FROM COLLIDERS TO SUPER COLLIDERS

University of Wisconsin, Madison, Wisconsin
May 11-22, 1987

Edited by
Vernon Barger and Francis Halzen

World Scientific
Singapore • New Jersey • Hong Kong

International Journal of Modern Physics A, Vol. 2, No. 4 (1987) 1035 – 1053

Decays of Higgs Bosons to Neutralinos and Charginos in the Minimal Supersymmetric Model: Calculation and Phenomenology

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Abstract

We give explicit formulas for the decays of the Higgs bosons of the minimal supersymmetric model to neutralinos and charginos. The important features of these decays are illustrated and their phenomenological implications discussed. When phase space allowed, this class of two-body decays is at least as important as, and often dominates, other types of Higgs decay modes, such as WW or ZZ and heavy fermion anti-fermion channels.

The problem of finding the Standard Model Higgs at the SSC has attracted a great deal of attention in recent years. In the minimal version of the Standard Model, exactly one physical Higgs scalar exists, with a mass which is undetermined by the theory. However, there are theoretical arguments to suggest that this is not the whole picture. In trying to go beyond the Standard Model, a number of points of view have been advanced. In one view, the Higgs boson (or an analogue set of particles) are rather heavy, with strong self-interactions. Such a picture emerges qualitatively, if one takes the Higgs mass parameter large in the Standard Model. Such a picture also emerges in technicolor or composite models. In these approaches, scalar bosons exist which are composites of more fundamental entities. The underlying new interactions are strong, and the typical mass scale for such bound states is of order 1 TeV.

In the second view, the Higgs boson is an elementary particle. The only known theory in which scalar particles are elementary, that possesses a mechanism for understanding the large hierarchy between the electroweak scale and the Planck scale, is supersymmetry. In the minimal supersymmetric extension of the Standard Model, there must be at least two Higgs doublets in the theory. The resulting number of physical Higgs bosons in this model is five: a charged Higgs pair ($H^{\pm}$), two neutral scalars (H_1^0 and H_2^0) and a neutral pseudoscalar (H_3^0). Thus, already in the minimal version of the theory, the phenomenology of the Higgs bosons is much richer than the Standard Model.

One does not need to invoke supersymmetry in order to study non-minimal Higgs structures in the Standard Model. However, there are two good reasons for doing so. The first reason is a practical one. Consider the fact that in the most general (CP-invariant) two-Higgs doublet version of the Standard Model, there are six free parameters: four Higgs masses, the ratio of vacuum expectation values of the two doublets (which we shall denote by $\tan\beta = v_2/v_1$), and a mixing angle (α) which appears when the H_1^0–H_2^0 mass matrix is diagonalized. (In fact, there are additional free parameters characterizing various Higgs self-couplings; however these will not interest us here.) Thus, this approach has virtually no predictive power, with the possible exception of suggesting that one search for a charged Higgs boson. On the other hand, the supersymmetric model leads to strong constraints on the parameters of the Higgs sector. As a result, six free parameters are reduced to two (only one more than in the Standard model with one Higgs doublet!). The second reason is a more theoretical one: namely, supersymmetry is considered to be the only sensible picture in which elementary scalars exist. Thus, if the second of the two points of views discussed above is accepted, one should consider a supersymmetric framework when one wishes to investigate search strategies for Higgs bosons.

Let us illustrate this argument by briefly discussing the case of the charged Higgs boson. One can take the two-doublet version of the Standard Model and ask: how does one find the charged Higgs boson at the SSC? At present, no convincing search strategy exists. However, if we place the two Higgs doublet model in a supersymmetric framework, new possibilities arise. We shall show in this report that supersymmetric decay modes of the charged Higgs may be a very large fraction of the total charged Higgs decay rate. This fact would significantly alter the methods by which one would search for the charged Higgs boson at

We begin by noting that both charged and neutral Higgs bosons can decay into squark and slepton pairs (if the decay is kinematically allowed). The Higgs-squark-squark vertex consists of terms which arise due to supersymmetry and terms which appear due to the presence of soft-supersymmetry breaking terms in the theory. First, consider the supersymmetric interactions. Analogous to the quark-quark-Higgs coupling, an $H\widetilde{q}\widetilde{q}$ interaction exists with strength proportional to gm_q^2/m_W. Note that it is the *quark* mass which appears in this expression; therefore, such terms are very small and can be neglected. (The coupling to the top-squarks would be an exception to this rule.) In addition, there is an additional interaction which is related by supersymmetry to the Wqq and Zqq coupling. This leads to an $H\widetilde{q}\widetilde{q}$ interaction proportional to gm_W and gm_Z. It is this interaction which allows the Higgs branching ratio into squarks (and sleptons) to be significant. Finally, there are contributions to the $H\widetilde{q}\widetilde{q}$ interaction which depend on the parameters of the soft supersymmetry breaking sector. These parameters are completely unconstrained at present, and can also lead to important contributions to the $H \to \widetilde{q}\widetilde{q}$ decay width. Thus, we conclude that the Higgs decay into squarks and slepton pairs can be an important contribution to the total decay rate, but that the precise branching ratios are model dependent. Actually, the most important parameter associated with the determination of the $H \to \widetilde{q}\widetilde{q}$ branching ratios is the squark mass. For example, H_2^0 cannot decay into squarks or selectrons. The reason is that $m_{H_2^0} \leq m_Z$, whereas the squarks and the selectron are known to have masses larger than $m_Z/2$. (Of course, this latter limit, especially for the slepton, assumes that the LSP is light.) Clearly, it is quite possible that all squarks and sleptons are so heavy that the decay of the Higgs into supersymmetric scalars is completely forbidden.

