Production and decays of a light ϕ^0 in the LRTH model under the LHC Higgs data

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ABSTRACT: In this paper we study the production and decays of a light pseudoscalar boson ϕ^0 with $m_{\phi^0} \leq m_h/2$ appeared in the left-right twin Higgs (LRTH) model, and explore its phenomenological consequences when the latest LHC Higgs data are taken into account. We found that (a) the decay rate $Br(h \rightarrow \phi^0 \phi^0)$ can be as large as 80% and can suppress significantly the visible $\gamma\gamma$ signal rate, but the latest LHC Higgs data put a strong constraint on it: $Br(h \rightarrow \phi^0 \phi^0) \leq 30\%$ at 3σ level; (b) the p -value of the LRTH model is around 0.6, smaller than that of the SM in most of the parameter space and approaches the SM value 0.8 for a sufficiently large f parameter; (c) the neutral pseudoscalar ϕ^0 dominantly decay into $b\bar{b}$ and the decay rate $Br(\phi^0 \rightarrow b\bar{b})$ can be larger than 80% for $m_{\phi^0} \leq 60$ GeV, and the second main decay mode is $\phi^0 \rightarrow \tau^+ \tau^-$ with a branching ratio about 14%; and (d) at the future $e^- e^+$ collider with $\sqrt{s} = 250$ GeV, the processes $e^+ e^- \rightarrow Zh \rightarrow Z(\phi^0 \phi^0) \rightarrow Z(4b, 2b2\tau)$ are promising for discovering such a light pseudoscalar ϕ^0 .

KEYWORDS: Phenomenological Models

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1 Introduction

The discovery of a neutral Higgs boson with a mass around 125 GeV at CERN’s Large Hadron Collider (LHC) has been confirmed by the ATLAS and CMS collaborations [1–6], which heralds the beginning of a new era of Higgs physics. So far the observed signal strengths, albeit with large experimental uncertainties, consistent with the Standard Model (SM) predictions [5, 6]. However, the SM suffers from the so-called gauge hierarchy problem and cannot provide a dark matter candidate.

During past three decades, many new physics (NP) models beyond the SM have been constructed by extending the Higgs sector in the SM, such as the Supersymmetric (SUSY) models [7], large extra-dimensions [8], two-Higgs doublet models (2HDM) [9], and little Higgs models [10–12] etc. Very recently, the twin Higgs models have been proposed [13–16] as a solution to the little hierarchy problem. Here we focus on the left-right twin Higgs (LRTH) model which is implemented with the discrete symmetry being identified with left-right symmetry [17, 18]. In the LRTH model, several physical Higgs bosons are still left after the spontaneous symmetry breaking. Another additional discrete symmetry is introduced under an odd $SU(2)_L$ doublet $\hat{h}$ while the other fields are even. The lightest particle in the neutral components $\hat{h}_2^0$ is stable and can be a candidate for weakly interacting massive particle (WIMP) dark matter. Besides $\hat{h}_2^0$, the LRTH model predicts the SM-like Higgs boson h and other three scalars: ϕ^0 and $\phi^\pm$. The neutral ϕ^0 is a pseudoscalar and thus there are no $\phi^0 W^+ W^-$ and $\phi^0 Z Z$ couplings at the tree level, which makes the ϕ^0

rather special. The particle spectrum and collider signatures of the LRTH model have been widely studied, for example, in refs. [19–27].

In a recent paper [28], we studied the properties of the SM-like Higgs boson h , calculated the new physics contributions to the decays $h \rightarrow (\gamma\gamma, Z\gamma, \tau\tau, WW^*, ZZ^*, \tau\tau)$ in the LRTH model, performed a globe fit to the current LHC Higgs data, and found that all the signal rates are suppressed when NP contributions are taken into account, while the LRTH prediction for $R_{\gamma\gamma}$ agrees well with the CMS measurement $R_{\gamma\gamma} = 0.77 \pm 0.27$ at 1σ level. In this paper, we will study the production and decays of the light pseudo-scalar ϕ^0 and to draw the possible constraints from currently available LHC Higgs data. If this neutral ϕ^0 were lighter than half of the SM-like Higgs boson h , i.e. $m_{\phi^0} < m_h/2$, the new decay channel $h \rightarrow \phi^0\phi^0$ will be opened with a sizable branching ratio. Because the 125 GeV SM Higgs decay width is small (the measured value is about 4 MeV), such an exotic decay mode can suppress greatly the visible signals of h and would have important phenomenological consequences [29–32]. We know that the current bound on the branching ratios to exotic states is still weak: a branching fraction as large as $\sim 60\%$ is allowed at the 2σ C.L. [5, 6]. If SM couplings are assumed, the universal Higgs fits constrain the invisible branching fraction to be less than 25% at 95% C.L. [33–35], which still leaves appreciable scope for such an exotic decay mode. Thus, we will investigate the constraints of the latest LHC Higgs data on the properties of such a light pseudoscalar ϕ^0 in the LRTH model. We will also study the possibility of detecting such a light boson ϕ^0 at high energy colliders.

This paper is organized as follows. In the next section, we briefly review the LRTH model and study the possible decay modes for a light pseudoscalar boson ϕ^0 . In section III, we investigate the decay branching ratios of $h \rightarrow \phi^0\phi^0$ and perform a fit using the latest LHC Higgs data. We study the possibility of detecting such a light pseudoscalar at the LHC experiments in section IV. Finally, we present our conclusion in section V.

