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Three-body decays of Higgs bosons in the MSSM

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We study several three-body decays of the heavy Higgs bosons $(H^0, A^0, H^\pm)$ predicted by the minimal supersymmetric extension of the standard model (MSSM): namely, $H^0 \to t\bar{b}W^-, t\bar{t}h^0, b\bar{b}h^0, h^0h^0h^0, ZZh^0, W^+W^-h^0$; $A^0 \to t\bar{b}W^-, Zh^0h^0$; $H^\pm \to b\bar{b} + W^\pm, t\bar{b}h^0, W^\pm h^0 h^0$, where h^0 is the light Higgs boson of the MSSM. One of the goals of this work is to study how the branching ratios of the dominant modes are affected after the inclusion of these three-body decays. We are also interested in searching for three-body decays that include additional b quarks in the final state, which could enhance the possibilities of detecting the MSSM Higgs bosons at future colliders.

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I. INTRODUCTION

The Higgs sector is one of the most important areas of the standard model (SM) that has not been tested yet [1]. The SM contains only one neutral Higgs boson, and although its detection would give more validity to the SM, there are some theoretical problems related to this boson that suggest the need for new physics. One of the preferred extensions of the SM is the supersymmetric (SUSY) one, mainly because of its capacity to alleviate the problem of naturalness [2]. Also, when grand unified theory (GUT) theories are extended to incorporate SUSY, they confront data in a better way than non-SUSY extensions (e.g., the unification of couplings, the ratio m_b/m_τ); the dark matter problem is also addressed successfully with SUSY. Although these assets do not give a proof for SUSY, they do keep it as a viable, and well-motivated, extension of the SM.

The minimal SUSY extension of the SM (MSSM) is a well-defined and widely studied model [3]. It doubles the spectrum of particles of the SM, with new free parameters obeying simple relations. The scalar sector of the MSSM [4] requires two Higgs doublets; thus, the remaining scalar spectrum contains two scalars (h^0 and H^0), one pseudoscalar (A^0), and one charged Higgs boson ($H^\pm$), whose detection would be a clear signal of new physics. The Higgs sector is specified at the tree level by fixing two parameters, which can be chosen as the mass of the pseudoscalar (m_A) and the ratio of vacuum expectation values of the two doublets ($\tan\beta = v_2/v_1$); then, the masses m_{h^0}, m_{H^0}, and $m_{H^\pm}$ and the mixing angle of the neutral Higgs sector (α) can be fixed. However, since radiative corrections that produce substantial effects on the predictions of the model [5] depend on the additional masses, it is necessary to specify also the squark masses, which are assumed to be degenerate.[1]

Current data from the CERN e^+e^- collider LEP I can exclude the light Higgs boson h^0 with masses up to about 50 GeV (for moderate values of $\tan\beta$), whereas the limit on the pseudoscalar A^0 is of about 40 GeV for the case $m_A \simeq m_h$. For the charged Higgs boson mass, the limit obtained from LEP is approximately of 41 GeV [6], whereas at Fermilab it is possible to extend the limit to $m_{H^\pm} > m_t - m_b$, provided that the top decay mode agrees with the SM prediction, as current results suggest [7].

The search for a combination of techniques that will allow the detection of the full SUSY Higgs spectrum at future colliders [LEP II, CERN Large Hadron Collider (LHC)] has been the subject of extensive work [8]. Actually, it is now known that current techniques will not be sufficient to test completely the Higgs sector of the MSSM. Nevertheless, it has been claimed recently [9] that if new techniques for vertex tagging of b quarks are implemented at some required level, then it can be possible to test the Higgs sector of the MSSM with the planned colliders, namely, that the existence of at least one member of the Higgs spectrum can be tested for the total parameter space. However, since the signatures that allow the detection of SUSY Higgs bosons are very similar to the SM case, it will be very difficult to establish for one signal only that it truly corresponds to a SUSY Higgs sector. In order to make some progress, one should consider the detection of more than one Higgs boson and test the mass relations among them; unfortunately, this can be done only for a limited region of parameter space. Another possibility, which is the one investigated in this paper, is to search for new decay modes that are not present in the SM case, for instance, three-body decay modes.

