HIGGS AT FUTURE LINEAR COLLIDER

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Higgs physics at the future e^+e^- linear collider, especially the measurements to be achieved at $\sqrt{s}$ =250–500 GeV, are reviewed. The subjects discussed in the Higgs session from experimental points of views are introduced. The key measurements and the problems to be solved are discussed.

1 Introduction

The studies of the Higgs boson [1] is the key to open the future generation of the particle physics. The Higgs couplings and their evolutions are significantly sensitive to the fundamental structure of interaction and contents of particles up to GUT scale ($\sim 10^{16}$ GeV), which becomes one of the strong motivations to introduce the supersymmetry (SUSY). The existence of the Higgs, and if it exists number of Higgs particles and masses, are of course the first questions to be answered by experiments. The possible mass regions of the lightest Higgs boson differ model by model. There are, however, strong indications that the mass is lower than 300 GeV where the first phase of various future e^+e^- linear collider (LC) projects cover well. The indirect measurements of the electroweak parameters at LEP/SLC/Tevatron give an upper mass bound of about 260 GeV at 95% CL [2] for the SM Higgs. When we assume the MSSM, the mass must be lower than 150 GeV. With additional SU(2) singlet to the MSSM (NMSSM), the upper bound is about 140 GeV assuming the finite Higgs coupling up to GUT scale [3], and even in more general scheme in SUSY the bound does not exceed 210 GeV [4]. Details of the theoretical discussions are reviewed in Ref [5]. So far the lower mass bound of the SM Higgs is around 90 GeV and about 80 GeV for the MSSM Higgs (h^0, A^0) at 95 % CL from currently running experiments at LEP-II [6]. The LEP-II might discover Higgs with mass up to 105–110 GeV for the SM-like Higgs, and exclusion to 110–115 GeV. Tevatron run2 in the following years is sensitive to the mass up to 120 GeV or more [7] provided the integrated luminosity exceeds a few fb^{-1}. At forthcoming LHC, there are varieties of channels in the SM and MSSM in which we have large discovery potential with enough significance in wide range of the mass of the Higgs bosons [8], while the detectable channels are limited due to huge backgrounds in the *pp* collisions and also the production yield could be much lower if nature is further beyond the MSSM.

The Higgs discovery itself is relatively easy at LC provided that we establish an accelerator(s) with luminosity of order of 10^{34} $cm^{-2}s^{-1}$ at the beam energy high enough to produce Higgs boson kinematically. We need only "one day" running to discover the SM-like Higgs, which is extremely different situation from other experiments like LHC. Even for the SUSY models beyond the MSSM, there always exist the lower limits of the production cross-section. Hence the observation of at least one Higgs is guaranteed if our understanding of the nature is not so bad. One can say, in other words, it is really a "big discovery" when we find no Higgs at LC. However our purpose of the experiment at LC is not only to judge the existence of the light Higgs. The real Higgs physics starts after the discovery. The LC gives us the unique opportunity to measure the cross-section and the branching ratio in percent order or less in its error, which results in the precise measurements of the Higgs gauge coupling and Yukawa-coupling, and furthermore derivation of Higgs self-couplings in multi-Higgs production. All of those, which are expected to be done only with the LC, are essential to give definite answers to physics models and to determine the fundamental structure of the interaction in nature up to GUT scale.

2 Higgs production, Decay and Physics Backgrounds

In the e^+e^- collision, the CP-even Higgs (h^0), either in SM or SUSY models, can be produced via Higgs-strahlung (Bijorken) process, $e^+e^- \to Z^{0*} \to h^0 Z^0$, and WW(ZZ)-fusion process [9], $e^+e^- \to \nu\bar{\nu}W^*W^* \to \nu\bar{\nu}h^0$ ($e^+e^- \to e^+e^-Z^*Z^* \to e^+e^-h^0$) as shown in Fig1. The WW-fusion process becomes important at high energy. This production has unique feature which enable us to measure directly the coupling of the Higgs with W-boson while the interference between Higgs-strahlung and the fusion process is not negligible. Fig2 (left) shows the production cross-section for the SM Higgs

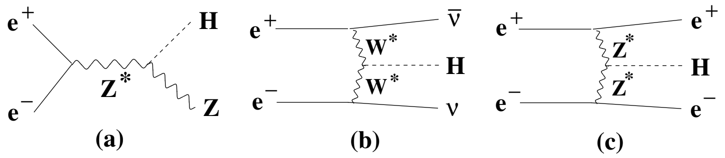

Figure 1: Diagrams of CP-even higgs production in (a) Higgs-strahlung (Bijorken) h^0Z^0 production, (b) WW-fusion and (c) ZZ-fusion process.

