Higgs boson productions at LHC as a probe of different littlest Higgs models with T-parity postprint

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Full Text

Preamble

Higgs Boson Production at the LHC as a Probe of Different Littlest Higgs Models with T-Parity

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Abstract

Higgs boson production at the LHC will serve as a sensitive probe of various little Higgs models. In this work, we comparatively study two littlest Higgs models with different T-parity constructions by examining their effects on three Higgs production processes at the LHC: single Higgs production, Higgs pair production, and Higgs boson production associated with a top-antitop quark pair. The two models are characterized by predicting a top partner that cancels the Higgs mass quadratic divergence contributed by the top quark, with even and odd T-parity respectively. We find that both models can alter the SM cross sections sizably and their corrections differ significantly. Therefore, Higgs boson production at the LHC may shed light on these two models or even distinguish them.

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Introduction

Little Higgs theory [1] has been proposed as an interesting solution to the hierarchy problem. In such a theory, the Higgs boson is a pseudo-Goldstone boson and its mass is protected by an approximate global symmetry, making it free from one-loop quadratic sensitivity to the cutoff scale. The littlest Higgs model [2] economically implements this idea. However, due to tree-level mixing of heavy and light mass eigenstates, electroweak precision tests can impose strong constraints on the model [3], which would require raising the mass scale of new particles well above the TeV scale and thus reintroduce fine-tuning in the Higgs potential [4]. To address this problem, a discrete symmetry called T-parity has been proposed [5], which forbids those tree-level contributions. In the pioneer version of this model (hereafter called model-I) [5], T-parity is implemented by simply adding the T-parity images of the original top quark interaction to make the Lagrangian T-invariant. A characteristic prediction of this model is a T-even top partner that cancels the Higgs mass quadratic divergence contributed by the top quark. Since the heavy top partner is T-even, it can be singly produced at the LHC, which is a crucial phenomenological signature of this model.

An alternative implementation of T-parity has recently been proposed (hereafter called model-II) [6], where all new particles, including the heavy top partner responsible for canceling the SM one-loop quadratic divergence, are odd under T-parity. An obvious virtue of this model is that the spectrum of the third-generation quark sector is simplified [6].

Many studies of the collider phenomenology for model-I have been performed [7]. However, the phenomenology of model-II is quite different from model-I [6], especially for the heavy top partner, which is T-odd and cannot be singly produced at the LHC.

To probe these models at the LHC, Higgs boson production processes are ideal channels. First, these littlest Higgs models mainly alter the Higgs sector of the SM, so Higgs properties may deviate from those of the SM Higgs boson. Second, the Higgs boson is the most important target of the LHC experiment [8], and its various production channels will be thoroughly explored. In this work, we select three typical Higgs production processes at the LHC as probes of these littlest Higgs models. The first is single Higgs boson production via gluon-gluon fusion, which is the dominant production mechanism at the LHC [9]. The second is Higgs pair production, which is rare but very important since it provides a way to probe the Higgs boson self-coupling [10]. The third is Higgs boson production in association with a top quark pair, which plays an important role in testing the Yukawa coupling [11]. These processes have been studied in model-I [12-15], but not yet in model-II. In this work, we comparatively study the effects of both models on these three Higgs production processes.

This paper is organized as follows. In Sec. II, we recapitulate the fermion and top quark Yukawa sectors of the models. Since model-I has been elucidated in detail in the literature, we focus on model-II. In Sec. III, we study the effects of these models on single Higgs, Higgs pair, and Higgs production associated with a top quark pair at the LHC. Finally, we present our conclusions in Sec. IV.

II. The Littlest Higgs Models with T-Parity

The original littlest Higgs model [2] is based on a non-linear sigma model describing the spontaneous breaking of a global SU(5) symmetry down to a global SO(5) at an energy scale f ~ TeV. The vacuum expectation value (VEV) of an SU(5) symmetric tensor Σ is proportional to Σ , where Σ represents a unit matrix. The low-energy dynamics of the non-linear sigma model is described by Σ(x) = e^{iΠ/f} Σ e$^{\{\mathrm{i}\Pi}$T/f} = e^{2iΠ/f} Σ , where Π(x) = ^a(x) X^a, with ^a(x) being the Goldstone bosons corresponding to the 14 broken generators X^a of the SU(5)/SO(5) breaking.

In the pioneer version of the littlest Higgs model with T-parity (model-I), T-parity in the top quark sector is implemented by simply adding the T-parity images of the original interaction to make the Lagrangian T-invariant. Thus, the heavy top partner that cancels the Higgs mass quadratic divergence contributed by the top quark is T-even. Detailed descriptions of this model exist in the literature [5], so we do not discuss it in detail here.

