Higgs Particle Decays in Supersymmetry

A. Bartl\textsuperscript{a}, H. Eberl\textsuperscript{b}, K. Hidaka\textsuperscript{c}, T. Kon\textsuperscript{d}, W. Majerotto\textsuperscript{b}, and Y. Yamada\textsuperscript{e}

\textsuperscript{a} Institut für Theoretische Physik, Universität Wien, A-1090 Vienna, Austria
\textsuperscript{b} Institut für Hochenergiephysik der Österreichischen Akademie der Wissenschaften, A-1050 Vienna, Austria
\textsuperscript{c} Department of Physics, Tokyo Gakugei University, Koganei, Tokyo 184, Japan
\textsuperscript{d} Faculty of Engineering, Seikei University, Musashino, Tokyo 180, Japan
\textsuperscript{e} Department of Physics, Tohoku University, Sendai 980-77, Japan

Abstract

We present a detailed study of the decays of the Higgs bosons $H^+$, $H^0$, and $A^0$ within the Minimal Supersymmetric Standard Model including SUSY–QCD corrections. We find that the supersymmetric modes $\tilde{t}\bar{b}$ ($\tilde{t}\tilde{t}$, and for large $\tan\beta$ $\tilde{b}\tilde{b}$) can dominate the $H^+$ ($H^0$, $A^0$) decays in a wide range of the model parameters due to the large Yukawa couplings and mixings of $\tilde{t}$ and $\tilde{b}$. Compared to the conventional modes $H^+ \rightarrow \tau^+\nu_{\tau}, \tilde{t}\tilde{b}$, and $H^0, A^0 \rightarrow t\bar{t}, b\bar{b}$, the supersymmetric modes can have an important impact on the Higgs boson searches at future colliders.

1 Introduction

The Minimal Supersymmetric Standard Model (MSSM) \cite{mssm} implies the existence of five physical Higgs bosons $h^0$, $H^0$, $A^0$, and $H^{\pm}$ \cite{higgsbosons}. For the search of these particles a precise knowledge of all possible decay modes is necessary.

The Higgs boson decays to supersymmetric (SUSY) particles could be very important if they are kinematically allowed. This can be the case for the charged Higgs boson $H^+$, and the neutral Higgs bosons $H^0$ and $A^0$. If all SUSY particles are very heavy, the $H^+$ decays dominantly into $t\bar{b}$; the decays $H^+ \rightarrow \tau^+\nu$ and/or $H^+ \rightarrow W^+ h^0$ are dominant below the $t\bar{b}$ threshold \cite{hfag, htc}. If all decay modes into SUSY particles are kinematically forbidden the $H^0$ and $A^0$ decay dominantly into...
The mass eigenstates \( \tilde{q} \) and \( H \), the tree–level decay width of \( k \), where \( (\tilde{q}_L, \tilde{q}_R) \), with \( \tilde{q} = \tilde{t} \) or \( \tilde{b} \) is given by \( \tilde{q}_L = \tilde{t} \) or \( \tilde{b} \) is given by \( \tilde{q}_R = \tilde{t} \) or \( \tilde{b} \). The squark mass matrix in the basis \( (\tilde{q}_L, \tilde{q}_R) \), with \( \tilde{q} = \tilde{t} \) or \( \tilde{b} \) is given by \( \tilde{q}_R \). The tree–level results \( \tilde{q}_L \), \( \tilde{q}_R \) and \( H \). The SUSY–QCD corrections in \( O(\alpha_s) \) were calculated in the on–shell scheme for the processes \( H^+ \to tb \) in \( \tilde{q}_L, \tilde{q}_R \), \( H^0, A_0 \to q\bar{q} \) in \( \tilde{q}_L \), for the decays of all Higgs particles into squark pairs in \( \tilde{q}_L \), including squark–mixing and a proper renormalization of the mixing angle \( \theta_{\tilde{q}} \).

