Higgs boson pair production process $e^+e^- \rightarrow ZHH$ in the littlest Higgs model at the ILC

Yaobei Liu$^a$, Linlin Du$^b$, Xuelei Wang$^b$

a: Henan Institute of Science and Technology, Xinxiang 453003, P.R.China

b: College of Physics and Information Engineering, Henan Normal University, Xinxiang 453007, P.R.China

March 26, 2022

Abstract

In this paper, we calculate the contribution of the littlest Higgs(LH) model to the process $e^+e^- \rightarrow ZHH$ at the future high energy $e^+e^-$ collider (ILC). The results show that, within the parameter spaces preferred by the electroweak precision, the deviation of the total cross sections from its SM value varies from a few percent to tens percent. The correction of the LH model to the process might be detected at the future ILC experiments in the favorable parameter space. On the other hand, we find that the correction of the LH model is sensitive to the trilinear Higgs coupling in some case and the process can also provide us a chance to probe such coupling in the LH model.

PACS number(s): 12.60Cn, 14.80.Mz, 12.15.Lk, 14.80.Cp

*E-mail:hnxxlyb2000@sina.com

†This work is supported in part by the National Natural Science Foundation of China(Grant No.10375017 and 10575029) and a grant from Henan Institute of Science and Technology(06040).
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. Among the extended models beyond the SM, the little Higgs model offers a very promising solution to the hierarchy problem in which the Higgs boson is naturally light as a result of nonlinearly realized symmetry [1, 2, 3]. The key feature of this kind of models 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 a scale of a few TeV and thus is naturally light.

The most economical little Higgs model is the littlest Higgs (LH) model, which is based on the $SU(5)/SO(5)$ nonlinear sigma model [4]. It consists of a $SU(5)$ global symmetry, which is spontaneously broken down to $SO(5)$ by a vacuum condensate $f$. In the LH 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 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. Measurement of these couplings would verify the structure of the cancelation of the Higgs mass quadratic divergence and prove the existence of the little Higgs mechanism [5].

The hunt for the Higgs boson and investigation of its properties is one of the most important goals of 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 114.4GeV-208GeV at 95% CL [6]. Studying the properties of the Higgs potential will reveal details of the mass-generation mechanism in spontaneously broken gauge theories, which can be obtained through measuring the Higgs boson self-interactions. Recently, the Higgs boson pair production processes have been widely considered, and the cross sections for these processes in the SM have been evaluated at linear colliders and hadron colliders. The phenomenology calculation show that it would be extremely difficult to measure the Higgs self-coupling $\lambda_{HHH}$ at the LHC [7], and $e^+e^-$ linear colliders, where the
study of the $e^+e^→ZHH$ and $HH\nu\nu$ can be performed with good accuracy, represent a possibly unique opportunity for performing the study of the trilinear Higgs self-coupling [8, 9, 10]. For the center of mass(c.m.) energy $\sqrt{s}$ from 500 GeV up to 1 TeV, the $ZHH$ production with intermediate Higgs boson mass is the most promising process among the various Higgs doublet-production processes. Since the cross section is relatively large and all the final states can be identified without large missing momentum, the process $e^+e^→ZHH$ is the best one among the various Higgs doublet-production processes to look for the Higgs self-coupling during the first stage of the future linear collider.

We know that the most important Higgs production process at the linear collider is the Higgs-strahlung process $e^+e^→ZH$. The correction effects of LH model to this process was studied in Ref.[11]. It is found that the correction effects mainly come from the heavy gauge boson $B_H$, in most parameter space, the deviation of the total cross section from its SM value is larger than 5%, which may be detected at the future ILC experiment. However, the double Higgs-strahlung process $e^+e^→ZHH$ includes the trilinear Higgs coupling which is different from the process $e^+e^→ZH$. For the process $e^+e^→ZHH$, the contribution of the LH model comes from not only the new heavy gauge bosons $B_H, Z_H$ but also the modification of the self-couplings of Higgs boson. So the process $e^+e^→ZHH$ can also provide some useful information about the modification of trilinear Higgs coupling in the LH model to complement the study of the process $e^+e^→ZH$. In this paper, we consider the double Higgs-strahlung process $e^+e^→ZHH$ and study whether the correction effects of LH model to this process can be detected at the future ILC experiment.