2 The left-right twin Higgs model

2.1 Outline of the LRTH model

This model is based on the global $U(4) \times U(4)$ symmetry with a locally gauged subgroup $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ [13–17]. 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 ($g_{2L} = g_{2R} = g_2$). Two Higgs fields, H and $\hat{H}$, are introduced and each transforms as $(4, 1)$ and $(1, 4)$, respectively. They are written as

$$H = \begin{pmatrix} H_L \\ H_R \end{pmatrix}, \quad \hat{H} = \begin{pmatrix} \hat{H}_L \\ \hat{H}_R \end{pmatrix}, \quad (2.1)$$

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

$$H_L \text{ and } \hat{H}_L : (2, 1, 1), \quad H_R \text{ and } \hat{H}_R : (1, 2, 1). \quad (2.2)$$

The global $U(4)_1(U(4)_2)$ symmetry is spontaneously broken down to its subgroup $U(3)_1(U(3)_2)$ with non-zero vacuum expectation values(VEV):

$$\langle H \rangle = (0, 0, 0, f)^T, \quad \langle \hat{H} \rangle = (0, 0, 0, \hat{f})^T. \quad (2.3)$$

Each spontaneously symmetry breaking yields seven Nambu-Goldstone bosons, which can be parameterized as

$$H = f e^{\frac{i\pi}{f}} \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}, \quad \text{with } \pi = \begin{pmatrix} -N/2 & 0 & 0 & h_1 \\ 0 & -N/2 & 0 & h_2 \\ 0 & 0 & -N/2 & C \\ h_1^* & h_2^* & C^* & 3N/2 \end{pmatrix}, \quad (2.4)$$

where π are the corresponding Goldstone fields. N is a neutral real pseudoscalar, C and C^* are a pair of charged complex scalar fields. (h_1, h_2) is the SM $SU(2)_L$ Higgs doublet. Accordingly, $\hat{H}$ is parametrized in the same way by its own Goldstone boson matrix $\hat{\pi}$, which contains $\hat{N}$, $\hat{C}$ and $\hat{h} = (\hat{h}_1^+, \hat{h}_2^0)$.

The original gauge symmetry $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ is broken 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 $W_H^\pm$, and Z_H with masses of TeV order. Then we are left with the SM-like physical Higgs boson h , one neutral pseudoscalar ϕ^0 , a pair of charged scalar $\phi^\pm$, and an odd $SU(2)_L$ doublet $\hat{h} = (\hat{h}_1^+, \hat{h}_2^0)$ which only couples to the gauge boson sector. The lightest particle in $\hat{h}$ is stable and thus can be a candidate for WIMP dark matter, which have been studied for example in refs. [21, 22].

The covariant kinetic terms of Higgs fields can be written as [19]

$$\mathcal{L}_H = (D_\mu H)^\dagger D^\mu H + (D_\mu \hat{H})^\dagger D^\mu \hat{H}, \quad (2.5)$$

where the covariant derivative is $D^\mu = \partial^\mu - ig_2 W_2^\mu - ig_1 n_{B-L} W_{B-L}^\mu$, and

$$W_2 = \frac{1}{2} \begin{pmatrix} W_L^0 & \sqrt{2}W_L^+ & 0 & 0 \\ \sqrt{2}W_L^- & -W_L^0 & 0 & 0 \\ 0 & 0 & W_R^0 & \sqrt{2}W_R^+ \\ 0 & 0 & \sqrt{2}W_R^- & -W_R^0 \end{pmatrix}, \quad W_{B-L} = \frac{W_1}{2} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \quad (2.6)$$

where g_1 and g_2 are the gauge couplings for $U(1)_{B-L}$ and $SU(2)_{L,R}$, $n_{B-L} = 1$ is the charge of the field under $U(1)_{B-L}$.

In the LRTH model, a pair of vector-like quarks (U_L, U_R) are introduced to cancel the one-loop quadratic divergence of Higgs mass induced by the top quark. The relevant Lagrangian can be written as [19]

$$\mathcal{L}_t = y_L \bar{Q}_{L3} \tau_2 H_L^* U_R + y_R \bar{Q}_{R3} \tau_2 H_R^* U_L - M \bar{U}_L U_R + h.c. \quad (2.7)$$

where $Q_{L3} = -i(u_{L3}, d_{L3})^T$ and $Q_{R3} = (u_{R3}, d_{R3})^T$.

The details of the LRTH model as well as the particle spectrum, Feynman rules, and some phenomenology analysis have been given for example in ref. [19]. Here we will focus on the properties of the light pseudoscalar ϕ^0 .

Figure 1. The upper constraint $m_{\phi^0} \leq 62.5$ GeV, according to the theoretical relation as given in eq. (2.9).

