THEORETICAL INTRODUCTION TO LINEAR COLLIDER PHYSICS *

YASUHIRO OKADA$^{1,2}$ †

$^1$ Institute of Particle and Nuclear Studies, KEK, Japan
$^2$ Department of Particle and Nuclear Physics, Graduate University of Advanced Studies, Japan

Abstract

Physics at an $e^+e^-$ linear collider is described as a theoretical introduction to Linear Collider Workshop 2002.

1 Introduction

There have been remarkable progresses in particle physics in the last century. New discoveries have changed our view on elementary particles and cosmology. In our current standpoint, goals of the elementary particle physics are not restricted to finding fundamental constitutes of matter and fundamental interactions. We have to address questions concerning the vacuum state of the Universe and the structure of space and time to understand the law of elementary particles. These issues are also closely related to questions like how the Universe have begun and evolved to today.

Current understanding of particle physics is based on the Standard Model (SM), which is a gauge theory of quarks and leptons. The gauge groups are $SU(3) \times SU(2) \times U(1)$: The $SU(3)$ group describes the strong interaction, and the $SU(2)$ and $U(1)$ groups correspond to the electromagnetic and the weak interactions.

---

*Talk given at International Workshop on Linear Colliders, August 26 - 30, 2002, Jeju Island, Korea. This work was supported in part by Grand-in-Aid for Scientific Research, (C) (No. 13640309).
†e-mail address: yasuhiro.okada@kek.jp
SM has been tested experimentally for the last three decades, and especially the gauge interaction among fermions and bosons has been studied very precisely at LEP and SLC experiments in 1990’s. The gauge structure of the SM is now well established experimentally.

The next important steps of the particle physics are:

• To establish the mechanism of the electroweak symmetry breaking and the particles’ mass generation.

• To find the physics scenario beyond the electroweak scale.

I would like to discuss how $e^+e^-$ linear collider (LC) experiments can play essential roles for these purposes. Studies of research potentials at an $e^+e^-$ LC have been carried out in world-wide, and its outcome is found in literatures, especially in recent reports [1, 2, 3].

2 Higgs physics

Higgs fields are introduced to break electroweak symmetry and generate masses for elementary particles. Although only one Higgs doublet field is necessary for this purpose, little is known about the structure of the Higgs sector. We do not know how many Higgs fields exists, whether there are fields other than weak doublet fields, and what is the mass of the Higgs particle. We have little information on couplings between the Higgs field and fermions/gauge bosons. We need the LC experiment to answer these questions.

2.1 Higgs boson mass

The Higgs boson mass is the most important parameter in the Higgs sector. Since particle mass is generated from interaction with the Higgs field in the SM, the mass of the particle carries information on the strength of its interaction to the Higgs field. This is also true for the Higgs boson mass itself. In particular, the Higgs-boson mass in the SM is expressed as $m_h = \sqrt{2\lambda v}$, where $\lambda$ is the Higgs self-coupling constant ($V = -\mu^2|\phi|^2 + \lambda|\phi|^4$). In general, a light Higgs boson corresponds to
weakly-coupled scenario for the mechanism of the electroweak symmetry breaking. Supersymmetry (SUSY), grand unified theory, and string unification are such examples. On the other hand, a heavy Higgs boson is a signal that some strong dynamics is behind the symmetry breaking.

The current experimental lower bond on the Higgs boson mass in the Standard Model is 114 GeV from LEP experiments at 95 % CL. On the other hand, from global analysis of the SM, we can derive the 95 % CL upper bound as 193 GeV [4]. Although this bound is valid for the SM Higgs boson, a weakly-coupled scenario is favored for the dynamics of the electroweak symmetry breaking.

