Higgs studies in ACFA Linear Collider Working Group

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Abstract

We report the important topics in ACFA report\cite{1} as well as the recent progress in the ACFA Higgs working group.

1 Introduction

While the $SU(2) \times U(1)$ gauge interaction has been precisely tested at LEP and SLC, we do not understand the mechanism of the gauge-symmetry breaking. The existence of a Higgs boson is expected to be discovered at TEVATRON or LHC. One of the main goals at a future Linear Collider (LC) is a precision study on the Higgs sector. At the machine with the center of mass energy ($\sqrt{s}$) of 300-500 GeV and an integrated luminosity ($L_I$) of 500 fb\textsuperscript{-1}, $O(10^5)$ Higgs bosons can be produced if the Higgs mass is smaller than 200 GeV. By measuring the Higgs couplings to gauge bosons and fermions as well as the Higgs-self coupling, we could reveal the structure of the Higgs sector. In addition, a TeV-scale LC may enable us to explore the heavy Higgs bosons beyond the standard model (SM). In this talk, we report results of recent activity in the ACFA Higgs Working Group.

2 Light Higgs Boson

2.1 Mass

The mass of the Higgs boson ($h$) is a key parameter in the Higgs sector. Assuming that the SM is valid up to the Planck scale ($\Lambda = 10^{19}$GeV), the mass of the Higgs

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boson is theoretically constrained in the range between 135 GeV and 180 GeV. In the two Higgs doublet model (THDM), the mass of the lightest CP-even Higgs boson ($m_h$) is expected in the region between 100 GeV and 180 GeV for $\Lambda = 10^{19}$ GeV in the decoupling regime where only one Higgs boson is light [2]. In the minimal supersymmetric standard model (MSSM), we can derive the upper bound of $m_h$ without reference to the cut-off scale. The lightest Higgs mass receives significant radiative corrections due to the top quark and stops[3] and detail studies show $m_h \lesssim 130$GeV. For the extended SUSY model with the gauge singlet field (NMSSM), the bound is about 150 GeV if we assume that the theory is valid up to the GUT scale[4, 5]. The maximal Higgs mass corresponds to a lower $\tan \beta$ value, which is quite different from the MSSM case where the Higgs mass bound increases as $\tan \beta$ grows.

2.2 Detectability
The detection of the light Higgs boson in the SM requires only a few fb$^{-1}$[1]. In the MSSM, we can detect at least one of two CP-even Higgs bosons through $e^+e^- \rightarrow hZ$. Furthermore, the discovery of at least one of three CP-even Higgs bosons is guaranteed in the NMSSM[5].

2.3 Model-Independent Analysis for the Higgs Boson Couplings
In order to distinguish various models, we introduce a model-independent parameterization for various couplings to the Higgs boson as follows[1],

$$L = x \frac{m_h}{v} h \bar{b}b + y (\frac{m_t}{v} h \bar{t}t + \frac{m_c}{v} h \bar{c}c) + z \frac{m_t}{v} h \tau \tau + u (gm_W h W^\mu W^\mu + \frac{g_2}{2} m_Z h Z^\mu Z^\mu)$$

where the following four parameters, $x$, $y$, $z$, and $u$, represent the multiplicative factors in the Higgs-boson coupling constants with down-type quarks, up-type quarks, charged-leptons and gauge bosons. The SM corresponds to $x = y = z = u = 1$. This expression is valid for the SM, MSSM, NMSSM, and multi-Higgs-doublet models without tree-level flavor changing neutral current. In Fig.1 we show the expected accuracy of the parameter determination at JLC with $\sqrt{s} = 300$ GeV and $L_I = 500$ fb$^{-1}$ for $m_h = 120$ GeV. The reference point is taken to be the SM case. We use the measurement accuracy listed in Table 2.7 of Ref.[1]. We can see that $u$ and $x$ parameters are determined to a few % level, and $y$ and $z$ are constrained to less than 10%. In the figure, we also show points corresponding to several input parameters in the MSSM. From the correlation of the four parameters determined at the LC experiment, it is possible to distinguish various models. For example, Type-I THDM which predicts the relation $x = y$ and the MSSM have different relation in $x$-$y$ space. For a large $\tan \beta$ value, the allowed range of the $x$-$z$ space can deviate from the $x=z$ line for the MSSM because of the SUSY corrections to the $h \bar{b}b$ vertex[6],
Fig.1: The inner (outer) contour is the 1σ (95% CL) curve. The points A-E correspond to the projections on each plane of the x, y, z, and u values evaluated in the following parameter sets of the MSSM. \((M_A, M_S, A_t/M_S, \tan \beta)\) are (1000,500,0,10), (600,550,-2,10), (550,1430,2,5), (450,25430,0,4) and (500,4810,2,30) for A-E, respectively. We also take the gluino mass and the higgsino mass parameter as 300GeV.

as shown for the point E. A detailed analysis of the general \(h\gamma\) couplings, with \(V = \gamma\) or \(Z\), is presented in Ref.[7].