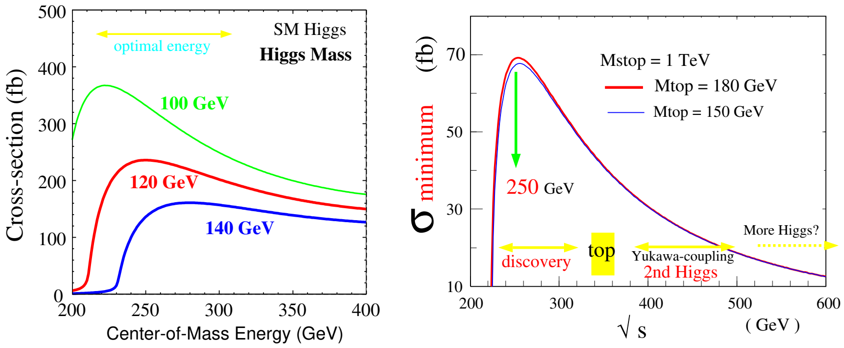

Figure 2: (Left) The production cross-section for 100, 120, and 140 GeV SM Higgs as a function of $\sqrt{s}$. (Right) The minimum cross-section of the CP-even higgs production in the NMSSM taken from Ref [3]. The two lines correspond to the top quark mass of 150 and 180 GeV.

as a function of centre-of-mass energy. We have approximately 10^5 Higgs events in a few years for 120 GeV Higgs at $\sqrt{s}$=300 GeV if we have the luminosity of 10^{34}

$cm^{-2}s^{-1}$. For the MSSM, the production cross-section of the h^0Z^0 process σ_{hZ}^{MSSM} can be written as $\sigma_{hZ}^{MSSM} = \sin^2(\beta - \alpha) \times \sigma_{HZ}^{SM}$, where σ_{HZ}^{SM} is the SM Higgs cross-section. The β is defined by $\tan\beta = v_1/v_2$, the ratio of the vacuum expectation values of two Higgs field doublets, and the α is the mixing angle of the two CP-even Higgs states. The α and β are related in the MSSM in terms of CP-odd Higgs boson (A^0) mass and other SUSY parameters. In more extended SUSY Higgs models such as NMSSM, the cross-section depends on more parameters. However, there exist absolute lower limits of the cross-section ($\sigma_{\rm minimum}$). Fig2 (right) shows the $\sigma_{\rm minimum}$ as a function of centre-of-mass energy for the NMSSM, taken from Ref [3]. For most general SUSY scenario, one may find in Ref [10].

The physics background processes which have event topologies similar to those of Higgs signals have cross-section just one or two orders of magnitude higher than the signal. For instance at $\sqrt{s}$=300 GeV the dominant background sources (cross-section) are $q\bar{q}(\gamma)$(35 pb), W^+W^-(17 pb), Z^0Z^0(1.0 pb), $We\bar{\nu}$(2.0 pb), $Z^0e^+e^-$(1.2 pb), while the 120 GeV SM Higgs cross-section is about 0.2 pb. The most severe backgrounds are the W and Z-pair production. Note that the physics background can be strongly suppressed by the polarised beam option [11], which is one of the big advantages of the LC. The situation is much better than LHC where several orders of magnitude higher background level is expected. However our ultimate purpose of the Higgs study is not only the Higgs discovery, but also to measure the Higgs properties precisely, in order to determine the direction of the future physics. The requirements on the purity and accuracy are far beyond those at LHC.

The other Higgs expected in the multi-Higgs models might also be discovered/measured. For MSSM or general two Higgs field doublets models (2HDM), there is an additional important channel, $e^+e^- \to A^0h^0$, while its production cross-section is expected to be suppressed in wide range of the parameter space for h^0 mass higher than 110 GeV, if we persist in the MSSM. Also the important channel would be A^0 (H^0) production radiated off the b or top quark [12] like $e^+e^- \to b\bar{b} \to b\bar{b}A^0$ via Yukawa-coupling. And multi-Higgs production like $e^+e^- \to Z^0h^0h^0$ could be observed via Higgs self-coupling [13]. The measurement of the self-coupling is extremely important subject, although the cross-section is expected to be so small and many other diagrams also contribute to the multi-Higgs final state.

