Determination of parameters of Higgs sector in the minimal supersymmetric Standard Model

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ABSTRACT

We examine whether parameters related to Higgs sector of the minimal supersymmetric standard model can be determined by detailed study of production cross section and decay branching ratios of the Higgs boson. Assuming that only the light Higgs boson is observed at a future $e^+e^-$ linear collider with $\sqrt{s} = 300 \sim 500\text{GeV}$, we show that values of $m_{\text{susy}}$ and $\tan\beta$ are restricted within a narrow limits in the $m_{\text{susy}}$ versus $\tan\beta$ plane by the combined analysis of the light Higgs properties. It is also pointed out that, in some case, the value of $\tan\beta$ may be restricted within a relatively low value, $\tan\beta = 1 \sim 5$.

In the search of the theory beyond the standard model, supersymmetric (SUSY) extension of the minimal standard model (SM) is considered to be an attractive and promising candidate. It is, therefore, important to investigate how the idea of SUSY can be explored in the future collider experiments such as LHC and $e^+e^-$ linear colliders. In this respect, the Higgs sector of the SUSY standard models can play a unique role. Since the Higgs sector has distinct features, its close investigation can give important information on the structure of these models.

In the minimal supersymmetric standard model (MSSM) the Higgs sector consists of two Higgs doublets, therefore, there exist five physical states; i.e. two CP-even neutral Higgs bosons ($h$ and $H$ with $m_h < m_H$), one CP-odd Higgs boson ($A$), and one pair of charged Higgs bosons ($H^\pm$). It is possible to derive specific predictions for this Higgs sector because the form of Higgs potential in the MSSM is very restricted in comparison with that in the general two Higgs doublets model. Especially, the upper bound on the mass of lightest CP-even neutral Higgs boson is given as about $130\text{GeV}$[1]. As for the possibility of Higgs boson discovery, it have been shown that at least one of CP-even neutral Higgs bosons is detectable at future $e^+e^-$ linear collider with $\sqrt{s} = 300 \sim 500\text{GeV}$[2]. Furthermore, the detectability of Higgs boson is guaranteed for large class of SUSY models with extended Higgs sector[3].
After the discovery of the Higgs boson in the MSSM, one of the questions of interest is what extent the parameters relating to the Higgs sector will be constrained from the detailed study of properties of the Higgs boson. By precisely measured branching ratios of the Higgs boson, the mass of CP-odd Higgs boson \( m_A \) can be constrained with almost independent of SUSY breaking mass scale \( m_{\text{susy}} \) even when the CP-odd Higgs boson will not be discovered at future linear colliders with \( \sqrt{s} = 300 \text{GeV} \). In this paper we consider the determination of parameters of Higgs sector in the MSSM assuming that only the lightest CP-even neutral Higgs boson will be observed at the future \( e^+e^- \) linear collider with \( \sqrt{s} = 300 \sim 500 \text{GeV} \). It is shown that the \( m_{\text{susy}} \)-tan \( \beta \) parameter space can be restricted within narrow region by precise measurements of Higgs boson properties.

Let us begin by listing the parameters of Higgs sector and the observables which can be used to determine these parameters. At the tree level, the masses of Higgs bosons and the mixing among Higgs bosons are parametrized by two parameters, i.e. CP-odd Higgs boson mass and the ratio of the vacuum expectation values \( \tan \beta = \frac{\langle H_2 \rangle}{\langle H_1 \rangle} \), where the \( H_1 \) is a Higgs doublet that couples to up-type quarks and the \( H_2 \) is a Higgs doublet that couples to down-type quarks and leptons. However, once the radiative corrections to the Higgs potential is taken into account, they bring new parameters in our analysis. In the calculation of the Higgs effective potential at one loop level, most important contribution comes from top and stop loop and therefore the relevant parameters are two stop masses \( m_{\tilde{t}_1}, m_{\tilde{t}_2} \), Higgsino mass parameter \( \mu \) and trilinear soft-breaking parameter \( A_t \).