This paper is organized as follows, In section two, we first briefly introduce the LH model, and then give the production amplitude of the process. The numerical results and discussions are presented in section three. Our conclusions are given in section four.

2 The process $e^+e^→ZHH$ in the LH model

The LH model is based on the $SU(5)/SO(5)$ nonlinear sigma model. At the scale $Λ_s \sim 4\pi f$, the global $SU(5)$ symmetry is broken into its subgroup $SO(5)$ via a vacuum condensate $f$, re-
sulting 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 \( SU(2) \times U(1) \) which is 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 characteristic signatures in the present and future high energy collider experiments \([12, 13, 14]\).

After EWSB, the final 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 \( W^\pm_L \) observed at experiments, and new heavy bosons \( Z_H, B_H \) and \( W^\pm_H \) that could be observed at future experiments. The masses of neutral gauge bosons are given to \( \mathcal{O}(v^2/f^2) \) by \([15]\):

\[
M_{Z_L}^2 = 0, \\
M_{Z_H}^2 = (M_Z^{SM})^2 \left( 1 - \frac{v^2}{f^2} \right) \left( 1 + \frac{1}{4} (c^2 - s^2)^2 + \frac{5}{4} (c^2 - s^2)^2 - \frac{x^2}{2} \right), \\
M_{Z_H}^2 = (M_Z^{SM})^2 \left( \frac{f^2}{s^2 c^2 v^2} - 1 + \frac{2 v^2}{2 f^2} \frac{(c^2 - s^2)^2}{2 c_W^2} + \chi_H \frac{g' c^2 s^2 + c^2 s^2}{c'e's'} \right), \\
M_{B_H}^2 = (M_Z^{SM})^2 \left( \frac{f^2}{s^2 c^2 v^2} - 1 + \frac{2 v^2}{2 f^2} \frac{5 (c^2 - s^2)^2}{2 s_W^2} - \chi_H \frac{g' c^2 s^2 + c^2 s^2}{c'e's'} \right),
\]

with \( x = \frac{4 v'}{v} \), \( \chi_H = \frac{5}{2} g g' \frac{s_{x'} c (c^2 + s^2)}{s_{x'} c^2 - g' s_{x'}^2} \), where \( v = 246 \text{ GeV} \) is the electroweak scale, \( v' \) is the VEV of the scalar \( SU(2)_L \) triplet and \( s_W (c_W) \) represents the sine(cosine) of the weak mixing angle. \( c(s = \sqrt{1 - c^2}) \) is the mixing parameter between \( SU(2)_1 \) and \( SU(2)_2 \) gauge bosons and the mixing parameter \( c'(s' = \sqrt{1 - c^2}) \) comes from the mixing between \( U(1)_1 \) and \( U(1)_2 \) gauge bosons. Using these mixing parameters, we can represent the SM gauge coupling constants as \( g = g_1 s = g_2 c \) and \( g' = g_1 s' = g_2 c' \). The mass of neutral scalar boson \( M_{\Phi^0} \) can be given as \([12]\):

\[
M_{\Phi^0}^2 = \frac{2 m_{f_0}^2 f^2}{v^2 (1 - x^2)}.
\]

The above equation about the mass of \( \Phi \) requires a constraint of \( 0 \leq x < 1 \), which shows the relation between the scale \( f \) and the VEV of the Higgs field doublet and triplet(\( v, v' \)).

