PHENOMENOLOGY OF THE HIGGS SECTOR IN
SUPERSYMMETRIC STANDARD MODEL *

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ABSTRACT
Several topics related to phenomenology of the Higgs sector in the supersymmetric standard model are reviewed. The upper bound of the lightest Higgs mass in the minimal supersymmetric standard model as well as extended version of it is discussed and it is shown that an $e^+e^-$ linear collider with $\sqrt{s} \sim 300 - 500$ GeV can find at least one Higgs boson in these models. It is also pointed out that the heavy Higgs mass scale may be determined from measurements of the Higgs boson decay branching ratios even if we only discover the lightest Higgs boson at early stage of the linear collider experiment.

1. Introduction

After the discovery of top quark at Fermilab and precise measurements of electroweak interaction at LEP and SLC experiments it has been more and more evident that the elementary particle physics is described by the Standard Model (SM). This model is based on two physical principles, i.e. the gauge principle and the Higgs mechanism. Although we can understand most of the experimental results by the $SU(3) \times SU(2) \times U(1)$ gauge symmetry, little is known about the dynamics behind the electroweak symmetry breaking. Therefore exploring the Higgs sector is the most important issue of the current high energy physics and the primary objective of future collider experiments.

Study of the Higgs sector is not only important to establish the SM but also crucial to search for physics beyond the SM. In this respect the mass of the Higgs boson itself gives us important information. For example, a heavy Higgs boson suggests that the dynamics of the electroweak symmetry breaking is governed by strong interaction. On the other hand if we assume that fundamental interactions are described by perturbation theory up to the Planck scale or a scale close to it, the Higgs boson is expected to exist below 200 GeV. Grand unified theory (GUT) and supersymmetric (SUSY) extension of the SM are examples of the latter case.

In this talk I would like to discuss phenomenological aspects of the supersymmetric standard model, especially some issues related to the Higgs sector of the SUSY model. Among various extensions of the SM, the SUSY SM is now supposed to be the most

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promising candidate of physics beyond the SM. Since early 80’s SUSY extensions of the SM and GUT have been extensively studied because SUSY is the unique symmetry to ensure the smallness of electroweak scale compared to the Planck scale by cancelling the quadratic divergence of scalar mass renormalization. More recently, SUSY theories attracted much attention since three gauge coupling constants measured precisely at LEP and SLC experiments are consistent with SUSY GUT although the simplest non-SUSY GUT is excluded experimentally.

In the following sections, I first discuss the Higgs sector of the minimal supersymmetric standard model (MSSM). It is shown that the upper bound of the lightest CP-even Higgs boson in this model is given by about 130 GeV, which is a prime target of future experiments at LHC and $e^+e^-$ linear colliders. Then the Higgs sector of extended version of the SUSY SM is reviewed. Finally, I show how the measurements of various Higgs decay branching ratios are useful to determine MSSM parameters in future $e^+e^-$ linear collider experiments.

2. The Higgs Sector in the MSSM

In order to construct a SUSY version of the SM we need to introduce a SUSY partner for each particle of the SM. For quarks and leptons their scalar partners, squarks and sleptons, are introduced. Corresponding to the $SU(3)$, $SU(2)$ and $U(1)$ gauge fields we need spin 1/2 gauge fermions called gluino, wino and bino respectively. Unlike the minimal SM the $SU(2)$-doublet Higgs field giving masses to up-type quarks and that to down-type quarks and leptons have to be introduced separately in SUSY models, therefore the Higgs sector contains at least two doublet Higgs fields. In the minimal SUSY extension, i.e. the MSSM, we introduce two Higgs doublets and their SUSY partners, higgsinos. The winos, bino and higgsinos can have mixings due to the electroweak symmetry breaking and form four neutral Majorana fermions (neutralinos) and two charged Dirac fermions (charginos). Therefore the MSSM is characterized as a two doublet-Higgs SM with scalar superpartners (squarks/sleptons) and fermionic superpartners (neutralinos/charginos).

