

Higgs and Z-boson FCNC decays correlated with B-meson decays in littlest Higgs model with T-parity (Postprint)

Authors: Han,X, Wang, L., Yang,JM

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Full Text

Preamble

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Xiao-Fang Han, Lei Wang, Jin Min Yang

Institute of Theoretical Physics, Academia Sinica, Beijing 100080, China

Abstract

In the littlest Higgs model with T-parity (LHT), new flavor-changing interactions between mirror fermions and Standard Model (SM) fermions can induce various FCNC decays for B-mesons, Z-boson, and Higgs boson. Since all these decays induced in the LHT model are correlated, we perform in this work a collective study of these processes, namely the Z-boson decay $Z \rightarrow b\bar{s}$, the Higgs boson decay $h \rightarrow b\bar{s}$, and the B-meson decays $B \rightarrow X_s\gamma$, $B_s \rightarrow \mu^+\mu^-$, and $B \rightarrow X_s\mu^+\mu^-$. We find that under current experimental constraints from the B-decays, the branching ratios of both $Z \rightarrow b\bar{s}$ and $h \rightarrow b\bar{s}$ can still deviate significantly from the SM predictions. In the parameter space allowed by the B-decays, the branching ratio of $Z \rightarrow b\bar{s}$ can be enhanced to 10^{-7} (about one order above the SM prediction) while $h \rightarrow b\bar{s}$ can be much suppressed relative to the SM prediction (about one order below the SM prediction).

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INTRODUCTION

The elegant idea of little Higgs [1] attempts to provide a solution to the hierarchy problem by regarding the Higgs boson as a pseudo-Goldstone boson whose mass is protected by an approximate global symmetry and free from one-loop quadratic sensitivity to the cutoff scale. The littlest Higgs model [2] is an economical implementation of this idea, but it is found to be subject to strong constraints from electroweak precision tests [3], which would require raising the mass scale of new particles far above the TeV scale and thus reintroduce fine-tuning in the Higgs potential [4]. To address this problem, a discrete symmetry called T-parity is proposed [5], which forbids tree-level contributions from heavy gauge bosons to observables involving only SM particles as external states. However, in such a littlest Higgs model with T-parity (LHT) [5], new flavor-changing interactions arise between mirror fermions and SM fermions (similar to the flavor-changing interactions between sfermions and fermions in supersymmetric models). These new flavor-changing interactions can have crucial phenomenological implications, particularly in inducing various flavor-changing neutral-current (FCNC) processes that must be examined.

Among the FCNC processes induced by these new flavor-violating interactions in the LHT model, the loop-induced B-decays such as $B \rightarrow X_s \gamma$, $B_s \rightarrow \mu^+ \mu^-$, and $B \rightarrow X_s \mu^+ \mu^-$ should be examined first due to available experimental data. Recently, these B-decays have been intensively studied in the LHT model and found to be sensitive to the new flavor-violating interactions [6–8]. In addition to these B-decays, the loop-induced FCNC decays of the Higgs and Z-boson, such as $Z \rightarrow b\bar{s}$ and $h \rightarrow b\bar{s}$, should also be examined as they are strongly correlated with the FCNC B-decays and sensitive to the flavor structure of new physics. In the future, there may be at least two avenues for producing Z-bosons in much larger quantities than at LEP. At the CERN Large Hadron Collider (LHC) with an integrated luminosity of 100 fb^{-1} , one expects 10^9 Z-bosons to be produced [9]. In particular, the GigaZ option at the proposed International Linear Collider (ILC) with an integrated luminosity of 30 fb^{-1} could produce more than 10^9 Z-bosons [10]. For Higgs boson studies, one may expect the ILC to scrutinize Higgs boson properties after discovery at the LHC.

These rare decays $Z \rightarrow b\bar{s}$ and $h \rightarrow b\bar{s}$ have been studied in the SM [11] and in various new physics models [12, 13]. In this work we study these decays in the LHT model. Since such decays are strongly correlated with the induced FCNC B-decays ($B \rightarrow X_s \gamma$, $B_s \rightarrow \mu^+ \mu^-$, and $B \rightarrow X_s \mu^+ \mu^-$), we collectively consider all these processes. We first review the analytic results for these B-decays given in [6–8] and then perform numerical calculations together with $Z \rightarrow b\bar{s}$ and $h \rightarrow b\bar{s}$. We show the constraints on the parameter space from current B-decay experiments and display the results for $Z \rightarrow b\bar{s}$ and $h \rightarrow b\bar{s}$ with and without the B-decay constraints.