Taking account of the gauge invariance of the Yukawa couplings and the \( U(1) \) anomaly cancellation, one can write the couplings of the neutral gauge bosons \( V_i (V_i = Z_L, B_H, Z_H) \) to electrons pair in the form of \( \lambda_{\mu}^{\nu \bar{e} e} = i g_{\mu} (g_{V_i}^{\nu \bar{e} e} + g_{A}^{\nu \bar{e} e} \gamma^5) \) with \([12]\):

\[
g_{V_i}^{\nu \bar{e} e} = - \frac{e}{4 s_W c_W} \left\{ (-1 + 4 s_W^2) - \frac{v^2}{f^2} \frac{1}{2} c^2 (c^2 - s^2) - \frac{15}{2} (c^2 - s^2)(c^2 - \frac{2}{5}) \right\}.
\]
\[ g_{A}^{Z_{L}, e} = -\frac{e}{4sw_{W}} \left\{ 1 + \frac{v^{2}}{f^{2}} \frac{1}{2} c^{2} (c^{2} - s^{2}) + \frac{5}{2} (c^{2} - s^{2}) (c^{2} - \frac{5}{2}) \right\}; \]
\[ g_{V}^{Z_{H}, e} = -\frac{e c}{4sw_{W}}; \]
\[ g_{V}^{H_{L}, e} = \frac{e}{2sw_{s'}} \left( \frac{3}{2} c^{2} - \frac{3}{5} \right); \]
\[ g_{A}^{B_{L}, e} = \frac{e}{2sw_{s'} c'} \left( \frac{1}{2} c^{2} - \frac{1}{5} \right). \]

The couplings of the gauge bosons to Higgs boson and self-Higgs coupling can be written as

\[ g_{Z_{L}, Z_{H}, H}^{H} = \frac{ie^{2} v g_{\mu \nu}}{2sw_{W}^{2}} \left\{ 1 - \frac{v^{2}}{f^{2}} \frac{1}{3} - \frac{3}{4} c^{2} + \frac{1}{2} (c^{2} - s^{2})^{2} + \frac{5}{2} (c^{2} - s^{2})^{2} \right\}; \]
\[ g_{H_{L}, Z_{H}, H}^{H} = \frac{ie^{2}}{2sw_{W}} v g_{\mu \nu}; \]
\[ g_{Z_{L}, Z_{H}, H}^{H} = -\frac{ie^{2}}{4sw_{W}^{2} c} (c^{2} - s^{2}) v g_{\mu \nu}; \]
\[ g_{L_{L}, Z_{H}, H}^{H} = \frac{ie^{2}}{4sw_{W} s' c} (s^{2} c^{2} + s^{2} e^{2}); \]
\[ g_{Z_{L}, Z_{L}, H}^{H} = \frac{ie^{2}}{2sw_{W}^{2}} v g_{\mu \nu}; \]
\[ g_{H_{L}, B_{H}, H}^{H} = \frac{ie^{2}}{4sw_{W}^{2} s' c} (c^{2} - s^{2}) v g_{\mu \nu}; \]
\[ g_{L_{L}, B_{H}, H}^{H} = -\frac{ie^{2}}{2sw_{W}^{2}} v g_{\mu \nu}; \]
\[ g_{H_{H}, H}^{H} = -i3m_{H}^{2} \left( 1 - \frac{11v^{2} x^{2}}{4f^{2}(1 - x^{2})} \right). \]

In the LH model, the heavy triple Higgs boson \( \Phi^{0} \) exchange can also contribute to the process \( e^{+} e^{-} \rightarrow ZHH \). However, compared to the contributions coming from the new gauge bosons, the contribution of \( \Phi^{0} \) exchanging is suppressed by the order \( v^{4}/f^{4} \), which can be seen from the couplings between gauge bosons and scalars\[12\]. Thus, we can ignore the contribution of the scalar triplets to the process \( e^{+} e^{-} \rightarrow ZHH \).

The relevant Feynman diagrams for the process \( e^{+} e^{-} \rightarrow ZHH \) in the LH model are shown in Fig.1 at the tree-level.