If we introduce some theoretical assumption, a possible mass range of the Higgs boson can be derived. For instance, if the SM is assumed to be valid without any change, except for a possible see-saw mechanism for neutrino mass generation, the upper and lower bounds of the Higgs boson mass are determined as a function of the cut-off scale ($\Lambda$) of the theory. For $\Lambda = 10^{19}$ GeV of the Planck scale, the lower and upper bounds are about 130 GeV and 180 GeV, respectively. The Higgs sector of the minimal supersymmetric standard Model (MSSM) consists of two Higgs doublets. A remarkable feature of this model is that the upper bound of the lightest CP-even Higgs boson can be derived without reference to the cutoff scale. For reasonable choice of parameters in the model, especially the stop mass and mixing parameters, the bound is given by 130 GeV [5]. For other models like general two Higgs doublets and SUSY models with extended Higgs sectors, we can derive the mass range of a Higgs boson whose properties are similar to the SM Higgs boson, if the cutoff scale is specified [6, 7]. The mass range is shown in Figure 1 for various models in the case of $\Lambda = 10^{19}$ GeV. We can see that at least one Higgs boson must exist near or less that 200 GeV under this theoretical assumption.

The Higgs boson search is currently undertaken at Fermilab TEVATRON. With an integrated luminosity of 15 fb$^{-1}$, it will become evident whether or not a Higgs boson exists for a relatively small mass range like 120 GeV. One of main goals of the LHC experiment, which is scheduled to start in 2007, is the discovery of a Higgs boson, irrespectively of its mass. The Higgs boson discovery is relatively easy if its mass exceeds 200 GeV, because the $h \rightarrow ZZ \rightarrow llll$ mode is available. For a smaller Higgs boson mass, the Higgs boson search involves other modes such as two photon and $W(\ast)W(\ast)$ decay modes, and $t\bar{t}h$ production. It is believed that the discovery of a SM Higgs boson is possible at LHC experiments with a low integrated luminosity of an order of 10 fb$^{-1}$. In addition, recent studies of prospects of the Higgs physics at LHC show that useful information on Higgs coupling constants will be obtained.
Figure 1: Mass range of a Higgs boson for various models. The upper and lower bound of the Higgs boson mass is derived from an assumption that each model is valid up to the cut-off scale of the theory, which is taken to be $10^{19}$ GeV. For the MSSM case, the mass bound is obtained without reference to the cutoff scale.

in the era of a high luminosity run ($\gtrsim 100\text{fb}^{-1}$), especially for a relatively light Higgs boson. Higgs boson production processes through a vector boson fusion play an essential role for this purpose [8].

2.2 Higgs physics at linear collides

Goals of Higgs physics at LCs are to establish the mass-generation mechanism for elementary particles and to clarify the dynamics of the electroweak symmetry breaking. With an integrated luminosity of 500 fb$^{-1}$, over 100,000 light Higgs bosons can be produced at a LC, and precise information on various couplings related to the Higgs boson will be obtained from measurements of production cross section and decay branching ratios. The LC is a Higgs factory in this sense.

Production of Higgs bosons

For a LC with center-of-mass energy of up to 500 GeV, we can detect the SM Higgs boson up to 400 GeV. The discovery of a Higgs boson only requires an inte-
grated luminosity of a few fb\(^{-1}\), if the Higgs boson mass is less than 200 GeV. If we consider models beyond the SM, the production cross section and decay modes may be different from the SM. For example, the production cross section of the lightest CP-even Higgs boson can be reduced for the MSSM and the next-to-minimal supersymmetric standard model (NMSSM), where an additional gauge-singlet Higgs field is introduced to the MSSM. However we can show quantitatively that at least one of Higgs bosons has a production cross section in the \(e^+e^- \rightarrow Zh_i\) process which is smaller only by a factor of two or three than that of the SM Higgs boson. Therefore, discovery of a Higgs boson is guaranteed in these models \[9\].

**Spin and parity of the Higgs boson**

In order to confirm that the observed particle has right properties for the Higgs boson, we first have to determine its spin and parity. The LC experiment is necessary for unambiguous determination of these basic quantum numbers. We can distinguish the CP property of a spin-0 particle from the angular distribution of the production angle. Furthermore, an energy scan at the production threshold region provides enough information to discriminate the spin and parity of the observed particles \[10\]. An integrated luminosity of several ten’s fb\(^{-1}\) are necessary for these determinations.

