUBLET MODEL WITH SCALAR DARK MATTER

A. Type-II two-Higgs-doublet model

In the type-II 2HDM with scalar DM, the scalar potential includes two parts: $\mathcal{V}_{2\text{HDM}}$ and $\mathcal{V}_S$. They are respectively the potential of the type-II 2HDM and the potential of the

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DM sector. $\mathcal{V}_{2HDM}$ with a softly broken discrete Z_2 symmetry is given by [14]

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

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

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

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 states h and H , one neutral pseudo-scalar A , and two charged scalars $H^\pm$.

In the type-II 2HDM, the up-type fermions obtain masses from the Φ_2 field, and the down-type fermions from the Φ_1 field [15,16]. The Yukawa interactions are given by

$$-\mathcal{L} = Y_{u2}\bar{Q}_L\tilde{\Phi}_2u_R + Y_{d1}\bar{Q}_L\Phi_1d_R + Y_{\ell1}\bar{L}_L\Phi_1e_R + \text{H.c.}, \quad (3)$$

where $Q_L^T = (u_L, d_L)$, $L_L^T = (\nu_L, l_L)$, $\tilde{\Phi}_{1,2} = i\tau_2\Phi_{1,2}^*$, and Y_{u2} , Y_{d1} , and $Y_{\ell1}$ are 3×3 matrices in family space.

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

$$\begin{aligned} y_V^h &= \sin(\beta - \alpha), & y_f^h &= [\sin(\beta - \alpha) + \cos(\beta - \alpha)\kappa_f], \\ y_V^H &= \cos(\beta - \alpha), & y_f^H &= [\cos(\beta - \alpha) - \sin(\beta - \alpha)\kappa_f], \\ y_V^A &= 0, & y_f^A &= -i\kappa_f \text{ (for } u), & y_f^A &= i\kappa_f \text{ (for } d, \ell), \\ & \text{with } \kappa_d = \kappa_\ell \equiv -\tan\beta, & \kappa_u &\equiv 1/\tan\beta, \end{aligned} \quad (4)$$

where α is the mixing angle of the two CP -even Higgs bosons, and V denotes Z or W .

B. 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

$$\mathcal{V}_S = \frac{1}{2}S^2(\kappa_1\Phi_1^\dagger\Phi_1 + \kappa_2\Phi_2^\dagger\Phi_2) + \frac{m_0^2}{2}S^2 + \frac{\lambda_S}{4!}S^4. \quad (5)$$

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 since it does not acquire a VEV. We can obtain the DM mass and the cubic interactions with the neutral Higgses from Eq. (5),

$$\begin{aligned} m_S^2 &= m_0^2 + \frac{1}{2}\kappa_1v^2\cos^2\beta + \frac{1}{2}\kappa_2v^2\sin^2\beta, \\ -\lambda_hvS^2h/2 &\equiv -(-\kappa_1\sin\alpha\cos\beta + \kappa_2\cos\alpha\sin\beta)vS^2h/2, \\ -\lambda_HvS^2H/2 &\equiv -(\kappa_1\cos\alpha\cos\beta + \kappa_2\sin\alpha\sin\beta)vS^2H/2. \end{aligned} \quad (6)$$

III. NUMERICAL CALCULATIONS

A. Parameter space

In this paper, we discuss two different scenarios as follows.

Case A: The light CP -even Higgs boson h is taken as the 125 GeV Higgs, i.e., $m_h = 125 \text{ GeV}$, 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 the SM particles.

Case B: The heavy CP -even Higgs boson H is taken as the 125 GeV Higgs, i.e., $m_H = 125 \text{ GeV}$. The light CP -even Higgs h is the only portal between the DM and SM sectors. The DM mass is taken to be slightly below the Higgs resonance, $m_h/2 = (1.0-1.2) \times m_S$. In the calculation of the thermally averaged cross section, the kinetic energy of the DM is non-negligible in the early Universe. As a result, the resonant condition in DM pair annihilation can be met for m_S slightly smaller than $m_h/2$. The temperature at the present time is much lower than the freeze-out temperature, and the velocity of DM is much smaller than that in the early Universe. The resonant condition for present-day DM pair annihilation is hardly satisfied for m_S slightly smaller than $m_h/2$. Therefore, a very small coupling of the DM and the light Higgs is possible to obtain the correct relic density, and accommodate the limits of the direct and indirect detections of DM. The situation will become complicated if the 125 GeV Higgs mediates the interactions between the DM and SM sectors simultaneously. Certainly, the coupling of the DM and the 125 GeV Higgs is required to be small enough to satisfy the bound from the invisible decay of the 125 GeV Higgs. For simplicity, we assume that the 125 GeV Higgs has no coupling to DM in Case B, namely $\lambda_H = 0$.

