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## Higgs-pair production in littlest Higgs model with T-parity postprint

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### Abstract

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### Full Text

### Preamble

#### Higgs-pair Production in Littlest Higgs Model with T-parity

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### Abstract

The Higgs-pair production process at the CERN Large Hadron Collider (LHC), which will provide a way to test the Higgs boson self-coupling, may be sensitive to new physics. In the framework of the littlest Higgs model with T-parity, such Higgs-pair production can proceed through additional loop diagrams and thus the production rate can be quite different from the Standard Model (SM) prediction. Our calculations show that, due to the loop contributions of both T-even and T-odd quarks predicted in this model, the production rate can be significantly enhanced relative to the SM prediction and also can be larger than the production rate in the minimal supersymmetric model. Also, we find that the T-odd quark contributions, which were ignored in a previous study, are equally important compared with the T-even quark contributions.

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## Introduction

To solve the fine-tuning problem of the Standard Model (SM), the little Higgs theory [?, ?, ?, ?, ?] was proposed as a kind of electroweak symmetry breaking mechanism accomplished by a naturally light Higgs sector. The Higgs boson remains light, being protected by the approximate global symmetry and free from one-loop quadratic sensitivity to the cutoff scale. The littlest Higgs model [?, ?, ?, ?] provides an economical approach which implements the idea of the little Higgs theory. Most of the constraints from the electroweak precision tests on little Higgs models [?, ?, ?, ?, ?, ?] come from the tree-level mixing of heavy and light mass eigenstates, which would require raising the mass of the new particles to be much higher than TeV scale and thus reintroduce the fine-tuning in the Higgs potential [?]. However, these tree-level contributions can be avoided by introducing a discrete symmetry called T-parity [?, ?, ?, ?]. In such a scenario, the top quark has a T-even partner (denoted as  $T$ ) and a T-odd partner (denoted as  $T'$ ). In addition, some extra T-odd fermions need to be also introduced in order to make the model T-parity invariant. These predicted new T-even and T-odd quarks will cause some effects in various processes, especially the top quark and Higgs boson processes [?, ?], at collider experiments. In this note we focus on the Higgs-pair production process at the LHC, which may be sensitive to new physics.

The Higgs-pair production process at the LHC will provide a way to probe the Higgs boson self-coupling  $\lambda$ . With design luminosity, it is possible for the LHC to establish that the SM Higgs boson has a non-zero self-coupling and that  $\lambda/\lambda_{\text{SM}}$  can be restricted to a range of 0-3.7 at 95% confidence level if its mass is between 150 and 200 GeV [?]. Such Higgs-pair production process has been studied in various new physics models [?, ?, ?, ?, ?, ?]. Recently, this process was studied in the littlest Higgs model without T-parity [?] and with T-parity [?]. However, the study in [?] only considered the contributions of T-even quarks but ignored the effects of the T-odd fermions. As shown in some recent analyses [?, ?, ?, ?, ?], the T-odd fermions can also cause some interesting collider phenomenology and their effects cannot be ignored. Given the popularity of the littlest Higgs model with T-parity and also the importance of the Higgs-pair production at the LHC as a probe of Higgs self-interaction, we in this note give a complete calculation for the Higgs-pair production in the littlest Higgs model with T-parity by considering the contributions of both T-even and T-odd quarks.

This work is organized as follows. In Sec. II we recapitulate the T-odd fermions and the top-quark sector of the littlest Higgs model with T-parity. In Sec. III, we calculate the Higgs-pair production at the LHC. Finally, we give our conclusion in Sec. IV.

## II. The Littlest Higgs Model with T-parity

### A. Fermion Sector

The original Littlest Higgs model [?] is based on a non-linear sigma model describing the spontaneous breaking of a global  $SU(5)$  down to a global  $SO(5)$  at an energy scale  $f$  (TeV). The vacuum expectation value (VEV) of an  $SU(5)$  symmetric tensor  $\Sigma$  is proportional to a specific matrix pattern. The low-energy dynamics of the non-linear sigma model is described by  $\Sigma(x) = e^{i\Pi/f}\Sigma_0 e^{i\Pi^T/f} = e^{2i\Pi/f}\Sigma_0$ , where  $\Pi(x) = \pi^a(x)X^a$  and  $\pi^a(x)$  are the Goldstone bosons corresponding to the 14 broken generators  $X^a$  for the  $SU(5) \rightarrow SO(5)$  breaking.

