We explore the parameter space of the singlet fermionic cold dark matter model with respect to constraints on, first, the relic density and second, gamma-ray lines up to 10 TeV. We compare our result with the latest experimental data from H.E.S.S., and show that except for the resonance regions, the parameter space of this model is not excluded.

Keywords: Dark matter; Gamma ray lines; indirect detection

I. INTRODUCTION

It is confirmed that more than 95% of the universe content is dark; about 70% dark energy, 25% dark matter (DM) and only about 5% is visible (baryonic). During recent decades, several models, beyond the Standard Model (SM) of particle physics, have been proposed to explain this puzzling dark part of the universe. The most important candidates for cold DM (CDM) are weakly interacting massive particles (WIMPs) which can resolve some related cosmological and astrophysical problems. The other important candidates are Axions and MACHOs. Although we cannot detect DM as a signal in a collider, because of its negligible interactions with SM particles, direct and indirect searches are still possible. The experiments of direct detection search for observing the recoil energy of atomic nuclei interacting with DM particles passing through the earth. Indirect detection efforts, however, search for possible visible products of decay or annihilation of DM. Gamma-rays are one of the final products which some experiments, such as Fermi-LAT, VERITAS and H.E.S.S., can measure their excess as an indirect detection of DM. In addition to direct and indirect detection bounds, there is an important bound on observed relic density of DM. Indeed, the present relic abundance of CDM, \( \Omega_{\text{CDM}} h^2 \), is \( 0.1123 \pm 0.0035 \) \([1]\) where \( h \approx 0.7 \) is the scaled Hubble constant in the units of 100 km/sec/Mpc.

Various scalar WIMPs have been widely considered in the literature (see for example \([2,4]\)). The situation is the same for fermionic DM (see for instance \([5,7]\) and SUSY DM \([8]\). Singlet fermionic cold dark matter (SFCDM) model is also one of an interesting model which consider a simple extension of the SM to a hidden sector where the fermionic DM can interact with the SM sector through Higgs portal with a typical coupling \( g_s \) \([9]\). Therefore, there are two Higgs bosons in this model that one of them must play the role of the SM Higgs with 125 GeV mass according to 2012 ATLAS and CMS reports \([10,11]\). Fixing the other Higgs mass to 750 GeV, in ref \([12]\) we study SFCDM parameter space confronting with recent direct detection data. As an important conclusion, this model was completely excluded by recent XENON100 \([13]\), PandaX II \([14]\) and LUX \([15]\) data. In the other work \([16]\), for DM masses below 200 GeV we analyze SFCDM annihilation to two photons comparing with 2010 Fermi-LAT \([17]\) data, the approximate cross section was used there and some couplings were fixed.

On the other hand, the existence of the other Higgs with the mass below 1 TeV has not yet been confirmed by LHC. Here we study two different sorts of model by fixing the mass of second Higgs to 1 and 2.5 TeV. We reconsider this model by calculating the cross section of annihilation of DM particles into monochromatic gamma-ray lines. We allow the mass of singlet fermion be in the range 200 MeV-10 TeV. The latest experimental data reported by H.E.S.S. is used for constraining the parameter space.

There are some issues here to which we should pay more attention. First, this analysis is done up to 10 TeV of the DM mass for the first time for this model. Second, for implementing the relic density constraint, we calculate the leading order of complete cross section of DM annihilation into SM final products within the perturbation theory. Therefore, it is important for us that \( g_s \) remains properly less than one. Third, in ref. \([18]\) by investigating the available parameter space for diphoton data in the combined LHC run-1 and run-2, authors show that for the second Higgs mass equal to 750 GeV, if it exists, the mixing angle between two Higgs bosons, \( \theta \), should be less than 0.01. It is reasonable that for heavier Higgs this constraint becomes stronger. Therefore, we perform our analysis in two parts: for \( \theta < 0.01 \) and \( \theta > 0.01 \). In addition, we investigate two different masses for the second Higgs: 1 TeV and 2.5 TeV. In each case, to cover the whole of parameter space, we investigate 44000 random sample models; 22000 models for
The letter is organized as follows: In the next section we briefly introduce the model of SFCDM. Section III is devoted to explore the parameter space allowed by the relic density condition. In section IV, using annihilation cross section of SFCDM into two photons, we perform numerical calculations on thermally-averaged velocity-weighted of this cross section and compare the results with recent experimental data. In the last section we conclude our results.

