Impact of Light Higgs Properties on the
Determination of \( \tan \beta \) and \( m_{\text{susy}} \)

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Abstract

We examine whether parameters related to the Higgs sector of the minimal supersymmetric standard model can be determined by detailed study of the production cross section and decay branching ratios of the Higgs boson. Assuming that only the light Higgs boson will be observed at a future \( e^+e^- \) linear collider with \( \sqrt{s} = 300 \sim 500 \) GeV, we show that values of \( m_{\text{susy}} \) and \( \tan \beta \) are restricted within a narrow region 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, \( \tan \beta \) may be restricted to a relatively small value, \( \tan \beta = 1 \sim 5 \).

The minimal supersymmetric standard model (MSSM) is considered to be an attractive candidate as a theory beyond the standard model (SM). In the MSSM, the Higgs sector consists of two Higgs doublets, and there exist five physical states: two CP-even Higgs bosons \( (h \text{ and } H) \), 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 the Higgs potential in the MSSM is very restricted in comparison with that in the general two Higgs doublets model. In particular, the upper bound on the mass of the lightest CP-even neutral Higgs boson is predicted as about 130 GeV.[1] As for the detectability of the Higgs boson, it has been shown that at least one CP-even neutral Higgs boson should be detectable at a future \( e^+e^- \) linear collider with \( \sqrt{s} = 300 \sim 500 \) GeV.[2] Furthermore, the detectability of the Higgs boson is claimed for a large class of SUSY standard models with extended Higgs sectors.[3]

Once the Higgs boson is discovered, one of the questions of interest is to what extent the parameters related to the Higgs sector will be constrained from the detailed study of properties of the Higgs boson. By branching ratios of the Higgs boson, the mass of a CP-odd Higgs boson \( (m_A) \) can be constrained almost independently of the SUSY breaking mass scale \( (m_{\text{susy}}) \) even if the CP-odd Higgs boson is not discovered at future linear colliders with \( \sqrt{s} = 300 \) GeV.[4]

In this paper we consider the determination of parameters of the Higgs sector in the MSSM assuming that only the lightest CP-even Higgs boson will be observed at a future \( e^+e^- \) linear collider with \( \sqrt{s} = 300 \sim 500 \) GeV. It is shown that the allowed \( m_{\text{susy}}-\tan \beta \) parameter space can be restricted within a narrow region by precise measurements of Higgs boson properties.

Let us begin by listing the parameters of the 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 angle among Higgs bosons are determined by two parameters, the CP-odd Higgs boson mass and the ratio of the vacuum expectation values \( (\tan \beta = \langle H_2 \rangle / \langle H_1 \rangle) \), where \( H_1 \) is a Higgs doublet that couples to up-type quarks and \( H_2 \) is a Higgs doublet that couples to down-type quarks and leptons. However, once the radiative corrections to the Higgs potential are taken into account, they bring out new parameters in our analysis. In the calculation of the Higgs effective potential at the one loop level, the most important contribution comes from the top and stop loop, and therefore the relevant parameters are two stop masses \( (m_{\tilde{t}_1}, m_{\tilde{t}_2}) \), a Higgsino mass parameter

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(μ), and a 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 related to the Higgs sector. As usual, for these three parameters, we take m_A, tan β, and m_{susy} defined by m_{susy} = \sqrt{m_{t_1}m_{t_2}}. Then the CP-even Higgs mass matrix is

\[ M_{\text{higgs}}^2 = \begin{pmatrix} m_Z^2 \cos^2 \beta + m_A^2 \sin^2 \beta & -(m_Z^2 + m_A^2) \cos \beta \sin \beta \\ -(m_Z^2 + m_A^2) \cos \beta \sin \beta & m_Z^2 \sin^2 \beta + m_A^2 \cos^2 \beta + \frac{\delta_t}{\sin^2 \beta} \end{pmatrix}, \tag{1} \]

where

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

represents the leading part of the radiative corrections due to the top-stop loop effect, with \( v = \sqrt{\langle H_2 \rangle^2 + \langle H_1 \rangle^2} \approx 174 \text{ GeV} \). The masses of CP-even Higgs bosons and the Higgs mixing angle, \( \alpha \), are given by

