The correction of the littlest Higgs model to the Higgs production process \( e^+e^- \rightarrow e^+e^-H \) at the ILC

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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 model, we study the process \( e^+e^- \rightarrow e^+e^-H \) at the ILC and calculate the correction of the littlest Higgs model to the cross section of this process. The results show that, in the favorable parameter spaces preferred by the electroweak precision data, the value of the relative correction is in the range from a few percent to tens percent. In most case, the correction is large enough to reach the measurement precision of the ILC. Therefore, the correction of the littlest Higgs model to the process \( e^+e^- \rightarrow e^+e^-H \) might be detected at the ILC 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 the Higgs boson mass suffers from an instability under radiative corrections in the SM. The natural 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 and the elucidation of the symmetry breaking mechanism 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 GeV $\sim$ 208 GeV at 95% CL [5]. While the discovery of the Higgs at the LHC has been established for a wide range of Higgs masses, only rough estimates on its properties will be possible, through measurements on the couplings of the Higgs to the fermions and gauge boson for example [9]. The most precise measurements will be performed in the clean environment of the future high energy $e^+ e^-$ linear collider, the International Linear Collider (ILC) with the center of mass (c.m.) energies $\sqrt{s} = 300$ GeV-1.5 TeV [10] and the yearly luminosity 500 $fb^{-1}$. At low energy, the main production processes of
the Higgs boson at linear collider experiments are the Higgs-strahlung process $e^+e^- \rightarrow ZH$ and the $WW$ fusion process $e^+e^- \rightarrow \nu\bar{\nu}H$ and the latter is dominant in the large parameter space. These two processes have been studied in the context of the SM [11] and the littlest Higgs model [12]. With the c.m. energy increasing, the cross section of the process $e^+e^- \rightarrow e^+e^-H$ increases significantly. So, at the ILC, such process becomes a welcome addition with a cross section about 20 fb which excesses that of $ZH$ production around 1TeV. With the large cross section at TeV scale, the ILC will open a promising window to probe Higgs and precisely determinate the $ZZH$ coupling via the process $e^+e^- \rightarrow e^+e^-H$. The calculation of the complete electroweak correction to the process is performed in detail in the reference [13]. If the Higgs boson is light, a few percent measurement precision can be reached at the ILC [10]. The purpose of this paper is to calculate the correction of the littlest Higgs model to the process $e^+e^- \rightarrow e^+e^-H$ and see whether the effect on this process can be observed at the future ILC experiments.

This paper is organized as follows. In section two, we first briefly introduce the littlest model, and then give the production amplitude of the process. 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 $e^+e^- \rightarrow e^+e^-H$

The littlest model is based on the a $SU(5)/SO(5)$ 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 breaking 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 $W_{H}^\pm$, which might produce the characteristic signatures at the present and future high energy collider experiments [14,15,16].

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 \(W_L^\pm\) observed at experiments, and new heavy bosons \(Z_H, B_H\) and \(W_H^\pm\) that could be observed at future experiments. The neutral gauge boson masses are given to leading order by \[1\] 
\[
M_{Z_L}^2 = (M_Z^{SM})^2 \left\{ 1 - \frac{v^2}{f^2} \left[ \frac{1}{6} + \frac{1}{4} (c^2 - s^2)^2 + \frac{5}{4} (c^2 - s^2)^2 + \frac{\chi^2}{2} \right] \right\},
\]
\[
M_{W}^2 = (M_W^{SM})^2 \left( \frac{f^2}{s^2 c^2 v^2} - 1 - \frac{x_H s_W^2}{s^2 c^2 c_W^2} \right),
\]
\[
M_{B_H}^2 = (M_B^{SM})^2 s_W^2 \left( \frac{f^2}{5 s^2 c^2 v^2} - 1 + \frac{x_H c_W^2}{4 s^2 c^2 s_W^2} \right),
\]
with \(\chi = \frac{4 f v'}{v}, x_H = \frac{5}{2} g g' \frac{s^2 c^2 (c^2 + s^2 c^2)}{g g' s^2 c^2 - g' s^2 c^2},\) where \(v = 246 \text{ GeV}\) 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. The parameter \(\chi < 1\) parametrizes the ratio of the triple and doublet vacuum expectation values. In the following calculation, we will take \(\chi = 0.5\).