The decays that can be used to search for the MSSM Higgs bosons depend on the regions of parameter space [8]; for instance, at LEP it will be possible to detect

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[1]Except for the top squark mass, which could be rather light.

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the decay $h \to b\bar{b}$, whereas at hadron colliders it will be possible to study the decays $H^0, h^0 \to ZZ^*$, $h \to \gamma\gamma$, and $H^{\pm} \to \tau\nu$. The evaluation of the branching ratios (BR's) has been done in previous works without including three-body decays in the total width,[2] which could be correct only for some regions of parameters, where the dominant modes are not sensitive to the inclusion of the three-body modes. For instance, in the region $m_{H^0} < 2m_t$, the decay $H^0 \to b\bar{b}$ dominates (the decay $H^0 \to t\bar{t}$ does not occur). However, in the region $m_t + m_b + m_W < m_{H^0} < 2m_t$, the decay $H^0 \to t\bar{t}^*$ could compete with $H^0 \to b\bar{b}$, due to the large Yukawa coupling $ht\bar{t}$ which could compensate the suppression coming from the three-body phase space. A similar situation appears for other decays of A^0 and $H^{\pm}$. Thus it seems interesting to evaluate the effect of the three-body decay modes into the total width of the SUSY Higgs bosons.

On the other hand, the possibility of detecting the decay $h^0 \to b\bar{b}$ at the future LHC collider, using vertex tagging of b quarks [9], makes it interesting to study other decay modes of the heavy Higgs bosons that could produce one or more light Higgs bosons (h^0), since the resulting final state would contain additional b quarks, which in turn could help for detection process. Some of the three-body decay modes of the heavy Higgs bosons ($H^0, A^0, H^{\pm}$) that have precisely this property are $H^0 \to h^0h^0h^0$, $A^0 \to Zh^0h^0$, $H^{\pm} \to W^{\pm}h^0h^0$.

This work contains an extensive study of the three-body decays of the SUSY Higgs bosons. The branching ratio of the three-body decays are compared with the dominant decay modes. Their effect on current detection techniques is evaluated as well as their implication in the search for new signatures, mainly those that lead to a large number of b quarks in the final state. Although the final conclusion regarding detectability of the signals requires an analysis of the backgrounds and this present study can be used only to estimate the production rates, it already helps to eliminate those decays that are highly suppressed (e.g., BR $< 10^{-6}$) and to identify more promising signals, namely, those with a BR of order 10^{-3}–10^{-4}.

This paper is organized as follows: Section II contains the calculation of the three-body modes for the scalar H^0. The corresponding modes for the pseudoscalar A^0 and charged Higgs $H^{\pm}$ are presented in Secs. III and IV, respectively. Finally, Sec. V contains our conclusions.

II. THREE-BODY DECAYS OF H^0

In order to calculate the decay widths of a SUSY Higgs boson of mass M_h, decaying into three particles of masses $m_{1,2,3}$, we shall perform a numerical integration for the expression of the squared amplitude over the three-body phase space: namely,

$$\frac{d\Gamma}{ds_1 ds_2} = \frac{1}{256\pi^3 M_h^3}|M|^2 \,, \tag{1}$$

where $|M|^2$ denotes the squared and averaged amplitude for the decay. The integration limits are written as $s_{1,2}^- < s_{1,2} < s_{1,2}^+$, with

$$s_1^{\pm} = m_1^2 + m_2^2 - \frac{1}{2s_2}[A \pm B] \,, \tag{2}$$

$$s_2^+ = (M_h - m_1)^2 \,, \tag{3}$$

$$s_2^- = (m_2 + m_3)^2 \,. \tag{4}$$

The constants that appear in the previous equations are defined as $A = (s_2 - M_h^2 + m_1^2)(s_2 + m_2^2 - m_3^2)$, $B = \lambda^{1/2}(s_2, M_h^2, m_1^2)\lambda^{1/2}(s_2, m_2^2, m_3^2)$, with $\lambda(x,y,x) = (x+y+z)^2 - 4yz$.

