The correction of the littlest Higgs model to the Higgs production process $e^-\gamma \rightarrow \nu_e W^- H$ in $e^-\gamma$ collisions

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Abstract

The littlest Higgs model is the most economical one among various little Higgs models. In the context of the littlest Higgs(LH) model, we study the process $e^-\gamma \rightarrow \nu_e W^- H$ and calculate the contributions of the LH model to the cross section of this process. The results show that, in most of parameter spaces preferred by the electroweak precision data, the value of the relative correction is larger than 10%. Such correction to the process $e^-\gamma \rightarrow \nu_e W^- H$ is large enough to be detected via $e^-\gamma$ collisions in the future high energy linear $e^+e^-$ collider(LC) experiment with the c.m energy $\sqrt{s}=500$ GeV and a yearly integrated luminosity $\mathcal{L} = 100 fb^{-1}$, which will give an ideal way to test the model.

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1 Introduction

The standard model (SM) provides an excellent effective field theory description of almost all particle physics experiments. But in the SM the Higgs boson mass suffers from an instability under radiative corrections. The naturalness argument suggests that the cutoff scale of the SM is not much above the electroweak scale: New physics will appear around TeV energies. The possible new physics scenarios at the TeV scale might be supersymmetry \[1\], dynamical symmetry breaking \[2\], extra dimensions \[3\]. Recently, a new model, known as little Higgs model has drawn a lot of interest and it offers a very promising solution to the hierarchy problem in which the Higgs boson is naturally light as a result of nonlinearly realized symmetry \[4, 5, 6, 7\]. The key feature of this model is that the Higgs boson is a pseudo-Goldstone boson of an approximate global symmetry which is spontaneously broken by a VEV at a scale of a few TeV and thus is naturally light. The most economical little Higgs model is the so-called littlest Higgs model, which is based on a \(SU(5)/SO(5)\) nonlinear sigma model \[7\]. It consists of a \(SU(5)\) global symmetry, which is spontaneously broken down to \(SO(5)\) by a vacuum condensate \(f\). In this model, a set of new heavy gauge bosons \(B_H, Z_H, W_H\) and a new heavy-vector-like quark \(T\) are introduced which just cancel the quadratic divergence induced by the \(SM\) gauge boson loops and the top quark loop, respectively. The distinguishing features of this model are the existence of these new particles and their couplings to the light Higgs. The measurement of these new particle effects might prove the existence of the littlest Higgs mechanism.

The hunt for the Higgs boson and the elucidation of the mechanism of symmetry breaking is one of the most important goals for present and future high energy collider experiments. Precision electroweak measurement data and direct searches suggest that the Higgs boson must be relative light and its mass should be roughly in the range of \(114.4 \text{ GeV} \sim 208 \text{ GeV} \) at 95% CL \[8\]. The high energy linear \(e^+e^-\) colliders \(LC\) has a large potential for the discovery of new particles \[9\]. Due to its rather clean environment, the \(LC\) will be perfectly suited for precise analysis of physics beyond the \(SM\) as well as for testing the \(SM\) with an unprecedented accuracy. An unique feature of the \(LC\) is that it can be transformed to \(\gamma\gamma\) or \(e\gamma\) colliders with the photon beams generated by laser-scattering method. Their effective luminosity and energy are expected to be comparable to those of the \(LC\). In some scenarios, they are the best instrument for the discovery of signatures of new physics.
Some phenomenological studies of the littlest Higgs model via $e\gamma$ or $\gamma\gamma$ collision has been done \cite{10}. The main W boson production mechanism is provided by the process $\gamma+e\rightarrow W+\nu$. The larger cross section for W boson production suggests that the process $e^{-}\gamma\rightarrow \nu_{e}W^{-}H$ can be exploited as a source for Higgs boson emitted from the W-boson line. In the context of the SM, this process has been studied at leading order \cite{11}. Since the final state consists of three particles two of which are heavy, the cross section at moderate energies ($\sqrt{s}\sim 500\text{GeV}$) is smaller than that of the standard $WW$ fusion mechanism $e^{+}e^{-}\rightarrow \nu\bar{\nu}H$, the Higgs-strahlung process $e^{+}e^{-}\rightarrow ZH$ and the $ZZ$ fusion mechanism $e^{+}e^{-}\rightarrow e^{+}e^{-}H$. These three processes have been studied in the context of the SM\cite{12,13} and the littlest Higgs model\cite{14}. However, at higher energies the cross section for the process $e^{-}\gamma\rightarrow \nu_{e}W^{-}H$ is nearly as large as that of the dominant $\nu\bar{\nu}H$ and the process for most of the mass of Higgs boson range accessible at linear colliders, and significantly larger than the cross section of the Higgs-strahlung process. A dedicated $e^{-}\gamma$ collider with back scattered laser beam therefore gives rise to a large Higgs production cross section through the process $e^{-}\gamma\rightarrow \nu_{e}W^{-}H$. Thus, it is very interesting to study this process in the popular specific models beyond the SM. The purpose of this paper is to calculate the corrections of new particles predicted by the littlest Higgs model to the process $e^{-}\gamma\rightarrow \nu_{e}W^{-}H$ and see whether the effects on this process can be observed in the future $LC$ experiments with the c.m energy $\sqrt{s}=500$ GeV.