B. Theoretical and experimental constraints

In our calculations, to implement the constraints from the Higgs searches at the LHC, we employ SUSHI [17] to compute the Higgs cross sections in gluon fusion and

$b\bar{b}$ -associated production at next-to-next-to-leading order (NNLO) in QCD. The results from SUSHi might not be reasonable for a small Higgs mass. In this paper, m_h is taken to be larger than 20 GeV, and the corresponding DM mass of Case B is larger than 10 GeV. The measurement of the branching fraction of $b \rightarrow s\gamma$ imposes the strongest limit on the charged Higgs mass of the type-II 2HDM, $m_{H^\pm} > 580$ GeV [18]. The S , T , and U oblique parameters give stringent constraints on the mass spectrum of Higgses of the type-II 2HDM [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 masses [19]. Therefore, to allow h to be light enough, we fix $m_A = 600$ GeV in Case B.

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

- (1) Theoretical constraints: The scalar potential of the model contains the potential of the type-II 2HDM and the potential of the DM sector. Vacuum stability, perturbativity, and tree-level unitarity impose constraints on the relevant parameters, which are discussed in detail in Refs. [3,9]. Here we employ the formulas from Refs. [3,9] to implement the theoretical constraints. Compared to Refs. [3,9], there are additional factors of $\frac{1}{2}$ in the κ_1 term and the κ_2 term of this paper.
- (2) The oblique parameters: The S , T , and U parameters can impose strong constraints on the mass spectrum of Higgses of 2HDM. 2HDMC [22] is employed to implement the constraints from the oblique parameters (S , T , U). The allowed values for these parameters are [23],

$$\begin{aligned} S &= -0.03 \pm 0.1, & T &= 0.01 \pm 0.12, \\ U &= 0.05 \pm 0.1. \end{aligned} \quad (7)$$

- (3) The flavor observables and R_b : SUPERISO-3.4 [24] is employed to calculate $\text{Br}(B \rightarrow X_s \gamma)$. Δm_{B_s} is calculated following the formulas in Ref. [25]. Besides, we perform the constraints of bottom quarks produced in Z decays, R_b , which is calculated using the formulas in Refs. [26,27]. The experimental data for $\text{Br}(B \rightarrow X_s \gamma)$ [28], Δm_s [28], and R_b [29] are given as

$$\begin{aligned} \text{Br}(B \rightarrow X_s \gamma) &= (3.32 \pm 0.16) \times 10^{-4}, \\ \Delta m_s &= 17.757 \pm 0.021 \text{ ps}^{-1}, \\ R_b &= 0.21474 \pm 0.00003. \end{aligned} \quad (8)$$

- (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 Case A, h is the 125 GeV Higgs, and the invisible decay $h \rightarrow SS$ is kinematically allowed,

TABLE I. Combined best-fit signal strengths $\hat{\mu}_{ggH+\tau H}(Y)$ and $\hat{\mu}_{VBF+VH}(Y)$, and a_Y , b_Y , and c_Y for the corresponding Higgs decay modes.