2.2 The mass and decay of the light scalar ϕ^0

In the LRTH model, the soft left-right symmetry breaking terms, so called μ -term, can generate mass for the light ϕ^0 :

$$V_\mu = -\mu_r^2 (H_R^\dagger \hat{H}_R + h.c.) + \hat{\mu}^2 H_L^\dagger \hat{H}_L. \quad (2.8)$$

The mass of ϕ^0 and new scalar self-interactions are given by [19]

$$m_{\phi^0}^2 = \frac{\mu_r^2 f \hat{f}}{\hat{f}^2 + f^2 \cos^2 x} \cdot \left\{ \frac{\hat{f}^2 \left[\cos x + \frac{\sin x}{x} (3 + x^2) \right]}{f^2 \left(\cos x + \frac{\sin x}{x} \right)^2} + 2 \cos x + \frac{f^2 \cos^2 x (1 + \cos x)}{2 \hat{f}^2} \right\}, \quad (2.9)$$

$$h\phi^0\phi^0 : \frac{vm_h^2}{54f^2} \cdot \left[11 + 15 \left(1 - \frac{2m_{\phi^0}^2}{m_h^2} \right) \right], \quad (2.10)$$

where $x = v/(\sqrt{2}f)$ and $v = 246$ GeV is the electroweak scale. Once f is fixed, the scale $\hat{f}$ can be determined from the electroweak symmetry breaking condition. In general $\hat{f}$ is larger f about 5 times or more [19, 20] and here we set $\hat{f} = 5f$ as a rough estimate.

From the expression of $m_{\phi^0}^2$ in eq. (2.9), one can see that the value of $m_{\phi^0}^2$ depend on two parameters μ_r and f . The value of μ_r cannot be too large, since the fine-tuning of the SM-like Higgs boson mass m_h will become severe for larger μ_r [19]. Assuming $4 \leq \mu_r \leq \text{GeV}$ and $500 \leq f \leq 1500$ GeV, one finds the upper constraint on m_{ϕ^0} : $m_{\phi^0} \leq 62.5$ GeV. In other words, the new decay channel $h \rightarrow \phi^0\phi^0$ can be opened in the parameter space of the LRTH model considered here. The lower limit of m_{ϕ^0} , say $m_{\phi^0} > 7$ GeV, comes from the non-observation of the decay $\Upsilon \rightarrow \gamma + X_0$ [36, 37]. As illustrated in figure 1, the upper

limit $m_{\phi^0} \leq 62.5 \text{ GeV}$ are guaranteed when the values of (f, μ_r) are in the light-dark region in the $f - \mu_r$ plane. The rare decays of $Z \rightarrow f\bar{f}\phi^0$ and $Z \rightarrow \phi^0\gamma$ have been studied in ref. [38].

In the LRTH model, the decays $\phi^0 \rightarrow gg, \gamma\gamma$ are mediated by the one loop Feynman diagrams involving the top quark and the new heavy quark T . The leading order decay widths can be written as [39]

$$\Gamma(\phi^0 \rightarrow gg) = \frac{\sqrt{2}G_F\alpha_s^2 m_{\phi^0}^3}{32\pi^3} \left| -\frac{1}{2}F_{1/2}(\tau_t)y_t - \frac{1}{2}F_{1/2}(\tau_T)y_T \right|^2, \quad (2.11)$$

$$\Gamma(\phi^0 \rightarrow \gamma\gamma) = \frac{\sqrt{2}G_F\alpha_e^2 m_{\phi^0}^3}{256\pi^3} \left| \frac{4}{3}F_{1/2}(\tau_t)y_t + \frac{4}{3}F_{1/2}(\tau_T)y_T \right|^2, \quad (2.12)$$

where $F_{1/2} = -2\tau[1 + (1 - \tau)f(\tau)]$ with $f(\tau) = [\sin^{-1}(1/\sqrt{\tau})]^2$ and $\tau_t = 4m_t^2/m_{\phi^0}^2$, $\tau_T = 4m_T^2/m_{\phi^0}^2$. The explicit expressions of the relevant couplings y_t and y_T are of the form

$$y_t = S_L S_R, \quad y_T = \frac{m_t}{m_T} C_L C_R, \quad (2.13)$$

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

$$S_L = \frac{1}{\sqrt{2}} \sqrt{1 - (y^2 f^2 \cos 2x + M^2)/N_t}, \quad C_L = \sqrt{1 - S_L^2}, \quad (2.14)$$

$$S_R = \frac{1}{\sqrt{2}} \sqrt{1 - (y^2 f^2 \cos 2x - M^2)/N_t}, \quad C_R = \sqrt{1 - S_R^2}, \quad (2.15)$$

with

$$N_t = \sqrt{(M^2 + y^2 f^2)^2 - y^4 f^4 \sin^2 2x}, \quad (2.16)$$

where $x = v/(\sqrt{2}f)$. The mass of the top quark and new heavy T -quark are therefore can also be written as [19]

$$m_t^2 = \frac{1}{2}(M^2 + y^2 f^2 - N_t), \quad m_T^2 = \frac{1}{2}(M^2 + y^2 f^2 + N_t). \quad (2.17)$$

The parameter y in eqs. (2.14)–(2.17) denotes the top quark Yukawa coupling, and can be determined by fitting the measured value of m_t according to eq. (2.17) for given values of the new physics parameters f and M .

For $\phi^0 \rightarrow f_i \bar{f}_i$ decays with f_i the leptons and/or light quarks, the decay width can be written as:

$$\Gamma(\phi^0 \rightarrow f_i \bar{f}_i) = \frac{N_C G_F v^2 m_i^2 m_{\phi^0}}{8\sqrt{2}\pi f^2} (1 - x_i)^{3/2}, \quad (2.18)$$

where $x_i = 4m_i^2/m_{\phi^0}^2$, $N_c = 3(1)$ for f_i being a quark (lepton). It is easy to see that the decays of ϕ^0 to those light final state fermions, such as $f_i = (e, \mu, u, d, s)$, are strongly suppressed due to the severe helicity suppression ($\propto m_i^2$), and therefore can be neglected safely.