\[ m_h^2 = \frac{1}{2} \left[ m_A^2 + m_Z^2 + \delta_t/\sin^2 \beta \right] + \sqrt{\left\{ (m_Z^2 - m_A^2) \cos 2\beta - \delta_t/\sin^2 \beta \right\}^2 + (m_Z^2 + m_A^2)^2 \sin^2 2\beta}, \tag{3} \]

\[ m_H^2 = m_A^2 + m_Z^2 - m_h^2 + \frac{\delta_t}{\sin^2 \beta}, \tag{4} \]

\[ \tan \alpha = \frac{(m_Z^2 + m_A^2) \cos \beta \sin \beta}{m_h^2 - (m_Z^2 \cos^2 \beta + m_A^2 \sin^2 \beta)}. \tag{5} \]

The lightest CP-even Higgs boson is mainly produced through the Higgs-strahlung process, \( e^+ e^- \rightarrow Zh \), at a \( e^+ e^- \) 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\(^1\), then the main decay mode of the Higgs boson is the \( h \rightarrow b\bar{b} \) mode. In this case, the behavior of the Higgs boson may be similar to that of a Higgs boson in the SM. The lightest Higgs boson then has sizable decay branching ratios in the modes \( h \rightarrow b\bar{b}, \tau\bar{\tau}, c\bar{c} \) and \( gg \)\(^2\)

With a reasonable luminosity of \( \sim 50 \text{ fb}^{-1}/\text{year} \), the mass of the Higgs boson, \( m_h \), can be determined precisely by the recoil mass distribution.\(^3\) The Higgs production cross section, \( \sigma(e^+ e^- \rightarrow Zh) \), is obtained by the branching ratio of the \( Z \) boson decaying into \( l\bar{l} (l = e, \mu) \) and the cross section of the event with the recoil mass around \( m_h \).\(^4\) The production cross section multiplied by the branching ratio of \( h \rightarrow X (X = \{b\bar{b}, \{\tau\bar{\tau}, \{c\bar{c} or gg\}) \) \) \( \sigma(e^+ e^- \rightarrow Zh) \Br(h \rightarrow X) \), can be obtained by the \( ZX \) production rate with the invariant mass of \( X \) being around \( m_h \).\(^5\)\(^6\)

The three parameters \( m_A, \tan \beta \) and \( m_{susy} \) will be restricted by the observables mentioned above. Expected experimental errors of observables have been estimated in detail.\(^7\) According to these estimates, the error of \( m_h \) should be \( 0.1 \sim 0.5\% \). Therefore, in the following, we treat the value of \( m_h \) as fixed. Thus there are two remaining degrees of freedom of parameters. Hereafter we choose \( m_{susy} \) and \( \tan \beta \) as free parameters and derive the value of \( m_A \) with the Higgs mass formula Eq. (3) for the fixed value of \( m_h \). For \( m_h = 120 \text{ GeV} \), Fig. \( 1 \) displays the contour plot of \( m_A \) in the \( m_{susy} \)-\( \tan \beta \) plane.

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\(^1\) In our analysis, we use the Higgs mass matrix including the \( L-R \) mixing effect of two stops.\(^1\)

\(^2\) If decays of the Higgs boson to the SUSY particles are observed, we can see obviously that the Higgs boson belongs to the SUSY model. We will not consider such a case because we are now interested in the case that the SM-like Higgs boson will be observed.

\(^3\) Since the availability of \( h \rightarrow WW^* \) depends crucially on the Higgs boson mass, we will not consider this mode here.

\(^4\) Although it is very difficult to measure the branching ratios of the modes \( c\bar{c} \) and \( gg \) separately, the sum of \( \Br(h \rightarrow c\bar{c}) \) and \( \Br(h \rightarrow gg) \) can be measured with reasonable precision.\(^6\) We denote the sum of \( \Br(h \rightarrow c\bar{c}) \) and \( \Br(h \rightarrow gg) \) as \( \Br(h \rightarrow c\bar{c} or gg) \).
Figure 1: Contour plots of the value of $m_A$ for $m_h = 120$ GeV are shown in the $m_{\text{susy}}$ versus tan $\beta$ plane. We take the top quark mass as $m_t = 175$ GeV. The Higgs mass formula Eq.(3) can not be satisfied for $m_h = 120$ GeV in the left and bottom left region in the figure. In large tan $\beta$ and large $m_{\text{susy}}$ region, the value of $m_A$ is always larger than 120 GeV when $m_h = 120$ GeV.