Taking account of the gauge invariance of the Yukawa coupling and the \(U(1)\) anomaly cancellation, we can write the couplings of the neutral gauge bosons \(V_i (V_i = Z_L, B_H, Z_H)\) to a pair of electrons in the form \(\lambda_{\mu}^{\nu \bar{e} e} = i g_{V^{\nu \bar{e} e}} + g_{A}^{\nu \bar{e} e} \gamma_5\) and denote the couplings of two gauge bosons to Higgs as \(\lambda_{\mu \nu}^{H V_i V_j}\). \(g_{V^{\nu \bar{e} e}}, g_{A}^{\nu \bar{e} e}\) and \(\lambda_{\mu \nu}^{H V_i V_j}\) can be written as \[1\] 
\[
g_{V^{\nu \bar{e} e}} = -\frac{e}{4 s_W c_W} \left\{ (-1 + 4 s_W^2) - \frac{v^2}{f^2} \left[ \frac{1}{2} c^2 (c^2 - s^2) - \frac{15}{2} (c^2 - s^2) (c^2 - \frac{2}{5}) \right] \right\},
\]
\[
g_{A}^{\nu \bar{e} e} = -\frac{e}{4 s_W c_W} \left\{ 1 + \frac{v^2}{f^2} \left[ \frac{1}{2} c^2 (c^2 - s^2) + \frac{5}{2} (c^2 - s^2) (c^2 - \frac{2}{5}) \right] \right\},
\]
\[
g_{V^{H Z_L}} = -\frac{e^2 v g_{\mu \nu}}{2 s_W c_W} \left\{ 1 - \frac{v^2}{f^2} \left[ \frac{1}{3} - \frac{3}{4} \chi^2 + \frac{1}{2} (c^2 - s^2)^2 + \frac{5}{2} (c^2 - s^2)^2 \right] \right\},
\]
\[
g_{V^{H Z_H}} = -\frac{e^2}{2 s_W} v g_{\mu \nu},
\]
\[
g_{A}^{H Z_H} = -\frac{e^2 (c^2 - s^2) v g_{\mu \nu}}{4 s_W c_W s c'},
\]
\[
g_{V}^{H Z_H} = -\frac{e^2 v g_{\mu \nu} (c^2 s^2 + s^2 c^2)}{4 s_W c_W c s c'},
\]
\[
\lambda_{\mu \nu}^{H Z_L B_H} = -\frac{e^2 v g_{\mu \nu}}{2 s_W},
\]
\[
\lambda_{\mu \nu}^{H Z_H B_H} = -\frac{e^2}{2 s_W} (c^2 - s^2) v g_{\mu \nu},
\]
\[
\lambda_{\mu \nu}^{H Z_L B_H} = -\frac{e^2 v g_{\mu \nu} (c^2 s^2 + s^2 c^2)}{4 s_W c_W c s c'},
\]
\[
\lambda_{\mu \nu}^{H B_H B_H} = -\frac{e^2}{2 s_W} v g_{\mu \nu},
\]
\[
\lambda_{\mu \nu}^{H Z_L B_H} = -\frac{e^2 (c^2 - s^2) v g_{\mu \nu}}{4 s_W c_W s c'},
\]
\[
\lambda_{\mu \nu}^{H Z_H B_H} = -\frac{e^2 v g_{\mu \nu} (c^2 s^2 + s^2 c^2)}{4 s_W c_W c s c'},
\]


The tree-level $e^+e^- \to e^+e^- H$ process is built up from the $s$-channel diagrams originating from $e^+e^- \to HV_i$ and the $t$-channel diagrams which are the fusion types. The relevant tree level Feynman diagrams of the process are shown in Fig.1.