Figure 2. (a) the branching ratios of the considered ϕ^0 decays as a function of m_{ϕ^0} for given values of $f = 500$ GeV and $M = 150$ GeV. (b) the branching ratio of the dominant $\phi^0 \rightarrow b\bar{b}$ decay versus M for fixed $m_{\phi^0} = 50$ GeV and $f = 500, 1500$ GeV.

In the LRTH model, consequently, the five major decay modes of ϕ^0 are $\phi^0 \rightarrow b\bar{b}, c\bar{c}, \tau^+\tau^-, g g$ and $\gamma\gamma$. The m_{ϕ^0} -dependence of the branching ratios, assuming $f = 500$ GeV and $M = 150$ GeV, are illustrated in figure 2a. The figure 2b shows the M -dependence of the branching ratio of the dominant $\phi^0 \rightarrow b\bar{b}$ decay for fixed $f = 500$ and 1500 GeV. For $\phi^0 \rightarrow f\bar{f}$ decays, furthermore, their decay rates in the LRTH model are strongly suppressed by a factor of $v^2/(2f^2) \leq 0.12$ when compared with those of the SM Higgs boson decays $H \rightarrow f\bar{f}$. From figure 2 one can see that:

1. The dominant decay mode of the light pseudoscalar ϕ^0 is $\phi^0 \rightarrow b\bar{b}$. In the considered region of $500 \text{ GeV} \leq f \leq 1500 \text{ GeV}$, the value of the branching ratio $Br(\phi^0 \rightarrow b\bar{b})$ is about 81% for $m_{\phi^0} = 50$ GeV, and has a rather weak dependence on the variations of the parameters f and M .
2. The partial width into $c\bar{c}$ is smaller than that into $\tau^+\tau^-$, this is because we use the running mass of the quarks evaluated at the scale m_{ϕ^0} to calculate the Yukawa coupling. In the allowed parameter spaces, $Br(\phi^0 \rightarrow \tau^+\tau^-) \simeq 14\%$.
3. $Br(\phi^0 \rightarrow g g)$ becomes large along with the increase of m_{ϕ^0} , which can reach 30% for $m_{\phi^0} = 200$ GeV. This is due to the enhancement from the contribution of heavy T -quark, which is non-decoupled in the triangle loops.
4. The values of $Br(\phi^0 \rightarrow \gamma\gamma)$ is very small: at the level of 10^{-5} to 10^{-3} in most of the parameter space. This is due to the absence of the coupling between ϕ^0 and the charged gauge bosons.

3 Effects of a light ϕ^0 and the LHC Higgs data

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 [40]. The free parameters in the LRTH model relevant for this work are f , M and m_{ϕ^0} . Following ref. [19], we here also assume

Figure 3. The f -dependence of $\Gamma(h \rightarrow \phi^0 \phi^0)$ (left) and $Br(h \rightarrow \phi^0 \phi^0)$ (right) for $M = 150$ GeV and three typical values of $m_{\phi^0} = 20, 40$ and 60 GeV.

that the values of the free parameters f and M are in the ranges of

$$500 \leq f \leq 1500 \text{ GeV}, \quad 0 \leq M \leq 150 \text{ GeV}. \quad (3.1)$$

while $8 \leq m_{\phi^0} \leq 62.5$ GeV according to the analysis in previous section.

3.1 The $h \rightarrow \phi^0 \phi^0$ decay

For $m_h \geq 2m_{\phi^0}$, the new decay channel $h \rightarrow \phi^0 \phi^0$ will open and the partial decay width is given by

$$\Gamma(h \rightarrow \phi^0 \phi^0) = \frac{g_{h\phi^0\phi^0}^2}{8\pi m_h} \sqrt{1 - \frac{4m_{\phi^0}^2}{m_h^2}}, \quad (3.2)$$

where $g_{h\phi^0\phi^0}$ is the coupling of $h\phi^0\phi^0$ vertex. The open of this new decay mode, consequently, can suppress greatly the visible signals of the boson h at the LHC. Thus, the major decay modes of the SM-like Higgs boson h in the LRTH model become now:

$$h \rightarrow \phi^0 \phi^0, \quad \text{and} \quad h \rightarrow f\bar{f} (f = b, c, \tau), VV^* (V = W, Z), gg, \gamma\gamma, \quad (3.3)$$

where W^*/Z^* denoting the off-shell charged or neutral electroweak gauge bosons. The branching ratio of $h \rightarrow \phi^0 \phi^0$ can be written as

$$Br(h \rightarrow \phi^0 \phi^0) = \frac{\Gamma(h \rightarrow \phi^0 \phi^0)}{\Gamma_{\text{LRTH}}(h) + \Gamma(h \rightarrow \phi^0 \phi^0)}, \quad (3.4)$$

where $\Gamma_{\text{LRTH}}(h)$ denotes the total decay width of SM-like Higgs boson h for $m_{\phi^0} > m_h/2$ in the LRTH model, which has been studied in refs. [28, 41].

In figure 3 we show the f -dependence of the decay width $\Gamma(h \rightarrow \phi^0 \phi^0)$ and the branching ratio $Br(h \rightarrow \phi^0 \phi^0)$ for $M = 150$ GeV and three typical values of m_{ϕ^0} : $m_{\phi^0} = 40 \pm 20$ GeV. One can see that both the decay width and decay rates for $h \rightarrow \phi^0 \phi^0$ decay becomes smaller rapidly along with the increase of the parameter f . This is because the couplings of $h\phi^0\phi^0$ is proportional to the suppression factor of $(v/f)^2$. For

Figure 4. The f -dependence of $R_{\gamma\gamma}$ in the LRTH model for $m_{\phi^0} = 50$ GeV and two typical values of parameters M as indicated.