Let us first discuss the MSSM Higgs sector. The most important feature is that the Higgs-self-coupling constant at the tree level is completely determined by the $SU(2)$ and $U(1)$ gauge coupling constants. After electroweak symmetry breaking, the physical Higgs states include two CP-even Higgs bosons ($h, H$), one CP-odd Higgs boson ($A$) and one pair of charged Higgs bosons ($H^\pm$) where we denote by $h$ and $H$ the lighter and heavier Higgs bosons respectively. Although at the tree level the upper bound on the lightest CP-even Higgs boson mass is given by the $Z^0$ mass, the radiative corrections weaken this bound. The Higgs potential is given by

\[ V_{Higgs} = m_1^2|H_1|^2 + m_2^2|H_2|^2 - m_3^2(H_1 \cdot H_2 + \tilde{H}_1 \cdot \tilde{H}_2) \\
+ \frac{g_2^2}{8}(\tilde{H}_1 \tau^aH_1 + \tilde{H}_2 \tau^aH_2)^2 + \frac{g_1^2}{8}(|H_1|^2 - |H_2|^2)^2 + \Delta V, \]

where $\Delta V$ represents the contribution from one-loop diagrams. Since the loop correction due to the top quark and its superpartner, the stop squark, is proportional to the
Figure 1: The upper bound on the lightest CP-even Higgs mass in the MSSM as a function of the top quark mass for various $\tan \beta$ and two large stop mass scales. The solid (dashed) line corresponds to $m_{\text{stop}}=1$ (10) TeV without left-right mixing of two stop states. These masses are calculated by the method with the renormalization group equation.

fourth power of the top Yukawa coupling constant and hence is large, the Higgs self-coupling constant is no longer determined only by the gauge coupling constants. The upper bound on the lightest CP-even Higgs mass ($m_h$) can significantly increase for a reasonable choice of the top-quark and stop-squark masses. Figure 1 shows the upper bound on $m_h$ as a function of top-quark mass for several choices of the stop mass and the ratio of two Higgs-boson vacuum expectation values ($\tan \beta = \frac{\langle H_0^2 \rangle}{\langle H_0^1 \rangle}$). We can see that, in the MSSM, at least one neutral Higgs-boson should exist below 130 - 150 GeV depending on the top and stop masses.

The Higgs boson in this mass range is a target of the future collider experiments both at LHC and $e^+e^-$ linear colliders. In the coming experiment at LEP II the SM Higgs boson is expected to be discovered if its mass is below 95 GeV. Since the upper bound exceeds the discovery limit of LEP II many efforts are made to clarify the discovery potential of the SUSY Higgs in LHC experiments. In this mass range the main decay mode of the SM Higgs boson is $h \rightarrow b\bar{b}$. Unfortunately because of QCD backgrounds we cannot use this mode in the LHC experiments and we have to rely on the two photon mode whose branching ratio is $O(10^{-3})$. In the SUSY case its branching ratio can be even smaller, and the search may be more difficult. Recent study shows that it is probably possible to get at least one signal of the SUSY Higgs sector in almost all parameter space but we may have to wait for several years before we find the signal. On the other hand an $e^+e^-$ linear collider with $\sqrt{s} \sim 300 - 500$ GeV is a suitable place to study the Higgs boson in this mass region. Here we can not only discover the Higgs boson easily but also measure various quantities, i.e. production cross sections and branching ratios related to the Higgs boson. These measurements are very important to clarify nature of
the discovered Higgs boson and distinguish the SM Higgs boson from Higgs particles associated with some extensions of the SM like the MSSM.

Other Higgs states, namely the $H, A, H^\pm$, are also important to clarify the structure of the model. Their existence alone is proof of new physics beyond the SM, but we may be able to distinguish the MSSM from a general two-Higgs model through the investigation of their masses and couplings. In the MSSM the Higgs sector is described by four independent parameters for which we take the mass of the CP-odd Higgs boson ($m_A$), $\tan \beta$, the top-quark mass ($m_t$) and the stop mass ($m_{\text{stop}}$). The top and stop masses enter through radiative corrections to the Higgs potential. Speaking precisely, there are left- and right-handed stop states which can mix to form two mass eigenstates; therefore more than just one parameter is required to specify the stop sector. In Figure 2, the masses for the $H, A$, and $H^\pm$ are shown as a function of $m_A$ for several choices of $\tan \beta$ and $m_{\text{stop}}=1$ TeV. We can see that, in the limit of $m_A \to \infty$, $m_h$ approaches a constant value which corresponds to the upper bound in Figure 1. Also in this limit the $H, A$ and $H^\pm$ become degenerate in mass.