**Mass-generation mechanism**

In the SM, all quarks, leptons and gauge bosons are massless, if there is no electroweak symmetry breaking. Masses of these particles are generated through interactions with the Higgs field, which is supposed to condense in the vacuum. Since the Higgs boson is a physical fluctuation mode around the vacuum expectation value, we need to determine the Higgs-fermion, Higgs-W-W, Higgs-Z-Z coupling constants, and compare them with values predicted from the masses of elementary particles, in order to test the mass generation mechanism. From the production cross sections of \(e^+e^- \rightarrow Zh\) and \(e^+e^- \rightarrow \nu\bar{\nu}h\) processes and Higgs decay branching ratios, these coupling constants can be determined precisely. For a Higgs boson mass of less than 140 GeV, the \(hWW\), \(hZZ\), \(hbb\), \(h\tau\tau\) coupling constants can be determined at accuracy of a few % level with an integrated luminosity of 500 fb\(^{-1}\) at \(\sqrt{s} = 300-500\) GeV \[1, 2, 3\]. We can also derive the total width of the Higgs boson with an error of 5 - 10 %. The top Yukawa coupling constant can be determined from \(e^+e^- \rightarrow t\bar{t}h\) production process, and the center-of-mass energy larger than 700 GeV is preferable for this purpose. In Figure 2, the mass and coupling constant relation is plotted for various particles. In general, the mass and coupling constant have a relation such as \(m_i = \kappa_i v\) in the SM, where \(v\) is the vacuum expectation value of the Higgs
field, and the $\kappa_i$ is a dimensionless coupling constant which can be obtained from a three-point coupling measurement. In this figure, the expected statistical error of each coupling measurement at LC experiments is shown for charm, $\tau$, bottom, W, Z, and top quark. For the Higgs boson, the error is derived from the measurement of the triple Higgs-boson coupling constant.

Figure 2: Test of mass-generation mechanism performed at LC experiments. Estimated statistical errors on $\kappa_i$ from Higgs boson couplings to various particles are shown, where $m_i = \kappa_i v$ holds in the SM. The Higgs boson mass is assumed to be 120 GeV. An integrated luminosity is 500 fb$^{-1}$ and the center-of mass energy is $\sqrt{s} = 300$ GeV except for the Higgs self-coupling ($\sqrt{s} = 500$ GeV) and the top Yukawa coupling ($\sqrt{s} = 700$ GeV) measurements.

**Higgs self-coupling constant**

The first information about the Higgs potential will be obtained from the measurement of the triple Higgs-boson coupling constant. For this purpose, we need to study double Higgs production processes, namely, $e^+e^- \rightarrow Zhh$ and $e^+e^- \rightarrow \nu\bar{\nu}hh$. 
In both of these processes, in addition to the diagram involving the triple Higgs-boson vertex, there are diagrams which only depend on vertexes with gauge bosons and Higgs boson(s). The production cross section is not simply proportional to the square of the self-coupling constant. For \( \sqrt{s} = 500 \text{ GeV} \), the \( e^+e^- \rightarrow Zhh \) has much larger cross section than the \( e^+e^- \rightarrow \nu\bar{\nu}hh \) process. For a higher energy, the production cross section of the latter process increases, which is an important future of the WW fusion process, whereas that for the former process decreases as \( 1/s \). For \( \sqrt{s} \gtrsim 1 \text{ TeV} \), the WW fusion process become more important for determination of the triple Higgs-boson coupling constant. It is expected that the sensitivity of the coupling measurement is about 20 (7) % for 1 (5) ab\(^{-1}\) at \( \sqrt{s} = 500 \) (3000) GeV [11]. The center-of-mass energy dependence of the estimated sensitivity on the coupling constant is shown in Figure 3, assuming 100 % efficiency for 1 ab\(^{-1}\) [12]. For \( \sqrt{s} \gtrsim 1 \text{ TeV} \), the sensitivity is further improved by using initial electron (and positron) polarization, because the production cross section of the WW fusion process is increased by a factor of 2 (4) with the electron (electron and positron) polarization.

