Higgs boson production in photon-photon collision at ILC: a comparative study in different little Higgs models (postprint)

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Full Text

Higgs Boson Production in Photon-Photon Collisions at the ILC: A Comparative Study of Different Little Higgs Models

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Abstract

We study the process $\gamma\gamma \to$ h $\to$ b¯b at the ILC as a probe of different little Higgs models, including the simplest little Higgs model (SLH), the littlest Higgs model (LH), and two types of littlest Higgs models with T-parity (LHT-I, LHT-II). Compared with the Standard Model (SM) prediction, the production rate is found to be sizably altered in these little Higgs models and, more interestingly, different models give different predictions. We find that the production rate can be possibly enhanced only in the LHT-II for some part of the parameter space, while in all other cases the rate is suppressed. The suppression can be 10% in the LH and as much as 60% in both the SLH and the LHT-I/LHT-II. The severe suppression in the SLH happens for a large tan β and a small mh, in which the new decay mode h $\to$ (is a light pseudo-scalar) is dominant; while for the

LHT-I/LHT-II the large suppression occurs when f and mh are both small so that the new decay mode h → A_H A_H is dominant. Therefore, the precision measurement of such a production process at the ILC will allow for a test of these models and even distinguish between different scenarios.

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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, which can be generally categorized into two classes. One class uses the product group, represented by the littlest Higgs model (LH), in which the SM SU(2)_L gauge group originates from the diagonal breaking of two (or more) gauge groups. The other class uses the simple group, represented by the simplest little Higgs model (SLH), in which a single larger gauge group is broken down to the SM SU(2)_L. However, due to the tree-level mixing of heavy and light mass eigenstates, electroweak precision tests can give strong constraints on these models, which would require raising the mass scale of new particles to much higher than a TeV and thus reintroduce fine-tuning in the Higgs potential.

To tackle this problem, a discrete symmetry called T-parity has been proposed, which forbids those tree-level contributions to electroweak observables. For the LH, there are two different versions of implementing T-parity in the top quark Yukawa interaction. In the pioneer version of this model (hereafter called LHT-I), T-parity is simply implemented by adding the T-parity images for the original top quark interaction to make the Lagrangian T-invariant. A characteristic prediction of this model is a T-even top partner which cancels the Higgs mass quadratic divergence contributed by the top quark. An alternative implementation of T-parity has been proposed (hereafter called LHT-II), where all new particles including the heavy top partner responsible for canceling the SM one-loop quadratic divergence are odd under T-parity. The implementation of T-parity in the SLH model has also been attempted.

These little Higgs models mainly alter the properties of the Higgs boson, and hence hints of these models can be unraveled from various Higgs boson processes. The Higgs decay and main production channels at the LHC have been studied in the SLH, the LH, and the LHT-I and LHT-II. While the LHC is widely regarded as a discovery machine for the Higgs boson and could possibly allow for measurement of decay partial widths at the 10%-30% level, precision measurement of Higgs properties can only be achieved at the proposed International Linear Collider (ILC). With the ILC, the Higgs nature can be scrutinized through production in photon-photon collisions, where the photon beam can be obtained by backscattering laser light from high-energy e± beams. Such a photon-photon collision option could possibly measure the rates of Higgs → b¯b process with precision of a few percent. In particular, the $\gamma\gamma$ production rate could be measured to about 2% for a light Higgs boson.

The process $\gamma\gamma \to$ h $\to$ b¯b is a sensitive probe for new physics because both the loop-induced h$\gamma\gamma$ coupling and the hb¯b coupling are sensitive to new physics. Considering the sizable alteration of Higgs couplings in various little Higgs models, we in this work study $\gamma\gamma \to$ b¯b as a probe of different little Higgs models, including the SLH, LH, LHT-I, and LHT-II. Note that this process has been studied in the LH and also in the SLH. In our study we give a comprehensive and comparative analysis for all these models. In addition, since a recent study of Z leptonic decay gave a new stronger bound on the parameter f in the SLH, we will consider such a new bound in our calculation for the SLH.