This paper is organized as follows. In section two, the littlest model is briefly introduced, and then the production amplitude of the process is given. The numerical results and discussions are presented in section three. The conclusions are given in section four.

## 2 The littlest Higgs model and the production amplitude of $e^{-}\gamma\rightarrow \nu_{e}W^{-}H$

The littlest Higgs model is based on the $SU(5)/SO(5)$ nonlinear sigma model. At the scale $\Lambda_{s}\sim 4\pi f$, the global $SU(5)$ symmetry is broken into its subgroup $SO(5)$ via a vacuum condensate $f$, resulting in 14 Goldstone bosons. The effective field theory of these Goldstone bosons is parameterized by a non-linear $\sigma$ model with gauged symmetry $[SU(2)\times U(1)]^{2}$, spontaneously broken down to its diagonal subgroup $SU(2)\times U(1)$, identified as the SM electroweak gauge
group. Four of these Goldstone bosons are eaten by the broken gauge generators, leaving 10 states that transform under the SM gauge group as a doublet $H$ and a triplet $\Phi$. This breaking scenario also gives rise to four massive gauge bosons $B_H, Z_H$ and $W^\pm_H$, which might produce the characteristic signatures in the present and future high energy collider experiments \[15, 16, 17\].

After the electroweak symmetry breaking, the mass eigenstates are obtained via mixing between the heavy and light gauge bosons. They include the light (SM-like) bosons $Z_L, A_L$ and $W^\pm_L$ observed at experiments, and new heavy bosons $Z_H, B_H$ and $W^\pm_H$ that could be observed in the future experiments. To obtain our numerical results, we write the masses of the relevant particles as \[15\]:

$$M^2_{W^\pm_L} = (m_W)^2 \left\{ 1 - v^2 f^2 \left[ \frac{1}{6} + \frac{1}{4} (c^2 - s^2)^2 + \frac{x^2}{4} \right] \right\}, \quad (1)$$

$$M^2_{W^\pm_H} \approx (m_W)^2 \left( \frac{f^2}{s^2 c^2 v^2} - 1 \right), \quad (2)$$

with $x = \frac{4 f v'}{v^2}$, where $m_W = e v/2 s_W$ is the mass of the SM gauge boson W, $v=246$ GeV is the electroweak scale, $v'$ is the vacuum expectation value of the scalar $SU(2)_L$ triplet and $s_W(c_W)$ represents the sine(cosine) of the weak mixing angle. We define $x = 4 f v'/v^2$ to parametrize this vacuum expectation value of the scalar triplet field $\phi$. The mass of neutral scalar boson $M_{\phi^0}$ can be given as \[15\]:

$$M^2_{\phi^0} = \frac{2 m^2_{H^0} f^2}{v^2 [1 - (4 v' f/v^2)^2]} = \frac{2 m^2_{H^0} f^2}{v^2 (1 - x^2)} \quad (3)$$

The above equation about the mass of $\Phi$ requires a constraint of $0 \leq x < 1$ (i.e., $4 v' f/v^2 < 1$), which shows the relation between the scale $f$ and the vacuum expectation values of the Higgs field doublet and the triplet($v, v'$).