This work is organized as follows. In Sec. II we recapitulate the LHT model and address the new flavor-violating interactions that contribute to the FCNC decays considered in this work. In Sec. III, IV, and V we examine the B-decays ($B \rightarrow X_s \gamma$, $B_s \rightarrow \mu^+ \mu^-$, and $B \rightarrow X_s \mu^+ \mu^-$), Z-boson decay $Z \rightarrow b \bar{s}$, and Higgs boson decay $h \rightarrow b \bar{s}$, respectively. Finally, we give our conclusion in Sec. VI.

II. THE LITTLEST HIGGS MODEL WITH T-PARITY

The LHT model [5] is based on a non-linear sigma model describing the spontaneous breaking of a global SU(5) symmetry down to a global SO(5) by a 5×5 symmetric tensor at the scale $f \sim \mathcal{O}(\text{TeV})$. From the SU(5)/SO(5) breaking, 14 Goldstone bosons arise, described by the ‘‘pion’’ matrix Π , given explicitly by

$$\Pi = \begin{pmatrix} -\frac{\omega^0}{2} - \frac{\eta}{\sqrt{20}} & -\frac{\omega^+}{\sqrt{2}} & \frac{i\phi^0 + \phi^P}{\sqrt{2}} \\ -\frac{\omega^-}{\sqrt{2}} & \frac{\omega^0}{2} - \frac{\eta}{\sqrt{20}} & \phi^- \\ -\frac{i\phi^0 + \phi^P}{\sqrt{2}} & \phi^+ & \sqrt{4}v + h + i\pi^0 \end{pmatrix}$$

Under T-parity, the SM Higgs doublet $H = (\pi^+/\sqrt{2}, (v+h+i\pi^0)/\sqrt{2})$ is T-even, while the other fields are T-odd. A subgroup $[SU(2) \times U(1)]_1 \times [SU(2) \times U(1)]_2$ of the SU(5) is gauged, and at the scale f it is broken into the SM electroweak symmetry $SU(2)_L \times U(1)_Y$.

The Goldstone bosons ω^0 , ω^\pm , and η are respectively eaten by the new T-odd gauge bosons Z_H , W_H , and A_H , which obtain masses

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

with g and g' being the SM SU(2) and U(1) gauge couplings, respectively. The Goldstone bosons π^0 and π^\pm are eaten by the SM T-even Z-boson and W-boson, which obtain masses

$$M_{W_L} = \frac{gv}{2} \left(1 - \frac{v^2}{12f^2}\right), \quad M_{Z_L} = \frac{gv}{2 \cos \theta_W} \left(1 - \frac{v^2}{12f^2}\right)$$

The photon A_L is also T-even and massless. Due to the mass corrections to SM bosons at $\mathcal{O}(v^2/f^2)$, the relation between G_F and v is modified from its SM form and is given by

$$\frac{1}{v^2} = \sqrt{2}G_F \left(1 - \frac{v^2}{6f^2}\right)$$

The top quark has a T-even partner T-quark and a T-odd T-quark. To leading order, their masses are given by

$$M_{T_+} = \frac{f}{v} \sqrt{\lambda_1^2 + \lambda_2^2}, \quad M_{T_-} = M_{T_+} \sqrt{1 + r^2}$$

where $r = \lambda_1/\lambda_2$ with λ_1 and λ_2 being the coupling constants in the Lagrangian of the top quark sector [5]. Furthermore, for each SM quark (lepton), a copy of mirror quark (lepton) with T-odd quantum number is added to preserve T-parity. We denote them by u_i^H , d_i^H , ν_i^H , and l_i^H , where $i = 1, 2, 3$ are generation indices. At $\mathcal{O}(v^2/f^2)$ their masses satisfy

$$m_{u_i^H} = \sqrt{2}\kappa_{qi}f, \quad m_{d_i^H} = m_{u_i^H} \left(1 - \frac{v^2}{8f^2}\right)$$

Here κ_{qi} are the diagonalized Yukawa couplings of the mirror quarks.