II. THE MODEL

We start with the following renormalizable Lagrangian [5]:

\[ \mathcal{L}_{\text{SFCDM}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{hid}} + \mathcal{L}_{\text{int}}, \]  

(1)

where \( \mathcal{L}_{\text{SM}} \) is the SM Lagrangian, \( \mathcal{L}_{\text{hid}} \) denotes the hidden sector Lagrangian which includes DM and \( \mathcal{L}_{\text{int}} \) is for interaction between these two sectors. With the following definitions, this Lagrangian describe the most minimal renormalizable extension of the SM which includes a singlet fermion field, \( \psi \), as CDM:

\[ \mathcal{L}_{\text{hid}} = \mathcal{L}_\psi + \mathcal{L}_S - g_s \bar{\psi} \psi S, \]

(2)

\[ \mathcal{L}_{\text{int}} = -\lambda_1 H^\dagger HS - \lambda_2 H^\dagger HS^2, \]

(3)

with

\[ \mathcal{L}_\psi = \bar{\psi}(i \partial - m_{\psi_0})\psi, \]

(4)

\[ \mathcal{L}_S = \frac{1}{2} (\partial\mu S)(\partial^\mu S) - \frac{m_0^2}{2} S^2 - \frac{\lambda_3}{3!} S^3 - \frac{\lambda_4}{4!} S^4. \]

(5)

where a singlet Higgs \( S \), in addition to the usual Higgs doublet \( H \), is used as a mediator between SFCDM and the SM particles. Respecting the relic abundance condition, singlet fermion should have a very weak interaction with the SM particles. After spontaneous symmetry breaking we have

\[ H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ h + v_0 \end{pmatrix}, \]

(6)

and

\[ S = s + x_0, \]

(7)

where \( v_0 \) and \( x_0 \) are the vacuum expectation values (VEVs) of the SM Higgs and singlet Higgs, respectively. Therefore, the fields \( h \) and \( s \) are naturally the fluctuations around the VEVs. Diagonalizing the mass matrix as follows gives the mass eigenstates:

\[ h_1 = \sin \theta s + \cos \theta h, \]

\[ h_2 = \cos \theta s - \sin \theta h. \]

(8)

The mixing angle \( \theta \) can be written in terms of the parameters in the Lagrangian [1]. The maximal mixing occurs at \( \theta = \pi/4 \), so that we can think \( h_1 \) as the SM Higgs-like scalar, and \( h_2 \) as the singlet-like one. After symmetry breaking, the mass of the singlet fermion becomes \( m_\psi = m_{\psi_0} + g_S x_0 \), which is an independent parameter in the model. The VEV of our singlet Higgs, \( x_0 \), is completely determined by minimization of the total potential. The SM Higgs mass is fixed to 125.01 GeV according to the 2012 ATLAS [10] and CMS [11] reports. Therefore, we encounter seven independent parameters, in addition to the SM ones, in this model: \( m_\psi, g_S \), second Higgs mass \( m_{h_2}, \lambda_1, \lambda_2, \lambda_3, \lambda_4 \).
### III. THE RELIC DENSITY

In the early universe when the interaction rate of a particle species drops below the expansion rate of the universe, it gets out of the equilibrium and its density number in the comoving volume does not change. This is called the ‘freeze-out’ mechanism. A WIMP can be thermally produced through a ‘freeze-out’ mechanism. A singlet fermion pair, $\bar{\psi}\psi$, can annihilation into the SM fermions, the gauge bosons and the Higgs bosons. The Boltzmann equation gives the evolution of the density number $n_\psi$ of a singlet fermion:

$$\frac{dn_\psi}{dt} + 3H n_\psi = - \langle \sigma_{\text{ann}}v \rangle \left[ n_\psi^2 - (n_{\text{eq}}^0)^2 \right],$$

