Invisible Higgs decay in the LRTH model confronted with latest LHC, XENON100 and LUX date

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Abstract

In the left-right twin Higgs (LRTH) model, the neutral $\hat{S}$ is a candidate for weakly interacting massive particle (WIMP) dark matter. If its mass is lighter than half of the SM-like Higgs boson, the SM-like Higgs boson $h$ can have new invisible decay $h \rightarrow \hat{S}\hat{S}$ which consequently suppress the diphoton signal rates at the LHC. In this paper, we examine the status of a light dark matter ($\hat{S}$) under current experimental constraints including the latest LHC Higgs data, the XENON100 and LUX limit on the dark matter scattering off the nucleon. The following observations have been obtained: (i) The current ATLAS (CMS) measurements $R_{\gamma\gamma}$ can exclude the invisible Higgs branching ratio $Br_{\text{inv}}$ about 34% (48%) at $2\sigma$ level; (ii) Global fits to the latest LHC and Tevatron Higgs data provide a strong constraint on $Br_{\text{inv}} < 20\% (30\%)$ at $2(3)\sigma$ level, which can be tested at the 14 TeV LHC experiment; (iii) For the spin-independent scattering cross section off the nucleon, the recent XENON100 data can exclude the invisible decay about 35%; while the LUX data obtained very recently can exclude an invisible decay branching ratio about 20%.

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I. INTRODUCTION

The discovery of a Higgs boson with a mass of roughly 125 GeV has been confirmed by both the ATLAS [1] and CMS [2] collaborations, which is also supported by the CDF and D0 collaborations at the Tevatron [3]. Among the major decay modes of a standard model (SM) Higgs boson studied at ATLAS and CMS experiments, the diphoton channel is one of the most important channels due to its high resolution and small background. The present updated experimental results from ATLAS ($R_{\gamma\gamma} = 1.17 \pm 0.27$ [4]) and CMS ($R_{\gamma\gamma} = 1.12^{+0.37}_{-0.32}$ [5]) are well consistent with the SM prediction in 1σ range, and can put strong constraints on various new physics (NP) models (see, for instance, [6–11]). However, the SM-like Higgs boson has also been interpreted in many NP models since the SM has the gauge hierarchy problem and cannot provide a dark matter (DM) candidate.

The weakly interacting massive particle (WIMP) is one popular candidate of DM. On the experimental side, various underground direct detection experiments, such as DAMA [12], CoGeNT [13] and CRESST [14], have found some DM-like events in the low region. Very recently, the CDMS-II Collaboration reports that three WIMP-candidate events were observed by using the silicon detectors [15]. This observation, however, seems to contradict with the XENON100 data [16] or the latest LUX data [17], which provided the most stringent upper limits on the spin-independent WIMP-nucleon scattering cross section for a WIMP with a mass above 10 GeV. On the other hand, the Planck collaboration has released its relic density for the DM [18]. The implications of the new results from the DM experiments have been discussed in many NP models [19, 20].

In this work we focus on the left-right Higgs (LRTH) model, which is implemented in left-right models within the twin Higgs mechanism [21, 22]. In the LRTH model, several physical Higgs bosons remain after the spontaneous symmetry breaking. Furthermore, another additional discrete symmetry is introduced under which the odd $SU(2)_L$ doublet $\hat{h}$ can only couples to the gauge boson sector. The lightest particle $\hat{S}$ in its neutral components is stable, and thus can be a good candidate for WIMP dark matter. The collider phenomenology of the LRTH model has been extensively studied for example in Refs. [23–25]. In particular, the relic density analysis of the dark matter in the LRTH model has been studied in Ref. [26].