The invariant production amplitudes of the process can be written as

\[ M = \sum_{V_{i}=Z_{L}, Z_{H}, B_{H}} M_{a}^{V_{i}} + \sum_{V_{i}, j=Z_{L}, Z_{H}, B_{H}} M_{b}^{V_{i}, V_{j}} + \sum_{V_{i}, j=Z_{L}, Z_{H}, B_{H}} M_{c}^{V_{i}, V_{j}} + \sum_{V_{i}=Z_{L}, Z_{H}, B_{H}} M_{d}^{V_{i}}, \]

with

\[ M_{a}^{V_{i}} = \mp_{c}(p_{1}) \wedge^{V_{i}, e} u_{c}(p_{2}) G^{\mu \nu}(p_{1} + p_{2}, M_{V_{i}}) \wedge^{H, HZV_{i}} v^{\rho}(p_{3}), \]
\[ M_{b}^{V_{i}, V_{j}} = \mp_{c}(p_{1}) \wedge^{V_{i}, e} u_{c}(p_{2}) G^{\mu \nu}(p_{1} + p_{2}, M_{V_{i}}) \wedge^{H, HZV_{j}} v^{\rho}(p_{3}), \]
\[ M_{c}^{V_{i}, V_{j}} = \mp_{c}(p_{1}) \wedge^{V_{i}, e} u_{c}(p_{2}) G^{\mu \nu}(p_{1} + p_{2}, M_{V_{i}}) \wedge^{H, HZV_{j}} v^{\rho}(p_{3}), \]
\[ M_{d}^{V_{i}} = \mp_{c}(p_{1}) \wedge^{V_{i}, e} u_{c}(p_{2}) G^{\mu \nu}(p_{1} + p_{2}, M_{V_{i}}) \wedge^{H, HZV_{i}} v^{\rho}(p_{3}). \]
Here, $G^{\mu\nu}(p, M) = \frac{-ig^{\mu\nu}}{p^2 - M^2}$ is the propagator of the particle. We can see that this process in the LH model receives additional contributions from the heavy gauge bosons $Z_H, B_H$. Furthermore, the modification of the relations among the SM parameters and the precision electroweak input parameters, the correction terms to the SM $HHH$ coupling can also produce corrections to this process. In our numerical calculation, we will also take into account these correction effects.

The main decay modes of $B_H$ and $Z_H$ are $V_i \rightarrow f \bar{f} (f \text{ represents any quarks and leptons in the SM})$ and $V_i \rightarrow ZH$. The decay widths of these modes have been explicitly given in references [12, 16].

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 [17] which can greatly simplify our calculation.
3 The numerical results and discussions

In the numerical calculation, we take the input parameters as $M_{Z_{SM}} = 91.187$ GeV, $s_W^2 = 0.2315$ [18]. For the light Higgs boson $H$, in this paper, we only take the illustrative value $M_H = 120$ GeV. In this case, the possible decay modes of $H$ are $b\bar{b}, c\bar{c}, l\bar{l}=[\tau, \mu \text{ or } e]$, $gg$ and $\gamma\gamma$. However, the total decay width $\Gamma_H$ is dominated by the decay channel $H \rightarrow b\bar{b}$. In the LH model, $\Gamma_H$ is modified from that in the SM by the order of $v^2/f^2$ and has been studied in Ref.[19]. The c.m. energy of the ILC is assumed as $\sqrt{s}=500$ GeV.

The absence of custodial $SU(2)$ global symmetry in the LH model yields weak isospin violating contributions to the electroweak precision observables. In the early study, global fits to the experimental data put rather severe constraints in the $f > 4$ TeV at 95% C.L.[20, 21]. However, their analysis is based on a simple assumption that the SM fermions are charged only under $U(1)_1$. If the SM fermions are charged under $U(1)_1 \times U(1)_2$, the constraints become relaxed: the substantial parameter space allows $f = 1 \sim 2$ TeV [22]. If only the $U(1)_Y$ is gauged, the experimental constraints are looser [22, 23]. Therefore, the new contributions are suppressed: $f = 1 \sim 2$ TeV allowed for the mixing parameters $c$ and $c'$ in the ranges of $0 \sim 0.5, 0.62 \sim 0.73$ [22, 24]. The parameter $x < 1$ parameterizes the ratio of the triplet and doublet VEV’s. Taking into account the constraints on $f, c, c', x$, we take them as the free parameters in our numerical calculation. The numerical results are summarized in Figs.(2-4).

