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

Xuelei Wang[1,2,a], Yaobei Liu[2], Jihong Chen[2], Hua Yang[3]

[1] CCAST (World Laboratory), P.O. BOX 8730, Beijing 100080, P.R. China
[2] College of Physics and Information Engineering, Henan Normal University, Xinxiang, Henan, 453007, P.R. China
[3] Department of Mathematics and Physics, College of Science, Information Engineering University, Zhengzhou, Henan, 450001, P.R. China

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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 $e^+e^- \to e^+e^-H$ 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 cases, the correction is large enough to reach the measurement precision of the ILC. Therefore, the correction of the littlest Higgs model to the process $e^+e^- \to e^+e^-H$ 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. A 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 [1–5], dynamical symmetry breaking [6], or extra dimensions [7–9]. Recently, a new model, known as the little Higgs model, has drawn a lot of interest and offers a very promising solution to the hierarchy problem in which the Higgs boson is naturally light as a result of a non-linearly realized symmetry [10–16]. 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 vacuum expectation value (VEV) at the 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 $SU(5)/SO(5)$ non-linear sigma model [16]. 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 ($B_{\rm H}, Z_{\rm H}, W_{\rm H}$) 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 boson. 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 symmetry breaking mechanism is one of the most important goals for present and future high energy collider experiments. The 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 [17, 18]. While the discovery of the Higgs boson at the LHC has been established for a wide range of Higgs masses, only rough estimates of its properties will be possible, through the measurements on the couplings of the Higgs boson to the fermions and gauge bosons for example [19]. 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 [20–23] and a yearly luminosity of 500 fb^{-1}. At the low energy, the main production processes of the Higgs boson at the linear collider experiments are the Higgs-strahlung process $e^+e^- \to ZH$ and the WW fusion process $e^+e^- \to \nu\bar{\nu}H$ and the latter is dominant in the large parameter spaces. These two processes have been studied in the context of the SM [24–30] and the littlest

[a] E-mail: wangxuelei@sina.com

Higgs model [31, 32]. With the c.m. energy increasing, the cross section of the process $e^+e^- \to e^+e^-H$ increases significantly. So, at the ILC, such a process becomes a welcome addition with the cross section about 20 fb which exceeds that of ZH production around 1 TeV. With a large cross section at the TeV scale, the ILC will open a promising window to probe the Higgs boson and precisely determine the ZZH coupling via the process $e^+e^- \to e^+e^-H$. The calculation of the complete electroweak correction to the process is performed in detail in [33, 34]. If the Higgs boson is light, a few percent measurement precision can be reached at the ILC [20–23]. The purpose of this paper is to calculate the correction of the littlest Higgs model to the process $e^+e^- \to e^+e^-H$ and to see whether the effect on this process can be observed at the future ILC experiments.

This paper is organized as follows. In Sect. 2, we first briefly introduce the littlest Higgs model, and then give the production amplitudes of the process. The numerical results and discussions are presented in Sect. 3. The conclusions are given in Sect. 4.

2 The littlest Higgs model and the production amplitudes of the process $e^+e^- \to e^+e^-H$

The littlest Higgs model is based on a $SU(5)/SO(5)$ non-linear sigma model. At the scale $\Lambda_s \sim 4\pi f$, the global $SU(5)$ symmetry is broken down to 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 σ model with the gauged symmetry $[SU(2)\times U(1)]^2$ which is spontaneously broken into 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 Φ. This breaking scenario also gives rise to four massive gauge bosons, B_H, Z_H and $W_\mathrm{H}^\pm$, which might produce the characteristic signatures at the present and future high energy collider experiments [35–41].

After the electroweak symmetry breaking, the mass eigenstates are obtained via the mixing between the heavy and light gauge bosons. They include the light (SM-like) bosons Z_L, A_L and $W_\mathrm{L}^\pm$ observed at experiments, and the new heavy bosons Z_H, B_H and $W_\mathrm{H}^\pm$ that could be observed at future experiments. The neutral gauge boson masses are given to leading order by [35]

$$M_{A_\mathrm{L}}^2 = 0\,, \tag{1}$$

$$M_{Z_\mathrm{L}}^2 = \left(M_Z^\mathrm{SM}\right)^2 \times\left\{1-\frac{v^2}{f^2}\left[\frac{1}{6}+\frac{1}{4}(c^2-s^2)^2+\frac{5}{4}(c'^2-s'^2)^2+\frac{\chi^2}{2}\right]\right\}, \tag{2}$$