(9)

where $H$ is the Hubble constant, $\langle \sigma_{\text{ann}}v \rangle$ is the thermal average of the annihilation cross section times the relative velocity, and $n_{\text{eq}}^0$ is the equilibrium density number of $\psi$. As the expansion rate of the universe exceeds the interaction rate of our WIMPs, this species falls out of equilibrium. Now its relic density $\Omega_\psi h^2$ which is defined as the ratio of the present and critical densities, is written roughly as follows:

$$\Omega_\psi h^2 \approx (1.07 \times 10^9)x_F \sqrt{g^*} M_{\text{Pl}} \langle \sigma_{\text{ann}}v \rangle,$$

(10)

where $x_F = m/T_F$ is the inverse freeze-out temperature determined by the following iterative equation:

$$x_F = \ln \left( \frac{m_\psi^2 \pi^2}{3} \sqrt{\frac{45}{45}} M_{\text{Pl}}^2 g^* \langle \sigma_{\text{ann}}v \rangle \right),$$

(11)

and $g_*$ denotes the effective degrees of freedom for the relativistic quantities in equilibrium [20]. The thermally averaged annihilation cross section times the relative velocity, $\langle \sigma_{\text{ann}}v \rangle$ is

$$\langle \sigma_{\text{ann}}v \rangle = \frac{1}{8m_\psi^4 T K_2^2 \left( \frac{m_\psi}{T} \right)} \int_4m_\psi^2 ds \sigma_{\text{ann}}(s) \left( s - 4m_\psi^2 \right) \sqrt{s} K_1 \left( \frac{\sqrt{s}}{T} \right),$$

(12)

where $K_{1,2}(x)$ are the modified Bessel functions [21]. The cross section for annihilation of a singlet fermion pair into SM final states and Higgs bosons, $\sigma_{\text{ann}}$, was reported in ref. [22]. Figure 1 shows the tree level Feynman diagrams for this cross section. The observed relic abundance of CDM is $0.1123 \pm 0.0035$ [1]. For two different values of
$m_{h_2} = 1 \text{ TeV}$ and $2.5 \text{ TeV}$, we investigate 44000 sample models randomly to cover the parameter space. Each of these two sets includes two parts corresponding to the mixing angle values $\theta < 0.01$ and $\theta > 0.01$. Satisfying the relic density constraint we derive the relative coupling $g_s$. The results are shown in fig. 2 Since we work at tree level in perturbation theory, all couplings should be less than one. Therefore, the values of $g_s > 1$ in fig. 2 destroy the perturbation expansion.

IV. ANNIHILATION TO PHOTON PAIR

The annihilation of a pair of SFCDM into a pair of photon, at leading order, occurs by a Higgs particle through $s$-channel. Although the photon is massless and cannot couple to the Higgs, the $H \gamma \gamma$ vertex can be generated with loops involving massive particles. The leading order Feynman diagrams for this process is shown in fig. 3. The cross
section is written as follows:

\[
\sigma v_{\gamma \gamma} = \frac{1}{8 \pi s} \frac{1}{4} \sum_{\text{spins}} |M_{\psi \psi \to \gamma \gamma}|^2, 
\]

(13)

where $\sqrt{s}$ is the energy in the center of mass frame, and

\[
M_{\psi \psi \to \gamma \gamma} = \sum_{j=1,2} \bar{v}(p) i g_s s_j u(p) \frac{i}{s - m_{H_j}^2 - i m_{H_j} \Gamma_j} M_{H_j \to \gamma \gamma},
\]

(14)

where $s_1$ and $s_2$ denote $\sin \theta$ and $\cos \theta$, respectively, and $M_{H_j \to \gamma \gamma}$ the amplitude for the decay of a Higgs into two photons. Here, $\Gamma_j = \Gamma_{hhh} + \Gamma_{hh} + \Gamma_{SM}$ is the sum of three decay rates for the heavier Higgs; first, the decay rate of a Higgs to three lighter Higgs particles, $\Gamma_{hhh} = \frac{g_{SM}^2}{32 \pi m_{h_2}^2} \sqrt{1 - \frac{4m_{h_2}^2}{m_{h_1}^2}}$, second, to two other ones $\Gamma_{hh} = \frac{g_{SM}^2}{32 \pi m_{h_2}^2} \sqrt{1 - \frac{4m_{h_2}^2}{m_{h_1}^2}}$ and third, to the SM particles, $\Gamma_{SM}$. For the lighter Higgs only the decay to the SM particles is allowed i.e. $\Gamma_1 = \Gamma_{SM}$.