The relative correction $\delta \sigma/\sigma^{SM}$ is plotted in Fig.2 as a function of the mixing parameter $c$ for $f=1$ TeV, $x = 0.5$, $M_H = 120$ GeV, $c' = 0.63, 0.67, 0.71$, respectively. In Fig.2, $\delta \sigma = \sigma^{tot} - \sigma^{SM}$ and $\sigma^{SM}$ is the tree-level cross section of the $ZHH$ production predicted by the SM. From Fig.2, we can see that the absolute value of the relative correction decreases with the mixing parameter $c$ increasing. For $x = 0.5$, the absolute value of $\delta \sigma/\sigma^{SM}$ is in the range of $8\% - 14\%$ in the most parameter space limited by the electroweak precision data. The curves also show that with an increase of the value of $c'$, the effect of the LH model is getting stronger. For $f < 3$ TeV, the mass of $B_{H}$ may be lighter than 500 GeV[14]. In most parameter spaces of the LH model, the mass of the heavy gauge boson $Z_{H}$ is larger than 1 TeV. So, there is no s-channel resonance effects in our numerical results.

To see the dependence of the relative correction on the parameter $x$, in Fig.3, we plot $\delta \sigma/\sigma^{SM}$ as a function of the mixing parameter $x$ for $c=0.3$, $c' = 0.67$ and three values of the
Figure 2: The relative correction $\delta \sigma / \sigma^{SM}$ as a function of the mixing parameter $c$ for $f = 1$ TeV, $x = 0.5$, $M_H = 120$ GeV and different values of the mixing parameter $c'$. Scale parameter $f$. From Fig.3 we can see that, the absolute value of the relative correction decreases as $f$ increasing. The curves also demonstrate that the effect of the LH model is not sensitive to $x$ in the range of $x \leq 0.75$. This is because the deviations of the cross section from the SM are mainly aroused by the contributions of the new gauge bosons when $x \leq 0.75$.

Figure 3: The relative correction $\delta \sigma / \sigma^{SM}$ as a function of the mixing parameter $x$ for $c = 0.3$, $c' = 0.67$, and $f = 1, 1.5, 2$ TeV, respectively.
However, the figure shows that the absolute values of $\delta \sigma / \sigma^{SM}$ raised quickly when we take the $x \to 1$ limit and in this case the main contribution to the cross section comes from the Feynman diagram involving the trilinear interaction of the SM Higgs boson, which is consistent with the conclusions for the contributions of the LH model to Higgs boson pair production at hadron colliders [25]. So, if $x$ is large enough the significant correction of the LH model to the trilinear Higgs coupling should be observable. The process $e^+e^- \to ZHH$ can open a unique window to probe the Higgs self-coupling which can complement the process $e^+e^- \to ZH$.

Figure 4: The relative correction $\delta \sigma / \sigma^{SM}$ as a function of the the scale parameter $f$ for $c=0.3$, $c' = 0.67$, $M_H = 120$ GeV, and three values of the mixing parameter $x$.

In general, the contributions of the LH model to the observables are dependent on the factor $1/f^2$. In order to obtain the generic conclusion, we also plot $\delta \sigma / \sigma^{SM}$ as a function of $f(1-3$ TeV) for three values of the parameter $x$ and take $c = 0.3$, $c' = 0.68$ in Fig 4. One can see that the absolute relative correction drops sharply with $f$ increasing, which is consistent with the conclusions for the corrections of the LH model to other observables. On the other hand, we can see that the absolute relative correction increases as the parameter $x$ increasing. For example, the absolute relative correction may reach about 20% when $x = 0.8$ and $f = 1$ TeV.