$m_{\phi} = 40$ GeV, we find $2\% \leq Br(h \rightarrow \phi^0 \phi^0) \leq 70\%$ for $500 \leq f \leq 1500$ GeV. For the case of $f = 500$ GeV, the decay width $\Gamma(h \rightarrow \phi^0 \phi^0)$ can be as large as 16 MeV and thus can suppress greatly the branching ratios for other decay modes of the SM-like Higgs boson h : such as the phenomenologically very interesting $h \rightarrow \gamma\gamma$ decay.

3.2 $h \rightarrow \gamma\gamma$ decay in the LRTH model

For the SM Higgs diphoton decay, the measured signal strength as reported by ATLAS [5] and CMS collaboration [6] are rather different,

$$R_{\gamma\gamma} = \frac{\sigma(H \rightarrow \gamma\gamma)}{\sigma^{\text{SM}}(H \rightarrow \gamma\gamma)} = \begin{cases} 1.55^{+0.33}_{-0.28}, & \text{ATLAS;} \\ 0.77 \pm 0.27, & \text{CMS.} \end{cases} \quad (3.5)$$

but these results are still consistent with the SM expectation within 2σ level due to rather large errors. If the excess (deficit) seen by ATLAS (CMS) were eventually confirmed by the near future LHC measurements, the extra NP contributions would be help to understand such excess or deficit [42–46].

At the LHC, the Higgs single production is dominated by the gluon-gluon fusion (ggF) process. The hadronic production cross section $\sigma(gg \rightarrow h)$ has a strong correlation with the decay width $\Gamma(h \rightarrow gg)$. Other main production processes of the Higgs boson include vector-boson fusion (VBF), associated production with a W/Z boson (VH) and associated production with a $t\bar{t}$ pair (ttH). For $m_h = 125.5$ GeV, the production cross sections for each production channels at LHC have been given for example in ref. [47]. In the LRTH model, the production rate of $h \rightarrow \gamma\gamma$ normalized to the SM values is generally defined as

$$R_{\gamma\gamma} = \frac{[\sigma(pp \rightarrow h) \times Br(h \rightarrow \gamma\gamma)]_{\text{LRTH}}}{[\sigma(pp \rightarrow h) \times Br(h \rightarrow \gamma\gamma)]_{\text{SM}}}. \quad (3.6)$$

In figure 4 we plot $R_{\gamma\gamma}$ versus f for $m_{\phi^0} = 50$ GeV and $M = 0, 150$ GeV, respectively. It can be seen from figure 4 that ratio $R_{\gamma\gamma}$ in the LRTH model is always smaller than unit, and will approach one (the SM prediction) for a large f . On the other hand, one can see

Figure 5. The contours of $R_{\gamma\gamma}$ in $m_{\phi^0} - f$ plane (left) and $Br(h \rightarrow \phi^0 \phi^0) - f$ plane (right) for three typical values of $R_{\gamma\gamma} \geq 0.5, 0.7$ and 0.9 .

that the ratio $R_{\gamma\gamma}$ is insensitive to the variation of the mixing parameter M . Since the ATLAS diphoton data is above the SM value by about 2σ , the predicted rate in the LRTH model is always outside the 2σ range of the ATLAS data. But the theoretical prediction for $R_{\gamma\gamma}$ in the LRTH model is in good agreement with the current CMS data within 1σ error for $f \geq 600$ GeV. The key point here is the large difference between the central values reported by ATLAS and CMS respectively. Further improvement of the $R_{\gamma\gamma}$ measurements from both ATLAS and CMS collaboration are greatly welcome and will play the key role in constraining the new physics models beyond the SM.

In figure 5 we show the contours of $R_{\gamma\gamma}$ in $f-m_{\phi^0}$ plane and $f-Br$ plane for $R_{\gamma\gamma} \geq 0.5, 0.7$, and 0.9 , respectively. One can see that the assumption $R_{\gamma\gamma} \geq 0.7$ will indicate $f \geq 700$ GeV for $m_{\phi^0} = 60$ GeV, but leads to a limit $f \geq 900$ GeV for $m_{\phi^0} = 30$ GeV. From figure 5b, it is easy to see that one can draw strong constraint on the exotic decay rate $Br(h \rightarrow \phi^0 \phi^0)$ from the measured Higgs diphoton rate. A limit of $R_{\gamma\gamma} \geq 0.7$, for example, can result in a strong constraint $Br(h \rightarrow \phi^0 \phi^0) \leq 26\%$.

3.3 Global fit within LRTH model

Now we perform a global fit to the LRTH model with the method proposed in refs. [48–56] by using the latest LHC Higgs data from both ATLAS [5, 57–62] and CMS collaboration [6, 63–67]. We use 20 sets of experimental data which include the measured signal strengths for $\gamma\gamma$, ZZ^* , WW^* , $b\bar{b}$ and $\tau^+\tau^-$ channels, as listed explicitly in table 3.3.

