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Signals of the littlest Higgs model with *T*-parity at eγ and ep collisions*

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Abstract The littlest Higgs model with T-parity predicts the existence of the neutral, weakly interacting, new gauge boson $\mathrm{B_H}$, which can be seen as an attractive dark matter candidate. We study production of the new gauge boson $\mathrm{B_H}$ via eγ and ep collisions. We find that $\mathrm{B_H}$ can be abundantly produced via the subprocesses $\mathrm{e^-\gamma \to L^- B_H}$ and $\mathrm{\gamma q \to B_H Q}$, which might give rise to characteristic signals. Some discussions about the SM backgrounds for this kind of signals are also given.

Key words the littlest Higgs model, the new gauge boson $\mathrm{B_H}$, the characteristic signal

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1 Introduction

The little Higgs model is proposed as an alternative solution to the hierarchy problem of the standard model (SM), which provides a possible kind of electroweak symmetry breaking (EWSB) mechanism accomplished by a naturally light Higgs sector[1] (for review, see Ref. [2]). In these models, the Higgs boson is a pseudo-Goldstone boson and its mass is protected by a global symmetry and quadratic divergence cancellations are due to the contributions from new particles with the same spin as the SM particles. The dynamics of the Higgs boson is described by a non-linear sigma model, valid up to the cutoff scale $\Lambda \sim 4\pi f \sim 10$ TeV. The little Higgs models generally predict the existence of the new gauge bosons, fermions, and scalar particles at the TeV scale. Some of these new particles can generate characteristic signatures at the present and future collider experiments[3, 4].

So far, a number of specific models have been proposed, which differ in the assumed higher symmetry and in the representations of the scaler multiplets. Among these models, the littlest Higgs (LH) model[1] is one of the simplest and phenomenologically viable models, which has all essential features of the little Higgs theory. However, the electroweak precision data produce rather severe constraints on the free parameters of the LH model, due to the large corrections to low-energy observables from the new particles and the triplet scalar vacuum expectation value (VEV)[5]. To alleviate this difficulty, a Z_2 discrete symmetry, named 'T-parity', is introduced into the LH model, which is called the LHT model[6, 7]. In the LHT model, all the SM particles are assigned with an even T-parity, while all the new particles are assigned with an odd T-parity, except for the little Higgs partner of the top quark. In the LHT model, the T-parity is an exact symmetry, the SM gauge bosons (T-even) do not mix with the T-odd new gauge bosons, and thus the electroweak observables are not modified at tree level. Beyond the tree level, small radiative corrections induced by the LHT model to the electroweak observables still allow the scale parameter f to be lower than 1 TeV[6, 8]. Since the contributions of the little Higgs models to observables are generally proportional to the factor $1/f^2$, a lower f is very important for the phenomenology of these models and might produce rich signatures in future high energy collider experiments[9—15].

An interesting feature of the LHT model is that it predicts the existence of the lightest T-odd particle, which is stable, electrically neutral, and weakly interacting, new gauge boson $\mathrm{B_H}$. It has been shown

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that it can be seen as an attractive dark matter candidate and might generate observable signals at the hadronic colliders[11, 15]. In this paper, we will discuss the production of the new gauge boson $\mathrm{B_H}$ via eγ and ep collisions and see whether it can produce observed signatures in future high energy $\mathrm{e^+e^-}$ and ep collider experiments, i.e. ILC[16] and THERA[17].

In the rest of this paper, we will give our results in detail. In Section 2, we give some free parameters, which are related to our calculation. The production of the gauge boson $\mathrm{B_H}$ via the processes $\mathrm{e^+e^-} \to \mathrm{e^-}\gamma \to \mathrm{L^-B_H}$ and $\mathrm{ep} \to \gamma\mathrm{q} \to \mathrm{B_HQ}$ at the ILC and THERA experiments is considered in Section 3 and Section 4, respectively. The relevant phenomenology discussions are given in these sections. Our conclusions are given in Section 5.

2 The relevant parameters about our calculation

Similar to the LH model, the LHT model[6, 7] is based on an $SU(5)/SO(5)$ global symmetry breaking pattern and the Higgs doublet of the SM is identified with a subset of the Goldstone boson fields associated with this breaking. A subgroup $[SU(2)_1 \times U(1)_1] \times [SU(2)_2 \times U(1)_2]$ of the $SU(5)$ is gauged, and at the scale f it is broken into the SM electroweak symmetry $SU(2)_\mathrm{L} \times U(1)_\mathrm{Y}$. This breaking scenario gives rise to four new gauge bosons $\mathrm{W_H^\pm}$, $\mathrm{Z_H}$, and $\mathrm{B_H}$. However, in the LHT model, T-parity is an automorphism which exchanges the $[SU(2)_1 \times U(1)_1]$ and $[SU(2)_2 \times U(1)_2]$ gauge symmetries. Under this transformation, the SM gauge bosons $\mathrm{W^\pm}$, Z, and γ are T-even and the new gauge bosons $\mathrm{W_H^\pm}$, $\mathrm{Z_H}$, and $\mathrm{B_H}$ are T-odd.

