

# Higgs couplings and Naturalness in the littlest Higgs model with T-parity at the LHC and TLEP

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ABSTRACT: Motivated by the recent LHC Higgs data and null results in searches for any new physics, we investigate the Higgs couplings and naturalness in the littlest Higgs model with T-parity. By performing the global fit of the latest Higgs data, electroweak precise observables and  $R_b$  measurements, we find that the scale  $f$  can be excluded up to 600 GeV at  $2\sigma$  confidence level. The expected Higgs coupling measurements at the future collider TLEP will improve this lower limit to above 3 TeV. Besides, the top partner mass  $m_{T_+}$  can be excluded up to 880 GeV at  $2\sigma$  confidence level. The future HL-LHC can constrain this mass in the region  $m_{T_+} < 2.2$  TeV corresponding to the fine-tuning being larger than 1%.

KEYWORDS: Hadronic Colliders, Phenomenological Models

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## 1 Introduction

The discovery of a Higgs boson [1–4] by the ATLAS [5] and CMS [6] collaborations at the LHC marks a milestone of an effort that has been ongoing for almost half a century and opens up a new era of particle physics. The existing measurements [7–10] and the global fits to the ATLAS and CMS Higgs data within remarkable precision [11–20] agree with the standard model (SM) predictions. This conclusion is consistent with the ATLAS and CMS null results in searches for any new physics. However, the experiments of cold dark matter [21] and neutrino oscillations [22] cannot be explained in the framework of the SM so that they are supposed to provide obvious evidence for the new physics beyond the SM. In particular, the facts that the SM can be an effective theory valid all the way up to the Planck scale and there is no symmetry protecting the scalar masses lead to the naturalness problem, i.e., why the Higgs boson mass is of the order of the electroweak scale and not driven by the radiative corrections to the Planck scale, remains unanswered.

Since the discovery of the Higgs boson the fine-tuning problem has become even more intriguing. Among many new physics models, Little Higgs models based on a collective symmetry breaking can provide a natural explanation of the fine-tuning by constructing the Higgs as a pseudo-goldstone boson. The littlest Higgs (LH) model [23–26] is an economical approach to implement the idea of the little Higgs theory. However, due to the large corrections to the electroweak precision observables (EWPO) from the mixing of the SM gauge bosons and the heavy gauge bosons, the original LH model is severely constrained by precision electroweak data. This constraint can be relaxed by introducing the discrete symmetry T-parity, which is dubbed as littlest Higgs model with T-parity(LHT) [27–30].

With current data, all properties of the observed Higgs-like particle turn out to be in rough agreement with expectations of the SM [31–35], but there are still some rooms for the new physics [36, 37], which may be ultimately examined at the LHC-Run2 and the future Higgs factories [38–49]. Since top partner is naturally related to the Higgs physics and plays an important role in the naturalness problem, one can obtain constraints from the Higgs data [50–55]. In this work, we will discuss the Higgs couplings and the naturalness problem in the LHT model at the LHC and Triple-Large Electron-Positron Collider (TLEP) [56, 57] by performing a global fit of the latest Higgs data,  $R_b$  and oblique parameters, and give the current and future constraints to the LHT parameters.

Recently, some similar works have been carried out in refs. [58–61]. Different from these papers, we perform a state-of-the-art global fit to obtain the indirect constraints on the breaking scale and the top partner with a comprehensive way. This method was widely used in the fit of the SM to the electroweak precision data. So, it will be also meaningful to explore what might happen in the LHT model with a global fit at future colliders. By building an overall likelihood function for the constraints from the EWPO,  $R_b$  measurements and Higgs data, we can obtain a well-defined statistical results of the exclusion limit on the breaking scale. More importantly, we obtain the exclusion limit on the top partner mass, which is obvious absent in other papers.

This paper is organized as follows. In section 2, we give a brief description of the LHT model. In section 3, we present the calculation methodology and the numerical results at the LHC and the TLEP. Finally, we draw our conclusions in section 4.

## 2 A brief review of the LHT model

The LHT model is a non-linear  $\sigma$  model based on the coset space  $SU(5)/SO(5)$ , where the spontaneous symmetry breaking is realised at the scale  $f$  via the vacuum expectation value (VEV) of an  $SU(5)$  symmetric tensor  $\Sigma$ , given by

$$\Sigma_0 = \langle \Sigma \rangle \begin{pmatrix} \mathbf{0}_{2 \times 2} & 0 & \mathbf{1}_{2 \times 2} \\ 0 & 1 & 0 \\ \mathbf{1}_{2 \times 2} & 0 & \mathbf{0}_{2 \times 2} \end{pmatrix}. \quad (2.1)$$