$$M_{Z_\mathrm{H}}^2 = \left(M_\mathrm{W}^\mathrm{SM}\right)^2\left(\frac{f^2}{s^2c^2v^2}-1-\frac{x_\mathrm{H}s_\mathrm{W}^2}{s'^2c'^2c_\mathrm{W}^2}\right), \tag{3}$$

$$M_{B_\mathrm{H}}^2 = \left(M_Z^\mathrm{SM}\right)^2 s_\mathrm{W}^2\left(\frac{f^2}{5s'^2c'^2v^2}-1+\frac{x_\mathrm{H}c_\mathrm{W}^2}{4s^2c^2s_\mathrm{W}^2}\right), \tag{4}$$

with $\chi=\frac{4fv'}{v^2}$, $x_\mathrm{H}=\frac{5}{2}gg'\frac{scs'c'(c^2s'^2+s^2c'^2)}{5g^2s'^2c'^2-g'^2s^2c^2}$, where $v=246$ GeV is the electroweak scale, v' is the VEV of the scalar $SU(2)_\mathrm{L}$ triplet and s_W (c_W) represents the sine (cosine) of the Weinberg weak mixing angle. The parameter $\chi<1$ parametrizes the ratio of the triple and doublet VEV. 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 $V_i (V_i = Z_\mathrm{L}, B_\mathrm{H}, Z_\mathrm{H})$ to a pair of electrons in the form $\Lambda_\mu^{V_i\bar{e}e}=\mathrm{i}\gamma_\mu(g_V^{V_i\bar{e}e}+g_A^{V_i\bar{e}e}\gamma^5)$ and denote the couplings of two gauge bosons to Higgs boson as $\Lambda_{\mu\nu}^{HV_iV_j}$. $g_V^{V_i\bar{e}e}$, $g_A^{V_i\bar{e}e}$ and $\Lambda_{\mu\nu}^{HV_iV_j}$ can be written as [35]

$$g_V^{Z_\mathrm{L}\bar{e}e} = -\frac{e}{4s_\mathrm{W}c_\mathrm{W}}\left\{\left(-1+4s_\mathrm{W}^2\right)-\frac{v^2}{f^2}\left[\frac{1}{2}c^2(c^2-s^2) -\frac{15}{2}(c'^2-s'^2)\left(c'^2-\frac{2}{5}\right)\right]\right\}, \tag{5}$$

$$g_A^{Z_\mathrm{L}\bar{e}e} = -\frac{e}{4s_\mathrm{W}c_\mathrm{W}}\left\{1+\frac{v^2}{f^2}\left[\frac{1}{2}c^2(c^2-s^2) +\frac{5}{2}(c'^2-s'^2)\left(c'^2-\frac{2}{5}\right)\right]\right\}, \tag{6}$$

$$g_V^{Z_\mathrm{H}\bar{e}e} = -\frac{ec}{4s_\mathrm{W}s}\,,\quad g_A^{Z_\mathrm{H}\bar{e}e} = \frac{ec}{4s_\mathrm{W}s}\,, \tag{7}$$

$$g_V^{B_\mathrm{H}\bar{e}e} = \frac{e}{2c_\mathrm{W}s'c'}\left(\frac{3}{2}c'^2-\frac{3}{5}\right), \quad g_A^{B_\mathrm{H}\bar{e}e} = \frac{e}{2c_\mathrm{W}s'c'}\left(\frac{1}{2}c'^2-\frac{1}{5}\right), \tag{8}$$

$$\Lambda_{\mu\nu}^{HZ_\mathrm{L}Z_\mathrm{L}} = \frac{\mathrm{i}e^2vg_{\mu\nu}}{2s_\mathrm{W}^2c_\mathrm{W}^2}\left\{1-\frac{v^2}{f^2}\left[\frac{1}{3}-\frac{3}{4}\chi^2+\frac{1}{2}(c^2-s^2)^2 +\frac{5}{2}(c'^2-s'^2)^2\right]\right\}, \tag{9}$$

$$\Lambda_{\mu\nu}^{HZ_\mathrm{H}Z_\mathrm{H}} = -\frac{\mathrm{i}e^2}{2s_\mathrm{W}^2}vg_{\mu\nu}\,,\quad \Lambda_{\mu\nu}^{HB_\mathrm{H}B_\mathrm{H}} = -\frac{\mathrm{i}e^2}{2c_\mathrm{W}^2}vg_{\mu\nu}\,, \tag{10}$$

