Single production of new gauge bosons from the littlest Higgs model at the TeV energy $e^-\gamma$ colliders

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Abstract: In the context of the littlest Higgs(LH) model, we study single production of the new gauge bosons $B_H$, $Z_H$ and $W_H^\pm$ via $e^-e^-$ collisions and discuss the possibility of detecting these new particles in the TeV energy $e^+e^-$ collider(LC). We find that these new particles can not be detected via the $e^-\nu\nu$ signal in all of the parameter space preferred by the electroweak precision data. However, the heavy gauge bosons $B_H$ and $Z_H$ may be observed via the decay channel $B_H(Z_H) \rightarrow l^+l^-$ in wide range of the parameter space. PACS number(s):12.60.Cn, 14.70.Pw, 13.66.Hk

It is widely believed that the hadron colliders, such as Tevatron and future LHC, can directly probe possible new physics beyond the standard model(SM) up to a few TeV, while the TeV energy linear $e^+e^-$ collider(LC) is also required to complement the probe of the new particles with detailed measurement[1]. A unique feature of the TeV energy LC is that it can be transformed to $\gamma\gamma$ or $e\gamma$ collider (photon colliders) by the laser-scattering method. The effective luminosity and energy of the the photon colliders are expected to be comparable to those of the LC. In some scenarios, they are the best instrument for the discovery of signal of new physics.

The $e^-\gamma$ collisions can produce particles which are kinematically not accessible at the $e^+e^-$ collisions at the same collider[2]. For example, for the process $e^-\gamma \rightarrow AB$ with light particle $A$ and new particle $B$, the discovery limits can be much higher than in other reactions. Furthermore, the initial state photon provides us with a possibility to directly probe the gauge boson self-interactions and its cross section is simply dependent on the coupling parameters, so the $e^-\gamma$ collider is particularly suitable for studying heavy gauge boson production. In this letter, we will study single production of the heavy gauge bosons $B_H$, $Z_H$ and $W_H$ predicted by the littlest Higgs(LH) model[3] via the $e^-\gamma$ collisions and discuss the possibility of detecting these new particles in the future LC experiments.

Little Higgs models[3,4] were recently proposed as the kind of models of electroweak symmetry breaking(EWSB), which can be regarded as the important candidates of new physics beyond the SM. The LH model[3] is one of the simplest and phenomenologically viable models, which realizes the little Higgs idea. It consists of a non-linear $\sigma$ model with a global $SU(5)$ symmetry, which is broken down to $SO(5)$ by a vacuum condensate $f \sim \Lambda_s/4\pi \sim TeV$. The gauged subgroup $SU(2)_1 \times U(1)_1 \times SU(2)_2 \times U(1)_2$ is broken at the same time to its diagonal subgroup $SU(2) \times U(1)$, identified as the SM electroweak gauge group. This breaking scenario gives rise to four massive gauge bosons $B_H$, $Z_H$ and $W_H^\pm$, which might produce characteristic signatures at the present and future collider experiments[5,6,7].

Global fits to the electroweak precision data produce rather severe constraints on the parameter space of the LH model[8]. However, if the SM fermions are charged under $U(1)_1 \times U(1)_2$, the constraints become relaxed. The scale parameter $f = 1 \sim 2 TeV$ is allowed for the mixing parameters $c$ and $c'$ in the ranges of $0 \sim 0.5$ and $0.62 \sim 0.73$, respectively[9].

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Taking account of the gauge invariance of the Yukawa couplings and the $U(1)$ anomaly cancellation, the relevant couplings of the gauge bosons $B_H$, $Z_H$ and $W_H$ to the SM fermions can be written as[5]:

$$
\begin{align*}
    g_{L}^{B_H\ell\ell} & = \frac{e}{2 CW_s s^{c}}(c'^2 - \frac{2}{5}), \\
    g_{R}^{B_H\ell\ell} & = \frac{e}{CW_s s^{c}}(c'^2 - \frac{2}{5}), \\
    g_{L}^{Z_H\ell\ell} & = -\frac{ec}{2 s W s}, ~ g_{R}^{Z_H\ell\ell} = 0; \\
    g_{L}^{W_H\ell\ell'} & = -\frac{ec}{\sqrt{2} s W s}, ~ g_{R}^{W_H\ell\ell'} = 0; \\
    g_{L}^{B_H\nu\nu} & = \frac{e}{2 CW_s s^{c}}(c'^2 - \frac{2}{5}), \\
    g_{R}^{B_H\nu\nu} & = 0; \\
    g_{L}^{Z_H\nu\nu} & = \frac{ec}{2 s W s}, ~ g_{R}^{Z_H\nu\nu} = 0.
\end{align*}
$$

