

# One-loop radiative corrections to the trilinear Higgs self-coupling

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**Abstract.** The one-loop corrections to the triple Higgs self-coupling are reported in the Littlest Higgs model with T-parity. Our results indicate that these corrections are no sensitive to high values of the symmetry breaking scale and the magnitude of one of momentum of one off-shell scalar boson legs.

## 1. Introduction

A measurement of the Higgs boson self-coupling will determine the structure of the Higgs potential, and will confirm that the observed scalar boson with mass of 125 GeV at the LHC [1, 2] really corresponds to the Higgs boson predicted by the Standard Model(SM). However, due to the high uncertainties on the  $hh$  cross sections measurements in both CMS and ATLAS [3], it is not clear if a meaningful measurement of the Higgs self-coupling could be possible in the latter case. In this sense, the Higgs self-coupling  $hhh$  was analyzed in processes such as  $gg$  double-Higgs fusion ( $gg \rightarrow hh$ ), VV double-Higgs fusion ( $qq' \rightarrow hhqq'$ ), double Higgs-strahlung ( $q\bar{q}' \rightarrow Vhh$ ), associated production with top-quarks  $q\bar{q}/gg \rightarrow t\bar{t}hh$ [4] and high energy photon-photon collisions via the  $\gamma\gamma \rightarrow t\bar{t}hh$  process [5]. Nevertheless, in these analyses the coupling  $hhh$  is independent of the 4-momentum of any Higgs boson leg. On other hand, it has been found that the Higgs boson self-coupling  $hhh$  at one loop level is very sensitive to new physics scenarios. In the SM, the top quark contribution is the dominant correction and this has a value of approximately of 9.8% [6, 7]. Another corrections to the self-coupling  $hhh$  were reported in models such as Two Higgs Doublet Models [6], and Minimal Supersymmetric Model (MSSM) with a light stop [7]. In this report we present the results to the Higgs self-coupling  $hhh$  at one loop level in the Littlest Higgs model (LHM) with T-parity. The LHM with T-parity is characterized by a global  $SU(5)$  and a gauge  $[SU(2)_1 \times U(1)_1] \times [SU(2)_2 \times U(1)_2]$  symmetries [8], and they are spontaneously broken at scale  $f \sim \mathcal{O}(TeV)$ . An important aspect of this model is that it offers an alternative to the hierarchy problem .

The present report is organized as follows. In the section 2 we review the theoretical set-up of LHM with T-parity necessary for our analysis. Analytic expressions for self-coupling  $hhh$  at one-loop level are presented in section 3. The numerical results for SM and LHM with T-parity are presented in section 4. Finally concluding remarks and an outlook are presented in section 5.



## 2. Littlest Higgs Model with T parity

The LHM is an effective theory based in the collective symmetry breaking approach, where in the first stage the global group  $SU(5)$  is broken to  $SO(5)$  at a scale  $f$  in the TeV range, via the symmetric tensor of vacuum expectation:

$$\Sigma_0 = \begin{pmatrix} \mathbf{0}_{2 \times 2} & \mathbf{0}_{2 \times 1} & \mathbf{1}_{2 \times 2} \\ \mathbf{0}_{1 \times 2} & 1 & \mathbf{0}_{1 \times 2} \\ \mathbf{1}_{2 \times 2} & \mathbf{0}_{2 \times 1} & \mathbf{0}_{2 \times 2} \end{pmatrix}.$$