$$\Lambda_{\mu\nu}^{HZ_\mathrm{L}Z_\mathrm{H}} = -\frac{\mathrm{i}e^2(c^2-s^2)vg_{\mu\nu}}{4s_\mathrm{W}^2c_\mathrm{W}sc}, \quad \Lambda_{\mu\nu}^{HZ_\mathrm{L}B_\mathrm{H}} = -\frac{\mathrm{i}e^2(c'^2-s'^2)vg_{\mu\nu}}{4s_\mathrm{W}c_\mathrm{W}^2s'c'}, \tag{11}$$

$$\Lambda_{\mu\nu}^{HZ_\mathrm{H}B_\mathrm{H}} = -\frac{\mathrm{i}e^2vg_{\mu\nu}}{4s_\mathrm{W}c_\mathrm{W}}\frac{(c^2s'^2+s^2c'^2)}{scs'c'}. \tag{12}$$

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

$$M = -\sum_{V_{i,j}=Z_\mathrm{L},Z_\mathrm{H},B_\mathrm{H}} M_a^{V_iV_j} + \sum_{V_{i,j}=Z_\mathrm{L},Z_\mathrm{H},B_\mathrm{H}} M_b^{V_iV_j}\,, \tag{13}$$

with

$$\begin{aligned} M_a^{V_iV_j} &= \overline{u}_e(p_4)\Lambda_\mu^{V_j\bar{e}e}u_e(p_2)G^{\mu\rho}(p_4-p_2,M_{V_j})\\ &\quad\times \Lambda_{\rho\tau}^{HV_iV_j}G^{\tau\nu}(p_1-p_3,M_{V_i})\overline{v}_e(p_1)\Lambda_\nu^{V_i\bar{e}e}v_e(p_3)\,,\\ M_b^{V_iV_j} &= \overline{u}_e(p_4)\Lambda_\mu^{V_j\bar{e}e}v_e(p_3)G^{\mu\rho}(p_3+p_4,M_{V_j})\\ &\quad\times \Lambda_{\rho\tau}^{HV_iV_j}G^{\tau\nu}(p_1+p_2,M_{V_i})\overline{v}_e(p_1)\Lambda_\nu^{V_i\bar{e}e}u_e(p_2). \end{aligned}$$

Here, $G^{\mu\nu}(p,M)=\frac{-\mathrm{i}g^{\mu\nu}}{p^2-M^2}$ is the propagator of the particle. There is a minus sign difference in the contributions of the s-channel and t-channel diagrams. We can see that one source of corrections of the littlest Higgs model to the process arises from the new heavy gauge bosons $Z_\mathrm{H}, B_\mathrm{H}$. 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 a correction effect. It should be noted that the masses of gauge bosons vary with the parameters c and c', and $M^2_{Z_\mathrm{H}}$ can equal the e^+e^- c.m. energy squared $(p_1+p_2)^2$ for certain values of parameters which can cause the s-channel resonance effect in Fig. 1b. For the gauge boson propagators connecting the outgoing e^+e^- in Fig. 1b , the time-like momentum can also hit the light gauge boson pole which can also cause the 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 $M^2_{V_i}-\mathrm{i}M_{V_i}\Gamma_{V_i}$ instead of the simple gauge boson mass term $M^2_{V_i}$ in the gauge boson propagators. The $-\mathrm{i}M_{V_i}\Gamma_{V_i}$ term is important in the vicinity of the resonance. We can take $\Gamma_{Z_\mathrm{L}}=2.4952\,\mathrm{GeV}$ (the total experimental width of the observed Z boson). The main decay modes of B_H and Z_H are $V_i\to f\bar{f}$ (f represents all the quarks and leptons in the SM) and $V_i\to ZH$. The decay widths of these modes have been explicitly given in [35, 42].

With the 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 [43, 44], which can greatly simplify our calculation.

3 The numerical results and discussions

The process $e^+e^-\to e^+e^-H$ has been studied in the SM and the one-loop electroweak correction has been considered [33, 34]. Because the t-channel contribution to the cross section rises depending on $\log(s/M_{V_i})$, the total cross section can reach the order of 10 fb with $\sqrt{s}=800\,\mathrm{GeV}$. The electroweak correction is negative and in the range from -2% to -4%. In this paper, we calculate the correction of the littlest Higgs model to the process in the tree level.

