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Leptonic Z decays in the littlest Higgs model with T parity

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The littlest Higgs model with T parity (called the LHT model) predicts the existence of the T-odd leptons, which can generate contributions to some leptonic processes at the one-loop level. We calculate their contributions to the leptonic Z decay processes $Z \rightarrow l\bar{l}'$, $Z \rightarrow l\bar{l}$, and $Z \rightarrow \nu\bar{\nu}$. We find that the T-odd leptons can give significant contributions to the branching ratios of these decay processes in most of the parameter space. The experimental measurement values might generate constraints on the free parameters of the LHT model.

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I. INTRODUCTION

A precise measurement of gauge boson production for pp scattering will be crucial at the LHC [1]. At the LHC, the gauge boson Z can be copiously produced via the Drell-Yan process and can be detected through its leptonic Z decay modes. Thus, considering the contributions of the new physics to the leptonic Z decays is very interesting, which will be important in testing the standard model (SM) and uncovering the possible signals of new physics.

In the SM, the lepton flavor-conserving (LFC) Z decays $Z \rightarrow l^+l^-$ ($l = e$, μ, and τ) can proceed at the tree level. Including QED contributions, the SM prediction values for the branching ratios (BRs) of these decay processes are [2]

$$\begin{aligned} \mathrm{BR}(Z \rightarrow e^+e^-) &= 3.3346\%, \\ \mathrm{BR}(Z \rightarrow \mu^+\mu^-) &= 3.3346\%, \end{aligned} \tag{1}$$

$$\mathrm{BR}(Z \rightarrow \tau^+\tau^-) = 3.3338\%, \tag{2}$$

and their experimental measurement values are

$$\begin{aligned} \mathrm{BR}(Z \rightarrow e^+e^-) &= 3.363 \pm 0.004\%, \\ \mathrm{BR}(Z \rightarrow \mu^+\mu^-) &= 3.366 \pm 0.007\%, \end{aligned} \tag{3}$$

$$\mathrm{BR}(Z \rightarrow \tau^+\tau^-) = 3.370 \pm 0.0023\%. \tag{4}$$

It is obvious that the discrepancy between the experimental and the SM prediction values is of the order of 1.0%. If new physics models have contributions to the LFC Z decays, this discrepancy might give constraints on the free parameters of the new physics models [3].

Since the lepton flavor is conserved in the SM, the lepton flavor violation (LFV) decay processes $Z \rightarrow l\bar{l}'$ exist at least in the one-loop level, and therefore their BRs are extremely small [4,5]. Their values are far below the experimental limits obtained at LEP1 [2]:

$$\begin{aligned} \mathrm{BR}(Z \rightarrow \tau^\pm\mu^\mp) &< 1.2 \times 10^{-5}, \\ \mathrm{BR}(Z \rightarrow \tau^\pm e^\mp) &< 9.8 \times 10^{-6}, \end{aligned} \tag{5}$$

$$\mathrm{BR}(Z \rightarrow \mu^\pm e^\mp) < 1.7 \times 10^{-6}, \tag{6}$$

and with the improved sensitivities at Giga-Z [6,7], these numbers could be pulled down to

$$\begin{aligned} \mathrm{BR}(Z \rightarrow \tau^\pm\mu^\mp) &< f \times 1.2 \times 10^{-8}, \\ \mathrm{BR}(Z \rightarrow \tau^\pm e^\mp) &< f \times 6.5 \times 10^{-8}, \end{aligned} \tag{7}$$

$$\mathrm{BR}(Z \rightarrow \mu^\pm e^\mp) < 2 \times 10^{-9}, \tag{8}$$

with $f = 0.2$–1.0. It is very interesting to study the new physics contributions to the LFV decay processes $Z \rightarrow l\bar{l}'$. This fact has led to a lot of works related to these decays in the literature [8–10].

In the SM, the decay width of the gauge boson Z into each family neutrino is calculated to be $\Gamma_{\nu\bar{\nu}} = 166.3 \pm 1.5$ MeV, and the current experimental value for the invisible Z decay width is $\Gamma_{\mathrm{inv}}^{\mathrm{exp}} = 499 \pm 1.5$ MeV [2]. It is well known that the mixing of the active neutrino with the sterile neutrino, additional generation fermions, or other new weakly interacting particles might give contributions to the invisible Z decay width. Using the experimental value of the invisible Z decay width, one can obtain constraints on the new physics [11–13].

The leptonic Z decays are free from the long distance effects and thus are clean. On the other hand, they carry considerable information about the free parameters of the model used. Therefore, it is worthwhile to analyze these decay processes in the context of the new physics models. In the present work, we first consider the LFV coupling vertex $Zl\bar{l}'$ induced by the new particles in the framework of the littlest Higgs model with T parity (called the LHT model) [14] and calculate the branching ratio $\mathrm{BR}(Z \rightarrow l\bar{l}')$. Then we study the contributions of the LHT model to the LFC decay process $Z \rightarrow l\bar{l}$ and analyze whether the LHT effect overcomes the discrepancy of the BR's value be-

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tween the experimental and the SM prediction results. Finally, in the context of the LHT model, we calculate the invisible Z decay width $\Gamma_{\rm inv}$ and compare our numerical results with the experimental values for $\Gamma_{\rm inv}$.

