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Pair production of the heavy leptons in future high energy linear e^+e^- colliders

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Abstract. The littlest Higgs model with T-parity predicts the existence of the T-odd particles, which can only be produced in pairs. We consider pair production of the T-odd leptons in a future high energy linear e^+e^- collider (ILC). Our numerical results show that, as long as the T-odd leptons are not too heavy, they can be copiously produced and their possible signals might be detected via the processes $e^+e^- \to \overline{L}_i L_j$ in future ILC experiments.

1 Introduction

Many popular specific models beyond the standard model (SM) predict the existence of heavy leptons. It is well known that, so far, a clear signal of such new fermions has not been found at high energy collider experiments. However, the experimental lower bounds for the heavy lepton mass were found to be 44 GeV by OPAL [1], 46 GeV by HLEPH [2], and 90 GeV by H1 Collaborations [3]. This means that, if this kind of new particles indeed exists, they should be detected in future high energy collider experiments. Any signal for such a kind of fermions in future high energy experiments will play an important role in the discovery of new physics beyond the SM.

Little Higgs theory [4] is proposed as an interesting solution to the so called hierarchy problem of the SM and can be regarded as one of the important candidates for new physics beyond the SM. Among of the little Higgs models, the littlest Higgs (LH) model [5] is one of the simplest and phenomenologically viable models, which has all essential features of the little Higgs models. However, the LH model suffers from severe constraints from precision electroweak measurements, which could only be satisfied by fine tuning the model parameters [6–14]. To avoid this serious problem, a new discrete symmetry (called T-parity) has been introduced, which forms the so called LHT model [15–17]. In this model, all dangerous tree level contributions to the low energy electroweak observables are forbidden by T-parity, and hence the corrections to the observables are loop suppressed. The LHT model is one of the attractive little Higgs models.

In order to implement T-parity in the fermion sector, one introduces three doublets of "mirror quarks" and three doublets of "mirror leptons", which have T-odd parity, transform vectorially under $SU(2)_L$ and can be given a large mass. A first study of the collider phenomenology of the LHT model was given in [18]. The possible signals of the T-odd fermions (mirror fermions) have been studied in [19–26]. In this paper, we will focus our attention on the T-odd leptons and see whether the possible signals of the LHT model can be detected in future high energy linear e^+e^- collider (ILC) experiments via the production related to the T-odd leptons.

Studying production and decay of the new charged leptons at high energy collider experiments is of special interest. It will be helpful to test the SM flavor structure and new physics beyond the SM. This fact has lead to many studies involving the new charged leptons at e^+e^- colliders [27–32], ep colliders [33–37], and hadron colliders [38–43]. Although there are lots of works on the new charged leptons in the literature, there is need for further study in the context of the LHT model. There are several motivations to perform this study. First, the LHT model is one of the attractive little Higgs models that predicts the existence of the T-odd heavy charged leptons. However, in previous works on studying the phenomenology of the LHT model, studies of the heavy charged leptons are very few. Second, a pair of T-odd leptons can be directly produced at the CERN large hadron collider (LHC) through s-channel exchange of the SM gauge bosons. However, its production cross section is very small in most of the parameter space of the LHT model [19, 25, 26]. So far, a complete study of pair production of the T-odd charged leptons has not been presented in the context of the LHT model. Third, studying the possible signals of the heavy charged leptons in future high energy colliders can help the collider experiments to test little Higgs models and distinguish different new physics models. Thus, in this paper we will concentrate our attention on pair production of the heavy charged leptons (T-odd) in future ILC experiments.

In the present work, we study the dynamical properties for production of the T-odd leptons and also for decay of

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the T-odd leptons into presently known particles. We also discuss how the signals can be clearly separated from the SM backgrounds with a great significance. After reviewing the LHT model in Sect. 2, the production processes and signatures of the T-odd leptons are studied in detail in Sect. 3. Finally, our conclusions and a simple discussion are given in Sect. 4.