![Figure 3](image.png)

Figure 3: Center-of-mass energy dependence of the sensitivity of the triple Higgs-boson coupling constant at LCs. The integrated luminosity is 1 ab\(^{-1}\) without efficiency corrections, without electron polarization (a) and with 100 % electron polarization (b) [12].
2.3 Study of the MSSM Higgs sector at LC

The study of the Higgs sector could also provide important information concerning possible new physics scenario. In particular, the MSSM has several characteristic features in the Higgs sector. First, the Higgs sector is a special type of a two Higgs doublet model. The physical Higgs modes contain two CP-even \( (h, H) \), one CP-odd \( (A) \), and one pair of charged Higgs bosons \( (H^\pm) \). There is a theoretical upper bound on the lighter CP-even Higgs boson \( h \), which is about 130 GeV. Since the form of the Higgs potential is restricted by the requirement of SUSY, the Higgs sector is parametrized by two parameters at the tree level, usually taken to be the CP-odd Higgs boson mass \( m_A \) and the ratio of the two vacuum expectation values \( \tan \beta \). Although the radiative correction to the Higgs potential introduces additional parameters like the stop mass, Higgs boson masses and couplings are very restrictive, and these features are useful in discriminating the MSSM from other models.

If only one of CP-even Higgs bosons is found at an earlier stage of the \( e^+e^- \) LC experiment and the LHC experiment, measurements of the coupling constants related to the Higgs boson can provide useful information on model parameters. For instance, the ratios of the branching ratios such as \( B(h \to WW)/B(h \to \tau\tau) \), \( B(h \to c\bar{c})/B(h \to \tau\tau) \) can be deviated from the SM prediction, if the heavy Higgs boson is not too heavy [3, 13, 14, 15, 16]. Indirect information on the heavy Higgs boson mass may be obtained for \( m_A \lesssim 600 \) GeV, as shown in Figure 4. On the other hand, \( B(h \to b\bar{b})/B(h \to \tau\tau) \) should be the same at the tree level in the MSSM as the SM prediction, but the deviation can be large due to SUSY loop corrections to the bottom Yukawa coupling constant, especially for a large \( \tan \beta \) [16, 17].

If the center-of-mass energy is large enough, heavy Higgs bosons can be produced directly. Contours of constant production cross sections \( (0.1 \text{ fb}^{-1}) \) for various processes in the case of \( \sqrt{s} = 500 \) and 1500 GeV are shown in the parameter space of \( m_A \) and \( \tan \beta \) for the MSSM in Figure 5 [18]. The discovery limit is essentially determined by the \( H-A \) and \( H^+-H^- \) pair production threshold except for limited regions of large and small \( \tan \beta \). However, heavy Higgs bosons can be seen in different modes depending on parameter regions. This will be useful to test the MSSM and to determine parameters of the model, especially \( \tan \beta \).

The photon-photon collider option of the LC can be especially important for the heavy Higgs searches. This is because that the s-channel single Higgs production
is possible through the photon-photon-Higgs boson coupling induced at one-loop level. Since the energy of the back-scattered photon can be 80% of the original electron beam, the heavy Higgs-boson mass reach can increase up to about 400 GeV for the 500 GeV collider. The discovery potential of the heavy Higgs boson at a photon-photon collider was investigated for $\sqrt{s_{ee}} = 630$ GeV, and it was shown that the photon-photon collider can cover the “wedge” of the MSSM parameter up to $m_A = 500$ GeV, where only one light Higgs boson is found at LHC [19]. The photon-photon collider is also useful to distinguish the CP property of the Higgs boson using transverse polarization and angular correlation of decay products ($H \to tt$, for instance) [20]. The mass reach is, however, reduced, if we utilize the transverse polarization.