This work is organized as follows. In Sec. II we recapitulate the models. In Sec. III we calculate the rate of $\gamma\gamma \to$ b¯b in these models. Finally, we give our conclusion in Sec. IV.

II. Little Higgs Models

A. Simplest Little Higgs Model

The SLH model is based on [SU(3) × U(1)_X]^2 global symmetry. The gauge symmetry SU(3) × 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 SU(3) with aligned VEVs f_1 and f_2. The uneaten five pseudo-Goldstone bosons can be parameterized as:

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

with f = √(f_1^2 + f_2^2) and t_β tanβ = f_2/f_1. Under the SM SU(2)_L gauge group, is a singlet CP-odd scalar, while H transforms as a doublet and can be identified as the SM Higgs doublet. The other five Goldstones are eaten by new gauge bosons Z', W'^{0}, W̄'^{0}, and W'±, which obtain masses proportional to f:

$$m_{W'}^2 = \frac{1}{2}g^2 f^2, \quad m_{W'}^2 = \frac{1}{2}g^2 f^2, \quad m_{Z'}^2 = \frac{g^2 f^2}{\cos^2\theta_W}$$

with _W being the electroweak mixing angle.

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. Since the first choice is not favored by electroweak precision data, we focus on the second embedding. The top, strange, and down quarks have heavy partner quarks T, S, and D, respectively. The mixing between light quarks and heavy partners can be parameterized by:

$$\lambda_q^1 c_\beta \lambda_q^c + \lambda_q^2 s_\beta \lambda_q^c$$

To leading order, the heavy partners have masses proportional to f:

$$m_Q^2 = \left[(\lambda_q^1 c_\beta)^2 + (\lambda_q^2 s_\beta)^2\right] f^2$$

where Q = T, D, S; q = t, d, s; c_β = f_1/√(f_1^2 + f_2^2), s_β = f_2/√(f_1^2 + f_2^2); and λ_q^1 and λ_q^2 are two dimensionless couplings in the q-quark Yukawa sector.

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 is massless. Therefore, one can introduce a tree-level term which can partially cancel the Higgs mass:

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

Then 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

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

with m_0^2 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.

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

$$v = \sqrt{\frac{-m^2}{\lambda}}, \quad m_h^2 = 2\lambda v^2, \quad m_\eta^2 = \mu^2 \frac{\sqrt{2}}{f s_\beta c_\beta}$$

The Coleman-Weinberg potential involves the following parameters: f, t_β, λ_t, λ, , m_ , m_h, v.

Due to the modification of the observed W-boson mass, v is defined as:

$$v^2 = v_{\text{SM}}^2 \left[1 + \frac{v_{\text{SM}}^2}{12 f^2}(t_\beta^2 + 1) + \frac{v_{\text{SM}}^4}{180 f^4}(t_\beta^4 + t_\beta^2 + 1)\right]$$

where v_{SM} = 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 in Eq. (10) from f, t_β, and m_h with the definition of v in Eq. (11).

B. Littlest Higgs Model

The LH model is based on a non-linear σ model in the coset space SU(5)/SO(5) with additional local gauge symmetry $[\mathrm{SU}(2) \times \mathrm{U}(1)]^2$. A VEV of an SU(5) symmetric tensor field breaks SU(5) to SO(5) at scale f with:

$$\Sigma_0 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}$$

The non-linear sigma fields are then parameterized by the Goldstone fluctuations as:

$$\Sigma(x) = e^{i\Pi/f}\Sigma_0 e^{i\Pi^T/f} = \begin{pmatrix} \Phi & H \\ H^T & \Phi^* \end{pmatrix}$$

where H is a doublet and ϕ is a triplet under the unbroken SU(2)_L. The other four Goldstones are eaten by new gauge bosons W_H$\pm$, Z_H, and A_H, which get masses of order f:

$$m_{Z_H}^2 = m_{W_H}^2 = m_{A_H}^2 = \frac{1}{4}g^2 f^2$$

with c, s, c', and s' being the mixing parameters in the gauge boson sector given by:

$$\cos\theta = \frac{g_1}{\sqrt{g_1^2 + g_2^2}}, \quad \cos\theta' = \frac{g_1'}{\sqrt{{g'}_1^2 + {g'}_2^2}}$$

$$\sin\theta = \frac{g_2}{\sqrt{g_1^2 + g_2^2}}, \quad \sin\theta' = \frac{g_2'}{\sqrt{{g'}_1^2 + {g'}_2^2}}$$

where g_j and g'_j are the SU(2)_j and U(1)_j (j = 1, 2) gauge coupling constants, respectively.