Table 1: Couplings of the light Higgs boson to a fermion pair in the MSSM and the SM. $u$, $d$ and $l$ represents up-type quarks ($u = \{u, c, t\}$), down-type quarks ($d = \{d, s, b\}$), and leptons ($l = \{e, \mu, \tau\}$).

|          | $h-u-u$ | $h-d-d$ | $h-l-l$ |
|----------|---------|---------|---------|
| MSSM     | $-i \frac{m_u \cos \alpha}{v} \sin \beta$ | $i \frac{m_d \sin \alpha}{v} \cos \beta$ | $i \frac{m_l \sin \alpha}{v} \cos \beta$ |
| SM       | $-i \frac{m_u}{v}$ | $-i \frac{m_d}{v}$ | $-i \frac{m_l}{v}$ |

The ratio of branching ratios, for example $\text{Br}(h \rightarrow c\bar{c} \text{ or } gg)/\text{Br}(h \rightarrow b\bar{b})$, will be determined with reasonable precision.\[7, 8, 10\] The formulas for the partial decay width of the Higgs boson in the MSSM are derived, for example, in Ref.\[11\]. Higgs-fermion-fermion couplings are listed in Table 1. The partial decay width for $h \rightarrow b\bar{b}$ and $h \rightarrow \tau\bar{\tau}$ are proportional to the down-type fermion-Higgs coupling, and then the ratio $\text{Br}(h \rightarrow \tau\bar{\tau})/\text{Br}(h \rightarrow b\bar{b})$ is the same as that in the SM. Therefore no information on the parameters of the Higgs sector in the MSSM are obtained from this ratio.\[4\] On the other hand, as reported in Ref.\[4\], the ratio $\text{Br}(h \rightarrow c\bar{c} \text{ or } gg)/\text{Br}(h \rightarrow b\bar{b})$ is a useful variable to constrain the value of $m_A$, because the ratio strongly depends on $m_A$ but is almost independent of $m_{\text{susy}}$.

The determination of tan $\beta$ has great implication for both the theoretical and experimental study of SUSY standard models, because not only the physics of the Higgs sector but also that of other SUSY sectors, for example the chargino and neutralino sector, depend on tan $\beta$. Therefore we must start to use other observables in order to determine the values of both $m_{\text{susy}}$ and tan $\beta$.

Hereafter we use abbreviated notation defined as follows: $\sigma_{Zh} \equiv \sigma(e^+e^- \rightarrow Zh)$, $\sigma_{Zh,\text{Br}(b\bar{b})} \equiv \sigma(e^+e^- \rightarrow Zh)\text{Br}(h \rightarrow b\bar{b})$ and $R_{\text{br}} \equiv \text{Br}(h \rightarrow c\bar{c} \text{ or } gg)/\text{Br}(h \rightarrow b\bar{b})$. These observables give us different constraints on the values of $m_{\text{susy}}$ and tan $\beta$. As discussed in Ref.\[4\], we obtain the

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5 This ratio is important to determine the bottom mass, as discussed, for example, in Refs.\[4, 8\].
Figure 2: Contours plots of (a) \( \sigma_{Zh} \), (b) \( \sigma_{Zh} Br(b\bar{b}) \), and (c) \( R_{br} \) are shown. We take the quark masses as \( m_t = 175 \text{ GeV} \), \( m_b(m_b) = 4.2 \text{ GeV} \) and \( m_c(m_c) = 1.3 \text{ GeV} \). The strong coupling constant is taken as \( \alpha_s(m_Z) = 0.12 \).

approximate relation

\[ R_{br} \propto \left( \frac{1}{\tan \beta \tan \alpha} \right)^2. \]

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

\[
\sigma_{Zh} \propto \sin^2(\alpha - \beta), \\
\sigma_{Zh} Br(b\bar{b}) \propto \sin^2(\alpha - \beta) \left( 1 + \frac{m^2_\tau}{3m^2_b} + R_{br} + f(\alpha, \beta) \right)^{-1},
\]

where

\[ f(\alpha, \beta) \equiv \left( \Gamma_{\text{tot}} - \sum_X \Gamma(h \to X) \right) / \Gamma(h \to b\bar{b}), \quad (6) \]