From Eq.(1) we can see that the couplings of the gauge boson $B_H$ to leptons vanish at $c' = \sqrt{2/5}$. Thus, in the parameter space around $c' = \sqrt{2/5}$, the contributions of $B_H$ to observables are significantly reduced. Ref.[7] has shown that a large portion of the parameter space($f = 1 \sim 2Tev$, $c = 0 \sim 0.5$, $c' = 0.62 \sim 0.73$) consistent with the electroweak precision data can accommodate the Tevatron direct searches to $B_H$ decaying into dileptons. The light $B_H$ is not excluded by the direct searches for the neutral gauge boson at the Tevatron. So, we will take $M_{B_H}$ and $M_{Z_H}$ in the ranges of $300 GeV \sim 900 GeV$ and $1 TeV \sim 3 TeV$ in our numerical estimation. The gauge bosons $W_H$ and $Z_H$ are almost degenerate in mass, we assume $M_{W_H} = M_{Z_H} = M$.

In Fig.1 and Fig.2 we plot the single production cross sections of the new gauge bosons $B_H$, $Z_H$, and $W_H^\pm$ via the processes $e^+e^- \rightarrow e^-\gamma \rightarrow e^- B_H$, $e^+e^- \rightarrow e^-\gamma \rightarrow e^- Z_H$ and $e^+e^- \rightarrow e^-\gamma \rightarrow W_H^\pm \nu_e$, as functions of the mixing parameters for three values of the masses $M_{B_H}$ and $M_{Z_H}$, the c.m. energy $\sqrt{s} = 1 TeV$ and $3 TeV$, respectively. From these figures, we can see that, in most of the parameter space preferred by the electroweak precision data, the single production cross sections decrease as the mixing parameters are decreasing. The single $B_H$ production cross section is larger than $30 fb$ for $c' \geq 0.68$ and $M_{B_H} \leq 600 GeV$. For $c = 0.5$ and $M = 1.9 TeV$, the single production cross sections of the new gauge bosons $Z_H$ and $W_H$ are $49 fb$ and $0.78 fb$, respectively.

![Figure 1: The single production cross section of $B_H$ as a function of $c'$ for $\sqrt{s} = 1 TeV$.](image1)

![Figure 2: The single production cross sections of $Z_H(W_H)$ as functions of $c$ for $\sqrt{s} = 3 TeV$. Solid and dashed lines correspond to the gauge bosons $Z_H$ and $W_H$, respectively.](image2)

In general, the heavy gauge bosons are likely to be discovered via their decays to leptons. If the gauge bosons $B_H$ and $Z_H$ decay into pair of neutrinos, the signal of the processes $e^+e^- \rightarrow e^-\nu\bar{\nu} \rightarrow e^- B_H(e^- Z_H)$ will be an isolated electron associated large missing energy. In the narrow width approximation, the number of observed events can be approximately written as $N(e\nu\bar{\nu}) = \mathcal{L} \varepsilon \sigma(e^- B_H(e^- Z_H)) \times Br(B_H(Z_H) \rightarrow \nu\bar{\nu})$, where $\varepsilon$ is the experimental efficiency for detecting the final state electron and $\mathcal{L}$ is the integrated luminosity of
the future LC experiments. Obviously, in wide range of the parameter space preferred by the electroweak precision data, the gauge bosons $B_H$ and $Z_H$ can generate several hundreds and up to thousand $e\nu\bar{\nu}$ events. For example, if we take $\mathcal{L} = 100 fb^{-1}$ and $\varepsilon = 95\%$, then the $B_H(Z_H)$ can generate 749(321) $e\nu\bar{\nu}$ events for $M_{B_H}(M_{Z_H}) = 600 GeV (1600 GeV)$ and the mixing parameter $c'(c) = 0.7(0.4)$.

The main backgrounds for the $e\nu\bar{\nu}$ signal come from the SM resonant processes $e^-\gamma \to e^- Z \to e^- \nu \bar{\nu}$ and $e^-\gamma \to W^- \nu \to e^- \nu_e\bar{\nu}_e$. The scattered electrons in the process $e^-\gamma \to e^- Z$ has almost same energy $E_e \approx \sqrt{s}/2$ for $\sqrt{s} \gg m_Z$. This process could be easily distinguished from the signal. Furthermore, the cross section of the process $e^-\gamma \to e^- Z$ decreases as $\sqrt{s}$ increasing, while the cross section of the process $e^-\gamma \to W^- \nu_e$ is approaching a constant at high energies. Thus, the most serious background process will be $e^-\gamma \to W^- \nu_e \to e^- \nu_e\bar{\nu}_e$.