The top quark loops, gauge boson loops, and scalar particle loops can generate the Higgs potential, which triggers electroweak symmetry breaking. The heavy bosons can further mix with light bosons, leading to corrections to the masses of heavy and light gauge bosons at $\mathrm{O}(\mathrm{v}^2/\mathrm{f}^2)$.

The components Φ^{++}, Φ^{+}, Φ^{0}, and Φ_P (neutral pseudo-scalar) of the triplet ϕ get a mass:

$$m_{\Phi}^2 = \lambda f^2 \left(1 + \frac{x^2}{4}\right)$$

where x is a free parameter of the Higgs sector proportional to the triplet VEV v' and defined as:

$$x = \frac{4fv'}{v^2}$$

with v being the LH Higgs VEV given by:

$$v = v_{\text{SM}} \left[1 - \frac{v_{\text{SM}}^2}{8f^2}\left(1 - \frac{x^2}{12}\right)\right]$$

In the fermion sector, there is an extra top quark partner T-quark, which cancels the Higgs mass one-loop quadratic divergence contributed by the top quark. The mixing between t and T can be parameterized by:

$$\lambda_1 \lambda_2 f$$

$$c_t = \frac{\lambda_1}{\sqrt{\lambda_1^2 + \lambda_2^2}}, \quad s_t = \frac{\lambda_2}{\sqrt{\lambda_1^2 + \lambda_2^2}}$$

where λ_1 and λ_2 are two dimensionless couplings in the top quark Yukawa sector. Together with f, these parameters control the T-quark mass:

$$m_T = \frac{s_t c_t v}{f} \lambda_2 f$$

C. Littlest Higgs Models with T-Parity

In the LHT-I, T-parity is simply implemented by adding the T-parity images for the original top quark interaction to make the Lagrangian T-invariant. A characteristic prediction of this model is a T-even top partner which cancels the Higgs mass quadratic divergence contributed by the top quark. Inspired by the way the top quadratic divergence is cancelled in the SLH, Ref. [11] proposes an alternative implementation of T-parity in LHT-II, where all new particles including the heavy top partner responsible for canceling the SM one-loop quadratic divergence are odd under T-parity. Thus, Higgs couplings with top quark and partners in the two models have sizable differences. Besides, for each SM quark (lepton), a copy of mirror quark (lepton) with T-odd quantum number is added to preserve T-parity. The Higgs couplings with down-type T-odd fermions are absent, and the couplings with up-type T-odd fermions are different in LHT-I and LHT-II. For these reasons, LHT-I and LHT-II can give distinct predictions for production rates of single Higgs, Higgs-pair, and a Higgs boson associated with a pair of top and anti-top quarks at the LHC.

For the SM down-type quarks (leptons), the Higgs couplings have two different cases:

$$g_{h\bar{d}d} \simeq \frac{m_d}{v}\left(1-\frac{v^2}{f^2}\right) \quad \text{for Case A}$$

$$g_{h\bar{d}d} \simeq \frac{m_d}{v}\left(1-\frac{v^2}{2f^2}\right) \quad \text{for Case B}$$

The same relation applies to lepton couplings.