2 The LHT model

In this section, we briefly review the essential features of the LHT model studied in [15–17], which are related to our calculation. Similar to the LH model, the LHT model is based on an SU(5)/SO(5) global symmetry breaking pattern. A subgroup $[\mathrm{SU}(2)\times\mathrm{U}(1)]_1\times[\mathrm{SU}(2)\times\mathrm{U}(1)]_2$ of the SU(5) global symmetry is gauged, and at the scale f it is broken into the SM electroweak symmetry $\mathrm{SU}(2)_\mathrm{L}\times\mathrm{U}(1)_Y$. T-parity is an automorphism that exchanges the $[\mathrm{SU}(2)\times\mathrm{U}(1)]_1$ and $[\mathrm{SU}(2)\times\mathrm{U}(1)]_2$ gauge symmetries. The T-even combinations of the gauge fields are the SM electroweak gauge bosons W^a_μ and B_μ. The T-odd combinations are T-parity partners of the SM electroweak gauge bosons.

After taking into account electroweak symmetry breaking (EWSB), at the order of ν^2/f^2, the masses of the T-odd set of the $\mathrm{SU}(2)\times\mathrm{U}(1)$ gauge bosons are given by

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

Here $\nu=246\,\mathrm{GeV}$ is the electroweak scale and f is the scale parameter of the gauge symmetry breaking of the LHT model. g' and g are the SM $\mathrm{U}(1)_Y$ and $\mathrm{SU}(2)_\mathrm{L}$ gauge coupling constants, respectively. Because of the smallness of g', the T-odd gauge boson B_H is the lightest T-odd particle, which can be seen as an attractive dark matter candidate [44–47].

To avoid severe constraints and simultaneously implement T-parity, one needs to double the SM fermion doublet spectrum [15–18, 48]. The T-even combination is associated with the $\mathrm{SU}(2)_\mathrm{L}$ doublet, while the T-odd combination is its T-parity partner. The masses of the T-odd fermions can be written in a unified manner as:

$$M_{F_i}=\sqrt{2}k_i f, \tag{2}$$

where k_i are the eigenvalues of the mass matrix k, and their values are generally dependent on the fermion species i.

The mirror fermions (T-odd quarks and T-odd leptons) have new flavor violating interactions with the SM fermions mediated by the new gauge bosons (B_H, $W^\pm_H$, or Z_H), which are parameterized by four CKM-like unitary mixing matrices, two for mirror quarks and two for mirror leptons [24–26, 49, 50]:

$$V_{Hu},\quad V_{Hd},\quad V_{Hl},\quad V_{H\nu}. \tag{3}$$

They satisfy

$$V^+_{Hu}V_{Hd}=V_\mathrm{CKM},\quad V^+_{H\nu}V_{Hl}=V_\mathrm{PMNS}, \tag{4}$$

where the CKM matrix V_CKM is defined through flavor mixing in the down-type quark sector, while the PMNS matrix V_PMNS is defined through neutrino mixing. Similar to [24], we will set the Majorana phases of V_PMNS to zero in our following calculation. The matrix V_{Hl} can give rise to the lepton flavor violating processes.

The couplings of the T-odd leptons to other particles, which are related to our analysis, are summarized as [24]

$$Z\overline{L}_iL_j:\quad \frac{\mathrm{i}e}{S_\mathrm{W}C_\mathrm{W}}\left[-\frac{1}{2}+S^2_\mathrm{W}\right]\gamma^\mu\delta_{ij},\quad \gamma\overline{L}_iL_j:-\mathrm{i}e\gamma^\mu\delta_{ij}; \tag{5}$$

$$Z_H\overline{L}_il_j:\quad \frac{\mathrm{i}e}{S_\mathrm{W}}\left[-\frac{1}{2}+\frac{S^2_\mathrm{W}}{8\left(5C^2_\mathrm{W}-S^2_\mathrm{W}\right)}\frac{\nu^2}{f^2}\right](V_{Hl})_{ij}\gamma^\mu P_\mathrm{L}; \tag{6}$$

$$B_H\overline{L}_il_j:\quad \frac{\mathrm{i}e}{C_\mathrm{W}}\left[\frac{1}{10}+\frac{5C^2_\mathrm{W}}{8\left(5C_\mathrm{W}-S^2_\mathrm{W}\right)}\frac{\nu^2}{f^2}\right](V_{Hl})_{ij}\gamma^\mu P_\mathrm{L}. \tag{7}$$