We next turn to the decay of the Higgs into charginos and/or neutralinos. These are fermions, which are the supersymmetric partners of the gauge and Higgs bosons. In general, they are mixtures of gaugino and Higgsino states; the mixing angles are determined by diagonalizing the respective neutral and charged mass matrices. The mass matrices depend on four parameters: M and M', which are Majorana mass terms of the wino and bino; μ, which is a supersymmetric Higgs mass term which appears in the superpotential; and $\tan\beta = v_2/v_1$. If we assume that the gaugino masses are unified at the grand unification scale, then we can relate M and M' (*viz.* $M' = \frac{5}{3}\tan^2\theta_W M$), which reduces the unknown parameters to three. (This same grand unificatin argument also relates M to the gluino mass: $M = (g^2/g_s^2)M_{\widetilde{g}}$.) Without loss of generality, one can define β to lie between 0 and $\pi/2$, and one can choose M to be positive. Once we have diagonalized the neutralino and chargino mass matrices, and computed the relevant mixing angles, the interactions with the Higgs can be computed. Here, only one more term enters: the neutral Higgs mixing parameter, α. (By an accident of history, this parameter lies between $-\pi/2$ and 0.) For further relations, see ref. 2.

In principle, the decay rate into charginos and neutralinos suffers the same problem as the corresponding rate into squarks and sleptons—namely, if the charginos and neutralinos are too heavy, then the corresponding decays will be absent. However, there are a few important aspects of the neutralinos and charginos which should be emphasized. First, we presume that the lightest neutralino will be the lightest supersymmetric particle (LSP). At present, there is no experimental constraint on the LSP mass. Even if we apply some theoretical prejudice, an LSP mass of, say, 10 GeV is completely within reason. Second, even if the basic mass parameters of the neutralino and chargino mass matrices are rather large, there may be a few mass eigenstates with not unreasonably large masses. The masses of the charginos and neutralinos, at $\tan\beta = 1.5$, for various M values as a function of μ are given as part of a companion contribution to these proceedings.[4] Even for $M = 200$ GeV, corresponding to a gluino mass of $M_{\widetilde{g}} \sim 800$ GeV, the lightest chargino and neutralino have mass of order 100 GeV over much of μ space, and can be even lighter. Finally, we note that the mass scales which appear in the chargino and neutralino mass matrices are unrelated to the squark and slepton masses. Thus, it is possible that, even if squark and sleptons are inaccessible at the SSC, the Higgs may still have important decays into a few of the lightest supersymmetric fermions.

For the rest of this report, we will assume that squarks and sleptons are too heavy to be relevant in Higgs decay. However, all Standard Model particles are incorporated, including modes containing t quarks (we take $m_t = 70$ GeV) and WW or ZZ pairs (as mentioned earlier, these are never actually important). We will compute the branching ratios of all the Higgses into charginos and/or neutralinos as a function of μ and M, for the representative choice of $\tan\beta = 1.5$. First, we present formulae for the partial widths into charginos $(\widetilde{\chi}_i^+)$ and neutralinos $(\widetilde{\chi}_i^0)$. In the minimal supersymmetric model, there are two charginos and four neutralinos. By convention, we label our states such that the masses *increase* with the subscript which labels the particle.

First, we give the decay rate for the neutral Higgs bosons:

$$\Gamma(H_k^0 \to \widetilde{\chi}_i\widetilde{\chi}_j) = \frac{g^2\lambda^{\frac{1}{2}}\left[(F_{ijk}^2 + F_{jik}^2)(m_H^2 - M_i^2 - M_j^2) - 4F_{ijk}F_{jik}\epsilon_i\epsilon_j\epsilon_k M_i M_j\right]}{16\pi m_H^3 \sin^2\beta(1+\delta(i,j))} \tag{1}$$

where the factor of ϵ_k is equal to 1 for the scalar Higgses $(k = 1,2)$, and is equal to -1 for for the pseudoscalar Higgs $(k = 3)$. We use the general notation $\widetilde{\chi}_i$ to denote either a neutralino or chargino; its (positive) mass will be denoted by M_i. The factor $\delta(i,j)$ is inserted only when there are two identical Majorana neutralinos in the final state. In that case, $\delta(i,j) = 1$, otherwise, it is equal to 0. The kinematical factor λ is given by:

$$\lambda = (M_i^2 + M_j^2 - m_H^2)^2 - 4M_i^2M_j^2 \tag{2}$$

The factor ϵ_i stands for the sign of the neutralino mass. When the neutralino mass matrix is diagonalized, we allow the sign of the ith eigenvalue (ϵ_i) to be either positive or negative. For the chargino, it is trivial to insure positive mass eigenvalues (by appropriate choice of the diagonalizing matrices), so we simply set $\epsilon = 1$ for all chargino states. The factors F_{ijk} are given in terms of the diagonalizing matrix elements for the charginos and neutralinos. Also appearing in the expressions below are M, M' and μ which are the neutralino and chargino mass matrix parameters discussed earlier. For the charginos, two 2×2 matrices U and V are required to diagonalize the mass matrix. For the neutralinos, the diagonalizing matrix Z is defined in the $(\widetilde{B}, \widetilde{W}_3, \widetilde{H}_1, \widetilde{H}_2)$-basis (where H_2 is the doublet that couples to the top-quark). We assume CP-invariant couplings, in which case U, V and Z are orthogonal matrices. We give the factors F_{ijk} below corresponding to two possible types of decay modes.

1. For $H_k^0 \to \widetilde{\chi}_i^+ \widetilde{\chi}_j^-$,

$$F_{ijk} = \frac{c_k}{\sqrt{2}} V_{i1} U_{j2} + \frac{d_k}{2m_W} (M V_{i1} U_{j1} + \mu V_{i2} U_{j2}). \tag{3}$$

2. For $H_k^0 \to \widetilde{\chi}_i^0 \widetilde{\chi}_j^0$,

$$\begin{aligned} F_{ijk} = {} & \frac{c_k}{2} \left[Z_{i3} Z_{j2} + Z_{j3} Z_{i2} - \tan\theta_W (Z_{i3} Z_{j1} + Z_{j3} Z_{i1}) \right] \\ & + \frac{d_k}{2m_W} \left[M Z_{i2} Z_{j2} + M' Z_{i1} Z_{j1} - \mu (Z_{i3} Z_{j4} + Z_{i4} Z_{j3}) - \epsilon_i M_i \delta_{ij} \right]. \end{aligned} \tag{4}$$

(Note, in eq. (4) δ_{ij} is the standard Kronecker delta function and is not to be confused with $\delta(i,j)$ which appeared earlier for neutralinos.)

