Pair production of the T-odd leptons at the \textit{LHC}

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Abstract

The T-odd leptons predicted by the littlest \textit{Higgs} model with T-parity can be pair produced via the subprocesses $gg \rightarrow \ell^+_H \ell^-_H$, $q\bar{q} \rightarrow \ell^+_H \ell^-_H$, $\gamma\gamma \rightarrow \ell^+_H \ell^-_H$ and $VV \rightarrow \ell^+_H \ell^-_H$ ($V=W$ or $Z$) at the \textit{CERN} Large Hadron Collider (\textit{LHC}). We estimate the hadronic production cross sections for all of these processes and give a simply phenomenology analysis. We find that the cross sections for most of the above processes are very small. However, the value of the cross section for the \textit{Drell–Yan} process $q\bar{q} \rightarrow \ell^+_H \ell^-_H$ can reach $270 $ fb.

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1. Introduction

The CERN Large Hadron Collider (LHC) will soon go into full operation and provide proton-proton collisions at a center-of-mass (c.m.) energy of 14 TeV, a factor of 7 higher than the Tevatron. There are strong theoretical reasons to expect that the LHC will discover new physics beyond the standard model (SM) up to TeV. Many popular new physics models beyond the SM predict the existence of the new charged leptons which are denoted as $L^{\pm}$. In general, as long as they are not too heavy, these new particles can be pair produced via the gluon fusion process $gg \rightarrow L^+L^-$, the Drell–Yan process $q\bar{q} \rightarrow L^+L^-$, the photon-induced process $\gamma\gamma \rightarrow L^+L^-$, and the weak gauge boson fusion process $VV \rightarrow L^+L^-$ ($V=W$ or $Z$) at the LHC.

Studying production and decay of the new charged leptons at current or in future high energy collider experiments is of special interest. Any signal for such kind of new fermions in future high energy experiments will play an important role in testing the SM flavor structure and discovery of new physics beyond the SM. This fact has lead to many works involving the new charged leptons at $e^+e^-$ colliders [1], $ep$ colliders [2], and hadron colliders [3,4,5].

The littlest Higgs model with T-parity, which is called the LHT model [6], is one of the attractive little Higgs models. The LHT model predicts the existence of the T-odd $SU(2)$ doublet fermions. These new fermions can produce rich phenomenology at present or in future high energy collider experiments [7,8,9,10,11]. In Ref.[12], we have studied pair production of the T-odd leptons in an international linear $e^+e^-$ collider (ILC). Our numerical results show that, in wide range of the parameter space, they can be copiously produced in pairs. The possible signatures of the T-odd leptons might be detected in future ILC experiments.

Since it is regarded as the cross section for pair production of the T-odd leptons is generally small at the LHC, so far there are few works involved their directly production at the LHC. However, considering the LHC will go into operation and it is possible to completely study the possible signals of the T-odd leptons at the LHC, it is need to carefully study pair production of the T-odd leptons at the LHC. So, in this note, we will
discuss various possible production channels of the T-odd lepton pairs at the LHC and compare their values of the production cross sections for different production channels. In the next section, we will give our numerical results. Our conclusion and a simply phenomenology analysis are given in the last section.

2. The numerical results

The LHT model [6] 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 $SU(2)_L \times U(1)_Y$. T-parity is an automorphism that exchanges the $[SU(2) \times U(1)]_1$ and $[SU(2) \times U(1)]_2$ gauge symmetries. To simultaneously implement T-parity, one needs to double the SM fermion doublet spectrum [6,7]. 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 the mirror quarks and leptons with vectorial couplings under $SU(2)_L \times U(1)_Y$. Only T-odd leptons are related our calculation, we denote them by

$$
\begin{pmatrix}
\nu^1_H \\
\ell^2_H
\end{pmatrix},
\begin{pmatrix}
\nu^2_H \\
\ell^2_H
\end{pmatrix},
\begin{pmatrix}
\nu^3_H \\
\ell^3_H
\end{pmatrix}
$$

with their masses satisfying to first order in $\nu/f$[10]

$$M^1_{\nu H} = M^1_{\ell H}, \quad M^2_{\nu H} = M^2_{\ell H}, \quad M^3_{\nu H} = M^3_{\ell H}. \quad (2)$$

Here $\nu = 246\text{GeV}$ is the electroweak scale and $f$ is the scale parameter of the gauge symmetry breaking of the LHT model. There are $M_i = \sqrt{2}k_i f$, in which $k_i$ are the eigenvalues of the mass matrix $k$ and their values are generally dependent on the lepton species $i$. The coupling expressions of the T-odd lepton to other particles are given in Refs.[7,10].

