QCD CORRECTIONS TO THE LIGHT HIGGS BOSON DECAY INTO A CHARM-ANTICHARM OR BOTTOM-ANTIBOTTOM PAIR WITHIN THE MINIMAL SUPERSYMMETRIC MODEL

H. KÖNIG *
Ottawa-Carleton Institute for Physics
Department of Physics, Carleton University
Ottawa, Ontario, Canada K1S 5B6

ABSTRACT

We present the results of the contributions to the decay rate of the lightest Higgs particle into a charm-anticharm and bottom-antibottom pair within the minimal supersymmetric standard model when scalar quarks and a gluino are taken within the relevant loop diagrams.

We show that in the case where the vacuum expectation values of the Higgs particles obey the condition $v_1 \ll v_2$ the scalar quarks and gluino change the decay rate by not more than a few per cent.

These small contributions make it difficult to distinguish the Higgs particle of the standard model from the supersymmetric one.

October 1992

* supported by Deutsche Forschungsgemeinschaft
I. INTRODUCTION

It is well known that there are two neutral scalar Higgs particles $H_1^0$, $H_2^0$ in the minimal supersymmetric extension of the standard model (MSSM)\cite{1,2}. $H_1^0$ has a mass supposed to be much higher than the Z boson mass $m_Z$, whereas the mass of $H_2^0$ is less than $m_Z$ at tree level. Recently it was shown that radiative corrections coming from the gauge coupling of $H_2^0$ to the scalar top quark and its Yukawa coupling to the top quark enhance its lower mass limit to about 130 GeV\cite{3}, which pushes the possibility of its discovery beyond LEP I but still within the limits of LEP II.

Because of its relatively small mass $H_2^0$ is the most likely Higgs particle to be discovered. The main decay modes of the light Higgs particle are final state leptons and quarks excluding the top quark, which we suppose to have a mass around 140 GeV. In experiment the final state quarks can be distinguished from the final state leptons. The QCD corrections to the Higgs decay rate into a charm-anticharm and bottom-antibottom pair with a gluon and quarks within the loop diagram was presented in\cite{4} (and references therein). There it was shown that these corrections are very high (several ten per cent).

In this short paper we analyse if the MSSM can lead to any new measurable contributions to the above decay rate. The paper is divided into two sections, in the next section we present and discuss the obtained results of the calculations whereas in the final section we give our conclusions and a brief outlook.

II. QCD CORRECTIONS TO $\Gamma(H_2^0 \to q\bar{q})$ WITHIN THE MSSM

In general there are many new diagrams in the MSSM, which lead to corrections to the decay mode of the Higgs into a quark-antiquark pair. There are diagrams with scalar quarks and neutralinos or charginos within the loop as well as Higgs bosons. All these diagrams are suppressed by the weak coupling constant $\alpha$. In this paper we are only interested in the loop diagram with scalar quarks and a gluino, which couple to the quarks by the strong coupling constant $\alpha_s$. Although the lightest neutralinos have an experimental lower mass limit of only around 30 GeV\cite{5}, which is much less than the gluino mass limit of about 70 GeV\cite{6}, their contributions are further suppressed by their diagonalizing angles. But we also consider a very small gluino mass of 2 GeV still allowed in its low mass window.

In the Higgs sector of the MSSM there are besides the Higgs mass parameters, two new angles $\alpha$ and $\beta$ coming from the ratio of the two Higgs vacuum expectation values $v_1$ and $v_2$ and the mixing angle of the real parts of the Higgs particles. These two angles are not independent. With $\tan \beta = v_2/v_1$ we have the well known relation $\tan 2\alpha = \frac{\tan 2\beta (m_{H_0}^2 + m_{H_2}^2)}{m_{H_3}^2 - m_Z^2}$, where $H_3^0$ is the mass eigenstate of the imaginary part of the Higgs particles. In order not to deal with too many parameters we consider two interesting cases where $v_1 \approx v_2$ (but $v_1$ smaller than $v_2$) and $v_1 \ll v_2$. In the first case we have $\sin \beta = \cos \beta = \cos \alpha = -\sin \alpha = 1/\sqrt{2}$, whereas in the second
case \( \sin \beta = 1, \cos \beta = 0 \) which gives \( \alpha = -\pi/2 \) or 0 in special cases considered in [7]. The consequences to the considered decay rate are shown below.