Within this work we will discuss the branching ratios of the Higgs decays including all SUSY–QCD corrections in \( O(\alpha_s) \). We will see that the decay modes into SUSY particles (squarks of the third generation, charginos and neutralinos) become more important when the QCD corrections are taken into account.

## 2 The Tree Level

We first review some tree–level results \( \tilde{q}_L \), \( \tilde{q}_R \). The squark mass matrix in the basis \( (\tilde{q}_L, \tilde{q}_R) \), with \( \tilde{q} = \tilde{t} \) or \( \tilde{b} \), is given by \( \tilde{q}_L \), \( \tilde{q}_R \) and \( H \). The expressions for the couplings \( \tilde{q}_L \), \( \tilde{q}_R \) and \( H \). The expressions for the couplings \( \tilde{q}_L \), \( \tilde{q}_R \) and \( H \). The tree–level decay modes into squarks can be large in the case \( \tilde{q}_L \), \( \tilde{q}_R \) and \( H \). The mass eigenstates \( \tilde{q}_L \), \( \tilde{q}_R \) are related to the SU(2)_L eigenstates \( \tilde{q}_a \) \( \tilde{q}_a \) \( \tilde{q}_a \). The tree–level decay width of \( H^k \to \tilde{q}_i \tilde{q}_j \) is then given by

\[
\Gamma^{\text{tree}}(H^k \to \tilde{q}_i \tilde{q}_j) = \frac{3\kappa(m_{H^k}, m_{\tilde{q}_i}, m_{\tilde{q}_j})}{16\pi m_{H^k}^3} |G_{ij}^\alpha|^2.
\]

For \( k = 1, 2, 3 \) \( H^k \) denotes the neutral Higgs bosons (i. e. \( H^1 \equiv h^0 \), \( H^2 \equiv H^0 \), \( H^3 \equiv A^0 \)) and \( \tilde{q} = \tilde{t}, \tilde{b} \). For \( k = 4 \) one has \( H^4 \equiv H^+ \) and \( \tilde{q} = \tilde{t}, \tilde{q} = \tilde{b}, (i, j = 1, 2) \), and \( \kappa(x, y, z) \equiv ((x - y - z)^2 - 4yz)^{1/2} \). The expressions for the couplings \( G_{ij}^\alpha \) are given in \( \tilde{q}_L \). The decay widths of \( H^+ \) and \( H^0 \) into squarks can be large in the case of large squark mixing. The decay width of \( A^0 \) into \( \tilde{q}_L \tilde{q}_\tilde{q} \) is directly proportional to \( |m_{A^0}(A^0 c_q + \mu)|^2 \) with \( c_t = \cot \beta \) and \( c_b = \tan \beta \). Starting from the threshold these widths are steeply increasing with increasing \( m_{H^k} \) up to a maximum and
then decreasing. For large \( m_{H^k} \) they become proportional to \( 1/m_{H^k} \).

The decay widths into quarks are given by

\[
\Gamma^{\text{tree}}(H^k \to q\bar{q}) = \frac{3g^2m_\chi^2(d_1^k)^2m_{H^k}}{32\pi m_W^2 \sin^2\beta} \left(1 - \frac{4m_d^2}{m_{H^k}^2}\right)^{(3/2-\delta_{k3})}, \quad (k = 1, 2, 3), \quad (7)
\]

\[
\Gamma^{\text{tree}}(H^+ \to t\bar{b}) = \frac{3\kappa(m_{H^+}^2, m_{H^0}^2, m_{H^0}^2)}{16\pi m_{H^+}^2} \times \left[(m_{H^+}^2 - m_t^2 - m_b^2)(y_t^2 + y_b^2) - 4m_t m_b y_t y_b\right], \quad (8)
\]

with \( d_1^1 = -d_2^1 = -\sin\alpha, \quad d_2^2 = d_3^2 = \cos\alpha, \quad d_3^3 = -\sin\beta, \quad \alpha \) being the \( h^0 - H^0 \) mixing angle, and the Yukawa couplings \( y_t \) and \( y_b \):

\[
y_t = \frac{g}{\sqrt{2}m_W} m_t \cot\beta, \quad y_b = \frac{g}{\sqrt{2}m_W} m_b \tan\beta. \quad (9)
\]

For large \( \tan\beta \) \( y_b \) can also become large and, therefore, the sbottom and bottom modes become important. The formulae for the decay widths into charginos and neutralinos have essentially the same structure as eq. (8) with the appropriate masses and couplings (without the color factor 3), see e. g. [2]. If the mass of the decaying Higgs particle is large, the decay widths into fermions (quarks, charginos/neutralinos, . . .) become proportional to \( m_{H^k} \).