For the moment, we assume that no significant effect is induced from the left-right mixing of the stop sector. Then, effectively there are three parameters relating to the Higgs sector. Usually, for these three parameters, we take \( m_A \), tan \( \beta \), and \( m_{\text{susy}} \) defined by \( m_{\text{susy}} = \sqrt{m_{\tilde{t}_1}m_{\tilde{t}_2}} \). Then the CP-even Higgs mass matrix is

\[
M_{\text{higgs}}^2 = \begin{pmatrix}
  m_Z^2 \cos^2 \beta + m_A^2 \sin^2 \beta & -(m_Z^2 + m_A^2) \cos \beta \sin \beta \\
  -m^2 m_Z^2 \sin 2\beta & m^2 m_Z^2 \sin^2 \beta + m_A^2 \cos^2 \beta + \delta_t / \sin^2 \beta
\end{pmatrix},
\]

where

\[
\delta_t = \frac{3m_{\tilde{t}}^4}{4\pi^2v^2} \ln \left( \frac{m_{\text{susy}}^2}{m_t^2} \right)
\]

represents the leading part of the radiative corrections stem from the top-stop loop effect.

The mass of neutral Higgses and Higgs mixing angle, \( \alpha \), are given by

\[
m_{h}^2 = \frac{1}{2} \left[ m_A^2 + m_Z^2 + \delta_t / \sin^2 \beta - \sqrt{\{(m_Z^2 - m_A^2) \cos 2\beta - \delta_t / \sin^2 \beta\}^2 + (m_Z^2 + m_A^2)^2 \sin^2 2\beta} \right],
\]

\[
m_{H}^2 = m_A^2 + m_Z^2 - m_h^2 + \delta_t / \sin^2 \beta,
\]

\[
\tan \alpha = \frac{(m_Z^2 + m_A^2) \cos \beta \sin \beta}{m_h^2 - (m_Z^2 \cos^2 \beta + m_A^2 \sin^2 \beta)}
\]
The lightest CP-even neutral Higgs boson is mainly produced through the Higgs bremsstrahlung process, \( e^+e^- \rightarrow Zh \), at \( e^+e^- \) linear collider with \( \sqrt{s} = 300 \sim 500 \text{GeV} \). If we assume that the decay modes of the Higgs boson to SUSY particles are not dominant, then the main decay mode of the Higgs boson is the \( h \rightarrow bb \) mode. In this case, the behavior of the Higgs boson may be similar to that of Higgs boson in the SM. The lightest Higgs boson then has sizable decay branching ratios in the modes \( h \rightarrow bb, \tau \bar{\tau}, c\bar{c} \) and \( gg \) 3.

With a reasonable luminosity of \( \sim 50 \text{fb}^{-1} \)/year, the mass of the Higgs boson, \( m_h \), can be determined precisely by the recoil mass distribution 4, 5, 6. The Higgs production cross section, \( \sigma(e^+e^- \rightarrow Zh) \), is obtained by the branching ratio of \( Z \) boson decaying to \( l\bar{l}(l = e, \mu) \) and the cross section of the event with the recoil mass around \( m_h \) 6. The production cross section multiplied by the branching ratio of \( h \rightarrow X(X = \{bb\}, \{\tau \bar{\tau}\}, \{c\bar{c} \text{ or } gg\}) \), \( \sigma(e^+e^- \rightarrow Zh)Br(h \rightarrow X) \), can be obtained by the \( ZX \) production rate with the invariant mass of \( X \) to be around \( m_h \) 4, 6.

The ratio of branching ratios or the ratio of partial decay widths are obtained by

\[
\frac{Br(h \rightarrow X_1)}{Br(h \rightarrow X_2)} = \frac{\Gamma(h \rightarrow X_1)}{\Gamma(h \rightarrow X_2)} = \frac{\sigma(e^+e^- \rightarrow Zh)Br(h \rightarrow X_1)}{\sigma(e^+e^- \rightarrow Zh)Br(h \rightarrow X_2)},
\]

where \( X_1 \) and \( X_2 \) are \( \{bb\}, \{\tau \bar{\tau}\} \) or \( \{c\bar{c} \text{ or } gg\} \). We can expect that \( Br(h \rightarrow \tau \bar{\tau})/Br(h \rightarrow bb) \) and \( Br(h \rightarrow c\bar{c} \text{ or } gg)/Br(h \rightarrow bb) \) will be determined in a reasonable precision 3, 4, 7.

