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Full Text

Higgs-pair Production and Decay in the Simplest Little Higgs Model

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Abstract

In the framework of the simplest little Higgs model (SLHM), we study the production of a pair of neutral CP-even Higgs bosons at the LHC. First, we examine the production rate and find that it can be significantly larger than the SM prediction. Then we investigate the decays of the Higgs pair and find that for a low Higgs mass their dominant decay mode is $hh \to \eta\eta\eta\eta$ (where η is a CP-odd scalar), while $hh \to b\bar{b}\eta\eta$ and $hh \to \eta\eta WW$ may also have sizable branching ratios. Finally, we comparatively study the rates of $pp \to hh \to b\bar{b}\tau^+\tau^-$, $pp \to hh \to b\bar{b}\gamma\gamma$, and $pp \to hh \to b\bar{b}WW$ in the SLHM and the littlest Higgs models (LHT). We find that for a light Higgs, compared with the SM predictions, all three rates can be sizably enhanced in the LHT but severely suppressed in the SLHM; while for an intermediately heavy Higgs, both the LHT and SLHM can sizably enhance the SM predictions.

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Introduction

Little Higgs theory has been proposed as an interesting solution to the hierarchy problem. So far various realizations of the little Higgs symmetry structure have been proposed [2-5], which can be generally categorized into two classes [6]. One class uses the product group structure, represented by the littlest Higgs model [4], in which the SM $SU(2)_L$ gauge group emerges from the diagonal breaking of two (or more) gauge groups. The other class uses the simple group structure, represented by the simplest little Higgs model (SLHM) [5], in which a single larger gauge group is broken down to the SM $SU(2)_L$. Different realizations give different phenomenology that will be tested at the LHC. Since these little Higgs models mainly alter the properties of the Higgs boson and the top quark, hints of these models may be unraveled from various Higgs boson and top quark processes [7].

Higgs-pair production at the LHC, albeit with a small production rate, is rather important because it provides a way to probe the Higgs self-coupling λ. With the designed luminosity, it is possible for the LHC to establish that the SM Higgs boson has a non-zero self-coupling and the ratio $\lambda/\lambda_{\rm SM}$ can be restricted to a range of $0 \leq \lambda/\lambda_{\rm SM} \leq 3.7$ at 95% confidence level if its mass is between 150 GeV and 200 GeV [8]. Such Higgs-pair production is sensitive to new physics and has been studied in various new physics models [9]. In the littlest Higgs models without and with T-parity, this process was studied in [10] and [11], respectively. In this work, we study this process in the SLHM. We first examine the Higgs-pair production rate in the SLHM and compare it with the SM prediction. Then we study the decays of the Higgs pair. Finally, we study the rates of $pp \to hh \to b\bar{b}\tau^+\tau^-$ and $pp \to hh \to b\bar{b}\gamma\gamma$ in both models.

This work is organized as follows. In Sec. II we recapitulate the SLHM. In Sec. III we calculate the Higgs-pair production cross section at the LHC. In Sec. IV we study the decays of the Higgs pair and the rates of $pp \to hh \to b\bar{b}\tau^+\tau^-$ and $pp \to hh \to b\bar{b}\gamma\gamma$. Finally, we give our conclusion in Sec. V.

II. Simplest Little Higgs Model

The SLHM is based on $[SU(3)\times U(1)_X]^2$ global symmetry. The gauge symmetry $SU(3)\times U(1)_X$ is broken down to the SM electroweak gauge group by two copies of scalar fields Φ_1 and Φ_2, which are triplets under the $SU(3)$ with aligned VEVs f_1 and f_2. The uneaten five pseudo-Goldstone bosons can be parameterized as

$$\Phi_1 = e^{i\frac{t_\beta\Theta}{\sqrt{2}f}} \begin{pmatrix} 0 \\ 0 \\ f_1 \end{pmatrix}, \quad \Phi_2 = e^{-i\frac{t_\beta\Theta}{\sqrt{2}f}} \begin{pmatrix} 0 \\ 0 \\ f_2 \end{pmatrix}$$