The LHT-I and LHT-II have the same kinetic term for the Σ field where T-parity can be naturally implemented by setting g_1 = g_2 and g'_1 = g'_2. Under T-parity, the SM bosons are T-even and the new bosons are T-odd. Therefore, the coupling H†ϕH is forbidden, leading to the triplet VEV v' = 0. In both LHT-I and LHT-II, the Higgs VEV v is modified as:

$$v = v_{\rm SM}\left(1+\frac{v_{\rm SM}^2}{12f^2}\right)$$

III. The Process $\gamma\gamma \to$ b¯b in Little Higgs Models

A. Calculations

We consider photon-photon collisions at the ILC with photon beams obtained by Compton backscattering of lasers from e± beams. The cross section $\sigma(\gamma\gamma \to$ h) at the ILC is obtained by folding the cross section σ̂_{γγ→h}(ŝ) with the photon luminosity:

$$\sigma(s) = \int_{x_{\min}}^{x_{\max}} dx \int_{\tau_{\min}}^{\tau_{\max}} d\tau\, f_{\gamma/e}(x) f_{\gamma/e}(\tau/x)\hat{\sigma}_{\gamma\gamma\to h}(\hat{s})$$

where f_{γ/e}(x) is the energy spectrum of the back-scattered photon. The cross section $\hat{\sigma}$ is given by:

$$\hat{\sigma}_{\gamma\gamma\to h}(\hat{s}) = \hat{\sigma}^{\rm SM}_{\gamma\gamma\to h}(\hat{s}) \times \frac{\Gamma(h\to b\bar{b})}{\Gamma_{\rm SM}(h\to b\bar{b})}$$

where ŝ = τs with √s being the center-of-mass energy of the ILC. The rate of $\gamma\gamma$ $\to$ b¯b can be approximately obtained by $\sigma(\gamma\gamma \to$ h) × BR(h $\to$ b¯b). So we need to calculate both the production cross section $\sigma(\gamma\gamma \to$ h) and the decay widths.

Now we discuss Higgs decays in little Higgs models. For tree-level decays h $\to$ f¯f (SM fermion pair), WW, and ZZ, the little Higgs models give corrections via modified couplings:

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

where XX denotes WW, ZZ, or fermion pairs, Γ(h $\to$ XX)*{SM} is the SM decay width, and g*{hXX} and g_{hXX}^{SM} are the couplings of hXX in the little Higgs models and SM, respectively.

The loop-induced decay h $\to$ gg will also be important for a low Higgs mass. The effective coupling of hgg is presented in Appendix A. In the SM, the main contributions are from the top quark loop, and the little Higgs models give corrections via modified couplings h¯tt. In addition, the decay width of h $\to$ gg can also be corrected by loops of heavy partner quarks T, D, and S in SLH (T quark in LH) (new T-even and T-odd quarks in LHT-I and LHT-II).

For the decay h $\to \gamma\gamma$, the main contributions are from the top quark loop and W-boson loop in the SM. The little Higgs models give corrections via modified couplings h¯tt and hWW. In these models, the new quarks that contribute to h $\to$ gg also contribute to h $\to \gamma\gamma$. In addition to contributions from fermion loops, the $\gamma\gamma$ decay width can also be corrected by loops of W' in SLH (W_H, Φ^+, Φ^{++} in LH, LHT-I, and LHT-II). The effective coupling of h$\gamma\gamma$ can be found in Appendix A.

In addition to SM decay modes, the Higgs boson in SLH, LHT-I, and LHT-II has new important decay modes that are kinematically allowed in parts of parameter space. In SLH, the new decay modes are h $\to$ and h $\to$ Z , with partial widths given by:

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

$$\Gamma(h \to Z\eta) = \frac{g_{hZ\eta}^2}{16\pi m_h^3}\sqrt{\lambda(1, x_Z, x_\eta)}$$

where x_ = 4m_ ^{2}/m_h^2 and λ(1, x, y) = (1 - x - y)^2 - 4xy.

In the LH, the new decay mode is h $\to$ A_H A_H, with partial width:

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

where x_{A_H} = 4m_{A_H}^{2}/m_h^2, and g_{hA_H A_H} is the coupling constant of hA_H A_H. Note that the breaking scale f in LHT-I may be as low as 500 GeV, and the constraint in LHT-II is expected to be even weaker. Therefore, for lower values of f, the lightest T-odd particle A_H may have a light mass, m_{A_H} < m_h. In the LH, electroweak precision data requires f larger than a few TeV, and thus the decay h → A_H A_H is kinematically forbidden.