Simultaneously the gauged subgroup  $[SU(2)_1 \times U(1)_1] \times [SU(2)_2 \times U(1)_2]$  of  $SU(5)$  is broken to the electroweak SM group  $SU(2) \times U(1)$ . Finally the gauged group  $SU(2) \times U(1)$  is broken to  $U(1)_{\text{em}}$  via the usual Higgs mechanism; however, this Higgs potential corresponds to Coleman-Weinberg potential which is generated by one-loop radiative corrections. On other hand, from the global symmetry breaking of  $SU(5)/SO(5)$  we generated 14 Nambu-Golstone bosons and four of these are absorbed by heavy gauge bosons ( $W_H^\pm, Z_H, A_H$ ), and the remaining ten Nambu-Golstone bosons are parametrized by the nonlinear sigma model

$$\mathcal{L}_\Sigma = \frac{f^2}{8} \text{Tr} |\mathcal{D}_\mu \Sigma|^2,$$

where  $\Sigma = e^{i\Pi/f} \Sigma_0 e^{i\Pi^T/f}$ , while the field  $\Pi$  and the covariant derivative  $\mathcal{D}_\mu$  are given in [9, 10]. The implementation of T-parity on the gauge fields consists in exchanging the two  $SU(2) \times U(1)$  factors; consequently the gauge coupling of the two  $SU(2) \times U(1)$  factors are equal and therefore the number of free parameters is reduced. The T-parity in the fermion sector is introduced by implementing a  $SU(2)_1$  doublet and another  $SU(2)_2$  doublet, where under the T-parity the even linear combination is associated to the SM  $SU(2)$  doublet, while the T-odd combination is associated with the called mirror fermion. The mirror fermions acquire mass through  $SU(5)$  and  $T$  invariant Yukawa interaction:

$$\mathcal{L}_{\text{mirror}}^{\text{LHM+T}} = -\kappa_{ij} f (\bar{\Psi}_2^i \xi + \bar{\Psi}_1^i \Sigma_0 \Omega \xi^\dagger \Omega) \Psi_R^j, \quad (1)$$

here  $\kappa_{ij}$  is a mixing matrix and it is different for each mirror fermion,  $\xi = e^{i\Pi/f}$ ,  $\Omega = \text{diag}(1, 1, 1, -1, 1, 1)$ ,  $\Psi_{1,2,R}$  is a multiplet with fermions doublets into its components. Then after expanding the Lagrangian (1) at  $\mathcal{O}(v^2/f^2)$ , the masses of the mirror up-quarks, mirror neutrinos and charged mirror leptons are given by:

$$m_{d_H} = m_{\ell_H} = \sqrt{2} \kappa_{ii} f, \quad (2)$$

$$m_{u_H} = m_{\nu_H} = \sqrt{2} \kappa_{ii} f \left( 1 - \frac{v^2}{8f^2} \right). \quad (3)$$

Where the mirror down-quark (mirror charged lepton) receive only corrections at  $\mathcal{O}(v^3/f^3)$ . Moreover, the Higgs couplings to the mirror up-quark and heavy mirror neutrino are given by

$$h \bar{u}_H u_H = h \bar{\nu}_H \nu_H \sim \frac{i \kappa_{ii} v}{2\sqrt{2} f}. \quad (4)$$

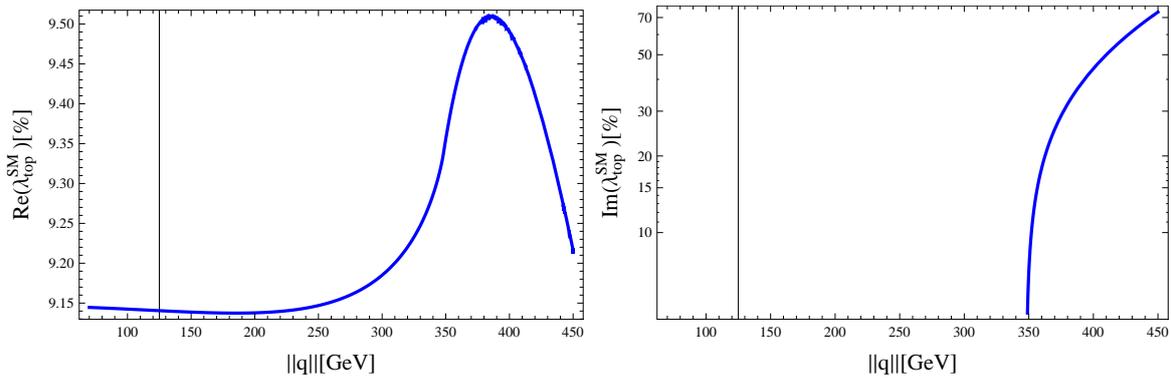
On other hand, the Higgs boson does not have direct coupling to mirror down-quarks and charged mirror leptons.