The VEV of  $\Sigma_0$  breaks the gauged subgroup  $[SU(2) \times U(1)]^2$  of  $SU(5)$  down to the SM electroweak  $SU(2)_L \times U(1)_Y$ , which leads to new heavy gauge bosons  $W_H^\pm, Z_H, A_H$ . After the EWSB, their masses up to  $\mathcal{O}(v^2/f^2)$  are given by

$$M_{W_H} = M_{Z_H} = gf \left( 1 - \frac{v^2}{8f^2} \right), \quad M_{A_H} = \frac{g'f}{\sqrt{5}} \left( 1 - \frac{5v^2}{8f^2} \right) \quad (2.2)$$

with  $g$  and  $g'$  being the SM  $SU(2)$  and  $U(1)$  gauge couplings, respectively. In order to match the SM prediction for the gauge boson masses, the VEV  $v$  needs to be redefined via the functional form

$$v = \frac{f}{\sqrt{2}} \arccos \left( 1 - \frac{v_{\text{SM}}^2}{f^2} \right) \simeq v_{\text{SM}} \left( 1 + \frac{1}{12} \frac{v_{\text{SM}}^2}{f^2} \right), \quad (2.3)$$

where  $v_{\text{SM}} = 246$  GeV is the SM Higgs VEV.

Under the unbroken  $SU(2)_L \times U(1)_Y$  the Goldstone boson matrix  $\Pi$  is given by

$$\Pi = \begin{pmatrix} 0 & \frac{H}{\sqrt{2}} & \Phi \\ \frac{H^\dagger}{\sqrt{2}} & 0 & \frac{H^T}{\sqrt{2}} \\ \Phi^\dagger & \frac{H^*}{\sqrt{2}} & 0 \end{pmatrix}, \quad (2.4)$$

where  $H$  is the little Higgs doublet  $(h^+, h)^T$  and  $\Phi$  is a complex triplet under  $SU(2)_L$  which forms a symmetric tensor

$$\Phi = \frac{-i}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\phi^{++} & \phi^+ \\ \phi^+ & \phi^0 + i\phi^P \end{pmatrix}. \quad (2.5)$$

$\phi^0$  and  $\phi^P$  are both real scalars, whereas the  $\phi^{++}$  and  $\phi^+$  are complex scalars. The other Goldstone bosons are the longitudinal modes of the heavy gauge bosons and therefore will not appear in unitary gauge. The mass of  $\Phi$  can be given by

$$m_\Phi = \frac{2m_H f}{v}, \quad (2.6)$$

where all components of the triplet are degenerate at the order we are examining.

When T-parity is implemented in the quark sector of the model, we require the existence of mirror partners with T-odd quantum number for each SM quark. We denote the up and down-type mirror quarks by  $u_H^i$  and  $d_H^i$ , where  $i(i = 1, 2, 3)$  is the generation index. After the EWSB, their masses up to  $\mathcal{O}(v^2/f^2)$  are given by

$$m_{d_H^i} = \sqrt{2}\kappa_i f, \quad m_{u_H^i} = m_{d_H^i} \left(1 - \frac{v^2}{8f^2}\right) \quad (2.7)$$

where  $\kappa_i$  are the diagonalized Yukawa couplings of the mirror quarks. One can notice that the down-type mirror quarks have no interactions with the Higgs.

In order to stabilize the Higgs mass, an additional T-even heavy quark  $T_+$  is introduced to cancel the large one-loop quadratic divergences caused by the top quark. Meanwhile, the implementation of T-parity requires a T-odd mirror partner  $T_-$  with  $T_+$ . The T-even quark  $T_+$  mix with the SM top-quark and leads to a modification of the top quark couplings relatively to the SM. The mixing can be parameterized by dimensionless ratio  $R = \lambda_1/\lambda_2$ , where  $\lambda_1$  and  $\lambda_2$  are two dimensionless top quark Yukawa couplings. This mixing parameter can also be used by  $x_L$  with

$$x_L = \frac{R^2}{1 + R^2}. \quad (2.8)$$

Considering only the largest corrections induced by EWSB, their masses up to  $\mathcal{O}(v^2/f^2)$  are then given by

$$m_t = \lambda_2 \sqrt{x_L} v \left[1 + \frac{v^2}{f^2} \left(-\frac{1}{3} + \frac{1}{2}x_L(1-x_L)\right)\right] \quad (2.9)$$

$$m_{T_+} = \frac{f}{v} \frac{m_t}{\sqrt{x_L(1-x_L)}} \left[1 + \frac{v^2}{f^2} \left(\frac{1}{3} - x_L(1-x_L)\right)\right] \quad (2.10)$$

$$m_{T_-} = \frac{f}{v} \frac{m_t}{\sqrt{x_L}} \left[1 + \frac{v^2}{f^2} \left(\frac{1}{3} - \frac{1}{2}x_L(1-x_L)\right)\right]. \quad (2.11)$$