The formulas for partial decay width of Higgs boson in MSSM is found, for example, in 8. Higgs-fermion-fermion couplings are listed in Table 9. The partial decay width for \( h \rightarrow bb \) and \( h \rightarrow \tau \bar{\tau} \) are proportional to the down-type fermion-Higgs coupling, and then the ratio \( Br(h \rightarrow \tau \bar{\tau})/Br(h \rightarrow bb) \) is the same as that in the SM. Therefore no information on the parameters of Higgs sector in the MSSM are obtained from this ratio. 3

On the other hand, as reported in 10, the ratio of \( Br(h \rightarrow c\bar{c} \text{ or } gg)/Br(h \rightarrow bb) \) is useful variable to constrain the value of \( m_A \), because \( Br(h \rightarrow c\bar{c} \text{ or } gg)/Br(h \rightarrow bb) \) depend on \( m_A \) strongly and almost independent of \( m_{\text{susy}} \).

The three parameters; \( m_A, \tan \beta \) and \( m_{\text{susy}} \); will be restricted by the observables mentioned above. The errors of observables have been estimated in detail 7. According to their estimation, the error of \( m_h \) is to be 0.1-0.5%. Therefore, in the following, we will treat the \( m_h \) as fixed variable. Then one of the three parameters is derived from other two with the formula of the lightest Higgs boson mass 3. Thus the remaining degrees of freedom of parameters are two. Hereafter we choose \( m_{\text{susy}} \) and \( \tan \beta \) as free parameters

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1. If the decay mode of Higgs boson to the SUSY particles will be observed, we can see obviously that the Higgs boson belongs to SUSY model. We are now interesting in the case that the SM-like Higgs boson will be observed. Therefore we will not consider about such a case.

2. Since availability of \( h \rightarrow WW^* \) depends crucially on the Higgs boson mass, we will not consider this mode here.

3. Although it is very difficult to measure the branching ratios of the mode \( c\bar{c} \) and \( gg \) separately, the sum of \( Br(h \rightarrow c\bar{c}) \) and \( Br(h \rightarrow gg) \) can be measured with reasonable precision 3, 4, 5, 6, 7. We denote the sum of \( Br(h \rightarrow c\bar{c}) \) and \( Br(h \rightarrow gg) \) as \( Br(h \rightarrow c\bar{c} \text{ or } gg) \).

4. This ratio is important to determine the bottom mass as discussed, for example, in 6, 7.
Table 1: Couplings of light Higgs boson to fermion pair in the MSSM and the SM. The $u$, $d$ and $l$ stand for up-type quarks, $u = \{u, c, t\}$; down-type quarks, $d = \{d, s, b\}$; leptons, $l = \{e, \mu, \tau\}$.

and then derive the value of $m_A$ with Higgs mass formula for the fixed value of $m_h$. For $m_h = 120\text{GeV}$, figure 1 shows the contour plot of $m_A$ in the $m_{\text{susy}}$ versus $\tan \beta$ plane.

We can constrain the value of $m_A$ by $\text{Br}(h \to c\bar{c} \text{ or } gg)/\text{Br}(h \to b\bar{b})$ [4]. The knowledge of the magnitude of $m_A$ is useful to set the center of mass energy at the next step of future $e^+e^-$ linear collider experiments.

However, determination of $m_{\text{susy}}$ is necessary to know SUSY breaking scale. Determination of $\tan \beta$ has great impact on both theoretical and experimental study of SUSY model, because not only the physics of Higgs sector but also that of other SUSY sector, for example chargino and neutralino sector, depend on $\tan \beta$. Therefore we must start to use other observables in order to determine the value of both $m_{\text{susy}}$ and $\tan \beta$.