where $f = \sqrt{f_1^2 + f_2^2}$ and $t_\beta \equiv \tan\beta = f_2/f_1$. Under the $SU(2)_L$ SM gauge group, η is a CP-odd singlet, while H transforms as a doublet and can be identified as the SM Higgs doublet. The kinetic term in the non-linear sigma model is

$$\mathcal{L}_{\rm kin} = \sum_{j=1,2} |D_\mu \Phi_j|^2$$

with $g_X = g\tan\theta_W/\sqrt{3-\tan^2\theta_W}$ and θ_W being the electroweak mixing angle. As Φ_1 and Φ_2 develop their VEVs, the new heavy gauge bosons Z', Y^0, and $W'^{\pm}$ acquire masses proportional to f.

The gauged $SU(3)$ symmetry promotes the SM fermion doublets into $SU(3)$ triplets. There are two possible gauge charge assignments for the fermions: the 'universal' embedding and the 'anomaly-free' embedding. The first choice is not favored by electroweak precision data [5], so we focus on the second embedding. The quark Yukawa interactions for the third generation and the first two generations can be written respectively as

$$\mathcal{L}_t = i\lambda_t \epsilon_{ijk} \Phi_1^i \Phi_2^j u_3^k + \text{h.c.},$$

$$\mathcal{L}_{1,2} = i\lambda_{dn} \epsilon_{ijk} \Phi_1^i Q_3^j d_n^k + i\lambda_{un} \epsilon_{ijk} \Phi_2^i Q_3^j u_n^k + \text{h.c.},$$

where $n = 1, 2$ are the first two generation indices; $i, j, k = 1, 2, 3$; $Q_3 = \{t_L, b_L, iT_L\}$; $Q_{1,2} = \{u_{nL}, d_{nL}, iD_{nL}\}$; u_3 runs over (u^c, c^c, t^c, T^c); d_n runs over $(d^c, s^c, b^c, D^c, S^c)$; u_n runs over (u^c, c^c, t^c). For simplicity, we assume the quark flavor mixing is small and neglect the mixing effects.

From the above equations, we can obtain the Higgs boson interactions and the mass terms for the three generations of quarks:

$$\mathcal{L}_t \simeq -\frac{\lambda_t}{2f^2} s_\beta \left[s_1 t_L + c_1 T_L\right] \bar{t}_c (h+v) + \text{h.c.},$$

$$\mathcal{L}_d \simeq -\frac{\lambda_{dn}}{2f^2} s_\beta \left[s_2 d_{nL} + c_2 D_{nL}\right] \bar{d}_{nc} (h+v) + \text{h.c.},$$

$$\mathcal{L}_q \simeq -\frac{\lambda_q}{2f^2} s_\beta c_\beta s_{3q} \bar{q}_L q_R (h+v) + \text{h.c.} \quad (q = u, c, b)$$

where $s_\beta \equiv \frac{t_\beta(h+v)}{\sqrt{2}t_\beta f}$, $c_\beta \equiv \frac{(h+v)(t_\beta^2+1)}{\sqrt{2}t_\beta f}$, with h and v being the neutral Higgs boson field and its VEV, respectively. The mass eigenstates (t_{mL}, T_{mL}) and (t^c_{mL}, T^c_{mL}) are obtained by mixing the corresponding interaction eigenstates. The diagonalization of the mass matrix was performed numerically in our analysis, and the relevant couplings with the Higgs boson can also be obtained without resorting to any expansion of v/f. Hereafter we denote the mass eigenstates without the subscript 'm' for simplicity.