The corrections to the Higgs couplings of the other two generations of T-even (SM-like) up-type quarks up to  $\mathcal{O}(v_{\text{SM}}^4/f^4)$  are given by

$$\frac{g_{h\bar{u}u}}{g_{h\bar{u}u}^{\text{SM}}} = 1 - \frac{3}{4} \frac{v_{\text{SM}}^2}{f^2} - \frac{5}{32} \frac{v_{\text{SM}}^4}{f^4} \quad u \equiv u, c. \quad (2.12)$$

For the T-even (SM-like) down-type quarks and charged leptons, the Yukawa interaction have two possible constructions [62]. The corresponding corrections to the Higgs couplings with respect to their SM values up to  $\mathcal{O}(v_{\text{SM}}^4/f^4)$  are given by ( $d \equiv d, s, b, l_i^\pm$ )

$$\begin{aligned} \frac{g_{h\bar{d}d}}{g_{h\bar{d}d}^{\text{SM}}} &= 1 - \frac{1}{4} \frac{v_{\text{SM}}^2}{f^2} + \frac{7}{32} \frac{v_{\text{SM}}^4}{f^4} && \text{Case A} \\ \frac{g_{h\bar{d}d}}{g_{h\bar{d}d}^{\text{SM}}} &= 1 - \frac{5}{4} \frac{v_{\text{SM}}^2}{f^2} - \frac{17}{32} \frac{v_{\text{SM}}^4}{f^4} && \text{Case B.} \end{aligned} \quad (2.13)$$

One can notice that Case B predicts a stronger suppression for the down-type fermion couplings to the Higgs boson.

The naturalness of the model can be quantified by how much the contributions from the heavy states ( $\delta\mu^2$ ) exceed the observed value of the Higgs mass squared parameter ( $\mu_{\text{obs}}^2$ ) [23]:

$$\Delta = \frac{|\delta\mu^2|}{\mu_{\text{obs}}^2}, \quad \mu_{\text{obs}}^2 = \frac{m_h^2}{2}. \quad (2.14)$$

Here  $m_h$  is the Higgs boson mass. In the LHT model, the dominant negative log-divergent contribution to the Higgs mass squared parameter comes from the top quark and its heavy partner  $T_+$  loops [23]

$$\delta\mu^2 = -\frac{3\lambda_t^2 m_{T_+}^2}{8\pi^2} \log \frac{\Lambda^2}{m_{T_+}^2} \quad (2.15)$$

where  $\Lambda = 4\pi f$  is the cut-off of the nonlinear sigma model,  $\lambda_t$  is the SM top Yukawa coupling and  $m_{T_+}$  is the mass of the heavy top partner.

### 3 Calculations and numerical results

In our numerical calculations, we take the SM input parameters as follows [63]:

$$m_t = 173.5 \text{ GeV}, \quad m_W = 80.385 \text{ GeV}, \quad \alpha(m_Z) = 1/127.918, \quad \sin^2 \theta_W = 0.231.$$

Our global fit is based on the frequentist theory. For a set of observables  $\mathcal{O}_i (i = 1 \dots N)$ , the experimental measurements are assumed to be Gaussian distributed with the mean value  $\mathcal{O}_i^{\text{exp}}$  and error  $\sigma_i^{\text{exp}}$ . The  $\chi^2$  can be defined as  $\chi^2 = \sum_i^N \frac{(\mathcal{O}_i^{\text{th}} - \mathcal{O}_i^{\text{exp}})^2}{\sigma_i^2}$ , where  $\sigma_i$  is the total error both experimental and theoretical. The likelihood  $\mathcal{L} \equiv \exp[-\sum \chi_i^2]$  for a point in the parameter space is calculated by using the  $\chi^2$  statistics as a sum of individual contributions from the latest experimental constraints. The confidence regions are evaluated with the profile-likelihood method from tabulated values of  $\delta\chi^2 \equiv -2 \ln(\mathcal{L}/\mathcal{L}_{\text{max}})$ . In three dimensions, 68.3% confidence regions (corresponding to  $1\sigma$  range) are given by  $\delta\chi^2 = 3.53$  and 95.0% confidence regions (corresponding to  $2\sigma$  range) are given by  $\delta\chi^2 = 8.02$ .