2.4 Indirect Determination of Heavy Higgs Boson Mass in MSSM

We discuss the extraction of the heavy Higgs mass from the branching ratios of the lightest Higgs boson in the MSSM[8]. Within the approximation that the stop mixing is neglected in the one-loop Higgs potential and the \(h\bar{b}\bar{b}\) vertex correction is small, four double ratios of the Higgs branching ratios, \((Br(h \rightarrow c\bar{c}) + Br(h \rightarrow gg))/Br(h \rightarrow b\bar{b})\), \((Br(h \rightarrow c\bar{c}) + Br(h \rightarrow gg))/Br(h \rightarrow \tau^+\tau^-)\), \(Br(h \rightarrow W^+W^-)/Br(h \rightarrow b\bar{b})\), and \(Br(h \rightarrow W^+W^-)/Br(h \rightarrow \tau^+\tau^-)\), are approximately given by \(R(m_A) \equiv (m_A^2 - m_h^2)^2/(m_A^2 + m_Z^2)^2\), for \(m_A > 200\)GeV and \(\tan \beta \gtrsim 2\), where \(m_A\) is the mass of the CP-odd Higgs boson. Since \(R(m_A)\) depends only on \(m_A\) once the lightest Higgs mass is measured, the double ratios of the branching ratios are useful to constrain the mass of the heavy Higgs boson. In Fig.2, we show the precision of the indirect determination on \(m_A\) from the above branching ratios at JLC with \(L_I = 500\) fb\(^{-1}\) at \(\sqrt{s} = 300\)GeV for \(m_h = 120\)GeV. The theoretical uncertainty of the branching ratio calculation in the SM and the estimated experimental statistical errors are summarized in Table 2 of Ref.[1]. The combined error to determine \(m_A\) from \((Br(h \rightarrow c\bar{c}) + Br(h \rightarrow gg))/Br(h \rightarrow \tau^+\tau^-)\) and \(Br(h \rightarrow W^+W^-)/Br(h \rightarrow \tau^+\tau^-)\) is 5.3%. In order to draw the constraints on \(m_A\), we use the 5.3% error and assume that these ratios normalized by the SM values are given by \(R(M_A)\)\(^1\). In the figure, we can see that accuracy of the \(m_A\)

\(^1\)However, in the presence of the stop mixing, the SUSY corrections on the relation between the double ratios of the Higgs branching ratios and \(R(m_A)\) can be significant for \(\tan \beta > 30\) or large \(|\mu| \simeq 2\)TeV even if \(\tan \beta\) is not large[9].
Fig. 2: Accuracy of the $M_A$ determination as a function of $M_A$ from branching ratio measurements. The dark area corresponds to the error of $M_A$ from $Br(h \rightarrow \tau^+\tau^-)$, $Br(h \rightarrow gg)$, $Br(h \rightarrow W^{(*)}W^{(*)})$, and $Br(h \rightarrow W^{(*)}W^{(*)})$ measurements at JLC. The light area is obtained by the assumption that $\Gamma(h \rightarrow W^{(*)}W^{(*)})/\Gamma(h \rightarrow \tau^+\tau^-)$ is determined in 15% accuracy, which corresponds to an estimated statistical error at LHC.

determination (dark area) is about $\pm 100$ GeV for $m_A = 500$ GeV. This is compared with the typical accuracy of $m_A$ expected at LHC from the measurement of the ratio $\Gamma(h \rightarrow W^{(*)}W^{(*)})/\Gamma(h \rightarrow \tau^+\tau^-)$ (light area).

2.5 Top Yukawa Coupling Constant

The top Yukawa coupling constant will be measured through the $t\bar{t}h$ production process. In the SM the production cross section becomes maximal around $\sqrt{s} = 700$ GeV for $m_h = 120$ GeV. The expected accuracy for the top Yukawa coupling in the SM is 4.2% at $\sqrt{s} = 700$ GeV with $L_I = 500$ fb$^{-1}$.

2.6 Higgs Self-coupling

The measurement of the Higgs self-coupling is crucial to test the Higgs mechanism. The trilinear Higgs coupling can be measured via $e^+e^- \rightarrow Zhh$ and $\nu\bar{\nu}hh$ if the Higgs boson is light\cite{10}. We have started systematic studies on the self-coupling measurement for various $m_h$ and $\sqrt{s}$\cite{11}. At $\sqrt{s} = 500$GeV with $L_I = 1$ab$^{-1}$, the expected statistical error of the trilinear coupling is about 20% for the SM Higgs boson for $m_h \lesssim 150$GeV. For $\sqrt{s} \gtrsim 1$ TeV, due to the enhancement of the $W$-fusion process, the accuracy is expected to be better than 10%\cite{11, 12}. Accurate information on the self-coupling is important to discriminate models beyond the SM. Even when all the Higgs couplings except for the self-interactions are in good agreement with the SM predictions, the Higgs self-couplings can significantly deviate from the SM prediction due to the non-decoupling quantum effects of heavy particles. In the THDM case, the radiative corrections of $O(100)\%$ on the self-coupling is possible\cite{13}. 
3 Heavy Higgs Boson