Here $S_\mathrm{W}=\sin\theta_\mathrm{W}$, C_W the cosine, and θ_W is the Weinberg angle. l_i and L_j represent the three family leptons e, μ, or τ and their T-odd partners, respectively. $P_\mathrm{L}=(1-\gamma_5)/2$ is the left-handed projection operator.

From the above discussion, we can see that the LHT model provides a new mechanism for lepton flavor violation (LFV), which comes from the flavor mixing in the mirror lepton sector. Thus, the LHT model can give significant contributions to some LFV processes, such as $l_i\to l_j\gamma$, $l_i\to l_jl_kl_l$, $\tau\to\mu\pi$ etc. [51–53]. In the next section, we will consider pair production of the T-odd leptons in future ILC experiments and further discuss their LFV signatures.

3 Pair production of the T-odd leptons at the ILC

In the LHT model [15–17], T-parity explicitly forbids the tree level contributions coming from the new particles to the observables involving only the SM particles and forbids the interactions that induce triplet vacuum expectation value (VEV) contributions. The SM particles are T-even, while the new particles are T-odd, except for the T-parity partner of the top quark. As a consequence, the electroweak precision measurement data allow for a relatively low value of the new particle mass scale $f\sim 500\,\mathrm{GeV}$ and the T-odd particles can only be produced in pairs. Pair production of the T-odd particles has been studied via pp [19, 25, 26], $e\gamma$ and ep collisions [54].

From the above discussion, we can see that pair production of the T-odd leptons at ILC proceeds via the s-channel and t-channel Feynman diagrams as shown in Fig. 1. The invariant scattering amplitude for the process

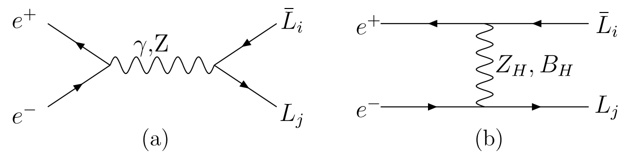

Fig. 1. Feynman diagrams for pair production of the T-odd leptons at the ILC

$e^+(P_1)e^-(P_2) \to \bar{L}_i(P_3)L_j(P_4)$ can be written as

$$\begin{aligned}
\mathrm{i}M &= \frac{e^2}{K_1^2}\bar{v}(P_1)\gamma^\mu u(P_2)\bar{u}(P_4)\gamma_\mu v(P_3) \\
&+ \frac{e^2}{4S_\mathrm{W}^2 C_\mathrm{W}^2}\frac{1}{K_1^2 - M_Z^2}\left[-\frac{1}{2} + S_\mathrm{W}^2\right]\bar{v}(P_1) \\
&\times \left(4S_\mathrm{W}^2 - 1 + \gamma_5\right)\gamma^\mu u(P_2)\bar{u}(P_4)\gamma_\mu v(P_3) \\
&+ \frac{a^2 (V_{Hl})_{ei}(V_{Hl})_{ej}}{K_2^2 - M_{Z_H}^2}\bar{v}(P_1)\gamma^\mu P_\mathrm{L} v(P_3)\bar{u}(P_4)\gamma_\mu P_\mathrm{L} u(P_2) \\
&+ \frac{b^2 (V_{Hl})_{ei}(V_{Hl})_{ej}}{K_2^2 - M_{Z_H}^2}\bar{v}(P_1)\gamma^\mu P_\mathrm{L} v(P_3)\bar{u}(P_4)\gamma_\mu P_\mathrm{L} u(P_2)\,,
\end{aligned} \tag{8}$$