In the following, we recapitulate an alternative T-parity construction (model-II). In model-II, for each generation of fermions (quarks and leptons), we introduce two doublets q and q , which are embedded into incomplete representations of SU(5) multiplets Q and Q , and a right-handed SO(5) multiplet Ψ_R that transforms nonlinearly under the full SU(5). The field content can be expressed as Q = (q , _R)^T, Q = (q , _R')^T, and Ψ_R = (U_R, u_R')^T, where q_A = (i d_L^A, i u_L$^{\mathrm{A})}$T with A = 1,2, and _R = (i d_R' , i u_R')^T. The first component of ˜_R is irrelevant to our study (as shown later), and the second component of ˜*R is i q_R. The mirror fermions can be given masses via a mass term [6]:* {ij}^f (Q̄_i 2 Σ Ω †) Ψ_jR + h.c., where   = e^{iΠ/f}, Ω = diag(1,1,1,1,1), and i,j = 1,2,3 are generation indices. For simplicity, we assume flavor-diagonal and universal   in our study.

The fields transform under SU(5) as: Q → V Q , Q → V* Q , Ψ_R → U Ψ_R,   → V   U†, Σ → V Σ V^T, where V is an SU(5) rotation matrix and U is the unbroken SO(5) rotation that is a nonlinear representation of SU(5). Under T-parity, the transformation laws are defined as: q   q , Σ → Σ = Σ Ω Σ† Ω Σ , and Ψ_R → -Ψ_R under T-parity. Following these transformations, the Lagrangian is T-invariant.

The Lagrangian contains new Higgs boson interactions and mass terms. For the first and second generations:

L_   - (1 + c_) [đ_L- d_R' + ū_L- u_R' - ū_L- q_R + ū_L+ _R] + h.c.,

where we have ignored generation indices, and c_ = cos((v+h)/f) and s_ = sin((v+h)/f) come from the nonlinear sigma model field , with h and v being the neutral Higgs boson field and its VEV, respectively. The fermion u_L- =

(u_L1 - u_L2)/√2 is T-odd, which together with u_R' gets a mass, while u_L+ = (u_L1 + u_L2)/√2 is T-even and massless. The same definition applies to down-type quarks. The fields q_R and _R can be given large Dirac masses by introducing additional fields, as described in detail in [5]. We simply assume their masses are ~ f. From the above equation, we see that the first component of the doublet ˜_R does not appear and the T-odd down-type quarks have no tree-level coupling to the Higgs boson.

For the top quark sector, to cancel the quadratic divergence of the Higgs mass induced by the top quark, additional singlets must be introduced:

Q = (q , U_L1, 0)^T and Q = (0 , U_L2, q)^T.

From the Lagrangian we obtain the Higgs boson interactions and mass terms for the third-generation fermions:

L_   - (1 + c_)/√2   f [đ_L- d_R' + ū_L- u_R' - ū_L- q_R - Ū_L- q_R - Ū_L- u_R' - ū_L+ _R + c_ Ū_L+ _R] + h.c.,

where the T-parity eigenstates are defined as U_L+ = (U_L1 + U_L2)/√2 (T-even) and U_L- = (U_L1 - U_L2)/√2 (T-odd). The U_L+ together with _R gets a Dirac mass.

Introducing additional singlets U^c and U^c under T-parity, the top quark Yukawa coupling can be written as [6]:

 f _{ijk} _{xy} (Q)*i Σ*{jx} Σ_{ky} U^c + (Σ Q)*i Σ*{jx} Σ_{ky} U^c + h.c.,

where indices i,j,k run from 1 to 3 while x,y = 4,5. This introduces mixing between light T-even and heavy T-even fermions, which can be removed by additional interactions [6]:

 ' f _{lmn} _{rs} (Ω Q)*l Σ* {mr} Σ' *{ns} U^c + (Ω Σ Q)*l Σ' *{mr} Σ* {ns} U^c + h.c.,

where indices l,m,n run from 3 to 5 while r,s = 1,2, Σ' = Ω Σ† Ω, and Σ' = Σ Σ' Σ under T-parity. Adding L_t and taking ' = , we obtain the simplified expression for the top quark Yukawa sector:

L_t   -   [√2 s_Σ ū*L+ U^c+* + (1 + c_Σ) Ū*L- U^c-*] + h.c.,

where c_Σ = cos(√2(v+h)/f) and s_Σ = sin(√2(v+h)/f) originate from the nonlinear sigma model field Σ, and U^c_± = (U^c ± U^c)/√2.

The Yukawa couplings of up-type quarks for the first and second generations are given by a similar Lagrangian to the top quark sector, but without introducing extra singlet fields:

 _u f _{ijk} _{xy} (Q)*i Σ*{jx} Σ_{ky} u^c + (Σ Q)*i Σ*{jx} Σ_{ky} u^c + h.c., where u^c transforms under T-parity. This contains the following Higgs boson interactions and mass terms for up-type quarks of the first and second generations:

L_u - _u f s_Σ ū_L+ u^c + h.c.

After diagonalizing the mass matrices, we obtain the mass eigenstates of new fermions. For each SM fermion doublet, there are d, q (T-odd), and (T-even). Additionally, the top quark has a T-odd partner T that cancels the one-loop quadratic divergence of the Higgs mass induced by the top quark.