3.1 Discovery Contour at the LC

Next, we discuss the discovery potential at the LC for the heavy Higgs bosons in the MSSM. In Fig. 3, we show the cross-section contours in $(m_A, \tan \beta)$ plane for the following processes: $e^+e^- \rightarrow ZH, Ah, AH, H^+H^-, W^\pm H^\mp, b\bar{b}A, t\bar{t}H, t\bar{t}A, t\bar{t}H$, and $\nu\bar{\nu}H$. We use GRACE/SUSY[14] to calculate the production cross-sections. One-loop induced process of $W^+H^-$ was calculated as in Ref.[15]. Masses of the Higgs bosons and the mixing angle of the neutral Higgs bosons are obtained by using FeynHiggs[16], where we assume the diagonal masses to be $(1\text{TeV})^2$ in the stop mass matrix and the maximal stop mixing. We adopt HDECAY[17] to calculate decay widths of the Higgs bosons. Fig. 3 shows the cross-section contours: (a) for $\sqrt{s} = 500$ GeV and $\sigma = 1$ fb, (b) for $\sqrt{s} = 500$ GeV and $\sigma = 0.1$ fb, (c) for $\sqrt{s} = 1.0$ TeV and $\sigma = 1$ fb, (d) for $\sqrt{s} = 1.0$ TeV and $\sigma = 0.1$ fb, (e) for $\sqrt{s} = 1.5$ TeV
and $\sigma = 1$ fb, and (f) for $\sqrt{s} = 1.5$ TeV and $\sigma = 0.1$ fb. These contours can be translated to the discovery contours if the sensitivity reach to those cross-sections. In Fig.3 (a), (c), (d), (e) and (f), the mass reach for $A$, $H$, and $H^{\pm}$ at the LC is determined by half of $\sqrt{s}$. In Fig.3(b), if the sensitivity reaches to 0.1fb, the discovery contours for the $b\bar{b}A$ and $b\bar{b}H$ modes go beyond $\sqrt{s}/2$ for large $\tan\beta$. For $\tan\beta \lesssim 10$, the $ZH (Ah)$ mode is available above $m_A > \sqrt{s}/2$. In Fig.3(c)-(f), cross-section contours of $e^+e^- \rightarrow t\bar{t}A$, $t\bar{t}H$, $b\bar{b}A$, and $b\bar{b}H$ exhibit the dependence on $\tan\beta$ in $350\text{GeV} \lesssim m_A \lesssim \sqrt{s}/2$. These processes include $e^+e^- \rightarrow AH$ followed by $A$ or $H$ decaying into the $b\bar{b}$ or $t\bar{t}$ quark pair. The $\tan\beta$ dependence shown in Fig.3(c)-(f) is caused by the branching ratio of the heavy Higgs bosons. Fig.3(c)-(e) also show that the LC will cover the region of moderate $\tan\beta \lesssim 10$ and $M_A \lesssim \sqrt{s}/2$ where the detection of the heavy Higgs bosons at LHC is expected to be difficult. If kinematically allowed, the heavy Higgs bosons are expected to be found in several modes at the LC. This would be useful in determining model parameters such as $\tan\beta$ and $m_A$ in the MSSM, or in discriminating different models from a consistent determination of these parameters.

### 3.2 Single Charged Higgs Production

The charged Higgs pair production cross-section can be $10 - 100$ fb if kinematically allowed. Above the pair-production threshold, the single charged Higgs production is still possible[18, 19, 20]. For large $\tan\beta$, production cross-sections for the processes, $e^+e^- \rightarrow \tau^+\nu H^-$ and $t\bar{t}H^-$, are enhanced[18, 19]. For small $\tan\beta$, the production cross-section of the $e^+e^- \rightarrow W^{\pm}H^{\mp}$ process becomes large due to the top and bottom quark loops[15]. In addition the SUSY loop corrections to this mode was calculated in Ref.[20].

### 3.3 Photon Collider

One of the important motivations for the $\gamma\gamma$ option is to study the s-channel production of the neutral Higgs bosons[21]. This provides the discovery potential for the MSSM heavy Higgs bosons in moderate-$\tan\beta$ parameter space. The kinematical reach will be extended to $0.8 \sqrt{s_{ee}}$, where $\sqrt{s_{ee}}$ is the center of mass energy for the $e^+e^-$ collider. In addition, we can determine the CP parity of the heavy Higgs boson through the process, $\gamma\gamma \rightarrow t\bar{t}$ by measuring the helicity of the top quark[23]. The yield of a heavy charged Higgs boson at a $\gamma\gamma$ collider is typically one order of magnitude larger than that at an $e^+e^-$ collider. Moreover, a polarized $\gamma\gamma$ collider can determine the chirality of the Yukawa couplings of fermions with charged Higgs boson via single charged Higgs boson production and, thus, discriminate models of new physics[24].
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