The new charged gauge boson $W'$ and the subprocess $eq \to \nu q'$ at $e^+e^-$ and $ep$ colliders

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Abstract

In the framework of the little Higgs models and the three-site Higgsless model, we discuss the contributions of the new charged gauge boson $W'$ to the process $eq \to \nu q'$ and the possibility of detecting $W'$ via this process in future high energy linear $e^+e^-$ collider (ILC) and $ep$ collider (THERA) experiments. Our numerical results show that the process $eq \to \nu q'$ is rather sensitive to the coupling $W' f f'$ and one can use this process to distinguish different new physics models in future ILC and THERA experiments.

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1. Introduction

Although any new charged gauge boson, generally called $W'$, is not found yet experimentally, its existence is now a relatively common prediction which results from many new physics scenarios. For example, little Higgs models [1], Higgsless models [2], non-commuting extended technicolor [3], and Randall-Sundrum model with bulk gauge fields [4] give examples where extension of gauge group lead to appearing of $W'$. If one of these new particles is discovered, it would represent irrefutable proof of new physics, most likely that the gauge group of the standard model (SM) must be extended. Thus, search for extra gauge boson $W'$ provides a common tool in quest for new physics at the next generation collider experiments [5].

Although the extra gauge boson $W'$ is not discovered yet there are experimental limits on its mass. The indirect limits can be placed on the existence of $W'$ through indirect searches based on the deviations from the SM, which can be obtained in precision electroweak measurements [6, 7]. Indirect searches for $W'$ being extracted from leptonic and semileptonic decays and also from cosmological and astrophysical data give very wide range for upper limits on $W'$ mass varying from 549GeV up to 23TeV [8]. The direct limits on $W'$ mass are based on hypothesis of purely right or left-handed interacting $W'$ with SM-like coupling constants [9]. At hadron colliders, the limits can be obtained by considering its direct production via the Drell-Yan process and its subsequent decay to lepton pairs or hadronic jets. Present bounds from measurements at the Tevatron collider exclude low $W'$ mass, $M_{W'} > 720GeV$ [10]. The CERN Large Hadron Collider (LHC) is expected to be able to discover $W'$ up to mass of $\approx 5.9TeV$ [11].

So far, there are some studies of indirect searches for $W'$ boson at high energy colliders. For example, Ref.[6] has examined the sensitivity of the process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ to the mass of $W'$ boson and found that this process is sensitive to $W'$'s mass up to several $TeV$. Ref.[7] further studied the sensitivity of the process $e\gamma \rightarrow \nu q + X$ to $W'$ boson and compared with the process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$, which find that, in many cases, this process is more sensitive to $W'$ boson than that of the process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$. Recently, Ref.[12] has explored the capability of the LHC to determine the $W'$ coupling helicity at low
integrated luminosities in the $l + E_T^{\text{miss}}$ discovery channel and Ref.[13] has further studied the process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ in the context of the little Higgs model. Ref.[14] has studied the possibility of detecting the $W'$ boson predicted by the three-site Higgsless model via the processes $pp \rightarrow W' \rightarrow WZ$ and $pp \rightarrow W'jj \rightarrow WZjj$ at the upcoming LHC. In this paper, we will calculate the corrections of the gauge boson $W'$ to the process $eq \rightarrow \nuq'$ in different extensions of the $SM$ and see whether this process can be used to distinguish different new physics models in future high energy collider experiments.

Little Higgs theory is proposed as an alternative solution to the hierarchy problem of the $SM$, which provides a possible kind of electroweak symmetry breaking (EWSB) mechanism accomplished by a naturally light Higgs boson [1]. In general, this kind of models predict the existence of the pure left-handed charged gauge boson $W'$, which has the $SM$-like couplings to ordinary particles. In this paper, we will first consider the process $eq \rightarrow \nuq'$ in this kind of models. The second kind of models are the Higgsless models, which have been proven to be viable alternative to the $SM$ and supersymmetric models in describing the breaking of the electroweak symmetry [15]. The three-site Higgsless model [16] is one of the simplest and phenomenologically viable models and has all essential features of the Higgsless models. Thus we will consider the contributions of the charged $KK$ gauge boson $W'$ predicted by the three-site Higgsless model to the process $eq \rightarrow \nuq'$.