It is well known that, at the LHC, the gluon distribution function is considerably larger than that for the quark. So we first consider the gluon-induced production of the T-odd lepton pairs. In order to produce the lepton pairs from gluon fusion mechanism, we must have a virtual quark triangular loop, which is connected to the lepton pairs by
a neutral boson (photon $\gamma$, gauge boson $Z$, or scalar $H$). However, the contributions of the photon vector coupling and the $Z$ vector coupling vanish due to Furry’s theorem [3]. From Refs.[7,10], one can see that the $Z$ axial-vector coupling to the T-odd leptons is equal to zero and the scalar $H$ can not couple to the T-odd quarks $T_-$ and $D_H$. Thus, the T-odd lepton pair can only be produced via the $s$-channel $H$ exchange diagram, in which the quark triangular loops include the top quark $t$, the up-type T-odd quark $U_H$, and the T-even vectorlike quark $T_+$. Using the relevant Feynman rules given in Refs.[7,10], we can easily calculate the hadronic production cross section $\sigma_g$ of the gluon fusion process $gg \rightarrow H \rightarrow \ell^+_H \ell^-_H$ at the LHC, which depend on the T-odd quark masses, the T-odd lepton masses, the mixing parameter $x_L$, and the scale parameter $f$. The mass of the T-even vectorlike top quark $T_+$ can be determined by the free parameters $x_L$ and $f$. To simply our calculation, we will take the free parameter $x_L = 0.5$ and the Higgs boson mass $M_H = 120 GeV$. For the T-odd quark masses, we will take $M^1_{U_H} = M^1_{U_H} = M^3_{U_H} = M_U$ and assume that their values are smaller than $4 TeV$. $M_\ell$ is the T-odd lepton mass taken as $M^1_{\ell_H} = M^2_{\ell_H} = M^3_{\ell_H} = M_\ell$ and assumed that its value is in the range of $200 GeV \sim 1000 GeV$. Recently, the improved parton distribution functions (PDFs) have been given in the literature, for example in Refs.[13,14]. However, as numerical estimation, we will use CTEQ6L PDF[15] for the gluon PDF and assume that the renormalization scale $\mu_R$ and the factorization scale $\mu_F$ have the relation $\mu_F = \mu_R = 2 M_\ell$. Our calculation results show that the production cross section $\sigma_g$ is very small and its value is smaller than $1 fb$ in most of the parameter space of the LHT model. This is because the coupling of the Higgs boson $H$ to the T-odd leptons is proportion to the factor $\nu^2/f^2$ and the production cross section $\sigma_g$ is suppressed at least by the factor $\nu^4/f^4$.

The T-odd lepton pairs can also be produced via the Drell − Yan process and the $\gamma\gamma$ fusion mechanism. The former process is induced by the $s$-channel $\gamma$ exchange and $Z$ exchange, while the latter process can proceed via the $t$-channel and $u$-channel T-odd lepton exchanges. Since the $H\gamma\gamma$ and $H\ell^+_H\ell^-_H$ couplings are very small, we will ignore the contributions of the $s$-channel process $\gamma\gamma \rightarrow H \rightarrow \ell^+_H \ell^-_H$. In this case, it is obvious that
the production cross sections of the subprocesses $q\bar{q} \to \ell^+_H \ell^-_H$ and $\gamma\gamma \to \ell^+_H \ell^-_H$ are only dependent on the model dependent parameter — the T-odd lepton mass $M_\ell$.

Figure 1: The production cross sections $\sigma_q$ (a) and $\sigma_\gamma$ (b) as function of the T-odd lepton mass $M_\ell$.