Among these new particles, the neutral gauge boson $\mathrm{B_H}$ is the lightest particle which can be seen as an attractive dark matter candidate[9—12]. At the order of ν^2/f^2, the mass of the neutral gauge boson $\mathrm{B_H}$ can be approximately written as:

$$M_{\mathrm{B_H}} \approx \frac{g'f}{\sqrt{5}}\left[1-\frac{5\nu^2}{8f^2}\right], \tag{1}$$

where g' is the SM $U(1)_\mathrm{Y}$ gauge coupling constant, and $\nu \approx 246$ GeV is the electroweak scale. At the order of ν^2/f^2, the couplings of the neutral gauge boson $\mathrm{B_H}$ with the first or second family fermions and their corresponding little Higgs partners can be approximately written as[10]:

$$\mathcal{L} = \mathrm{i}Yg'\bar{Q}\gamma_\mu p_\mathrm{L} q B_\mathrm{H}^\mu + \mathrm{h.c.}\ , \tag{2}$$

where $Y = 1/10$, q = u,d,c,s,e, or μ, and Q is the T-odd partner of the T-even SM fermion q. The more exact expressions of these couplings have been recently given in Ref. [15]. According the formula given in Ref. [15], the coupling constant Y is generally not equal to 1/10. However, for the scale parameter $f \geqslant 500$ GeV, the coupling constant Y is very close to this value. Thus, as numerical estimation, we will assume that there is a universal coupling constant $Y = 1/10$ for the couplings of the gauge boson $\mathrm{B_H}$ to the SM quark and lepton partners, as shown in Eq. (2). Furthermore, as in Refs. [10,11], we also assume a universal T-odd fermion mass M_Q for the little Higgs partners of the first and second family fermions, and take $M_\mathrm{Q} \approx M_{\mathrm{B_H}} + 20$ GeV.

In the LHT model, because of the T-parity, the SM gauge bosons (T-even) do not mix with the T-odd new gauge bosons. Thus, the electroweak observables are not modified at tree-level. The new heavy T-odd particles, such as T-odd gauge bosons, T-odd fermions, and T-odd triplet scalars, can only have contributions to the electroweak observables at loop level, which are typically small. So the scale parameter f can be as low as 500 GeV[8]. In this paper, we will take the scale f as free parameter and assume that its value is in the range of 500 GeV—2000 GeV.

3 Production of the new gauge boson $\mathbf{B_H}$ at e$\boldsymbol{\gamma}$ collision

There are two Feynman diagrams, depicted in Fig. 1, contributing production of the new gauge boson $\mathrm{B_H}$ associated with the T-odd partner $\mathrm{L^-}$ of the lepton $\mathrm{e^-}$ via $\mathrm{e^-}\gamma$ collision. The corresponding scattering amplitude can be written as:

$$\begin{aligned} M = {} & eYg'Q_\mathrm{L}\bar{u}(L)\left[\frac{\not{\varepsilon}_2 P_\mathrm{L}(\not{P}_\gamma + \not{P}_\mathrm{e} + m_\mathrm{e})\not{\varepsilon}_1}{\hat{s}-m_\mathrm{e}^2} + \right. \\ & \left. \frac{\not{\varepsilon}_1(\not{P}_\mathrm{L} - \not{P}_\gamma + M_\mathrm{L})\not{\varepsilon}_2 P_\mathrm{L}}{\hat{u}-M_\mathrm{L}^2}\right]u(\mathrm{e})\ , \end{aligned} \tag{3}$$

where $\hat{s} = (P_\gamma + P_\mathrm{e})^2 = (P_{\mathrm{B_H}} + P_\mathrm{L})^2$, $\hat{u} = (P_\mathrm{L} - P_\gamma)^2 = (P_\mathrm{e} - P_{\mathrm{B_H}})^2$. ε_1 and ε_2 are the polarization vectors of the gauge bosons γ and $\mathrm{B_H}$, respectively. M_L is the mass of the SM lepton partner $\mathrm{L^-}$ and taken as $M_\mathrm{L} = M_\mathrm{Q} = M_{\mathrm{B_H}} + 20$ GeV.