To implement T-parity in the fermion sector requires the introduction of mirror fermions. For each SM lepton/quark doublet, two fermion doublets  $q_1(2, 1)$  and  $q_2(1, 2)$  are introduced under the  $SU(2)_1 \times SU(2)_2$  gauge symmetry. They can be embedded into incomplete  $SU(5)$  multiplets  $\Psi_1$  and  $\Psi_2$ . A right-handed  $SO(5)$  multiplet  $\Psi_R$  transforming nonlinearly under the full  $SU(5)$  is introduced to give mass to the extra fermions. The field content can be expressed as:

$$\Psi_1 = \begin{pmatrix} q_1 \\ \psi_R \end{pmatrix}, \quad \Psi_2 = \begin{pmatrix} q_2 \\ \tilde{\psi}_R \end{pmatrix}, \quad \Psi_R = \text{diag}(1, 1, 1, 1, 1)$$

The first component of  $\psi_R$  is irrelevant to our study (as shown later) and the second component of  $\psi_R$  is  $iq_R$  [?, ?, ?, ?]. The mirror fermions can be given  $O(f)$  masses via a mass term:

$$\mathcal{L}_\kappa = \kappa_{ij} f (\bar{\Psi}_i \Sigma_0 \Omega \xi^\dagger \Omega) \Psi_R + \text{h.c.}$$

where  $\xi = e^{i\Pi/f}$ ,  $\Omega = \text{diag}(1, 1, 1, 1, 1)$  and  $i, j = 1, 2, 3$  are generation indices. For simplicity we assume flavor-diagonal and universal  $\kappa$  in our study.

The fields transform under  $SU(5)$  as:

$$\Psi_1 \rightarrow V^* \Psi_1, \quad \Psi_2 \rightarrow V \Psi_2, \quad \Psi_R \rightarrow U \Psi_R, \quad \xi \rightarrow V \xi U^\dagger, \quad \Sigma \rightarrow V \Sigma V^T$$

where  $V$  is an  $SU(5)$  rotation matrix and  $U$  is the unbroken  $SO(5)$  rotation. Under T-parity the transformations are defined as:

$$\Psi_1 \leftrightarrow -\Sigma_0 \Psi_2, \quad \Psi_R \rightarrow -\Omega \xi^\dagger \Omega$$

Thus  $q_1 \leftrightarrow -q_2$  and  $\Sigma \rightarrow \Sigma_0 \Omega \Sigma^\dagger \Omega \Sigma_0$  under T-parity. Following the above transformation, the Lagrangian is T-invariant.

The Lagrangian contains new Higgs boson interactions and mass terms for the T-odd fermions:

$$\mathcal{L}_\kappa \simeq -\frac{\kappa f}{\sqrt{2}} \bar{d}_L d'_R + \frac{\kappa f}{\sqrt{2}} [(1 + c_\xi) \bar{u}_L u'_R - \bar{u}_L \chi_R - \bar{u}_L q_R] + \text{h.c.}$$

where we have ignored generation indices, and  $c_\xi = \cos\left(\frac{v+h}{f}\right)$  and  $s_\xi = \sin\left(\frac{v+h}{f}\right)$  come from the non-linear sigma model field  $\xi$ , with  $h$

and  $v$  being the neutral Higgs boson field and its VEV, respectively [?]. The mirror fermion  $u_L^- = (u_{L1} + u_{L2})/\sqrt{2}$  is T-odd, and  $u_L^+ = (u_{L1} - u_{L2})/\sqrt{2}$  is T-even and massless. The same definitions also apply to the down-type mirror quarks. The fermions  $q_R$  and  $\chi_R$  can obtain large Dirac masses by introducing additional fermions, as described in detail in [?, ?]. We also assume the Dirac mass terms  $m_q \bar{q}'_L q_R - m_\chi \bar{\chi}'_L \chi_R$ . From the Lagrangian we can see that the first component of the doublet  $\psi_R$  does not appear and the T-odd down-type quarks have no tree-level couplings with the Higgs boson. After diagonalizing the mass matrix, we obtain the mass eigenstates  $u$ ,  $\chi$  and  $q$ , which couple to  $h$  and  $hh$ , respectively.