When fitting the various observable, we considered the correlation coefficients given in ref. [68] due to the independent data for different exclusive search channels by two collaborations. The global χ^2 function is defined as:

$$\chi^2 = \sum_{i,j} (\mu_i - \hat{\mu}_i)(\sigma^2)_{ij}(\mu_j - \hat{\mu}_j), \quad (3.7)$$

Channel	Signal strength $\hat{\mu}_i$	LRTH predictions μ_i		
		f=800	f=1000	f=1200
ATLAS [5, 57–62]				
ggF+ttH, $\gamma\gamma$	1.60 ± 0.41	0.635	0.794	0.876
VBF+VH, $\gamma\gamma$	1.94 ± 0.82	0.726	0.856	0.928
ggF+ttH, ZZ^*	1.51 ± 0.52	0.639	0.798	0.879
VBF+VH, ZZ^*	1.99 ± 2.12	0.732	0.861	0.931
ggF+ttH, WW^*	0.79 ± 0.35	0.639	0.798	0.879
VBF+VH, WW^*	1.71 ± 0.76	0.732	0.861	0.931
VH tag, $b\bar{b}$	$0.2^{+0.7}_{-0.6}$	0.720	0.861	0.931
ggF+ttH, $\tau^+\tau^-$	2.31 ± 1.61	0.639	0.798	0.879
VBF+VH, $\tau^+\tau^-$	-0.20 ± 1.06	0.732	0.861	0.931
CMS [6, 63–67]				
ggF+ttH, $\gamma\gamma$	0.49 ± 0.39	0.635	0.794	0.876
VBF+VH, $\gamma\gamma$	1.65 ± 0.87	0.726	0.856	0.928
ggF+ttH, ZZ^*	0.99 ± 0.46	0.639	0.798	0.879
VBF+VH, ZZ^*	1.05 ± 2.38	0.732	0.861	0.932
0/1 jet, WW^*	0.76 ± 0.21	0.621	0.798	0.853
$Z(\nu\bar{\nu})h, b\bar{b}$	1.04 ± 0.77	0.720	0.861	0.925
$Z(l^+l^-)h, b\bar{b}$	0.82 ± 0.97	0.720	0.861	0.925
$W(l\nu)h, b\bar{b}$	1.11 ± 0.87	0.720	0.861	0.925
0/1 jet, $\tau^+\tau^-$	$0.76^{+0.49}_{-0.52}$	0.641	0.799	0.936
VBF tag, $\tau^+\tau^-$	$1.40^{+0.60}_{-0.57}$	0.734	0.873	0.936
VH tag, $\tau^+\tau^-$	$0.77^{+1.48}_{-1.43}$	0.732	0.861	0.931
χ^2	14.60	24.85	17.40	15.41
p -value	0.80	0.21	0.63	0.75

Table 1. The measured Higgs signal strengths $\hat{\mu}_i$ and the theoretical predictions μ_i in the LRTH model. Here we set $m_{\phi^0}=40$ GeV, $M=150$ GeV and $f = 800, 1000$, and 1200 GeV. The following corrections are included in the fit: $\rho_{\gamma\gamma} = -0.27$, $\rho_{ZZ^*} = -0.5$, $\rho_{WW^*} = -0.18$, $\rho_{\tau^+\tau^-} = -0.49$ for ATLAS, and $\rho_{\gamma\gamma} = -0.5$, $\rho_{ZZ} = -0.73$ for CMS.

where $\sigma_{ij}^2 = \sigma_i \rho_{ij} \sigma_j$, $\hat{\mu}_i$ and σ are the measured Higgs signal strengths and their 1σ error, ρ_{ij} is the correlation matrix, μ_i is the corresponding theoretical predictions in terms of the LRTH parameters. The details about the statistical treatment are presented in appendix A.

In figure 6a we plot χ^2 versus f for $M = 150$ GeV and $m_{\phi^0} = 20, 40$ and 60 GeV, respectively. One can see that the value of χ^2 of the LRTH model is larger than that for SM for most of parameter space of f and approaches the SM value for a sufficiently large f . For a light pseudoscalar ϕ^0 , for example setting $m_{\phi^0} = 20$ GeV, the Higgs data will lead to effective constraint on the value of the parameter f : $f \geq 1000$ (900) GeV at the 2σ (3σ) level.

In figure 6b we plot the p -values versus m_{ϕ^0} for $M = 150$ GeV and $f = 800, 1000$ and 1200 GeV, respectively. We note that the goodness of the fit in the SM, measured by

Figure 6. (a) the values of χ^2 versus f for $M = 150$ GeV and $m_{\phi^0} = 20, 40$ and 60 GeV; (b) the p -values versus m_{ϕ^0} for $M = 150$ GeV and $f = 800, 1000$ and 1200 GeV.

Figure 7. The contours of χ^2 of the branching ratio $Br(h \rightarrow \phi^0 \phi^0)$ at the 1σ , 2σ and 3σ level.

the p -value, is about 0.80, which means that the SM has a chance of 80% to be the true interpretation of the data. One can see that the p -value become smaller for the LRTH model in large part of its parameter space, and approaches the SM value for a sufficiently large f . For $m_{\phi^0} = 40$ GeV and $f = 1000(1200)$ GeV, its p -value is about 0.63(0.75).

In figure 7 we plot the contours of χ^2 for $Br(h \rightarrow \phi^0 \phi^0)$ against the parameter f . One can see that the current LHC Higgs data can put strict constraint on the exotic decay $h \rightarrow \phi^0 \phi^0$: for example, $Br(h \rightarrow \phi^0 \phi^0)$ should be less than 30% at 3σ level.