\( X = b\bar{b}, \tau\bar{\tau}, c\bar{c}, gg \). Here \( \Gamma_{\text{tot}} \) is the total decay width of the light Higgs boson. In Fig. 2(a)~(c) display the contour plots of \( \sigma_{Zh}, \sigma_{Zh} Br(b\bar{b}) \) and \( R_{br} \), respectively, in the \( m_{\text{susy}} \)-tan \( \beta \) plane for \( m_h = 120 \text{ GeV} \). The shape of the contours in Fig. 2(b) is somewhat different from the other two in the left side of the figure. Fig. 2(a) for \( \sigma_{Zh} \) is similar to Fig. 2(c) for \( R_{br} \). However, Fig. 2(a) displays gentle slope, as compared with Fig. 2(c).

Now we combine these observables to estimate 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 \( m_{\text{susy}} \)-tan \( \beta \) plane for a fixed value of \( m_h \). The value of \( m_A \) is derived from the Higgs mass formula Eq. (3) point-by-point in the \( m_{\text{susy}} \)-tan \( \beta \) plane.

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

Definition of \( \chi^2 \) is given by

\[
\chi^2 \equiv \left\{ \frac{(\sigma_{Zh} - \sigma^0_{Zh})}{\delta \sigma_{Zh}} \right\}^2 + \left\{ \frac{\sigma_{Zh} Br(b\bar{b}) - \sigma^0_{Zh} Br(b\bar{b})}{\delta \sigma_{Zh} Br(b\bar{b})} \right\}^2 + \left( \frac{R_{br} - R^0_{br}}{\delta (R_{br})} \right)^2, \quad (7)
\]

6 In order to distinguish “true” values of \( m_A \) and \( m_{\text{susy}} \) from \( m_A \) and \( m_{\text{susy}} \) as fitting parameters, the index “0” is appended to the “true” values.
Table 2: List of errors for each observable discussed in Ref. \[8\]. $R_{br}$ is defined by $R_{br} \equiv Br(h \rightarrow c\bar{c} \text{ or } gg)/Br(h \rightarrow bb)$ \[1\].

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

Figure 3: Contour plot of $\chi^2$ with $\chi^2 = 4.61$ (a) for $(m_h, m_A^0, m_{susy}^0) = (120 \text{ GeV}, 200 \text{ GeV}, 3500 \text{ GeV})$ and (b) for $(m_h, m_A^0, m_{susy}^0) = (120 \text{ GeV}, 250 \text{ GeV}, 1000 \text{ GeV})$. $\chi^2 < 4.61$ inside a narrow region.

where $\delta(\sigma_{Zh})$, $\delta(\sigma_{Zh}Br(bb))$ and $\delta(R_{br})$ represent expected experimental errors. The estimated error of each observable reported in Ref. \[8\] is summarized in Table 2. $\sigma_{Zh}^0$, $\sigma_{Zh}Br(bb)^0$ and $R_{br}^0$ are the central values derived from the input parameters, $m_h$, $m_A^0$ and $m_{susy}^0$. The values of $\sigma_{Zh}$, $\sigma_{Zh}Br(bb)$ and $R_{br}$ are calculated at each point in the $m_{susy}$ versus tan $\beta$ plane. To calculate the 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 Figs. 3(a) and (b) with a 95\% CL contour. We find in Fig. 3(a) that the tan $\beta$ is restricted within a relatively small value, tan $\beta < 4.5$, and the value of $m_{susy}$ is weakly restricted, $m_{susy} > 1 \text{ TeV}$. Fig. 3(b) displays the contour plot of $\chi^2$ for other input value. In Fig. 3(b), although the upper bounds on $m_{susy}$ and tan $\beta$ are not obtained in the displayed region, the allowed $m_{susy}$-tan $\beta$ parameter space is restricted within a narrow region.

Next, in order to show how each observable contributes to constrain the $m_{susy}$-tan $\beta$ parameter space, we show the $\chi^2$ contour plots in Fig. 4 by using just two observables among the three observables. We can see from Fig. 4 that $R_{br}$ contributes strongly to the constraint on the $m_{susy}$-tan $\beta$ plane.

