SLAC–PUB–4408
SCIPP–87/109
UCD–87–25
November 1987
(T/E)

Probing the Non-Minimal Higgs Sector at the SSC*

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Abstract

Non-minimal Higgs sectors occur in the Standard Model with more than one Higgs doublet, as well as in theories that go beyond the Standard Model. In this report, we discuss how Higgs search strategies must be altered, with respect to the Standard Model approaches, in order to probe the non-minimal Higgs sectors at the SSC.

Presented at the Workshop on Experimental Area for the Supercollider,

July 7–17, 1987

⋆ Work supported in part by the Department of Energy, contracts DE–AC03-76SF00515 and DE–AS03–76ER70191.

A. Introduction

A great deal of effort has been focused on the search for the minimal Higgs of the Standard Model at the SSC. The term "minimal Higgs" implies that the $SU(2) \times U(1)$ electroweak theory consists of the minimal choice of one complex Higgs doublet. In such a theory, there is only one physical Higgs scalar in the spectrum, whose mass is a free parameter not fixed by the theory. This minimal choice is somewhat arbitrary. Given the fact that there is no experimental information concerning the Higgs sector at present, one must resort to theoretical arguments to constrain the unknown Higgs sector, even in the context of the Standard Model.

Two theoretical constraints exist. First, it is an experimental fact that $\rho = m_W^2/(m_Z^2 \cos^2\theta_W)$ is very close to 1. This almost certainly implies that the Higgs bosons are either $SU(2)$ weak doublets or singlets. (Other choices are possible, but rather ugly.) Second, there are severe limits on the existence of flavor-changing neutral currents (FCNC's). In the model with the minimal Higgs, tree-level flavor changing neutral currents are automatically absent. This continues to be true in non-minimal models in which fermions of a given electric charge couple to no more than one Higgs doublet.[1] An example of a model satisfying this requirement is the minimal supersymmetric extension of the Standard Model. This model (of which we will have more to say below) possesses two Higgs doublets of opposite hypercharge; the $Y = -1$ doublet couples only to down-type quarks and leptons, and the $Y = 1$ doublet couples only to up-type quarks and leptons. In this report, we shall concentrate on the two-Higgs doublet extension of the Standard Model. In addition, we will choose the Higgs–fermion coupling described above, which is compatible with the supersymmetric extension of the Standard Model. This framework is useful in that it adds new phenomena (*e.g.*, charged Higgs), introduces a minimal number of new parameters, and satisfies the theoretical constraints mentioned above. Two-Higgs-doublet models possess five physical Higgs bosons: a charged pair ($H^\pm$), two neutral CP-even scalars (H_1^0 and H_2^0), and a neutral CP-odd pseudoscalar (H_3^0). Here, we have made an implicit assumption that the Higgs potential is CP-invariant, so that the neutral Higgses have definite CP quantum numbers. The terms "scalar" and "pseudoscalar" refer to the way in which these neutral Higgses couple to fermion pairs. Instead of the one free parameter of the minimal model, this model has at least six free parameters: four Higgs masses, the ratio of vacuum expectation values:

$$\tan\beta = v_2/v_1, \tag{1}$$

and a Higgs mixing angle, α. The angle α arises when one diagonalizes the 2×2 neutral scalar Higgs mass matrix, whose eigenstates are H_1^0 and H_2^0. For definiteness, we will always take $m_{H_1^0} \geq m_{H_2^0}$. Note that $v_1^2 + v_2^2$ is fixed by the W mass. (Additional Higgs self-coupling parameters do not concern us here.)

There are two phenomenologically crucial types of Higgs couplings: those to fermion-antifermion pairs and those to two vector bosons. The couplings of the physical Higgses to fermion pairs are rather similar to those of the minimal model Higgs, especially if $\tan\beta$ is around 1. Let v_1 (v_2) be the vacuum expectation value of the Higgs field which couples only to down-type (up-type) fermions. Then (in 3rd generation notation), the $H_3^0 t\bar{t}$ ($H_3^0 b\bar{b}$) coupling is suppressed (enhanced) if $\tan\beta > 1$, and vice versa if $\tan\beta < 1$. Similar results hold for H_1^0 and H_2^0, although the couplings also involve the mixing angle α which can reduce the size of the couplings somewhat. For the charged Higgs we have:

$$g_{H^+t\bar{b}} = \frac{g}{2\sqrt{2}m_W}[m_t \cot\beta(1+\gamma_5) + m_b \tan\beta(1-\gamma_5)]. \tag{2}$$

Of even greater importance are the Higgs couplings to vector bosons. The H_3^0 couplings to vector boson pairs are forbidden at tree level. Of course, the $Z^0 H_i^0 H_j^0$ couplings are forbidden, when $i = j$ by Bose symmetry. When $i \neq j$, this coupling is only present when the two Higgses have opposite CP quantum numbers. Vertices involving neutral particles only and one or two photons clearly vanish at tree level, although they are generated at one-loop. (The same is true for the coupling of all neutral Higgs bosons to a pair of gluons. The radiatively generated $H_k^0 gg$ vertex is important since the two-gluon fusion is one of the major production mechanisms for neutral Higgses at a hadron collider.) Two other vertices, $H^+W^-Z^0$ and $H^+W^-\gamma$, also vanish at tree level. This turns out to be a general feature of models with only Higgs doublets and singlets.[2] Again, these vertices are radiatively generated at one-loop, and lead to interesting rare decays of the charged Higgs.[3] All other three-point tree-level vertices involving gauge and Higgs bosons are allowed. Probably the most important vertices for phenomenology are couplings of H_1^0 and H_2^0 to W^+W^- and Z^0Z^0. These couplings tend to be somewhat suppressed compared to their values in the minimal-Higgs model. However, there is a sum rule:

$$g^2_{H_1^0 VV} + g^2_{H_2^0 VV} = [g^{minimal}_{H^0 VV}]^2 \tag{3}$$

which holds separately for $V = W$ or Z. Without further information, one cannot be certain as to how the H^0VV coupling strength is divided between H_1^0 and H_2^0. However, as discussed later in this report, in supersymmetric models the coupling of the heavier Higgs (H_1^0) to vector bosons is severely suppressed.

Having summarized the general properties of the two-Higgs doublet model, we briefly turn to the implications for the Higgs search at the SSC. Because of the fact that we now have (at least) six free parameters in the Higgs sector, there are only a few general statements one can make concerning the phenomenology of the Higgs at the SSC. First, if the scalar Higgs has couplings to WW and ZZ which are similar to their values in the Standard Model, and its mass is between about $2m_W$ and 800 GeV, then it should be possible to detect this Higgs at the SSC by observing its decay into a pair of vector bosons (followed by subsequent decay of the vector bosons into lepton pairs), as described by the Heavy Higgs Group.[4] On the other hand, for masses less than $2m_W$, we are in the regime of the "intermediate mass Higgs", in which the dominant Higgs decay is into the heaviest quark pair which is kinematically allowed. While the two-photon and ZZ^* (rare) decay modes may be useful over a large portion of the m_t-m_H parameter space, the ability to successfully observe such a Higgs at the SSC is not certain, especially if the top is not very heavy (e.g. $m_t \sim 55\ GeV$) and the Higgs has mass just above the $t\bar{t}$ decay threshold.[3][5] In supersymmetric models, detection of the heavy Higgs (H_1^0) via its Standard Model decay modes is particularly problematical. As alluded to above, the decay of H_1^0 into vector boson pairs (even when kinematically allowed) is extremely suppressed. Similarly, the vector boson fusion production mechanism is numerically unimportant, thereby reducing the production cross-section for the heaviest Higgs case. Since m_H is almost certain to be above $2m_t$ for this Higgs, even the two photon decay mode (useful for $m_H < 2m_t$) cannot be employed and detection would be extremely difficult.