In our calculations, the SM input parameters are taken from [30]. For SM decay channels, relevant higher-order QCD and electroweak corrections are considered using the code Hdecay. In SLH, the new free parameters are f, t_β, x_t, λt, λ, *, m_ . As shown above, the parameters , m_ can be determined by f, tβ*, m_h, and v. The small mass of the d (s) quark requires one of the couplings λ_d^1 (λ_s^1) to be very small, so there is almost no mixing between SM down-type quarks and their heavy partners. We assume λd^1 *(*λs^1) is small, and take x_d λ = 1.1×10^{-4} (x_s $\lambda = 2.1 \times 10^{-3}$), which can make the masses of D and S in the range of 1-2 TeV with other parameters fixed as in our calculation. In fact, our results show that contributions from d and D (s and S) are very small compared with effects from t and T. Electroweak precision data can give strong constraints on the scale f. Ref. [4] shows that LEP-II data requires f > 2 TeV. In addition, contributions to electroweak precision data can be suppressed by large tβ*. Ref. [7] gives a lower bound f > 4.5 TeV from the oblique parameter S, while a recent study of Z leptonic decay gives a stronger bound f > 5.6 TeV. Considering these bounds, in our numerical calculation we will take several values of t*β for f = 2 TeV, f = 4 TeV, and f = 5.6 TeV.

In the LH model, the new free parameters are f, c_t (r), c, c', and x, where 0 < c_t < 1, 0 < c < 1, 0 < c' < 1, 0 < x < 1. Taking f = 1 TeV, f = 2 TeV, and f = 4 TeV, we scan over these parameters in the above ranges and show scatter plots. Note that the widths Γ(h → t¯t), Γ(h → gg), and Γ(h → $\gamma\gamma$) involve the parameter c_t which can control Higgs couplings with t, T, and m_T. For a light Higgs boson, the decay mode h → t¯t is kinematically forbidden. For the decays h → gg and h → $\gamma\gamma$, the c_t dependence of the top-quark loop can cancel that of the T-quark loop to a large extent. Therefore, the rate $\sigma(\gamma\gamma \to$ b¯b) is not sensitive to c_t for a light Higgs boson.

In LHT-I and LHT-II, the parameters c, c', and x are fixed as c = c' = x = 0. The heavy T-even and T-odd quarks only have large contributions to the decay widths of h → gg and h → $\gamma\gamma$, which are not sensitive to the actual values of their masses as long as they are much larger than half of the Higgs boson mass. Similar to the LH model, the result is not sensitive to c_t in LHT-I and LHT-II. Taking c_t = 1/√2 (λ_1 = λ_2) can simplify the top quark Yukawa sector in LHT-II, and this choice is also favored by electroweak precision data. Therefore, in our numerical calculations we take c_t = 1/√2.

B. Discussions

The numerical results for the rate $\sigma(\gamma\gamma \rightarrow b^{-}b)$ are shown in Figs. 1, 2, and 3, normalized to the SM prediction. We see that the rate in all these little Higgs models can have sizable deviations from the SM prediction, and the magnitude of deviation is sensitive to the scale f.

Fig. 1 [Figure 1: see original paper] shows that the SLH model always suppresses the rate, and the suppression is more sizable for large tan β. When tan β is large enough, such as t_β = 10 for f = 2 TeV (t_β = 18 for f = 4 TeV or t_β = 25 for f = 5.6 TeV), the suppression can be as much as 90%. The reason for such severe suppression is that the decay mode h $\rightarrow$ can be dominant in some parts of parameter space, making the total Higgs decay width much larger than the SM value. Note that tan β cannot be too large for a fixed f in order for perturbation theory to remain valid, as the correction to the Higgs VEV is proportional to $\tan^2\beta$ v_{SM}^{2}/f^2. If we require (v_{SM}^{2}/f^2) $<$ 0.1 in the expansion of v, the value of tan β should be below 10, 20, and 28 for f = 2 TeV, 4 TeV, and 5.6 TeV, respectively.

Fig. 2 [Figure 2: see original paper] shows that the LH model also always suppresses the rate $\sigma(\gamma\gamma \rightarrow b^{-}b)$, but the suppression can only reach about 10%. For a light Higgs boson or large f, the suppression is small and not sensitive to the parameters c, c', c_t, and x. For example, for f = 2 TeV the suppression is only a few percent.