### 3. One loop correction to self-coupling $hhh$

In analogy with the SM, in LHM with parity T there are contributions arising from heavy mirror fermions, heavy bosons and scalars bosons. However, these contributions are suppressed by the energy scale  $f^1$ , but since the contributions of the SM fermions are proportional to the fourth power of its mass, it is logical to expect that the main contributions arise from mirror fermions in the LHM with T-parity. Therefore for this work we consider only the contributions of mirror fermions. Then, from the couplings (4) and masses (3) of the mirror fermions, the renormalizable expression for this result is given by:

$$\lambda_{f_H}^{\text{LHM+T}}(q) = \sum_{i=1}^3 \frac{\kappa_{ii}^2 m_{f_H} m_W N_c v^3}{3\pi^2 2^{\frac{11}{2}} 3! g m_h^2 f^3} \left[ 18 - \int_{x=0}^1 \int_{y=0}^{1-x} \Xi_f^{\text{SM}}(x, y, s_{f_H}, s_q) dx dy \right], \quad (5)$$

where  $N_c$  is the number of colors,  $s_{f_H}^2 = m_{f_H}^2/m_h^2$  and  $s_q^2 = q^2/m_h^2$ , with  $f_H$  a heavy mirror up-quark or heavy mirror neutrino, and the sum comprises three families of mirror fermions and  $\Xi_f^{\text{SM}}$  is a dimensionless function .



**Figure 1.** Real (left) and imaginary (right) contributions of top-quark to  $\lambda_{hhh}$  factor, as function of the 4-momentum magnitude of the off-shell scalar boson. There is no induced imaginary part for  $\|q\| < 2m_t$  and  $\lambda_{\text{top}}^{\text{SM}} \simeq 9.14049\%$  in the Higgs boson resonance region. The vertical line indicate the Higgs boson resonances ( $\|q\| = 125$  GeV).

## 4. Numerical results and discussion

### 4.1. Standard framework

To start, we analyzed the Higgs boson resonance region and we find  $\lambda_{\text{top}}^{\text{SM}} = 9.14049\%$  for the top-quark, whereas for the bottom-quark ( $\lambda_b^{\text{SM}} \simeq 3.442 \times 10^{-6}\% + i6.4810 \times 10^{-9}\%$ ) and tau lepton ( $\lambda_\tau^{\text{SM}} \simeq 2.535 \times 10^{-8}\% + i7.962 \times 10^{-12}\%$ ) the respective contributions are very suppressed. Then, in the Higgs boson resonance region the main contribution to the  $\lambda_{hhh}$  factor comes from the top-quark. Thus, in the next analysis we consider only the top-quark. In order to compare our results with previous work, the Eq. (1) of [6] gives  $\lambda_{hhh}^{\text{eff}}(\text{SM}) \simeq 9.8221\%$  and this result was obtained by the diagrammatic approach. On other hand,  $\lambda_{\text{top}}^{\text{SM}} \simeq 9.14693\%$  can be obtained from  $\Delta\hat{\Gamma}_H^3$  of the Eq. (32) in the reference [11]. These contributions are very similar to our results, but it is important to mention that these contributions were obtained with some approximations for the 4-momentum magnitude of the off-shell scalar boson. On other hand, for the 4-momentum