Decay $H^0 \to t\bar{t}^*$. For the region $m_t + m_b + m_W < m_{H^0} < 2m_t$, the decay $H^0 \to tt$ is not allowed, but the resulting final state can be achieved also with one t quark being off shell, namely, $H^0 \to t\bar{b}W^-$. Since this mode includes the large Yukawa coupling $ht\bar{t}$, it is interesting to compare it with the dominant one, namely, $H^0 \to bb$.

Using the Feynman rules for the minimal model, as summarized in Ref. [11], we can write the amplitudes for this mode, whose Feynman graphs are shown in Fig. 1. We shall write down explicitly the amplitude and Feynman graphs only for the present case, in the following sections, we shall skip those details and present only the final results.

The amplitudes that correspond to each graph are

$$M_a = -iC_1\bar{u}(p_1)\gamma^{\mu}(1-\gamma_5)\frac{q_1 + m_2}{s_1 - m^2}v(p_3)\epsilon(p_2) \,, \tag{5}$$

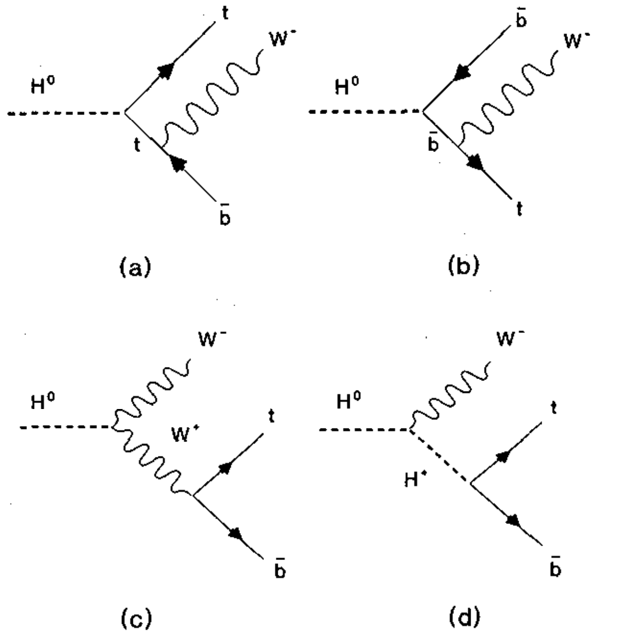

FIG. 1. Feynman graphs for the decay $H^0 \to t\bar{b}W^-$.

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[2] After completion of this work, we became aware of a paper where decays of MSSM Higgs bosons below threshold are also considered [10].

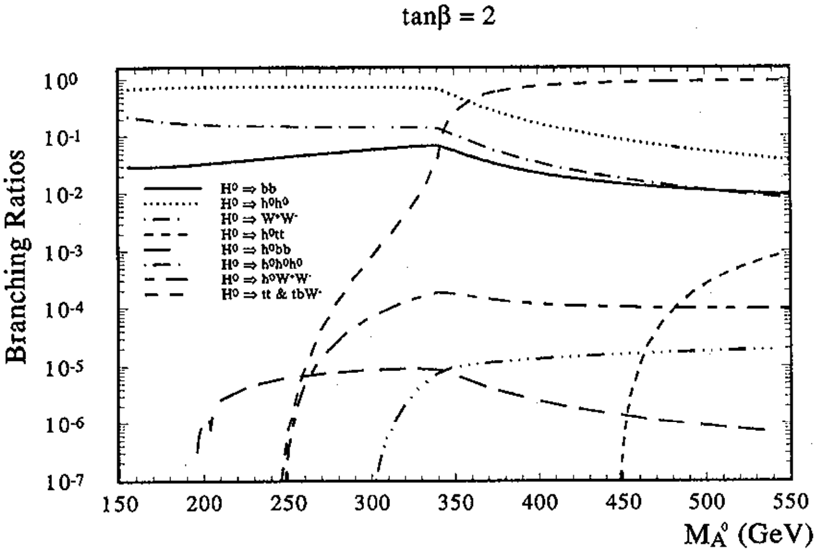

FIG. 2. Summary of branching ratios for the decays of H^0.