Y	$\hat{\mu}_{ggH+\tau H}(Y)$	$\hat{\mu}_{VBF+VH}(Y)$	a_Y	b_Y	c_Y
$\gamma\gamma$	1.16	1.05	18.29	4.43	6.60
ZZ^*	1.42	0.47	10.18	1.37	0.92
WW^*	0.98	1.38	24.54	3.69	7.11
$\tau\tau$	1.06	1.12	3.36	1.84	8.72
$b\bar{b}$	1.15	0.65	1.07	0.0	11.10

which will be strongly constrained by the experimental data of the 125 GeV Higgs. In Case B, H is the 125 GeV Higgs, and the invisible decay $H \rightarrow SS$ is absent since the HSS coupling is taken to be zero. However, the decay $H \rightarrow hh$ is kinematically allowed for $m_h < 62.5$ GeV. We perform the χ^2 calculation for the signal strengths of the 125 GeV Higgs in the $\mu_{ggF+\tau H}(Y)$ and $\mu_{VBF+VH}(Y)$ channels with Y denoting the decay modes $\gamma\gamma$, ZZ , WW , $\tau^+\tau^-$, and $b\bar{b}$,

$$\begin{aligned} \chi^2(Y) &= \begin{pmatrix} \mu_{ggH+\tau H}(Y) - \hat{\mu}_{ggH+\tau H}(Y) \\ \mu_{VBF+VH}(Y) - \hat{\mu}_{VBF+VH}(Y) \end{pmatrix}^T \begin{pmatrix} a_Y & b_Y \\ b_Y & c_Y \end{pmatrix} \\ &\times \begin{pmatrix} \mu_{ggH+\tau H}(Y) - \hat{\mu}_{ggH+\tau H}(Y) \\ \mu_{VBF+VH}(Y) - \hat{\mu}_{VBF+VH}(Y) \end{pmatrix}. \end{aligned} \quad (9)$$

$\hat{\mu}_{ggH+\tau H}(Y)$ and $\hat{\mu}_{VBF+VH}(Y)$ are the 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 [30]. These values are listed in Table I.

We pay particular attention to the surviving samples with $\chi^2 - \chi^2_{\min} \leq 6.18$, where $\chi^2_{\min}$ denotes the minimum of χ^2 . These samples correspond to the 2σ range in any two-dimensional plane of the model parameters when explaining the Higgs data.

In addition, ATLAS and CMS reported upper limits on the branching ratio of the invisible decay of the 125 GeV Higgs. In our calculation we impose the constraints, $\text{Br}(h \rightarrow SS) < 0.34$ [30].

- (5) The nonobservation of additional Higgs bosons: We employ HIGGSBOUNDS [31,32] to implement the exclusion constraints from the searches for the neutral and charged Higgses at LEP at the 95% confidence level. Especially for Case B, the searches for a light Higgs at LEP can impose stringent constraints on the parameter space.

At the LHC, 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 the type-II 2HDM, the contributions of the b -quark loop interfere destructively with those of the top-quark loop. The cross section decreases with an increase of $\tan\beta$, reaches a minimum value for a moderate value of $\tan\beta$, and is dominated by

TABLE II. 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 ϕ' and A searches at the LHC. Here ϕ' denotes the non-SM-like CP -even Higgs in the 2HDM.