## B. Top-quark Yukawa couplings

To cancel the quadratic divergence of the Higgs mass induced by the top quark requires completing the  $Q_1$  and  $Q_2$  multiplets for the third generation to representations of the  $SU(3)_1$  and  $SU(3)_2$  subgroups of the full  $SU(5)$ :

$$Q_1 = (q_1, U_{L1}, 0_2)^T, \quad Q_2 = (0_2, U_{L2}, q_2)^T$$

In addition to the SM right-handed top quark field  $u_R$ , one must also introduce additional singlets  $U_{R1}$  and  $U_{R2}$ .

For the top-quark Yukawa couplings, one can write down the following Lagrangian [?, ?, ?, ?]:

$$\mathcal{L}_t = \lambda_1 f \epsilon_{ijk} \epsilon_{xy} (\bar{Q}_1)_i \Sigma_{jx} \Sigma_{ky} + \lambda_2 f (\bar{U}_{L1} U_{R1} + \bar{U}_{L2} U_{R2}) + \text{h.c.}$$

where the indices  $i, j, k$  run from 1 to 3 whereas  $x, y = 4, 5$ . Note that under T-parity these fields transform as:

$$Q_1 \leftrightarrow -\Sigma_0 Q_2, \quad U_{R1} \leftrightarrow -U_{R2}, \quad u_R \rightarrow u_R$$

Therefore, the T-parity eigenstates are defined as  $U_L^- = (U_{L1} + U_{L2})/\sqrt{2}$  (T-odd),  $U_L^+ = (U_{L1} - U_{L2})/\sqrt{2}$  (T-even), and the same definitions also apply to the right-handed singlets.

From the above Lagrangian we can obtain the following Higgs boson interactions and mass terms for the fermions:

$$\mathcal{L}_t \simeq -\lambda_1 f \left( \bar{u}_L^+ u_R + \frac{1 + c_\Sigma}{\sqrt{2}} \bar{U}_L^+ u_R \right) - \lambda_2 f (\bar{U}_L^+ U_R^+ + \bar{U}_L^- U_R^-) + \text{h.c.}$$

where  $c_\Sigma = \cos\left(\frac{\sqrt{2}(v+h)}{f}\right)$  and  $s_\Sigma = \sin\left(\frac{\sqrt{2}(v+h)}{f}\right)$  come from the non-linear sigma model field  $\Sigma$  [?]. The T-odd Dirac fermion  $T'$  ( $T'_L \equiv U_L^-$ ,  $T'_R \equiv U_R^-$ ) obtains a mass  $m_{T'} = \lambda_2 f$  and has no tree-level coupling with the Higgs boson. The left-handed (right-handed) top quark and T-even T-quark are linear combinations of  $u_L^+$  and  $U_L^+$  ( $u_R^+$  and  $U_R^+$ ). After diagonalizing the mass matrix, we can obtain the mass eigenstates  $t$  and  $T$  as well as their couplings with the Higgs boson.

### III. Higgs-pair Production at LHC

Now we examine Higgs pair production in the littlest Higgs model with T-parity at the LHC. The production can proceed through gluon-gluon fusion and  $b\bar{b}$  annihilation at parton level, with the former being the dominant one [?]. The Feynman diagrams for Higgs-pair production via gluon-gluon fusion are shown in Fig. 1 [Figure 1: see original paper]. In the SM the dominant contributions are from diagrams analogous to Fig. 1(a, c, d) with top-quark loops. In the littlest Higgs model with T-parity, the top-quark loops give additional contributions through the tree-level  $hh\bar{t}t$  coupling and the modified  $h\bar{t}t$  coupling. In addition to the top-quark loops, the loops of new T-even and T-odd quarks also come into play. All these particles should be summed over in our loop calculations. (As we pointed out earlier, the calculations in [?] did not include the contributions of T-odd quarks.)

The calculations of the loop diagrams in Fig. 1 are straightforward. Each loop diagram is composed of scalar loop functions [?] which are evaluated using LoopTools [?, ?]. The calculations are tedious and the analytical expressions are lengthy, which are not presented here.

We numerically checked our results by comparing our  $gg \rightarrow hh$  parton cross section with [?]. The calculations in [?] considered the loop effects of (i) the top-quark and T-even T-quark, (ii) the heavy neutral triplet Higgs boson  $\Phi^0$ , and (iii) the first and second generation quarks. Since the dominant contributions are from (i) [?], their results should be in approximate agreement with ours if we only keep the contributions of the top-quark and T-even T-quark with the same input parameters. We made such a comparison in Table I and find that our results agree quite well with [?].