Fig. 3 [Figure 3: see original paper] shows that LHT-I always suppresses the rate but LHT-II can either suppress or enhance the rate, depending on the Higgs mass and scale f. For each model the rate in Case A is always above the rate in Case B because the hb^{-}b coupling in Case A is less suppressed than in Case B. Also, we see that for f = 500 GeV and m_h in the range of 130-150 GeV, the rate in both models drops drastically. The reason for such severe suppression is similar to what happens in the SLH model: the opening of a new decay mode (now h $\rightarrow$ A_H A_H). From these results we see that the Higgs production process $\gamma\gamma \rightarrow b^{-}b$ can be a powerful probe for various little Higgs models. As shown in the literature, the photon-photon collision option of the ILC can probe top-quark-related new physics more effectively than e^+e^- collisions. Therefore, such a photon-photon collision option is well motivated from the viewpoint of probing new physics.

IV. Conclusion

We studied the process $\gamma\gamma \rightarrow b^{-}b$ at the photon-photon collision option of the ILC as a probe of different little Higgs models, including the SLH, LH, LHT-I, and LHT-II. We obtained the following observations: (i) Compared with the SM prediction, the SLH, LH, and LHT-I always suppress the rate of $\gamma\gamma \rightarrow b^{-}b$, while LHT-II can either suppress or enhance the rate depending on the Higgs mass and scale f; (ii) The deviation of the production rate from its SM prediction is sensitive to the scale f in all these models. In the SLH, the deviation is also sensitive to tan β; (iii) The production rates in SLH and LHT-I/LHT-II can be severely suppressed in parts of parameter space where new decay modes are open and dominant: h → for SLH and h → A_H A_H for LHT-I/LHT-II. Therefore, precision measurement of this production process at the ILC will allow for tests of these models and even distinguish between different scenarios.

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Appendix A: The Effective Couplings of Higgs-Photon-Photon and Higgs-Gluon-Gluon

The effective Higgs-photon-photon coupling can be written as:

$$\mathcal{L}_{h\gamma\gamma} = I F_{\mu\nu} F^{\mu\nu} h$$

where F^{ } is the electromagnetic field strength tensor. With Higgs boson couplings to charged fermion f_i, vector boson V_i, and scalar S_i given by:

$$\mathcal{L}_{\text{int}} = \sum_f y_f \bar{f}_i f_i h + \sum_V y_V V_i^\dagger V_i h + \sum_S y_S S_i^\dagger S_i h$$

the factor I in Eq. (A1) can be written as:

$$I = \frac{1}{16\pi^2 v} \left[\sum_f N_c^f Q_f^2 y_f I_{1/2}(\tau_f) + \sum_V Q_V^2 y_V I_1(\tau_V) + \sum_S Q_S^2 y_S I_0(\tau_S) \right]$$

where Q_X (X denotes f_i, V_i, and S_i) is the electric charge for particle X running in the loop, and N_c^f is the color factor for f_i. The dimensionless loop factors are:

$$I_{1/2}(\tau) = -2\tau \left[1 + (1-\tau) f(\tau)\right]$$
$$I_1(\tau) = 2 + 3\tau + 3\tau(2-\tau) f(\tau)$$
$$I_0(\tau) = \tau \left[1 - \tau f(\tau)\right]$$

where τ_X = 4m_X^2/m_h^2 and:

$$f(\tau_X) = \begin{cases} \left[\sin^{-1}\left(\sqrt{1/\tau_X}\right)\right]^2, & \tau_X \geq 1 \\ -\frac{1}{4}\left[\ln\left(\frac{\eta_+}{\eta_-}\right) + i\pi\right]^2, & \tau_X < 1 \end{cases}$$

with _± = 1 ± √(1 - τ_X). When masses of particles in the loops are much larger than half the Higgs boson mass, we get:

$$I_{1/2}(\tau) \to -\frac{4}{3}, \quad I_1(\tau) \to 7, \quad I_0(\tau) \to -\frac{1}{6}$$

The effective Higgs-gluon-gluon coupling can be written as:

$$\mathcal{L}_{hgg} = I_{hgg} G^a_{\mu\nu} G^{\mu\nu}_a h$$

where G^a_{ } = _ g^a_ - *g^a_ + g_s f^{abc} g^b_ g^c_ . The factor I*{hgg} from contributions of quarks running in the loops is given by:

$$I_{hgg} = \frac{1}{16\pi^2 v} \sum_q y_q I_{1/2}(\tau_q)$$

with τ_q = 4m_q^2/m_h^2.