New flavor interactions arise between the mirror fermions and SM fermions, mediated by T-odd gauge bosons or T-odd Goldstone bosons. In general, besides charged-current flavor-changing interactions, FCNC interactions between mirror fermions and SM fermions can also arise from mismatched rotation matrices. For example, FCNC interactions exist between mirror down-type quarks and SM down-type quarks, where the mismatched mixing matrix is denoted by V_{Hd} . Following [6, 8], we parameterize V_{Hd} with three angles θ_{12}^d , θ_{13}^d , θ_{23}^d and three phases δ_{12}^d , δ_{13}^d , δ_{23}^d .

III. FCNC B-DECAYS

The decays $B \rightarrow X_s \gamma$, $B_s \rightarrow \mu^+ \mu^-$, and $B \rightarrow X_s \mu^+ \mu^-$ can be induced at loop level by the new flavor-changing interactions in the LHT model and have been recently studied in [8]. We check the results of [8] and provide the following brief descriptions of these decays without giving detailed expressions (all functions in our discussions can be found in [8]).

- (1) For $B \rightarrow X_s \gamma$, the LHT contributions enter through modifications of the quantities

$$T_{D'}^0(x_t) = \frac{2\lambda_t^{(s)} C_{7\gamma}^{0\text{SM}}}{8G_F(M_W)}, \quad T_{E'}^0(x_t) = \frac{2\lambda_t^{(s)} C_{8G}^{0\text{SM}}}{8G_F(M_W)}$$

where the CKM factor $\lambda_t^{(s)} = V_{ts} V_{tb}^*$, and $C_{7\gamma}^{0\text{SM}}$ and $C_{8G}^{0\text{SM}}$ are leading-order Wilson coefficients. With LHT effects, D' and E' are replaced by $T_{D'}$ and $T_{E'}$:

$$T_{D'} = T_{D'}^{\text{even}} + T_{D'}^{\text{odd}}, \quad T_{E'} = T_{E'}^{\text{even}} + T_{E'}^{\text{odd}}$$

where superscripts ‘even’ and ‘odd’ denote contributions from T-even and T-odd particles, respectively. Note that for LHT contributions we only consider

leading-order effects while for the SM prediction we include next-to-leading-order QCD corrections. The SM prediction for $B \rightarrow X_s \gamma$ has been calculated to NNLO [14].

- (2) The branching ratio of $B_s \rightarrow \mu^+ \mu^-$ in the SM depends on a function Y_{SM} , and LHT effects enter through modification of Y_{SM} [8]. With LHT effects, Y_{SM} is replaced by

$$Y_s = Y_{\text{SM}} + \bar{Y}^{\text{even}} + \bar{Y}^{\text{odd}}$$

where \bar{Y}^{even} and \bar{Y}^{odd} represent effects from T-even and T-odd particles, respectively. The branching ratio normalized to the SM prediction is then given by

$$\frac{\text{Br}(B_s \rightarrow \mu^+ \mu^-)}{\text{Br}(B_s \rightarrow \mu^+ \mu^-)_{\text{SM}}} = \left| \frac{Y_s}{Y_{\text{SM}}} \right|^2$$

with $\text{Br}(B_s \rightarrow \mu^+ \mu^-)_{\text{SM}} = 3.66 \times 10^{-9}$.

- (3) The branching ratio of $B \rightarrow X_s \mu^+ \mu^-$ in the SM depends on functions Y_{SM} , Z_{SM} , and $D'^0(x_t)$ (Y_{SM} and D'^0 are the same as in $B_s \rightarrow \mu^+ \mu^-$), and LHT effects enter through modifications of these functions. The modifications of Y_{SM} and D'^0 have been given above, and the modification of Z_{SM} is given by [8]

$$Z_s = Z_{\text{SM}} + \bar{Z}^{\text{even}} + \bar{Z}^{\text{odd}}$$

where \bar{Z}^{even} and \bar{Z}^{odd} represent effects from T-even and T-odd particles, respectively.

- (4) The experimental values for these three B-decays are given by [15]

$$\text{Br}(B \rightarrow X_s \gamma) = (3.52 \pm 0.25) \times 10^{-4} (E_\gamma > 1.6 \text{ GeV}), \quad \text{Br}(B_s \rightarrow \mu^+ \mu^-) < 7.5 \times 10^{-8}, \quad \text{Br}(B \rightarrow X_s \mu^+ \mu^-) = 4.3$$

Note that throughout this work we perform calculations in the 't Hooft-Feynman gauge and take SM input parameters from [16].