$$M_b = -iC_2\bar{u}(p_1)\gamma^\mu(1-\gamma_5)\frac{q_2+m_2}{s_1-m^2}v(p_3)\epsilon(p_2) \ , \quad (6)$$

$$M_d = -iC_4\bar{u}(p_1)\frac{a_1+a_2\gamma_5}{s_3-m_{H^\pm}^2}v(p_3)\epsilon(p_2) \ , \quad (7)$$

where $C_1 = g^2 m_t \cos\alpha/4\sqrt{2}m_W\cos\beta$, $C_2 = g^2 m_t \sin\alpha/4\sqrt{2}m_W \sin\beta$, $C_4 = g^2\sin(\beta-\alpha)/4\sqrt{2}m_W$, $a_{1,2} = m_b\tan\beta \pm m_t\cot\beta$, and $s_3 = (M_h^2 + m_t^2 + m_b^2 + m_W^2) - s_1 - s_2$. The contribution from graph (c) happens to be suppressed, because of the factor $\cos(\beta-\alpha)$.

The results for the branching ratio, obtained after numerical integration of the differential decay width, are shown in Figs. 2 and 3. Figure 2 contains the BR's of H^0 evaluated for $\tan\beta = 2$, including all the decays that are discussed in detail in the following sections, whereas Fig. 3 shows results only for the mode $H^0 \to t\bar{b}W^-$, for several values of $\tan\beta$. One can appreciate that the

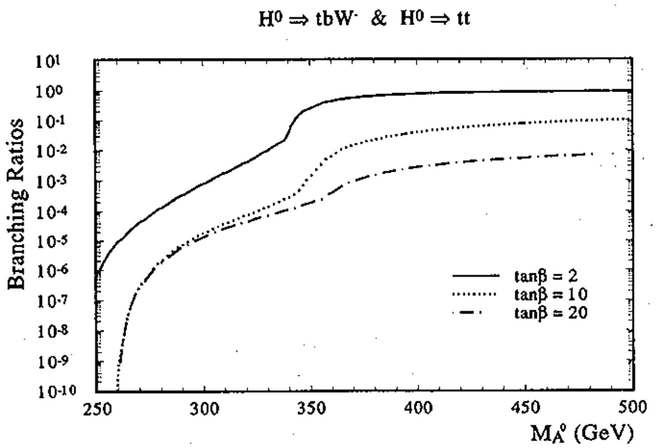

FIG. 3. Branching ratios for the decay $H^0 \to t\bar{b}W^-$, as a function of m_{A^0} for several values of $\tan\beta$.

BR for this mode is negligible for most values of parameters, and consequently it does not affect significantly the dominant decay mode. We can also see that the BR decreases with $\tan\beta$, as is expected because the Yukawa coupling $H^0t\bar{t}$ decreases with $\tan\beta$. For low values of $\tan\beta$, the result for the BR is similar to the corresponding SM Higgs boson decay [12]. Figure 3 shows also the result for the two-body decay $H^0 \to t\bar{t}$, which dominates for $m_{H^0} > 2m_t$.

Decays $H^0 \to ZZ + h^0, W^+W^-h^0$. In the MSSM the decays $H^0 \to ZZ, W^+W^-$ are highly suppressed for most regions of parameter space, because the vertex H^0ZZ contains the factor $\cos(\beta-\alpha)$. Apparently, the decays $H^0 \to ZZ + h^0, W^+W^- + h^0$, will be also very suppressed, as actually happens when h^0 is radiated from one of the vector bosons. However, there are also other contributions that are not proportional to the factor $\cos(\beta-\alpha)$, which could enhance the result; one of these contributions comes from the decay chain $H^0 \to h^0 + h^{0*}(\to ZZ/WW)$. The results for the branching ratio of the mode $H^0 \to W^+W^-h^0$ are presented in Figs. 2 and 4, where one can appreciate that this mode becomes important for moderate values of m_{A^0} and $\tan\beta \simeq 1$, where it reaches the value BR$\simeq 10^{-4}$. Figure 2 shows also the results for the mode $H^0 \to ZZh^0$, whose BR is similar to the mode $H^0 \to W^+W^-h^0$.