Consider next the pseudoscalar Higgs. As described above, the pseudoscalar does not couple to vector boson pairs at tree level. The phenomenological implications of this fact are devastating. First, the important vector boson fusion mechanism for production of a Higgs boson is absent. Second, the dominant decay of the pseudoscalar Higgs will be into the heaviest quark pair available, independent of the Higgs mass. Thus, the search for the pseudoscalar Higgs will be very difficult once $m_{H_3^0} > 2m_t$, while for $m_{H_3^0} < 2m_t$ the 2γ decay mode may allow observation. Note, however, that if such an object could be found in the mass region above $2m_W$, then the absence of decays into vector boson pairs would be strong evidence for the pseudoscalar nature of the object. (An exception to this rule occurs in supersymmetric models, which predict Higgs *scalars* with suppressed couplings to the vector boson channels. Nevertheless, such an observation would be definitive evidence for a non-minimal Higgs sector.)

Finally, consider the charged Higgs boson. Because of the absence of tree-level coupling of the charged Higgs to vector boson pairs (WZ and $W\gamma$), the detection of the charged Higgs is likely to be at least as difficult as detection of the pseudoscalar Higgs. An exception, to be discussed later, occurs if $m_t > m_{H^\pm} + m_b$, and the decay $t \to H^+ + b$ has a large branching ratio. In contrast, for $m_t < m_{H^\pm} + m_b$ the total cross-section for the production of a single charged Higgs is smaller than that typical of a neutral Higgs, since the gluon-gluon fusion and vector-boson-fusion mechanisms are not available in this case. Instead, we must rely on the coupling to heavy quarks. This point will be discussed further below.

In summary, the detection of non-minimal Higgses is at best equivalent to the detection of the heavy minimal Higgs when the dominant decay is into vector boson pairs. Otherwise, (*e.g.* in the case of the pseudoscalar and charged Higgs) the prospect for detection is substantially worse, since it is very difficult to detect a Higgs whose primary decay products contain t and b quark initiated hadron jets. Thus, in order to have any hope for observing such Higgs bosons at the SSC, alternative decay modes must be studied. There are two basic approaches. The first approach involves the search for rare decay modes, with the hope that the decrease in background will compensate the decrease in signal due to a presumably small branching ratio. The second approach is to look for completely new final states which may constitute an important fraction of all Higgs boson decays. An example of this approach is to make use of the supersymmetric model, and investigate the branching ratio of the various Higgses into supersymmetric final states.

In this report, we will focus much of our attention on the charged Higgs boson, since its discovery would unequivocably signal the presence of a non-minimal Higgs sector. The report (a preliminary version of which appears in ref. 6) is organized as follows. In Sections B and C, we assess the feasibility of observing the charged Higgs boson at the SSC. QCD backgrounds to observing the H^+ via its $t\bar{b}$ decay are large, so we concentrate on the search for the charged Higgs boson via rarer decay modes. We briefly survey a number of possible charged Higgs decays: $H^\pm \to W^\pm\gamma$, $H^\pm \to W^\pm + quarkonium$, $H^\pm \to W^\pm H^0$, and $H^\pm \to W^\pm H^0\gamma$, and in Section C, we turn to an extensive study of the $\tau\nu$ decay. A detailed Monte Carlo analysis is presented, and various possible regions of parameter space are examined. In Section D, implications of the previous section for detector design are considered. Finally, in Section E, we briefly consider the implications of the "low-energy" supersymmetry approach for the phenomenology of Higgs bosons at the SSC. Our conclusions are summarized in Section F.

B. Search for the Charged Higgs Boson–General Considerations

First, let us make a few remarks about the production mechanism of a singly charged Higgs boson at the SSC. Which production mechanism is dominant depends upon the relative mass of the t quark and the $H^\pm$. If the top quark has a moderate mass, but $m_t > m_{H^\pm} + m_b$, then the rate for $gg \to t\bar{t}$ followed by t decay to the $H^\pm$ is very large. Relative to the t decay rate to charged W's we have:

$$\frac{\Gamma(t \to H^+ b)}{\Gamma(t \to W^+ b)} = \frac{p_{H^+}}{p_{W^+}} \frac{m_t^2(m_t^2 - m_{H^+}^2)}{(m_t^2 + 2m_W^2)(m_t^2 - m_W^2)} \cot^2\beta, \tag{4}$$

where p_{H^+} and p_{W^+} are the center-of-mass momenta of the H^+ and W^+ for the respective decays. Thus, the H^+ channel is fully competitive with the W^+ mode. If $m_t < m_{H^\pm} + m_b$, then one must turn to other production modes for the charged Higgs. Naively, one might expect that, at SSC energies, there will be a non-negligible amount of top-quarks (and bottom-quarks) inside the proton, so that one could use $t\bar{b}$ fusion to create the H^+ (and, of course, $b\bar{t}$ fusion for H^-). Although this is in some sense true, it turns out that the application of the parton model to this subprocess overestimates the charged Higgs cross-section by about a factor of 2. The reason for this is that, even at SSC energies, the top quark distribution function is not present at full strength (as compared to other massless quarks). So, effectively, the t-quark distribution function is of $\mathcal{O}(\alpha_s)$. This means that other partonic subprocesses which are $\mathcal{O}(\alpha_s)$ down from $t\bar{b} \to H^+$ are competitive with $t\bar{b}$ fusion, if they do not involve an initial t-quark.

The sub-process which turns out to be most important is $\bar{b} + gluon \to \bar{t} + H^+$. In fact, there is a subtle point involved here, since the leading logarithm of this process (for $m_{H^+} \gg m_t$) corresponds precisely to the $t\bar{b}$ fusion process. In ref. 7 a method of calculation is developed which avoids any problem of double counting, and shows how to correctly evaluate the charged Higgs production cross-section. Numerical analysis[8] shows that the correct procedure at SSC energies, for Higgs and top masses of interest, is to omit entirely the $t\bar{b}$ fusion contribution, and include only the exact $2 \to 2$ subprocess $\bar{b}g \to \bar{t}H^+$ We will make use of this result in the analysis presented below. For ease of reference, we give the cross section for $H^\pm$ production from ref. 8 in fig. 1.

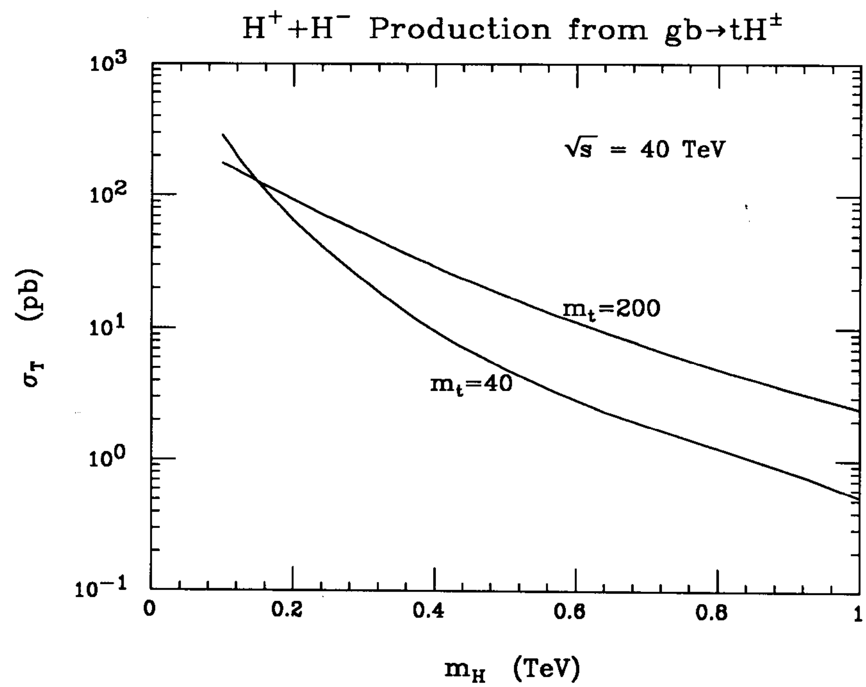

Figure 1: Charged Higgs total cross section from ref. 8. The cross section is computed for $\tan\beta = 1$, and is displayed for $m_t = 40$ and $200\ GeV$.