In the chargino/neutralino sector one has quite generally the following behaviour:

- \( M \ll |\mu|: \quad \tilde{\chi}_1^\pm \) is gaugino–like \( \rightarrow \Gamma^{\text{tree}} \) is small,
- \( M \gg |\mu|: \quad \tilde{\chi}_1^0 \) is higgsino–like \( \rightarrow \Gamma^{\text{tree}} \) is large.

We have calculated the widths of all important modes of \( H^+, H^0 \) and \( A^0 \) decays:

(i) \( H^+ \rightarrow t\bar{b}, c\bar{s}, \tau^+\nu_\tau, W^+h^0, \bar{t}_i\bar{b}_j, \bar{\chi}_i^+\chi_j^0, \bar{\tau}_i^+\nu_\tau, \bar{\ell}_i^+\nu_\ell (\ell = e, \mu), \)

(ii) \( H^0 \rightarrow t\bar{t}, b\bar{b}, c\bar{c}, \tau^-\tau^+, W^+W^-, Z^0Z^0, h^0h^0, A^0A^0, W^\pm H^\pm, Z^0A^0, \)

\( \bar{t}_i\bar{\ell}_j, \bar{b}_i\bar{b}_j, \bar{\ell}_i^+\nu_\ell (\ell = e, \mu, \tau), \chi_i^+\chi_j^-, \bar{\chi}_i^0\chi_j^0, \) and

(iii) \( A^0 \rightarrow t\bar{t}, b\bar{b}, c\bar{c}, \tau^-\tau^+, Z^0h^0, \bar{t}_1\bar{t}_2, \bar{t}_2\bar{t}_1, \bar{b}_1\bar{b}_2, \bar{b}_2\bar{b}_1, \bar{\tau}_1\bar{\tau}_2, \bar{\tau}_2\bar{\tau}_1, \)

\( \bar{\chi}_i^+\chi_j^-, \bar{\chi}_i^0\bar{\chi}_j^0. \)

Formulse for these widths are found e. g. in ref. [2]. In principle, also the decays \( H^+ \rightarrow \tilde{u}_L\tilde{d}_L, \tilde{c}_L\tilde{s}_L \) and \( H^0 \rightarrow \tilde{q}_\alpha\tilde{\bar{q}}_\alpha \) \( (q = u, d, c, s \) and \( \alpha = L, R) \) could contribute via their gauge couplings. As the squarks of the first two generations are supposed to be heavy, these decays will be strongly phase-space suppressed. Even if they were kinematically allowed, they would have a rate at most comparable to that of \( H^+ \rightarrow \tilde{\ell}_i^+\nu_\ell, H^0 \rightarrow \tilde{\ell}_i^-\ell_j^+ \) and \( \tilde{\nu}_\ell\tilde{\nu}_\ell \) (see fig. 2 below). We have neglected loop induced decay modes (such as \( H^+ \rightarrow W^+Z^0, W^+\gamma, H^0 \rightarrow gg, \) and \( \gamma\gamma \)) and three-body decay modes [13, 12].