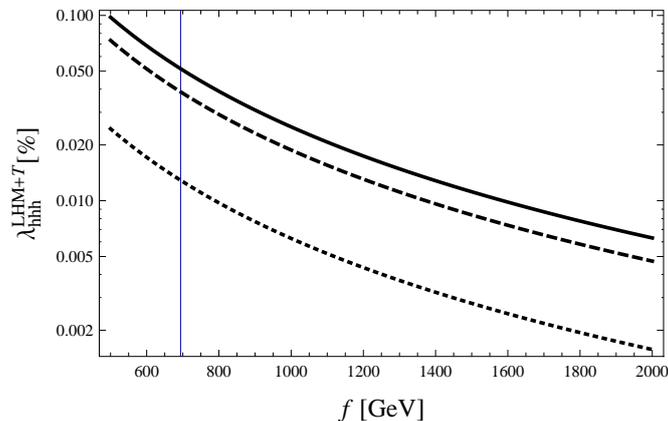
<sup>1</sup> The masses of heavy bosons and heavy scalar are directly proportional to the symmetry breaking scale  $f$ , as well as the mirror fermion masses [8].

magnitude of the off-shell scalar boson outside of Higgs boson resonance region; figure 1 shows the real and imaginary part of  $\lambda_{\text{hhh}}$  factor, as function of the 4-momentum magnitude of the off-shell scalar boson.

We obtained that there are no imaginary parts for  $\|q\| > 2m_t$ . Nevertheless, we will show that the imaginary part increases considerably for higher values of  $\|q\|$  and the real part remains basically stable, although it has a small maximum after  $\|q\| = 2m_t$ . A high contribution to  $\lambda_{\text{hhh}}$  factor (for higher values of  $\|q\|$ ) can violate unitarity, but the gauge bosons and self-coupling can reduce this large imaginary contribution.

#### 4.2. Littlest Higgs Model with T parity

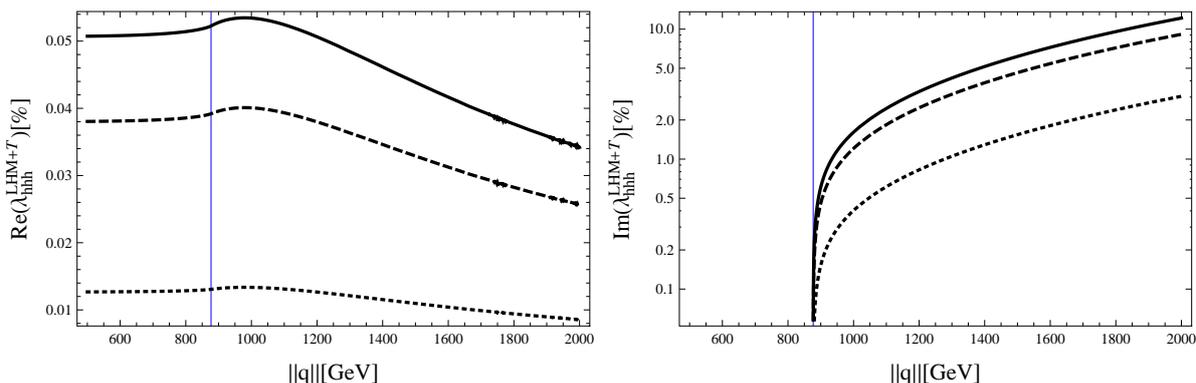
In the LHM with parity T there are two different contributions of the mirror fermion, one for mirror up-quarks and another for heavy mirror neutrinos. Consequently there are two different types of mixing matrices  $\kappa_{ii}$ , but for our analysis we will consider that such matrices have the same order of magnitude e.g.  $\kappa_{i\ell_H} \sim \kappa_{iq_H} \equiv \kappa_{ii}$ . Then, only two free parameters of the LHM with parity T are involved in the contribution (5), the symmetry breaking scale  $f$  and the mixing matrix  $\kappa_{ii}$ . Constraints on these parameters are discussed in Ref. [10], where it is considered that the mirror up-quarks are heavier than all the heavy gauge bosons. This corresponds to values of  $\kappa_{ii} \gtrsim 0.45$ , which makes the decay  $q_H \rightarrow V_H q$  ( $V_H = W_H^\pm, Z_H$ ) kinematically allowed, while for  $\kappa_{ii} \lesssim 0.45$  the only kinematically allowed decay of mirror quark is  $q_H \rightarrow A_H q$ , and finally for  $\kappa_{ii} \lesssim 0.1$  the mirror quarks are stable. Thus, for  $0.1 \lesssim \kappa_{ii} \lesssim 0.45$  and the results from the 8 TeV run at the LHC, the combined analyses of electroweak precision physics and Higgs precision physics give a lower bound  $f \gtrsim 694$  GeV at 95% C.L., while  $f \gtrsim 638$  GeV was obtained from direct searches in  $pp \rightarrow q_H q_H$  and  $pp \rightarrow q_H A_H$  processes at 95% C.L. Therefore in the following analysis we will consider  $\kappa_{ii} = 0.45$ , and the region between 500 GeV and 2000 GeV for the symmetry breaking scale  $f$ . Moreover, for simplicity we consider that the masses of the three mirror families are the same, then the sum over family is replaced by a factor of three.