Channel	Experiment	Mass range [GeV]	Luminosity
$gg/b\bar{b} \rightarrow \phi'/A \rightarrow \tau^+\tau^-$	ATLAS 8 TeV [44]	90–1000	19.5–20.3 fb $^{-1}$
$gg/b\bar{b} \rightarrow \phi'/A \rightarrow \tau^+\tau^-$	CMS 8 TeV [45]	90–1000	19.7 fb $^{-1}$
$gg/b\bar{b} \rightarrow \phi'/A \rightarrow \tau^+\tau^-$	ATLAS 13 TeV [46]	200–1200	13.3 fb $^{-1}$
$gg/b\bar{b} \rightarrow \phi'/A \rightarrow \tau^+\tau^-$	CMS 13 TeV [47]	90–3200	12.9 fb $^{-1}$
$gg \rightarrow \phi'/A \rightarrow \tau^+\tau^-$	CMS 13 TeV [48]	200–2250	36.1 fb $^{-1}$
$b\bar{b} \rightarrow \phi'/A \rightarrow \tau^+\tau^-$	CMS 13 TeV [48]	200–2250	36.1 fb $^{-1}$
$b\bar{b} \rightarrow \phi'/A \rightarrow \tau^+\tau^-$	CMS 8 TeV [49]	20–80	19.7 fb $^{-1}$
$b\bar{b} \rightarrow \phi'/A \rightarrow \mu^+\mu^-$	CMS 8 TeV [50]	25–60	19.7 fb $^{-1}$
$pp \rightarrow \phi'/A \rightarrow \gamma\gamma$	ATLAS 13 TeV [51]	200–2400	15.4 fb $^{-1}$
$gg \rightarrow \phi'/A \rightarrow \gamma\gamma$	CMS 8 + 13 TeV [52]	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 [53]	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 [53]	70–110	35.9 fb $^{-1}$
$VV \rightarrow \phi' \rightarrow \gamma\gamma + V\phi'(\phi' \rightarrow \gamma\gamma)$	CMS 8 TeV [53]	80–110	19.7 fb $^{-1}$
$VV \rightarrow \phi' \rightarrow \gamma\gamma + V\phi'(\phi' \rightarrow \gamma\gamma)$	CMS 13 TeV [53]	70–110	35.9 fb $^{-1}$
$gg/VV \rightarrow \phi' \rightarrow W^+W^-$	ATLAS 8 TeV [54]	300–1500	20.3 fb $^{-1}$
$gg/VV \rightarrow \phi' \rightarrow W^+W^-(\ell\nu\ell\nu)$	ATLAS 13 TeV [55]	300–3000	13.2 fb $^{-1}$
$gg \rightarrow \phi' \rightarrow W^+W^-(\ell\nu qq)$	ATLAS 13 TeV [56]	500–3000	13.2 fb $^{-1}$
$gg/VV \rightarrow \phi' \rightarrow W^+W^-(\ell\nu qq)$	ATLAS 13 TeV [57]	200–3000	36.1 fb $^{-1}$
$gg/VV \rightarrow \phi' \rightarrow W^+W^-(e\nu\mu\nu)$	ATLAS 13 TeV [58]	200–3000	36.1 fb $^{-1}$
$gg/VV \rightarrow \phi' \rightarrow ZZ$	ATLAS 8 TeV [59]	160–1000	20.3 fb $^{-1}$
$gg \rightarrow \phi' \rightarrow ZZ(\ell\ell\nu\nu)$	ATLAS 13 TeV [60]	300–1000	13.3 fb $^{-1}$
$gg \rightarrow \phi' \rightarrow ZZ(\nu\nu qq)$	ATLAS 13 TeV [61]	300–3000	13.2 fb $^{-1}$
$gg/VV \rightarrow \phi' \rightarrow ZZ(\ell\ell qq)$	ATLAS 13 TeV [61]	300–3000	13.2 fb $^{-1}$
$gg/VV \rightarrow \phi' \rightarrow ZZ(\ell\ell\ell\ell)$	ATLAS 13 TeV [62]	200–3000	14.8 fb $^{-1}$
$gg/VV \rightarrow \phi' \rightarrow ZZ(\ell\ell\ell\ell + \ell\ell\nu\nu)$	ATLAS 13 TeV [63]	200–2000	36.1 fb $^{-1}$
$gg/VV \rightarrow \phi' \rightarrow ZZ(\nu\nu qq + \ell\ell qq)$	ATLAS 13 TeV [64]	300–5000	36.1 fb $^{-1}$

the b -quark loop for a large enough value of $\tan\beta$. The cross section of the CP -even Higgs in gluon fusion depends on $\sin(\beta - \alpha)$ in addition to the Higgs mass and $\tan\beta$. We use SUSHi [17] to compute the Higgs cross sections in gluon fusion and $b\bar{b}$ -associated production at NNLO in QCD. A complete list of the searches for additional Higgses considered by us is summarized in Table II and Table III where some channels are taken from Ref. [33]. References [34,35] showed that the LHC searches for the charged Higgs fail to constrain the model for $m_{H^\pm} > 500$ GeV. Therefore, the search channels for the charged Higgs are not included in this paper.

- (6) The DM observables: We use MICROMEGAS [36] to calculate the relic density and present-day DM pair annihilation. The model file is generated using FEYNRULES [37]. For $10 \text{ GeV} < m_S < 50 \text{ GeV}$, the DM will annihilate into $b\bar{b}$ dominantly in this model.