Decays $H^0 \to t\bar{t} + h^0, b\bar{b} + h^0$. The Yukawa coupling $H^0b\bar{b}$ increases when $\tan\beta$ is large. Thus it is possible that for large $\tan\beta$ the decay $H^0 \to b\bar{b} + h^0$ can compete with the two-body decays into light fermions. A similar situation can be expected for the decay $H^0 \to t\bar{t} + h^0$, but for small values of $\tan\beta$ instead. The results for the branching ratios are presented in Fig. 2. For $\tan\beta = 2$, we find $B(H^0 \to t\bar{t} + h^0) = 10^{-3}$. However, the BR decreases with $\tan\beta$, as is expected. On the other hand, the decay $H^0 \to b\bar{b} + h^0$ becomes important only when the parameters take on values such that the dominant contribution comes from the on-shell decay $H^0 \to h^0h^0(\to b\bar{b})$. However, the values of the BR for the present decay

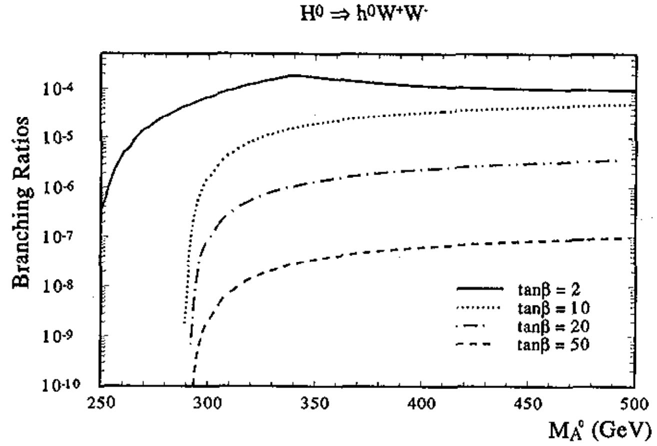

FIG. 4. Branching ratios for the decay $H^0 \to W^+W^-h^0$, as a function of m_{A^0} for several values of $\tan\beta$.

do not modify the dominant decay mode, unless m_{A^0} is large.

Decay $H^0 \to h^0h^0h^0$. The decay mode into $h^0h^0h^0$ leads to a very interesting final state that contains six b quarks, which could help to detect H^0 at hadron colliders, as was mentioned in the Introduction. One of the contributions to this graph comes from the four-point vertex $H^0h^0h^0h^0$, which involves a global factor that is a function of α and β, and it is not suppressed *a priori*. As can be seen from Fig. 2, the corresponding BR happens to be very small (BR$< 10^{-5}$), such that does not seem detectable.[3]

Decay $H^0 \to A^0A^*$. The two-body decay $H^0 \to A^0A^0$ is open only for a small window, because m_{H^0} approaches m_{A^0} very rapidly, and this makes it hard to visualize the BR. Thus it seems interesting to evaluate the three-body decay $H^0 \to A^0 + A^{0*}$ to obtain the correct behavior of the BR for $m_{H^0} < 2m_{A^0}$. The results for this mode are presented in Fig. 5, and one can notice the smooth behavior of the BR. For large values of $\tan\beta$, the BR decreases softly when it approaches the on-shell region.

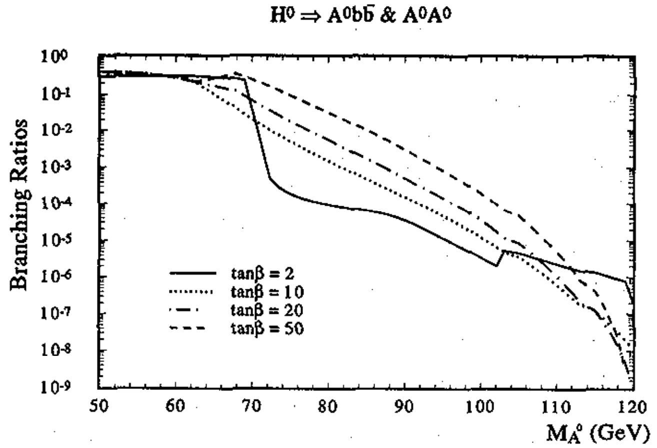

FIG. 5. Branching ratios for the decay $H^0 \to b\bar{b}A^0$, as a function of m_{A^0} for several values of $\tan\beta$. The non-dotted lines correspond to the on-shell contribution from $H^0 \to A^0A^0$.