Recently, we studied the properties of the SM-like Higgs boson $h$ [27], calculated the new physics contributions to the decays $h \rightarrow (\gamma\gamma, Z\gamma, \tau\tau, WW^*, ZZ^*, \tau\tau)$ in the LRTH model, and performed a globe fit to the available LHC Higgs data after Summer 2013. During the 2014 Summer Conferences, most new Higgs boson results with improvements were presented by both ATLAS and CMS Collaborations [28, 29]. Especially the signal strength of the diphoton decay channel of ATLAS has changed from $1.6 \pm 0.3$ to $1.17 \pm 0.27$ [4] and that of CMS from $0.77 \pm 0.27$ to $1.12^{+0.37}_{-0.32}$ [5]. If the mass of the DM is less than half of the Higgs mass, the Higgs could decay into the light DM pairs with a large invisible branching ratio $Br_{\text{inv}}$, which is very sensitive to the NP, since the SM invisible Higgs branching ratio is very small ($Br(h \rightarrow ZZ^* \rightarrow 4\nu) \simeq 0.001$) [30]. The upper bound on the invisible decay rates of the state discovered at the LHC have been analyzed in Refs. [31]. The invisible decay width of the SM-like Higgs boson has also been investigated in various NP models, taking into account the constraints obtained from the recent data [32,33]. In this paper, we will study the invisible decay mode $h \rightarrow \hat{S}\hat{S}$ of the SM-like Higgs boson $h$ and to draw the possible constraints from the latest LHC and DM experimental data.
This paper is organized as follows. In the next section, we recapitulate the dark matter sector in the LRTH model. In Sec. III, we investigate the invisible Higgs decay branching ratio in light of the latest LHC and Tevatron Higgs data, the XENON100 and LUX data. Finally, we give our conclusion in last section.

II. THE LRTH MODEL

The details of the LRTH model as well as the particle spectrum and Feynman rules have been given in Ref.[23]. Here we will focus on the dark matter sector in the LRTH model. This model is based on the global symmetry $U(4) \times U(4)$ with a locally gauged $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ subgroup. The twin symmetry is identified as the left-right symmetry which interchanges L and R, implying that the gauge couplings of $SU(2)_L$ and $SU(2)_R$ are identical. A pair of Higgs fields ($H$ and $\hat{H}$) are introduced and each transforms as $(4, 1)$ and $(1, 4)$ respectively under the global symmetry, which can be written as

$$H = \begin{pmatrix} H_L \\ H_R \end{pmatrix}, \quad \hat{H} = \begin{pmatrix} \hat{H}_L \\ \hat{H}_R \end{pmatrix},$$

(1)

where $H_{L,R}$ and $\hat{H}_{L,R}$ are two component objects which are charged under the $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ as

$$H_L \text{ and } \hat{H}_L : (2, 1, 1), \quad H_R \text{ and } \hat{H}_R : (1, 2, 1).$$

(2)

The global $U(4)_{1,2}$ symmetry is spontaneously broken down to its subgroup $U(3)_{1,2}$ with non-zero vacuum expectation values(VEV) as

$$< H > = \begin{pmatrix} 0 \\ 0 \\ f \end{pmatrix}, \quad < \hat{H} > = \begin{pmatrix} 0 \\ 0 \\ \hat{f} \end{pmatrix}.$$

(3)

The Higgs VEVs also break $SU(2)_R \times U(1)_{B-L}$ down to the SM $U(1)_Y$. Six out of the 14 Goldstone bosons are respectively eaten by the SM gauge bosons $W^\pm$ and $Z$, and additional gauge bosons $W^\pm_H$, and $Z_H$ with masses of TeV order. Then we are left with one SM-like physical Higgs boson $h$, a neutral pseudoscalar $\phi^0$, a pair of charged scalar $\phi^\pm$, and an odd $SU(2)_L$ doublet $\hat{h} = (\hat{h}_1^+, \hat{h}_2^0)$. The lightest particle in $\hat{h}$ is stable and thus can be a candidate for dark matter.