In this model, the elastic scattering of S on a nucleon receives contributions from the process with t -channel exchange of h and H in Case A, and only h exchange in Case B. If both h and H contribute to the DM interactions with nucleons, the spin-independent cross section is given by [38]

$$\sigma_{p(n)} = \frac{\mu_{p(n)}^2}{4\pi m_S^2} [f^{p(n)}]^2, \quad (10)$$

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

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

with $C_{Sq} = \frac{\lambda_h}{m_h^2} m_q y_q^h + \frac{\lambda_H}{m_H^2} m_q y_q^H$. The values of the form factors $f_q^{p,n}$ and $f_g^{p,n}$ are extracted using MICROMEGAS [36].

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

Channel	Experiment	Mass range [GeV]	Luminosity
$gg \rightarrow \varphi' \rightarrow \varphi_s \varphi_s \rightarrow (\gamma\gamma)(b\bar{b})$	CMS 8 TeV [65]	250–1100	19.7 fb ⁻¹
$gg \rightarrow \varphi' \rightarrow \varphi_s \varphi_s \rightarrow (b\bar{b})(b\bar{b})$	CMS 8 TeV [66]	270–1100	17.9 fb ⁻¹
$gg \rightarrow \varphi' \rightarrow \varphi_s \varphi_s \rightarrow (b\bar{b})(\tau^+\tau^-)$	CMS 8 TeV [67]	260–350	19.7 fb ⁻¹
$gg \rightarrow \varphi' \rightarrow \varphi_s \varphi_s \rightarrow (\gamma\gamma)(b\bar{b})$	ATLAS 13 TeV [68]	275–400	3.2 fb ⁻¹
$gg \rightarrow \varphi' \rightarrow \varphi_s \varphi_s \rightarrow (\gamma\gamma)(b\bar{b})$	CMS 13 TeV [69]	250–900	2.7 fb ⁻¹
$gg \rightarrow \varphi' \rightarrow \varphi_s \varphi_s \rightarrow b\bar{b}b\bar{b}$	ATLAS 13 TeV [70]	300–3000	13.3 fb ⁻¹
$gg \rightarrow \varphi' \rightarrow \varphi_s \varphi_s \rightarrow (b\bar{b})(\tau^+\tau^-)$	CMS 13 TeV [71]	250–900	12.9 fb ⁻¹
$gg \rightarrow \varphi' \rightarrow \varphi_s \varphi_s \rightarrow b\bar{b}b\bar{b}$	CMS 13 TeV [72]	750–3000	35.9 fb ⁻¹
$gg \rightarrow \varphi' \rightarrow \varphi_s \varphi_s \rightarrow (b\bar{b})(\tau^+\tau^-)$	CMS 13 TeV [73]	250–900	35.9 fb ⁻¹
$gg \rightarrow \varphi' \rightarrow \varphi_s \varphi_s \rightarrow (WW^*)(\gamma\gamma)$	ATLAS 13 TeV [73]	260–500	13.3 fb ⁻¹
$gg \rightarrow A \rightarrow \varphi_s Z \rightarrow (\tau^+\tau^-)(\ell\ell)$	CMS 8 TeV [67]	220–350	19.7 fb ⁻¹
$gg \rightarrow A \rightarrow \varphi_s Z \rightarrow (b\bar{b})(\ell\ell)$	CMS 8 TeV [74]	225–600	19.7 fb ⁻¹
$gg \rightarrow A \rightarrow \varphi_s Z \rightarrow (\tau^+\tau^-)Z$	ATLAS 8 TeV [75]	220–1000	20.3 fb ⁻¹
$gg \rightarrow A \rightarrow \varphi_s Z \rightarrow (b\bar{b})Z$	ATLAS 8 TeV [75]	220–1000	20.3 fb ⁻¹
$gg/b\bar{b} \rightarrow A \rightarrow \varphi_s Z \rightarrow (b\bar{b})Z$	ATLAS 13 TeV [76]	200–2000	3.2 fb ⁻¹
$gg/b\bar{b} \rightarrow A \rightarrow \varphi_s Z \rightarrow (b\bar{b})Z$	ATLAS 13 TeV [77]	200–2000	36.1 fb ⁻¹
$gg \rightarrow \varphi_s \rightarrow AA/\varphi'\varphi' \rightarrow \tau^+\tau^-\tau^+\tau^-$	ATLAS 8 TeV [78]	4–50	20.3 fb ⁻¹
$pp \rightarrow \varphi_s \rightarrow AA/\varphi'\varphi' \rightarrow \tau^+\tau^-\tau^+\tau^-$	CMS 8 TeV [79]	5–15	19.7 fb ⁻¹
$pp \rightarrow \varphi_s \rightarrow AA/\varphi'\varphi' \rightarrow (\mu^+\mu^-)(b\bar{b})$	CMS 8 TeV [79]	25–62.5	19.7 fb ⁻¹
$pp \rightarrow \varphi_s \rightarrow AA/\varphi'\varphi' \rightarrow (\mu^+\mu^-)(\tau^+\tau^-)$	CMS 8 TeV [79]	15–62.5	19.7 fb ⁻¹
$gg \rightarrow A(\varphi') \rightarrow \varphi'(A)Z \rightarrow (b\bar{b})(\ell\ell)$	CMS 8 TeV [80]	40–1000	19.8 fb ⁻¹
$gg \rightarrow A(\varphi') \rightarrow \varphi'(A)Z \rightarrow (\tau^+\tau^-)(\ell\ell)$	CMS 8 TeV [80]	20–1000	19.8 fb ⁻¹