III. THREE-BODY DECAYS OF A^0

The results for all the branching ratios of A^0 evaluated in this section are presented in Fig. 6, for $\tan\beta = 2$. For similar reasons to the case of H^0, it is interesting to compare these modes with the dominant ones.

Decays $A^0 \to t\bar{t}^*, t\bar{t}h^0, b\bar{b}h^0$. From Fig. 6, one can appreciate that the BR for the decay mode $A^0 \to t\bar{t}^*$ is negligible for most values of parameters, and consequently it does not affect significantly the dominant decay mode. Moreover, the BR should decrease with $\tan\beta$, because the Yukawa coupling $A^0t\bar{t}$ decreases with $\tan\beta$. Figure 6 shows also the BR for the mode $A^0 \to t\bar{t} + h^0$ and $A^0 \to b\bar{b} + h^0$. For low values of $\tan\beta$, the BR for $A^0 \to t\bar{t} + h^0$ can reach values $\simeq 10^{-3}$, which seem "promising" for detection. On the other hand, the decay $A^0 \to b\bar{b}+h^0$ becomes important for large values of $\tan\beta$, because the coupling $A^0b\bar{b}$ grows with $\tan\beta$. It can reach values of about 10^{-5}, which still seems too low to expect detection.

Decay $A^0 \to Zh^0h^0$. The decay $A^0 \to Zh^0$ is allowed for some regions of parameters, where it could reach a substantial BR ($\simeq 0.1$). However, because of the large QCD backgrounds, it seems difficult to observe the signal at the future LHC collider. On the other hand, in the decay $A^0 \to Zh^0h^0$ there is one extra h^0 that could help to further tag the signal, if it were possible to apply the techniques of vertex tagging for b quarks at LHC, as it was mentioned before. The results for the BR are presented in Fig. 6, for $\tan\beta = 2$, and one can notice that the BR for this mode is at most $\simeq 10^{-5}$, and unfortunately it is not large enough to expect its detection. For larger values of $\tan\beta$, we find that the BR is even smaller.

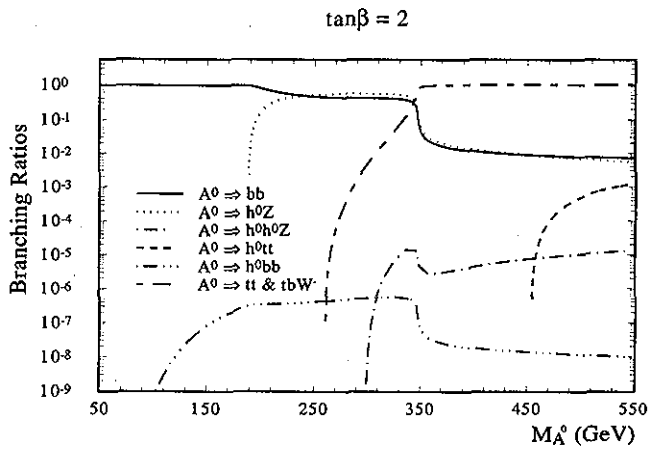

FIG. 6. Summary of branching ratios for the decays of A^0.

[3] This result is only valid for the MSSM and may be different for the general two-Higgs-doublet model, where the number of free parameters should allow for a larger result.