4 Phenomenology of a light ϕ^0

When the decay $h \rightarrow \phi^0 \phi^0$ is open, the decays $h \rightarrow \phi^0 \phi^0 \rightarrow 4b$, $2b2\tau$ or 4τ are the major promising channels to detect such a light pseudoscalar at the LHC experiments. As demonstrated in ref. [69], the process $pp \rightarrow W/Zh \rightarrow l + 4b + X$ (l denotes one lepton and

Figure 8. The value of C_{4b}^2 versus f for three values of m_{ϕ^0} .

X denotes anything) may provide a clean signature out of the backgrounds for a light Higgs boson. Following the suitable cuts, the signal rate depends on an overall scaling factor

$$C_{4b}^2 = \left(\frac{g_{VVh}^{\text{NP}}}{g_{VVh}^{\text{SM}}} \right)^2 \times Br(h \rightarrow \phi^0 \phi^0) \times Br^2(\phi^0 \rightarrow b\bar{b}), \quad (4.1)$$

which determines the cross section of the process $Vh \rightarrow V4b$ at the LHC [69, 70]. In the LRTH model, $y_V = g_{VVh}^{\text{LRTH}}/g_{VVh}^{\text{SM}} = 1 - v^2/(6f^2)$ [19]. The DELPHI Collaboration [71] has made model-independent searches for the process $e^+e^- \rightarrow Zh \rightarrow ZAA \rightarrow Z + 4b$ with A a pseudoscalar particle. However, the experimental upper bound on C_{4b}^2 is relaxed for this model ($C_{4b}^2 \geq 1$ for $m_h = 110$ GeV and $m_A = 12$ GeV), and it is the same case in the simplest little Higgs (SLH) model [72].

In figure 8 we plot the factor C_{4b}^2 versus the parameter f in the LRTH model. One can see that, for $f = 500$ GeV and $m_{\phi^0} = 20$ GeV, the value of C_{4b}^2 can be as large as 0.5. However, it is smaller than 0.2 after considering the bound of global fit at 3σ level. Noticing that the value of C_{4b}^2 is directly proportional to the factor $y_V^2 = (1 - v^2/(6f^2))^2$ in the LRTH model and thus becomes larger for a large f . For the process $pp \rightarrow W/Zh \rightarrow l + 4b + X$, the authors of refs. [69, 70] have shown that the cut on invariant mass of the four bottom quarks can suppress efficiently the relevant backgrounds. It is worth of mentioning that Cheung et al. studied the $h \rightarrow \eta\eta$ decay [69], calculated the total signal and background cross sections at parton level in the SLH model with $C_{4b}^2 = 0.16$ [69], and found a significance $S/\sqrt{B} = 3.7$ for a luminosity of 30 fb^{-1} . Of course, a much higher luminosity is needed to discover such a light scalar. For example, even for $C_{4b}^2 = 0.11$ in the SLH model, the significance $S/\sqrt{B}$ can be increased from 1.4 to 4.4 for a luminosity of 300 fb^{-1} . Considering the LHC Higgs data bound at 3σ level, we estimate the value of C_{4b}^2 is approximately 0.19 in the LRTH model ($C_{4b}^2 \simeq 0.3 \times 0.8^2$). Therefore, we hope that by using the suitable cuts, the possible signatures of the light scalar in the LRTH model may be detected via the process $pp \rightarrow Vh \rightarrow V4b$ at the LHC with a high luminosity of 300 fb^{-1} . Certainly, detailed confirmation of the observability of the signals would require Monte-Carlo simulations of the signals and backgrounds, which is beyond the scope of this paper.

Figure 9. The cross section of $e^+e^- \rightarrow h\phi^0$ at an electron-positron collider with $\sqrt{s} = 250$ GeV for $f = 500, 800$ GeV.

Figure 10. The cross sections at an electron-positron collider with $\sqrt{s} = 250$ GeV and $m_{\phi^0} = (40 \pm 20)$ GeV; (a) $e^+e^- \rightarrow Zh \rightarrow Z(\phi^0\phi^0) \rightarrow Z(4b)$, (b) $e^+e^- \rightarrow Zh \rightarrow Z(\phi^0\phi^0) \rightarrow Z(2b2\tau)$.

The light scalar ϕ^0 can also be produced associated with the SM-like Higgs h at the International Linear Collider (ILC), which has been studied in ref. [73]. The numerical results show that the resonance production cross section can be significantly enhanced at the high energy linear collider with $\sqrt{s} \simeq m_{Z_H}$. On the other hand, the properties of SM-like Higgs h can be precisely measured through the Zh associated production at the linear collider [74–76]. Here we calculate the cross sections of the process $e^+e^- \rightarrow h\phi^0$ and $e^+e^- \rightarrow Zh \rightarrow Z(\phi^0\phi^0) \rightarrow Z(4b, 2b2\tau)$ at an electron-positron collider with $\sqrt{s} = 250$ GeV, as shown in the figure 10. As shown in figure 9, the associated production rate $Br(e^+e^- \rightarrow h\phi^0)$ is smaller than the order of 10^{-2} fb at $\sqrt{s}=250$ GeV, which can hardly be utilized to search for the light scalar h . However, the production cross sections of processes $e^+e^- \rightarrow Zh \rightarrow Z4b$ and $e^+e^- \rightarrow Zh \rightarrow Z(\phi^0\phi^0) \rightarrow Z(2b2\tau)$ can reach 120 fb and 20 fb respectively, as illustrated in figure 10. Certainly, the cross sections would become smaller when we consider the global fit bound at 3σ level (reduced about two thirds). Since these signals are free of the SM background, such production process may contribute the light scalar discovery at an electron-positron collider.