**Figure 2.** Prediction to  $\lambda_{\text{hhh}}$  factor in the LHM with T-parity, as a function of the symmetry breaking scale  $f$ . We have used the Higgs resonance region and  $\kappa_{ii} = 0.45$ , to obtain the heavy mirror up-quark (dashed line), heavy mirror neutrino (dotted line) and the sum of both contributions (black line). The vertical line corresponds to the lower bound  $f = 694$  GeV.

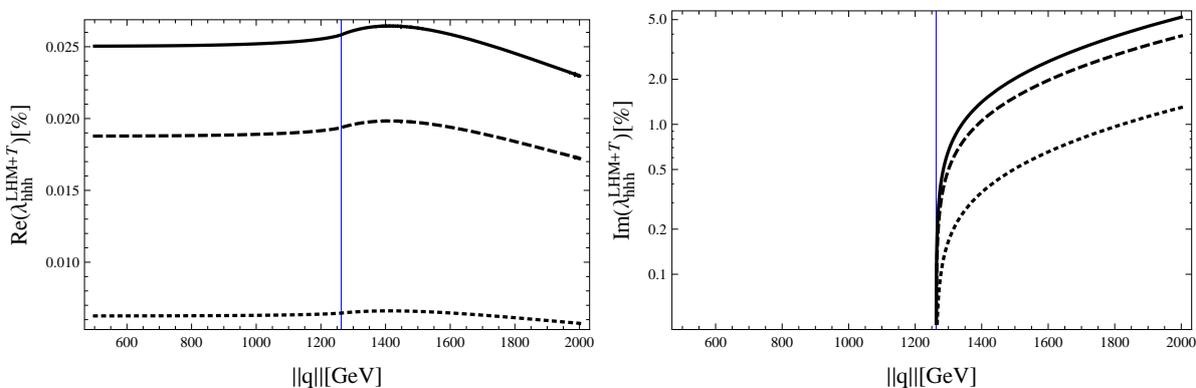
In the Fig. 2 we plot the mirror up quark, mirror neutrino and the sum of both contributions to the  $\lambda_{\text{hhh}}$  factor, as a function of the symmetry breaking scale  $f$  for  $\kappa_{ii} = 0.45$  and for the Higgs resonance region. We also include the lower bound  $f \gtrsim 638$  GeV, which is given by the vertical line. Mathematically speaking, the difference between the contributions of heavy mirror up-quarks and heavy mirror neutrinos is the number of color  $N_c$ , consequently the mirror

up-quark correction is the dominant contribution. We note that the corrections decrease softly with increasing symmetry breaking scale  $f$ , where the sum of both contributions for  $f = 500$  GeV is the  $\lambda_{\text{hhh}}^{\text{LHM+T}} \simeq 0.0977\%$  and for  $f = 2000$  GeV is the  $\lambda_{\text{hhh}}^{\text{LHM+T}} \simeq 0.0062\%$ , while that for the lower bound  $f = 694$  GeV is the  $\lambda_{\text{hhh}}^{\text{LHM+T}} \simeq 0.0512\%$ . It is important to note that there is no imaginary part in the regime of the Higgs resonance region, but for high 4-momentum of the off-shell scalar boson an imaginary part is induced, Figures 3 and 4 show this situation.