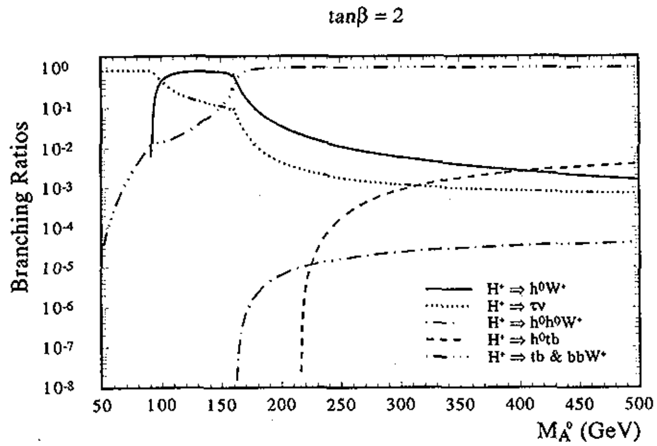

FIG. 7. Summary of branching ratios for the decays of $H^{\pm}$.

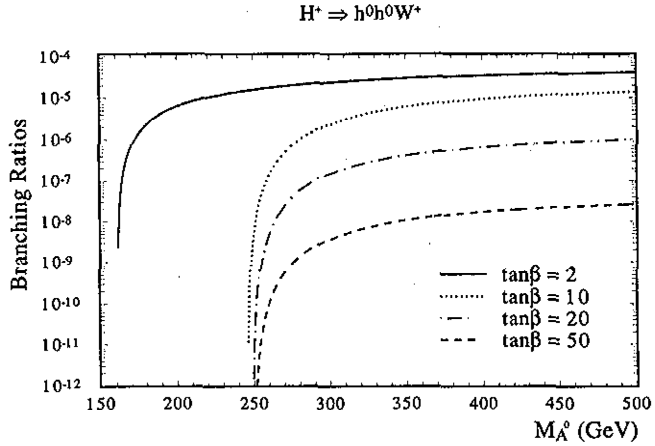

FIG. 9. Branching ratios for the decay $H^{\pm} \to W^{\pm}h^{0}h^{0}$, as a function of m_{A^0} for several values of $\tan\beta$.

IV. THREE-BODY DECAYS OF $H^{\pm}$

Decay $H^{\pm} \to b\bar{b}W^{\pm}$. For $m_{H^{\pm}} < m_t + m_b$, the dominant decay of $H^{\pm}$ is into $\tau + \nu$. However, the three-body decay $H^{\pm} \to b\bar{b} + W^{\pm}$ involves the large Yukawa coupling proportional to m_t, which could lead to a BR comparable to the two-body mode. The results for this mode are presented in Fig. 7. One can appreciate that the corresponding BR does not reach large values; thus, its effect on the dominant decay mode is not significant. In fact, in the same region of parameter space, the decay $H^{\pm} \to Wh^{0}$ is the one that becomes dominant, even above the decay into $\tau\nu$.

Decay $H^{\pm} \to t\bar{b}h^{0}$. For $m_{H^{\pm}} > m_t + m_b$, the dominant decay of $H^{\pm}$ is into $t + \bar{b}$, which is difficult to detect at hadron colliders because of the large QCD backgrounds. However, the three-body decay $H^{\pm} \to t\bar{b}h^{0}$ involves the same Yukawa coupling as the dominant mode and includes an extra light Higgs boson h^{0} that can be used to tag the signal, if the corresponding BR is large enough. The results for the branching ratio are presented in Figs. 7 and 8. For low values of $\tan\beta(\simeq 2)$, one finds $B(H^{+} \to t\bar{b}h^{0}) > 10^{-3}$, which seems quite "promising"

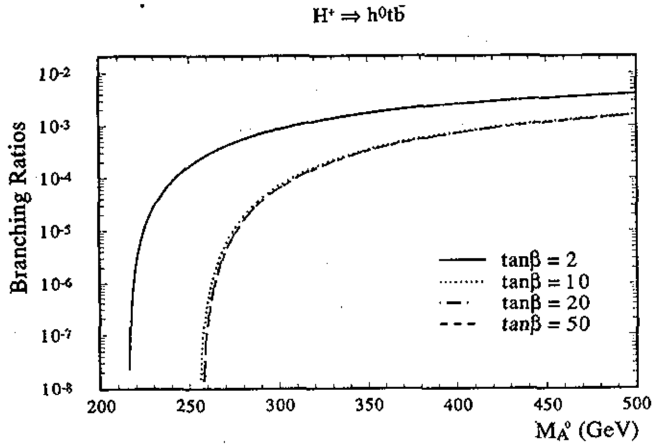

FIG. 8. Branching ratios for the decay $H^{+} \to t\bar{b}h^{0}$, as a function of m_{A^0} for several values of $\tan\beta$.

for detection. For larger values of $\tan\beta$, the BR decreases only moderately, as Fig. 8 shows.