Both $\sigma(e^+e^- \to Zh)$ and $\sigma(e^+e^- \to Zh)\text{Br}(h \to b\bar{b})$ depend on the angle $\alpha$ and $\beta$ as follows,

$$
\sigma(e^+e^- \to Zh) \propto \sin^2(\alpha - \beta),
$$

$$
\sigma(e^+e^- \to Zh)\text{Br}(h \to b\bar{b}) \propto \sin^2(\alpha - \beta) \left( \frac{\sin \alpha}{\cos \beta} \right)^2.
$$

As discussed in [4], we obtain the following approximate relation,

$$
\frac{\text{Br}(h \to c\bar{c} \text{ or } gg)}{\text{Br}(h \to b\bar{b})} \propto \left( \frac{1}{\tan \beta \tan \alpha} \right)^2.
$$

Therefore these observables give us different constraint on the value of $m_{\text{susy}}$ and $\tan \beta$. Hereafter we use shortened notations defined as follows, $\sigma_{Zh} \equiv \sigma(e^+e^- \to Zh)$, $\sigma_{Zh}\text{Br}(b\bar{b}) \equiv \sigma(e^+e^- \to Zh)\text{Br}(h \to b\bar{b})$ and $R_{\text{br}} \equiv \text{Br}(h \to c\bar{c} \text{ or } gg)/\text{Br}(h \to b\bar{b})$.

Figure 2(a)(b)(c) show the contour plots of $\sigma_{Zh}$, $\sigma_{Zh}\text{Br}(b\bar{b})$ and $R_{\text{br}}$ respectively in the $m_{\text{susy}}$ versus $\tan \beta$ plane when $m_h = 120\text{GeV}$. The shape of contours in figure 2(b) is somewhat different from the other two in the left side of the figure. Figure 2(a) of $\sigma_{Zh}$ is similar to figure 2(c) of $R_{\text{br}}$, however, figure 2(a) shows gentle slope as compared to figure 2(c).
Now we combine these observables to estimate for the constraints on the values of $m_{\text{susy}}$ and $\tan \beta$. For this purpose, we take $m_{\text{susy}}$ and $\tan \beta$ as fitting parameters and then perform the $\chi^2$ test in the $m_{\text{susy}}$ versus $\tan \beta$ plane for the fixed value of $m_h$, for example $m_h = 120\text{GeV}$. As for the value of $m_A$, its value is derived from Higgs mass formula(3) at point by point in the $m_{\text{susy}}$ versus $\tan \beta$ plane.

However, we input the values of $m_h$, $m_A^0$ and $m_{\text{susy}}^0$ as true values for the $\chi^2$ test, because these variables have clear physical meanings as a mass of particles or a typical mass scale for $m_{\text{susy}}$. As for $\tan \beta$, the ”true” value is calculated from the input parameters; $m_h$, $m_A^0$ and $m_{\text{susy}}^0$; by Higgs mass formula(3).

Definition of $\chi^2$ is given by

$$\chi^2 \equiv \left\{ \left( \frac{\sigma_{Zh} - \sigma_{Zh}^0}{\delta \sigma_{Zh}} \right)^2 + \left( \frac{\sigma_{Zh} Br(b\bar{b}) - \sigma_{Zh} Br(b\bar{b})^0}{\delta (\sigma_{Zh} Br(b\bar{b}))} \right)^2 + \left( \frac{R_{br} - R_{br}^0}{\delta (R_{br})} \right)^2 \right\}. \tag{7}$$

The $\delta (\sigma_{Zh})$, $\delta (\sigma_{Zh} Br(b\bar{b}))$ and $\delta (R_{br})$ are the expected experimental errors. The estimated error of each observable reported in [4] is summarized in Table 2. The $\sigma_{Zh}^0$, $\sigma_{Zh} Br(b\bar{b})^0$ and $R_{br}^0$ are the central value derived from the input parameters, $m_h$, $m_A^0$ and $m_{\text{susy}}^0$. The $\sigma_{Zh}$, $\sigma_{Zh} Br(b\bar{b})$ and $R_{br}$ are the variables calculated at each point in the $m_{\text{susy}}$ versus $\tan \beta$ plane. To calculate Higgs production cross section, we use $\sqrt{s} = 350\text{GeV}$.