The layout of the present paper is as follows: After giving a brief review of the essential features of the LHT model, we study the branching ratios of the LFV decay process $Z \rightarrow l\bar{l}'$ in Sec. II. The contributions of the new particles predicted by the LHT model to the decay widths $\Gamma_{l\bar{l}}$ and $\Gamma_{\rm inv}$ are calculated in Sec. III and IV, respectively. In these sections, we also compare our numerical results with the experimental measurement values and try to obtain constraints on the free parameters of the LHT model. Our conclusions are given in Sec. V.

II. THE LEPTON FLAVOR VIOLATION DECAY $Z \rightarrow l\bar{l}'$

The LHT model [14] is based on an $SU(5)/SO(5)$ global symmetry breaking pattern. A subgroup $[SU(2) \times U(1)]_1 \times [SU(2) \times U(1)]_2$ of the $SU(5)$ global symmetry is gauged, and at the scale f it is broken into the SM electroweak symmetry $SU(2)_L \times SU(1)_Y$. T parity is an automorphism that exchanges the $[SU(2) \times U(1)]_1$ and $[SU(2) \times U(1)]_2$ gauge symmetries. The T-even combinations of the gauge fields are the electroweak gauge bosons, and the T-odd combinations are their T-parity partners. After taking into account electroweak symmetry breaking, at the order of ν^2/f^2, the masses of the T-odd set of the $SU(2) \times U(1)$ gauge bosons are given by

$$M_{B_H} = \frac{g'f}{\sqrt{5}}\left[1 - \frac{5\nu^2}{8f^2}\right], \qquad M_{Z_H} \approx M_{W_H} = gf\left[1 - \frac{\nu^2}{8f^2}\right], \tag{9}$$

where g' and g are the SM $U(1)_Y$ and $SU(2)_L$ gauge coupling constants, respectively. $\nu = 246$ GeV is the electroweak scale.

To avoid severe constraints and simultaneously implement T parity, one needs to double the SM fermion doublet spectrum [14,15]. The T-even combination is associated with the SM $SU(2)_L$ doublet, while the T-odd combination is its T-parity partner. The T-odd fermion sector consists of three generations of mirror quarks and leptons with vectorial couplings under $SU(2)_L \times U(1)_Y$. Only T-odd leptons are related to our calculation, and we denote them by

$$\begin{pmatrix} \nu_H^1 \\ l_H^1 \end{pmatrix}, \qquad \begin{pmatrix} \nu_H^2 \\ l_H^2 \end{pmatrix}, \qquad \begin{pmatrix} \nu_H^3 \\ l_H^3 \end{pmatrix} \tag{10}$$

with their masses satisfying to first order in v/f [16]

$$M^1_{\nu_H} = M^1_{l_H} \qquad M^2_{\nu_H} = M^2_{l_H}, \qquad M^3_{\nu_H} = M^3_{l_H}. \tag{11}$$

The T-odd leptons (mirror leptons) have new flavor violating interactions with the SM leptons mediated by the T-odd gauge bosons and at higher order by the triplet scalar Φ, which are parameterized by two Cabibbo-Kobayashi-Maskawa–like unitary mixing matrices V_{Hl} and $V_{H\nu}$. They satisfy $V^+_{H\nu} V_{Hl} = V_{\rm PMNS}$, in which the Pontecorvo-Maki-Nakagata-Saki (PMNS) matrix $V_{\rm PMNS}$ is defined through neutrino mixing. As no constraints on the PMNS phases exist, we will set the three Majorana phases of $V_{\rm PMNS}$ to equal zero in our numerical estimations, which is similar with Refs. [16,17].

From the above discussions, we can see that the LHT model provides a new mechanism for lepton flavor violation, which comes from the flavor mixing in the mirror lepton sector. It has been shown that the LHT model can give significant contributions to some LFV processes, such as $l_i \rightarrow l_j\gamma$, $l_i \rightarrow l_j l_k l_l$, $\tau \rightarrow \mu\pi$, etc. [16,18]. In the present paper, we first consider the contributions of the LHT model to the LFV Z decay process $Z \rightarrow l\bar{l}'$. The relevant Feynman diagrams for $Z \rightarrow \tau\bar{e}$ are shown in Fig. 1. The Feynman diagrams for the LFV decay processes $Z \rightarrow \tau\bar{\mu}$ and $Z \rightarrow \mu\bar{e}$ are similar to Fig. 1.