Section 2 of this paper contains the elemental formula, which are related to our calculation. Based on the structure of the extended electroweak gauge group, the little Higgs models can be divided into two classes [17, 18]: the product group models and the simple group models. The littlest Higgs model ($LH$) [19] and the $SU(3)$ simple group model [18, 20] are the simple examples of these two kinds of little Higgs models, respectively. The contributions of these two models to the process $eq \rightarrow \nuq'$ are considered and the relevant phenomenology analysis in future high energy linear $e^+e^-$ collider ($ILC$) [21] and $ep$ collider ($THERA$) [22] are given in section 3. Section 4 gives our numerical results obtained in the framework of three-site Higgsless model. In the last section the summary and discussion are given.
2. The relevant formula about our calculation

To consider the $W'$ contributions to the process $eq \to \nu q'$ in different new physics scenarios, we write down the lowest dimension effective Lagrangian of $W'$ interactions to ordinary fermions in most general form (possible higher dimension effective operators are not taken into account in our numerical calculation):

$$\mathcal{L} = \frac{e}{\sqrt{2S_W}} V_{ij} \bar{f}_i \gamma^\mu (g_L P_L + g_R P_R) f_j W'_\mu + h.c.,$$  \hspace{1cm} (1)

where $S_W = \sin \theta_W$ ($\theta_W$ is the Weinberg angle), $V_{ij}$ is the CKM matrix element, and $P_L(R) = (1 \mp \gamma_5)/2$ is the left-(right-) handed projection operator. In the SM case, the coupling constant $g_L$ is equal to one and $g_R$ is equal to zero.

The production cross section $\hat{\sigma}(\hat{s})$ of the process $e(P_1) + q(P_2) \to \nu(P_3) + q'(P_4)$ contributed by the SM gauge boson $W$ and the new charged gauge boson $W'$ can be written as:

$$\hat{\sigma}(\hat{s}) = \int d\hat{t} \frac{d\hat{\sigma}}{d\hat{t}}$$  \hspace{1cm} (2)

with

$$\frac{d\hat{\sigma}}{d\hat{t}} = \frac{\pi \alpha^2}{4S_W^2} \left[ \frac{1}{(t - M_W^2)^2} + \frac{2g_L^{Wq'q'}g_L^{W\nu\nu}}{(t - M_W^2)(t - M_{W'}^2)} + \frac{(g_L^{Wq'q'}g_L^{W\nu\nu})^2}{(t - M_{W'}^2)^2} \right],$$  \hspace{1cm} (3)

and $\hat{t} = (P_1 - P_4)^2$. In above equations, we have assumed that $W'$ is the pure left-handed charged gauge boson.

The process $eq \to \nu q'$ can be seen as the subprocess of the charged current (CC) process $ep \to \nu q' + X$. Measurement and QCD analysis of the production cross section for the SM CC process $ep \to \nu q' + X$ at the HERA collider have been extensively studied [23]. Including the contributions of the SM gauge boson $W$ and new gauge boson $W'$, the production cross section $\sigma_T(S)$ of the CC process $ep \to \nu q' + X$ at the $ep$ colliders can be written as:

$$\sigma_T(S) = \sum_q \int_{x_{\text{min}}}^1 f_q(x, \mu) \hat{\sigma}(\hat{s}) dx$$  \hspace{1cm} (4)

with $x_{\text{min}} = m_q^2/S$ and $\hat{s} = xS$, in which the center-of-mass (c.m.) energy $\sqrt{S}$ is taken as $320 GeV$ for the HERA collider and as $1 TeV$ for the THERA collider. $q$ represents the quarks $u, c, d,$ or $s$. In our numerical estimation, we will use CTEQ6L parton
distribution function (PDF) \[24\] for the quark distribution function \(f_q(x, \mu)\) and assume that the factorization scale \(\mu\) is of order \(\sqrt{\hat{s}}\). To take into account detector acceptance, the angle of the observed jet, \(\theta_q\), will be restricted to the range \(10^\circ \leq \theta_q \leq 170^\circ\) \[23\].