Using the equivalent photon approximation (EPA) approach [16], the hadronic cross section $\sigma_\gamma$ at the LHC can be obtained by folding the cross section for the subprocess $\gamma\gamma \to \ell^+_H \ell^-_H$ with the photon distribution function $f_{\gamma/p}$, which can be written as $f_{\gamma/p} = f_{\gamma/p}^{el} + f_{\gamma/p}^{inel}$. $f_{\gamma/p}^{el}$ and $f_{\gamma/p}^{inel}$ are the elastic and inelastic components of the equivalent photon distribution of the proton, which have been extensively studied in Refs. [17, 18]. Our numerical results are given in Fig.1, in which the pair production cross sections $\sigma_q$ (Fig.1a) and $\sigma_\gamma$ (Fig1.b) are plotted as functions of the T-odd mass $M_\ell$. In our numerical calculation, we have assumed that the photon distribution function $f_{\gamma/p}$ includes both the elastic and inelastic components of the equivalent photon distribution of the proton and have taken the CTEQ6L PDFs for the quark distribution functions $f_{q_i/p}$. One can see from Fig.1 that the production cross section of the T-odd lepton pairs induced by the Drell – Yan process is significantly larger than that for the $\gamma\gamma$ fusion mechanism. For $200 GeV \leq M_\ell \leq 1000 GeV$, the values of the cross sections $\sigma_q$ and $\sigma_\gamma$ are in the ranges
of $270.6\, fb \sim 0.3\, fb$ and $26.4\, fb \sim 0.11\, fb$, respectively. If we assume the yearly integrated luminosity $\mathcal{L}_{\text{int}} = 100\, fb^{-1}$ for the LHC with the c.m. energy $\sqrt{s} = 14\, TeV$, then there will be several up to ten thousands of the $\ell^+_H\ell^-_H$ events to be generated per year.

It is well known that one of the main tasks of the LHC is to determine whether the breaking of the electroweak symmetry is due to the SM Higgs boson. The vector boson fusion (VBF) mechanism is the second most copious source for the SM Higgs boson production at the LHC, which can be used to directly study the exact dynamics of the electroweak symmetry breaking. The new charged lepton pairs can also be produced via the VBF mechanism at the LHC [4]. Pair production of the T-odd leptons predicted by the LHT model can be induced by the s-channel processes $W^\pm W^\mp \rightarrow \gamma, Z, H \rightarrow \ell^+_H\ell^-_H$ and $ZZ \rightarrow H \rightarrow \ell^+_H\ell^-_H$, and can also proceed via the t-channel T-odd neutrino $\nu_H$ exchange and T-odd lepton $\ell_H$ exchange for the processes $W^\pm W^\mp \rightarrow \ell^+_H\ell^-_H$ and $ZZ \rightarrow \ell^+_H\ell^-_H$, respectively.

![Figure 2: The production cross section $\sigma_W$ for the subprocess $W^+W^- \rightarrow \ell^+_H\ell^-_H$ as a function of the T-odd lepton mass $M_\ell$.](image)

For $M_\ell > 200\, GeV$, the c.m. energy $\sqrt{s}$ of the subprocesses $W^\pm W^\mp \rightarrow \ell^+_H\ell^-_H$ is larger
than 400GeV and there is $s \gg M_H^2$. In this energy region, the gauge bosons $W^\pm$ coming from quark or antiquark can be treated as on-shell. So, in our estimating the hadronic production cross section of the subprocesses $W^\pm W^\mp \rightarrow \ell^+_H \ell^-_H$, we will adopt the effective $W$-boson approximation (EWA) method \cite{19} and include all contributions of the longitudinal and transverse $W$-boson components. The structure functions for the gauge bosons $W^\pm$ are taken as the forms given by Ref.\cite{20}, in which authors have shown that the EWA method approximates very well the exact result. Considering the coupling of the Higgs boson $H$ to the T-odd lepton pairs, which can be approximately written as $-\frac{i M_H \nu^2}{4 f^2}$, is very small, we have neglected the contributions of $H$ exchange. Our numerical results are shown in Fig.2. One can see from Fig.2 that the value of the production cross section can only reach $2.5 fb$ in most of the parameter space, which is smaller than that for the $\gamma\gamma$ fusion mechanism.

Similar with that for the processes $W^\pm W^\mp \rightarrow \ell^+_H \ell^-_H$, we can also neglect the contributions of the $s$-channel $H$ exchange to the process $ZZ \rightarrow \ell^+_H \ell^-_H$. Thus, this process is mainly induced by the $t$-channel and $u$-channel T-odd lepton exchanges. It is well known that the structure function for the gauge boson $Z$ is smaller than that for the gauge boson $W$, the hadronic cross section for the subprocess $ZZ \rightarrow \ell^+_H \ell^-_H$ is suppressed at least by an order of magnitude compared to that for the subprocess $W^\pm W^\mp \rightarrow \ell^+_H \ell^-_H$. For $200 GeV \leq M_\ell \leq 1000 GeV$, its value is in the range of $1.35 \times 10^{-1} fb \sim 2.5 \times 10^{-3} fb$. We further estimate the hadronic cross section for the subprocess $Z\gamma \rightarrow \ell^+_H \ell^-_H$, our numerical results show that its value is in the range of $1.25 fb \sim 6.9 \times 10^{-3} fb$ for $200 GeV \leq M_\ell \leq 1000 GeV$.