If the Higgs is of the SM-like, the dominant decay branch is $b\bar{b}$ for mass lower than 130 GeV. However, once the decay channel into W pair opens kinematically, most of the Higgs decays to W pair [14]. The decay of the MSSM Higgs depends also on α and β. In other words, the measurements of the decay branching rate result in the determination of SUSY parameters. For the mass region between 100 and 140 GeV where we expect the lightest Higgs in MSSM and NMSSM, the $b\bar{b}$ branch still dominates in wide range of the parameter space. A good b-flavour tagging is the one of the essential techniques to measure the Higgs boson.

3 Model Detectors and Studies of Important Measurements for Higgs

There are varieties of model detectors considered in the world for LC projects. The details of model detectors and their simulation methods are found elsewhere in these proceedings. These detectors have the expected performance high enough to satisfy the most of the requirements of the Higgs measurements as follows;

- Good energy measurements of charged tracks, neutral particles, and jets, in order to reconstruct Higgs boson mass.
- Precise positioning of the primary and the secondary vertices in order to tag the b-quark and c-quark from Higgs decay. The primary vertex resolution is good enough at LC since the beam size of less than μm is used in the primary vertex fitting. To establish the Higgs tagging with more than 80 % for $b\bar{b}$ decay with reasonable purity against background process we need to tag the secondary vertex with its decay length less than 1 mm. Furthermore, the c-quark tagging might require more accuracy. The dominant part of the charged particle from the b-hadron decay have its momentum less than 3 GeV. The detector is required to have less materials in vertex detectors.
- Good hermeticity of the detector. It is essential especially for the neutrino channel, $e^+e^- \rightarrow h^0 \nu\bar{\nu}$. It is also important for detection of Higgs decay to W-pair for the $h^0 \rightarrow WW^{(*)} \rightarrow l\nu q\bar{q}$ events.
- Particle identification especially for leptons. The τ-identification performance is one of the keys of the Higgs studies. A fine segmentation of the calorimetry with enough neutral hadron/γ discrimination might help.

With these model detectors and simulators, we have studied various aspects of the Higgs measurements. Some of these are introduced below.

The important measurements feasible at early stage of LC might be the mass of the Higgs, the coupling of Higgs with weak bosons, natural width of the Higgs, and Yukawa-coupling strength to fermions. The measured cross-section of the Z^0h^0 production and WW-fusion process determine the coupling between Higgs and the weak gauge bosons. Also the relative strength of the coupling with fermions are determined by the measurements of the Higgs decay branching. The absolute strength of the Yukawa-couplings, as well as the Higgs total decay width, are derived in a model independent fashion with combination of the cross-section measurement and the branching ratio measurements to $f\bar{f}$ and W^+W^- (or Z^0Z^0). These results would judge whether we live in the SM-like nature or in SUSY world or further beyond. And if SUSY, we could indirectly measure SUSY parameters such as other Higgs masses.

3.1 Mass Measurements

The Higgs boson mass is the fundamental value which might give us information up to GUT scale as we discussed above. A precise measurement of the Higgs mass with an accuracy of about 100 MeV or less is necessary in order to obtain fruitful results from the other measurements such as branching ratio for Higgs around 140 GeV. Because the Higgs branching ratio is a strong function of its mass mainly due to kinematic phase space factor of Higgs decay into W-pair. The Higgs mass can be obtained either with direct reconstruction of the jets from Higgs, or with recoil mass in case the associated Z^0 decays to e^+e^- or $\mu^+\mu^-$, or with all information combined with fitting. Precise calibration of the detector and beam energy measurement are essential. Calibration runs at Z^0 pole might be helpful [15]. It should be noted that the actual e^+e^- collision energy has a large spread at LC due to significant beamstrahlung effect [16] in exchange for the high luminosity. This makes significant distortion of the reconstructed Higgs mass as well as the background processes. The reconstructed mass distributions of the Higgs in muon channel with/without the beamstrahlung effect are shown in Ref[17]. A. Juste [18] has improved significantly the reconstructed mass in the four-jet final state with convolutions of the beamstrahlung effect in calculations of the mass. In order to utilise such improved methods, precise estimation of the beam-collision energy spectra as well as the absolute value of the peak energy would be required.

3.2 Cross-section Measurements

The cross-section measurements of the Z^0h^0 (and WW-fusion) process mean the direct determination of the coupling between Higgs and weak bosons. The ZZh coupling is directly measured with Higgs-strahlung process using $e^+e^-\to q\bar{q}h^0$, $\mu^+\mu^-h^0$, $\tau^+\tau^-h^0$ or $e^+e^-h^0$ (with small contribution from ZZ-fusion). The neutrino channel $e^+e^-\to h^0\nu\bar{\nu}$ is important to measure WWh coupling via WW-fusion process [19]. The comparison between ZZh and WWh couplings verify the $SU(2)\times U(1)$ structure, which is essential to establish the Higgs mechanism. Once the $SU(2)\times U(1)$ coupling is established, all channels are combined to precisely determine both ZZh and WWh couplings. In order to measure the cross-section independently of the Higgs decay branching, one can use the recoil mass distribution of the muon or electron pairs in $e^+e^-\to\mu^+\mu^-h^0$ or $e^+e^-h^0$ channels [20]. Once we measure the branching ratio (Br) to $b\bar{b}$ or W^+W^- so on, the other channels can also be combined to increase the statistics a lot. In this case, however, the precision of the cross-section measurement is limited by that of the Br measurements.