where

$$K_1^2 = (P_1 + P_2)^2\,, \quad K_2^2 = (P_4 - P_2)^2\,; \tag{9}$$

$$a = \frac{e}{S_\mathrm{W}}\left[-\frac{1}{2} + \frac{S_\mathrm{W}^2}{8\,(5C_\mathrm{W}^2 - S_\mathrm{W}^2)}\frac{v^2}{f^2}\right],$$

$$b = \frac{e}{C_\mathrm{W}}\left[-\frac{1}{10} + \frac{5C_\mathrm{W}^2}{8\,(5C_\mathrm{W}^2 - S_\mathrm{W}^2)}\frac{v^2}{f^2}\right]. \tag{10}$$

From (8)–(10) we can see that, except for the SM input parameters $\alpha_e = 1/128.8$, $S_\mathrm{W}^2 = 0.2315$, and $M_Z = 91.187$ GeV [55], the production cross sections $\sigma(\overline{L}_i L_j)$ for the processes $e^+e^- \to \overline{L}_i L_j$ are dependent on the model dependent parameters f, k (or M_{L_i}), $(V_{Hl})_{ei}$, and $(V_{Hl})_{ej}$. 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 calculation, we take $V_{Hl} = V_\mathrm{PMNS}$, which means that the T-odd leptons have no impact on the flavor violating observables in the neutrino sector. For the matrix V_PMNS, we take the standard parameterization form with parameters given by the neutrino experiments [56–60]. References [51–53] have shown that, for $V_{Hl} = V_\mathrm{PMNS}$, to make the $\mu \to e\gamma$ and $\mu^- \to e^-e^+e^-$ decay rates consistent with the present experimental upper bounds, the spectrum of the T-odd leptons must be quasi-degenerate. Thus, in our numerical estimation, we will assume $M_{L_e} = M_{L_\mu} = M_{L_\tau} = M_L$ and take the parameters f and M_L as free parameters.

Our numerical results are shown in Figs. 2 and 3, in which we plot the production cross sections $\sigma(\bar{L}_\mu L_\mu)$ and $\sigma(\bar{L}_e L_\mu)$ as functions of the scale parameter f for the center-of-mass value $\sqrt{s} = 2$ TeV and three values of the T-odd lepton mass M_L. Since the value of the matrix element $(V_\mathrm{PMNS})_{e\tau}$ is smaller than that of $(V_\mathrm{PMNS})_{e\mu}$, the production cross sections $\sigma(\bar{L}_\tau L_\tau)$ and $\sigma(\bar{L}_e L_\tau)$ [or $\sigma(\bar{L}_\mu L_\tau)$] are smaller than $\sigma(\bar{L}_\mu L_\mu)$ and $\sigma(\bar{L}_e L_\mu)$, respectively. Therefore, in Figs. 2 and 3 we have not given the curves for the production cross sections $\sigma(\bar{L}_\tau L_\tau)$, $\sigma(\bar{L}_e L_\tau)$, and $\sigma(\bar{L}_\mu L_\tau)$. Using the unitarity based PDG parametrization and the available data from oscillation experiments, [56–60] have constructed the PMNS matrix V_PMNS, in which the values of the matrix elements $(V_\mathrm{PMNS})_{e\mu}$ and $(V_\mathrm{PMNS})_{ee}$ are given in the ranges of $0.4871 \sim 0.6193$ and $0.7575 \sim 0.8819$, respectively. To simply our calculation, we have taken the values of $(V_\mathrm{PMNS})_{e\mu}$ and $(V_\mathrm{PMNS})_{ee}$ as 0.55 and 0.82 in Figs. 3 and 2, respectively. From Figs. 2 and 3, we can see that the values of the production cross sections increase as the scale parameter f decreases and as the T-odd lepton mass M_L decreases. For $M_L = 400$ GeV and $500\,\mathrm{GeV} \le f \le 2000$ GeV, the values of $\sigma(\bar{L}_\mu L_\mu)$ and $\sigma(\bar{L}_e L_\mu)$ are in the ranges of 93.1 fb $\sim$ 31 fb and 171.5 fb $\sim$ 33.5 fb, respectively, while for $M_L = 800$ GeV and $500\,\mathrm{GeV} \le f \le 2000$ GeV, their values are in the ranges of 37.7 fb $\sim$ 24.3 fb