The LHT model also predicts the existence of the T-odd scalar triplet Φ with mass M_Φ of order TeV. Neglecting the mass splitting between various components of the T-odd scalar triplet Φ, its contributions to the electroweak parameters S, T, and U vanish [19]. Reference [19] has also shown that the effects of Φ on the precision electroweak observables decouple with growing M_Φ. Furthermore, the T-odd scalar triplet Φ can contribute to the LFV Z decay process $Z \rightarrow l\bar{l}'$ at the order higher than v^2/f^2 via its couplings to the T-odd leptons and ordinary leptons. Thus, as a numerical estimation, we will neglect its contributions in this paper, and the relevant Feynman diagrams have not been shown in Fig. 1.

The amplitude of the LFV decay $Z \rightarrow l\bar{l}'$ is given by

$$M(Z \rightarrow l\bar{l}') = \varepsilon^\mu \bar{u}(p)\Gamma_\mu u(p'), \tag{12}$$

where p and p' are the momenta of the leptons l and l', respectively. ε^μ is the polarization vector of the on-shell gauge boson Z. The effective vertex Γ_μ can be obtained via calculating Fig. 1, which can be generally written as

$$\Gamma_\mu = \gamma_\mu(f_V - f_A\gamma_5) + q^\nu(if_M + f_E\gamma_5)\sigma_{\mu\nu}, \tag{13}$$

where $\sigma_{\mu\nu} = \frac{i}{2}[\gamma_\mu, \gamma_\nu]$ and q is the momentum transfer with $q^2 = (p - p')^2$. The form factors f_V, f_A, f_M, and f_E include all of the contributions from the diagrams in Fig. 1. For simplicity, we omit the explicit expressions for these form factors. In calculations of the one-loop diagrams, we have used LOOPTOOLS [20] and ignored the masses of the final state leptons l and l'.

It is obvious that, except for the SM input parameters $\alpha_e = 1/128.8$, $S_W^2 = 0.2315$, and $M_Z = 91.187$ GeV [2],

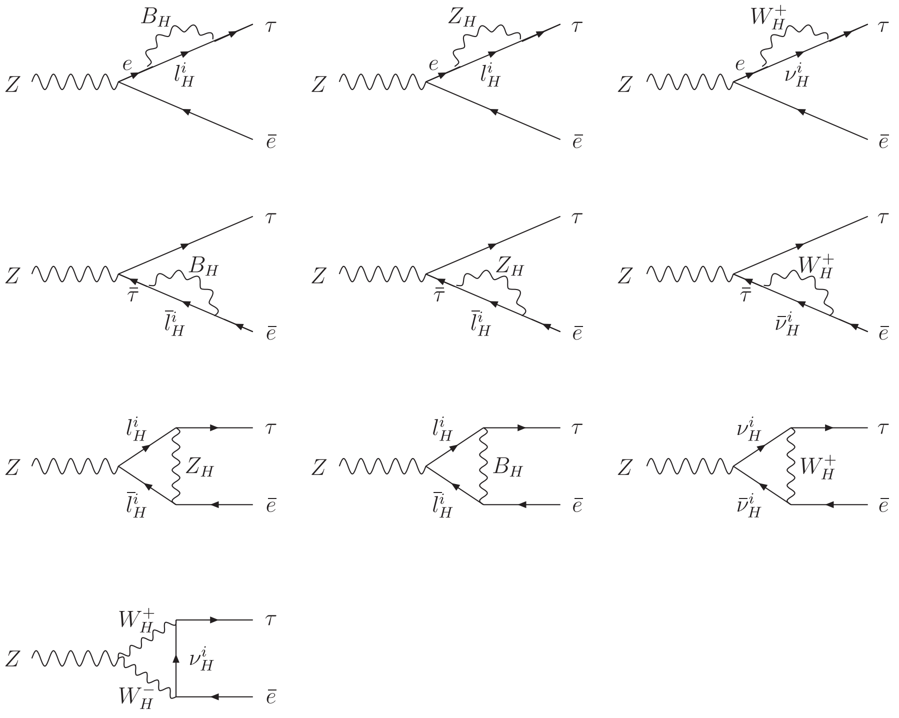

FIG. 1. The leading Feynman diagrams for the LFV Z decay $Z \to \tau\bar{e}$ in the LHT model.

the branching ratio $\mathrm{BR}(Z \to l\bar{l}')$ is dependent on the model-dependent parameters f, $(V_{Hl})_{ij}$, and the T-odd leptons masses. The matrix elements $(V_{Hl})_{ij}$ can be determined through $V_{Hl} = V_{H\nu}V_{\mathrm{PMNS}}$. To avoid any additional parameters introduced and to simply our calculations, we take $V_{Hl} = V_{\mathrm{PMNS}}$ and $V_{H\nu} = I$, which means that the T-odd leptons have no effects on the flavor violating observables in the neutrino sector [16,18]. For the PMNS matrix V_{PMNS}, we take the standard parameterization form with parameters given by the neutrino experiments [21].