Taking account of the gauge invariance of the Yukawa coupling and the $U(1)$ anomaly cancelation, the couplings of the relevant couplings of the gauge boson $W^\pm_L$ and $W^\pm_H$ to ordinary particles and the Higgs boson can be written as follows in the LH model \[15\]:

$$g^W_{\mu\nu} = -g^W_{\mu\nu} = -\frac{ie}{2 \sqrt{2} s_W} \left[ 1 - \frac{v^2}{2 f^2} c^2 (c^2 - s^2) \right], \quad (4)$$

$$g^W_{\mu\nu} = -g^W_{\mu\nu} = -\frac{ie}{2 \sqrt{2} s_W} c, \quad (5)$$

$$g^W_{\mu\nu} = \frac{ie^2}{2 s_W^2} g_{\mu\nu} \left( 1 - \frac{v^2}{3 f^2} + \frac{1}{2} (c^2 - s^2)^2 \frac{v^2}{f^2} - \frac{3 v x}{f} \right), \quad (6)$$

$$g^W_{\mu\nu} = -\frac{ie^2}{2 s_W} \frac{c^2 - s^2}{2 s c} v g_{\mu\nu}. \quad (7)$$
we write the gauge boson-fermion couplings in the form of $i\gamma^\mu(g_V + g_A\gamma^5)$. With all momenta out-going, the three-point gauge boson self-couplings can be written in the form of:

$$V_1^\mu(k_1)V_2^\rho(k_2)V_3^\nu(k_3) = -ig_{V_1V_2V_3}[g^{\mu\nu}(k_1 - k_2)^\rho + g^{\nu\rho}(k_2 - k_3)^\mu + g^{\rho\mu}(k_3 - k_1)^\nu],$$

(8)

The coefficients $g_{V_1V_2V_3}$ are given as:

$$g_{A_LW_L^+W_H^-} = g_{A_LW_H^+W_L^-} = -e, \quad g_{A_LW_L^+W_H^-} = 0,$$

(9)

Compared with the process $e^-\gamma \rightarrow \nu eW^-H$ in the SM, this process in the LH model receives additional contributions from the heavy boson $W_{H}^\pm$, proceed through the Feynman diagrams depicted in Fig1. Furthermore, the modification of the relations among the SM parameters, the precision electroweak input parameters, the correction terms to the SM $W\nu e$ and $WWH$ coupling can also produce corrections to this process.

In order to write a compact expression for the amplitudes, it is necessary to define the triple-boson couplings coefficient as:

$$\Gamma^{\alpha\beta\gamma}(p_1,p_2,p_3) = g^{\alpha\beta}(p_1 - p_2)^\gamma + g^{\beta\gamma}(p_2 - p_3)^\alpha + g^{\gamma\alpha}(p_3 - p_1)^\beta,$$

(10)
with all momenta out-going. The invariant production amplitudes of the process can be written as:

\[ M = M^a + M^b + M^c, \]  

with

\[
M_a = [AG^{\mu\nu}(p_1 - p_3, M_{W_L}) + BG^{\mu\nu}(p_1 - p_3, M_{W_H})] \bar{\nu}_e(p_3)\gamma^{\mu}(1 - \gamma^5)u_e(p_1)
\]

\[
G^{\mu\alpha}(p_2 - p_4, M_{W_L})\Gamma^{\alpha\beta\gamma}(p_2 - p_4, -p_2, p_4)\varepsilon^\rho(p_2)\varepsilon^\sigma(p_4)
\]

\[
M_b = [AG^{\mu\nu}(p_4 + p_5, M_{W_L}) + BG^{\mu\nu}(p_4 + p_5, M_{W_H})] G(p_1 + p_2)
\]