Under few assumptions involving mainly flavour independence in the mirror fermion sector, the LHT model can be parametrised by only three free parameters, i.e., the scale  $f$ , the ratio  $R$  and the Yukawa couplings of the mirror quarks  $\kappa_j$ . Considering the recent constraint from the searches for the monojet, we require the lower bound on the Yukawa couplings of the mirror quarks are  $\kappa_j \geq 0.6$  [61]. We scan over these parameters within the following ranges [58–61, 64]

$$500\text{GeV} \leq f \leq 2000\text{GeV}, \quad 0.1 \leq R \leq 3.3, \quad 0.6 \leq \kappa_j \leq 3,$$

where we assume the three generations  $\kappa_j$  are degenerate. The couplings of the UV operators are set as  $c_s = c_t = 1$ . The likelihood function  $\mathcal{L}$  is constructed from the following constraints:

1. EWPO: these oblique corrections can be described in terms of the Peskin-Takeuchi S, T and U parameters [65]. Firstly, the top partner can contribute to the propagators of the electroweak gauge bosons at one-loop level. In contrast to  $T_+$ , the T-odd top partner  $T_-$  does not contribute to S, T, U parameters since it is an  $SU(2)_L$  singlet

which does not mix with the SM top quark. Secondly, the T-odd mirror fermions give a contribution to the T parameter at one-loop, which can have a noticeable effect on the EWPO due to a large number (twelve) of doublets in the SM; thirdly, another important correction to both the S and T parameters follows from the modified couplings of the Higgs boson to the SM gauge bosons. Finally, other possible contributions arise from new operators which parametrize the effects of the UV physics on weak scale observables. All these different contributions to the oblique parameters should be summed up. We calculate  $\chi^2$  by using the formulae in refs. [64, 66, 67] and adopting the experimental values of S, T and U in the ref. [63].

2.  $R_b$ . The branching ratio  $R_b$  is very sensitive to the new physics beyond the SM, the precision experimental value of  $R_b$  may give a severe constraint on the new physics. In the LHT model, there are new fermions and new gauge bosons, which can contribute to the  $Zb\bar{b}$  coupling and give corrections to the  $R_b$  at one-loop level [68]. The final combined result from the LEP and SLD measurements show  $R_b = 0.21629 \pm 0.00066$  [63], which is consistent with the SM prediction  $R_b^{\text{SM}} = 0.21578^{+0.0005}_{-0.0008}$ .
3. Higgs data. The experimental results are given in terms of signal strengths  $\mu(X; Y)$ , which is defined as the ratio of the observed rate for Higgs process  $X \rightarrow h \rightarrow Y$  relative to the prediction for the SM Higgs,  $\mu(X; Y) \equiv \frac{\sigma(X)BR(h \rightarrow Y)}{\sigma(X_{\text{SM}})BR(h_{\text{SM}} \rightarrow Y)}$ . We confront the modified Higgs interactions and the one-loop contribution of the new particles in the LHT model with the available Higgs data. We calculate the  $\chi^2$  values by using the public package HiggsSignals-1.2.0 [69, 70], which includes 81 channels from the LHC and Tevatron and these experimental data are listed in ref. [71]. In our calculations, the Higgs mass  $m_h$  is fixed as 126 GeV. Note that for the Higgs data, the HiggsSignals has provided the calculation of  $\chi^2$ , where both experimental (systematic and statistical) uncertainties as well as SM theory uncertainties are included.

In figure 1, we show the results of the global fit to the above three kinds of constraints in the plane of  $R$  versus  $f$  for Case A and Case B, respectively. We can see that the lower bound on the symmetry breaking scale at 95% C.L. is

$$f > 670 \text{ GeV} \quad \text{Case A,} \tag{3.1}$$

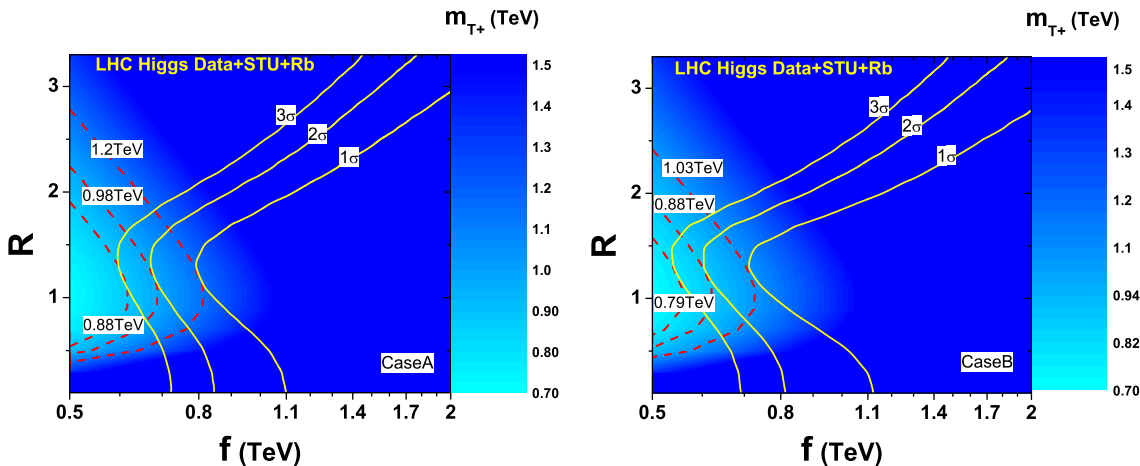
$$f > 600 \text{ GeV} \quad \text{Case B.} \tag{3.2}$$