In the standard model the Feynman coupling of the Higgs particle to the fermions is given by \( -ig_2 m_f/2m_W \) which in the MSSM has to be changed to \( -ig_2 m_f \cos \alpha/2m_W \sin \beta \) and \( +ig_2 m_f \sin \alpha/2m_W \cos \beta \) for the couplings of the light Higgs particle \( H_2^0 \) to the charm-anticharm and bottom-antibottom pair respectively.

The diagrams we have to consider for the considered decay mode are given in Fig.1. The couplings of \( H_2^0 \) to scalar quarks are given in Fig.110 in [2] and the gluino coupling to scalar quarks in Eq.C89 in [1].

In our calculations we neglect the charm and bottom quark masses relative to their scalar partners. This simplifies the calculations enormously; e.g. we also do not have to consider mixing terms of the scalar partners of the left and right handed quarks, which are proportional to the quark masses – that is we simply can take \( m_{\tilde{q}_L} = m_{\tilde{q}_R} \) if \( \tilde{q} = \tilde{c}, \tilde{b} \) for the scalar quarks.

The tree level decay rate is given by

\[
\Gamma^q_0 = \frac{N_C G_F m_{H_2^0} m_q^2}{4\sqrt{2\pi}} \beta_0^3 \left\{ \cos^2 \alpha \sin^2 \beta \right\}.
\]  

(1)

Here \( N_C \) is the colour factor, \( G_F \) the Fermi constant and \( \beta_0 = (1 - 4m_q^2/m_{H_2^0}^2)^{1/2} \).

The first term in the curly bracket is for the decay rate to charm-anticharm quarks and the second one for the bottom-antibottom quarks. The corrections coming from the loop diagrams in the standard model [4] and those in Fig.1 change \( \Gamma^q_0 \) into

\[
\Gamma^q = \Gamma^q_0 (1 + \Delta_{\text{rad.}}^{\text{St.}} + \Delta_{\text{rad.}}^{\text{SUSY}})
\]

(2)

\( \Delta_{\text{rad.}}^{\text{St.}} \) is given in Eq.8 in [4] and \( \Delta_{\text{rad.}}^{\text{SUSY}} \) is

\[
\Delta_{\text{rad.}}^{\text{SUSY}} = \frac{8 \alpha_s}{3 \sqrt{2\pi}} \sin(\alpha + \beta) \left\{ \frac{\sin \beta}{\cos \alpha} \frac{\cos \beta}{\sin \alpha} \right\} \int_0^1 d\alpha_1 \int_0^{1-\alpha_1} d\alpha_2 \frac{-m_{H_2^0}^2}{F_{\tilde{g}\tilde{g}}} \right\}
\]

(3)

The terms in the curly bracket are to be understood as in Eq.1. The \( \alpha_2 \)-integration can be done easily by hand and the \( \alpha_1 \)-integration we do numerically.

First of all we see that the angles \( \alpha \) and \( \beta \) are important. E.g. in the case with \( v_1 \approx v_2 \) (\( v_1 \) smaller than \( v_2 \)) we have \( \sin(\alpha + \beta) \) goes to zero and the MSSM does not contribute at all to the radiative correction of this decay rate. In the case \( v_1 \ll v_2 \) (that is \( \cos \beta \) goes to zero) we have \( \sin \alpha \) goes to zero keeping the charm coupling unchanged and the bottom coupling at a fixed value. Because we are only interested in the maximal influence the MSSM gives to this decay rate we have to keep \( v_1 \ll v_2 \) and set the values in the curly brackets in Eq.1 and Eq.3 equal to 1.