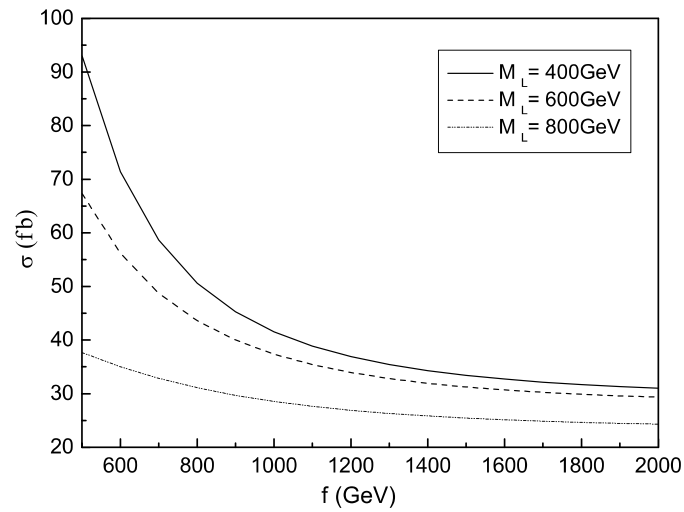

Fig. 2. The production cross section $\sigma(\overline{L}_\mu L_\mu)$ as a function of the scale parameter f for $\sqrt{s} = 2$ TeV and three values of the T-odd lepton mass M_L

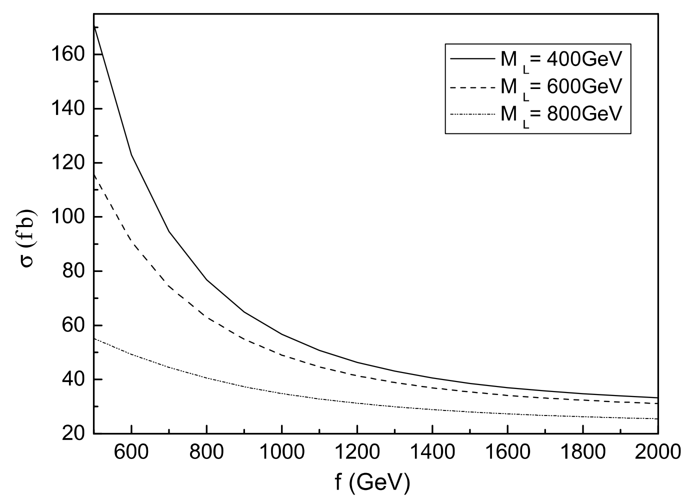

Fig. 3. Same as Fig. 2 but for the production cross section $\sigma(\overline{L}_e L_\mu)$

and 55.2 fb $\sim$ 25.8 fb, respectively. If we assume that the ILC experiment with $\sqrt{s} = 2$ TeV has a yearly integrated luminosity of $\mathcal{L} = 100\,\mathrm{fb}^{-1}$ and if we assume $M_L < 900$ GeV and $f \leq 2$ TeV, then there will be several hundreds up to thousands of $\bar{L}_\mu L_\mu$ or $\bar{L}_e L_\mu$ events to be generated per year.