Even in the case where $m_{H^\pm} > m_t$, the raw number of charged Higgs events is substantial. However, for a given Higgs decay mode, the desired signal is generally swamped by huge backgrounds. To have any chance of seeing a signal, a trick must be employed. One trick that we shall explore is that of a 'stiff lepton trigger', first proposed in ref. 8. In the production mechanisms, $\bar{b}g \to \bar{t}H^+$ and $bg \to tH^-$, one attempts to trigger on the t or $\bar{t}$ produced in association with the charged Higgs. One approach to doing this is to note that the final state t and $\bar{t}$ quarks are typically moving nearly parallel to the original beam. Ordinarily, they would just be lost inside the beam jets. However, if the t-quark decays semi-leptonically, the electron or muon will be kicked out with sufficiently large p_T (of order $m_t/2$), so that it can be used to trigger the desired event. Even the leptons coming from decays of the secondary b quarks that arise from t decay will contribute to this trigger, so that a trigger in which a stiff lepton with $p_T^l > 10\ GeV$ is required retains $\sim 45\%$ of the $H^\pm$ events, while rejecting all but 1% to 2% of most types of background processes.[8]

The first question that one must ask is whether the possibility of such a trigger could even make the observation of the charged Higgs in its major tb decay mode feasible. For simplicity of notation let us consider production and detection of the single charge state, H^-. If we imagine for a moment that the stiff lepton trigger is 100% efficient in eliminating events without a spectator t quark and that the $\bar{t}$ quark can also be triggered upon with 100% efficiency, then the only backgrounds are $gb \to t\bar{t}b$ (i.e. a QCD subprocess leading to exactly the same final state) and $gg \to t\bar{t}g$. The latter is a background to the extent that a g jet cannot be distinguished from a b jet. (We ignore the generally smaller $gq \to t\bar{t}q$ backgrounds.) These backgrounds have been computed in ref. 9. We will sketch the results for the typical case of $m_{H^\pm} = 100\ GeV$ and $\tan\beta = 1$. First, we require that all outgoing jets have $|y| < 5$ and total energies above $10\ GeV$. In addition, we require that the b jet (or g) have energy larger than $50\ GeV$, and that the laboratory angular separation between the $\bar{t}$ and b (or g) be at least 15 degrees. Finally, we assume that it will be possible to achieve a resolution of order 10% in the $\bar{t}$-$b(g)$ mass, and accept only events with $M_{\bar{t}b(g)}$ within the range $95\ GeV$ to $105\ GeV$. The results for the cross sections are:

$$\begin{aligned}\sigma(t + H^-) &\sim 64\ pb \\ \sigma(t + \bar{t}b) &\sim 200\ pb \\ \sigma(t + \bar{t}g) &\sim 2600\ pb.\end{aligned} \tag{5}$$

It is relatively straightforward to find additional cuts that reduce the $t + \bar{t}b$ background below the signal rate (without sacrifice of too much cross section). Thus the most important question is whether efficient procedures for distinguishing b jets from g jets to one part in 40 can be developed. Of course, the above discussion has so far ignored backgrounds such as $gg \to ggg$ (and similar ones involving light quarks) which enter to the extent that t jets cannot be distinguished from g and light quark jets. It was shown in ref. 9 that a set of cuts can be found that reduce the $gg \to ggg$ cross section sufficiently, so that discrimination between b, t and g jets to one part in ~ 40 would make this background comparable to the signal (which is about 1 pb after cuts). This factor of 40 might be achievable, based on the stiff lepton trigger example discussed earlier. The major problem will be whether or not this can actually be done with high efficiency. In addition, there is the question of what mass resolution in the $\bar{t}b$ channel can actually be achieved. Clearly these are questions requiring a detailed Monte Carlo study. We do not feel that one should be very optimistic about direct detection of the $H^\pm$ in the tb channel; however, the above results do suggest that further study is warranted.

Since the dominant decay mode of the charged Higgs is a very problematical mode of discovery, it is imperative to examine other possible rarer decay modes. The obvious strategy is to choose distinctive final states in order that the increased signal-to-background can more than compensate the reduced branching ratio. In this report we shall consider five interesting rare decays, involving standard model particles and/or Higgs bosons, neglecting temporarily the possibility of exotic final states (*e.g.* containing supersymmetric particles). First, among the possible final state fermion pairs, we consider the $\tau\nu$ decay mode. The branching ratio in the two-Higgs-doublet model is:

$$BR(H^\pm \to \tau\nu) \approx \frac{m_\tau^2 \tan^2\beta}{3(m_t^2 \cot^2\beta + m_b^2 \tan^2\beta)}, \tag{6}$$

where we have assumed that the dominant decay of the charged Higgs is into $t\bar{b}$ (or $b\bar{t}$). Thus, unless $\tan\beta$ is quite large, we expect a branching ratio of $BR(H^\pm \to \tau\nu) \lesssim 10^{-3}$, when $m_{H^+} > m_t + m_b$ and $m_t \gtrsim 55\ GeV$. Of course, if the top quark mass is larger than the charged Higgs mass, then $BR(\tau\nu)$ can be substantially bigger; at $\tan\beta = 1$ roughly 35% of the charged Higgs decays are to $\tau\nu$, and the number could be substantially higher if $\tan\beta > 1$. To be more specific requires a definite model, which also includes the W^+H^0 modes to be discussed later. As an example, if the branching ratio for $H^+ \to \tau^+\nu$ is computed in the minimal supersymmetry model,[8] for $m_{H^\pm} < m_t + m_b$ and all supersymmetric particle modes forbidden, a typical choice of parameters yields a $\tau\nu$ mode branching ratio ranging between 10% and 40%, and even higher for small $m_{H^\pm}$. To evaluate whether it is feasible to detect the charged Higgs in this mode, we must carefully evaluate the charged Higgs production and the competing backgrounds to the $H^+ \to \tau\nu$ final state. A detailed discussion of the detectibility of the charged Higgs via the $\tau\nu$ mode is presented in Section C.

What about other rare decay modes of the charged Higgs boson? Within the context of Standard Model-particle final states, the only possibilities that come to mind are $H^\pm \to W^\pm\gamma$, $H^\pm \to W^\pm + quarkonium$, $H^\pm \to W^\pm H^0$, and $H^\pm \to W^\pm H^0\gamma$ (where H^0 can, in principle, be either of the neutral scalars, H_1^0 or H_2^0). The rate for the first mode has been computed in ref. 3. In general the branching ratio is quite small, and the event rate too low to compete with the $W^\pm\gamma$ continuum background. An exception to this statement occurs when the charged Higgs mass is much smaller than the mass of the heavier neutral Higgs (H_1^0). However, note that in the supersymmetric models to be discussed later the $H^\pm$ and H_1^0 masses are always quite similar.

The $W^\pm + quarkonium$ mode branching ratios were considered in ref. 10. The modes $H^+ \to W^+\Upsilon$ and $H^+ \to W^+\Theta$ (where Θ is the $t\bar{t}\ {}^3S_1$ bound state) were computed; both are quite sensitive to the value of m_t which enters the loop diagram calculations and controls the phase space. The conclusions of ref. 10 are easily summarized. If $H^+ \to t\bar{b}$ is not allowed, then the branching ratio for $H^+ \to W^+\Upsilon$ is quite significant (typically $1 - 3 \times 10^{-2} BR(H^+ \to \tau^+\nu)$)

when $m_{H^\pm}$ is just below $m_t + m_b$, although it falls rapidly with increasing m_t. Together with $t\bar{t}$ production followed by $t \to H^+ b$ and $\bar{t} \to W^- \bar{b}$, one finds a significant rate for production of two b jets, two leptonically decaying W's and a leptonically decaying Υ. In contrast, since $H^+ \to t\bar{b}$ is always allowed if $H^+ \to W^+ \Theta$ is allowed, the latter decay always has a very small branching ratio (typically $\lesssim 10^{-5}$).