It has been shown \[7\] that in suitable kinematic region the process \(e\gamma \to \nu q' \bar{q}\) can be approximated quite well by the process \(eq \to \nu q'\), where the quark \(q\) described by the quark parton content of the photon approach \[25\]. The hard photon beam of \(e\gamma\) collision can be obtained from laser backscattering at the high energy \(e^+e^-\) collider experiments. The expression for the effective cross section of the subprocess \(eq \to \nu q'\) at the ILC is given by

\[
\sigma_I = \sum_q \int dx_1 dx_2 f_{\gamma/e}(x_1) f_{q/\gamma}(x_2) \hat{\sigma}(\hat{s}),
\]

where \(f_{\gamma/e}(x_1)\) is the photon distribution \[26\], \(f_{q/\gamma}\) is the distribution function for the quark content in the photon. To obtain our numerical results we will use Aurenche, Fontannaz and Guillet (AFG) distribution \[27\] for \(f_{q/\gamma}\). Other distributions are available in \[28\].

In the following sections, we will discuss possibility of detecting the new charged gauge boson \(W'\) in future THERA and ILC experiments via considering its contributions to the subprocess \(eq \to \nu q'\) in different new physics scenarios.

3. The subprocess \(eq \to \nu q'\) in the little Higgs models

According to the structure of the extended electroweak gauge group, the little Higgs models can be generally divided into two classes \[17, 18\]: product group models, in which the \(SM SU(2)_L\) is embedded in a product gauge group, and simple group models, in which it is embedded in a large simple group. The \(LH\) model \[19\] and the \(SU(3)\) simple group model \[18, 20\] are the simplest examples of the product group models and the simple group models, respectively. To predigest our calculation, we will discuss the subprocess \(eq \to \nu q'\) in the context of these two simplest models.

In the \(LH\) model, the coupling constants of the \(SM\) gauge boson \(W\) and the new gauge boson \(W_H\) to the first and second generation fermions, which are related to our
calculation, can be written as [29]:

\[ g_{L}^{W qq'} = \frac{ie}{\sqrt{2} S_{W}} [1 - \frac{\nu^2}{2 f^2} c^2 (c^2 - s^2)], \quad g_{R}^{W qq'} = 0; \] \hspace{1cm} (6)

\[ g_{L}^{Wqq'R} = \frac{ie}{\sqrt{2} S_{W}} s, \quad g_{R}^{Wqq'R} = 0. \] \hspace{1cm} (7)

Here \( \nu \approx 246 GeV \) is the electroweak scale, \( c (s = \sqrt{1 - c^2}) \) is the mixing parameter between the \( SU(2)_{1} \) and \( SU(2)_{2} \) gauge bosons, and \( f \) is the scale parameter of the gauge symmetry breaking.

![Figure 1](image.png)

Figure 1: At the THERA, the relative correction parameter \( R \) as function of the mixing parameter \( c \) for the LH model (a) and of the parameter \( t_{\beta} \) for the \( SU(3) \) simple group model (b) for three values of the scale parameter \( f \).

Similar with the LH model, the \( SU(3) \) simple group model [18, 20] also predicts the existence of the new charged gauge boson, which is represented by \( X \). In the \( SU(3) \) simple group model, the coupling constants of the \( SM \) gauge boson \( W \) and the new gauge boson \( X \) to the first and second generation fermions can be written as:

\[ g_{L}^{W qq'} = \frac{ie}{\sqrt{2} S_{W}} (1 - \frac{1}{2} \delta_{\nu}^2), \quad g_{R}^{W qq'} = 0; \] \hspace{1cm} (8)
with $\delta_\nu = -\nu/2 f t_\beta$. Here $f = \sqrt{f_1^2 + f_2^2}$ and $t_\beta = \tan \beta = f_2/f_1$, in which $f_1$ and $f_2$ are the vacuum condensate values of the two sigma-model fields $\Phi_1$ and $\Phi_2$, respectively.