The new gauge boson B_H is the lightest T-odd particle, which can be seen as an attractive dark matter candidate [44–47]. The T-odd lepton L_i mainly decays to $B_H l_i$ ($l_i = e$, μ or τ) and we have $\mathrm{Br}(L_i \to B_H l_i) \approx 100\%$ [19, 25, 26, 59, 60]. In this case, the signature of the process $e^+e^- \to \bar{L}_\mu L_\mu$ is the opposite-sign same-flavor leptons $\bar{\mu}\mu$ plus large missing energy; i.e. $\bar{\mu}\mu + B_H B_H$. The large transverse missing energy can be used to distinguish the signal events from the SM signal events generated by the process $e^+e^- \to \gamma/Z \to \bar{\mu}\mu$, which cannot be considered as background. The intrinsic SM backgrounds come from the processes $e^+e^- \to \mu\bar{\mu}Z \to \mu\bar{\mu}\nu\bar{\nu}$ and $e^+e^- \to W^+W^- \to \mu\bar{\mu}\nu_\mu\bar{\nu_\mu}$. However, at the ILC experiment with $\sqrt{s} = 2$ TeV, the cross section of the former process is about 2 fb, while the one of the latter process is about 11.2 fb, which is smaller than the cross section of the process $e^+e^- \to \bar{L}_\mu L_\mu$ in most of the parameter space of the LHT model. Thus, the signal event $\bar{\mu}\mu + B_H B_H$ should be easily separated from the SM background with great significance. We expect that, as long as it is not too heavy, the T-odd lepton should be detected via the process $e^+e^- \to \bar{L}_\mu L_\mu$ in future ILC experiments.

The LFV process $e^+e^- \to \bar{L}_e L_\mu$ can give rise to the signal events with opposite-sign and different-flavor leptons and large missing energy ($\bar{e}\mu + \not{E}_\mathrm{T}$), i.e. $e^+e^- \to \bar{L}_e L_\mu \to \bar{e}\mu B_H B_H$. Although the LFV signal is quite spectacular, it is not free of the SM background. The leading SM backgrounds of the signal event $\bar{e}\mu + \not{E}_T$ mainly come from the WW pair production process $e^+e^- \to W^+W^- \to \bar{e}\mu\nu_e\overline{\nu_\mu}$. To see whether the LFV signals of the T-odd leptons can be detected in future ILC experiments, we further calculate the ratio of the signal over the square root of the background $R = S/\sqrt{B}$, which is called the statistical significance. Our numerical results are shown in Fig. 4, in which we have taken the integrated luminosity $\mathcal{L} = 100\,\mathrm{fb}^{-1}$ for $\sqrt{s} = 2$ TeV and the branching ratios $\mathrm{Br}(W^+ \to \bar{e}\nu_e) = (10.66 \pm 0.17)\%$ and $\mathrm{Br}(W^- \to \mu\bar{\nu}_\mu) = (10.60 \pm 0.15)\%$ [55]. From Fig. 4 one can see that, in most of the parameter space of the LHT model, the value of the statistical significance R is larger than 33. Furthermore, if we apply appropriate cuts on the SM backgrounds, the value of the ratio R can be clearly improved. For example, [61] has shown that appropriate kinematical cuts can strongly reduce the WW background. Thus, the possible signals of the T-odd leptons should be easily detected via the LFV process $e^+e^- \to \bar{L}_e L_\mu$ in future ILC experiments.

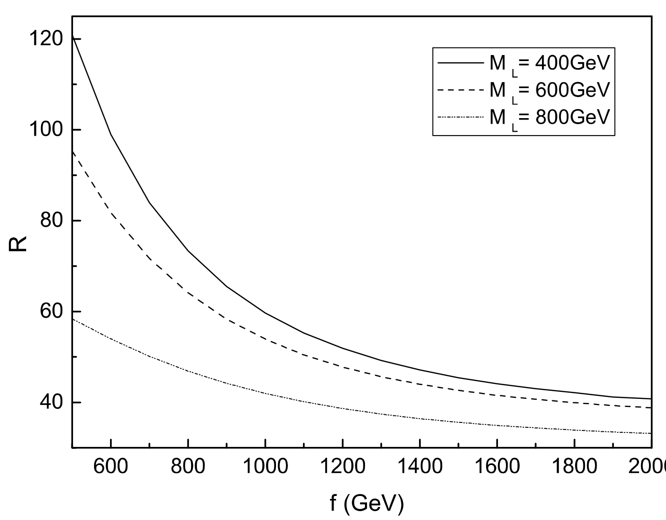

Fig. 4. The statistical significance $R = S/\sqrt{B}$ as a function of the scale parameter f for three values of the T-odd lepton mass M_L