Once the interactions are given, we can obtain the effective hγγ and hgg couplings from the above formulas. Below we list the relevant Higgs interactions in SLH, LH, LHT-I, and LHT-II. Higgs interactions with light fermions are not listed since their contributions can be ignored.

(1) In SLH, Higgs couplings with quarks are given by:

$$\mathcal{L}_t \simeq -\lambda_t^1 c_\beta \bar{t}'_L t'_R - \lambda_t^2 s_\beta \bar{T}'_L T'_R - \lambda_t^c \bar{t}'_L T'_R - \lambda_t^c \bar{T}'_L t'_R + \text{h.c.}$$

$$\mathcal{L}_d \simeq -\lambda_d^1 c_\beta \bar{d}'_L d'_R - \lambda_d^2 s_\beta \bar{D}'_L D'_R - \lambda_d^c \bar{d}'_L D'_R - \lambda_d^c \bar{D}'_L d'_R + \text{h.c.}$$

$$\mathcal{L}_s \simeq -\lambda_s^1 c_\beta \bar{s}'_L s'_R - \lambda_s^2 s_\beta \bar{S}'_L S'_R - \lambda_s^c \bar{s}'_L S'_R - \lambda_s^c \bar{S}'_L s'_R + \text{h.c.}$$

where:

$$c_1 \equiv \frac{v_{SM}}{f} \frac{t_\beta}{\sqrt{t_\beta^2 + 1}}, \quad c_2 \equiv \frac{v_{SM}}{f} \frac{1}{\sqrt{t_\beta^2 + 1}}$$

$$s_1 \equiv \frac{h+v}{\sqrt{2}t_\beta f}, \quad s_2 \equiv \frac{(h+v)t_\beta}{\sqrt{2}f}, \quad s_3 \equiv \frac{(h+v)(t_\beta^2+1)}{\sqrt{2}t_\beta f}$$

After diagonalization of the mass matrices, we obtain mass eigenstates (t, T), (d, D), and (s, S), which was performed numerically in our analysis, and the relevant Higgs couplings can be obtained without resorting to any expansion of v/f (the diagonalization of quark mass matrices in LH, LHT-I, and LHT-II was also performed numerically).

The Higgs coupling with gauge bosons is given by:

$$\mathcal{L}_V \simeq y_{WW} W^+ W^- h + 2 y_{W'W'} {W'}^+ {W'}^- h$$

where:

$$y_{WW} = \frac{2m_W^2}{v_{SM}} \left[1 - \frac{v_{SM}^2}{12f^2} \frac{t_\beta^4 + t_\beta^2 + 1}{t_\beta^2}\right]$$

$$y_{W'} \simeq -\frac{2m_W^2}{f^2}$$

(2) In LH, Higgs couplings with heavy quarks are given by:

$$\mathcal{L}_t \simeq -\frac{\lambda_1\lambda_2 f}{\sqrt{\lambda_1^2+\lambda_2^2}} \bar{u}_L u_R + \frac{\lambda_2^2 f}{\sqrt{\lambda_1^2+\lambda_2^2}} \bar{U}_L u_R - \lambda_2 f \bar{U}_L U_R + \text{h.c.}$$

where:

$$c_\Sigma \equiv \cos\frac{\sqrt{2}(v+h)}{f}, \quad s_\Sigma \equiv \sin\frac{\sqrt{2}(v+h)}{f}$$