The Planck Collaboration reported the relic density of cold DM in the Universe, $\Omega_c h^2 = 0.1198 \pm 0.0015$ [39]. The PandaX-II experiment (2017) imposed stronger constraints on the spin-independent DM-nucleon cross section than XENON (2017) for $m_S > 100$ GeV [40,41]. In May of this year, the XENON Collaboration released an updated bound which increases current constraints on the cross section by a factor of ~ 7 for small DM mass and ~ 2 for large DM mass [42]. For $m_S < 50$ GeV, the bounds of XENON1T (2018) are much stronger than those of PandaX-II (2017). The Fermi-LAT searches for DM annihilation from dSphs gave the upper limits on the averaged cross sections of DM annihilation to e^+e^- , $\mu^+\mu^-$, $\tau^+\tau^-$, $u\bar{u}$, $b\bar{b}$, and WW [43]*.

IV. RESULTS AND DISCUSSIONS

A. Case A

In Fig. 1, we show λ_H and λ_h in Case A allowed by theoretical constraints, the oblique parameters, the signal data of the 125 GeV Higgs, flavor observables, R_b , and the exclusion limits from searches for Higgs at LEP. The left

panel shows that vacuum stability, perturbativity, unitarity, and the oblique parameters impose upper and lower limits on λ_H , $-5 < \lambda_H < 7$. Because the invisible decay $h \rightarrow SS$ 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. However, the renormalization group analysis shows that the size of λ_H increases with energy, and so it eventually meets a Landau pole at a higher energy scale, if λ_H is too large at low energy [81]. Since this paper deals with the early Universe at high energy, we limit $|\lambda_H|$ to be smaller than 1.0 in the following discussions.

In Fig. 2, we project the surviving samples on the planes of $\tan\beta$ versus m_H and λ_H versus m_H after imposing the “pre-LHC” constraints (denoting theory, the oblique parameters, 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, and XENON1T (2018). Because the signal data of the 125 GeV Higgs impose 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 650 GeV. With an increase of m_H , λ_H and $\tan\beta$ are favored to have large values, which can enhance the couplings of HSS and $Hb\bar{b}$.

FIG. 1. In Case A, the surviving samples projected on the planes of λ_H versus λ_h and λ_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.

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 spaces are excluded by XENON1T (2018), and only the narrow regions of $M_H < 240$ GeV and $\tan\beta$ around 1.0 are allowed. For $\tan\beta$ around 1.0 and $|\sin(\beta - \alpha)|$ close to 1.0, y_d^H/y_u^H approaches -1.0 . For such a case, the DM interactions with nucleons mediated by H can have a large isospin violation, which may significantly weaken the

bounds from XENON1T. Because $\tan\beta$ is restricted to be around 1.0, an appropriate value of λ_H is required to obtain the correct relic density. For example, for the samples allowed by XENON1T (2018) in the right panel, $|\lambda_H|$ approaches 1.0 for m_H around 240 GeV.