We can write $M_{H_j \to \gamma \gamma}$ as follows \cite{23, 24}:

\[
M_{H_j \to \gamma \gamma} = \frac{\sqrt{1 - s_i^2} g_s}{8 \pi m_W} \left[ 3 \left( \frac{2}{3} \right)^2 F_i + F_W \right], \quad \text{for} \quad i \neq j
\]

(15)

where $F_i = -2\tau[1+(1-\tau)f(\tau)]$, $F_W = 2 + 3\tau + 3\tau(2-\tau)f(\tau)$, and $g$ is the weak coupling constant. Here, $\tau = 4m_i^2/s$ with $i = t, W$ and

\[
f(\tau) = \begin{cases} 
\sin^{-1} \left( \frac{1}{\sqrt{\tau}} \right)^2, & \text{for } \tau \geq 1 \\
-\frac{1}{4} \left( \ln \frac{1 + \sqrt{1-\tau^2}}{1 - \sqrt{1-\tau^2}} - i\pi \right)^2, & \text{for } \tau < 1.
\end{cases}
\]

We can then derive the thermally-averaged velocity-weighted annihilation cross section to diphoton $\langle \sigma v \rangle_{\gamma \gamma}$, by putting the Eq. (13) in Eq. (12). For all 44000 models, which we considered in the previous section for consistency with relic density, we derive $\langle \sigma v \rangle_{\gamma \gamma}$ and illustrate them in fig. 4. This figure also shows the latest H.E.S.S. bounds for the Einasto profile. From this figure we see that, there are no points in the parameter space with $\theta < 0.01$ which satisfy the relic density condition along with perturbation criteria. Moreover, the resonance regions inevitably are excluded. For $\theta > 0.01$ there are also some regions of parameter space close to the resonance with cross sections near to the upper limits that may be excluded with future more precise experiments. For $m_\psi > 2m_{h_2}$ there are no regions with $g_s < 1$, therefore, the perturbation theory used for this analysis is not suitable and maybe the effective theories here can give us more detail.
FIG. 4. Thermally-averaged velocity-weighted annihilation cross section of SFCDM pair to two photons in terms of the DM mass for $m_{h_2} = 1$ TeV (top) and $m_{h_2} = 2.5$ TeV (bottom). Solid line shows the 2017 H.E.S.S. upper limit for the Einasto profile [19].

V. SUMMARY AND CONCLUSIONS

In this letter we have studied the parameter space of SFCDM model, up to 10 TeV, by computing the leading order of the thermally averaged annihilation cross section times relative velocity, within the perturbation theory. By calculating the annihilation cross section of a DM pair to two gamma-ray lines, we have also confronted it with the latest H.S.S.E. data. We have used the most minimal and renormalizable extension of the SM for SFCDM model. In this model, one adds a singlet fermion as CDM and a new scalar Higgs as a mediator to the SM content. We have scan the relevant parameter space with 88000 sample models; 44000 for $m_{h_2} = 1$ TeV and 44000 for $m_{h_2} = 2.5$ TeV. In each case we have separated the parameter space into two parts corresponding to $\theta < 0.01$ and $\theta > 0.01$. We have then
imposed the relic density condition and found the corresponding $g_s$ and illustrate it in fig. 2. Thermally-averaged velocity-weighted annihilation cross section is represented in fig. 3. As a result we see that, for $\theta < 0.01$ there are no regions where the perturbation theory used here works properly. This becomes important if the results of ref. [18], that put the upper limit 0.01 for the mixing angle, is also hold for $m_{h_2} > 750$ GeV. From figure 4 we see that, except resonance regions, indirect detections could not exclude the model.

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