3 Direct Search for New Physics

Although the SM is very successful so far, there are strong motivations to search for physics beyond it. First, the SM only deals with three of the four fundamental interactions, and the gravity is not included. Unification of all gauge interactions as well as gauge interactions with gravity can be addressed only in the context of
There are many theoretical proposals for physics beyond the SM. We can expect some signals at the TeV scale, if introduction of new physics is motivated to explain the separation between the weak scale and the Planck scale. SUSY and a scenario with large extra-dimensions are typical examples. In both case, we will be led to a conceptual change on space-time, if it is true.

3.1 Supersymmetry

Since the three gauge coupling constants determined at LEP and SLC experiments turned out to be consistent with the prediction of supersymmetric grand unified theory, unified models based on SUSY has been a prime candidate of the physics beyond the SM. In SUSY models, a superpartner is introduced for each of an ordinary particle. New particles include scalar partners of quarks and leptons (squarks and sleptons), fermionic superpartners (gluino, charginos, and neutralinos). The mass spectrum of these particles depends on SUSY breaking scenarios. Therefore, the experimental determination of the spectrum will point to a specific scenario. For
SUSY search, LHC experiments will provide a crucial test. In a typical mass spectrum such as one in the minimal supergravity model, colored SUSY particles up to 2 TeV can be discovered. In addition, a light Higgs boson should exist below about 130 GeV for the MSSM, which is an important check point for this model.

Roles of the LC experiment are not restricted to discovery of new SUSY particles. Masses, quantum numbers, and various couplings of SUSY particles will be measured in a good accuracy. Determination of these quantities without relying on some specific model of SUSY breaking is very important to test and establish a new symmetry principle of Nature. In many cases of SUSY studies, beam polarization can be a very useful tool. This is because SUSY is a symmetry between boson and fermion, so that spin information is important. Furthermore, the concept of chirality is extended to the squark and slepton sectors in SUSY, so that the initial electron polarization is very useful to distinguish left-handed or right-handed superparticles.

There are many issues to be addressed on SUSY at LCs.

- Determination of mass and spin of SUSY particles from decay energy distributions, production angle distributions, and threshold scans in pair production processes.
- Reconstruction of chargino and neutralino mass matrices from production cross sections and angular distributions with possible effects of CP violation [21].
- Determination of the selectron-electron-bino coupling through $e^+e^- \rightarrow \tilde{e}_R^+\tilde{e}_R^-$ for a test of a SUSY relation (Figure 6 (a)) [22].
- Search for lepton flavor violation in slepton pair production [23, 24].
- Test of the gaugino mass GUT relation (Figure 6 (b)) [25].

These measurements play important roles in determination of SUSY Lagrangian in a model-independent way, and proving SUSY.

In order to obtain a whole picture of a SUSY model, it is most likely that information from LHC and LCs has to be combined. For instance, the neutralino mass determined at a LC will provide an important input for the LHC analysis. Combining colored SUSY particle masses from LHC and slepton/chargino/neutralino masses from a LC, we may be able to figure out the origin of SUSY breaking [26].
Figure 6: Examples of SUSY studies at LCs: (a) Test of a SUSY relation from $e^+e^- \rightarrow \tilde{e}_R^+\tilde{e}_R^-$ [22]. (b) Test of the SU(2) and U(1) GUT relation from right-handed selectron and chargino production processes [25].

3.2 Large extra-dimensions

Recently, a scenario with a large extra-dimensions is proposed, motivated by string theory [27]. If there are extra-space dimensions where only gravity can propagate, the fundamental scale of gravity where all interactions are unified can be close to the weak scale. The smallness of the gravity can be attributed to the existence of the large extra-space, and the Planck scale of $10^{19}$ GeV is not a real physical scale. In this case there is no fundamental problem of hierarchy between the Planck and weak scales.