In the numerical calculation, we take the input parameters as $M_Z^\mathrm{SM}=91.187\,\mathrm{GeV}$, $s^2_\mathrm{W}=0.2315$ [45, 46]. For the light Higgs boson H, in this paper, we only take the illustrative value $M_\mathrm{H}=120\,\mathrm{GeV}$. The c.m. energy of the ILC is assumed as $\sqrt{s}=800\,\mathrm{GeV}$. In the littlest Higgs model, there are three free parameters, f, c, c', involved in the production amplitudes. The custodial $SU(2)$ global symmetry is explicitly broken, which can generate the large contribution to the electroweak observables. However, if we carefully adjust the $U(1)$ section of the theory, the contribution to the electroweak observables can be reduced and the constraints become relaxed. The scale parameter $f=1\sim2\,\mathrm{TeV}$ is allowed for the mixing parameters c and c' in the ranges of $0\sim0.5$, $0.62\sim0.73$, respectively [47–49]. 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.

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

To see the dependence of the relative correction on the parameter c', in Fig. 3, we plot $\delta\sigma/\sigma^\mathrm{SM}$ as a function of

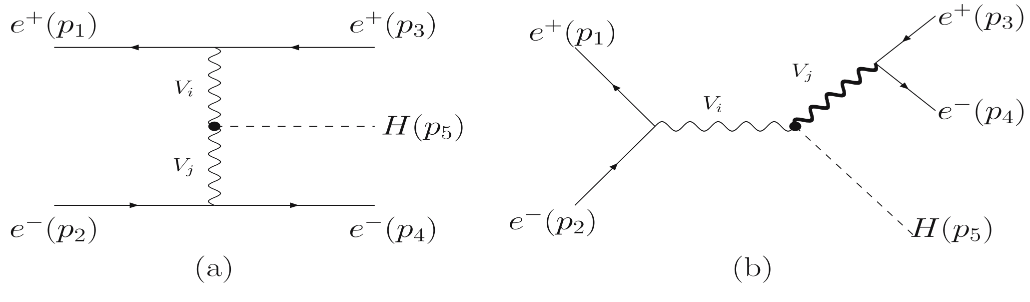

Fig. 1. Feynman diagrams of the process $e^+e^-\to e^+e^-H$ in the littlest Higgs model

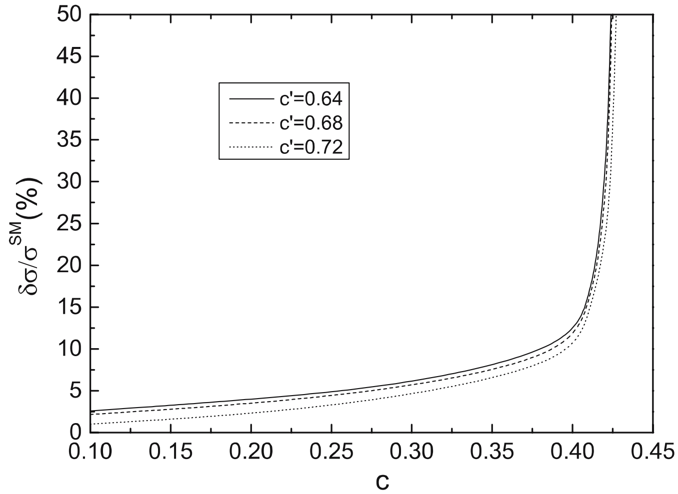

Fig. 2. The relative correction $\delta\sigma/\sigma^{\rm SM}$ as a function of the mixing parameter c for $f = 1$ TeV, $M_{\rm H} = 120$ GeV and three values of the parameter c'