In order to cancel the one-loop quadratic divergence of Higgs mass induced by the top quark, a pair of vector-like quarks are introduced, which are singlets under $SU(2)_L \times SU(2)_R$. The masses of the SM-like top quark and heavy T-quark and the relevant Higgs couplings are given by [23]

$$m^2_t = \frac{1}{2}(M^2 + y^2 f^2 - N_t), \quad m^2_T = \frac{1}{2}(M^2 + y^2 f^2 + N_t),$$

$$h\bar{t}t : -\frac{m_t}{v} C_L C_R, \quad h\bar{T}T : -\frac{y}{\sqrt{2}} (S_R S_L - C_L C_R x).$$

(4)

(5)
where the mixing angles $S_{L,R}$ and $C_{L,R}$ are

$$S_L = \frac{1}{\sqrt{2}} \sqrt{1 - (y^2 f^2 \cos 2x + M^2)/N_t}, \quad C_L = \sqrt{1 - S_L^2},$$

$$S_R = \frac{1}{\sqrt{2}} \sqrt{1 - (y^2 f^2 \cos 2x - M^2)/N_t}, \quad C_R = \sqrt{1 - S_R^2},$$

with

$$N_t = \sqrt{(M^2 + y^2 f^2)^2 - y^4 f^4 \sin^2 2x},$$

where $x = v/(\sqrt{2} f)$. The parameter $M$ is essential to the mixing between the SM-like top quark and its partner $T$, and therefore constrained by $Z \to b\bar{b}$. The top Yukawa coupling $y$ can then be determined by fitting the experimental value of the light top quark mass.

In addition to the Coleman-Weinberg potential arising from gauge boson contributions, the soft left-right symmetry breaking terms, so called “$\mu$-term”, can give masses for $\hat{h}_1\pm$ and $\hat{h}_2^0$ [23]:

$$V_\mu = -\mu_r^2 (H_R^\dagger \hat{H}_R + h.c.) + \hat{\mu}_2^2 \hat{H}_L^\dagger \hat{H}_L.$$

In order not to reintroduce fine tuning, $\mu_r$ should be smaller than the value of $f/4\pi$. Note that $\hat{\mu}_2^2$ could have either sign, which can allow us to vary the masses of $\hat{h}_2^0$ and $\hat{h}_{1\pm}$ as a free parameter.

The complex scalar $\hat{h}_2^0$ can be written as $\hat{h}_2^0 = (\hat{S} + i\hat{A})/\sqrt{2}$, where $\hat{S}$ and $\hat{A}$ are the scalar and pseudoscalar fields, respectively. $\hat{S}$ is lighter than $\hat{A}$, and can be a candidate of dark matter. The mass splitting between $\hat{S}$ and $\hat{A}$ can be obtained by introducing a quartic term in the Higgs potential [26]:

$$V_H = -\frac{\lambda_5}{2} [(H_L^\dagger \hat{H}_L)^2 + h.c.].$$

From above equation we can get the Higgs coupling $h\hat{S}\hat{S} : \lambda_5 v(1 - \frac{v^2}{3 f^2})$. Ref. [26] shows that the low mass region of $m_{\hat{S}} \sim 30 - 70$ GeV can give a relic density in the WMAP $3\sigma$ range. Here we focus on such low mass region where the invisible decay $h \to \hat{S}\hat{S}$ are open.

Besides the SM-like decay modes, the Higgs boson can have additional important decay mode $h \to \hat{S}\hat{S}$, whose partial width at tree level is given by

$$\Gamma(h \to \hat{S}\hat{S}) = \frac{g_{h\hat{S}\hat{S}}^2}{32\pi m_h} \sqrt{1 - \frac{4m_{\hat{S}}^2}{m_h^2}},$$

where $g_{h\hat{S}\hat{S}}$ is the coupling of $h\hat{S}\hat{S}$. The expression of $g_{h\hat{S}\hat{S}}$ come from both the Higgs coupling in Eq. (10) and the Coleman-Weinberg potential, which is complicated and can be found in [34]. Of course, the new decay modes $h \to \hat{A}\hat{A}$ and $h \to \hat{h}_1\hat{h}_1$ can also be open for low values of $m_{\hat{A}}$ and $m_{\hat{h}_1}$, but their decay branching ratios are relatively small. In this work, we mainly consider the branching ratio of the invisible Higgs decay under current experimental constraints and thus we can safely neglect them and take $Br_{\text{inv}}$ as an input parameter.
III. NUMERICAL RESULTS AND DISCUSSIONS