The constants c_k and d_k are given by:

$$c_k = \begin{cases} \sin(\beta - \alpha), & k = 1 \\ \cos(\beta - \alpha), & k = 2 \\ \cos 2\beta, & k = 3 \end{cases}, \tag{5}$$

and

$$d_k = \begin{cases} -\sin\alpha, & k = 1 \\ \cos\alpha, & k = 2 \\ \cos\beta, & k = 3 \end{cases}. \tag{6}$$

For the decay of the charged Higgs boson, we have

$$\Gamma(H^+ \to \widetilde{\chi}_i^+ \widetilde{\chi}_j^0) = \frac{g^2 \lambda^{\frac{1}{2}} \left[(F_L^2 + F_R^2)(m_H^2 - M_i^2 - M_j^2) - 4 F_L F_R \epsilon_j M_i M_j \right]}{16 \pi m_H^3}, \tag{7}$$

where F_L and F_R are given by:

$$F_L = \cos\beta \left[Z_{j4} V_{i1} + \frac{1}{\sqrt{2}} (Z_{j2} + Z_{j1} \tan\theta_W) V_{i2} \right] \tag{8}$$

$$F_R = \sin\beta \left[Z_{j3} U_{i1} - \frac{1}{\sqrt{2}} (Z_{j2} + Z_{j1} \tan\theta_W) U_{i2} \right] . \tag{9}$$

In the first series of figures we present a full survey of all channels as a function of the parameter μ at $M = 200$ *GeV*. For this set of graphs we have chosen the charged Higgs mass to be $m_{H^\pm} = 500$ *GeV*.

1. In fig. 1 we give branching ratios for the charged Higgs boson, H^+. As well as showing individual channels, we display the total chargino+neutralino branching ratio in comparison to the $\tau^+\nu$ mode. We note that there are four or five $\tilde{\chi}^+\tilde{\chi}^0$ channels with branching ratios between 10% and 20% over a significant range of μ surrounding $\mu = 0$. The third graph shows that in combination they can account for as much as 80% of the charged Higgs decays. In comparison, the $\tau^+\nu$ mode has branching ratio $\lesssim .001$ over the entire μ range, and is even smaller where the $\tilde{\chi}^+\tilde{\chi}^0$ modes are maximum. The third graph also exhibits an important general feature: for high enough $|\mu|$ the neutralino/chargino decays become suppressed, dropping to a level determined primarily by the lightest available mode ($\tilde{\chi}_1^+\tilde{\chi}_1^0$ in the H^+ case being discussed). At low values of M the μ range over which neutralino/chargino modes are dominant expands, while at higher M values it contracts. This is easily explained by the increasing mass of the heavier chargino and neutralino states with increasing $|\mu|$ at fixed M. (See the mass graphs of ref. 4.) Decay to the lightest $\tilde{\chi}\tilde{\chi}$ state survives at large $|\mu|$, as remarked above, since the lightest $\tilde{\chi}$ states have masses that are roughly μ independent at fixed M. Eventually, for high enough M the masses of the lightest states become sufficiently heavy that even the light chargino/neutralino modes are phase space forbidden over most of the μ range. These same remarks apply also to the heavier neutral Higgs bosons, H_1^0 and H_3^0, to be discussed below.
2. In fig. 2 we present a series of four graphs showing the branching ratios for H_1^0 to all $\tilde{\chi}\tilde{\chi}$ channels. Note the importance of the $\tilde{\chi}^+\tilde{\chi}^-$ channels and the fact that all the channels combined account for most of the H_1^0 decays for $|\mu| \lesssim 200$ *GeV*, in exact parallel to the H^+ results above.
3. In fig. 3 we present four graphs showing the branching ratios for H_3^0 decay to all $\tilde{\chi}\tilde{\chi}$ channels. The results parallel closely those for H_1^0.
4. In fig. 4 we present results for H_2^0 at $M = 50$ *GeV*. We choose a lower M value than above since H_2^0 is so light that, except for a very narrow range

of μ near 0, $\tilde{\chi}\tilde{\chi}$ decays are forbidden when $M \gtrsim 100\ GeV$. Even at this low M value only the three channels displayed on the one graph are not phase-space forbidden. When allowed, however, the neutralino/chargino channels can be very substantial, especially $\tilde{\chi}_1^0\tilde{\chi}_1^0$.

5. Finally, we reemphasize that other than the $\tilde{\chi}\tilde{\chi}$ modes the only significant decays of all the Higgs bosons are to channels containing heavy fermions (assuming sleptons, squarks, etc. are heavy).

In order to judge sensitivity of these results to the parameters M and $m_{H^\pm}$ we have given several additional sets of graphs.

1. The first set, in fig. 5, gives results for H^+ decays at $M = 50\ GeV$, keeping $m_{H^\pm} = 500\ GeV$. The primary change is that the range of $|\mu|$ over which the $\tilde{\chi}^+\tilde{\chi}^0$ decays dominate expands. This is to be expected, since at small M the heavy chargino and neutralino masses remain light enough to be phase-space-allowed until higher values of $|\mu|$. (See the earlier remarks associated with fig. 1.)
2. The second set, in fig. 6, gives results for H^+ decay for $m_{H^\pm} = 150\ GeV$, at $M = 200\ GeV$. As expected, there are fewer available channels. Also the allowed μ range of those that do appear is more restricted, but when open these channels have branching ratios very similar to those that pertained at $m_{H^\pm} = 500\ GeV$.
3. Results for H_1^0 and H_3^0 have the same general features as described above for $H^\pm$, for both of the two parameter changes discussed.