After diagonalization, we obtain mass eigenstates t and T and their couplings with the Higgs boson:

$$\mathcal{L}_{h\bar{t}t} = y_t \bar{t} t h + y_T \bar{T} T h$$

where:

$$y_t = \frac{m_t}{v}\left(1 + \frac{v^2}{f^2}\right), \quad y_T = \frac{m_T}{v}\left(1 - \frac{v^2}{f^2}\right)$$

Higgs couplings with gauge bosons are given by:

$$\mathcal{L}_V = y_{WW}W^+W^-h + 2y_{W_HW_H}W_H^+W_H^-h + y_{\Phi^+\Phi^-}\Phi^+\Phi^-h + y_{\Phi^{++}\Phi^{--}}\Phi^{++}\Phi^{--}h$$

where:

$$y_{\Phi^+} = \frac{m_{\Phi^+}^2}{v}\left(1+\frac{v^2}{3f^2}\right), \quad y_{W_H} = \frac{2m_{W_H}^2}{v}\left(1-\frac{v^2}{f^2}\right), \quad y_{\Phi^{++}} = \frac{m_{\Phi^{++}}^2}{v}\left(1+O\left(\frac{v^2}{f^2}\right)\right)$$

Since the $h\Phi^{++}\Phi^{--}$ coupling is very small, contributions from the doubly-charged scalar can be ignored.

(3) In LHT-I, Higgs couplings with heavy quarks are given by:

$$\mathcal{L}_\kappa \simeq -\frac{\lambda_1\lambda_2 f}{\sqrt{\lambda_1^2+\lambda_2^2}}\bar{u}_L u_R' - m_\chi \bar{\chi}_L\chi_R - \frac{\lambda_2^2 f}{\sqrt{\lambda_1^2+\lambda_2^2}}\bar{u}_L\chi_R + \text{h.c.}$$

where:

$$c_\xi \equiv \cos\frac{\sqrt{2}(v+h)}{f}, \quad s_\xi \equiv \sin\frac{\sqrt{2}(v+h)}{f}$$

After diagonalization, we obtain T-odd mass eigenstates u, q, and . There are three generations of T-odd particles, which we assume to be degenerate. Mass eigenstates t and T are obtained by mixing interaction eigenstates.

Higgs interactions with gauge bosons in LHT-I can be obtained from LH couplings by taking c = s = 1/√2 and x = 0.

(4) In LHT-II, Higgs couplings with the first two generations of heavy quarks are given by:

$$\mathcal{L}_q \simeq -\frac{\lambda_1\lambda_2 f}{\sqrt{\lambda_1^2+\lambda_2^2}}\bar{u}_L u_R' - m_q\bar{q}_L q_R - m_\chi \bar{\chi}_L\chi_R + \text{h.c.}$$

Mass eigenstates of u, q, and   are obtained by diagonalizing the mass matrix.

Higgs couplings with the third generation of heavy quarks are:

$$\mathcal{L}_q \simeq -\frac{\lambda_1\lambda_2 f}{\sqrt{\lambda_1^2+\lambda_2^2}}\bar{u}_L u_R' - m_q\bar{q}_L q_R - \frac{\lambda_2^2 f}{\sqrt{\lambda_1^2+\lambda_2^2}}\bar{U}_L q_R - \frac{\lambda_2^2 f}{\sqrt{\lambda_1^2+\lambda_2^2}}\bar{U}_L u_R' + \frac{\lambda_1^2 f}{\sqrt{\lambda_1^2+\lambda_2^2}}\bar{u}_L\chi_R + \text{h.c.}$$

where c_t is taken as 1/√2. After diagonalization, we obtain mass eigenstates t, T, q, and .

Higgs interactions with gauge bosons in LHT-II are the same as in LHT-I.

Note that in the lepton sector, SLH, LHT-I, and LHT-II also predict neutral heavy neutrinos, which do not contribute to h$\gamma\gamma$ and hgg couplings at one-loop level. Although charged heavy leptons and down-type T-odd quarks are predicted in LHT-I and LHT-II, they do not have direct couplings with the Higgs boson. From Eqs. (A1) and (A9), we find that effective couplings of h$\gamma\gamma$ and hgg are related to the Higgs VEV v and running α and α_s in these models.

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