After taking into account electroweak symmetry breaking (EWSB), at the leading order, the masses of the new charged gauge bosons $W_H$ and $X$ can be written as:

$$M_{W_H} = \frac{gf}{2sc}, \quad M_X = \frac{gf}{\sqrt{2}}.$$  \hfill (10)

Except for the SM input parameters $\alpha = 1/128.8$, $S_{W}^2 = 0.2315$, and $M_W = 80.14\,\text{GeV}$ [8], the contributions of the LH model and the $SU(3)$ simple group model to the production cross section of the subprocess $eq \to \nu q'$ dependent on the free parameters $(f, c)$ and $(f, t_\beta)$, respectively. Considering the constraints of the electroweak precision data on these free parameters, we will assume $1\,\text{TeV} \leq f \leq 3\,\text{TeV}$ and $0 < c \leq 0.6$ for the LH model [30], and $1\,\text{TeV} \leq f \leq 3\,\text{TeV}$ and $t_\beta > 1$ for the $SU(3)$ simple group model [17, 18, 20] in our numerical estimation.

![Figure 2](image.png)

Figure 2: Same as Fig.1 but for ILC.

To illustrate the contributions of the new physics model to the subprocess $eq \to \nu q'$, we define the relative correction parameter $R = \frac{\sigma(i) - \sigma(SM)}{\sigma(SM)}$, in which $\sigma(i)$ and $\sigma(SM)$ represent
the effective cross sections predicted by the new physics model and the SM, respectively. The relative correction parameters for the LH model and the SU(3) simple group model at the THERA and ILC experiments are plotted in Fig.1 and Fig.2, respectively. In these figures, we have assumed the CKM matrix elements $V_{ud} \approx V_{cs} \approx 1$ and taken the c.m. energy $\sqrt{S} = 1000\text{GeV}$ and $500\text{GeV}$ for the THERA and ILC experiments, respectively. One can see from these figures that the LH model can give positive contributions to the effective cross sections at the THERA and ILC experiments, while the SU(3) simple group model can give negative contributions. The absolute value of the relative correction parameter $R$ for the SU(3) simple group model is slightly smaller than that for the LH model. For the SU(3) simple group model, the values of $R$ at the THERA are approximately equal to those at the ILC. However, in most of the parameter spaces for the LH model and the SU(3) simple group model, all of the absolute values of the relative correction parameter $R$ are smaller than 4.3%.

![Figure 3: For the LH model, SS as a function of the mixing parameter $c$ for three values of $f$ at the THERA (a) and the ILC (b).](image)

In order to see if the correction effects of the LH model and the SU(3) simple group model on the processes $ep \rightarrow \nu q' + X$ and $e^+e^- \rightarrow \nu q' + X$ can be observed in the future THERA and ILC experiments, we define the statistical significance ($SS$) of the signal
Figure 4: For the $SU(3)$ simple group model, $SS$ as a function of the parameter $t_\beta$ for three values of $f$ at the $THERA$ (a) and the $ILC$ (b).

as:

$$SS^i = \frac{|\sigma(i) - \sigma(SM)|}{\sqrt{\sigma(SM)}} \sqrt{\mathcal{L}}.$$  (11)

Here $i$ represents the $LH$ model or the $SU(3)$ simple group model. In our numerical calculation, we will assume the values of yearly integrated luminosity $\mathcal{L}$ as $4fb^{-1}$ and $100fb^{-1}$ for the $THERA$ experiment with $\sqrt{S} = 1000GeV$ and $ILC$ experiment with $\sqrt{S} = 500GeV$, respectively. Our numerical results are summarized in Fig.3 and Fig.4.

One can see from these figures that, for these two little Higgs models, the value of $SS$ at the $THERA$ is larger than that at the $ILC$. For the assumed integrated luminosity, the effects of the little Higgs models on the subprocess $eq \rightarrow \nu q'$ can generally be easier detected at the $THERA$ than at the $ILC$. For same high energy collider experiment ($ILC$ or $THERA$), the $SS$ value contributed by the $LH$ model is larger than that by the $SU(3)$ simple group model. For the $ILC$ experiment with $\sqrt{S} = 500GeV$ and $\mathcal{L} = 100fb^{-1}$, if we take $f = 2TeV$, $0.2 \leq c \leq 0.6$ and $1 \leq t_\beta \leq 2.5$, the values of $SS$ are in the ranges of $2.6 \sim 23.1$ and $15.8 \sim 2.5$ for the $LH$ model and the $SU(3)$ simple group model, respectively. Thus, with reasonable values of the free parameters, the possible
signatures of the new charged gauge boson $W'$ predicted by the $LH$ model or by the $SU(3)$ simple group model might be detected via the subprocess $eq \rightarrow \nu q'$ in the future $ILC$ and $THERA$ experiments.