III. The Effects in Higgs Boson Productions at the LHC

The relevant Feynman rules in our calculations are obtained after diagonalizing the mass matrices, which is performed numerically in our analyses. We assume a Higgs mass of 150 GeV and take other SM parameters as m_t = 172.7 GeV, m_Z = 91.187 GeV [16], using the two-loop running coupling constant _s(Q) with _s(m_Z) = 0.118. For parton distributions we use CTEQ6L [17] with renormalization scale _R and factorization scale _F chosen as _R = _F = m_h for single Higgs production and _R = _F = 2m_h for Higgs pair production. To simplify the top quark Yukawa sector, we have taken Yukawa coupling constants ’ = . The new free parameters are thus the breaking scale f and . Our calculations show that results are not very sensitive to in the allowed parameter space, so we take = 3.0 and retain only f as a free parameter. Reference [18] shows that the scale f in model-I may be below 1 TeV, and the constraint in model-II is expected to be even weaker [6].

Our calculations involve loop diagrams, which are straightforward to compute. Each loop diagram is composed of scalar loop functions [19] calculated using LOOPTOOLS [20]. Since the explicit expressions of these form factors are lengthy, we do not present them in this paper.

[Figure 1: see original paper] The main parton-level Feynman diagrams for single Higgs boson production via gluon-gluon fusion in model-II. Here, f_i = t, , T, q for the third generation, and f_i = , u, q for the first two generations.

[Figure 2: see original paper] The parton-level Feynman diagrams for Higgs pair production via gluon-gluon fusion in model-II. Here, f_i can be a T-even quark (i = 1,2 with f = u and f = for three generations) or a T-odd quark (for the third generation, i = 1,2,3 with f = T, f = u and f = q; while for the first and second generations, i = 1,2 with f = u and f = q). Diagrams obtained by exchanging the two gluons or the two Higgs bosons are not shown.

At the LHC, single Higgs production via gluon-gluon fusion is dominated by the top quark loop in the SM. In model-II, the Feynman diagrams for this process are shown in Fig. 1. Due to the modified h t̄ t coupling, the top quark loop may give corrections to the SM prediction. In addition to the top quark loop, loops of new T-even and T-odd quarks also contribute. In model-I, the corrections also arise from these two sources. The relevant Feynman diagrams and rules are described in detail in [12].

Higgs pair production at the LHC can proceed through gluon-gluon fusion and $\bar{b}b$ annihilation at the parton level, with the former being dominant [21]. The main Feynman diagrams for the process $gg \to hh$ in model-II are shown in Fig. 2. In the SM, the dominant contributions come from diagrams (a), (c), and (d) with top quarks running in the loops. In model-II, the top quark can give new corrections through the tree-level $hh\bar{t}t$ coupling and the modified $h\bar{t}t$ coupling. Additionally, since the Higgs boson interacts with the introduced T-even and T-odd quarks, we have additional diagrams with these new quarks in the loops. In model-I, the correction diagrams are similar and are presented in [14]. In our calculation, we ignore contributions from light quark loops.

[Figure 3: see original paper] The parton-level Feynman diagrams for $h\bar{t}t$ production at the LHC in model-II. The u-channel diagrams obtained by exchanging the two gluons in (a)-(c) are not shown.

The production of $h\bar{t}t$ at the LHC can proceed through gg fusion and $q\bar{q}$ annihilation at the parton level. In both model-II and model-I, the tree-level Feynman diagrams are the same as in the SM, shown in Fig. 3. The corrections mainly arise from the modified $h\bar{t}t$ coupling.

In Figs. 4-6 we plot the corrections to the SM predictions for the production rates versus the parameter f. For model-I we take $r = 1.0$, and our results agree with [12, 14, 15].

[Figure 4: see original paper] The corrections to the SM single Higgs boson production rate versus the parameter f at the LHC.

[Figure 5: see original paper] The corrections to the SM Higgs pair production rate versus the parameter f at the LHC.

[Figure 6: see original paper] The corrections to the SM $h\bar{t}t$ production rate versus the parameter f at the LHC.

The figures show that contributions from both models can significantly alter the SM cross sections in the allowed parameter space. The corrections are sensitive to the scale f, with the magnitude becoming more sizable for lower values of f. Furthermore, the corrections in model-II are much more significant than in model-I. For example, for model-II (model-I) the correction is -43% (-25%) with $f = 800$ GeV in Fig. 4, 41% (19%) with $f = 1$ TeV in Fig. 5, and -30% (-13.5%) with $f = 600$ GeV in Fig. 6.

IV. Conclusion

In this work, we comparatively studied two typical littlest Higgs models with different T-parity constructions by examining their effects on three Higgs production processes at the LHC: single Higgs production, Higgs pair production, and Higgs boson production associated with a top-antitop quark pair. We found that both models can alter the SM cross sections sizably and their corrections differ significantly. Therefore, Higgs boson production at the LHC may shed light on these two models or even distinguish them.

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