The generally large branching ratios for supersymmetric Higgs bosons to decay to neutralino/chargino channels implies many new signatures for Higgs detection. Typically, for much of M and μ space, depending of course on the Higgs masses, H_1^0 and H_3^0 will decay primarily to $\tilde{\chi}_1^+\tilde{\chi}_1^-$ or $\tilde{\chi}_1^\pm\tilde{\chi}_2^\mp$. The H^+ decays tend to be spread more evenly among the various $\tilde{\chi}_i^+\tilde{\chi}_j^0$ modes; $j = 1$ (the LSP) is important but so are higher j values. The resulting $\tilde{\chi}$ states have a variety of signatures. The $\tilde{\chi}_1^+$ and $\tilde{\chi}_2^0$ decay via virtual W, Z, squark and slepton exchange into quark jets (or lepton pairs) plus the LSP. However, as discussed in ref. 4 in these proceedings, the heavier $\tilde{\chi}_2^+$ and $\tilde{\chi}_{3,4}^0$ often decay via two body modes containing W, Z or a light Higgs and a lighter chargino or neutralino. The W and Z modes could prove very useful in tagging Higgs events and should be much freer of backgrounds than the Standard Model heavy quark decays that dominate when chargino/neutralino modes are absent. To fully assess the possibility of detecting the supersymmetric Higgs in the chargino/neutralino type modes will require a substantial Monte Carlo effort. A study appropriate to the M and μ near 0 limit was undertaken in ref. 5, with encouraging results. A more complete study, which is relevant to a larger range of the supersymmetric parameters, must now be undertaken.

Acknowledgements

We would like to thank the University of Wisconsin Physics Department for its hospitality during the workshop. One of us (H.E.H.) would like to gratefully acknowledge the hospitality of the ETH, Zurich where parts of this manuscript were written. This work was partially supported by the Department of Energy.

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FIGURE CAPTIONS

1) The branching ratios for $H^{\pm}$ to various chargino+neutralino channels as a function of μ at $M = 200\ GeV$. We take $\tan\beta = 1.5$ and $m_{H^{\pm}} = 500\ GeV$. These latter two parameters fix the masses of all the other Higgs and the value of the mixing angle α as follows: $m_{H_1^0} = 501\ GeV$; $m_{H_2^0} = 35.2\ GeV$; $m_{H_3^0} = 493\ GeV$; and $\alpha = -0.60$ radians. Our notation for the curves is specified below. a) For the graph of branching ratios to channels containing the lighter chargino, $\widetilde{\chi}_1^+$, we indicate the accompanying neutralino by: solid=$\widetilde{\chi}_1^0$; dashes=$\widetilde{\chi}_2^0$; dots=$\widetilde{\chi}_3^0$; and dotdash=$\widetilde{\chi}_4^0$. b) This same sequence is also followed for the graph of branching ratios to channels containing the heavier chargino, $\widetilde{\chi}_2^+$. c) The third graph shows the total branching ratio of $H^+ \to \widetilde{\chi}_i^+\widetilde{\chi}_j^0$, summed over all i and j (solid), in comparison to that for the $\tau^+\nu$ mode (dashes).

2) Branching ratios to neutralinos and charginos for the heavier neutral scalar Higgs boson, H_1^0. The parameters chosen are the same as for fig. 1. We give four graphs. a) The first is for channels containing charginos. The curves are: solid=$\widetilde{\chi}_1^+\widetilde{\chi}_1^-$; dashes=$\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^{\mp}$; dots=$\widetilde{\chi}_2^+\widetilde{\chi}_2^-$. b) The second graph is

for channels containing the lightest neutralino, $\widetilde{\chi}_1^0$. The curves are for a given second neutralino: solid=$\widetilde{\chi}_1^0$; dashes=$\widetilde{\chi}_2^0$; dots=$\widetilde{\chi}_3^0$; dotdash=$\widetilde{\chi}_4^0$. c) The third graph is for channels in which the lightest neutralino is $\widetilde{\chi}_2^0$. The second neutralino is specified by: solid=$\widetilde{\chi}_2^0$; dashes=$\widetilde{\chi}_3^0$; dots=$\widetilde{\chi}_4^0$. d) The fourth graph is for channels containing only $\widetilde{\chi}_3^0$ and $\widetilde{\chi}_4^0$. The curves are: solid=$\widetilde{\chi}_3^0\widetilde{\chi}_3^0$; dashes=$\widetilde{\chi}_3^0\widetilde{\chi}_4^0$; dots=$\widetilde{\chi}_4^0\widetilde{\chi}_4^0$.

3) This set of graphs follows the same pattern as specified in fig. 2, but is for decays of the H_3^0.

4) This set of graphs is for H_2^0. However, we present the $M = 50\ GeV$ case. Even though this is a small M value, since H_2^0 is so light, only three channels are open and are displayed on a single graph: solid=$\widetilde{\chi}_1^+\widetilde{\chi}_1^-$; dashes=$\widetilde{\chi}_1^0\widetilde{\chi}_1^0$; dots=$\widetilde{\chi}_1^0\widetilde{\chi}_2^0$. Of course, the $\widetilde{\chi}$'s are obviously very light; in particular, the $\widetilde{\chi}_1^+$ is possibly light enough to be in conflict with experiment (see ref. 4). At $M = 200\ GeV$, the neutralino and chargino modes are phase space forbidden except for a very tiny region of μ near 0. In this region the lightest chargino is again sufficiently light that conflict with experiment is possible.

5) We present results for H^+ decay at $M = 50\ GeV$, following the format of fig. 1. We keep $m_{H^\pm} = 500\ GeV$ and $\tan\beta = 1.5$, so that all parameters in the Higgs sector are the same as for fig. 1.

6) We give the H^+ branchings ratios for $M = 200\ GeV$, but changing to $m_{H^\pm} = 150\ GeV$. (We keep $\tan\beta = 1.5$.) The format is the same as in fig. 1, except that all decays to $\widetilde{\chi}_2^+$ are kinematically forbidden and the associated graph does not appear. The complete parameters for the Higgs sector for this value of $m_{H^\pm}$ are: $m_{H_1^0} = 154\ GeV$; $m_{H_2^0} = 29.3\ GeV$; $m_{H_3^0} = 126\ GeV$; and $\alpha = -.72$ radians.