Our numerical results are summarized in Figs. 2–4, in which we have plotted the BRs as functions of the T-odd lepton mass for $f = 500$ and 1000 GeV. For Figs. 2 and 3, which correspond the LFV processes $Z \to \tau\bar{e}$ and $Z \to \tau\bar{\mu}$, respectively, we have taken $M_{l_H}^1 = M_{l_H}^2 = M_1$ and $M_{l_H}^3 = M_3$. For the LFV process $Z \to \mu\bar{e}$ given in Fig. 4, we have taken $M_{l_H}^2 = M_{l_H}^3 = M_3$ and $M_{l_H}^1 = M_1$. One can

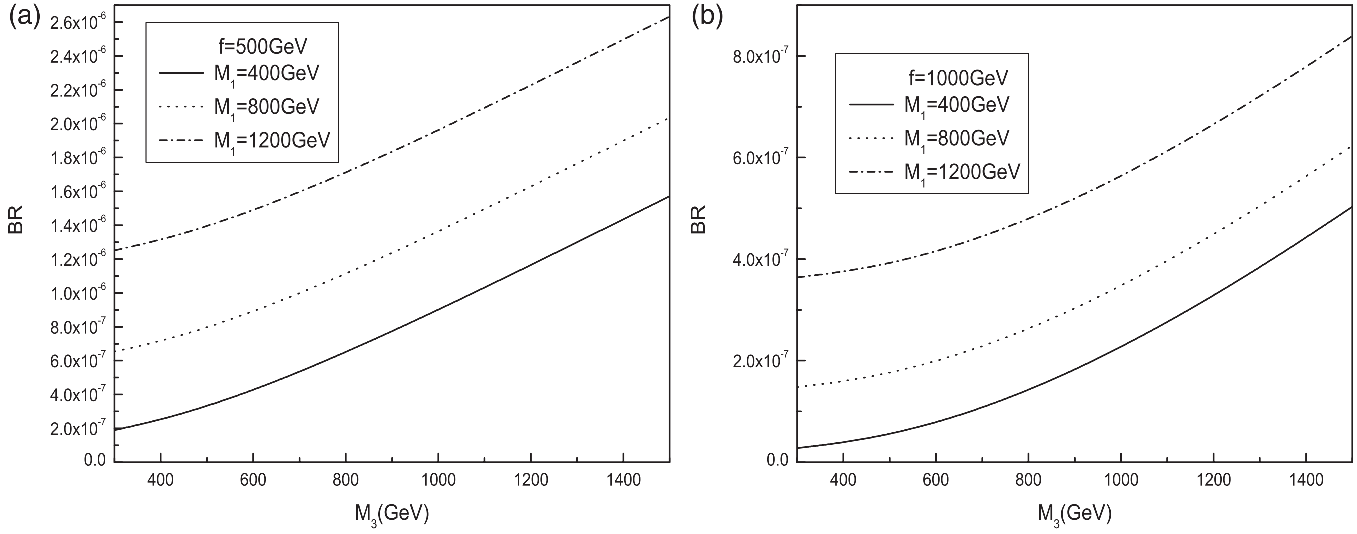

FIG. 2. The branching ratio $\mathrm{BR}(Z \to \tau\bar{e})$ as a function of the third family T-odd lepton mass M_3 for $f = 500$ (a) and 1000 GeV (b). We have taken $M_{l_H}^1 = M_{l_H}^2 = M_1 = 400$, 800, and 1200 GeV.

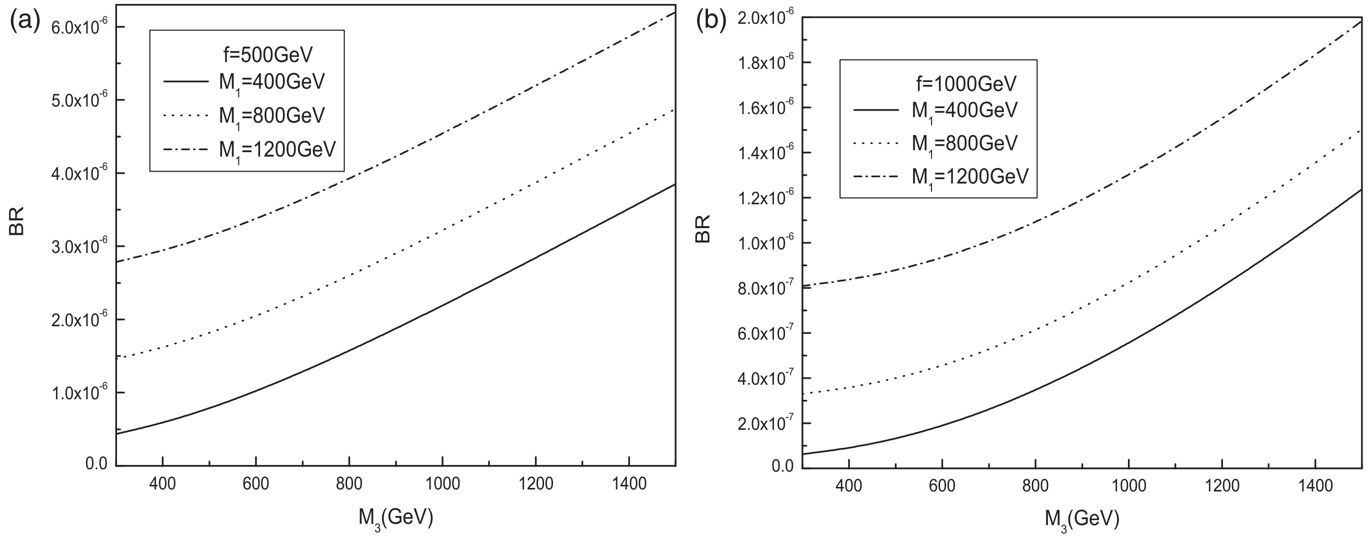

FIG. 3. The same as Fig. 2 but for the LFV decay process $Z \to \tau\bar{\mu}$.