To compare the signal with background and discuss the possibility of detecting these new particles, we calculate the ratio of signal over square root of the background $(S/\sqrt{B})$ and find that, for the gauge bosons $B_H$ and $Z_H$, the value of $S/\sqrt{B}$ is smaller than 2 in most of the parameter space allowed by the precision electroweak constraints. Thus, the gauge bosons $B_H$ and $Z_H$ can not be observed via the decay channel $B_H(Z_H) \to \nu\bar{\nu}$ in the future $e^-\gamma$ collider.

If the gauge bosons $B_H$ and $Z_H$ decay to pair of charged leptons, then the signal of the processes $e^-\gamma \to e^- B_H$ and $e^-\gamma \to e^- Z_H$ is three jets, two of the three jets are reconstructed to the new gauge boson mass. Comparing with the signal $e^-\nu\bar{\nu}$, the signal $e^- l^+l^-$ has small background, which mainly comes from the SM resonant process $e^-\gamma \to e^- Z \to e^- l^+l^-$ (The contributions of the SM process $e^-\gamma \to e^- l^+l^-$ to the background can be safely neglected at high energy[10]). It is evident that these new gauge bosons can be easier detected from the $B_H(Z_H) \to l^+l^-\nu\bar{\nu}$ decay channel than from the $B_H(Z_H) \to \nu\bar{\nu}$ decay channel.

In Fig.3 and Fig.4 we plot the $S/\sqrt{B}$ for the signal $e^- l^+l^-$ as function of the gauge boson masses $M_{B_H}$ and $M_{Z_H}$, respectively. As long as the values of the mixing parameters $c'$ and $c$ are in the ranges of $0.70 \sim 0.73$ and $0.4 \sim 0.5$, respectively, all values of the $S/\sqrt{B}$ for the gauge bosons $B_H$ with $M_{B_H} \leq 650 GeV$ and $Z_H$ with $M_{Z_H} \leq 1700 GeV$ are larger than 5. Thus, in the sizable parameter space preferred by the electroweak data, these new gauge bosons should be observed via detecting the $e^- l^+l^-$ signal in the future LC experiments.

The decay $W_H^\pm \to l\nu$ can manifest itself via events that contain an isolated charged lepton and missing energy. The signal of single production of the gauge bosons $W_H^\pm$ in the $TeV$ $e^-\gamma$ collider should be an isolated charged lepton associated with large missing energy. However, the background coming from the process $e^-\gamma \to W^-\nu_e \to l\nu\nu_e$ is very large and makes that the value of $S/\sqrt{B}$ is smaller than 2 in most of the parameter space preferred by the electroweak

![Figure 3](image-url)  
Figure 3: The $S/\sqrt{B}$ for the signal $e^- l^+l^-$ as a function of $M_{B_H}$ for four values of the mixing parameter $c'$.

![Figure 4](image-url)  
Figure 4: The $S/\sqrt{B}$ for the signal $e^- l^+l^-$ as a function of $M_{Z_H}$ for five values of the mixing parameter $c$. 

The decay $W_H^\pm \to l\nu$ can manifest itself via events that contain an isolated charged lepton and missing energy. The signal of single production of the gauge bosons $W_H^\pm$ in the $TeV$ $e^-\gamma$ collider should be an isolated charged lepton associated with large missing energy. However, the background coming from the process $e^-\gamma \to W^-\nu_e \to l\nu\nu_e$ is very large and makes that the value of $S/\sqrt{B}$ is smaller than 2 in most of the parameter space preferred by the electroweak
precision data. Thus, we have to say that the new gauge boson $W_H$ can not be detected in the future $e^-\gamma$ collider.

The TeV $e^-\gamma$ collider is particularly suitable for studying single production of the heavy gauge bosons. In the context of the LH model, we have studied the possibility of detecting the heavy gauge bosons $B_H$, $Z_H$ and $W_H^\pm$ via $e^-\gamma$ collision in the future LC experiment with the integrated luminosity $L = 100/\text{fb}^{-1}$. We find that these new particles can be significantly produced in wide range of the parameter space preferred by the electroweak precision data. The gauge boson $B_H$ should be observed via detecting the $e^-l^+l^-$ signal, except for the mixing parameter $c' \approx \sqrt{2}/5$. It is very difficult to detect the gauge boson $Z_H$ via the $Z_H \to \nu\tau$ decay channel, but it is possible to detect $Z_H$ via the $Z_H \to l^+l^-$ channel. With reasonable value of the free parameters, the value of $S/\sqrt{B}$ for $Z_H$ can reach 19. Certainly, a more detailed study of $e^-\gamma$ collisions with polarized beams is needed, in order to enhance the possibility of detecting these heavy gauge bosons and to distinguish between the LH model and other specific models beyond the SM.

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