The Yukawa and gauge interactions break the global symmetry and then provide a potential for the Higgs boson. However, the Coleman-Weinberg potential alone is not sufficient since the generated Higgs mass is too heavy and the new CP-odd scalar η is massless. Therefore, one can introduce a tree-level μ term which can partially cancel the Higgs mass [5, 12]:

$$\mu^2(\Phi_1^\dagger\Phi_2 + \text{h.c.}) = 2\mu^2 f^2 s_\beta c_\beta \cos\left(\frac{\sqrt{2}s_\beta c_\beta f}{\sqrt{H^\dagger H}}\right).$$

The scalar potential becomes

$$V = m^2 H^\dagger H + \lambda(H^\dagger H)^2 + m_\eta^2\eta^2 + \lambda' H^\dagger H\eta^2 + \cdots$$

where

$$m^2 = m_0^2 - \frac{\mu^2}{t_\beta f^2}, \quad \lambda = \lambda_0 + \frac{\mu^2}{4f^2 s_\beta^3 c_\beta^3},$$

with m_0 and λ_0 being respectively the one-loop contributions to the Higgs boson mass and the quartic couplings from fermion loops and gauge boson loops [5].

The Higgs VEV, the Higgs boson mass, and the mass of η are given by

$$v = \frac{2m^2 f s_\beta c_\beta}{\mu^2}, \quad m_h^2 = 2\lambda v^2, \quad m_\eta^2 = m_0^2 + \lambda' v^2.$$

The Coleman-Weinberg potential involves the following parameters: f, t_β, μ, m_η, m_h, v. Due to the modification of the observed W gauge boson mass, v is defined as [12]

$$v^2 = v_0^2\left(1 - \frac{v_0^2}{12f^2}\frac{t_\beta^4 + t_\beta^2 + 1}{t_\beta^2}\right),$$

where $v_0 = 246$ GeV is the SM Higgs VEV. Assuming that there are no large direct contributions to the potential from physics at the cutoff, we can determine other parameters from f, t_β, and m_h with the definition of v in Eq. (15).

III. Higgs-Pair Production at LHC

At the LHC the Higgs-pair production can proceed through gluon-gluon fusion and $b\bar{b}$ annihilation, as shown in Figs. 1 and 2, respectively. For the $b\bar{b}$ annihilation process, the SLHM can give additional contributions through the tree-level $hhb\bar{b}$ coupling and the modified $hb\bar{b}$ coupling. For the gluon-gluon fusion process, the top-quark loops give additional contributions through the tree-level $hht\bar{t}$ coupling and the modified $ht\bar{t}$ coupling. In addition to the top-quark loops, the loops of the new heavy partner quarks T, D, and S also come into play. Due to the large top quark Yukawa coupling and the large parton distribution function of gluons at the LHC, the contributions from the gluon-gluon fusion process dominate over those from the $b\bar{b}$ annihilation process.

The calculations of the loop diagrams in Fig. 1 [Figure 1: see original paper] are straightforward. Each loop diagram is composed of scalar loop functions [13] which are calculated using LoopTools [14]. The calculations are tedious and the analytical expressions are lengthy, so they are not presented here. The hadronic cross section at the LHC is obtained by convoluting the parton cross section with the parton distribution functions. In our calculations we use CTEQ6L [15] to generate the parton distributions with the renormalization scale μ_R and the factorization scale μ_F chosen to be $\mu_R = \mu_F = 2m_h$, and we use the two-loop running coupling constant α_s with $\alpha_s(m_Z) = 0.118$.

The SM input parameters relevant to our study are taken as $m_t = 171.2$ GeV and $m_Z = 91.1876$ GeV [16]. The free SLHM parameters are f, t_β, m_h, x_d, and x_s. As shown above, the parameters μ, m_η can be determined by f, t_β, m_h, and v. The small mass of the d (s) quark requires one of the couplings λ_d^1 and λ_d^2 (λ_s^1 and λ_s^2) to be very small, so there is almost no mixing between the SM down-type quarks and their heavy partners. We assume $\lambda_d^1 = 1.1 \times 10^{-3}$ and $\lambda_s^1 = 2.1 \times 10^{-4}$, which can make the masses of D and S in the range of 1-2 TeV with other parameters fixed as in our calculations. In fact, our results show that the contributions from d and D (s and S) are small compared with the effects from t and T. Therefore, different choices of x_d and x_s do not have sizable effects on our results.