The invariant production amplitudes of the process can be written as:

$$M = -\sum_{V_{i,j}=Z_L,Z_H,B_H} M_{V_iV_j}^a + \sum_{V_{i,j}=Z_L,Z_H,B_H} M_{V_iV_j}^b,$$

with

$$M_{V_iV_j}^a = \overline{u}_e(p_4) \gamma_\mu v_e(p_3) G^{\mu\rho}(p_4-p_2, M_{V_j}) \gamma_\rho v_e(p_1) \gamma_\nu u_e(p_3),$$

$$M_{V_iV_j}^b = \overline{u}_e(p_4) \gamma_\mu v_e(p_3) G^{\mu\rho}(p_3+p_4, M_{V_j}) \gamma_\rho v_e(p_1) \gamma_\nu u_e(p_2).$$

Here, $G^{\mu\nu}(p,M) = \frac{-ig^{\mu\nu}}{p^2-M^2}$ is the propagator of the particle. There is minus sign difference in the contributions of $s$-channel and $t$-channel diagrams. We can see that the one source of the corrections of the littlest Higgs model to the process arises from the new heavy gauge bosons $Z_H, B_H$. On the other hand, the littlest Higgs model can generate the correction to the mass of $Z$ boson 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 into account such correction effect. It should be noted that the masses of gauge bosons vary with the parameters $c$ and $c'$, and $M_{Z_H}^2$ can equal to $e^+e^-$ c.m. energy square $(p_1+p_2)^2$ for the certain values of parameters which will cause the $s$-channel resonance effect in Fig.1(b). For the gauge boson propagators of Fig.1(b) connecting outgoing $e^+e^-$, the time-like momentum can also hit the
light gauge boson pole which can also cause some resonance effect. In this case, we should take into account the effect of the widths of gauge bosons in the calculation. i.e., we should take the complex mass term \( M_{V_i}^2 - i M_{V_i} \Gamma_{V_i} \) instead of the simple gauge boson mass term \( M_{V_i}^2 \) in the gauge boson propagators. The \(-i M_{V_i} \Gamma_{V_i}\) term is important in the vicinity of the resonance. We can take \( \Gamma_{Z_L} = 2.4952 \text{ GeV} \) (the total experimental width of observed Z boson). The main decay modes of \( B_H \) and \( Z_H \) are \( V_i \rightarrow f \bar{f} \) (f represents any quarks and leptons in the SM) and \( V_i \rightarrow ZH \). The decay widths of these modes have been explicitly given in references \([14, 17]\).

With above production amplitudes, we can obtain the production cross section directly. In the calculation of the cross section, instead of calculating the square of the amplitudes analytically, we calculate the amplitudes numerically by using the method of the references \([18]\) which can greatly simplify our calculation.

### 3 The numerical results and discussions

The process \( e^+e^- \rightarrow e^+e^-H \) has been studied in the SM and the one-loop electroweak correction has been considered \([13]\). Because the t-channel contribution to the cross section rises depending on \( \text{Log}(s/M_{V_i}) \), the total cross section can reach the order of 10 fb with \( \sqrt{s} = 800 \text{ GeV} \). The electroweak correction is negative and in the range from \(-2\%\) to \(-4\%\). In this paper, we calculate the littlest Higgs correction to the process in the tree level.

In the numerical calculation, we take the input parameters as \( M_{Z}^{SM} = 91.187 \text{ GeV}, s_{W}^2 = 0.2315 \) \([19]\). For the light Higgs boson H, in this paper, we only take the illustrative value \( M_{H} = 120 \text{ GeV} \). The c.m. energy of the ILC is assumed as \( \sqrt{s} = 800 \text{ GeV} \). In the littlest Higgs model, there are three free parameters, \( f, c, c' \), involved in the production amplitude. 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 \( 0 \sim 0.5, 0.62 \sim 0.73 \) \([20]\). Taking into account the constraints on \( f, c, c' \), we take them as the free parameters in our numerical calculation. The numerical results are summarized in Figs.(2-4)
Figure 2: The relative correction $\delta \sigma/\sigma^{SM}$ as a function of the mixing parameter $c$ for $f=1$ TeV, $M_H = 120$ GeV and three values of the mixing $c'$. 