3.3 Branching Ratio Measurements

The measurements of the branching ratio (Br) of the Higgs is one of the keys to distinguish the SM from other models such as SUSY. Once we determine the Higgs mass, the branching ratios of the SM Higgs are calculable with the known SM parameters. On the other hand, for SUSY Higgs, the branching can be affected by other SUSY parameters such as A^0 mass or $\tan\beta$, which result in the different branching ratio from the SM case. The key measurements are $\mathrm{Br}(h^0\to b\bar{b})$, $\mathrm{Br}(h^0\to W^+W^-)$, $\mathrm{Br}(h^0\to\tau^+\tau^-)/\mathrm{Br}(h^0\to b\bar{b})$, $\mathrm{Br}(h^0\to c\bar{c}(+gg))/\mathrm{Br}(h^0\to b\bar{b})$. When we combine the $\mathrm{Br}(h^0\to W^+W^-)$ with the measured cross-section σ_{h^0}, the total width of the Higgs Γ_{h^0} can be deduced as follows;

$$\Gamma_{h^0} = \frac{\Gamma_{h^0\to W^+W^-}}{\mathrm{Br}(h^0\to W^+W^-)} = \Gamma^{SM}_{h^0} \times \frac{\mathrm{Br}^{SM}(h^0\to W^+W^-)}{\mathrm{Br}(h^0\to W^+W^-)} \times \frac{\sigma_{h^0}}{\sigma^{SM}_{h^0}} \quad , \tag{1}$$

where $\Gamma^{SM}_{h^0}$ is the total width for the SM Higgs and $\sigma^{SM}_{h^0}$ is the production cross-section for the SM Higgs. In a similar manner, the absolute strength of the Yukawa-couplings of the Higgs boson to fermions can be deduced in a model independent fashion, using the relative branching ratio $\mathrm{Br}(\mathrm{h}^0 \rightarrow \mathrm{f}\bar{\mathrm{f}})/\mathrm{Br}(\mathrm{h}^0 \rightarrow \mathrm{W}^+\mathrm{W}^-)$ together with the measured cross-section. The ratio $\mathrm{Br}(\mathrm{h}^0 \rightarrow \tau^+\tau^-)/\mathrm{Br}(\mathrm{h}^0 \rightarrow \mathrm{b}\bar{\mathrm{b}})$ is also one of the essential measurements. While the different absolute values of the Yukawa-coupling strength are expected in models, the ratio $\mathrm{Br}(\mathrm{h}^0 \rightarrow \tau^+\tau^-)/\mathrm{Br}(\mathrm{h}^0 \rightarrow \mathrm{b}\bar{\mathrm{b}})$ is the same at a first order in the SM and type-II 2HDM like MSSM. On the other hand, if we assume the Type-II coupling, the measurement serves as the precise measurement of the running b-quark mass at the Higgs mass. The measurements of $\mathrm{Br}(\mathrm{h}^0 \rightarrow gg)/\mathrm{Br}(\mathrm{h}^0 \rightarrow \mathrm{b}\bar{\mathrm{b}})$ or $\mathrm{Br}(\mathrm{h}^0 \rightarrow \mathrm{c}\bar{\mathrm{c}}(+gg))/\mathrm{Br}(\mathrm{h}^0 \rightarrow \mathrm{b}\bar{\mathrm{b}})$ are to be used to determine the Yukawa-coupling for up-type quarks since the gluonic decay occurs mainly via the top quark loop. The ratios relative to those of the SM are proportional to $\tan^{-2}\alpha \times \tan^{-2}\beta$ which can be approximated as $[(m_{\mathrm{A}}{}^2 - m_{\mathrm{h}}{}^2)/(m_{\mathrm{A}}{}^2 - m_{\mathrm{Z}}{}^2)]^2$ for large $\tan\beta$, which leads the indirect estimation of CP-odd Higgs A^0 mass [21,22]. However one should note that the theoretical ambiguities is large due to uncertainty of α_s and running c-quark mass. Theoretical and experimental improvements are awaited. Many studies have been done for varieties of decay channels with simulation of model detectors, at the typical benchmark points in centre-of-mass energies and Higgs masses. Some of the results are summarised in Tab 1. When we assume a model such as MSSM, the results of the various decay modes can be combined to estimate the masses of the other Higgs and other model parameters, like m_{A}, m_{H} and $\tan\beta$ of the MSSM, for the assumed model. Results of the combination performed by M. Battaglia for the MSSM are found in Ref [26]. These estimated values would be examined in comparison with results from LHC and/or those from the next stage of the LC, from which we could obtain the answer for the physics up to GUT scale.