The $H^+ \to W^+ H_1^0$ and $H^+ \to W^+ H_2^0$ decays are potentially quite important due to the large contributions from longitudinal W polarization states. These modes have been explored in ref. 3. Defining the Feynman coupling for $H^+ W^- H^0$ as the coefficient of $-i(p+p') \cdot \epsilon_W$ (where p and p' are the four-momenta of H^+ and H^0, respectively) we have a sum rule analogous to that of eq. (3):

$$g^2_{H^+ W^- H_1^0} + g^2_{H^+ W^- H_2^0} = g^2/4. \tag{7}$$

Again, a specific model is required to determine both the division of the coupling strengths and the relation between the H^+, H_1^0 and H_2^0 masses. Defining the ratio $R_{WH^0} \equiv BR(H^+ \to W^+ H^0)/BR(H^+ \to t\bar{b})$, we obtain:

$$R_{WH_2^0} = \frac{2\cos^2(\beta-\alpha) p_W^3 m_{H^+}^2}{3 p_{\bar{b}} [(m_t^2 \cot^2\beta + m_b^2 \tan^2\beta)(m_{H^+}^2 - m_t^2 - m_b^2) - 4 m_t^2 m_b^2]} \tag{8}$$

where p_W and $p_{\bar{b}}$ are the center-of-mass momenta of the indicated final state particles, and α is the scalar Higgs mixing angle. The corresponding formula for H_1^0 is obtained by replacing $\cos(\beta-\alpha)$ with $\sin(\beta-\alpha)$. To determine just how important these modes could potentially be, we consider the case where the outgoing H_2^0 has a mass of 40 GeV and saturates the allowed coupling strength (*i.e.*, $\cos(\beta-\alpha) = 1$ in eq. (8)). At $\tan\beta = 1$ and $m_t = 55$ GeV the ratio $R_{WH^0} \equiv BR(H^+ \to W^+ H^0)/BR(H^+ \to t\bar{b})$ rises from ~ 0.17 at $m_{H^\pm} = 140$ GeV to ~ 1.2 at $m_{H^\pm} = 200$ GeV, passing 10 in the vicinity of $m_{H^\pm} = 460$ GeV. However, if the minimal supersymmetric model is employed, the importance of such modes is greatly reduced. First, the mass relations are such that $H^+ \to W^+ H_1^0$ is never allowed. Second, $g_{H^+ W^- H_2^0}$ has the same severe suppression that characterizes the $H_1^0 WW$ and $H_1^0 ZZ$ couplings, as discussed earlier. At $m_t = 55$ GeV the resulting $R_{WH_2^0}$ value is 0 at $\tan\beta = 1$ (since by eqs. (13) and (17), $\cos(\beta-\alpha) = 0$ at this point), and it reaches a maximum as a function of m_{H^+} of $\sim 2\times 10^{-2}$ at $\tan\beta = 1.5$ and $\sim 7 \times 10^{-2}$ at $\tan\beta = 3$. As m_{H^+} increases beyond the location of the maximum $R_{WH_2^0}$ falls slowly. The H_2^0 masses implied by the choices of m_{H^+} and $\tan\beta$ in the above range are of order 20 to 40 GeV. Thus H_2^0 would decay to $b\bar{b}$. In fact, the above branching ratios for $\tan\beta \geq 1.5$ imply an effective $W^+ H_2^0$ associated production cross section (~ 1 pb) that is not very different from the associated production cross section considered in searches for the intermediate mass Standard Model neutral Higgs (using $W^* \to WH^0$).[11] Of course, outside the context of the minimal supersymmetry model considerably larger cross sections are possible. The studies of the intermediate mass Higgs region[11] suggest that the $b\bar{b}$ mass resolution will be sufficient to recognize a 1 pb level W^+H^0 signal over backgrounds coming from mixed QCD/Electroweak processes such as $qq' \to W^+b\bar{b}$, when the H^0 mass is in the vicinity of 120 GeV (and the $t\bar{t}$ mode is not allowed). This would undoubtedly be much more difficult at lower $b\bar{b}$ invariant mass; problems would include decreased $b\bar{b}$ mass resolution and significantly larger backgrounds. On the other hand, charged Higgs production can be tagged using the "stiff-lepton" trigger discussed earlier. In addition charged Higgs decay would lead to Jacobian peaks in the outgoing W^+ and $b\bar{b}$-system transverse momenta that might allow for effective cuts that would further reduce backgrounds. Clearly, a detailed Monte Carlo study is required to fully assess the situation, but this mode looks relatively promising.

Finally, we summarize the results of ref. 3 for the decays $H^+ \to W^+H^0\gamma$. As in the previous case, the strength for such modes is divided between the H_1^0 and H_2^0. The useful branching ratio relative to the $t\bar{b}$ decay channel of the H^+ depends upon the minimum energy allowed for the γ. Let us adopt a requirement of $E_\gamma > 20\ GeV$ in the H^+ rest frame. For $\tan\beta = 1$, $m_t = 40\ GeV$, an H^0 mass of 55 GeV, and maximal coupling, the ratio $R_{WH^0\gamma} \equiv BR(H^+ \to W^+H^0\gamma)/BR(H^+ \to t\bar{b})$ is 0.01 at $m_{H^\pm} = 300\ GeV$ and rises steadily with increasing $m_{H^\pm}$, passing 0.1 by $m_{H^\pm} \sim 520\ GeV$. This would clearly provide a very viable signature and rate for H^+ detection, even accounting for the need to reconstruct the H^0 in a $b\bar{b}$ decay mode. However, just as in the W^+H^0 mode case, the minimal supersymmetric model predicts that $H^+ \to W^+H_1^0\gamma$ is phase-space-forbidden, while $H^+ \to W^+H_2^0\gamma$ is severely suppressed. In this particular model, $R_{WH_2^0\gamma}$ (where we have taken $E_\gamma > 20\ GeV$, $m_t = 55\ GeV$, and $\tan\beta = 1.5$, as an example) reaches a maximum of $\sim 2.6 \times 10^{-5}$ at $m_{H^\pm} \sim 400\ GeV$ and decreases (slowly) thereafter. The resulting event rate at the SSC would not be useful!

Thus, to summarize, the 'rare' decay mode of the charged Higgs that is significant in the largest class of models (including, in particular, the minimal supersymmetric model) is the $\tau\nu$ channel. Thus, we shall focus on this mode in the following section.

C. Search for the Charged Higgs Boson Via its $\tau\nu$ Decay

As discussed in Section B, there are two different scenarios to consider when discussing the detectability of the $H^\pm$ in any of its decay modes. In the first, $m_t > m_{H^\pm} + m_b$ and we will look for $H^\pm$ in the decays of the t and $\bar{t}$ quarks produced via $gg \to t\bar{t}$. In the second, $H^\pm$ must be produced inclusively via the $gb \to H^\pm t$ fusion processes.

The first case, $m_{H^\pm} + m_b < m_t$, can be expected to provide the clearest signal for the charged Higgs, because both the production cross section, $\sigma(gg \to t\bar{t})$, and the branching ratio for $H^+ \to \tau^+\nu_\tau$ are large. The main difficulty is to distinguish the charged Higgs signal, $t \to bH^+$, from the standard decay, $t \to bW^+$, with the subsequent decay of $H^\pm$ and $W^\pm$ to a lepton and neutrino. Unlike the case of W decay, charged Higgs decay yields a violation of "lepton universality" that can be used to distinguish between the two possible top decay modes. Specifically, in the case of charged Higgs decay, the branching ratio for decay to the τ lepton is much larger than that for decay to an electron or a muon. But, in the case of W boson decay, all three leptons are produced equally.