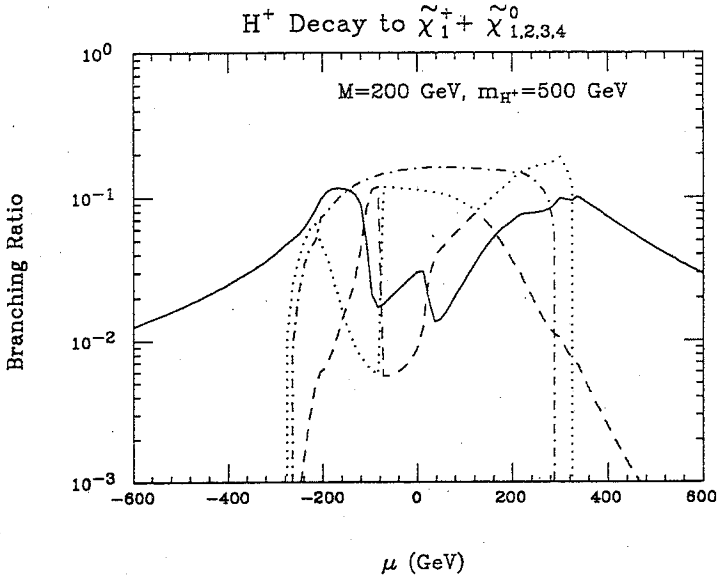


Figure 1a

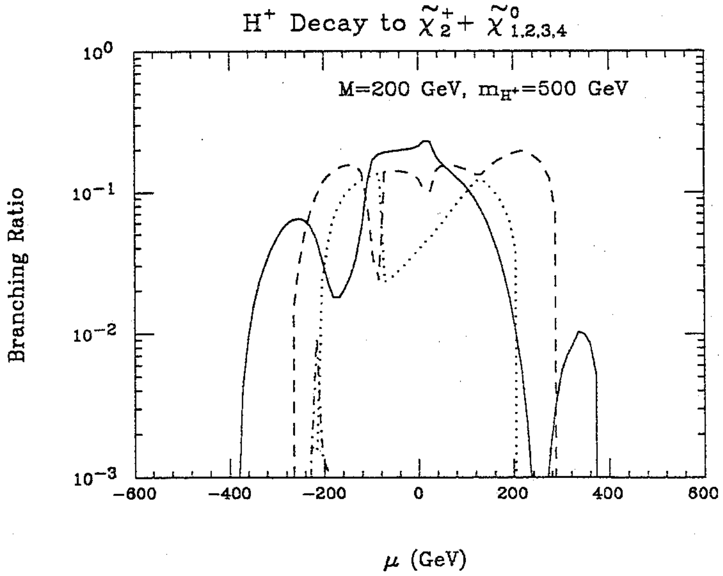


Figure 1b

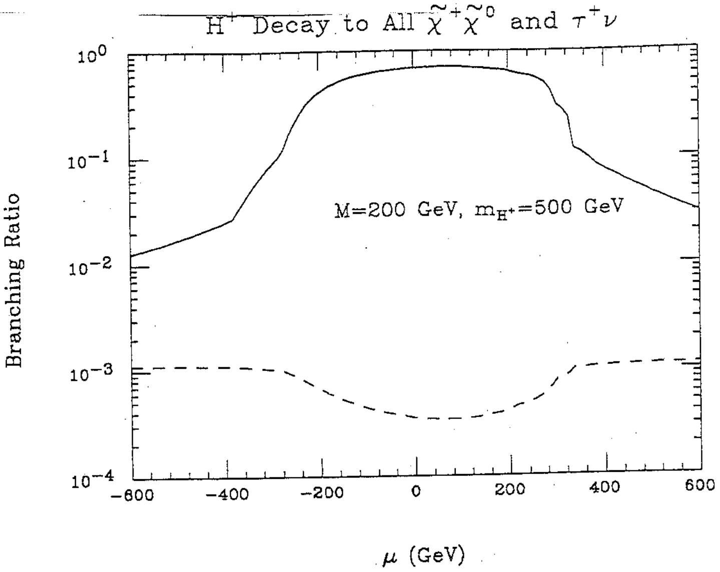


Figure 1c

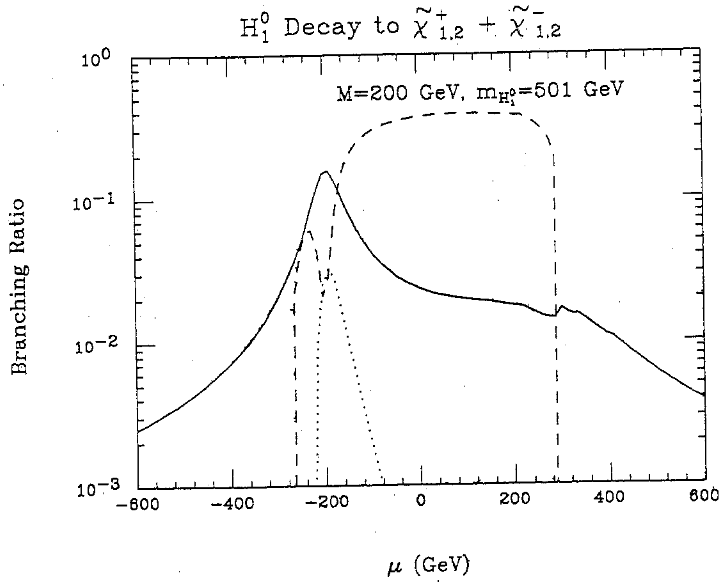
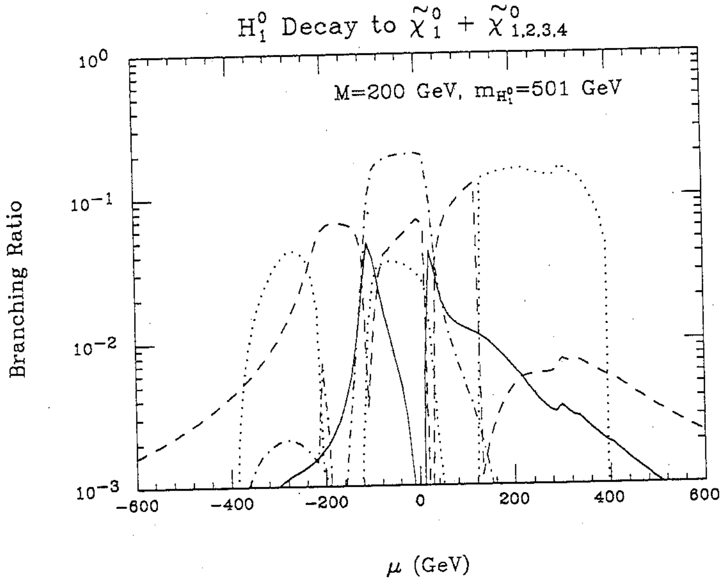