In the LRTH model, the decays $h \to gg, \gamma\gamma, Z\gamma, f\bar{f}, WW^*$ and $ZZ^*$ all receive contributions from the modified couplings $hXX$ and the new heavy particles. For the $h \to \gamma\gamma$ decay, for example, the SM contribution includes the top quark loop and the $W^\pm$ boson loop, while in the LRTH model, the Feynman diagrams involving the $T$–quark and $W_H$ boson also provide the additional contributions to the decay $h \to \gamma\gamma$, respectively. For the $h \to gg$ decay, the LRTH model gives the corrections via the modified couplings $h\bar{b}t$ and the heavy T-quark, which can suppress the cross section of $gg \to h$ sizably. The corresponding expressions of $\Gamma(h \to gg)$ and $\Gamma(h \to \gamma\gamma)$ are given in the Appendix A.

One can see that all these new contributions are sensitive to the parameters $f$ and $M$, which has been studied in our previous work [27].

The total decay width of SM-like Higgs $\Gamma_{LRTH}^{total}(h \to XX)$ can be defined as

$$\Gamma_{LRTH}^{total} = \frac{\Gamma_{LRTH}}{1 - Br_{inv}}, \quad (12)$$

where $\Gamma_{LRTH}$ denotes the decay width of SM-like Higgs for $m_h > m_h/2$. In this case, the invisible decay modes cannot be open, which has been studied in our recent work [27].

In our calculations, we take the SM-like Higgs mass as $m_h = 125.5$ GeV. The SM input parameters relevant in our study are taken from [35]. The free parameters involved are $f$, $M$ and the invisible decay branching ratio $Br_{inv}$. The indirect constraints on $f$ come from the $Z$-pole precision measurements, the low energy neutral current process and high energy precision measurements off the $Z$-pole, requiring approximately $f > 500$ GeV. On the other hand, it cannot be too large since the fine tuning is more severe for large $f$. The mixing parameter $M$ is constrained by the $Z \to b\bar{b}$ branching ratio and oblique parameters. Following Ref. [23], we will assume that the values of the free parameters $f$ and $M$ are in the ranges of

$$500 \text{GeV} \leq f \leq 1500 \text{GeV}, \quad 0 \leq M \leq 150 \text{GeV}. \quad (13)$$

A. Implication of LHC Higgs data on the invisible decay

For $m_h = 125.5$ GeV, the production cross sections for each production channels at the LHC could be found in Ref. [36]. In the SM, the dominant production process is $gg \to h$ by the top quark loop, while the LRTH model can give corrections via the modified coupling of $h\bar{t}t$ and the heavy T-quark loop. The hadronic cross section $\sigma(gg \to h)$ has a strong correlation with the decay width $\Gamma(h \to gg)$. Thus, the Higgs production diphoton rates in the LRTH model normalized to the SM values can be defined as:

$$R_{\gamma\gamma} = \frac{[\Gamma(h \to gg) \times Br(h \to \gamma\gamma)]_{LRTH}}{[\Gamma(h \to gg) \times Br(h \to \gamma\gamma)]_{SM}}, \quad (14)$$

with

$$Br(h \to \gamma\gamma)_{LRTH} = \frac{\Gamma(h \to \gamma\gamma)_{LRTH}}{\Gamma_{LRTH}^{total}} = \frac{\Gamma(h \to \gamma\gamma)_{LRTH}}{\Gamma_{LRTH}}(1 - Br_{inv}). \quad (15)$$
As mentioned in Appendix A, the decay width \( \Gamma(h \to gg)_{LRTH} \) and \( \Gamma(h \to \gamma\gamma)_{LRTH} \) depend on the parameters \( f \) and \( M \). The ratio \( R_{\gamma\gamma} \) can therefore be determined by three parameters \( f, M, \) and \( Br_{\text{inv}} \).