As is discussed in ref. 12, events containing τ's can be enhanced by triggering on isolated charged tracks. The isolated track can be either a lepton or a hadron. Of course, W decay to e, μ, τ can also produce an isolated charged track, so we will have to use a statistical technique to uncover a signal for charged Higgs production against the background of charged W production in top quark decays. If the source of the isolated track is the decay of the charged Higgs, the ratio of the probability that the isolated track is a hadron to the probability that the track is a lepton (hereafter referred to as $R(h/l)$) is the same as that in the decay of the τ. For simplicity, we will assume that the decay of the charged Higgs and W boson to quarks can be rejected completely. In the case of W boson decay, the ratio $R(h/l)$ is smaller than for tau decay, because an electron or muon directly produced from the W decay cannot be distinguished from a single track coming from a tau decay. Thus, $R(h/l)$ for W decay is $h(\tau)/(l(\tau)+2)$, where $h(\tau)$ and $l(\tau)$ are the branching fractions for single charged hadrons and leptons, respectively, in tau decay. Using the measured decay branching fractions of the τ, we find that if there is no charged Higgs in the t decays, the measured $R(h/l)$ will be 0.22. In contrast, if we assume for the moment that the branching ratio for $t \to W^+b$ is equal to that for $t \to H^+b$, one finds $R(h/l) = 0.59$.

We should not ignore the possibility that the top quark is light enough to have a large production cross section at existing accelerators such as the Tevatron, yet heavy enough that $m_t > m_{H^\pm} + m_b$, so that $BR(H^\pm \to \tau\nu)$ is large. In such a case, the SSC might not be required for the discovery of the $H^\pm$. Even in the supersymmetric model where $m_{H^\pm} \geq m_W$, the charged Higgs could be quite near its lower limit and the t quark could be only moderately heavier, yet still light enough to be produced at the Tevatron with a substantial rate. We have made a first exploration of this possibility. As an example we shall take $m_{H^\pm} = 85\ GeV$ and consider two possible t quarks masses: 110 GeV and 120 GeV. The signal for $H^\pm$ production that we focus on is that discussed above, namely an excess number of isolated singly charged hadrons (h) produced in t quark decays via the chain

$$t \to H^+b \qquad H^+ \to \tau^+\nu, \text{ with } \tau^+ \to e^+, \mu^+ \text{ or } h^+ + X, \tag{9}$$

where X can contain only π^0's and/or ν's and $h^+ = \pi^+$ or K^+, as compared to the normal sequence

$$t \to W^+b \qquad W^+ \to e^+, \mu^+ \text{ or } \tau^+ + \nu, \tag{10}$$

with the τ^+ decaying as above. The first process produces substantially more isolated singly charged hadrons than does the second. Assuming $\tan\beta = 1$ we find, using eq. (4), that for $m_{H^\pm} = 85\ GeV$, $BR(t \to H^+) = 31\%(27\%)$ for $m_t = 120\ GeV(110\ GeV)$. Larger masses for the $H^\pm$ result in smaller branching ratios, and, therefore, less sensitivity.

In order to see whether charged Higgs from t-quark decay are observable at the Tevatron, one of us (L. Galtieri) has performed a Monte Carlo study using ISAJET. This study does not incoporate any detector simulation. In addition, detailed QCD background studies were not done. The conclusions that we reach are probably optimistic; therefore, this procedure only sets an upper bound to the discovery limit of the charged Higgs. The branching ratios for $t \to H^+b$ and $t \to W^+b$ were computed using eq. (4) with $\tan\beta = 1$. Assuming only Standard Model decays, the branching ratio for $H^\pm \to \tau\nu$ (for $\tan\beta = 1$) is approximately 35%. We select events in which the ISAJET generated particle list shows that there is a lepton (e or μ), with laboratory transverse momentum $p_T > 20\ GeV$, coming from the decay of one of the top quarks (t_1). Experimentally there is a significant chance that such a lepton will be relatively isolated, and we shall call it an 'isolated lepton'. However, isolation criteria were not actually implemented (and events chosen accordingly) for this first study. In the present context, such a lepton is most likely to originate from the $W^\pm$ or $H^\pm$ appearing in the decay of t_1. Note that leptons from τ decay (for example, $t_1 \to W^\pm$ (or $H^\pm$) $b \to \tau\nu b \to \ell\nu\nu\nu b$) are also included if the p_T condition is satisfied. For the second top (t_2) decay we require a 'prompt' charged particle coming from the $W^\pm$ or $H^\pm$ having $p_T > 10\ GeV$ and count how often this is a hadron or a lepton; an excess of hadrons is the signature for Higgs decay of the top. The 'prompt' charged particle can be a charged lepton (e or μ) as in the case of t_1 decay, or a single charged hadron ($\pi^\pm$ or $K^\pm$) from τ decay. Thus, only decays of the τ's into one charged prong are considered. We assume that experimentally a narrow cone surrounding a 'prompt' charged hadron can be defined which contains all the energy of the neutral hadronic decay products that might be associated with this charged track. Thus, in calculating the p_T of the charged hadron coming from τ decay, associated photon (π^0) momentum (for example, π^0's from ρ or K^* decays of the τ) is added to the charged particle momentum. This is done in order to have larger detection efficiency for the given p_T cut. Finally, to reduce possible QCD background, we require the lepton or hadron from the second top to be central, *i.e.*, $|\eta| < 1.5$.

Two choices of integrated luminosity are considered: a) the Tevatron (TEV-I) to run 5 years at its maximum yearly yield of 10 pb^{-1}; and b) an upgraded Tevatron (TEV-II) to run for two years at 500 $pb^{-1}/year$. The results are shown in Table 1, where l stands for an isolated charged lepton and h for an isolated charged hadron; the notation " N_{evts}" refers to number of events. It is clear from this table that it is not possible to discover the $H^\pm$ at TEV-I, whereas the possibility of its discovery at TEV-II cannot be excluded. For example, at TEV-II the difference between the $H^\pm + W^\pm$ and the $W^\pm$ alone (for $m_t = 120\ GeV$) is $\Delta R(h/l) = (.351 \pm .032) - (.176 \pm .018) \simeq 0.18 \pm .04$, a nominally significant effect. Nonetheless, it is certainly possible that one may not be able to rule out charged Higgs with $m_{H^\pm} < m_t - m_b$ by the time the SSC is ready to turn on.

Table 1

Sensitivity of Tevatron to Charged Higgs with $m_t > m_{H^\pm} + m_b$

	$\int \mathcal{L}\, dt$ (pb^{-1})	m_t (GeV)	σ (pb)	$gg \to t\bar{t}$ N_{evts}	top decay	$t_1 \to l$ N_{evts}	$t_2 \to l$ N_{evts}	$t_2 \to h$ N_{evts}	$R(h/l)$
TEV-I	50	120	16.6	830	$W^\pm$	158	32.4	5.7	$.18 \pm .08$
					$W^\pm + H^\pm$	132	22.5	7.9	$.35 \pm .15$
TEV-I	50	110	27.0	1350	$W^\pm$	252	50.6	9.3	$.18 \pm .06$
					$W^\pm + H^\pm$	216	37.0	12.6	$.34 \pm .11$
TEV-II	1000	120	16.6	16600	$W^\pm$	3160	648	114	$.18 \pm .02$
					$W^\pm + H^\pm$	2640	450	158	$.35 \pm .03$
TEV-II	2000	110	27.0	27000	$W^\pm$	5049	1012	185	$.18 \pm .01$
					$W^\pm + H^\pm$	4320	740	252	$.34 \pm .03$

At the SSC, when $m_t > m_{H^\pm} + m_b$ one anticipates that this type of procedure will provide a clear signal for $H^\pm$ production, due to the high machine luminosity and energy. To verify this, one of us (H. Yamamoto) has performed a Monte Carlo study using PYTHIA. Here a Monte Carlo simulation was performed using experimentally defined triggering procedures developed in ref. 12. However, this simulation did not include the effects of (unknown) momentum and energy resolution.