5 Conclusions

The LRTH model predicts one neutral pseudoscalar particle ϕ^0 , which may be lighter than half of the Higgs boson mass. In this work we focus on the case of $m_{\phi^0} < m_h/2$ so that the new decay mode $h \rightarrow \phi^0 \phi^0$ can be open. In this work, we firstly calculated the decay widths and the branching ratios of the $h \rightarrow \phi^0 \phi^0$ decay, as well as the major decay modes of the ϕ^0 itself: such as $\phi^0 \rightarrow (b\bar{b}, c\bar{c}, \tau^+ \tau^-)$ and $\phi^0 \rightarrow (gg, \gamma\gamma)$ decays. We then examined the f , M and m_{ϕ^0} -dependence of the decay widths and corresponding branching ratios, and checked the possible constraints on the LRTH model from the latest LHC Higgs data on such a possibility. We performed a global fit by using 20 sets of the measured Higgs signal strengths as reported by ATLAS and CMS collaboration for $\gamma\gamma$, ZZ^* , WW^* , $b\bar{b}$ and $\tau^+ \tau^-$ channels. We also studied the detection of ϕ^0 at future electron-positron collider experiments.

From our numerical calculations and the phenomenological analysis we found the following points:

1. Without the LHC constraints, the branching ratio of the decay $h \rightarrow \phi^0 \phi^0$ can be as large as 80% and it can suppress significantly the visible $\gamma\gamma$ signal rate. The current LHC Higgs data for the $\gamma\gamma$ channel can place strong limit on such a decay: for example, $Br(h \rightarrow \phi^0 \phi^0) \leq 26\%$ for $R_{\gamma\gamma} \geq 0.7$.
2. The p -value of the SM Higgs boson is 0.80, which means that the SM is a reasonably good fit to the Higgs data. In the LRTH model, its p -value is smaller than that of the SM in most of the parameter space and approaches the SM value for a sufficiently large f parameter.
3. The latest LHC Higgs data constrain the branching ratio $Br(h \rightarrow \phi^0 \phi^0)$ to be less than 30% at 3σ level.
4. The neutral scalar ϕ^0 dominantly decay into $b\bar{b}$ and the decay rate $Br(\phi^0 \rightarrow b\bar{b})$ can be larger than 80% for $m_{\phi^0} \leq 60$ GeV. The second main decay mode is $\phi^0 \rightarrow \tau^+ \tau^-$ with a branching ratio about 14%. At the future $e^- e^+$ collider with $\sqrt{s} = 250$ GeV, the processes $e^+ e^- \rightarrow Zh \rightarrow Z(\phi^0 \phi^0) \rightarrow Z(4b, 2b2\tau)$ are promising for discovering such a light pseudoscalar ϕ^0 .

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A The statistical treatment and data

Take the $h \rightarrow \gamma\gamma$ for instance, the Higgs signal strength $\mu_{\gamma\gamma}$ can be defined as

$$\mu_{\gamma\gamma} = \frac{\epsilon_{ggF}\sigma_{ggF} + \epsilon_{VBF}\sigma_{VBF} + \epsilon_{VH}\sigma_{VH}}{\epsilon_{ggF}\sigma_{ggF}^{SM} + \epsilon_{VBF}\sigma_{VBF}^{SM} + \epsilon_{VH}\sigma_{VH}^{SM}} \times \frac{Br(h \rightarrow \gamma\gamma)}{Br(h \rightarrow \gamma\gamma)_{SM}}, \quad (\text{A.1})$$

where the coefficients ϵ accounting for the relative weight of each production channel given in [5, 6, 50]. The SM production cross sections and decay widths are taken from [47].

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

$$\delta\hat{\mu}_i = \sqrt{\frac{(\delta\hat{\mu}_+)^2 + (\delta\hat{\mu}_-)^2}{2}}, \quad (\text{A.2})$$

where $\delta\hat{\mu}_\pm$ are the one-sided errors given by the experimental collaborations [5, 6]. For plotting distributions of a function of one (two) parameter, the 68% (1σ), 95% (2σ) and 99.7% (3σ) confidence level (CL) intervals are obtained by $\chi^2 = \chi^2_{\min} + 1$ (2.3), $+4$ (6.18), and $+9$ (11.83), respectively [53].

For two correlated observables, the correlation coefficient ρ is applicable to the following formula

$$\chi^2_{1,2} = \frac{1}{(1 - \rho^2)} \cdot \left[\frac{[\mu_1 - \hat{\mu}_1]^2}{\sigma_1^2} + \frac{[\mu_2 - \hat{\mu}_2]^2}{\sigma_2^2} - 2\rho \frac{[\mu_1 - \hat{\mu}_1] \cdot [\mu_2 - \hat{\mu}_2]}{\sigma_1 \sigma_2} \right]. \quad (\text{A.3})$$

Assuming the goodness-of-fit statistics follow a χ^2 probability density function, the p -value for the hypothesis is given by [40]

$$p = \int_{\chi^2}^{\infty} \frac{z^{n/2-1} e^{-z/2}}{2^{n/2} \Gamma(n/2)} dz, \quad (\text{A.4})$$

where n is the degrees of freedom ($n = 20$ in this work).

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