In Fig.1 we plot \( R_{\gamma\gamma} \) versus \( Br_{\text{inv}} \) for \( M = 150 \) GeV and \( f = 1000 \) GeV, respectively. It can be seen from Fig.1(a) that ratio \( R_{\gamma\gamma} \) in the LRTH model is always smaller than unit, and will approach one (the SM prediction) for \( Br_{\text{inv}} = 0 \) and a large scale \( f \). On the other hand, we can see from Fig.1(b) that the ratio is insensitive to the mixing parameter \( M \).

The predicted rate is outside the 1\( \sigma \) ranges of the ATLAS and CMS datas in the most of parameter spaces. For \( f = 500 \) GeV, the predicted rate is always outside the 2\( \sigma \) range of the ATLAS data, while the current CMS diphoton rate can exclude the invisible decay branching ratio about 20\% at 2\( \sigma \) range. In the reasonable parameter spaces, the value of \( R_{\gamma\gamma} \) is in good agreement with the ATLAS (CMS) data in 2\( \sigma \) range for \( Br_{\text{inv}} < 0.34 \) (0.48).

![Graph](image1.png)

**FIG. 1.** \( Br_{\text{inv}} \)-dependence of \( R_{\gamma\gamma} \) for (a) \( M = 150 \) GeV and \( 500 \) GeV \( \leq f \leq 1500 \) GeV, and (b) \( f = 1000 \) GeV and \( M = 0 \) and \( 150 \) GeV, respectively.

Now we perform a global fit to the LRTH model with the method proposed in [37-39] with the latest Higgs data (see Tables I-V in [40]). We consider the 29 Higgs signal strength observables from ATLAS, CMS, CDF and D0 collaborations for \( \gamma\gamma, ZZ^*, WW^*, b\bar{b} \) and \( \tau^+\tau^- \) channels, as listed explicitly in Table I.

The global \( \chi^2 \) function is defined as:

\[
\chi^2 = \sum_{i,j} (\mu_i - \hat{\mu}_i)(\sigma^2)_{ij}^{-1}(\mu_j - \hat{\mu}_j),
\]

where \( \sigma^2_{ij} = \sigma_i \rho_{ij} \sigma_j \), \( \mu_i \) and \( \sigma \) are the measured Higgs signal strengths and their 1\( \sigma \) error, \( \rho_{ij} \) is the correlation matrix, \( \mu_i \) is the corresponding theoretical predictions in terms of the LRTH parameters. The details about the statistical treatment are presented in Appendix B.

In Fig. 2(a) we plot values of \( \chi^2 \) versus \( Br_{\text{inv}} \) for \( M = 150 \) GeV. One can see that the value of \( \chi^2 \) is larger than that for SM for most of parameter space and approaches the SM value for \( Br_{\text{inv}} = 0 \). From Fig.2(b) we can see that he value of \( \chi^2 \) is insensitive to the
TABLE I. The measured Higgs signal strengths and the corresponding theoretical predictions of $\mu_i$ in terms of the LRTH parameters in each of the channels considered in this work. Here we consider $\text{Br}_{\text{inv}} = 0.1, 0.2, 0.3$, $M=150\text{ GeV}$ and $f = 1000\text{ GeV}$.