An interesting aspect of this scenario is that we can test this idea from collider experiments. Fairly model-independent signals of this scenario are emissions of Kaluza-Klein graviton modes ($e^+e^- \rightarrow \gamma G_{KK}$) and virtual graviton exchange in $e^+e^- \rightarrow f\bar{f}$ processes. The sensitivity of LC experiments can be comparable to the LHC search for extra-dimensions. The cross section of the graviton emission process depends on the fundamental scale and the number of extra-dimensions. For a larger number of extra-dimensions, the cross section rises more quickly. Experiments with different collider energies are useful to determine the number of dimensions. Figure 7 illustrates how we can determine the number of the extra-dimensions from experiments at LCs with two different center-of-mass energies [28]. If a signal is seen at one beam energy, the energy upgrade is useful to figure out the structure of
extra-space. By determination of the fundamental scale and the number of extra-dimension, we can also derive the size of extra-space. The information of the number of the extra-dimensions can be also obtained by the analysis of the differential cross section with a fixed center-of-mass energy.

![Graph showing the determination of the number of extra-dimensions at LCs with the center-of-mass energy of 500 and 800 GeV [28].](image)

Figure 7: Determination of the number of extra-dimensions at LCs with the center-of-mass energy of 500 and 800 GeV [28].

If some signals of the extra-space are available within the energy of the LC, thresholds of signals of strong gravity or string may be open at LHC. These signals include production of black holes and string resonance states. In order to establish a new picture of space-time, both LHC and LCs will be necessary.

4 Precision studies of top and gauge boson processes

The studies on the top quark and the W and Z bosons are guaranteed at the LC experiment. These studies provides fundamental parameters of the particle physics. In addition, we may be able to look for new physics effects from precise determination of anomalous coupling constants involving these particles.
The top quark is the heaviest particle observed so far. Its production and decay are only studies at TEVATRON. An $e^+e^-$ collider can provide a unique opportunity to scan the threshold region. We can determine the top quark mass at the level of accuracy of 100 MeV and less, and the width to a few % [29, 30]. The mass determination is improved by an order of magnitudes or more compared to LHC. The width measurement will be practically only possible at the threshold scan of an $e^+e^-$ collider. An example of the studies at the top production threshold is shown in Figure 8.

![Figure 8: Top quark threshold scan for determination of the top mass and width [31].](image)

The anomalous coupling measurements can be carried out at the threshold region as well as at the open-top-production region [32]. Anomalous couplings of the top and photon/Z boson include the top electric dipole moment which is induced by CP violation outside the SM. The accuracies of electronic dipole moments determinations are $10^{-19}$-$10^{-18}$ e cm, for instance. At LHC, information on the gluon anomalous coupling will be available.

Triple and quadratic anomalous couplings of gauge bosons will be also measured precisely at LCs. Although constraints on these coupling constants are already obtained by LEP and TEVATRON experiments, the higher energy and beam polarization are advantages of the LC experiment for this study. These measurements are particularly important when a light Higgs boson is not found at the LHC and LC experiments, in which case something is missing in our current understanding.
of the electroweak symmetry breaking. Sensitivities to triple gauge boson coupling constants $\kappa_V$ and $\lambda_V$ defined in $\mathcal{L}_{WWV}/g_W^2 = ig_1^V (W^\dagger_{\mu\nu} W^\mu V^\nu - W^\dagger_{\mu V} W^{\nu\mu}) + i\kappa_V W^\dagger_{\mu} V_{\mu} V^\nu + i\lambda_V m_W W^\dagger_{\mu} W^\nu V^\nu\lambda$ are $10^{-4}$-$10^{-3}$ at LC experiments [1, 2, 3].