The constraints are stronger than the electroweak precision constraints in ref. [64], which is because the main constraint here comes from the Higgs data. For the top partner mass, we can see that the combined indirect constraints can exclude  $m_{T_+}$  at 95% C.L. up to

$$m_{T_+} > 980 \text{ GeV} \quad \text{Case A,} \tag{3.3}$$

$$m_{T_+} > 880 \text{ GeV} \quad \text{Case B.} \tag{3.4}$$

It's worth noting that they are stronger than the lower bound set by the ATLAS direct searches for the SU(2) singlet top partner,  $m_T > 640 \text{ GeV}$  [72]. Our study may play a complementary role to the direct searches in probing top partner.



**Figure 1.** The global fit of the constraints on the LHT model in the  $R - f$  plane for Case A and Case B. The yellow lines from right to left respectively correspond to  $1\sigma$ ,  $2\sigma$  and  $3\sigma$  exclusion limits.

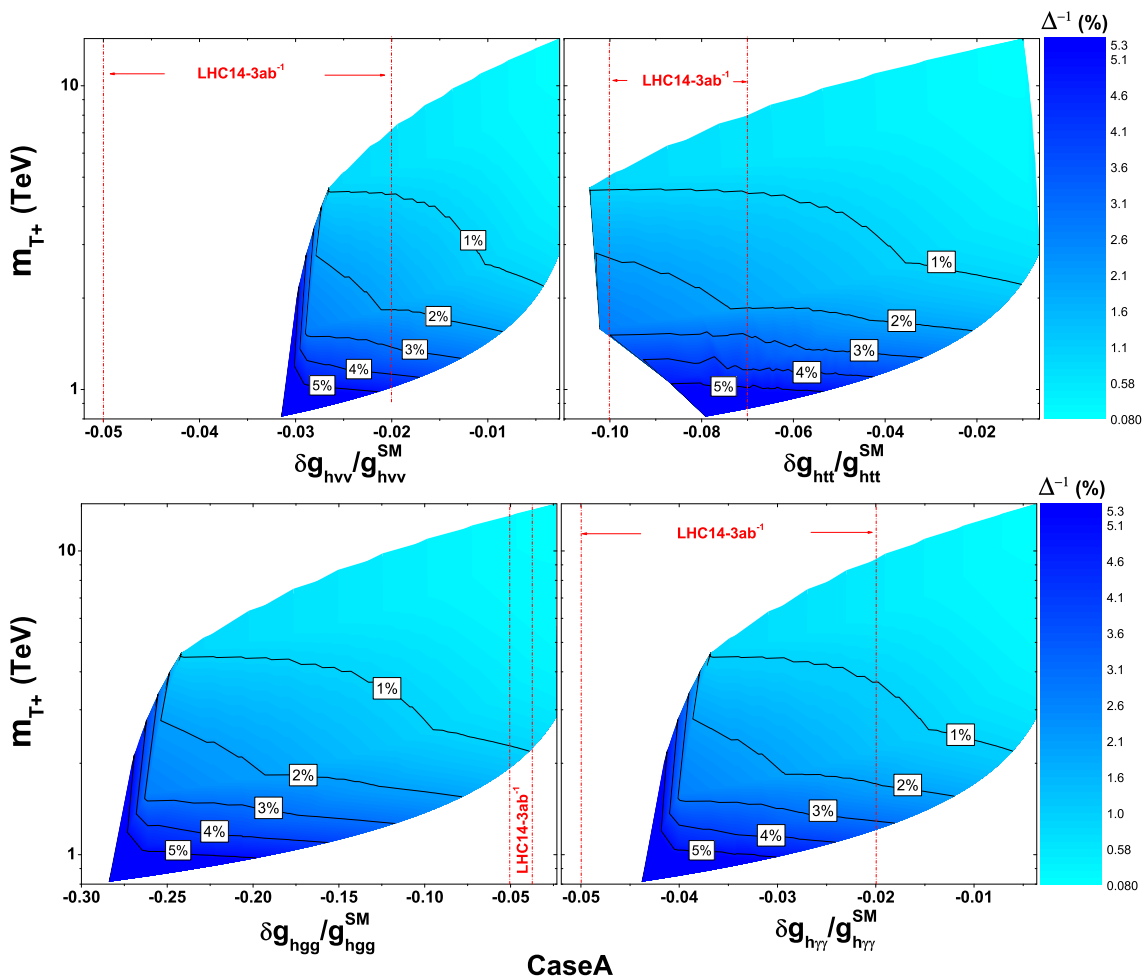
Facility	HL-LHC	TLEP
$\sqrt{s}$	14TeV	240GeV
$\int \mathcal{L} dt$	3000( $\text{fb}^{-1}$ )	10000( $\text{fb}^{-1}$ )
$\kappa_\gamma$	2–5%	1.7%
$\kappa_g$	3–5%	1.1%
$\kappa_W$	2–5%	0.85%
$\kappa_Z$	2–4%	0.16%
$\kappa_u$	7–10%	–
$\kappa_d$	4–7%	–
$\kappa_c$	7–10%	1.0%
$\kappa_s$	4–7%	–
$\kappa_t$	7–10%	–
$\kappa_b$	4–7%	0.88%