The neutral Higgs-boson couplings to gauge bosons and fermions are determined by the ratio of vacuum expectation values $\tan \beta$ and the mixing angle $\alpha$ of the two CP-even Higgs particles defined as

$$ReH_1^0 = \frac{1}{\sqrt{2}}(v \cos \beta - h \sin \alpha + H \cos \alpha)$$
$$ReH_2^0 = \frac{1}{\sqrt{2}}(v \sin \beta + h \cos \alpha + H \sin \alpha).$$

(2)

For Higgs-boson production, the Higgs-bremsstrahlung process $e^+e^- \to Zh$ or $ZH$ and the associated production $e^+e^- \to Ah$ or $AH$ play complimentary roles. Namely $e^+e^- \to$
$Zh$ ($ZH$) is proportional to $\cos(\beta - \alpha)(\sin(\beta - \alpha))$, and $e^+e^- \rightarrow Ah$ ($AH$) is proportional to $\sin(\beta - \alpha)(\cos(\beta - \alpha))$, so at least one of the two processes has a sizable coupling. It is useful to distinguish the following two cases when we discuss the properties of the Higgs particles in the MSSM, namely (i) $m_A \lesssim 150$ GeV, (ii) $m_A \gg 150$ GeV. In case (i), the two CP-even Higgs bosons can have large mixing, and therefore the properties of the neutral Higgs boson can be substantially different from those of the minimal SM Higgs. On the other hand, in case (ii), the lightest CP-even Higgs becomes a SM-like Higgs, and the other four states, $H, A, H^\pm$ behave as a Higgs doublet orthogonal to the SM-like Higgs doublet. In this region, $\cos(\beta - \alpha)$ approaches unity and $\sin(\beta - \alpha)$ goes to zero so that $e^+e^- \rightarrow Zh$ and $e^+e^- \rightarrow AH$ are the dominant production processes.

Scenarios for the Higgs physics at a future $e^+e^-$ linear collider are different for two cases. In case (i) it is possible to discover all Higgs states with $\sqrt{s} = 500$ GeV, and the production cross-section of the lightest Higgs boson may be quite different from that of the SM so that it may be clear that the discovered Higgs is not the SM Higgs. On the other hand, in case (ii), only the lightest Higgs may be discovered at the earlier stage of the $e^+e^-$ experiment, and we have to go to a higher energy machine to find the heavier Higgs bosons. Also, since the properties of the lightest Higgs boson may be quite similar to those of the SM Higgs boson we need precision experiments on the production and decay of the particle in order to investigate possible deviations from the SM.

3. The Higgs sector in extended versions of the SUSY SM

Although the MSSM is the most widely studied model, there are several extensions of the SUSY version of the SM. If we focus on the structure of the Higgs sector, the MSSM is special because the Higgs self-couplings at the tree level are completely determined by the gauge coupling constants. It is therefore important to know how the Higgs phenomenology is different for models other than the MSSM.

A model with a gauge-singlet Higgs boson is the simplest extension. This model does not destroy the unification of the three gauge coupling constants since the new light particles do not carry the SM quantum numbers. Moreover, we can include a term $W_\lambda = \lambda NH_1 H_2$ in the superpotential where $N$ is a gauge singlet superfield. Since this term induces $\lambda^2|H_1 H_2|^2$ in the Higgs potential, the tree-level Higgs-boson self-coupling depends on $\lambda$ as well as the gauge coupling constants. There is no definite upper-bound on the lightest CP-even Higgs-boson mass in this model unless a further assumption on the strength of the coupling $\lambda$ is made. If we require all dimensionless coupling constants to remain perturbative up to the GUT scale we can calculate the upper-bound of the lightest CP-even Higgs-boson mass. In Figure 3, the upper bound of the Higgs-boson mass is shown as a function of the top-quark mass. In this figure we have taken the stop mass as 1 TeV and demanded that no dimensionless coupling constant may blow up below the GUT scale ($\sim 10^{16}$ GeV). We can see that the upper bound is given by 130 $\sim 140$ GeV for this choice of the stop mass. The top-quark-mass dependence is not significant compared to the MSSM case because the maximally allowed value of $\lambda$ is larger (smaller) for a smaller (larger) top mass.