5 Summary

Current understanding of elementary particle physics is based on the SM, in which the gauge principle and the electroweak symmetry breaking are two basic ingredients. Nature of gauge interactions has been studied experimentally in full details last twenty years, but we know little about the electroweak symmetry breaking and the Higgs mechanism. The most important next step of the high energy physics is to clarify the dynamics of electroweak symmetry breaking and the mass generation mechanism of elementary particles. For this purpose, an $e^+e^-$ LC is necessary. The LC with the center-of-mass energy of up to 500 GeV and an integrated luminosity of 500 fb$^{-1}$ can be considered as a Higgs factory. We can determine the coupling constants related to the mass generation mechanism very precisely. In order to determine the top Yukawa coupling constant and the Higgs self-coupling constant with good precisions, a higher center-of-mass energy is required. The LC experiments will also play essential roles in finding and studying new physics signals, such as SUSY and the scenario with a large extra-dimensional space. For these analysis, the LHC and linear collider experiments can be complementary to each other. The clean experimental environment, availability of the beam polarization, capability of energy scan at the LC is very useful for these studies. In addition to direct search for new signals, precise studies on the SM processes including the top quark and the W boson provide alternative ways to look for new physics effects.

The high energy physics has been developed by concurrent running of hadron and lepton machines. Since the end of the LEP operation, there is no energy frontier $e^+e^-$ machine. There are very strong physics cases to construct the $e^+e^-$ LC which can operate concurrently with the LHC experiment. The physics of the TeV energy scale may or may not be what we are expecting, but whatever it may be, it will be necessary for us to have both machines to elucidate the physics at the electroweak scale and beyond.
References

[1] T. Abe et al. [American Linear Collider Working Group Collaboration], “Linear collider physics resource book for Snowmass 2001,” in Proc. of the APS/DPF/DPB Summer Study on the Future of Particle Physics (Snowmass 2001) , arXiv:hep-ex/106055, hep-ex/106055, hep-ex/106057, hep-ex/106058.

[2] J. A. Aguilar-Saavedra et al. [ECFA/DESY LC Physics Working Group Collaboration], “TESLA Technical Design Report Part III: Physics at an e+e- Linear Collider,” arXiv:hep-ph/0106315.

[3] K. Abe et al. [ACFA Linear Collider Working Group Collaboration], “Particle physics experiments at JLC,” arXiv:hep-ph/0109166.

[4] M. W. Grünewald, Plenary talk at ICHEP02, Amsterdam, July 24-31, 2002.

[5] Y. Okada, M. Yamaguchi and T. Yanagida, Prog. Theor. Phys. 85 (1991) 1; Phys. Lett. B 262 (1991) 54; J. R. Ellis, G. Ridolfi and F. Zwirner, Phys. Lett. B 257 (1991) 83; H. E. Haber and R. Hempfling, Phys. Rev. Lett. 66 (1991) 1815.

[6] S. Kanemura, T. Kasai and Y. Okada, Phys. Lett. B 471 (1999) 182.

[7] J. R. Espinosa and M. Quiros, Phys. Rev. Lett. 81 (1998) 516.

[8] D. Zeppenfeld, in Proc. of the APS/DPF/DPB Summer Study on t he Future of Particle Physics (Snowmass 2001) ed. N. Graf, eConf C010630 (2001) P123 [arXiv:hep-ph/0203123].

[9] J. i. Kamoshita, Y. Okada and M. Tanaka, Phys. Lett. B 328 (1994) 67.

[10] D. J. Miller, S. Y. Choi, B. Eberle, M. M. Muhlleitner and P. M. Zerwas, Phys. Lett. B 505 (2001) 149.

[11] M. Battaglia, E. Boos and W. M. Yao, in Proc. of the APS/DPF/DPB Summer Study on the Future of Particle Physics (Snowmass 2001) ed. N. Graf, eConf C010630 (2001) E3016 ,arXiv:hep-ph/0111276.

[12] Y. Yasui, S. Kanemura, S. Kiyoura, K. Odagiri, Y. Okada, E. Senaha and S. Yamashita, in these Proceedings., arXiv:hep-ph/0211047.
[13] J. Kamoshita, Y. Okada and M. Tanaka, in Proc. of Workshop on Physics and Experiments with Linear Collider, Morioka-Appi, September 8-12, 1995; Phys. Lett. B 391 (1997) 124.