**Table 1.** Expected precision on the Higgs couplings to quarks and vector bosons at the HL-LHC and the TLEP.

The expected precision for the Large Hadron Collider High-Luminosity Upgrade (HL-LHC) and the TLEP are assumed in table 1, which comes from the table 14 and table 16 of the Higgs working group report [73].

In the LHT model, the loop-induced couplings  $hgg$  and  $h\gamma\gamma$  can receive contributions from both the modified couplings and the new particles. The decay  $h \rightarrow gg$  can be corrected by the modified  $ht\bar{t}$  coupling and the loops of top partner  $T_+$  and T-odd mirror quarks. In addition to these corrections involved in the decay  $h \rightarrow gg$ , the decay  $h \rightarrow \gamma\gamma$  can be also corrected by the modified  $hWW$  coupling and the loops of  $W_H$ ,  $\phi^+$ ,  $\phi^{++}$ . Besides, the couplings  $hc\bar{c}$ ,  $hs\bar{s}$ ,  $hb\bar{b}$ ,  $hZZ$  are also modified, they can exert an effect on our fit.

In figure 2 and figure 3, we show the shifts of the Higgs couplings  $hVV$ ,  $ht\bar{t}$ ,  $hgg$ ,  $h\gamma\gamma$  for the above samples in the  $2\sigma$  range. In order to investigate the observability, we compare



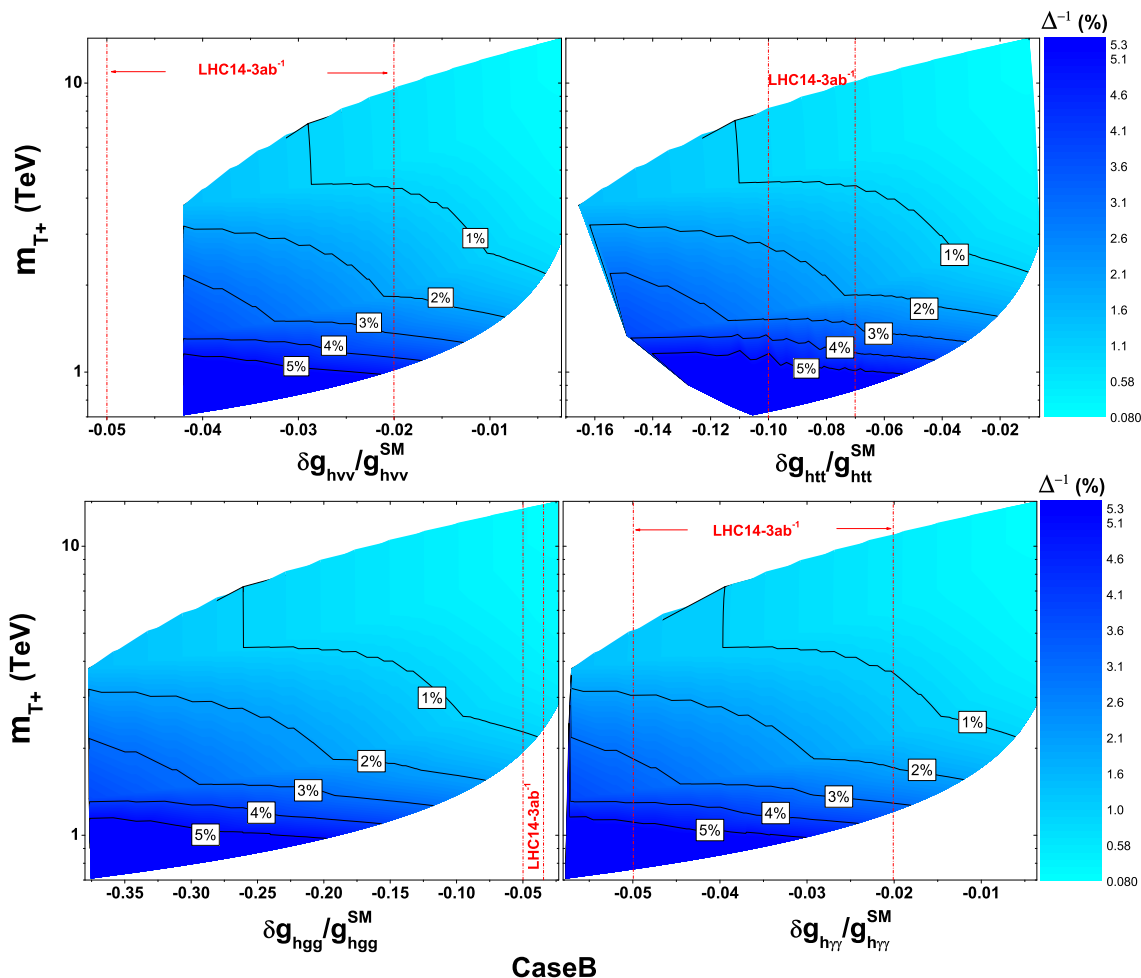
**Figure 2.** The shifts of the Higgs couplings for the samples in the  $2\sigma$  allowed range in figure 1 for Case A. The red dash-dot lines represent the expected measurement uncertainties at HL-LHC.