Figure 2a



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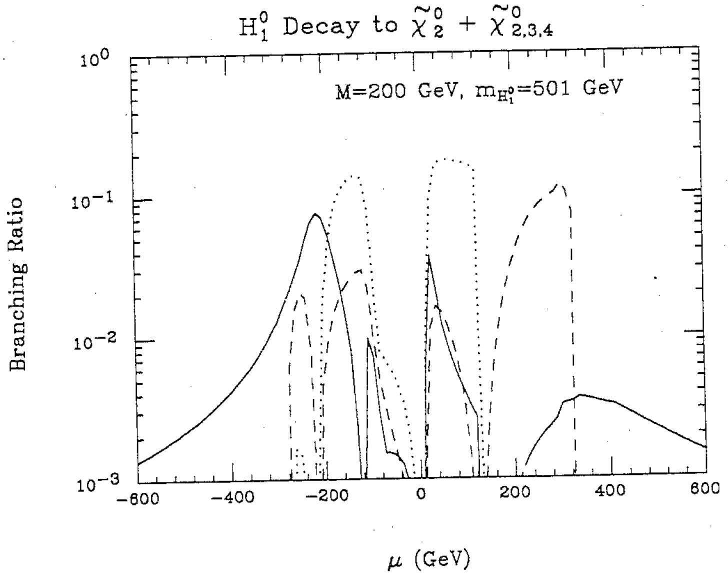