As has been mentioned above, the total cross section of $e^+e^- \to ZHH$ can reach the order of $10^{-1}$ fb at the ILC. This cross section amounts to about 100 events with the integrated luminosity of 1000 $fb^{-1}$. The 1σ statistical error corresponds to about 10% precision. The reference [26] have reviewed the expected experimental precision with which the ZHH cross
section can be measured. Even we consider the systemic error of the ILC, the ILC can measure the cross section with the precision of 17% assuming a 120 GeV Higgs and the integrated luminosity 1000 $fb^{-1}$ at 500 GeV. The sensitivity can be further improved when a multi-variable selection based on a neural network is applied which can reduce the uncertainty from 17% to 13%. The relative correction of the LH model to the cross section is only comparable to the ILC measurement precision and might be detected at the ILC in the favorable parameter spaces(for example, small value of $f$) preferred by the electroweak precision. The statistical accuracy to measure the trilinear Higgs coupling is 22% for $M_H = 120$ GeV with an integrated luminosity of 1000$fb^{-1}$, using the neural network selection[20]. Only for small $f$ and large $x$, the correction of the LH model to the trilinear Higgs coupling can be detected.

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 various little Higgs models, the littlest Higgs(LH) 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 LH model. In this paper, we study the potential to detect the contribution of the LH model via the process $e^+e^- \rightarrow ZHH$ 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 cross section correction of the LH model to the process $e^+e^- \rightarrow ZHH$. We find that the correction is significant even when we consider the constraint of electroweak precision data on the parameters. The relative correction varies from a few percent to tens of percents. The LH 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 LH model and study its properties. In some favorable case, the relative correction of the LH model to the process $e^+e^- \rightarrow ZHH$ might be large enough to be measured with high precision at the ILC.
Furthermore, the process can also open a unique window into the trilinear Higgs coupling in LH model.
References

[1] N. Arkani-Hamed, A. G. Cohen, and H. Georgi, *Phys. Lett.* B513, 232(2001).

[2] N. Arkani-Hamed, A. G. Cohen, T. Gregoire, and J. G. Wacker, *JHEP* 0208 020(2002); N. Arkani-Hamed, A. G. Cohen, E. Katz, A. E. Nelson, T. Gregoire, and J. G. Wacker, *JHEP* 0208 021(2002).

[3] I. Low, W. Skiba, and D. Smith, *Phys. Rev.* D66, 072001(2002); M. Schmaltz, *Nucl. Phys. Proc. Suppl.* 117, 40(2003); W. Skiba and J. Terning, *Phys. Rev.* D68, 075001(2003).

[4] N. Arkani-Hamed, A. G. Cohen, E. Katz, A. E. Nelson, *JHEP* 0207 034(2002).

[5] Wolfgang, Kilian, Jurgen Reuter, *Phys. Rev.* D70, 015004(2004).

[6] M. W. Grunewald, in the Proceedings of the Workingshop on Electroweak Precision Data and the Higgs Mass, [hep-ex/0304023](http://arxiv.org/abs/hep-ex/0304023). The LEP collaboratations, the LEP Electroweak Working Group and the SLD Heavy Flavour Group, [hep-ex/0412015](http://arxiv.org/abs/hep-ex/0412015).

[7] U. Baur, T. Plehn, D. Rainwater, *Phys. Rev. Lett.* 89, 151801(2002).

[8] V. Barger and T. Han *Mod, Phys. Lett.*, A5, 667(1999); A. Djouadi, W. Killian, M. Muhlleitner and P. M. Zerwas, *Eur.Phys.J.* C10, 27(1999); R. Casalbuon and L. Marconi, *J. Phys.* G29, 1053(2003).

[9] G. Belanger, *et al.*, [hep-ph/0309010](http://arxiv.org/abs/hep-ph/0309010), Zhang Ren-You, *et al.*, *Phys. Lett.* B578, 349(2004).

[10] M. Battaglia, E. Boss, W. M. Yao [hep-ph/011276](http://arxiv.org/abs/hep-ph/011276), A. Djouadi, W. Killian, M. Muhlleitner and P. M. Zerwas, [hep-ph/0001169](http://arxiv.org/abs/hep-ph/0001169).