Figure 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 XENON1T (2018) bounds. As m_S decreases, the values of present-day DM pair annihilation

FIG. 2. In Case A, the surviving samples projected on the planes of $\tan\beta$ versus m_H and λ_H versus m_H . All the samples are allowed by the “pre-LHC” constraints 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 and the XENON1T (2018).

FIG. 3. The surviving samples projected on the planes of $\langle\sigma v\rangle_{ss \rightarrow b\bar{b}}$ versus m_s in Case A. The meanings of the inverted triangles (sky blue) and crosses (black) are the same as in Fig. 2.

into $b\bar{b}$ in this model significantly exceed the Fermi-LAT upper limits.

B. Case B

Now we discuss 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 “pre-LHC”

constraints, the signal data of the 125 GeV Higgs, the searches for the additional Higgses at the LHC, the DM relic density, XENON1T (2018), 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 1–1.5 for $m_h < 62$ GeV. For such a range of m_h , the decay $H \rightarrow hh$ is kinematically open, and enhances the total width of the 125 GeV Higgs. The width of $H \rightarrow hh$ is strongly constrained by the global fit to the signal data of the 125 GeV Higgs, which easily satisfies the searches for a light Higgs via $H \rightarrow hh$ channels at the LHC. The right panel shows that $\sin(\beta - \alpha)$ imposes 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 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 $53 \text{ GeV} < m_h < 120 \text{ GeV}$ with m_A being taken as 600 GeV, such as $\tan\beta > 1.3$ for $m_h = 55 \text{ GeV}$, $\tan\beta > 2.3$ for $m_h = 70 \text{ GeV}$, and $\tan\beta > 2.7$ for $m_h = 110 \text{ GeV}$. The AhZ coupling is proportional to $\cos(\beta - \alpha)$ and not suppressed by $\sin(\beta - \alpha)$. However, the cross section of $gg \rightarrow A$ will sizably decrease with an increase 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 $m_h < 80 \text{ GeV}$ and $m_h > 90 \text{ GeV}$. In the range of $80 \text{ GeV} < m_h < 90 \text{ GeV}$, there is no available experimental data for $b\bar{b} \rightarrow h \rightarrow \tau^+\tau^-$ from ATLAS and CMS.

Figure 4 shows that a narrow region of m_h around 60 GeV and $m_A = 600 \text{ GeV}$ is excluded by the joint constraints of the 125 GeV Higgs signal data and the

FIG. 4. The surviving samples projected on the planes of $\tan\beta$ versus m_h and $\sin(\beta - \alpha)$ versus m_h in Case B. 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 from the relic density, XENON1T (2018), and Fermi-LAT.

FIG. 5. The surviving samples projected on the planes of $\tan\beta$ versus m_S , λ_h versus m_S , and $\frac{m_h}{2m_S}$ versus m_S in Case B. All the samples are allowed by the “pre-LHC” constraints, the signal data of the 125 GeV Higgs, and the relic density. Also the crosses (black) are allowed by XENON1T (2018), and the circles (red) are allowed by XENON1T (2018) and Fermi-LAT.

$gg \rightarrow A \rightarrow hZ$ channels at the LHC. In the other region of m_h , DM with a mass of 10–50 GeV is allowed by the constraints of the relic density, XENON1T (2018), and the Fermi-LAT searches for DM annihilation from dSphs. Certainly, the DM coupling with h plays an important role.