From this figure we can see that the lightest Higgs boson is at least kinematically accessible at an $e^+e^-$ linear collider with $\sqrt{s} \sim 300 - 500$ GeV. This does not, however, mean that the lightest Higgs boson is detectable. In this model the lightest Higgs boson
is composed of one gauge singlet and two doublets, and if it is singlet-dominated its couplings to the gauge bosons are significantly reduced, hence its production cross-section is too small. In such a case the heavier neutral Higgs bosons may be detectable since these bosons have a large enough coupling to gauge bosons. In fact we can put an upper-bound on the mass of the heavier Higgs boson when the lightest one becomes singlet-dominated. By quantitative study of the masses and the production cross-section of the Higgs bosons in this model, we can show that at least one of the three CP-even Higgs bosons has a large enough production cross-section in the $e^+e^- \rightarrow Zh_i^0$ ($i = 1, 2, 3$) process to be detected at an $e^+e^-$ linear collider with $\sqrt{s} \sim 300 - 500$ GeV. For this purpose we define the minimal production cross-section, $\sigma_{\text{min}}$, as a function of $\sqrt{s}$ such that at least one of these three $h_i^0$ has a larger production cross section than $\sigma_{\text{min}}$ irrespective of the parameters in the Higgs mass matrix. The $\sigma_{\text{min}}$ turns to be given by one third of the SM production cross-section with the Higgs boson mass equal to the upper-bound value. In Figure 4 we show $\sigma_{\text{min}}$ as a function of $\sqrt{s}$ for $m_{\text{stop}} = 1$ TeV. From this figure we can conclude that the discovery of at least one neutral Higgs boson is guaranteed at an $e^+e^-$ linear collider with an integrated luminosity of 10 fb$^{-1}$.

4. Determination of the heavy Higgs mass scale from branching measurements in the MSSM

In the previous section we have discussed the detectability of the Higgs boson in the SUSY SM with a gauge singlet Higgs field. Since the situation is better for the case of the MSSM we can show that at least one CP-even Higgs boson of the MSSM can be discovered at the first stage of an $e^+e^-$ linear collider experiment where the CM energy is $\sim 300 - 500$ GeV.
Figure 4: Minimal production cross section, $\sigma_{\text{min}}$, for the SUSY SM with a gauge singlet Higgs for the top mass $m_t=150$ and 180 GeV and $m_{\text{stop}}=1$ TeV.

If a Higgs boson is discovered, the next question is to determine whether this boson is the SM Higgs boson or a Higgs boson associated with some extension of the SM. For this purpose it is important to know to what extent the non-minimality of the Higgs boson can be detected through the investigation of the production cross-section and decay branching ratios. Here we would like to consider this problem in the context of the MSSM, that is, we would like to know whether the parameters in the Higgs sector are determined by various observable quantities related to the Higgs boson. Although it is possible to discover all five Higgs states at the first stage of the linear collider experiment, we may at first be able to find only one CP-even Higgs boson. In such a case it is important to determine the heavy Higgs mass scale because the heavy Higgs bosons become targets of the second stage of the $e^+e^-$ linear-collider experiments after the beam energy is increased.

In the following analysis let us assume that only one CP-even Higgs boson is discovered at the $e^+e^-$ linear-collider experiment. The free parameters required to specify the Higgs sector in the MSSM can be taken to be the CP-odd Higgs-boson mass ($m_A$), the ratio of two vacuum expectation values ($\tan \beta$) and masses of the top quark and the stop squark. The latter two parameters ($m_t, m_{\text{stop}}$) are necessary to evaluate the Higgs potential at the one-loop level. Suppose that the lightest CP-even Higgs boson is discovered such that its mass ($m_h$) is precisely known. Then we can solve for one of the free parameters, for example, $\tan \beta$, in terms of the other parameters. Assuming the top-quark mass is well determined by the time when the $e^+e^-$ linear collider is under operation, the unknown parameters for the Higgs sector are then $m_A$ and $m_{\text{stop}}$. The question is, to what extent these parameters are constrained from observable quantities such as the production cross-section and the various branching ratios.
Figure 5: $R_{br} \equiv \frac{Br(h \to cc)+Br(h \to gg)}{Br(h \to bb)}$ as a function of $m_A$ for $m_{suy} = 1, 5$ TeV and $m_h = 100, 110$ GeV. The following parameters are used for the calculation of the branching ratios: $m_t = 170$ GeV, $m_c(m_c) = 1.2$ GeV, $m_b(m_b) = 4.2$ GeV, $\alpha_s(m_Z) = 0.12$.