The technique for triggering on τ leptons from charged Higgs decay relies on the event shape of the charged Higgs events and on the topology of possible background events.

(1) The charged particle with highest p_T relative to the beam direction is chosen as a candidate for the isolated charged particle emerging from τ decay. We demand that no other charged particles are within a narrow cone around this candidate particle. The narrow cone, illustrated in fig. 2, is defined by requiring that the half angle ψ satisfies $\cos\psi = 0.999$.

(2) The candidate track can be associated with γ's (π^0's). The charged particle momentum and the photon momenta in the narrow cone are summed vectorially. The resultant transverse momentum magnitude, $|\vec{p}_T(narrow\ cone)|$,

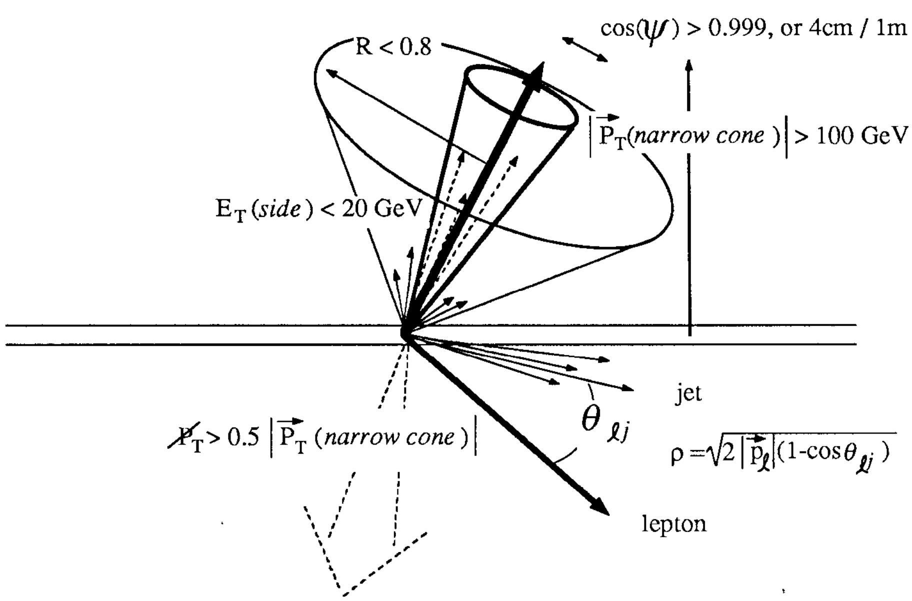

Figure 2: We illustrate the cones used to define an isolated charged track.

must exceed 100 GeV and the pseudo-rapidity of the narrow cone three-momentum must satisfy $|\eta(narrow\ cone)| < 1.5$.

(3) Around the narrow cone, a broader region is defined by requiring that $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$ satisfy $\Delta R < 0.8$. We require that the E_T sum in this region (excluding the region in the narrow cone) be smaller than 20 GeV. This defines what we mean by an *isolated* charged particle track.

(4) Next, we require that the missing $|\vec{p}_T|$ of the whole event must exceed 50 % of the $|\vec{p}_T(narrow\ cone)|$. The idea of this requirement is to select events containing a rather energetic neutrino, such as that which would emerge in charged Higgs decay.

(5) Finally, the event should have an additional 'stiff' lepton (e or μ) with $p_T >$ 5 GeV, an angle with respect to the beam that satisfies $5° < \theta_{lepton} < 175°$, and the charge of this lepton must be opposite in sign from the charge of the observed isolated high p_T charged track. Since the lepton is supposed to come from the other top quark, that is produced in association with the charged Higgs, it is required to be isolated from the nearest reconstructed jet. The isolation condition[13] is given by $\sqrt{2|\vec{p}_\ell|(1-\cos\theta_{\ell j})} > 0.8$, where $\vec{p}_\ell$ is the momentum of the lepton and $\theta_{\ell j}$ is the angle between the lepton and the nearest reconstructed jet which is found by the Lund cluster algorithm.[14]

The results of this study are summarized in Table 2. Table 2 gives the number of events per year for three classes of events: 1) events which contain a single isolated track; 2) events which contain a stiff lepton in addition to an isolated lepton track; 3) events which contain a stiff lepton in addition to an isolated hadron track. In classes 2) and 3), the first stiff lepton can be thought of as coming from one t quark, while the second isolated lepton or hadron comes from the other t quark. The final column of the table gives the ratio of events of class 3) to events of class 2). The results are given for two cases: in the first we assume that there is no charged Higgs particle; while in the second case we assume that the charged Higgs and W's are produced with equal probability in t decay.

Table 2

Comparison of R(h/l)'s with and without $\mathbf{t \to H^{\pm}b}$

$m_{H^\pm} = 100\ GeV$, $m_t = 200\ GeV$, $p_T(narrow\ cone) > 50\ GeV$, $L = 10^4\ pb^{-1}$. "τ candidate" refers to the isolated track which is used to identify the τ; l (h) in the 3rd (4th) column means that the isolated track for the τ candidate is identified to be a hadron (lepton).

Process	τ candidate	l + stiff lepton	h + stiff lepton	$R(h/l)$
$t \to W^{\pm} + b$ (no $H^{\pm}$)	2.1×10^6	2.5×10^5	2.3×10^4	0.09
$t \to W^{\pm}$ or $H^{\pm} + b$	1.2×10^6	7.5×10^4	3.0×10^4	0.38

One important observation from this table is that $R(h/l)$ differs by a factor of 4 in these two cases. This number is the ratio of two different kinds of events, and is independent of the distribution functions or the total production cross section of the $t\bar{t}$ pair. Secondly, the difference in the number of isolated charged tracks (*i.e.* τ candidates) comes from the fact that an electron or muon directly produced from the W boson is more easily tagged than a charged particle produced from the τ decay, because the former is more energetic and is isolated in nature. But the difference between the absolute production rate for τ candidates, when the charged Higgs is present and when it is not, is useful only if one can estimate the total cross section of $t\bar{t}$ pair production.

The main problem in the overall significance of the signal for charged Higgs production obtained from $R(h/l)$ is misidentification of leptons (electrons and muons directly produced from the W boson) as isolated hadrons. However, even if we allow for a reasonable level of the misidentification probabilities of electrons and muons, the tighter cuts mentioned below should allow us to distinguish between the case where the charged Higgs is present in top decay from the case in which it is not.

As state earlier, the numbers given in Table 2 are based on the PYTHIA Monte Carlo, which carries out the hadronization of partons and decays of particles. When tracing back to the parent of the isolated tracks, it was found that sometimes a hadron which comes from the few body decay of a charmed particle produced in the b quark jets was identified as an isolated charged track. This means that the results shown in Table 2 are somehow dependent on the fragmentation models and the decay model used in the PYTHIA Monte Carlo. The PYTHIA Monte Carlo is fairly well tuned using the currently available data, but still it is desirable to find a way to make the result independent of the treatment of hadronization and fragmentation. A tighter selection of isolated charged tracks was tried in order to reject this kind of background. The efficiency dropped, but the dependence on hadronization became weaker. This analysis is still going on, and no conclusion can be drawn as to the dependence on the hadronization models, but the results shown in Table 2 seem to still be valid.