see from these figures that the contributions of the LHT model to the LFV process $Z \to l\bar{l}'$ increase as the T-odd lepton mass increases and the scale parameter f decreases. In most of the parameter space, the values of the branching ratios $\mathrm{BR}(Z \to \tau\bar{e})$ and $\mathrm{BR}(Z \to \tau\bar{\mu})$ cannot overcome the current experimental limits given in Eq. (5), while they can overcome the improved sensitivities at Giga-Z, given in Eq. (7). For the LFV process $Z \to \mu\bar{e}$, its current experimental limit can give severe constraints on the free parameters of the LHT model. If one would like to reduce the contributions of the LHT model to the LFV process $Z \to l\bar{l}'$ and make its BR value satisfy the current or future experimental limits, one has to enhance the value of the scale parameter f, reduce the mass splitting between three generations of the T-odd leptons, or make the matrix V_{Hl} much more hierarchical than the PMNS matrix V_{PMNS}.

III. THE LEPTON FLAVOR CONSERVATION DECAY $Z \to l\bar{l}$

In the SM, the LFC decay process $Z \to l\bar{l}$ exists at the tree level. The partial Z decay width $\Gamma(Z \to l\bar{l})$ including QED and QCD corrections can be written as [2]

$$\Gamma(Z \to l\bar{l}) = \frac{G_F M_Z^3}{6\sqrt{2}\pi}[(\bar{g}_V^l)^2 + (\bar{g}_A^l)^2] \times (1 + \delta\rho + \delta\rho_l + \delta_{\mathrm{QED}}). \qquad (14)$$

The vector and axial-vector $Zl\bar{l}$ couplings $\bar{g}_V^l$ and $\bar{g}_A^l$

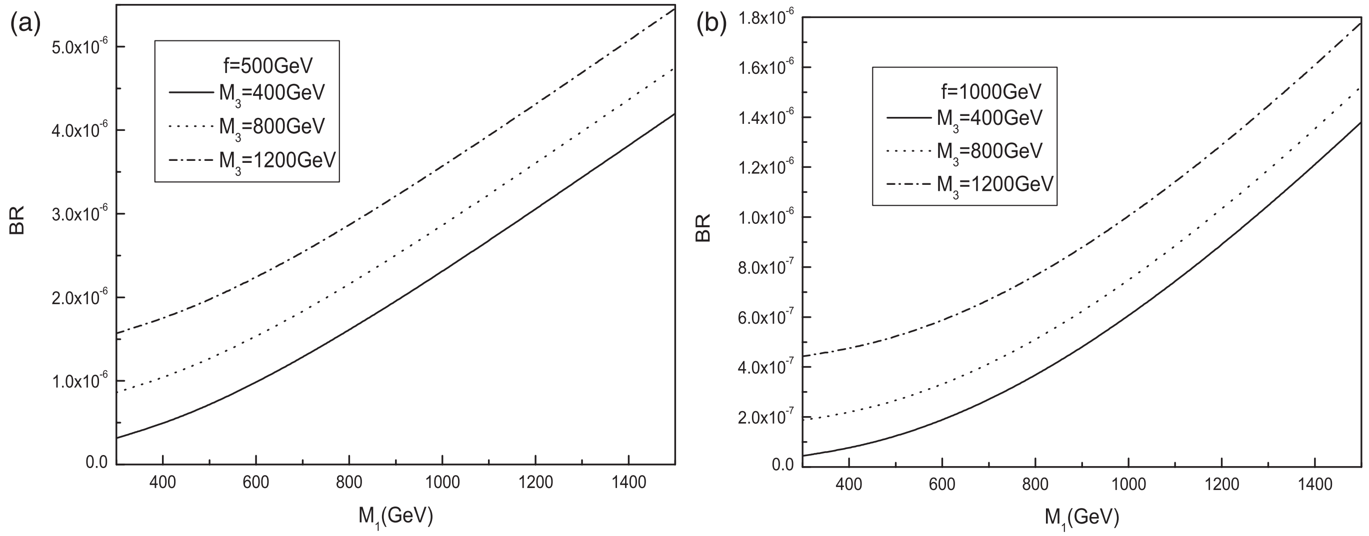

FIG. 4. The branching ratio $\mathrm{BR}(Z \to \mu\bar{e})$ as a function of the mass parameter M_1 for $f = 500$ (a) and 1000 GeV (b). We have taken $M_{l_H}^1 = M_{l_H}^2 = M_1$ and $M_3 = 400$, 800, and 1200 GeV.