In Eq.9 in [4] the authors kept the strong coupling constant \( \alpha_s \) as a running function of the Higgs mass. It is well known that the MSSM changes the running of
the coupling constant. The final value of $\alpha_s$ at the weak scale $m_Z$ depends where the SUSY breaking scale lies and varies from $\alpha_s = 0.125$ for the SUSY breaking scale at the weak scale to 0.118 for the SUSY breaking scale at 1 TeV [8]. If we suppose that the SUSY breaking scale is above 1 TeV the standard renormalisation equations for the strong coupling constant apply. To keep our results independent of the real values of $\alpha_s$ we define $C_{\text{SUSY}}^{\text{max}} = \frac{\Delta_{\text{SUSY}}^{\text{rad.}}}{\Delta_{\text{St.}}^{\text{rad.}}}$, which shows us the maximal radiative correction of the gluino and scalar quarks in the MSSM compared to the radiative correction of the quarks and gluon within the standard model independent of the strong coupling constant.

In the following we consider three different cases. In case I we take the gluino mass and scalar quark masses to be 80 GeV slightly above the experimental lower mass limit [6]. In case II we take more realistic values with $m_{\tilde{q}} = 100$ GeV and $m_{\tilde{g}} = 150$ GeV. In case III we consider the still experimentally allowed low mass window of the gluino with $m_{\tilde{g}} = 2$ GeV and $m_{\tilde{q}} = 80$ GeV, which leads to the highest contribution.

In Fig.2 we have plotted $\Gamma_c^0$ (higher solid line), $\Gamma_{\text{St.}}^c \equiv \Gamma_0^c(1 + \Delta_{\text{St.}}^{\text{rad.}})$ (lower solid line) and $\Gamma_c^0$ in the case I (dashed line), case II (dash-dotted line) and case III (dotted line). The supersymmetric radiative correction has a minus sign relative to the standard radiative correction, which leads to a small enhancement over $\Gamma_{\text{St.}}^c$. The highest contribution is in case III for $m_{\mu_2^0} = 140$ GeV and lies at 7.45%.

In Fig.3 we present the same results as in Fig.2 for $\Gamma_0^b$, $\Gamma_{\text{St.}}^b$ and $\Gamma_b$ in the three different cases considered above. Here $\Gamma_{\text{St.}}^b$ is enhanced at most by 4.99%.

Finally in Fig.4 we present the absolute values for the $\alpha_s$ independent parameter $C_{\text{max}}^{\text{SUSY}}$ as defined above. The upper line of identical lines is for the bottom decay mode and the lower one for the charm one. $C_{\text{max}}^{\text{SUSY}}$ is higher for the bottom quark which leads to a lower enhancement of $\Gamma_b^b$ relative to $\Gamma_b^c$ coming from the relative minus sign of the SUSY correction relative to the standard correction.

If we take the gluino mass at a very high value (larger than 500 GeV) we get an enhancement over $\Gamma_{\text{St.}}^{c,b}$ below 1%.

As a result even for small masses of the gluino the decay rate of the Higgs particle into a charm-anticharm or bottom-antibottom pair turns out to be a poor experimental quantity to distinguish the standard Higgs particle from the lightest supersymmetric one.

**IV. CONCLUSIONS AND OUTLOOK**

Under simplifying assumptions such as neglecting the charm and bottom quark masses compared to their supersymmetric partners and in the case $v_1 \ll v_2$ we have shown the maximal contribution of the MSSM to the decay rate of the lightest supersymmetric particle into a charm-anticharm or bottom-antibottom quark pair. We have seen that the contribution of the scalar quarks and gluino to this decay rate lies in the range of a few per cent for a light gluino mass and drops under 1% if the gluino mass is taken to be heavy (500 GeV). These small values make the considered
decay rate very unlikely to distinguish the standard Higgs particle from the lightest supersymmetric one.