The results above can be understood as follows. Once the value of $m_h$ is fixed, tan $\beta$ and $m_{susy}$ are strongly correlated by the Higgs mass formula Eq. (3). We can consider Fig. 1 as showing the value of tan $\beta$ as a function of $m_{susy}$ for fixed values of $m_h$ and $m_A$. From Fig. 1, the $m_{susy}$-tan $\beta$ parameter space is restricted within a relatively narrow region even if $m_A$ varies.

Of course when $m_A < \sqrt{s}/2$, the CP-odd Higgs boson will be produced by an associated production process, $e^+e^- \rightarrow AH$. In this case we can use many observables depending on SUSY parameters and should convert the strategy of our analysis to another one. Since we assume that only a light Higgs boson will be discovered, we constrain our analysis to $m_A > \sqrt{s}/2 \sim 180 \text{ GeV}$. Hereafter we will not consider the case $m_A < 180 \text{ GeV}$.
Figure 4: Contour plots of $\chi^2$ with $\chi^2 = 4.61$ when we use just two observables among $\sigma_{Zb}, \sigma_{Zh}Br(b\bar{b})$ and $R_{br}$: (a) $\sigma_{Zb}$ and $\sigma_{Zh}Br(b\bar{b})$, (b) $\sigma_{Zh}$ and $R_{br}$, (c) $\sigma_{Zh}Br(b\bar{b})$ and $R_{br}$. Input values of the parameters are taken to be the same as in Fig. 3(a).

from $\sim 200$ GeV to larger than 1 TeV. However the constraint obtained from Fig. 1 is weak as compared with that from Fig. 3(a). We can see from Fig. 1 that $R_{br}$ contributes strongly to the constraint on the $m_{\text{susy}}$-tan $\beta$ plane. In Figs. 3(a) and 4, the value of $m_A$ is restricted within about $180$–$230$ GeV by $R_{br}$, and as a result the region satisfying the constraints becomes narrow as compared with that obtained in Fig. 1. The reason why the upper bound on tan $\beta$ is obtained in Fig. 3(a) is, in addition to $R_{br}$, $\sigma_{Zh}Br(b\bar{b})$ contributes effectively to the constraint on the $m_{\text{susy}}$-tan $\beta$ plane.

So far, we have neglected the $L$-$R$ mixing of the stop sector. We can include the $L$-$R$ mixing effects and take non-zero values of $A_t$ and $\mu$ in our analysis. In this case, examples are shown in Fig. 4. The contour should be shifted by varying the values of $A_t$ and $\mu$. However, the result of our analysis will not change essentially, because $R_{br}$ is almost independent of the parameters of the stop sector, as shown in Ref. [4].

With regard to theoretical aspects, the requirement of Yukawa coupling unification in SUSY-GUT [2] restricts the value of tan $\beta$ to two solutions. One is the small tan $\beta$ solution, tan $\beta = 1$ $\sim$ 3, and the other 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 a large value of tan $\beta$ will be excluded by precise measurements of light Higgs properties at a future linear collider, for example as we have shown in Fig. 3(a), the experiments may rule out the top-bottom-tau Yukawa unification scenario even if only the lightest CP-even Higgs boson is observed.

We now conclude our discussion. We have examined whether the parameters of the Higgs sector in the MSSM can be determined by detailed study of Higgs properties. We have found that the values of tan $\beta$ and $m_{\text{susy}}$ are restricted within a very narrow region even if only the light Higgs boson is discovered. $R_{br}$ contributes strongly to the constraint on the $m_{\text{susy}}$-tan $\beta$ plane. We also have shown that the upper bound on tan $\beta$ may be obtained by combining analysis of observables when $\sigma_{Zh}Br(b\bar{b})$ contributes effectively to the constraint. However, to obtain a more strict constraint on both $m_{\text{susy}}$ and tan $\beta$, we need constraints inferred from other quantities obtained from heavy Higgs and/or SUSY particles.

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Figure 5: Contour plots of $\chi^2$ with $\chi^2 = 4.61$ including the L-R mixing effect of two stops. The values shown in the parenthesis represent $(A_t, \mu)$ in GeV. Input values of other parameters are taken to be the same as in Fig. 3(a).

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