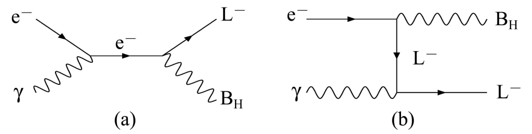

Fig. 1. Feynman diagrams contributing to the process $\mathrm{e^-}\gamma \to \mathrm{L^-B_H}$.

The effective cross section $\sigma_1(s)$ at ILC with the center-of-mass energy $\sqrt{s}$ can be obtained by folding the cross section $\hat{\sigma}_1(\hat{s})$ for the subprocess $\mathrm{e^-}\gamma \to \mathrm{L^-B_H}$ with the photon distribution function $f_{\gamma/\mathrm{e}}$[18]:

$$\sigma_1(s) = \int_{(M_{\mathrm{B_H}}+M_\mathrm{L})^2/s}^{0.83} \mathrm{d}x\hat{\sigma}_1(\hat{s})f_{\gamma/\mathrm{e}}(x)\ , \tag{4}$$

where $\hat{s}=xs$.

From the above equations, we can see that, except the SM input parameters, the effective cross section $\sigma_1(s)$ is dependent on the scale parameter f and the center-of-mass energy $\sqrt{s}$. So, we plot the cross section $\sigma_1(s)$ as a function of f for $\sqrt{s}=1$ TeV in Fig. 2. One can see from Fig. 2 that the value of $\sigma_1(s)$ is strongly dependent on the scale parameter f. For 500 GeV $\leqslant f \leqslant$ 2000 GeV, the value of the production cross section σ_1 is in the range of 16.4 fb—1.5fb. If we assume that the ILC experiment with $\sqrt{s}=1$ TeV has a yearly integrated luminosity of $\mathcal{L}=500\ \mathrm{fb}^{-1}$, then there will be several hundreds up to ten thousands of the new gauge boson $\mathrm{B_H}$ associated with the SM lepton partner L^- to be generated per year.

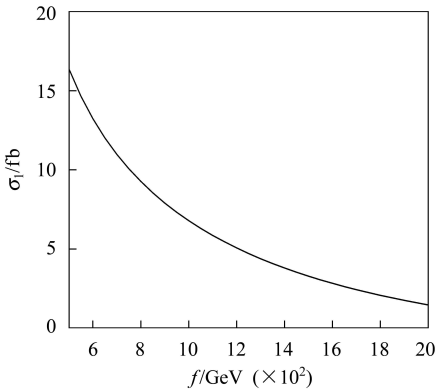

Fig. 2. The effective cross section σ_1 as a function of the scale parameter f for the center-of-mass energy $\sqrt{s}$=1 TeV.

For $M_{\mathrm{L}}=M_{\mathrm{B_H}}+20$ GeV, the lepton partner L mainly decays to $\mathrm{B_H l}$ and there is $Br(\mathrm{L}\rightarrow\mathrm{B_H l})\approx 1$[10, 11]. Thus, the signal of the process $\mathrm{e}^-\gamma\rightarrow\mathrm{L}^-\mathrm{B_H}$ should be an isolated charged lepton associated with large missing energy. The most large backgrounds for the signal $\mathrm{l}^-+\not{E}$ come from the SM processes $\mathrm{e}^-\gamma\rightarrow\mathrm{e}^-\mathrm{Z}\rightarrow\mathrm{e}^-\nu\nu$ and $\mathrm{e}^-\gamma\rightarrow\mathrm{W}^-\nu_{\mathrm{e}}\rightarrow\mathrm{l}^-\nu\nu_{\mathrm{e}}$. The scattered electron in the process $\mathrm{e}^-\gamma\rightarrow\mathrm{e}^-\mathrm{Z}$ has almost the same energy $E_{\mathrm{e}}=\sqrt{s}/2$ for $\sqrt{s}\gg M_{\mathrm{Z}}$. Thus, the process $\mathrm{e}^-\gamma\rightarrow\mathrm{e}^-\mathrm{Z}$ could be easily distinguished from the signal[19]. So, the most serious background process is $\mathrm{e}^-\gamma\rightarrow\mathrm{W}^-\nu_{\mathrm{e}}\rightarrow\mathrm{l}^-\nu\nu_{\mathrm{e}}$. To discuss whether the possible signals of the LHT model can be detected via the process $\mathrm{e}^-\gamma\rightarrow\mathrm{L}^-\mathrm{B_H}$ in future ILC experiments, we further calculate the ratio of the signal over the square root of the background ($R_1=N_1/\sqrt{B}$). Our numerical results show that the SM backgrounds are much large and the value of the ratio R_1 is smaller than 0.5 in most of the parameter space of the LHT model.