This might be very different if we were considering the decay of the heaviest neutral scalar Higgs particle \( H_1^0 \) into quarks. Here we have to consider many more decay modes. First of all it might be heavy enough to decay into a top-antitop quark pair, which makes the calculation more difficult. Here we cannot neglect the mixing of the scalar partners of the left and right handed top quark which becomes proportional to the top quark mass. Secondly we also have to consider the decay of \( H_1^0 \) into \( W^+W^- \) and \( Z^0Z^0 \) bosons. A calculation of the \( H_1^0 \) into \( Z^0Z^0 \) bosons was recently considered in [9]. The authors there have taken quarks and their supersymmetric partners within the relevant loop diagrams. However in a complete calculation one has also to take charginos and neutralinos as well as Higgs bosons into account. These particles might give significant contribution to this decay mode and should also be considered [10].

IV. ACKNOWLEDGEMENTS

The author would like to thank P. Kalyniak for useful discussions. This work was supported by the Deutsche Forschungsgemeinschaft.
REFERENCES

[1] H.E. Haber and G.L. Kane, Phys.Rep.117(1985)75.
[2] J.F. Gunion et al, “The Higgs Hunter’s Guide”, Addison-Wesley Publishing Company, Redwood City, CA 1990.
[3] H. Haber and R. Hempfling, Phys.Rev.Lett. 66(1991)1815;
Y. Okada et al, Prog.Theor.Phys.85(1991)1; Phys.Lett. B262(1991)54;
J. Ellis et al, Phys.Lett.B257(1991)83;
for a more general analysis leading to a higher mass limit of about 150 GeV see
G.L. Kane et al, “Calculable upper limit on the mass of the lightest Higgs boson in any perturbatively valid supersymmetric theory”, October 1992, Bulletin-board: hep-ph@xxx.lanl.gov-9210242.
[4] P. Kalyniak et al., Phys.Rev.D43(1991)3664.
[5] G. Wormser, “Searches for SUSY particles at LEP”, October 1992, LAL-92-56.
[6] Review of Particle Properties, Phys.Rev.D45(1992)Part II.
[7] J.F. Gunion and H.E. Haber, Nucl.Phys.B278 (1986)449.
[8] P. Langacker and M. Polansky, ”Uncertainties in Coupling Constant Unification”, October 1992, UPR-0513T, Bulletin-board: hep-ph@xxx.lanl.gov-9210235;
P. Langacker, ”Proton Decay”, Bulletin-board: hep-ph@xxx.lanl.gov-9210238;
V. Barger et al., ”Supersymmetric Grand Unification: Two Loop Evolution of Gauge and Yukawa Couplings”, September 1992, Mad/PH/711, Bulletin-board: hep-ph@xxx.lanl.gov-9209232.
[9] D. Pierce and A. Papadopoulos, ”Radiative Corrections to the Higgs boson decay $\Gamma(H \rightarrow ZZ)$ in the minimal supersymmetric model”, June 1992, UCB-PTH-92/23, LBL-32498, Bulletin-board: hep-ph@xxx.lanl.gov-9206257.
[10] H. König, ”Higgs boson decay into $t\bar{t}$ quarks, $W^+W^-$ and $Z^0Z^0$ bosons within the minimal supersymmetric standard model”, in preparation.
FIGURE CAPTIONS

Fig. 1  The diagrams with scalar quarks and gluino within the loop, which contribute to the decay rate of the lightest Higgs particle into a quark-antiquark pair within the MSSM.

Fig. 2  $\Gamma_0^c$ (upper solid line), $\Gamma_{St.}^c$ (lower solid line) and $\Gamma^c$ as a function of $m_{H^0}$. The $\Gamma^c$ are: Case I (dashed line), case II (dash-dotted line), case III (dotted line).

Fig. 3  As in Fig. 2 for the b-quark.

Fig. 4  The absolute value of $C_{\text{max}}^{\text{SUSY}}$ as a function of $m_{H^0}$. Lines for the various cases are as in Fig. 2. The upper line of the same line is for the b-quark and the lower one for the c-quark.