IV. Z-BOSON FCNC DECAY $Z \rightarrow b \bar{s}$

The relevant Feynman diagrams are shown in Fig. 1 [Figure 1: see original paper]. The LHT contributions come from both T-even and T-odd particles. The T-even particle contributions include both SM contributions and those from the top quark's T-even partner (T-quark). The T-odd particle diagrams are induced by interactions between SM quarks and mirror quarks mediated by

heavy T-odd gauge bosons or Goldstone bosons. The loop diagram calculations in Fig. 1 are straightforward. Each loop diagram involves scalar loop functions [17], calculated using LOOPTOOLS [18]. The relevant Feynman rules can be found in [8]. We have verified that divergences from T-even contributions cancel at $\mathcal{O}(v^2/f^2)$. For T-odd particle contributions, divergences do not cancel at $\mathcal{O}(v^2/f^2)$, arising from diagrams with T-odd Goldstone bosons. Such leftover divergence in the LHT model was first found in calculations of $B_s \rightarrow \mu^+ \mu^-$ and $B \rightarrow X_s \mu^+ \mu^-$ in [8] and understood as sensitivity of decay amplitudes to the ultraviolet completion of the theory.

In our numerical calculations we follow [8] to remove the divergent term $1/\epsilon$ and take the renormalization scale $\mu = \Lambda$ with $\Lambda = 4\pi f$ being the cutoff scale of the LHT model.

Regarding the involved parameters f and r , some constraints come from electroweak precision data [19], which however depend on the masses of T-odd fermions and the parameter δ_c (related to details of the ultraviolet completion). Hence, in our numerical calculations we relax constraints on f and r , letting them vary in the ranges

$$500 \text{ GeV} \leq f \leq 1500 \text{ GeV}, \quad 0.5 \leq r \leq 2.0$$

In addition to f and r , the matrix V_{Hd} and the masses of d_i^H ($i = 1, 2, 3$) are also involved. To simplify calculations, we consider three scenarios for these parameters:

- (I) We assume $V_{Hd} = 1$ or assume degeneracy for the masses of d_i^H . In the former case, there is no flavor mixing between mirror down-type quarks and SM down-type quarks, so loop contributions from T-odd particles vanish. In the latter case, due to Eq.(5), the masses of u_i^H are also degenerate. Then, due to unitarity of the flavor mixing matrices between mirror quarks and SM quarks, loop contributions from T-odd particles vanish. The remaining contributions from T-even particle loops depend on two parameters: the breaking scale f and the ratio r .
- (II) We assume $V_{Hd} = V_{CKM}$. In this scenario, in addition to T-even particle contributions, T-odd particles also contribute. The parameters involved are then f , r , $m_{d_i}^H$, and $m_{\nu_i}^H$ (the loop contributions to $B_s \rightarrow \mu^+ \mu^-$ and $B \rightarrow X_s \mu^+ \mu^-$ involve mirror lepton masses $m_{\nu_i}^H$). As shown in Eq.(5), mirror fermion masses are proportional to f , which we assume as

$$m_{d_1}^H = m_{d_2}^H = 600 \text{ GeV}, \quad m_{d_3}^H = 1400 \text{ GeV}, \quad m_{\nu_1}^H = m_{\nu_2}^H = m_{\nu_3}^H = 600 \text{ GeV}$$

We have verified that these parameters satisfy constraints from four-fermion interaction operators [20].

(III) We keep δ_{13}^d as a free parameter, while for other parameters in V_{Hd} we assume

$$\theta_{12}^d = \theta_{23}^d = 0, \quad \theta_{13}^d = 0.99, \quad \delta_{12}^d = \delta_{23}^d = 0, \quad \delta_{13}^d \in [0, 2\pi)$$

For the masses $m_{d_i}^H$ and $m_{\nu_i}^H$, we make the same assumptions as in scenario II.

Scanning over the parameters in the ranges specified above, we obtain the scatter plots in Fig. 2 [Figure 2: see original paper], where we also show constraints from the B-decays $B \rightarrow X_s \gamma$, $B_s \rightarrow \mu^+ \mu^-$, and $B \rightarrow X_s \mu^+ \mu^-$.