It is well known that an appropriate cut on the SM background can generally enhance the ratio of signal over square root of the background. It has been shown that, with the suitably cut on the final lepton transverse momentum and rapidity, the SM background $\mathrm{l}^-\nu\nu_{\mathrm{e}}$ can be reduced by more than one order of magnitude[19]. Furthermore, beam polarization of the electron and positron beams would lead to a substantial enhancement of the production cross sections for some specific processes with a suitably chosen polarization configuration. Thus, we expect that we might use these methods to discriminate the signal $\mathrm{l}^-+\not{E}$ from the SM background.

4 Production of the neutral gauge boson $\mathrm{B_H}$ at ep collision

Similar to the process $\mathrm{e}^-\gamma\rightarrow\mathrm{L}^-\mathrm{B_H}$, production of the new gauge boson $\mathrm{B_H}$ associated with the T-odd partner of the SM quark at the THERA proceeds via the s-channel and t-channel Feynman diagrams, as shown in Fig. 3. The invariant scattering amplitude for the subprocess $\gamma\mathrm{q}\rightarrow\mathrm{B_H Q}$ (q = u, c, d or s) can be written as:

$$M = eYg'Q_{\mathrm{Q}}\bar{u}(L)\left[\frac{\not{\varepsilon}_2 P_{\mathrm{Q}}(\not{P}_\gamma+\not{P}_{\mathrm{q}}+m_{\mathrm{q}})\not{\varepsilon}_1}{\hat{s}-m_{\mathrm{q}}^2}+\frac{\not{\varepsilon}_1(\not{P}_{\mathrm{Q}}-\not{P}_\gamma+M_{\mathrm{Q}})\not{\varepsilon}_2 P_{\mathrm{Q}}}{\hat{u}-M_{\mathrm{Q}}^2}\right]u(q)\ , \tag{5}$$

where $\hat{s}=(P_\gamma+P_{\mathrm{q}})^2=(P_{\mathrm{B_H}}+P_{\mathrm{Q}})^2$, $\hat{u}=(P_{\mathrm{Q}}-P_\gamma)^2=(P_{\mathrm{q}}-P_{\mathrm{B_H}})^2$. ε_1 and ε_2 are the polarization vectors of the gauge bosons γ and $\mathrm{B_H}$, respectively.

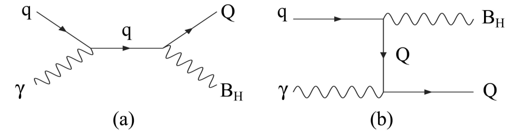

Fig. 3. Feynman diagrams contributing to the process $\gamma\mathrm{q}\rightarrow\mathrm{B_H Q}$.

After calculating the cross section $\hat{\sigma}_{\mathrm{i}}(\hat{s})$ of the subprocess $\gamma\mathrm{q}\rightarrow\mathrm{B_H Q}$, the total cross section $\sigma_2(s)$ of $\mathrm{B_H Q}$ production can be obtained by folding $\hat{\sigma}_{\mathrm{i}}(\hat{s})$ with the parton distribution functions:

$$\sigma_2(s)=\sum_{\mathrm{i}}\int_{\tau_{\min}}^{0.83}\mathrm{d}\tau\int_{\tau/0.83}^{1}\frac{\mathrm{d}x}{x}\,f_{\gamma/\mathrm{e}}\left(\frac{\tau}{x}\right)f_{\mathrm{i/p}}(x)\hat{\sigma}_{\mathrm{i}}(\hat{s}), \tag{6}$$

with $\hat{s}=\tau s$, $\tau_{\min}=\dfrac{(M_{\mathrm{B_H}}+M_{\mathrm{Q}})^2}{s}$, i = u,c,d and s. The backscattered high energy photon distribution function has been given in Ref. [18]. In our calculation, we will take the CTEQ6L parton distribution function for $f_{\mathrm{i/p}}(x)$[20].

Our numerical results are shown in Fig. 4, in which we have taken $\sqrt{s}=1$ TeV. One can see from Fig. 4 that the production cross section σ_2 is smaller than σ_1 in all of the parameter space. This is because, compared with σ_1, σ_2 is suppressed by the parton distribution function $f_{\mathrm{i/p}}(x)$ and the charge factor Q_{q}^2. For 500 GeV $\leqslant f \leqslant$ 2000 GeV, the value of the cross section σ_2 is in the range of 14.6 fb—2.4×10^{-3}fb. If we assume that the THERA collider with $\sqrt{s}=1$ TeV has a yearly integrated luminosity of $\mathcal{L}=470\ \mathrm{fb}^{-1}$[17], then there will be several and up to hundreds of the $\mathrm{B_H Q}$ events to be generated per year.