**Figure 3.** Real (left) and imaginary (right) contributions of the  $\lambda_{\text{hhh}}$  factor, as function of the 4-momentum magnitude of the off-shell scalar boson. We have used  $f = 700$  GeV and  $\kappa_{ii} = 0.45$ , to obtain the heavy mirror up-quarks (dashed line), heavy mirror neutrinos (dotted line) and the sum of both contributions (black line). The vertical line corresponds to  $\|q\| = 2m_{f_H} \simeq 877$  GeV.

For  $f = 700$  GeV and  $\kappa_{ii} = 0.45$  we show the real and imaginary part of  $\lambda_{\text{hhh}}^{\text{LHM+T}}$  factor, as function of the 4-momentum magnitude of the off-shell scalar boson in the Fig 3. The numerical behavior is similar to the fermionic SM contribution (see Fig. 1), but in a smaller scale. There is a small maximum in the real part after of  $2m_{f_H} \simeq 877$  GeV and where also the imaginary part is induced. Moreover, the imaginary part increases with the 4-momentum magnitude of the off-shell scalar boson, such as the top quark in the SM, which is considerably reduced by contributions of heavy gauge bosons and self-coupling contributions. In particular, we have  $\text{Re}(\lambda_{\text{hhh}}^{\text{LHM+T}}) \simeq 0.0507\%$  and  $\text{Re}(\lambda_{\text{hhh}}^{\text{LHM+T}}) \simeq 0.0341\%$  for the real part of the sum of both contributions, in  $\|q\| = 500$  GeV and  $\|q\| = 2000$  GeV respectively.



**Figure 4.** The same situation as in figure 3 but for  $f = 1000$  GeV, where now  $2m_{f_H} \simeq 1263$  GeV.

If the symmetry breaking scale is increased to  $f = 1000$  GeV, the corrections decrease softly and we have the same behavior than the previous case, but now with  $2m_{f_H} \simeq 1263$  GeV. In this case we have used the same values of  $\|q\|$  than the previous case, to obtain  $\text{Re}(\lambda_{\text{hhh}}^{\text{LHM+T}}) \simeq 0.0250\%$  and  $\text{Re}(\lambda_{\text{hhh}}^{\text{LHM+T}}) \simeq 0.0229\%$  for the sum of both contributions respectively. Thus, we can see that the correction to the  $\lambda_{\text{hhh}}$  factor in LHM with parity T is not very sensitive to higher values of the symmetry breaking scale  $f$ , and of the 4-momentum magnitude of the off-shell scalar boson  $\|q\|$ .

## 5. Conclusions

We have studied the one loop correction to the self-coupling  $hhh$  in the Littlest Higgs Model with T-parity, which is induced by heavy mirror up-quarks and heavy mirror neutrinos. For this purpose, we consider the symmetry breaking scale  $f$  between 500 and 2000 GeV. Also, the constraint value of  $\kappa_{ii} = 0.45$  was obtained from direct searches in  $pp \rightarrow q_H q_H$  and  $pp \rightarrow q_H A_H$  processes. In the Higgs resonance region, our result shows that the self-coupling correction is  $\lambda_{\text{hhh}}^{\text{LHM+T}} \simeq 0.0977\%$  for  $f = 500$  GeV, while that for  $\lambda_{\text{hhh}}^{\text{LHM+T}} \simeq 0.0062\%$  for  $f = 500$  GeV. Moreover, because of the larger mass of mirror fermions, there are not imaginary parts in the Higgs resonance region. However, for high values of 4-momentum magnitude of the off-shell scalar boson  $\|q\|$  imaginary contributions may arise. It is important to note that mirror fermion correction is two orders of magnitude lower than the top-quark SM contribution, although is comparable with the gauge bosons contribution of SM. Finally, we show that the self-coupling correction  $\lambda_{\text{hhh}}^{\text{LHM+T}}$  increased when the  $\kappa_{ii}$  value is increased.

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