The contour plots of $\chi^2$ for $m_h = 120\text{GeV}$ are shown in Figure 3(a)(b) with 95%CL contour. We find in figure 3(a) that the $\tan \beta$ is restricted within a relatively small value, $\tan \beta < 4.5$, and the value of $m_{\text{susy}}$ is weakly restricted, $m_{\text{susy}} > 1\text{TeV}$. Figure 3(b) shows the contour plot of $\chi^2$ for other input value. In figure 3(b), although the upper bound on the $m_{\text{susy}}$ and $\tan \beta$ is not restricted in the displayed region, the $m_{\text{susy}}$-$\tan \beta$ parameter space is restricted within a narrow limits.

| $m_h$ (GeV) | $\delta (m_h)$ | $\delta (\sigma_{Zh})$ | $\delta (\sigma_{Zh} Br(b\bar{b}))$ | $\delta (R_{br})$ |
|------------|----------------|--------------------------|-------------------------------------|-------------------|
| 110        | 0.1 $\sim$ 0.5% | $\sim$ 7%                 | $\sim$ 2.5%                         | $\sim$ 14%        |
| 120        | 0.1 $\sim$ 0.5% | $\sim$ 7%                 | $\sim$ 3.5%                         | $\sim$ 14%        |

Table 2: List of error for observables discussed in [4]. $R_{br}$ is defined by $R_{br} \equiv Br(h \rightarrow c\bar{c} \text{ or } gg)/Br(h \rightarrow b\bar{b})$.

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5In order to distinguish ”true” value of $m_A$ and $m_{\text{susy}}$ from the mass of $m_A$ and $m_{\text{susy}}$ as fitting parameters, the index ”0” is appended to the ”true” variables.

6Of course when $m_A < \sqrt{s}/2$, the CP-odd Higgs boson will be produced by associated production process, $e^+e^- \rightarrow Ah$. In this case we can use many observables depending on SUSY parameters and should convert a strategy of our analysis to another one. Since we assume that only light Higgs boson is discovered, we constrain our analysis for $m_A > \sqrt{s}/2 \sim 180\text{GeV}$. Hereafter we will not consider the case for $m_A < 180\text{GeV}$.
This results can be understood as follows. Once the value of $m_h$ is fixed, $\tan\beta$ and $m_{\text{susy}}$ is strongly correlated by Higgs mass formula (3). We can consider that figure 4 shows the value of $\tan\beta$ as a function of $m_{\text{susy}}$ for fixed values of $m_h$ and $m_A$. From figure 4, the $m_{\text{susy}}$-tan $\beta$ parameter space is restricted within a relatively narrow region even if $m_A$ vary from $\sim 200\text{GeV}$ to larger than 1 TeV. However the constraint obtained from figure 4 is somewhat weak as compared to figure 3(a)(b). Figure 4 show the contour of $\chi^2$ superposed by the curves for central value of each observable. We can see from figure 4 that the $R_{br}$ contribute strongly to the constraint on the $m_{\text{susy}}$-$\tan\beta$ plane. In figures 3(a) and 4, the value of $m_A$ is restricted within about 180-$\sim$230GeV by $R_{br}$ and as a result the region satisfying the constraints become narrow as compared to that obtained by figure 4. The reason why the upper bound on $\tan\beta$ is obtained in figure 3(a) is, in addition to $R_{br}$, the $\sigma_{Z\bar{b}}B_r(b\bar{b})$ contribute effectively to the constraint on the $m_{\text{susy}}$-$\tan\beta$ plane.

So far, we have neglected the L-R mixing of stop sector. In case of taking account of the L-R mixing effect, contours in figures should be shifted with varying the value of $A_t$ and $\mu$ parameter. However the result in our analysis will not change essentially, because $R_{br}$ is almost independent of the parameters of stop sector as shown in 4.