### 3 Numerical Results including SUSY–QCD corrections

In the following branching ratios including SUSY–QCD corrections in \( \mathcal{O}(\alpha_s) \) will be shown. For further details concerning the theoretical calculation of these corrections
We have considered two scenarios: of the MSSM, taking \( M = (\alpha_2/\alpha_s(m_Z))m_\tilde{g} = (3/5\tan^2\theta_W)M', M_{\tilde{Q}}(\bar{t}) \): \( M_U : M_D : M_L : M_E = 1 : 8 : 10 : 1 \) and \( A = A_t = A_b = A_r \). Here \( M' \) is the SU(2) (U(1)) gaugino mass, \( \alpha_2 = g^2/4\pi \), and \( (M_{\tilde{L},E}, A_r) \) are the mass matrix parameters of the slepton sector \([5, 6]\). We have taken \( m_\tilde{g} \sim 50 \) GeV, \( m_\tilde{b} = 5 \) GeV, \( m_Z = 91.2 \) GeV, \( m_W = 80 \) GeV, \( \sin^2\theta_W = 0.23 \), \( \alpha_2 = 0.0337 \), and \( \alpha_s = \alpha_s(m_H^+) \) for the \( H^+ \) decay. We have used \( \alpha_s(Q) = 12\pi/\{(33-2n_f)\ln(Q^2/\Lambda^2_{\text{QCD}})\} \), with \( \alpha_s(m_Z) = 0.12 \), and the number of quark flavors \( n_f = 5(6) \) for \( m_b < Q \leq m_t \) (for \( Q > m_t \)).

We have considered two scenarios:

| Parameter set | \( \tan\beta \) | \( M \) [GeV] | \( \mu \) [GeV] | \( M_{\tilde{Q}} \) [GeV] | \( A \) [GeV] |
|---------------|----------------|--------------|--------------|----------------|--------------|
| I             | 2.5            | 160          | 350          | 95             | 300          |
| II            | 2.5            | 300          | -100         | 100            | -200         |

We have implemented the new Higgs mass bound from ALEPH \([1]\), \( m_{h^0} \geq 70 \) GeV for \( \tan\beta = 2.5 \). This leads for the parameter set I to \( m_{A^0} \gtrsim 250 \) GeV and for the parameter set II to \( m_{A^0} \gtrsim 180 \) GeV.

For the parameter set I we have (in GeV units)

\[
(m_{\tilde{t}_1}, m_{\tilde{t}_2}, m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}, m_{\tilde{\chi}^0_1}, m_{\tilde{\chi}^0_1}) = (96, 255, 100, 130, 465, 73, 137),
\]

and for the parameter set II

\[
(m_{\tilde{t}_1}, m_{\tilde{t}_2}, m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}, m_{\tilde{\chi}^0_1}, m_{\tilde{\chi}^0_1}) = (100, 257, 113, 137, 820, 92, 108).
\]

Fig. 1 (a) shows the tree-level and the SUSY–QCD corrected decay widths \( \sum_{i,j} \Gamma(H^+ \to \tilde{t}_i\tilde{b}_j) \) and \( \Gamma(H^+ \to \tilde{t}\tilde{b}) \) and Fig. 1 (b) shows the tree-level and the SUSY–QCD corrected decay widths \( \sum_{i,j} \Gamma(H^0 \to \tilde{t}_i\tilde{t}_j) \) and \( \Gamma(H^0 \to \tilde{t}\tilde{t}) \) using the parameter set I. The modes into bottom quarks and sbottoms are very small compared to the top and stop modes in Fig. 1 (b) and therefore not shown.

Fig. 2 a–c show SUSY–QCD corrected branching ratios larger than 1% for the parameter set I and Fig. 2 d–f for the parameter set II. All SUSY modes are summed up, e. g. in the \( H^0 \) decay into \( \tilde{t}\tilde{t} \equiv \sum_{i,j} \text{Br}(H^0 \to \tilde{t}_i\tilde{t}_j) \).

In most cases, the SUSY–QCD corrections to the Higgs decays into quarks are negative and into squarks positive. Therefore, the branching ratios for decays into squarks are enhanced by including the SUSY–QCD corrections.

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Figure 1: Tree–level and SUSY–QCD corrected decay widths
Figure 2: Higgs particles branching ratios including SUSY–QCD corrections to quark and squark modes in $\mathcal{O}(\alpha_s)$