4 Machine-Related Effects

While LC projects have great potential to discover Higgs particles and to precisely measure the Higgs properties, one has to consider crucially the realistic experimental environment. In order to achieve the precise measurements, luminosity of about 10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ is required at LC, which is about 2 order higher than that at LEP. The extremely high luminosity and the beam structure necessary for the acceleration in the linear collider cause more severe experimental situation than that at LEP/SLC in addition to the energy spread mentioned above. These are i) the large number of noise hits on the vertex detectors due to huge number of low energy $\mathrm{e}^+\mathrm{e}^-$ pairs created by beam-beam interaction [16] and ii) the overlap of two or more physics events especially two-photon [23] background [a] in a same bunch due to very high luminosity per bunch. It can reach to 1 $\mu\mathrm{b}^{-1}$ level at LC which is 2–3 orders of magnitude higher than that at LEP/SLC. Studies of the Higgs measurements with such expected experimental condition have been attempted [24]. The most inner layer of the vertex detector might have the noise hit density of about 1 hits/mm^2, which makes proper associations of the hits difficult especially for the low momentum

[a] Note that the two-photon process include "normal" two-photon process in which the two virtual photon interacts, and interaction between a virtual photon and real photon induced by the beamstrahlung effect, which may roughly doubles the cross-section.

tracks. For the event overlapping, there are two major effects in the measurements. One is the effect on the kinematics such as reconstructed mass of the Higgs and the selection bias. The other effect is on the flavour tagging which relies on the tracks displaced from the event primary vertex. These are the future subjects to be solved to make high luminosity data meaningful.

5 Summary

The future linear e^+e^- collider (LC) gives us fantastic occasions to investigate the physics up to GUT scale through studies of Higgs production and decay properties. The existence of the light Higgs predicted in SUSY models is first to be clarified. At LC, we may need only a few days to discover (at least one of) the Higgs bosons if the current design luminosity values of on-going LC projects are realised. There is always a potential for us to find unexpected "big things" through Higgs hunting and measurements even at very early stage of the experiments. The precise measurements of the Higgs properties such as cross-section and decay branching expected to be achieved at LC are essential to determine the future direction of the particle physics. Varieties of studies have been made with model detectors. Typical values in these results are found in Tab1. However, the high luminosity required for the precise measurements would make severe experimental condition. Expected situations as well as systematic uncertainties of the measurements have to be considered crucially in the future studies. We hope we start the experiment as soon as possible to determine the direction of the next generation of the particle physics.

$\sqrt{s}$	300 GeV	350 GeV	500 GeV
$\Delta\sigma/\sigma$	4.2 % [25]	4.7 % [20]	3.3 % [26]
ΔM_{h^0}	—	(a)230 MeV [20]	60 MeV [18]
$\Delta Br/Br$			
$h^0 \to b\bar{b}$	1.8 % [25]	3.8 % [26]	3.8 % [26]
$h^0 \to W^+W^-$	8 % [25]	8 % [26]	8 % [26]
$h^0 \to \tau^+\tau^-$	7 % [22]	9 % [26]	9 % [26]
$h^0 \to c\bar{c}+gg$	10 % [25]	—	—
$h^0 \to c\bar{c}$	35 % [25]	21 % [26]	13 % [26]
$h^0 \to gg$	16 % [25]	8 % [26]	8 % [26]
$h^0 \to \gamma\gamma$	—	(b) 14 % [27]	8 % [26]
$\Delta(\sigma_{h\nu\bar{\nu}} \cdot Br(bb))$	2.0 % [19]	—	—

Table 1: Summary table of numbers presented at the Higgs session for 120 GeV SM-like Higgs, normalised to $\mathcal{L}$=200 fb^{-1} simply by $\sqrt{\mathcal{L}}$. Reference is on each values. All numbers are statistical only. Note in the table (a) only with e^+e^- and $\mu^+\mu^-$ channels; (b) with $\mathcal{L}$=1000 fb^{-1}.

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