On the theoretical aspect, the requirement of yukawa coupling unification in SUSY-GUT[11] restricts the value of $\tan\beta$ within two solutions. One is the small $\tan\beta$ solution, $\tan\beta = 1 \sim 3$. Another one is the large $\tan\beta$ solution, $\tan\beta \sim 50$. There are mainly two types of scenarios for yukawa coupling unification. These are the bottom-tau yukawa unification and the top-bottom-tau yukawa unification scenarios. The requirement of bottom-tau yukawa coupling unification suggests both the small $\tan\beta$ solution and the large $\tan\beta$ solution. However the requirement of top-bottom-tau yukawa coupling unification suggests only the large $\tan\beta$ solution. Therefore, if large value of $\tan\beta$ will be excluded by precise measurements of light Higgs properties at the future linear collider, as we have shown in case of figure 3(a), the experiments may rule out the top-bottom-tau yukawa unification scenario even when only the lightest Higgs boson will be observed.

We conclude our discussion. We have examined whether the parameters of Higgs sector in the MSSM can be determined by detailed study of Higgs properties. We show that the value of $\tan\beta$ and $m_{\text{susy}}$ is restricted within the very narrow limits even when only the light Higgs boson is discovered and its mass is determined precisely. The $R_{br}$ contributes largely to the constraint on the $m_{\text{susy}}$-$\tan\beta$ plane. We also show that, in some case, the upper bound on $\tan\beta$ may be obtained by combining analysis of observables such as $\sigma_{Z\bar{b}}$, $\sigma_{Z\bar{b}}B_r(b\bar{b})$ and $R_{br}$. However to obtain more strict constraint on both $m_{\text{susy}}$ and $\tan\beta$, we have need of constraints by other quantities obtained from heavy Higgs and/or SUSY particles.

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Figure Caption

**Figure 1:** Contour plot of the $m_A$ for $m_h = 120$GeV are shown in the $m_{susy}$ versus tan $\beta$ plane. We take the top quark mass as $m_t = 175$GeV. The Higgs mass formula(3) can not be satisfied for $m_h = 120$GeV in the left and bottom left region of figure. In the large tan $\beta$ and large $m_{susy}$ region, the value of $m_A$ is always larger than 120GeV which is the value of $m_h$.

**Figure 2:** Contours plot of (a) $\sigma_{Zh}$; (b) $\sigma_{Zh} Br(b\bar{b})$; and (c) $R_{br}$ are shown. We take the quark masses as $m_t = 175$GeV, $m_b(m_h) = 4.2$GeV and $m_c(m_c) = 1.3$GeV. The strong coupling constant is taken as $\alpha_s(m_Z) = 0.12$.

**Figure 3:** Contour plot of $\chi^2$ with $\chi^2 = 4.61$ (a) for $(m_h, m_A, m_{susy})=(120$GeV, 200GeV, 3500GeV) and (b) for $(m_h, m_A, m_{susy})=(120$GeV, 250GeV, 1000GeV). $\chi^2 < 4.61$ for the inside of a narrow region.

**Figure 4:** Contour plot of $\chi^2$ with $\chi^2 = 4.61$; curves giving the central values of $\sigma_{Zh}$, $\sigma_{Zh} Br(b\bar{b})$ and $R_{br}$ are superposed on the figure. Input values are taken to be the same as figure 3(a).
Figure 1:
Figure 2:
Figure 3: (a)
Figure 3: (b)
Figure 4:

- $\sigma_{zh}^0 = 164.6 \text{ fb}^{-1}$
- $\sigma_{zh}^0 \text{Br}^0 = 135.2 \text{ fb}^{-1}$
- $R_{br}^0 = 0.0448$

Input:
- $m_t = 120 \text{ GeV}$
- $m_A = 200 \text{ GeV}$
- $m_{\text{susy}} = 3500 \text{ GeV}$

$\chi^2 = 4.61$

Value of each observables for the input parameters.