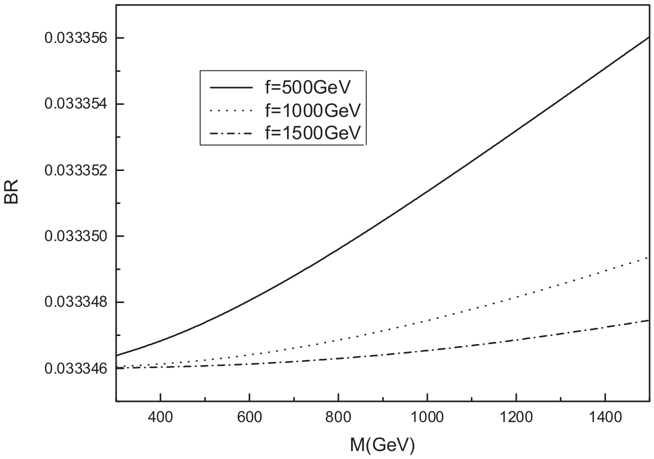

FIG. 5. The branching ratio $\mathrm{BR}(Z \to e\bar{e})$ as a function of the mass parameter M for three values of the parameter f. We have assumed $M^1_{l_H} = M^2_{l_H} = M^3_{l_H} = M$.

comprise one-loop and higher electroweak and internal QCD corrections through the form factors $\delta\rho_l$ and k_l, which can be written as

$$\bar{g}^{\,l}_V = \sqrt{\rho_l}(\tfrac{1}{2} - 2\sin^2\theta^l_{\mathrm{eff}}), \qquad \bar{g}^l_A = \sqrt{\rho_l} \times \tfrac{1}{2}, \tag{15}$$

with $\sin^2\theta^l_{\mathrm{eff}} = k_l \sin^2\theta_W$, in which θ_W is the Weinberg angle. The term $\delta\rho$ is the deviation from the SM prediction for the ρ parameter $\rho = M_Z \cos\theta_W / M_W = 1 + \delta\rho$, and δ_{QED} accounts for the final state photon radiation.

In the LHT model, all of the SM particles are assigned with an even T parity, while all of the new particles are assigned with an odd T parity, except for the little Higgs partner of the top quark. If the T parity is an exact symmetry, the SM gauge bosons do not mix with the T-odd gauge bosons, and thus the electroweak observables are not modified at the tree level. So the LHT model can only contribute the partial width $\Gamma(Z \to l\bar{l})$ at the one-loop level. According to discussions given in Sec. II, the one-loop contributions of the T-odd triplet scalar Φ to the decay width $\Gamma(Z \to l\bar{l})$ can be neglected. The contributions of the LHT model to the Weinberg angle θ_W and the parameter ρ have been extensively studied in Refs. [14,19]. It has been shown that, as long as the scale parameter $f \geq 500$ GeV, the LHT model can be consistent with precision electroweak data. However, the T-odd leptons have contributions to $\Gamma(Z \to l\bar{l})$ via correcting the parameter ρ_l. The relevant Feynman diagrams are similar with those given in Fig. 1, only assuming $l' = l = e$, μ, or τ.

In this section, we focus our attention on the contributions of the LHT model to the LFC decay process $\Gamma(Z \to l\bar{l})$. So in our numerical estimation, we will take the T-odd leptons degenerating in mass and assume $M_{l_H} = M_{\nu_H} = M$. This means that the T-odd leptons have no contributions to the LFV processes, which is the minimal flavor violation limit of the LHT model [18,22]. In this case, the decay width $\Gamma(Z \to l\bar{l})$ depends on the mass parameter M, the scale parameter f, and the unitary mixing matrix V_{Hl}. Similar to Sec. II, we also take $V_{Hl} = V_{\mathrm{PMNS}}$. Our numerical results are given in Figs. 5 and 6 in which we plot the branching ratio $\mathrm{BR}(Z \to l\bar{l})$ ($l = e$, μ, or τ) as a function of the mass parameter M for three values of the scale parameter f. One can see from these figures that the LHT model generates the positive contributions to these branching ratios $\mathrm{BR}(Z \to e\bar{e})$, $\mathrm{BR}(Z \to \mu\bar{\mu})$, and $\mathrm{BR}(Z \to \tau\bar{\tau})$. Their values increase as M increases and f decreases. However, in most of the parameter space of the LHT model, the values of the BRs cannot overcome their experimental measurement values.