| Channel | Signal strength $\hat{\mu}_i$ | Theor. prediction $\mu_i$  |
|---------|-------------------------------|---------------------------|
|         | ATLAS [4, 41–43]              |                           |
| ggF, $\gamma\gamma$ | 1.32 ± 0.38 | 0.845 0.751 0.657 |
| WH, $\gamma\gamma$ | 1.0 ± 1.6 | 0.900 0.800 0.700 |
| ZH, $\gamma\gamma$ | $0.1^{+4.7}_{-0.1}$ | 0.900 0.800 0.700 |
| ttH, $\gamma\gamma$ | 1.6$^{+2.1}_{-1.8}$ | 0.896 0.796 0.697 |
| Inclusive, $ZZ^*$ | 1.66$^{+0.40}_{-0.38}$ | 0.85 0.756 0.661 |
| Inclusive, $WW^*$ | 0.99 ± 0.30 | 0.85 0.756 0.661 |
| VH tag, $bb$ | $0.2^{+0.7}_{-0.6}$ | 0.878 0.78 0.683 |
| ttH tag, $bb$ | $1.8^{+1.66}_{-1.57}$ | 0.873 0.776 0.679 |
| ggF, $\tau^+\tau^-$ | $1.1^{+1.3}_{-1.0}$ | 0.824 0.732 0.641 |
| VBF+VH, $\tau^+\tau^-$ | $1.6^{+0.9}_{-0.8}$ | 0.878 0.78 0.641 |
|         | CMS [5, 44–46]                |                           |
| ggF, $\gamma\gamma$ | 1.12$^{+0.9}_{-0.32}$ | 0.845 0.751 0.657 |
| VBF, $\gamma\gamma$ | 1.58$^{+0.07}_{-0.68}$ | 0.900 0.800 0.700 |
| VH, $\gamma\gamma$ | $-0.16^{+1.16}_{-0.79}$ | 0.900 0.800 0.700 |
| ttH, $\gamma\gamma$ | 2.69$^{+2.31}_{-1.83}$ | 0.896 0.796 0.697 |
| Inclusive, $ZZ^*$ | 0.93$^{+0.29}_{-0.25}$ | 0.85 0.756 0.661 |
| 0/1 jet, $WW^*$ | 0.74$^{+0.22}_{-0.20}$ | 0.849 0.755 0.661 |
| VBF tag, $WW^*$ | 0.60$^{+0.57}_{-0.46}$ | 0.849 0.755 0.661 |
| VH tag (2$f2\nu2j$), $WW^*$ | 0.39$^{+1.37}_{-1.87}$ | 0.914 0.813 0.711 |
| VH tag (3$f3\nu$), $WW^*$ | 0.56$^{+1.27}_{-0.95}$ | 0.914 0.813 0.711 |
| VH tag, $bb$ | 1.0 ± 0.5 | 0.878 0.78 0.683 |
| ttH tag, $bb$ | 0.67$^{+1.30}_{-1.33}$ | 0.874 0.776 0.679 |
| 0 jet, $\tau^+\tau^-$ | 0.34 ± 1.09 | 0.719 0.639 0.559 |
| 1 jet, $\tau^+\tau^-$ | 1.07 ± 0.46 | 0.435 0.386 0.338 |
| VBF tag, $\tau^+\tau^-$ | 0.94 ± 0.41 | 0.837 0.744 0.651 |
| VH tag, $\tau^+\tau^-$ | $-0.33\pm 1.02$ | 0.878 0.78 0.683 |
|         | Tevatron [47]                 |                           |
| $h \rightarrow \gamma\gamma$ | 5.97$^{+3.39}_{-3.12}$ | 0.847 0.753 0.658 |
| $h \rightarrow WW^*$ | 0.94$^{+0.30}_{-0.33}$ | 0.852 0.757 0.662 |
| $h \rightarrow bb$ | 1.50$^{+0.69}_{-0.72}$ | 0.878 0.78 0.683 |
| $\chi^2$ | 16.38 | 19.49 22.88 28.11 |
| $p$-value | 0.97 | 0.91 0.78 0.51 |
mixing parameter $M$, and thus we can safely take $M = 150$ GeV as the typical value in latter calculations.

In Fig. 3 we plot the contours of $\chi^2$ in $f - \text{Br}_{\text{inv}}$. One can also see that, the current Higgs data can give strict constraint on the exotic decay $h \rightarrow \hat{S}\hat{S}$, i.e. the invisible decay branching ratio $\text{Br}_{\text{inv}}$ to be less than 30% at $3\sigma$ level, and reduced to less than 20% at $2\sigma$ level. Such case may be tested at the 14 TeV LHC with 100 fb$^{-1}$ integrated luminosity, where a 95% C.L. upper limit on the invisible decay: $\text{Br}_{\text{inv}} < 0.18$ [48]. The $\chi^2$ at the minimum is $\chi^2_{\text{min}} = 17.67$, i.e. almost the same as for the SM. With 29 degrees of freedom this corresponds to a $p$-value of 0.91, as compared to a $p$-value of 0.95 for the SM.