them with the corresponding expected measurement uncertainties of the Higgs couplings in table 1 at HL-LHC with a luminosity of  $3000 \text{ fb}^{-1}$ . The value of the fine-tuning for each point is also calculated by using the eq. (2.14). From figure 2 and figure 3, we can have some observations as follows:

1. The values of the fine-tuning for the samples are cornered to be smaller than about 6% by the above global fit.
2. For the Higgs couplings  $hVV$  and  $ht\bar{t}$ , they are suppressed by the high order factor  $\mathcal{O}(v^2/f^2)$ . The deviation of the Higgs couplings  $g_{hVV}$  from the SM predictions are at percent level and the deviation of the Higgs coupling  $g_{ht\bar{t}}$  from the SM prediction can reach over 10%.

For the loop-induced couplings  $g_{hgg}$  and  $g_{h\gamma\gamma}$ , on one hand they are corrected by the high order factor, on the other hand they are corrected by the loop contributions of the new particles. For the effects of these loop diagrams, there are cancellation

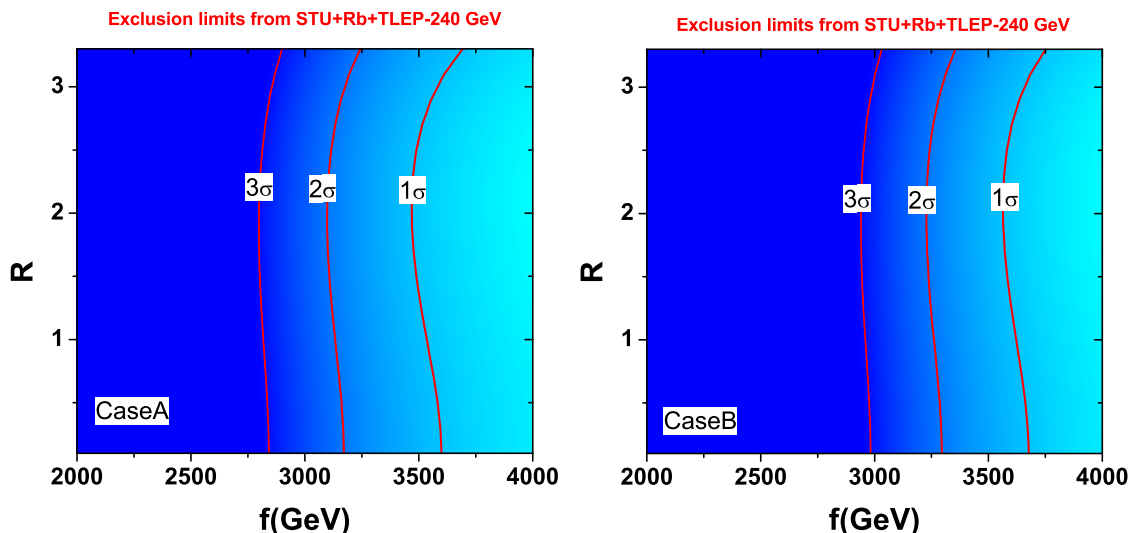




**Figure 3.** The shifts of the Higgs couplings for the samples in the  $2\sigma$  allowed range in figure 1 for Case B. The red dash-dot lines represent the expected measurement uncertainties at HL-LHC.