Decay $H^{\pm} \to W^{\pm} + h^{0}h^{0}$. The decay $H^{\pm} \to W^{\pm} + h^{0}$ can reach a substantial BR, of about 0.1, for some region of parameter space. However, its detection at hadron colliders seems a difficult task, again because of the large QCD backgrounds. On the other hand, for the decay considered here, $H^{\pm} \to W^{\pm} + h^{0}h^{0}$, there is again an extra h^{0}, which could be used to tag further the signal, as was mentioned previously. The results for the branching ratio are presented in Fig. 9, where one can appreciate that for large values of m_{A^0} and $\tan\beta \simeq 10$ it reaches the value BR$\simeq 4 \times 10^{-5}$, which seems just on the verge of being detectable.

V. CONCLUSIONS

We have studied several three-body decays of the heavy Higgs boson of the minimal supersymmetric extension of the standard model (MSSM), $(H^{0}, A^{0}, H^{\pm})$, namely, $H^{0} \to t\bar{b}W^{-}, t\bar{t}h^{0}, b\bar{b}h^{0}, h^{0}h^{0}h^{0}, ZZh^{0}, W^{+}W^{-}h^{0}$ for the heavy scalar H^{0}; $A^{0} \to t\bar{b}W^{-}, h^{0}h^{0}Z$ for the pseudoscalar A^{0}; and $H^{\pm} \to b\bar{b}W^{\pm}, t\bar{b}h^{0}, W^{\pm}h^{0}h^{0}$ for the charged Higgs boson. We found that the branching ratios (BR's) of the dominant modes are not affected significantly after the inclusion of those three-body decays for large regions of parameter space.

Some of the decay modes that we have evaluated for the MSSM have very peculiar signatures, for instance, $H^{0} \to h^{0}h^{0}h^{0}, ZZh^{0}, W^{+}W^{-}h^{0}$; $A^{0} \to h^{0}h^{0}Z$; and $H^{\pm} \to W^{\pm}h^{0}h^{0}$. These modes could produce a number of b quarks in the final state, which could enhance the possibilities to detect them at future colliders. In order to fully answer the question of detectability, it is necessary to perform a detailed study of the signals and backgrounds, which is beyond the scope of this work.

The branching ratios of those decay modes that produce additional b quarks in the final state are found to be small for the MSSM, where the parameters are severely constrained, except for the decay modes $H^{\pm} \to$

$W^{\pm}h^0h^0, t\bar{b}h^0$, whose BR's reach the values 4×10^{-5} and $\simeq 10^{-3}$, respectively.

However, all those interesting modes are also allowed for the general two-Higgs-doublet model, where we have seven free parameters in the potential that can be chosen to give a large $B(\simeq 10^{-3})$, which would be promising for detection. In models beyond the MSSM, the prediction for the parameters will differ, in general, from the MSSM [13]; thus, the search for the modes with very distinct signatures (e.g., $H^0 \to ZZh^0, h^0h^0h^0$, $A^0 \to Zh^0h^0$, $H^{\pm} \to W^{\pm} + h^0h^0$) could be used to distinguish among those models.[4] Something similar can be said for the left-right symmetric models, where there will be even more peculiar signatures. For instance, in the conventional model [11], there is a double-charged Higgs boson (Δ^{++}), which could decay into the three-body mode $W^+W^+h^0$, whose signature would help to separate the signal from the backgrounds.

Thus, if one light Higgs boson were found and if it were possible to detect its decay into $b\bar{b}$, then nature could have provided us with the technique to study the full spectroscopy of Higgs bosons.

[4]Another interesting decay is $H^0 \to t\bar{t} + Z$, which was not evaluated here, it can have a BR $\simeq 10^{-3}$. For low values of $\tan\beta$, the BR for the SUSY case will be similar, but will decrease for larger values.

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