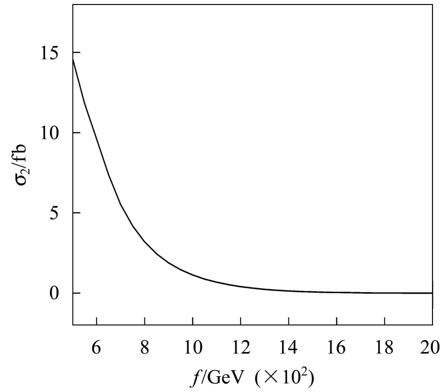

Fig. 4. The effective cross section σ_2 as a function of the scale parameter f for the center-of-mass energy $\sqrt{s}=1$ TeV.

From the above discussions, we can see that the SM quark partner Q mainly decays to $\mathrm{B_H q}$ (q = u, c, d or s) and there is $Br(\mathrm{Q}\rightarrow\mathrm{B_H q})\approx1$. In this case, the signal of the $\mathrm{B_H Q}$ production at the THERA collider is one jet plus large missing energy. The backgrounds of the one jet+ $\not{E}$ signal mainly come from the SM charged current(CC) process $\mathrm{ep}\rightarrow\nu\mathrm{X}$ and the SM subprocess $\gamma\mathrm{q}\rightarrow\mathrm{Zq}$ with $\mathrm{Z}\rightarrow\nu\bar{\nu}$. Measurement and QCD analysis of the production cross section of the SM CC process $\mathrm{ep}\rightarrow\nu\mathrm{X}$ at the HERA collider have been extensively studied[21]. Its cross section is much larger than that of the process $\mathrm{ep}\rightarrow\gamma\mathrm{q}\rightarrow\mathrm{Zq}$. Thus, we only take the SM CC process $\mathrm{ep}\rightarrow\nu\mathrm{X}$ as background of the process $\mathrm{ep}\rightarrow\gamma\mathrm{q}\rightarrow\mathrm{B_H Q}$. We have checked the SM background and found that it is well above the signal of the one jet plus missing energy from the LHT model. However, this kind of SM backgrounds have been well studied and will be precisely measured at the THERA collider experiments, one can still look for excess in the one jet+ $\not{E}$ signal to search for the possible signals of the LHT model.

5 Conclusions

To avoid the severe constraints from the electroweak precision data on the LH model, T-parity is introduced into this model, which forms the LHT model. An interesting feature of the LHT model is that it predicts the existence of the neutral, weakly interacting, new gauge boson $\mathrm{B_H}$, which can be seen as an attractive dark matter candidate. This model can generate vary different signals from those for the LH model in the present or future high energy experiments.

In this paper, we discuss the production of the new gauge boson $\mathrm{B_H}$ predicted by the LHT model at the ILC and THERA collider experiments via considering the subprocesses $\mathrm{e}^-\gamma\rightarrow\mathrm{L^-B_H}$ and $\gamma\mathrm{q}\rightarrow\mathrm{B_H Q}$. We find that the new gauge boson $\mathrm{B_H}$ can be abundantly produced at these collider experiments. The signals of the associated production of $\mathrm{L^-B_H}$ and $\mathrm{B_H Q}$ are an isolated charged lepton with large missing energy and one jet with large missing energy, respectively. Thus, the possible signals of the LHT model might be detected at the ILC and THERA experiments by searching for one jet (or charged lepton) with large missing energy. We further give some discussions about the SM backgrounds for this kind of signals. Despite the fact that the SM backgrounds are much large, it also needs a careful study on the SM backgrounds in order to search for these signals of the LHT model in the future ILC and THERA collider experiments.

Certainly, if the new gauge boson $\mathrm{B_H}$ and the SM quark partner Q are enough light, the process $\mathrm{ep}\rightarrow\gamma\mathrm{q}\rightarrow\mathrm{B_H Q}$ can occur at the HERA with $\sqrt{s}=320$ GeV, which can also generate the characteristic signals at the HERA experiments. However, considering the constraints on the mass parameters $M_{\mathrm{B_H}}$ and M_{Q}, we have not calculated the cross section of this process at the HERA collider experiments.

Other specific models beyond the SM, such as SUSY and extra dimension models, can also generate the similar signals with those of the $\mathrm{L^-B_H}$ and $\mathrm{B_H Q}$ events. More studies about this kind of signals are needed and they will be helpful to discriminate various specific models beyond the SM in future high energy collider experiments.

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