FIG. 2. (a) The global fit values of $\chi^2$ versus $\text{Br}_{\text{inv}}$ for $M = 150$ GeV and two values of $f$ as indicated; (b) $\chi^2$ versus $M$ for $\text{Br}_{\text{inv}} = 0.2$ and three values of $f$ as indicated.

FIG. 3. The contours of $\chi^2$ in $f - \text{Br}_{\text{inv}}$ are shown for the $1\sigma$, $2\sigma$, and $3\sigma$ regions.
B. Implication of DM direct search experiments on the invisible decay

At present the stringent limit on the spin-independent component of elastic scattering cross section $\sigma_{\text{SI}}$ become available from XENON100 [16] and LUX [17] experiments. In LRTH model, the elastic scattering of $\hat{S}$ on a nucleus receives the dominant contributions from the Higgs boson exchange diagrams. Thus the LHC bounds on $\text{Br}_{\text{inv}}$ can be turned into bounds on the DM scattering off nucleons, mediated by Higgs exchange [49]. The spin-independent cross section between $\hat{S}$ and the nucleon is given by [50]:

$$\sigma_{\text{SI}} = \eta \mu_r^2 m_p^2 \frac{g^2}{M_W^2} \left( \frac{\Gamma_{\text{LRTH}} \times \text{Br}_{\text{inv}}}{1 - \text{Br}_{\text{inv}}} \right) \left[ C_U (f_u^N + f_c^N + f_t^N) + C_D (f_d^N + f_s^N + f_b^N) \right]^2,$$  \hspace{1cm} (17)

with $\eta = 2/(m_H^2 m_S^2 \beta)$, $\mu_r$ is the reduced mass and $f_q^N, (f_g^N)$ are the quark (gluon) coefficients in the nucleon. We take the values $f_s^p = 0.0447$, $f_u^p = 0.0135$, and $f_d^p = 0.0203$ from an average of recent lattice results [51]. The gluon and heavy quark ($Q = c, b, t$) coefficients are related to those of light quarks, and $f_q^g = f_Q = \frac{2}{27} (1 - \sum_{q=u,d,s} f_q^0)$ at leading order.

![Graphs showing $\sigma_{\text{SI}}$ as a function of $m_S$ for different $\text{Br}_{\text{inv}}$.](image)

**FIG. 4.** $\sigma_{\text{SI}}$ as a function of the mass of the DM particle $m_S$, and assuming $\text{Br}_{\text{inv}} = (0.10, 0.15, 0.20, 0.25, 0.30, 0.35)$, respectively. The red solid and dashed curves show the XENON100 and LUX exclusion limit.

For a given dark matter candidate mass, we can translate the exclusion limit set by XENON100 and LUX experiments into an upper bound on the invisible branching ratio of the SM-like Higgs boson. The results for $\sigma_{\text{SI}}$ versus the DM mass and for different $\text{Br}_{\text{inv}}$
are displayed in Fig. 4, where the solid line and dashed line indicate the current limits from XENON100 (solid line) and LUX (dashed line) experiments. We see that the recent XENON100 data can exclude the invisible decay about 35%. For $Br_{\text{inv}} = 0.3$, there are only a small surviving parameter space for $m_{\tilde{S}} \geq 35 \text{ GeV}$. Clearly, one can see that the latest LUX result can exclude a large part of the allowed parameter space, but still leaves a light dark matter viable, i.e. $Br_{\text{inv}} < 0.2$. For $Br_{\text{inv}} = 0.15$, the mass of dark matter should be larger than 40 GeV.

IV. CONCLUSIONS

The LRTH model can provide the scalar boson $\hat{S}$ as a natural candidate for the WIMP dark matter. In this paper, we examine the status of a light dark matter (which open new decay channels of the SM-like Higgs boson) under current experimental constraints including the latest LHC Higgs data, the XENON100 and latest LUX limit on the dark matter scattering off the nucleon. From the numerical results we obtain the following observations:

1. The LRTH prediction for $R_{\gamma\gamma}$ agree well with the CMS measurement at 1$\sigma$ level, but differ with the ATLAS result. The current ATLAS (CMS) measurements $R_{\gamma\gamma}$ can exclude the invisible Higgs branching ratio $Br_{\text{inv}}$ about 34% (48%) at 2$\sigma$ level.