4. The subprocess $eq \rightarrow \nu q'$ in the three-site Higgsless model

So far, various kinds of models for $EWSB$ have been proposed, among which Higgsless model [2] is one of the attractive new physics models. In this kind of models, $EWSB$ can be achieved via employing gauge symmetry breaking by boundary condition in higher dimensional theory space [31], and the unitary of longitudinally polarized $W$ boson and $Z$ boson scattering is preserved by exchange of new vector gauge bosons [32]. Reconstructed Higgsless models [15, 16] have been used as tools to compute the general properties of Higgsless models and to illustrate the phenomenological properties of this kind of new physics models beyond the $SM$.

The simplest deconstructed Higgsless model incorporates only three sites on the deconstructed lattice, which is called the three-site Higgsless model [16]. In this model, the ordinary fermions are ideally delocalized, which preserves the characteristic of vanishing precision electroweak corrections up to subleading order [33]. Furthermore, the three-site Higgsless model is capable of approximating much of the interesting phenomenology associated with extra dimensional models and more complicated deconstructed Higgsless models [34].

The three-site Higgsless model [16] has a standard color group and an extended $SU(2)_1 \times SU(2)_2 \times U(1)$ electroweak gauge group, which is similar to that of the $BESS$ model [35]. Once $EWSB$ occurs in this model, the gauge sector consists of a massless photon, two relatively light massive gauge bosons which are identified with the $SM$ $W$ and $Z$ gauge bosons, as well as two heavy gauge bosons which are denoted as $Z'$ and $W'$.

In the three-site Higgsless model, the coupling constants of the charged gauge bosons $W$ and $W'$ to ordinary fermions can be written as:

$$g_L^{Wff'} = \frac{iS_W}{e} [g(1-x_1)a_{22} + \tilde{g}x_1a_{12}], \quad g_R^{Wff'} = 0;$$

$$g_L^{W'ff'} = \frac{iS_W}{e} [g(1-x_1)a_{21} + \tilde{g}x_1a_{11}], \quad g_R^{W'ff'} = 0.$$
Here the parameter $x_1$ is a measure of the amount of fermion delocalization ($0 < x_1 \ll 1$) [16, 33]. In principle, the value of $x_1$ for a given fermion species depends indirectly on the mass of the fermion. However, since we are only interested in light fermions, we can assume that the parameter $x_1$ has the same value for the first- and second- generation fermions. The expression forms of the parameters $g, \tilde{g}, a_{22}, a_{12}, a_{21}, \text{ and } a_{11}$ have been given by [36] in terms of the $W$ and $W'$ masses $M_W$ and $M_W'$. In our numerical estimation, we will assume $M_{Z'}^2 = M_{H'}^2 + (M_Z^2 - M_{H'}^2)$, and take $x_1$ and $M_{W'}$ as free parameters.

Figure 5: The relative correction parameter $R$ varies as the parameter $x_1$ for three values of the $W'$ mass $M_{W'}$ at the THERA (a) and the ILC (b).

Our numerical results obtained in the content of the three-site Higgsless model are given in Fig.5 and Fig.6, in which we have assumed $M_{W'}=700 GeV$, 1050GeV, and 1400GeV. One can see from these figures that the contributions of the three-site Higgsless model to the subprocess $eq \rightarrow \nu q'$ depend rather significantly on the free parameter $x_1$. The value of the relative correction parameter $R$ is positive or negative, which depends on the value of the free parameter $x_1$. The value of $R$ for the ILC experiment with $\sqrt{S} = 500GeV$ is approximately equal to that for the THERA experiment with $\sqrt{S} = 1TeV$. However, the statistical significance $SS$ of the signal for the THERA ex-
experiment is larger than that for the ILC experiment. In wide range of the parameter space, the value of $SS$ is significantly large. Thus, we expect that the correction effects of the three-site Higgsless model to the subprocess $eq \to \nu q'$ can be observed in the future THERA and ILC experiments.