Electroweak precision data can give strong constraints on the scale f. Reference [5] shows that LEP-II data requires $f > 2$ TeV. In addition, the contributions to electroweak precision data can be suppressed by large t_β. Reference [17] gives a lower bound of $f > 4.5$ TeV from the oblique parameter S, while a recent study of Z leptonic decay gives a stronger bound of $f > 5.6$ TeV [18]. Considering these bounds, we take $f = 4$ TeV or $f = 5.6$ TeV with a large $\tan\beta$ to illustrate our results.

In Fig. 3 [Figure 3: see original paper], we take several values of $\tan\beta$ and plot the hadronic cross section of Higgs-pair production at the LHC versus the Higgs boson mass. We find that compared with the SM prediction, the cross section in the SLHM can be significantly enhanced for large $\tan\beta$. For example, with $\tan\beta = 18$ (25) and $f = 4$ TeV (5.6 TeV), the cross section can be enhanced by 80% for $m_h = 110$ GeV. Of course, for perturbation theory to remain valid, $\tan\beta$ cannot be too large for fixed f. As shown in Eq. (15), the correction to the Higgs VEV is proportional to $\tan^2\beta v_0^2/f^2$. If we require $(\tan^2\beta v_0^2/f^2) < 0.1$ in the expansion of v, the value of $\tan\beta$ should be below 20 (28) for $f = 4$ TeV (5.6 TeV). For larger f, the value of $\tan\beta$ can be larger and partially cancel the suppression of v/f. Therefore, the maximal value of the cross section does not always decrease with increasing f.

IV. Final States of Higgs-Pair Production

The Higgs-pair production can give various final states, depending on the decay modes of the Higgs boson. The SLHM corrections to the tree-level decays $h \to f\bar{f}, WW, ZZ$ mainly come from the corresponding modified couplings:

$$\Gamma(h \to XX) = \Gamma(h \to XX)_{\rm SM} \left(\frac{g_{hXX}}{g_{hXX}^{\rm SM}}\right)^2 ,$$

where XX denotes WW, ZZ, or fermion pairs, and $\Gamma(h \to XX)_{\rm SM}$ is the SM decay width. g_{hXX} and $g_{hXX}^{\rm SM}$ are the couplings of hXX in the SLHM and SM, respectively. The couplings g_{hWW} and g_{hZZ} can be found in [12].

For low Higgs mass, the loop-induced decay $h \to gg$ is also important. In addition to the top quark loops, the loops of new heavy quarks (T, D, S) come into play. For another important loop-induced decay mode $h \to \gamma\gamma$, in addition to the contributions from the top quark and W boson, the new charged heavy fermions (T, D, S) and gauge bosons $W'^{\pm}$ make contributions. Following the approach in [19], the partial decay width of $h \to \gamma\gamma$ can be calculated at one-loop level. For the SM decay channels, the relevant higher-order QCD and electroweak corrections are considered using the code Hdecay [20].

In addition to the SM decay modes, the Higgs boson in the SLHM has two new important decay modes, $h \to \eta\eta$ and $h \to Z\eta$, in the kinematically allowed parameter space. Their partial widths are given by

$$\Gamma(h \to \eta\eta) = \frac{m_h^3}{32\pi f^2} \left(\frac{t_\beta}{t_\beta^2 + 1}\right)^2 \sqrt{1 - 4x_\eta}\,(1 - 2x_\eta + 2x_\eta^2)\,,$$

$$\Gamma(h \to Z\eta) = \frac{m_h^3}{48\pi f^2} \left(\frac{t_\beta}{t_\beta^2 + 1}\right)^2 \left(1 - \frac{m_Z^2}{m_h^2}\right)^3 \lambda^{1/2}(1, x_\eta, x_Z)\,(1 + 2x_Z)\,,$$

where $x_\eta = 4m_\eta^2/m_h^2$, $x_Z = m_Z^2/m_h^2$, and $\lambda(1,x,y) = (1-x-y)^2 - 4xy$. These two decay channels can be dominant in the allowed parameter space [12] and provide new signatures of Higgs-pair production.