The background due to misidentification of a charged lepton as a charged hadron, and vice versa, in processes with larger cross section, *i.e.* pure QCD processes (in which only light quarks and gluons are involved) or processes in which a single gauge boson is produced in association with one or more jets, has not yet been studied. However, the background situation is far better than that which we encounter below in the case where $m_{H^\pm} + m_b > m_t$. In the present situation, the events of interest arise from $t\bar{t}$ production which is a strong QCD process with a cross section that is of order a hundred times larger than the $bg \to H^\pm t$ production process that is the dominant mechanism for charged Higgs production when $m_{H^\pm} + m_b > m_t$.

We turn now to the second case, where $m_{H^\pm} + m_b > m_t$. Existing theoretical models suggest that this is more likely to be the case than $m_t > m_{H^\pm} + m_b$. Detection of a charged Higgs that does not result from t decay is impossible at the Tevatron, so we shall focus only on the SSC. Before presenting a detailed Monte Carlo analysis of the charged Higgs search via its $\tau\nu$ mode in this case, let us make some quick estimates to determine the extent of the difficulty of separating the signal from the anticipated background. Using the cross-sections discussed in fig. 1, one can make a quick comparison between signal and likely backgrounds. It immediately becomes clear that the signal-to-noise is much smaller than 1, except for the limited mass range where $m_t - m_b \lesssim m_{H^\pm} \lesssim m_b + m_t$ where the top quark is still not heavy enough to decay to $H^\pm + b$. The problem here is that both real and virtual W bosons can also decay into $\tau\nu$ final states. Even when we employ the trick of a stiff-lepton trigger, there is an irreducible background process which is not rejected, namely $g\bar{b} \to \bar{t}W^+$ and its charge conjugate. The event topology for this reaction is identical to that of the signal, and only the lower mass of the W^+ can be used to separate this background from the signal (using rapidity cuts and the Jacobian peak in the p_T spectrum of the single charged particles from τ decay[15]). To illustrate the magnitude of the problem, we give in fig. 3 the cross section for $g\bar{b} \to \bar{t}W^+$[6][16] and its charge conjugate, compared to $g\bar{b} \to \bar{t}H^+$ and its charge conjugate, as a function of the t quark mass at $m_{H^\pm} = 300\ GeV$.

No branching ratios for the $W^\pm \to \tau\nu$ or $H^\pm \to \tau\nu$ decays have been incorporated. In comparing m_t dependence it should be kept in mind that $BR(W^\pm \to \tau\nu)$ is m_t independent once the tb channel is closed, while $BR(H^\pm \to \tau\nu)$ falls

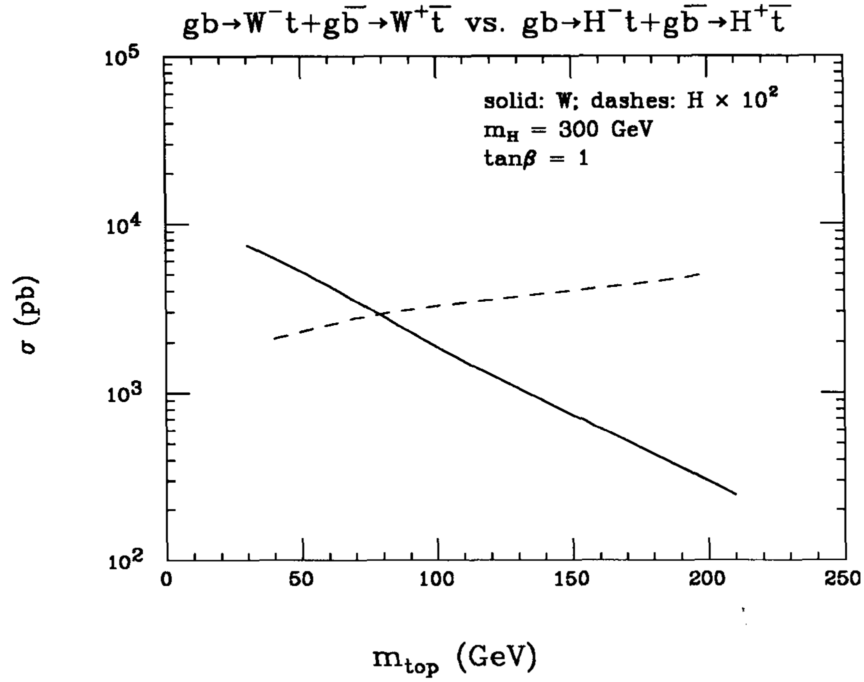

Figure 3: We give the cross section for $g\bar{b} \rightarrow \bar{t}W^+$ and its charge conjugate, compared to $g\bar{b} \rightarrow \bar{t}H^+$ and its charge conjugate, as a function of the t quark mass at $m_{H^\pm} = 300\ GeV$. No branching ratios for the $W^\pm \rightarrow \tau\nu$ or $H^\pm \rightarrow \tau\nu$ decays have been incorporated. In comparing m_t dependence it should be kept in mind that $BR(W^\pm \rightarrow \tau\nu)$ is m_t independent once the tb channel is closed, while $BR(H^\pm \rightarrow \tau\nu)$ falls like $1/m_t^2$. This calculation is taken from ref. 6.

like $1/m_t^2$. The cross section for $gb \rightarrow tH^\pm$ presented in fig. 3 can be adjusted for $\tan\beta \neq 1$ by using

$$\sigma(gb \rightarrow tH^\pm) \propto m_t^2 \cot^2\beta + m_b^2 \tan^2\beta. \qquad (11)$$

We choose "typical" values of $m_{H^\pm} = 300\ GeV$, $\tan^2\beta \sim 3$ and $m_t = 70\ GeV$. Including branching ratios for the $\tau\nu$ decays of the W and H, we have $S/B \sim 10^{-4}$ with a signal of 200 events where the small signal rate is due in part to the small $H^\pm \rightarrow \tau\nu$ branching ratio which is of order 10^{-3}. The means for discriminating between this background and the charged Higgs signal are limited and can probably never achieve better than a factor of 10 discrimination. Using such a factor it quickly becomes clear that $BR(H^\pm \rightarrow \tau\nu) \gtrsim 0.5$ is required before one could detect the charged Higgs in this manner.

Despite this pessimistic outlook, we have pursued the detection of the charged Higgs when $m_t \leq m_{H^\pm} + m_b$ using the PYTHIA Monte Carlo. We employ the techniques of ref. 12 outlined earlier for identifying the τ lepton from charged Higgs decay and for triggering on the stiff lepton from the decay of the top quark, produced in association with the charged Higgs. Even though the production mechanism is $gb \to H^{\pm}t$ (instead of $gg \to t\bar{t}$ with $t \to H^{\pm}b$) the final state is very similar to that considered earlier and the same techniques apply. The case of $m_{H^{\pm}} = 300\ GeV$ and $m_t = 40\ GeV$ was already studied in ref. 12, with the conclusion that it is very difficult to observe charged Higgs production because of the small branching ratio of $H^{+} \to \tau^{+}\nu_{\tau}$. During the present workshop we have continued to employ the above triggering techniques in the study of additional choices for the charged Higgs and top quark mass. Table 3 summarizes our results.

Table 3

Expected number of events for the charged Higgs and backgrounds

$L = 10^4\ pb^{-1}$

Process	Isolated Lepton	Stiff Lepton	$m_{H^{\pm}}(GeV)$	$m_t(GeV)$
$H^{\pm}+t$	13	1.7	300	40
$H^{\pm}+t$	10	1.5	400	40
$H^{\pm}+t$	8	1.0	500	40
$H^{\pm}+t$	1.7	0.7	300	200
$W^{\pm}+q(g)$	7×10^5	9×10^3	300	40
$W^{\pm}+q(g)$	2×10^3	1.3×10^3	300	200
W^*	7.5×10^4	< 80	300	40
$W^{\pm}+Z$	400	4	300	40

Table 3 shows the expected number of events per year for several choices of $m_{H^{\pm}}$ and m_t after selecting events with an isolated charged particle as described earlier, and after imposing the additional requirement of the existence of a stiff lepton on the opposite side of the τ jet. Also shown in Table 3 are the main sources of background. As can be seen, the main conclusion of ref. 12 is not changed; that is, the event rate is very small for the mass range of $m_{H^{\pm}} = 300 - 500\ GeV$, and the background is much larger than the signal.