2. The SM-like Higgs boson can decay into the light dark matter pair and its branching ratio can reach 30%(20%) at 3(2)$\sigma$ level under the latest Higgs data, which can be tested at the 14 TeV LHC experiment.

3. For the spin-independent scattering cross section off the nucleon, the recent XENON100 data can exclude the invisible decay about 35%, while the latest LUX result can exclude an invisible decay branching ratio about 20%. For $Br_{\text{inv}} = 0.15$, the mass of dark matter should be larger than 40 GeV.

Appendix A: The Higgs decays $h \to gg, \gamma\gamma$

In the LRTH model, the LO decay widths of $h \to gg, \gamma\gamma$ are given by

$$\Gamma(h \to gg) = \frac{\sqrt{2} G_F \alpha^2 m_h^3}{32 \pi^3} \left| -\frac{1}{2} F_{1/2}(\tau_t) y_t y_{G_F} - \frac{1}{2} F_{1/2}(\tau_T) y_T \right|^2,$$

$$\Gamma(h \to \gamma\gamma) = \frac{\sqrt{2} G_F \alpha^2 m_h^3}{256 \pi^3} \left| \frac{4}{3} F_{1/2}(\tau_t) y_t y_{G_F} + \frac{4}{3} F_{1/2}(\tau_T) y_T + F_1(\tau_W) y_W \right|^2,$$

with

$$F_1 = 2 + 3\tau + 3\tau (2 - \tau) f(\tau), \quad F_{1/2} = -2\tau [1 + (1 - \tau) f(\tau)],$$

$$f(\tau) = \left[ \sin^{-1} (1/\sqrt{\tau}) \right]^2, \quad g(\tau) = \sqrt{\tau - 1} \sin^{-1} (1/\sqrt{\tau}),$$

for $\tau_i = 4m_i^2/m_h^2 \geq 1$. The relevant couplings $y_t$ and $y_T$ can be written as

$$y_t = S_L S_R, \quad y_T = \frac{m_t}{m_T} C_L C_R,$$
which can be determined by the parameters $f$ and $M$ due to Eqs. (4-8). Here we have neglected the contributions from $W_H$ and $\phi^\pm$ for the $h \to \gamma\gamma$ decay, this is because their contributions are even much smaller than that for the T-quark.

Appendix B: The statistical treatment

For diphoton channel, the Higgs signal strength can be written as

$$\mu_{\gamma\gamma} = \frac{\epsilon_{ggF}\sigma_{ggF} + \epsilon_{VBF}\sigma_{VBF} + \epsilon_{VH}\sigma_{VH}}{\epsilon_{ggF}\sigma_{ggF}^{SM} + \epsilon_{VBF}\sigma_{VBF}^{SM} + \epsilon_{VH}\sigma_{VH}^{SM}} \times \frac{\text{Br}(h \to \gamma\gamma)}{\text{Br}(h \to \gamma\gamma)^{SM}},$$  \hspace{1cm} (B1)

where the coefficients $\epsilon$ accounting for the relative weight of each production channel are listed in Tables I-V in [40]. The SM production cross sections and decay widths are taken from [36].

The errors on the reported Higgs signal strengths $\hat{\mu}_i$ are symmetrized by

$$\delta\hat{\mu}_i = \sqrt{\left(\delta\hat{\mu}_+\right)^2 + \left(\delta\hat{\mu}_-\right)^2},$$  \hspace{1cm} (B2)

where $\delta\hat{\mu}_\pm$ are the one-sided errors given by the experimental collaborations [4, 5]. For plotting distributions of a function of one (two) parameter, the 68% (1$\sigma$), 95% (2$\sigma$) and 99.7% (3$\sigma$) C.L. intervals are obtained by $\chi^2 = \chi^2_{\text{min}} + 1$ (2.3), +4 (6.18), and +9 (11.83), respectively [38].

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