In Fig. 5, we project the surviving samples on the planes of $\tan\beta$ versus m_S , λ_h versus m_S , and $\frac{m_h}{2m_S}$ versus m_S . From Fig. 5, we find that for appropriate values of $\tan\beta$, λ_h , and m_h , DM with a mass of 10–50 GeV is allowed by the “pre-LHC” constraints, the signal data of the 125 GeV Higgs, the searches for the additional Higgses at the LHC, the DM relic density, XENON1T (2018), and Fermi-LAT. The right panel shows that XENON1T (2018) excludes the region of $\frac{m_h}{2m_S} > 1.12$ and $30 \text{ GeV} < m_S < 50 \text{ GeV}$. In such ranges, the kinetic energy of DM in the early Universe cannot 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, which causes the spin-independent DM-nucleon cross section to exceed the upper limits of XENON1T (2018). Several points with $\frac{m_h}{2m_S}$ very close to 1.0 are allowed by XENON1T (2018), but excluded by the Fermi-LAT limits. This is because the resonant condition for present-day 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 1.0–1.5 for $10 \text{ GeV} < m_S < 28 \text{ GeV}$. The middle panel shows that $|\lambda_h|$ is allowed to be as low as 10^{-5} because of the h resonance contributions to DM pair annihilation.

In Fig. 6, we project the surviving samples on the planes of $\text{Br}(h \rightarrow SS)$ versus m_h and $\text{Br}(h \rightarrow SS)$ versus $\frac{m_h}{2m_S}$. Figure 6 shows that in the parameter space allowed by

FIG. 6. Same as Fig. 5, but projected on the planes of $\text{Br}(h \rightarrow SS)$ versus m_h and $\text{Br}(h \rightarrow SS)$ versus $\frac{m_h}{2m_S}$.

TABLE IV. The ranges of m_S and several corresponding key parameters surviving all bounds with $\lambda_H = 0$.

m_S	$\tan\beta$	$ \lambda_h $	$m_h/2m_S$
10–28 GeV	1.0–1.5	2×10^{-5} – 2×10^{-3}	1.004–1.175
28–39 GeV	1.7–10	7×10^{-5} – 1.5×10^{-3}	1.01–1.11
39–44 GeV	2.3–20	1×10^{-4} – 2×10^{-3}	1.01–1.113
44–50 GeV	2.3–11	1×10^{-4} – 2.6×10^{-3}	1.004–1.113

XENON1T (2018) and Fermi-LAT, $\text{Br}(h \rightarrow S\bar{S})$ is smaller than 2% for $m_h < 60$ GeV and smaller than 0.1% for $60 \text{ GeV} < m_h < 120$ GeV. The current searches for DM at the LHC do not impose constraints on the parameter space.

As we discussed above, DM with a mass below 50 GeV is excluded in all parameter spaces of Case A, and allowed in some parameter spaces of Case B. In Table IV, we simply summarize the ranges of m_S and several corresponding key parameters surviving all bounds.

V. CONCLUSION

The type-II 2HDM with scalar DM provides a WIMP-DM candidate economically. Some recent studies did not find the parameter space where DM with a mass below 50 GeV is allowed by the constraints from the Higgs searches at the LHC and DM experiments. In this paper, we examined DM with a mass below 50 GeV in the model after imposing the theoretical and experimental constraints.

We first discussed a general scenario in which both 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 found that DM with a mass of 10–50 GeV is disfavored by the joint constraints of the 125 GeV Higgs signal data, the relic density, XENON1T (2018), and Fermi-LAT.

Next, we considered 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 the Higgs resonance, $m_h/2 = (1.0 \sim 1.2) \times m_S$. We found that the signal data of the 125 GeV Higgs restrict $\tan\beta$ to be in the range of 1–1.5 for $m_h < 62$ GeV. The $gg \rightarrow A \rightarrow hZ$ channels at the LHC give lower bounds on $\tan\beta$ for $53 \text{ GeV} < m_h < 120$ GeV and $m_A = 600$ GeV. 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. For appropriate values of $\tan\beta$, λ_h , and m_h , DM with a mass of 10–50 GeV is allowed by the “pre-LHC” constraints, the signal data of the 125 GeV Higgs, the searches for the additional Higgses at the LHC, the DM relic density, XENON1T (2018), and Fermi-LAT. For example, $\tan\beta$ is restricted to be in the range of 1.0–1.5 for $10 \text{ GeV} < m_S < 28$ GeV, and $\frac{m_h}{2m_S} > 1.12$ is excluded for $30 \text{ GeV} < m_S < 50$ GeV.

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