Figure 6: $SS$ as a function of the parameter $x_1$ for three values of the $W'$ mass $M_{W'}$, at the THERA (a) and the ILC (b).

5. Conclusions and discussions

Most of all the new physics models beyond the SM predict the existence of the new charged gauge boson $W'$, which might generate observed signatures in future high energy collider experiments. The $W'$ arised from different new physics models can induce different physical signatures. Thus, it is very interesting to study the correction effects of the new gauge boson $W'$ on some observables. It will be helpful to test the SM and further to distinguish different new physics models.

The process $eq \to \nu q'$ mediated by the charged gauge boson $W'$ can be seen as the subprocess of the processes $ep \to \nu q' + X$ and $e^+ e^- \to \nu q' + X$. One can use the subprocess $eq \to \nu q'$ to detect the possible signals of the new charged gauge boson $W'$ in future THERA and ILC experiments. Ref.[39] has studied the contributions of the
four fermion contact terms to this subprocess. In this paper, we study the contributions of the $W'$ predicted by the little Higgs models and the three-site Higgsless model to this subprocess and discuss the possibility of detecting $W'$ in future THERA and ILC experiments. Our numerical results are summarized in Table 1.

Table 1: The contributions of the LH model, $SU(3)$ simple group model, and the three-site Higgsless model to the subprocess $eq \rightarrow \nu q'$ at the THERA and ILC experiments.

| Models | LH | $SU(3)$ | HL |
|--------|----|---------|----|
| $f = 2 TeV$ | $f = 2 TeV$ | $M_{W'} = 1050 GeV$ |
| $0.2 \leq c \leq 0.6$ | $1 \leq t_\beta \leq 2.5$ | $0.002 \leq x_1 \leq 0.08$ |
| $R(\%)$ | THERA | ILC | THERA | ILC | THERA | ILC |
| $0.12 \sim 0.89$ | $-0.75 \sim -0.12$ | $-0.74 \sim -0.12$ | $12.1 \sim -4.5$ | $13.2 \sim -3.6$ |
| $SS$ | $8.4 \sim 68.1$ | $2.6 \sim 23.1$ | $52.2 \sim 8.4$ | $15.8 \sim 2.5$ | $845.5 \sim 314.2$ | $280.8 \sim 76.1$ |

The contributions of the three-site Higgsless model to the subprocess $eq \rightarrow \nu q'$ are generally larger than those for the LH model or the $SU(3)$ simple group model. The effects of the three-site Higgsless model on this subprocess can generally be easier detected than those for the little Higgs models. However, it can enhance or reduce the effective cross sections of the subprocess $eq \rightarrow \nu q'$ at the THERA and ILC experiments, which depends on the value of the free parameter $x_1$. Thus, we can use the subprocess $eq \rightarrow \nu q'$ to detect the possible signatures of the new charged gauge boson $W'$ and further distinguish the three-site Higgsless model and the little Higgs models in future THERA or ILC experiments.

In this paper, we have assumed that the hard photon beam is obtained from laser backscattering. Certainly, we can also take that the hard photon beam arises from Weizsäcker Williams bremsstrahlung [37]. Furthermore, in our numerical estimation, we have taken $AFG$ PDFs for the quark distribution functions in the photon. Other PDFs can also be used to give our numerical results. These will change the above numerical
results. However, they can not change our physical conclusions.

In order to satisfy the electroweak precision constraints by avoiding tree-level contributions of the new particles and restoring the custodial $SU(2)$ symmetry, a discrete symmetry (called T-parity) is introduced to the $LH$ model, which forms the so called $LHT$ model [38]. Under T-parity, particle fields predicted by this model are divided into T-even and T-odd sectors. The T-even sector consists of the $SM$ particles and a heavy top $T_+$, while the T-odd sector contains heavy gauge bosons ($B_H, Z'_H, W^\pm_H$), a scalar triplet ($\Phi$), and the so-called mirror fermions ($L_H, Q_H$). The mirror quark can be produced via the process $eq \rightarrow \nu H Q_H$ mediated by the T-odd charged gauge boson $W_H$, which can give similar signal with that from the process $eq \rightarrow \nu q'$. We will study the process $eq \rightarrow \nu H Q_H$ in near future works.

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