\[
\bar{\nu}_e(p_3)\gamma^{\mu}(1 - \gamma^5)\gamma^\rho u_e(p_1)\varepsilon^\rho(p_2)\varepsilon^\sigma(p_4)
\]

\[
M_c = [AG^{\mu\nu}(p_1 - p_3, M_{W_L})G^{\rho\sigma}(p_4 + p_5, M_{W_L}) + BG^{\mu\nu}(p_1 - p_3, M_{W_H})G^{\rho\sigma}(p_4 + p_5, M_{W_H})] \]

\[
\bar{\nu}_e(p_3)\Gamma^{\rho\sigma\alpha}(p_2 - p_4 - p_5, -p_2, p_4 + p_5)\gamma^{\mu}(1 - \gamma^5)u_e(p_1)\varepsilon^\alpha(p_2)\varepsilon^\sigma(p_4)
\]

\[
A = \frac{e^4v}{4\sqrt{2}s_W^3} [1 - \frac{v^2}{2f^2}(c^2 - s^2)] [1 - \frac{v^2}{f^2} \frac{1}{3} - \frac{1}{2}(c^2 - s^2)^2 + \frac{3fx}{v}],
\]

\[
B = \frac{e^4v}{8\sqrt{2}s_W^3} \frac{(c^2 - s^2)}{s^2}
\]

Here, \( G^{\mu\nu}(p, M) = \frac{-ig^{\mu\nu}}{p^2 - M^2} \) is the propagator of the particle.

We can see that one source of the corrections of the littlest Higgs model to the process arises from the new heavy gauge bosons \( W_H^\pm \). On the other hand, the littlest Higgs model can generate the correction to the mass of gauge boson W in the SM and to the tree-level coupling vertices, which can also produce the correction to the process. In our numerical calculation, we will also take account of such correction effect.

The hard photon beam of the \( e\gamma \) collider can be obtained from laser backscattering at the \( e^+ e^- \) linear collider. Let \( \hat{s} \) and \( s \) be the center-of-mass energies of the \( e\gamma \) and \( e^+ e^- \) systems, respectively. After calculating the cross section \( \sigma(\hat{s}) \) for the subprocess \( e^- \gamma \to \nu_e W^- H \), the total cross section at the \( e^+ e^- \) linear collider can be obtained by folding \( \sigma(\hat{s}) \) with the photon distribution function that is given in Ref [18]:

\[
\sigma(\text{tot}) = \int_{(M_W + M_H)^2/s}^{x_{\text{max}}} dx \sigma(\hat{s}) f_\gamma(x),
\]

where

\[
f_\gamma(x) = \frac{1}{D(\xi)} [1 - x + \frac{1}{1 - x} - \frac{4x}{\xi(1 - x)} + \frac{4x^2}{\xi^2(1 - x)^2}],
\]
with
\[
D(\xi) = \left(1 - \frac{4}{\xi} - \frac{8}{\xi^2}\right)\ln(1 + \xi) + \frac{1}{2} + \frac{8}{\xi} - \frac{1}{2(1 + \xi)^2},
\] (16)

In the above equation, \(\xi = 4E_e\omega_0/m_e^2\) in which \(m_e\) and \(E_e\) stand, respectively, for the incident electron mass and energy, \(\omega_0\) stands for the laser photon energy, and \(x = \omega/E_e\) stands for the fraction of energy of the incident electron carried by the backscattered photon. \(f_\gamma\) vanishes for \(x > x_{max} = \omega_{max}/E_e = \xi/(1 + \xi)\). In order to avoid the creation of \(e^+e^-\) pairs by the interaction of the incident and backscattered photons, we require \(\omega_0x_{max} \leq m_e^2/E_e\), which implies that \(\xi \leq 2 + 2\sqrt{2} \simeq 4.8\). For the choice of \(\xi = 4.8\), we obtain
\[
x_{max} \approx 0.83, \quad D(\xi_{max}) \approx 1.8.
\] (17)

For simplicity, we have ignored the possible polarization for the electron and photon beams.

In the calculation of \(\sigma(\hat{s})\), instead of calculating the square of the amplitudes analytically, we calculate the amplitudes numerically by using the method of the references[19]. This greatly simplifies our calculation.