We show that one particular ratio of two branching ratios,

$$R_{br} \equiv \frac{Br(h \to cc) + Br(h \to gg)}{Br(h \to bb)},$$

is especially useful to constrain the heavy Higgs mass scale. In the MSSM, each of the two Higgs doublets couples to either up-type or down-type quarks. Therefore, the ratio of the Higgs couplings to up-type quarks and to down-type quarks is sensitive to the parameters of the Higgs sector, i.e. the angles $\alpha$ and $\beta$ in Section 2. Since the gluonic width of the Higgs boson is generated by a one-loop diagram with an internal top-quark, the Higgs-gluon-gluon coupling is essentially proportional to the Higgs-top coupling. Then $R_{br}$ is proportional to square of the ratio of the up-type and down-type Yukawa coupling constants. Since the up-type (down-type) Yukawa coupling constant contains a factor $\frac{\cos \alpha}{\sin \beta}$ $(\frac{\sin \alpha}{\cos \beta})$ compared to the SM coupling constant, $R_{br}$ is proportional to $(\tan \alpha \tan \beta)^{-2}$. In Figure 5 $R_{br}$ is shown as a function of $m_A$ for $m_{suy}(\equiv m_{stop}) = 1, 5$ TeV. From this figure we can see that $R_{br}$ is almost independent of $m_{stop}$. In fact, it can be shown that $R_{br}$ in the MSSM, normalized by $R_{br}$ in the SM, is approximately given by,

$$\frac{R_{br}(MSSM)}{R_{br}(SM)} \approx \left( \frac{m_t^2 - m_A^2}{m_Z^2 + m_A^2} \right)^2$$

for $m_A \gg m_h \sim m_Z$. Measuring this quantity to a good accuracy is therefore important for constraining the scale of the heavy Higgs mass. Note that $R_{br}$ approaches the SM value in the large $m_A$ limit. We can see that $R_{br}$ is reduced by 20% even for $m_A = 400$.
GeV. By simulation study for $e^+e^-$ linear collider experiments it is shown that the sum of the charm and gluonic branching ratios can be determined reasonably well. The statistical error in the determination of $R_{br}$ after two years at an $e^+e^-$ linear collider with $\sqrt{s} = 300$ GeV is 17%. We also need to know the theoretical ambiguity of the calculation of the branching ratios in $h \rightarrow b\bar{b}, c\bar{c}, gg$. At the moment the theoretical error in the calculation of $R_{br}$ is estimated to be rather large ($\sim 20\%$) due to uncertainties in $\alpha_s$ and $m_c$. But these uncertainties can be reduced in future from both theoretical and experimental improvements.

5. Conclusions

I have reviewed some aspects of the Higgs physics in the SUSY SM. I have shown that an future $e^+e^-$ linear collider is an ideal place to study the SUSY Higgs sector. At earlier stage of the experiment with $\sqrt{s} \sim 300 - 500$ GeV, it is easy to find a light Higgs boson predicted in SUSY standard models. In particular, both in the MSSM and the SUSY SM with a gauge singlet Higgs, at least one of neutral Higgs bosons is detectable. More importantly, detailed study on properties of the Higgs boson is possible at an $e^+e^-$ linear collider through measurements of various production cross-sections and branching ratios. As an example we show that the measurement of Higgs couplings to $c\bar{c}/gg/b\bar{b}$ gives us important information on the Higgs sector of the MSSM. It is therefore very important to build an $e^+e^-$ linear collider along with LHC, then combining both results we will be able to clarify the Higgs sector of the SM and explore physics beyond the SM such as the SUSY SM.

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