[14] I. Nakamura and K. Kawagoe, Phys. Rev. D 54 (1996) 3634.

[15] G. Borisov and F. Richard, arXiv:hep-ph/9905413.

[16] M. Carena, H. E. Haber, H. E. Logan and S. Mrenna, Phys. Rev. D 65 (2002) 055005 [Erratum-ibid. D 65 (2002) 099902].

[17] M. Carena, S. Mrenna and C. E. Wagner, Phys. Rev. D 60 (1999) 075010; K. S. Babu and C. F. Kolda, Phys. Lett. B 451 (1999) 77; H. E. Haber, M. J. Herrero, H. E. Logan, S. Penaranda, S. Rigolin and D. Temes, Phys. Rev. D 63 (2001) 055004; J. Guasch, W. Hollik and S. Penaranda, Phys. Lett. B 515 (2001) 367.

[18] S. Kiyoura, S. Kanemura, K. Odagiri, Y. Okada, E. Senaha, S. Yamashita and Y. Yasui, in these Proceedings., arXiv:hep-ph/0301172.

[19] D. M. Asner, J. B. Gronberg and J. F. Gunion, Phys. Rev. D 67 (2003) 035009.

[20] J. F. Gunion and J. G. Kelly, Phys. Lett. B 333 (1994) 110; M. Kramer, J. H. Kuhn, M. L. Stong and P. M. Zerwas, Z. Phys. C 64 (1994) 21; G. J. Gounaris and G. P. Tsirigoti, Phys. Rev. D 56 (1997) 3030 [Erratum-ibid. D 58 (1998) 059901]; S. Y. Choi and J. S. Lee, Phys. Rev. D 62 (2000) 036005; E. Asakawa, J. i. Kamoshita, A. Sugamoto and I. Watanabe, Eur. Phys. J. C 14 (2000) 335; K. Hagiwara, Nucl. Instrum. Meth. A 472 (2001) 12; E. Asakawa, in Physics and Experiments with Future Linear e+e− Colliders (LCWS 2000), Fermilab, Batavia, Illinois, 24-28 Oct 2000, arXiv:hep-ph/0101234.

[21] S. Y. Choi, A. Djouadi, M. Guchait, J. Kalinowski, H. S. Song and P. M. Zerwas, Eur. Phys. J. C 14 (2000) 535; S. Y. Choi, J. Kalinowski, G. Moortgat-Pick and P. M. Zerwas, Eur. Phys. J. C 22 (2001) 563.

[22] M. M. Nojiri, K. Fujii and T. Tsukamoto, Phys. Rev. D 54 (1996) 6756.

[23] N. V. Krasnikov, Phys. Lett. B 388 (1996) 783.

[24] N. Arkani-Hamed, H. C. Cheng, J. L. Feng and L. J. Hall, Phys. Rev. Lett. 77, 1937 (1996).
[25] T. Tsukamoto, K. Fujii, H. Murayama, M. Yamaguchi and Y. Okada, Phys. Rev. D 51 (1995) 3153.

[26] G. A. Blair, W. Porod and P. M. Zerwas, Phys. Rev. D 63 (2001) 017703.

[27] N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Lett. B 429 (1998) 263; Phys. Rev. D 59 (1999) 086004.

[28] G.W. Wilson, LC-PHSM-2001-010. http://www.desy.de/~lcnotes

[29] K. Fujii, T. Matsui and Y. Sumino, Phys. Rev. D50 (1994) 4341.

[30] M. Martinez and R. Miquel, hep-ph/0207315.

[31] Figure prepared for “JLC Project” by K. Fujii and Y. Sumino. http://lcdev.kek.jp/RMdraft/

[32] R. Frey, in Proc. of Workshop on Physics and Experiments with Linear Collider, Morioka-Appi, September 8-12, 1995, hep-ph/9606201; R. Frey et al., hep-ph/9704243.