Figure 2c

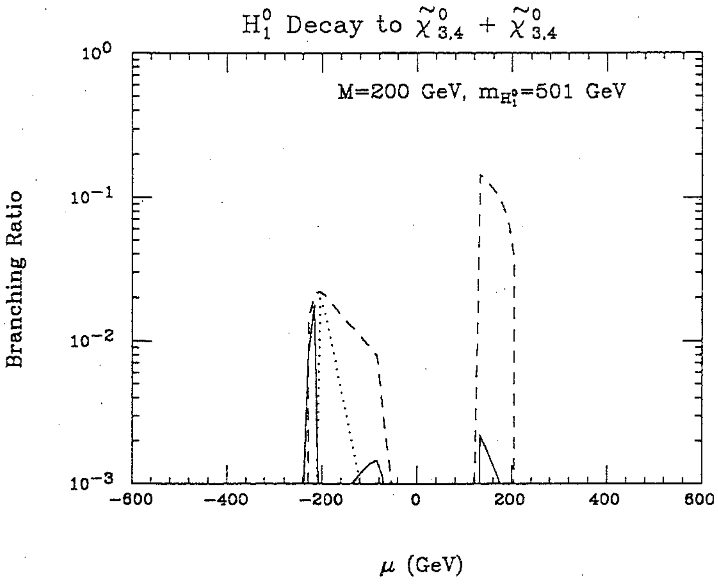

Figure 2d

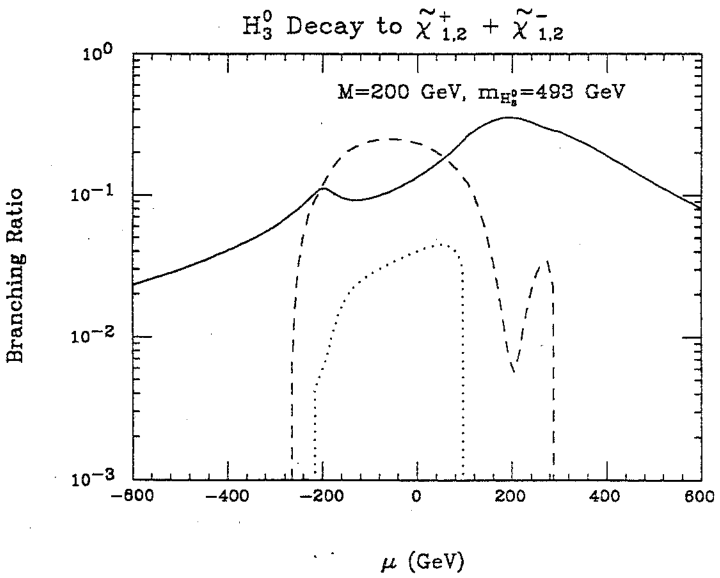

Figure 3a

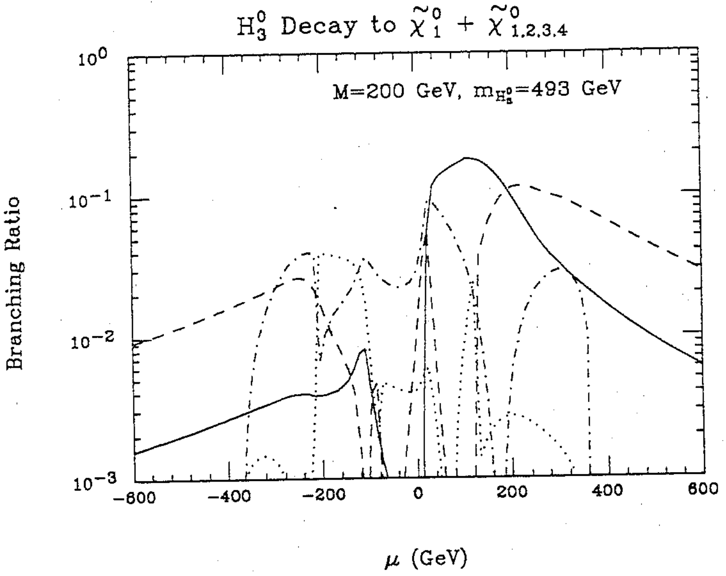

Figure 3b

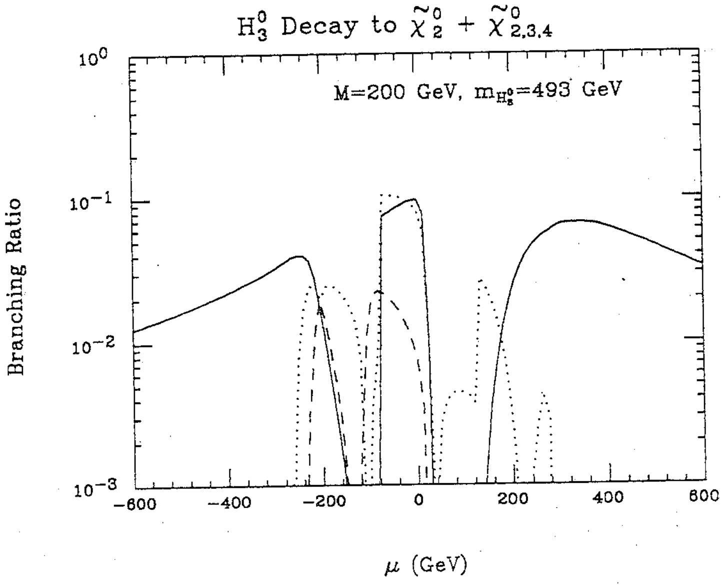

Figure 3c

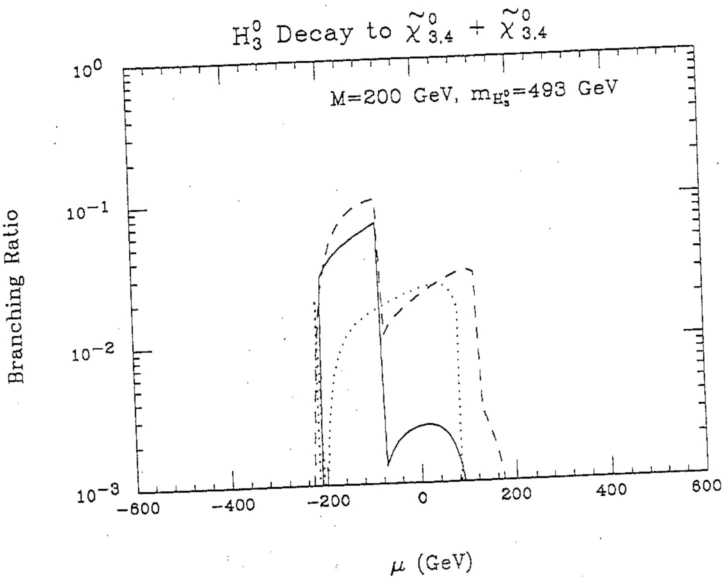

Figure 3d

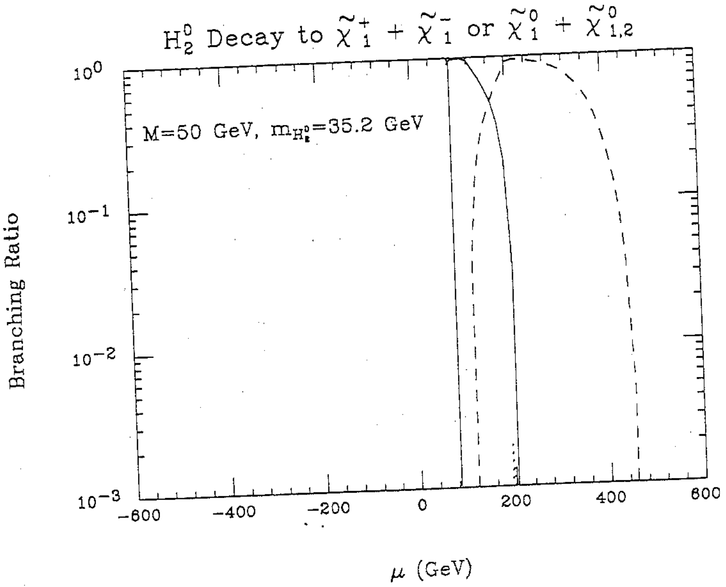

Figure 4

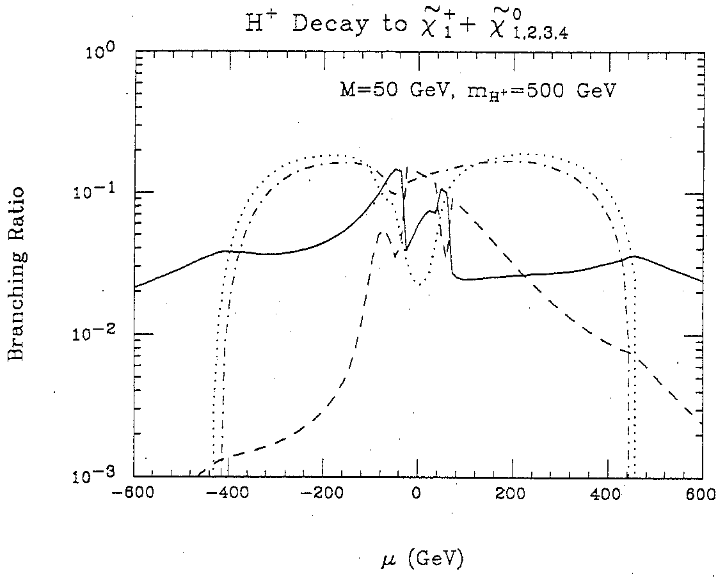

Figure 5a