[11] C. X. Yue, S. Z. Wang, D. Q. Yu, *Phys. Rev.* D68, 115004(2003).

[12] T. Han, H. E. Logan, B. McElrath, and L. T. Wang, *Phys. Rev.* D67, 095004(2003).

[13] G. Burdman, M. Perelstein, and A. Pierce, *Phys. Rev. Lett.* 90, 241802(2003); T. Han, H. E. Logan, B. McElrath, and L. T. Wang, *Phys. Lett.* B563, 191(2003); G. Azuelos et al., [hep-ph/0402037](http://arxiv.org/abs/hep-ph/0402037), H. E. Logan, *Phys. Rev.* D70, 115003(2004); G. Cho and A. Omete, *Phys. Rev.* D70, 057701(2004).
[14] S. C. Park and J. Song, *Phys. Rev.* D69, 115010(2004).

[15] J. A. Conley, J. Hewett, and M. P. Le, *Phys. Rev.* D72, 115014(2005).

[16] C. X. Yue, W. Wei, F. Zhang, *Nucl. Phys.* B716, 199(2005).

[17] K. Hagiwara and D. Zeppenfeld, *Nucl. Phys.* B313, 560(1989); V. Barger, T. Han, and D. Zeppenfeld, *Phys. Rev.* D41, 2782(1990).

[18] Particle Data Group, D. E. Groom *et al.*, *Eur.Phys.J.C* 15, 1(2000); Particle Data Group, K. Hagiwara *et al.*, *Phys. Rev.* D66, 010001(2002).

[19] J.J. Liu, W. G. Ma, G. Li, R. Y. Zhang, H. S. Hou, *Phys. Rev.* D70, 115001(2004); H. E. Logan, *Phys. Rev.* D70, 115003(2004); S. R. Choudhury, N. Gaur, A. Goyal, N. Mahajan, *Phys. Lett.* B601, 164(2004); Gi-Chol Cho and Aya Omote, *Phys. Rev.* D70, 057701(2004); G. A. Gonzalez-Sprinberg, R. Martinez, and J. Alexis Rodriguez, *Phys. Rev.* D71, 035003(2005).

[20] J. L. Hewett, F. J. Petriell and T. G. Rizzo, *JHEP* 0310 062(2003).

[21] C. Csaki, J. Hubisz, G. D. Kribs, P. Meade, and J. Terning, *Phys. Rev.* D67, 115002(2003).

[22] C. Csaki, J. Hubisz, G. D. Kribs, P. Meade, and J. Terning, *Phys. Rev.* D68, 035009(2003); T. Gregoire, D. R. Smith, and J. G. Wacker, *Phys. Rev.* D69, 115008(2004); I. Low, W. Skiba, and D. Smith, *Phys. Rev.* D66, 072001(2002).

[23] A. E. Nelson, [hep-ph/0304036](http://arxiv.org/abs/hep-ph/0304036) E. Katz, J. Katz. Lee, A. E. Nelson, and D. G. E. Walker, [hep-ph/0312287](http://arxiv.org/abs/hep-ph/0312287)

[24] R. Casalbuoni, A. Deandrea, M. Oertel, *JHEP* 0402 032(2004); S. Chang and H. J. He, *Phys. Lett.* B586, 95(2004); M. Chen and S. Dawson, *Phys. Rev.* D70, 015003(2004); W. Kilian and J. Reuter, *Phys. Rev.* D70, 015004(2004).

[25] J. J. Liu, W. G. Ma, G. Li, R. Y. Zhang, and H. S. Hou, *Phys. Rev.* D70, 015001(2004).
[26] TESLA Technical Design Report, Part III "Physics at an $e^+e^-$ Linear Collider", TESLA Report 2001-23, hep-ph/0106315; K. Abe et al.[ACFA Linear Collider Working Group], hep-ph/0109166; G. Laow et al., ILC Technical Review Committee, second report, 2003, SLAC-R-606.