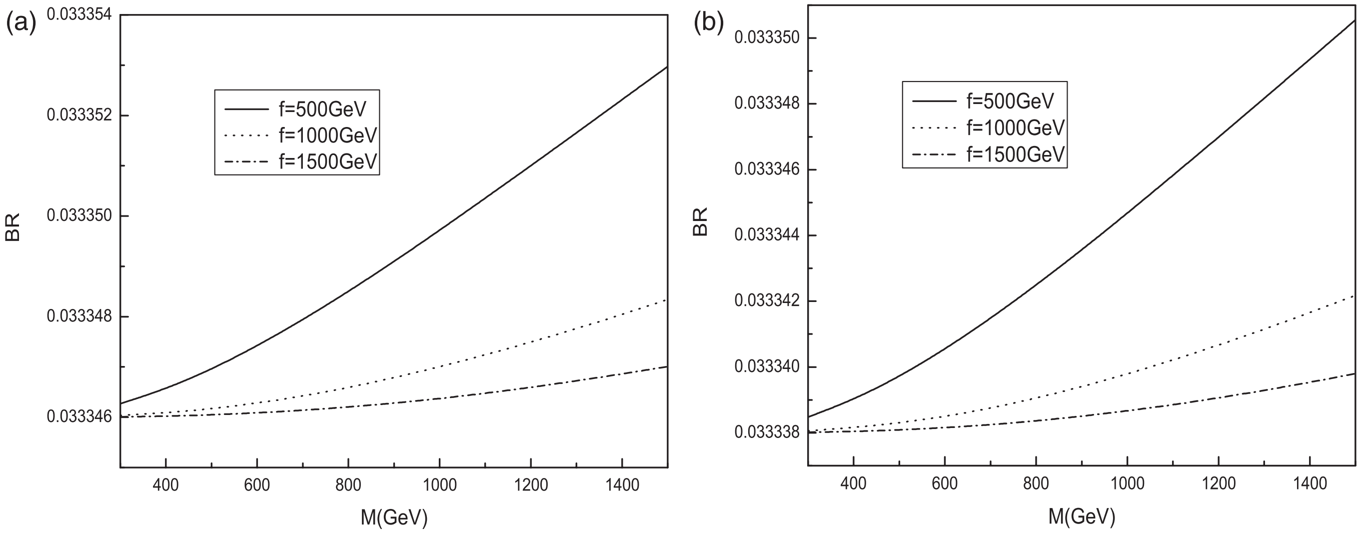

FIG. 6. The same as Fig. 5 but for the LFC decay processes $Z \to \mu\bar{\mu}$ (a) and $Z \to \tau\bar{\tau}$ (b).

IV. THE INVISIBLE Z DECAY $Z \to \nu\bar{\nu}$

The SM has been extensively tested by experiments at the CERN e^+e^- collider LEP, the Fermilab Tevatron, and elsewhere. At the LEP, the coupling of the gauge boson Z to neutrinos is constrained by the invisible Z decay width $\Gamma_{\rm inv}$, which receives contributions from all neutrinos flavors. Thus, it is possible to constrain new physics contributions to the $Z\nu\bar{\nu}$ coupling that respect universality.

From the above discussions, we can see that the LHT model can contribute the $Z\nu\bar{\nu}$ coupling at the one-loop level. The relevant Feynman diagrams are plotted in Fig. 7. Similar to Fig. 1, we also neglect the contributions of the T-odd triplet scalar Φ. The contributions of the LHT model to the invisible Z decay width $\Gamma_{\rm inv}$ are dependent on the mass parameter $M_{\nu_H} = M_{l_H} = M$, the unitary mixing matrix $V_{H\nu}$, and the scale parameter f. In this section, we also assume $V_{H\nu} = I$. In Fig. 8, we plot the invisible Z decay width $\Gamma_{\rm inv}$ including the contributions of the LHT model as a function of the mass parameter M for three values of the parameter f. To compare our calculation value with the experimental value $\Gamma_{\rm inv}^{\rm exp} = 499 \pm 1.5$ GeV and see whether it can give new constraints on the LHT model, we give $\Gamma_{\rm inv}^{\rm exp}$ in Fig. 8, in which the horizontal solid and dotted lines indicate the central and maximal values of the experimental measurement for $\Gamma_{\rm inv}$, respectively. One can see from Fig. 8 that, in the case of $V_{H\nu} = I$ and $M_{\nu_H} = M_{l_H} = M$, if one demands the LHT prediction value for $\Gamma_{\rm inv}$ to be in the ranges allowed by the LEP experiments, the mass parameter M must be smaller than 700 GeV for $f \leq 1000$ GeV and smaller than 900 GeV for $f \leq 1.5$ TeV.

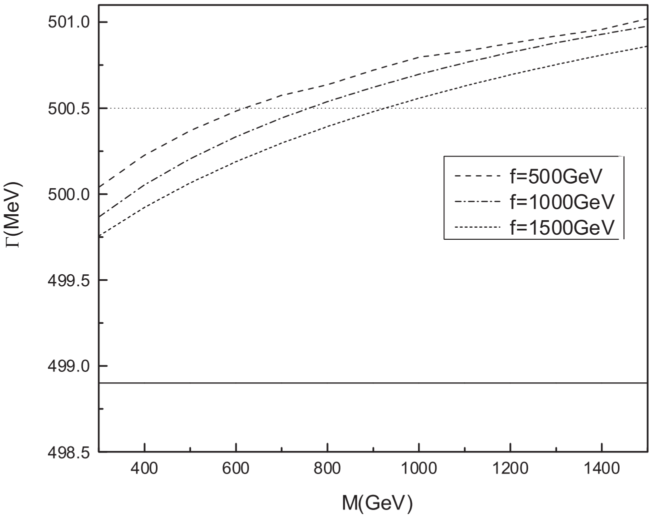

FIG. 8. The invisible Z decay width $\Gamma_{\rm inv}$ as a function of M for three values of f. The horizontal solid and dotted lines denote the central and upper values of $\Gamma_{\rm inv}^{\rm exp}$, respectively.