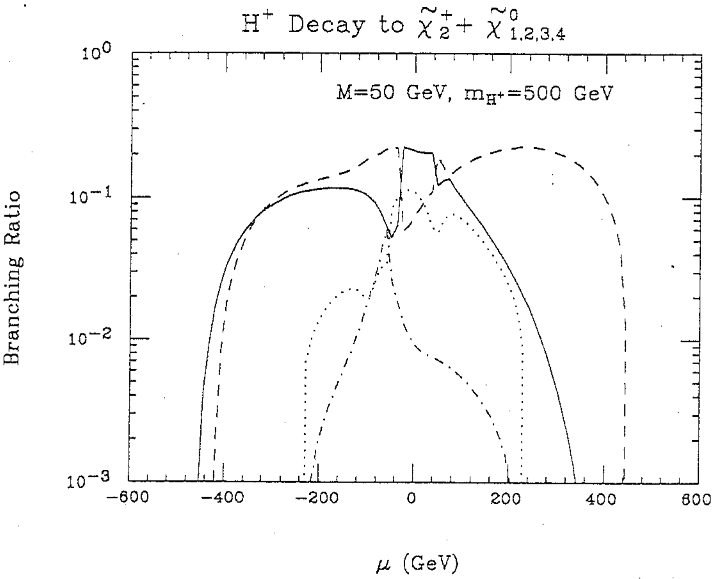

Figure 5b

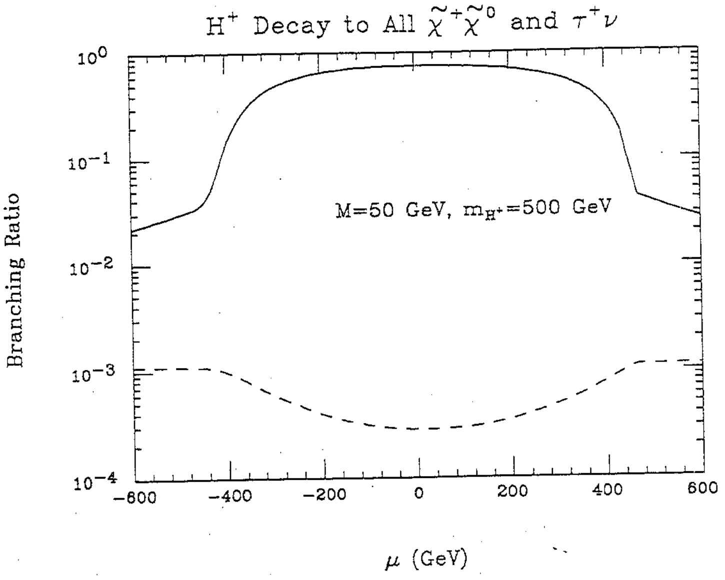

Figure 5c

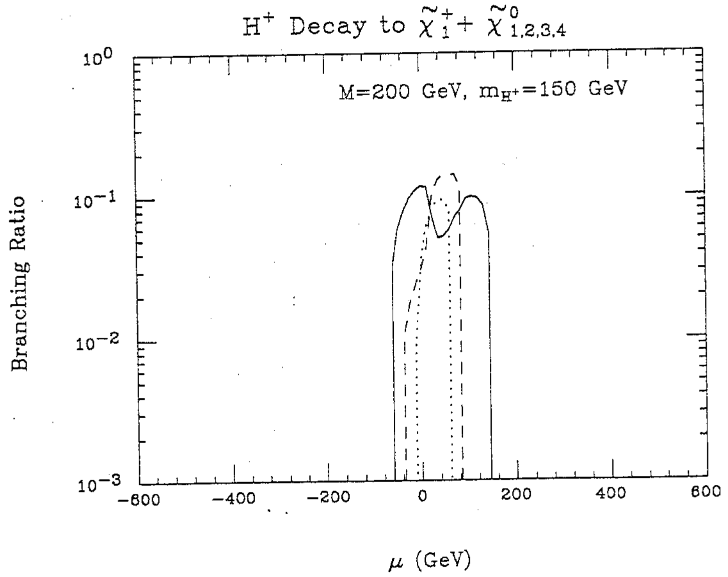

Figure 6a

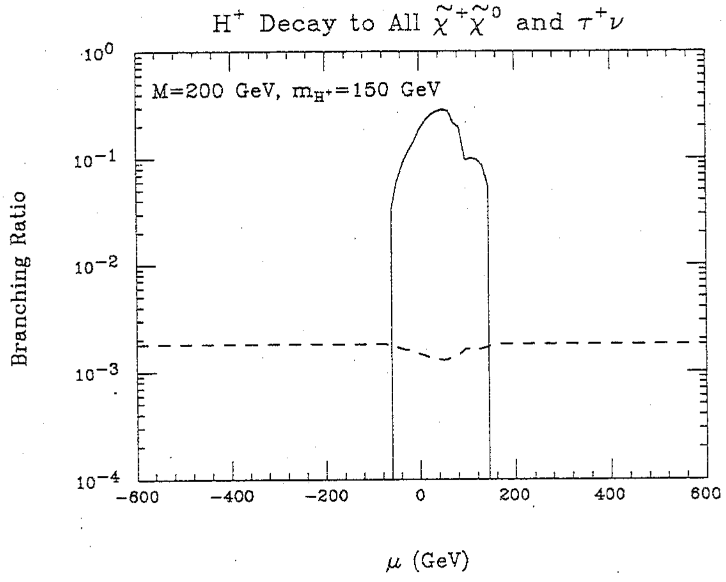
H⁺ Decay to All χ̃⁺χ̃⁰ and τ⁺ν
M=200 GeV, m_H⁺=150 GeV
Branching Ratio
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
−600
−400
−200
0
200
400
600
μ (GeV)

Figure 6b