3 The numerical results and discussions

In the LH model, the relation among the Fermi coupling constant \(G_F\), the gauge boson W mass \(M_W\) and the fine structure constant \(\alpha\) can be written as[20]:
\[
\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{2M_W^2 s_W^2} \left[1 - c^2(c^2 - s^2)\frac{v^2}{f^2} + 2c^2 v^2 \frac{f^2}{f^2} - \frac{5}{4}(c^2 - s^2)\frac{v^2}{f^2}\right]
\] (18)

So we have
\[
\frac{e^2}{s_W^2} = \frac{4\sqrt{2}G_F M_W^2}{\left[1 - c^2(c^2 - s^2)\frac{v^2}{f^2} + 2c^2 v^2 \frac{f^2}{f^2} - \frac{5}{4}(c^2 - s^2)\frac{v^2}{f^2}\right]}
\] (19)

In the following numerical calculation, we take the input parameters as \(G_F = 1.16637 \times 10^{-5}\,\text{GeV}^{-2}\), \(M_Z^{SM} = 91.18\,\text{GeV}\), \(s_W^2 = 0.2315\) and \(M_W = 80.45\,\text{GeV}\) [21]. For the light Higgs boson \(H\), in this paper, we only take the illustrative value \(M_H = 120\,\text{GeV}\). The value of the relative correction parameter is insensitive to the degree of the electron and positron polarization and the c.m. energy \(\sqrt{s}\). Therefore, we do not consider the polarization of the initial states and take \(\sqrt{s} = 500\,\text{GeV}\) in our numerical calculation. There are four parameters, \(f, c, c', x\), involved
in the expression of the relative correction parameter \( \delta \sigma / \sigma^{SM} \) with \( \delta \sigma = |\sigma^{\text{tot}} - \sigma^{SM}| \) and \( \sigma^{SM} \) is the tree-level cross section of \( e^-\gamma \rightarrow \nu_e W^- H \) production predicted by the SM. In the LH model, the custodial \( SU(2) \) global symmetry is explicitly broken, which can generate large contributions to the electroweak observables. However, if we carefully adjust the \( U(1) \) section of the theory the contributions to the electroweak observables can be reduced and the constraints become relaxed. The scale parameter \( f = 1 \sim 2 \text{ TeV} \) is allowed for the mixing parameters \( c \) and \( c' \) in the ranges of \( 0 \sim 0.5, 0.62 \sim 0.73 \) [22]. In order to obtain the correct EWSB vacuum and avoid giving a TeV-scale VEV to the scalar triplet \( \phi \), we should have that the value of parameter \( x = 4f v'/v^2 \) is smaller than 1 [15, 22]. The numerical results are summarized in Figs.(2-4)

\[
\text{Figure 2: The relative correction } \delta \sigma / \sigma^{SM} \text{ as a function of the mixing parameter } c \text{ for } f=1 \text{ TeV, } x=0.1 \text{ and three values of the mixing parameter } c'.
\]

The relative correction \( \delta \sigma / \sigma^{SM} \) is plotted in Fig.2 as a function of the mixing parameter \( c \) for \( f=1 \text{ TeV, } x=0.1 \) and \( c' = 0.65, 0.68, 0.72 \) respectively. From Fig.2, we can see that the relative correction \( \delta \sigma / \sigma^{SM} \) increases with the mixing parameter \( c \) increasing and sensitive to the mixing parameter \( c' \). For \( x(4f v'/v^2)=0.1 \), the value of the relative correction \( \delta \sigma / \sigma^{SM} \) is larger than 9% in all of the parameter space preferred by the electroweak precision data. When the mixing parameter \( c \) gets close to 0.5, the value of the relative correction \( \delta \sigma / \sigma^{SM} \) is larger than 20% in most of the parameter space in the LH model.
To see the dependence of relative correction on the parameter \( c' \), in Fig.3, we plot \( \delta \sigma/\sigma^{SM} \) as a function of the mixing parameter \( c' \) for \( f=1\text{TeV}, \ x=0.1 \), and three values of the mixing parameter \( c \). We can see that the relative correction decreases slowly as the mixing parameter \( c' \) and is also sensitive to the mixing parameter \( c \). In most of the parameter space of the LH model, the value of \( \delta \sigma/\sigma^{SM} \) is larger than 10\%, which might be detected in the future LC experiments.