V. CONCLUSIONS

In order to implement T parity in the fermion sector of the LHT model, the T-odd $SU(2)$ doublet fermions, which are called the mirror fermions of the SM fermions, have to

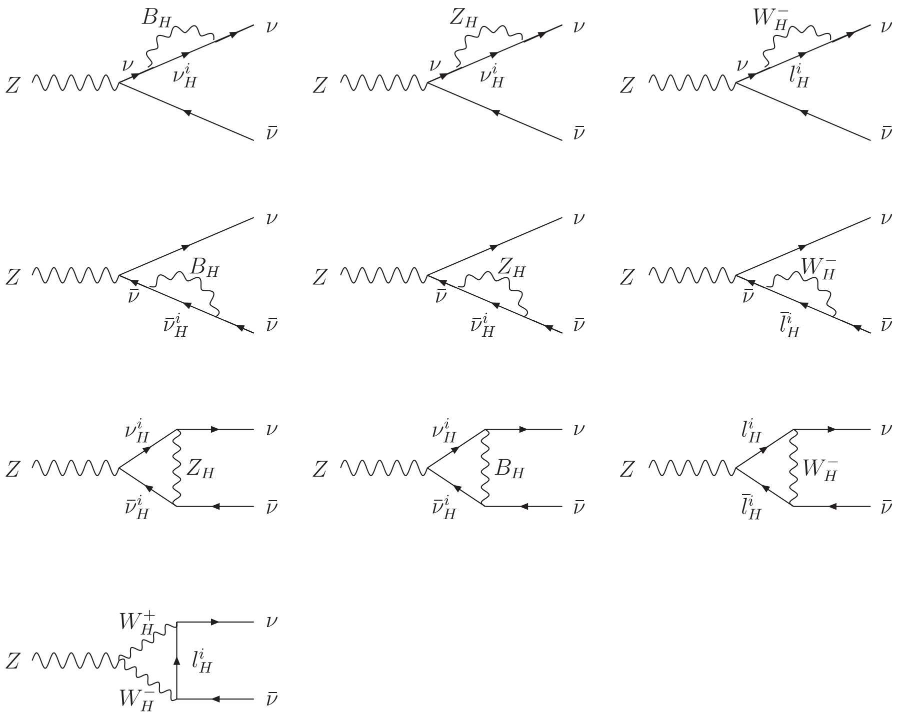

FIG. 7. The leading Feynman diagrams for the LFV Z decay $Z \to \nu\bar{\nu}$ in the LHT model.

be introduced. The mirror fermions can couple to ordinary fermions mediated by the T-odd gauge bosons and at higher order by the T-odd scalar triplet Φ. Thus, these new fermions can generate correction effects on some observables at the one-loop level. Furthermore, flavor mixing in the mirror fermion sector gives rise to a new source of flavor violation, which might generate significant contributions to some flavor violation processes.

The SM gauge boson Z will be abundantly produced at the LHC and the future high energy linear e^+e^- collider experiments. It is possible to examine its properties with unprecedented precision. In this paper, we consider the contributions of the LHT model to the leptonic Z decays. Our numerical results show that if one demands the branching ratio $\mathrm{BR}(Z \rightarrow l\bar{l}')$ below the present (for $Z \rightarrow \mu\bar{e}$) and the future (for $Z \rightarrow \tau\bar{\mu}$ and $Z \rightarrow \tau\bar{e}$) experimental upper bounds, the relevant mixing matrix V_{Hl} must be rather hierarchical, unless the spectrum of the T-odd leptons is quasidegenerate. Our conclusions are similar with those given by Refs. [16,18]. For the LFC decay $Z \rightarrow l\bar{l}$, the LHT model can give positive contributions, which is favored by the current high energy collider experiments. However, the current experimental values for $\mathrm{BR}(Z \rightarrow l\bar{l})$ ($l = \tau$, μ, and e) cannot give severe constraints on the free parameters of the LHT model, although the coupling of the gauge boson Z to individual neutrino flavor has not been tested with comparably good accuracy. The couplings of the gauge boson Z to three family neutrino flavors can be constrained by the measurement invisible Z decay width Γ_{inv}. In this paper we also calculate the contributions of the LHT model to the invisible Z decay width and compare our result with its experimental value. We find that the upper limit of $\Gamma_{\mathrm{inv}}^{\mathrm{exp}}$ can give constraints on the free parameters M and f.

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