The relative correction $\delta \sigma/\sigma^{SM}$ is plotted in Fig.2 as a function of the mixing parameter $c$ for $f=1$ TeV, $c' = 0.64, 0.68, 0.72$ and $M_H = 120$ GeV, in which $\delta \sigma = \sigma^{tot} - \sigma^{SM}$ and $\sigma^{SM}$ is the tree-level cross section of $e^+e^-H$ production predicted by the SM. From Fig.2, we can see that the relative correction $\delta \sigma/\sigma^{SM}$ increases sharply when $c$ approaches 0.45. This is because in this range the mass of $Z_H$ may equal to the c.m. energy $\sqrt{s}$ (800 GeV) which can make the large s-channel resonance effect in Fig.1(b). The value of the relative correction varies in a wide range from a few percent to tens percent. There exists a special case that when $c' = \sqrt{2/5}$, the heavy photon $B_H$ has no contribution to the process because the coupling of the $B_H$ to the electrons vanishes.

To see the dependence of the relative correction on the parameter $c'$, in Fig.3, we plot $\delta \sigma/\sigma^{SM}$ as a function of the mixing parameter $c'$ for $f=1$ TeV, $M_H = 120$ GeV, and three values of the mixing parameter $c$. We can see that the relative correction decrease with the mixing parameter $c'$ increasing and is more sensitive to the parameter $c$. For $c > 0.3$, the value of $\delta \sigma/\sigma^{SM}$ is larger than 5%, which might be detected in the future LC experiments.

In general, the contributions of the littlest Higgs model to the observables are dependent on the factor $1/f^2$. To see the effects of $f$ and the Higgs mass on the cross section, in Fig 4, we plot $\delta \sigma/\sigma^{SM}$ as a function of $f$ for three values of Higgs mass($M_H = 120, 150, 180$ GeV) and
take $c = 0.4$, $c' = 0.68$. One can see that the relative correction drops sharply with $f$ increasing. For example, the relative correction is below 2% when $f = 2$ TeV. This case is similar to the contributions of the littlest Higgs model to other observables. On the other hand, the curves show that the relative correction is not sensitive to the Higgs boson mass.

In contrast to the electroweak correction, the correction of the littlest Higgs model is positive. Therefore, such significant positive correction is a definite signal of the new physics model. As has been mentioned above, the total cross section of $e^+ e^- \rightarrow e^+ e^- H$ can reach the order of 20 fb at the ILC. This cross section amounts to about $10^4$ events with the integrated luminosity of 1000 $fb^{-1}$. The 1σ statistical error corresponds to about 1% precision. Even we consider the systemic error of the ILC, the ILC can measure the cross section with a few percent precision[10] and the relative correction of the littlest Higgs model to the cross section is comparable to the ILC measurement precision. So, such correction might be detected at the ILC.

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

![Figure 3: The relative correction $\delta\sigma/\sigma^{SM}$ as a function of the mixing parameter $c'$ for $f=1$ TeV, $M_H = 120$ GeV and $c=0.1$(dotted line), 0.3(dashed line) and 0.4(solid line).]
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 $e^+e^- \rightarrow e^+e^-H$ at the future ILC 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 correction of the littlest Higgs model to the cross section of the process $e^+e^- \rightarrow e^+e^-H$. We find that the correction is significant even when we consider the constraint of electroweak precision data on the parameters. The contribution mainly comes from $t$-channel due to the high c.m. energy enhancing effect. But when $c$ approaches 0.45, the mass of heavy $Z_H$ can equal to the $e^+e^-$ c.m. energy which can cause the resonance effect arising from s-channel $Z_H$ propagator, and the correction sharply increases in this case. The relative correction varies from a few percent to tens percent. The littlest Higgs model is a weak interaction theory and it is hard to detect its contributions and measure its couplings at the LHC. With the high c.m. energy and luminosity, the future ILC will open an ideal window to probe into the littlest Higgs model and study its properties. In most case, the relative correction of the littlest model to the process $e^+e^- \rightarrow e^+e^-H$ is large enough for
people to measure the contribution of the model with the high precision at the ILC. Therefore, the process $e^+e^- \rightarrow e^+e^-H$ will open an ideal window to test the littlest Higgs model.
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