between  $t(W_L)$  and the corresponding partner  $T_+(W_H)$  so that the effective  $g_{hgg}$  and  $g_{h\gamma\gamma}$  couplings are reduced. The deviation of the Higgs coupling  $g_{h\gamma\gamma}$  from the SM prediction is at percent level, that is because the dominant contribution to the coupling  $g_{h\gamma\gamma}$  comes from the  $W_L(W_H)$  over the  $t(T_+)$ . The Higgs coupling  $g_{hgg}$  from the SM prediction can reach about 30%, that is because the dominant contribution to the coupling  $g_{hgg}$  comes from the  $ht\bar{t}$  coupling and  $t(T_+)$  loops, where the contribution of  $ht\bar{t}$  coupling accounts for about 10% and the contributions of  $t(T_+)$  loops account for about 20%. Furthermore, we can see that the deviations for Case A are less than that for Case B, which originate from the stronger suppression for the down-type fermion couplings to the Higgs boson in Case B.

Furthermore, we can see that all changes of the Higgs couplings are negative. In the LHT model, in order to cancel the quadratic divergence of the Higgs mass, the heavy gauge bosons and the additional heavy quark  $T_+$  are introduced. This leads



**Figure 4.** The expected exclusion limits on the  $R - f$  plane for Case A and Case B from the global fit of EWPO,  $R_b$  and TLEP.

to negative modification of the relevant couplings with respect to the SM. Besides, the non-linear expansion of the model field suppresses these couplings at the order  $\mathcal{O}(v^2/f^2)$ .

3. In figure 2 and figure 3, we attempt to show the expected constraints from the future individual Higgs coupling measurements on the top partner and naturalness at the HL-LHC. The couplings  $hVV$  and  $ht\bar{t}$  are modified at the order  $\mathcal{O}(v^2/f^2)$ , which can determine the scale  $f$  and help us understand the nature of the Higgs boson in the LHT model. Apart from this, the coupling  $hgg$  can provide the information for the cancelation between  $t$  and the corresponding partner  $T_+$ , while the coupling  $h\gamma\gamma$  can provide the information for the cancelation between  $W_L$  and the corresponding partner  $W_H$ . So, we can see that the individual Higgs coupling measurements can help us understand the different parts of the LHT model.
4. The future measurements of the  $g_{hgg}$  coupling at the HL-LHC will be able to exclude the  $m_{T_+} < 2.2$  TeV, which corresponds to the fine-tuning being larger than about 1%. However, other expected measurements, such as  $g_{hVV}$ ,  $g_{ht\bar{t}}$  and  $g_{h\gamma\gamma}$  couplings, can only improve the limits for the top partner mass mildly.

In figure 4, we present the prospect of improving the constraints on the scale  $f$  at a possible future Higgs factory TLEP with  $\sqrt{s} = 240$  GeV. In our fit, the  $\chi^2$  can be defined as

$$\chi^2 = \sum_i^N \frac{(\mu_i - 1)^2}{\sigma_i^2} \tag{3.5}$$

where  $\mu_i$  represents the signal strength prediction from the LHT model and  $\sigma_i$  represents the  $1\sigma$  uncertainty i.e. the expected measurement precision at the TLEP. We use the Snowmass Higgs working group results to simply estimate the exclusion

limits. Given that the super-high luminosity of  $10000\text{fb}^{-1}$  can be achieved at the TLEP, we assume that all the measured Higgs couplings will be the same as the SM predictions with the expected measurement uncertainties in table 1. From the figure 4, we can see that the lower bound on the scale  $f$  will be pushed up to 3.1 TeV for Case A and 3.25 TeV for Case B at 95% C.L..

## 4 Conclusions

In this paper, we investigated the Higgs couplings and naturalness in the LHT model under the available constraints from the current Higgs data and the EWPO. By performing the global fit, we find that the scale  $f$  can be excluded up to 670 GeV for Case A and 600 GeV for Case B at  $2\sigma$  level. The precise measurements of the Higgs couplings at the future collider TLEP will constrain this limit to above 3 TeV. Besides, the top partner mass  $m_{T_+}$  can be excluded up to 980 GeV for Case A and 880 GeV for Case B at  $2\sigma$  level. This mass can be constrained in the region  $m_{T_+} < 2.2\text{ TeV}$  at the HL-LHC corresponding to the fine-tuning being larger than 1%.

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