**Table I:** Comparison of our results with [?] for the contributions of the top-quark and T-even T-quark to  $gg \rightarrow hh$  cross section using the same parameters and Feynman rules.

$\sqrt{\hat{s}}$ (GeV)	$\hat{\sigma}(gg \rightarrow hh)$ (ours)	$\hat{\sigma}(gg \rightarrow hh)$ (in [?])
300	0.0902	0.0947
400	0.3459	0.3595
500	0.4514	0.4685
600	0.4953	0.5138
700	0.4922	0.5107
800	0.4841	0.5022
900	0.3616	0.3754
1000	0.2385	0.2478
1100	0.1985	0.2063
1200	0.0636	0.0659

Note that in the littlest Higgs model with T-parity, T-parity forbids the gener-

ation of a VEV for the triplet scalar field and also forbids the contributions of the new T-odd particles to processes with external SM fermions at tree level. Therefore, the electroweak precision constraints on the model with T-parity are generically quite weak and, as a result, the symmetry breaking scale  $f$  may be as low as 500 GeV [?]. When expanding in the power series of  $v/f$ , we need to keep some higher orders since  $v/f$  may not be so small (for example,  $v/f \approx 0.5$  for  $f = 500$  GeV). Therefore, when expanding  $c_\Sigma$  and  $s_\Sigma$  to diagonalize the mass matrix, we keep terms up to order  $(v^5/f^5)$ . The diagonalization of the mass matrix was performed numerically in our analyses (approximate expressions are given in [?, ?]).

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 [?] to generate the parton distributions with the renormalization scale  $\mu_R$  and the factorization scale  $\mu_F$  chosen to be  $\mu_R = \mu_F = 2m_h$ , and the two-loop running coupling constant  $\alpha_s$  with  $\alpha_s(m_Z) = 0.118$ . The SM parameters involved are taken as  $m_t = 172.7$  GeV [?] and  $m_Z = 91.187$  GeV [?]. We fix  $m_h = 150$  GeV in our numerical calculations. The new free parameters involved are the symmetry breaking scale  $f$ , the ratio  $r = \lambda_1/\lambda_2$ ,  $\kappa$ ,  $m_q$  and  $m_\chi$ . Our calculations show that the results are not sensitive to  $\kappa$ ,  $m_q$  and  $m_\chi$  for  $m_q, m_\chi > 3$  TeV, which is in agreement with the finding in [?]. Thus, we take  $\kappa = 1.0$ ,  $m_q = m_\chi = 5$  TeV and retain  $f$  and  $r$  as free parameters.

In Fig. 2 [Figure 2: see original paper] we plot the hadronic Higgs-pair production cross section at the LHC versus the parameter  $f$  for several values of  $r$ . Here, we include all effects from the top-quark, T-even and T-odd quarks (three generations). The figure shows that the contributions of this model increase the SM cross section in the allowed parameter space, and the magnitude of such corrections depends on the parameters  $r$  and  $f$ . The corrections are sensitive to the scale  $f$  and become more sizable for lower values of  $f$ . For example, for  $r = 0.5$ , the total cross section can reach 30 fb. We also show a typical prediction from the minimal supersymmetric model taken from the first reference of [?]. Note that in the minimal supersymmetric model the Higgs boson mass  $m_h$  is upper bounded by 135 GeV and cannot be as heavy as 150 GeV which we choose for both the SM and the littlest Higgs model. We see that the production rate in the littlest Higgs model with T-parity can be larger than the supersymmetric model prediction in the allowed parameter space.

The comparison of the results with and without T-odd quark contributions is shown in Fig. 3 [Figure 3: see original paper]. We see that the contributions of T-odd quarks are equally important and thus cannot be neglected. For example, with (without) the contributions of T-odd quarks, the cross section is 29 fb (21 fb) for  $r = 1.0$ .

## IV. Conclusion

In the framework of the littlest Higgs model with T-parity we calculate the production of a pair of neutral CP-even Higgs bosons at the LHC. We find that, due to the loop contributions of both T-even and T-odd quarks predicted in this model, the production rate can be significantly enhanced relative to the Standard Model prediction. Also, we find that the T-odd quark contributions, which were ignored in previous studies, are equally important compared with the T-even quark contributions and thus cannot be neglected.

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