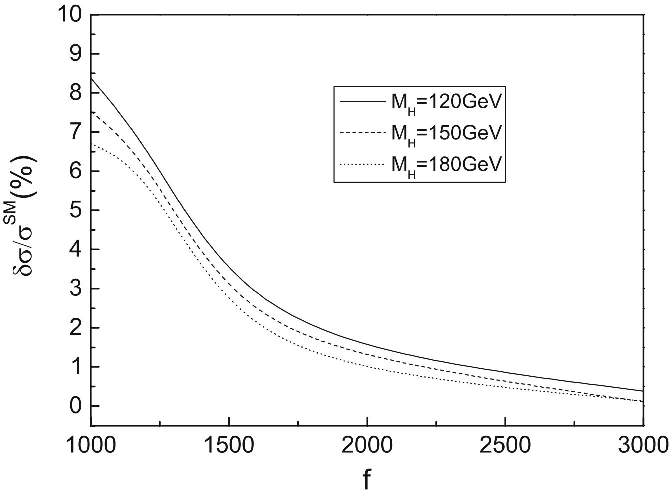

Fig. 4. The relative correction $\delta\sigma/\sigma^{\rm SM}$ as a function of the scale parameter f for $c = 0.4$, $c' = 0.68$ and three values of the Higgs boson mass

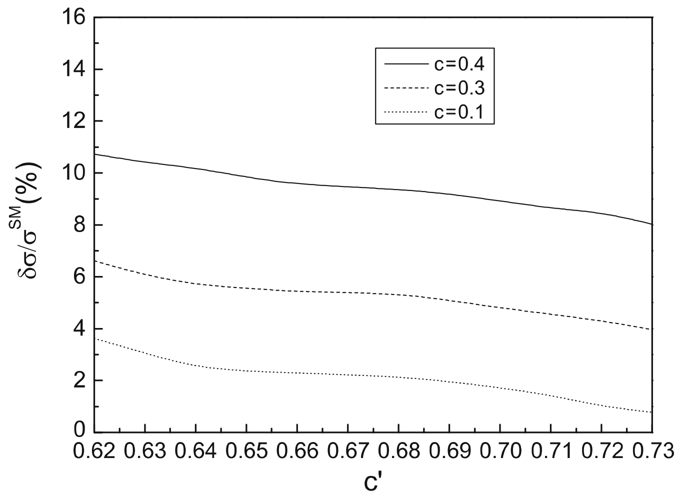

Fig. 3. The relative correction $\delta\sigma/\sigma^{\rm SM}$ as a function of the mixing parameter c' for $f = 1$ TeV, $M_{\rm H} = 120$ GeV and $c = 0.1$ (*dotted line*), 0.3 (*dashed line*) and 0.4 (*solid line*)

the parameter c' for $f = 1$ TeV, $M_{\rm H} = 120$ GeV, and three values of the parameter c. We can see that the relative correction decreases with c' increasing and is more sensitive to the parameter c. For $c > 0.3$, the value of $\delta\sigma/\sigma^{\rm SM}$ 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 effect of f and the Higgs mass on the cross section, in Fig. 4 we plot $\delta\sigma/\sigma^{\rm SM}$ as a function of f for three values of Higgs boson mass ($M_{\rm H} = 120$, 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. 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 a significant positive correction is a definite signal of the new physics model. As has been mentioned above, the total cross section of $e^+e^- \to e^+e^-H$ 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 when we consider the systemic error of the ILC, the ILC can measure the cross section with a few percent precision [20–23], and the relative correction of the littlest Higgs model to the cross section is comparable to the ILC measurement precision. So, such a correction might be detected at the ILC.

4 Conclusions

The little Higgs model, which can solve the hierarchy problem, is a promising alternative new physics 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 the clue of the littlest Higgs model. In this paper, we study the potential to detect the contribution of the littlest Higgs model via the process $e^+e^- \to e^+e^-H$ at the future ILC experiments.

In the parameter spaces ($f = 1 \sim 2$ TeV, $c = 0 \sim 0.5$, $c' = 0.62 \sim 0.73$) delimited by the electroweak precision data, we calculate the correction of the littlest Higgs model to the cross section of the process $e^+e^- \to e^+e^-H$. We find that the correction is significant even when we consider the constraint of the electroweak precision data on the parameters. The relative correction varies from a few percent to tens of percents. In the parameter space region outside the $Z_{\rm H}$ resonance vicinity, there should exist s-channel suppression at high energy; the contribution mainly comes from t-channel diagrams. The littlest Higgs model is a weak interaction theory and it is hard to detect its contribution 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 the littlest Higgs model and study its properties. In most cases, the relative correction of the littest model to the process $e^+e^- \to e^+e^-H$ is large enough to measure the contribution of the model with high precision at the ILC. Therefore, the process $e^+e^- \to e^+e^-H$ will open an ideal window to test the littlest Higgs model.

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