Fig. 2 shows that contributions are sensitive to the scale f , with more sizable deviations from SM predictions for lower f values. Constraints from B-decays are significant, with scenario III being most stringently restrained. In parameter space allowed by the 2σ experimental bounds of these B-decays, the branching ratio of $Z \rightarrow b\bar{s}$ can reach the order of 10^{-7} , about one order above the SM prediction.

V. HIGGS BOSON FCNC DECAY $h \rightarrow b\bar{s}$

The relevant Feynman diagrams involving T-even particles in the loops can be obtained from the corresponding diagrams in Fig. 1 by replacing the Z-boson with the Higgs boson. For T-odd particle contributions, the diagrams are more complicated. Note that the divergence of T-odd contributions for h or Z decay appears at $\mathcal{O}(v^2/f^2)$. Such divergence is mainly due to the absence of Fig. 1(i) with down-type mirror quarks in the loops since the Higgs boson does not couple to down-type mirror quarks. Since these leftover divergences in T-odd contributions appear at $\mathcal{O}(1)$, the prediction is subject to severe theoretical uncertainty, although we can treat the divergences in the same way as for Z-decay and B-decays discussed above. Unlike the uncertainty in Z-decay which is correlated with uncertainty in B-decays (and thus can be constrained by B-decays), the uncertainty in $h \rightarrow b\bar{s}$ caused by such T-odd contributions cannot be constrained by B-decays since contributions from diagrams mediated by the Higgs boson can be neglected in B-decays. To avoid such large unconstrained uncertainty from T-odd contributions, we perform numerical calculations only for scenario I where T-odd contributions vanish.

To evaluate the branching ratio of $h \rightarrow b\bar{s}$, we need the total decay width of the Higgs boson. In addition to SM decay channels, a new important channel $h \rightarrow A_H A_H$ arises (A_H is a candidate for cosmic dark matter), which may be dominant in some parameter space of the LHT model [21]. The total decay width is given by

$$\Gamma_{\text{total}} = \Gamma_{h \rightarrow \text{fermions}} + \Gamma_{h \rightarrow W_L W_L} + \Gamma_{h \rightarrow Z_L Z_L} + \Gamma_{h \rightarrow A_H A_H}$$

In Fig. 3 Figure 3: see original paper we scan over r and f in the ranges of Eq.(13) and present scatter plots for the branching ratio with $m_h = 140$

GeV. In Fig. 3(b) we show the dependence of the branching ratio on the Higgs boson mass by fixing parameters r and f allowed by electroweak precision data and B-decays. In our calculations we keep terms up to $\mathcal{O}(v/f)$ and verify that divergences cancel to this order.

From Fig. 3 we see that the branching ratio in the LHT model is below the SM prediction, with significant deviation for low f values. In parameter space allowed by B-decays at the 2σ level, the branching ratio can be one order below the SM prediction because in some parameter space the decay $h \rightarrow A_H A_H$ may be dominant and greatly enhance the total width.

VI. CONCLUSION

The littlest Higgs model with T-parity may have a flavor problem since it predicts new flavor-changing interactions between mirror fermions and Standard Model fermions, which can induce various FCNC decays. Since all these decays induced in this model are correlated, we have performed in this work a collective study of FCNC decays of B-mesons, Z-boson, and Higgs boson. We found that under current experimental constraints from B-decays, the branching ratios of both $Z \rightarrow b\bar{s}$ and $h \rightarrow b\bar{s}$ can still deviate significantly from SM predictions. In parameter space allowed by B-decays, the branching ratio of $Z \rightarrow b\bar{s}$ can be enhanced to 10^{-7} (about one order above the SM prediction) while $h \rightarrow b\bar{s}$ can be much suppressed relative to the SM prediction (about one order below the SM prediction).

We remark that unlike FCNC B-decays, testing these rare Z-boson and Higgs boson decays at collider experiments is quite challenging. For instance, testing this rare Z-boson decay may require the GigaZ option of the ILC. Theoretically, for testing the LHT model, these rare decays are complementary to direct production of T-quark [22] and production of top quark or Higgs boson [23], whose cross sections can be sizably altered by the LHT model.

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