4 Conclusions and discussion

The LHT model is one of the attractive little Higgs models that provides a possible dark mater candidate. To simultaneously implement T-parity, the LHT model introduces new mirror fermions (T-odd quarks and T-odd leptons). 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 T-odd leptons can only be produced through weak processes and their production cross sections are generally small at the LHC. So, in this paper we study pair production of the T-odd lepton in future ILC experiments. Our numerical results show that, as long as the T-odd leptons are not too heavy, they can be copiously produced in pairs. For example, for $500\,\mathrm{GeV} \leq f \leq 2000\,\mathrm{GeV}$ and $M_L = 600$ GeV, the production cross section for the process $e^+e^- \to \bar{L}_\mu L_\mu$ is in the range of 67.4 fb $\sim$ 29.3 fb. Furthermore, the pair production process $e^+e^- \to \bar{L}_\mu L_\mu$ can generate the nice signal event $\mu\bar{\mu} + \not{E}_T$, which might easily be separated from the SM background with great significance.

The T-odd leptons can also be produced in pairs via the LFV processes $e^+e^- \to \bar{L}_i L_j (i \neq j)$. Except the free parameters f and M_L, their production cross sections are dependent on the PMNS matrix elements $(V_\mathrm{PMNS})_{ei}$ and $(V_\mathrm{PMNS})_{ej}$. Considering the bounds of the neutrino oscillation experiment data on these matrix elements, we calculate the production cross section of the LFV process $e^+e^- \to \bar{L}_e L_\mu$. We find that its value can be significantly large in most of the parameter space of the LHT model. The SM backgrounds of this process mainly come from the SM process $e^+e^- \to W^+W^-$. Even if no cuts are applied and the electron beam and the position beam are not polarized, the value of the ratio R can be larger than 33 in most of the parameter space.

In conclusion, we have considered pair production of the T-odd leptons, and we discussed the possibility of detecting these new particles in future ILC experiments. We find that, as long as the T-odd leptons are not too heavy, they can be copiously produced in pairs via the processes $e^+e^- \to \bar{L}_i L_j$, and their signatures might be observed in future ILC experiments. Thus, we expect that the future ILC experiments can be seen as an ideal tool to detect the T-odd leptons predicted by the LHT model. Even if we cannot observe the signals in future ILC experiments, at least, we can obtain the bounds on the free parameters of the LHT model.

The LHT model might give significant contributions to some LFV processes, such as $l_i \to l_j\gamma$, $l_i \to l_j l_k l_l$, $\tau \to \mu\pi$, etc. The present experimental upper bounds of the branching ratios $\mathrm{Br}(\mu \to e\gamma)$ and $\mathrm{Br}(\mu^- \to e^-e^+e^-)$ can give severe constraints on the free parameters of the LHT model [51–53]. Considering these constraints, we have assumed $M_{L_e} = M_{L_\mu} = M_L$ for $V_{Hl} = V_{\mathrm{PMNS}}$ in our numerical estimation. From our numerical results, we can see that the values of the cross section $\sigma(\overline{L}_e L_\mu)$ and $\sigma(\overline{L}_\mu L_\mu)$ increase as the scale parameter f decreases, which is similar to that for the branching ratios $\mathrm{Br}(\mu \to e\gamma)$ and $\mathrm{Br}(\mu^- \to e^-e^+e^-)$. However, even for $M_L = 400\,\mathrm{GeV}$ and $f \leq 2000\,\mathrm{GeV}$, the values of $\sigma(\overline{L}_\mu L_\mu)$ and $\sigma(\overline{L}_e L_\mu)$ are larger than 31 fb and 33 fb, respectively. Thus, we can say that the strong constraints on the LHT model that come from the LFV processes $\mu \to e\gamma$ and $\mu^- \to e^-e^+e^-$ do not strongly change our conclusions on the production of the T-odd leptons in future ILC experiments.

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