3. Conclusions and discussions

In this letter, we consider various possible production channels of the T-odd lepton pairs at the LHC. We find that the most important production channel for the T-odd lepton pairs predicted by the LHT model is the Drell – Yan process, i.e. $q\bar{q} \rightarrow \ell^+_H \ell^-_H$. For $200 GeV \leq M_\ell \leq 1000 GeV$, the value of the hadronic production cross section is in the range of $270.6 fb \sim 0.3 fb$. The second important production channel is the $\gamma\gamma$ fusion mechanism, i.e. $\gamma\gamma \rightarrow \ell^+_H \ell^-_H$. With reasonable values of the free parameters for the LHT
model, the production cross section value can reach 26.4 fb.

The T-odd leptons are always heavier than the T-odd gauge boson $B_H$. They are lighter or heavier than the T-odd gauge bosons $W_H$ and $Z_H$, which depend on the values of the coupling parameter $k_i = k_1^l = k_2^l = k_3^l$. For $k_i < 0.45$, there is $M_i < M_{Z_H} \approx M_{W_H}$. Thus, for $k_i > 0.45$, the possible decay modes of the T-odd lepton $\ell_H$ are $B_H\ell$, $Z_H\ell$, and $W_H\nu$. However, as long as $k_i \leq 1$, $\ell_H$ mainly decays to $B_H\ell$ and there is $Br(\ell_H \to B_H\ell) \simeq 100\%$ for $k_i < 0.45$. If we assume that the T-odd lepton $\ell_H$ decays to $B_H\ell$, then pair production process of the T-odd leptons at the LHC, i.e. the process $PP \to \ell_H^+\ell_H^- + X$, can give rise to the $B_H B_H l^+l^-$ final state. The new gauge boson $B_H$ predicted by the LHT model is the stable and lightest T-odd particle, which can be seen as an attractive dark matter candidate [7]. Certainly, if the T-parity is violated by anomalies, the T-odd gauge boson $B_H$ can decay into the SM gauge boson pairs $WW$ and $ZZ$ [21,22]. If we assume that T-parity is strictly conserved and the T-odd gauge boson $B_H$ can be seen as missing energy, then pair production of the T-odd leptons at the LHC can induce the opposite-sign same-flavor leptons plus missing energy ($\ell^+\ell^- + E_T$) signature. The main backgrounds for this kind of signals come from the SM processes $PP \to ZZ + X$, $PP \to \tau\tau + X$, and $PP \to W^+W^- + X$, in which the lepton $\tau$ and the gauge bosons $Z$ and $W$ decay leptonically. Detailed analysis of the signals and backgrounds have been given in Ref.[23]. They have shown that the ZZ background can be eliminated by calculating the invariant mass of the charged lepton pair, which can reconstruct the $Z$ boson mass. It is possible to extract the $\ell^+\ell^- + E_T$ signal from the $\tau\tau$ background by applying suitable cuts. The $W^+W^-$ background is much large, so it is very challenging to extract the $\ell^+\ell^- + E_T$ signal from this background. However, it has been shown that the appropriate cuts can significantly suppress the $W^+W^-$ background [24]. Certainly, detailed confirmation of the observability of the $\ell^+\ell^- + E_T$ signal, which comes from the subprocess $q\bar{q} \to \ell_H^+\ell_H^-$, would require Monte-Carlo simulations of the signal and background.

Although the contributions of the $\gamma\gamma$ fusion mechanism to pair production of the T-odd lepton pairs at the LHC are much smaller than those for the Drell – Yan process.
For $M_{l} \geq 200 GeV$, its production cross section can only reach $26.4 fb$. However, due to absence of the proton remnants, this production process has clean experimental conditions and well defined final states, which can be selected and precisely reconstructed [25]. The $SM$ backgrounds coming from the partonic interactions, such as $PP \rightarrow W^{+}W^{-}$, $ZZ$, and $\tau\tau$, can be significantly omitted by using the large rapidity gap technique and the dedicated very forward detectors [26]. The irreducible backgrounds, such as $\gamma\gamma \rightarrow W^{+}W^{-}$ and $\gamma\gamma \rightarrow \tau\tau$ can be largely suppressed by applying acceptance cuts. Certainly, detailed detector simulation studies are needed.

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