Fig. 4 [Figure 4: see original paper] shows the decay branching ratios of the Higgs pair versus the Higgs boson mass (we only plot decay modes with branching ratio above 0.1). We see that the dominant decay channel is $hh \to \eta\eta\eta\eta$ for Higgs mass below 140 GeV. In the SM, the decay $hh \to b\bar{b}b\bar{b}$ has the largest branching ratios. Besides, the decays $hh \to b\bar{b}\eta\eta$ and $hh \to \eta\eta WW$ can also be important, with branching ratios much larger than $hh \to b\bar{b}b\bar{b}$ in some parts of parameter space.

The decays of η have been studied in [22, 23]. For 10 GeV $< m_\eta <$ 100 GeV, η decays mainly into $b\bar{b}$, $\tau^+\tau^-$, or gg. With increasing m_η, the branching ratios of $\eta \to \tau^+\tau^-$ decrease while the decay $\eta \to gg$ increases and may surpass the ratio of $\eta \to b\bar{b}$. The branching ratio of $\eta \to \tau^+\tau^-$ is about 10% of $\eta \to b\bar{b}$.

In the SM the promising channels are $pp \to hh \to b\bar{b}\tau^+\tau^-$ and $pp \to hh \to b\bar{b}\gamma\gamma$ for $m_h <$ 140 GeV [24], and $pp \to hh \to b\bar{b}WW$ for heavier Higgs masses. Fig. 5 [Figure 5: see original paper] shows the rates of $\sigma(pp \to hh) \times \mathrm{BR}(hh \to b\bar{b}\tau^+\tau^-)$, $\sigma(pp \to hh) \times \mathrm{BR}(hh \to b\bar{b}\gamma\gamma)$, and $\sigma(pp \to hh) \times \mathrm{BR}(hh \to b\bar{b}WW)$, and compares our results with the predictions of two types of littlest Higgs models with T-parity (LHT-I and LHT-II). The detailed descriptions of LHT-I and LHT-II can be found in [3, 25]. We see that for $m_h <$ 130 GeV all three rates can be sizably enhanced in LHT-I and LHT-II, but significantly suppressed in the SLHM. For larger values of m_h, both the SLHM and LHT-I/LHT-II can sizably enhance the SM predictions (in the SLHM for $m_h >$ 150 GeV, while in the LHT for $m_h >$ 170 GeV).

V. Conclusion

In the framework of the simplest little Higgs model (SLHM), we studied the production of a pair of neutral CP-even Higgs bosons at the LHC and obtained the following observations: (i) The Higgs-pair production rate in the SLHM can be significantly larger than the SM prediction; (ii) For a low Higgs mass the dominant decay mode of the Higgs pair is $hh \to \eta\eta\eta\eta$ (where η is a CP-odd scalar), while $hh \to b\bar{b}\eta\eta$ and $hh \to \eta\eta WW$ may also have sizable branching ratios; (iii) For a light Higgs boson, all the rates of $pp \to hh \to b\bar{b}\tau^+\tau^-$, $pp \to hh \to b\bar{b}\gamma\gamma$, and $pp \to hh \to b\bar{b}WW$ are suppressed in the SLHM, while for an intermediately heavy Higgs, all three rates can be sizably enhanced in both the littlest Higgs models and the SLHM.

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Note: Figure translations are in progress. See original paper for figures.