In Fig.4, we plot \( \delta \sigma/\sigma^{SM} \) as a function of the parameter \( x(x = 4f' v'/v^2 < 1) \) for three values of the scale parameter \( f(f=1, 1.5, 2\text{TeV}) \) and take \( c = 0.3, c' = 0.68 \). One can see that the relative correction increases with the value of parameter \( x \) increasing. This is because the contribution of littlest Higgs model not only comes from new gauge bosons \( W_H \) but also comes from correction to the couplings vertices of SM gauge boson and Higgs boson. For the fixed \( f, c \) and \( c' \), the correction cross section \( \delta \sigma \) mainly proportional to the factor \( 3xf'/v \) at the order of \( v^2/f^2 \), which come from the coupling vertices of \( W_LW_LH \) in the LH model. As long as \( c > 0.1 \), the value of \( \delta \sigma/\sigma^{SM} \) is larger than 10\% in most of the parameter space of the LH model. On the other hand, we can see that the value of \( \delta \sigma/\sigma^{SM} \) decreases as \( f \) increasing, which is consistent with the conclusions for the corrections of the LH model to other observables.

As has been mentioned above, the value of the relative correction is larger than 10\% in

Figure 3: The relative correction \( \delta \sigma/\sigma^{SM} \) as a function of the mixing parameter \( c' \) for \( f=1 \text{ TeV}, x = 0.1 \text{ GeV} \) and \( c=0.1 \) (dotted line), 0.3 (dashed line) and 0.5 (solid line).
most of the parameter space preferred by the electroweak precision data, the cross section of $e^-\gamma \to \nu_e W^- H$ can amounts to about $10^3$ events with the integrated luminosity of $100\,fb^{-1}$. The $1\sigma$ statistical error corresponds to about 1% precision. So, such correction might be detected via $e\gamma$ collisions in future LC experiment with $\sqrt{s}=500$ GeV and $\mathcal{L} = 100\,fb^{-1}$.

Figure 4: The relative correction $\delta\sigma/\sigma^{SM}$ as a function of the the parameter $x(x = 4f'v'/v^2 < 1)$ for $c = 0.3$, $c' = 0.68$ and three values of the scalar parameter $f$.

4 Conclusion

The little Higgs model, which can solve the hierarchy problem, is a promising alternative model of new physics beyond the standard model. Among the various little Higgs models, the littlest Higgs model is one of the simplest and phenomenologically viable models. The distinguishing feature of this model is the existence of the new scalars, the new gauge bosons, and the vector-like top quark. These new particles contribute to the experimental observables, which could provide some clues of the existence of the littlest Higgs model. In this paper, we study the potential to detect the contribution of the littlest Higgs model via the process $e^-\gamma \to \nu_e W^- H$ at the future LC experiments.

In the parameter spaces($f = 1 \sim 2$ TeV, $c = 0 \sim 0.5$, $c' = 0.62 \sim 0.73$) limited by the electroweak precision data, we calculate the cross section correction of the littlest Higgs model.
to the process $e^-\gamma \rightarrow \nu_e W^- H$. We find that the correction is significant even when we consider the constraint of electroweak precision data on the parameters. In most of parameter space, the relative correction can be over 10%, which can be seen as the new signals of light Higgs boson and should be detected via this process at the future LC experiment. The littlest Higgs model is a weak interaction theory and it is hard to detect its contributions and measures its couplings at the LHC. With the high c.m. energy and luminosity, the future $LC$ experiment will open an ideal window to probe into the littlest Higgs model and study its properties. With the relative correction over 10% of the littlest Higgs model, we believe that the process $e^-\gamma \rightarrow \nu_e W^- H$ can provide us significant signal of the LH model at future $LC$ experiment.
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