Finally we have examined the special case where $m_{H^{\pm}} = m_t$, for the particular choice of $m_{H^{\pm}} = m_t = 200\ GeV$. In this case, the main source of charged Higgs production is, once again, $bg \to H^{-}t$, plus the charge conjugate process. The production rate, $\sigma(bg \to H^{\pm}t) \times BR(H^{\pm} \to \tau\nu)$ is shown in Table 4, for an integrated luminosity of $L = 10^4\ pb^{-1}$ per year.

Table 4

τ signal in $H^{\pm}$ decay and background from $W^{\pm}$ decay

$m_{H^{\pm}} = m_t = 200\ GeV,\ L = 10^4\ pb^{-1}$

Process	$\sigma \cdot BR(pb)$	Events/year
$H^{\pm} + t,\ H^{\pm} \rightarrow \tau\nu_{\tau}$	100	2960
$W^{\pm} + t,\ W^{\pm} \rightarrow \ell\nu_{\ell}$	240	9000

The expected number of events per year after the signal selection is around 3000. The main source of background is associated $W^{\pm}t$ production with the subsequent decay of the $W^{\pm}$ to a lepton and a neutrino. The Higgs particle is tagged by a single charged track from the τ decay, and it is impossible to clearly separate this Higgs decay mode from the W decay. Also, this W is associated with a top quark on the opposite side, and the stiff lepton cut does not help to reduce this background. As can be seen from Table 4, the S/B ratio is around 0.3 to 0.4, both in the production rate $\sigma \times BR$ and the observed number after signal selection. The statistical significance of the signal is reasonable, and if one can estimate the background rate, it may be possible to establish the excess over other known sources. However, because this method for the identification of the Higgs particle is not a direct reconstruction of the particle by an invariant mass, it may be difficult to prove that this excess originates from the production of a new particle, *i.e.* the charged Higgs particle.

In summary, if $m_{H^{\pm}} > m_t$, it will be very difficult to observe a signal for the charged Higgs boson at a hadron collider via the decay mode $H^{\pm} \rightarrow \tau\nu$; but the present studies indicate that it should be possible to find evidence for the charged Higgs if $m_{H^{\pm}} \leq m_t$.

D. Detector Requirements for the Charged Higgs Search

We have seen that detection of a charged Higgs boson requires triggering on high p_T isolated charged particles, in this case the τ and the relatively isolated electrons and muons from top quarks. Obviously, we need a detector with good lepton identification power and good momentum resolution for isolated particles. In addition, we have to identify taus through their specific decay modes ($\tau^{\pm} \rightarrow \pi^{\pm} + \nu(+\pi^{o}\text{'s})$ or $\pi^{\pm}\pi^{-}\pi^{+} + \nu$) and they should be distinguished from e's, μ's and QCD jets. Similar requirements emerge in tagging the leptons from top semi-leptonic decays and our techniques can be applied to the search for the intermediate mass neutral Higgs boson and for heavy quarks or lepto-quarks. We have developed a number of tricks to enhance the distinctive topologies typical of such triggers. However, their implementation places definite demands upon the detector. In this section, we give the basic detector requirements and discuss technical innovations that will be needed to implement them.

1. Tracking Devices

Vertex detector

It is not easy to select taus by using the impact parameter method at SSC, since the impact parameter is relatively small for taus, of $\mathcal{O}(100\ \mu m)$, and it is almost a Lorentz boost invariant variable. Therefore, high momentum does not help to reconstruct the secondary vertex, unless we can find the tau decays in the fiducial volume of the vertex detector. The problem of tagging would be less severe if the decay mode $H^{\pm} \rightarrow t + b$ were large enough to be observed above background, since the vertex detector *could* be used to find secondary vertices from B-hadron decays.

Central tracking device

It is essential to have a tracking device to detect charged Higgs bosons. However, reconstruction of the charged tracks is necessary only in the vicinity ($\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 1$) of the isolated large p_T energy clusters or high p_T muon candidates. The magnetic field should not be so high as to disturb the calorimetry. The requirements for the tracking devices are:

(1) Momentum resolution: $\Delta p_T/p_T \approx 0.0005 p_T\ (GeV)\ \oplus 0.02^*$. The muon momentum must be measured with an accuracy of 10% for $p_T = 200\ GeV$. Since electron identification will require using $p_{TR} \approx E_{EM}$ (where p_{TR} is the momentum of the track measured by the tracking device and E_{EM} is the electromagnetic energy measured by the calorimeter), good resolution will be necessary. Good resolution is also essential in order to select a charged pion from tau decay ($\tau^{\pm} \rightarrow \pi^{\pm} + \nu\ (+\pi^o\text{'s})$), by efficiently rejecting isolated electrons, for example, from W-boson decays.

(2) Double track resolution: The three charged pions from $\tau^{\pm} \rightarrow A_1^{\pm} + \nu \rightarrow \pi^{\pm}\pi^{-}\pi^{+} + \nu$ must be reconstructed as three separated charged tracks.

(3) Rapidity range: Not optimized yet, but we need at least $|\eta| < 2.5$.

(4) Pattern recognition: This is related to double track resolution but is a more complicated issue. We do not have to reconstruct all the tracks but charged particles from isolated taus and leptons from top quarks must be reconstructed. Even for these cases, we have to deal with a high multiplicity of charged particles in a narrow cone.

In order to have a cheap and fast tracking device with both good momentum resolution and powerful pattern recognition ability, we recommend using a combination of two devices. First, a small number of expensive layers with very good position accuracy ($\sigma \approx \mathcal{O}(10\mu m)$) separated by large distances can provide good momentum resolution. However, it is difficult to connect the hit points if the layers are far from each other. For connecting the hits between the expensive layers, a second, cheaper, device with a large number of layers may facilitate

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* $a \oplus b$ means quadratic sum of a and b, *i.e.* $\sqrt{a^2 + b^2}$.

pattern recognition. A candidate for the expensive layers might be a silicon strip detector, assuming it can be made to work in such an enviornment, while the cheaper layers could be straw chambers. Possible problems are that such a tracking detector might require more material than a conventional chamber and that it could be difficult to make radiation hard.

2. Calorimetry

Calorimetry is essential to look for isolated energy clusters and for determining the missing p_T at an early stage of the on/off-line analysis. The calorimeter must be designed to have a fast high p_T isolated energy trigger with or without accompanying missing p_T.

EM-Calorimeter

(1) Energy resolution: $\Delta E/E \approx 0.15/\sqrt{E(GeV)} \oplus 0.02$ is sufficient.

(2) Segmentation: The lateral segmentation of the electromagnetic and hadronic parts should be matched. A lateral cell size of $\Delta\eta \times \Delta\phi$ which is at least 0.03×0.03 is needed to separate the isolated energy clusters. Longitudinal segmentation is necessary for e/π separation, especially to identify the charged pions associated with π^o's from electrons. For example, the decay products of a charged rho arising from $\tau^\pm \rightarrow \rho^\pm\nu \rightarrow \pi^\pm\pi^o\nu$ should be efficiently distinguished from electrons and from other hadronic jets, *e.g.* by examining the longitudinal shower pattern.

(3) Hermeticity: The electromagnetic calorimeter should be hermetic over as large an $|\eta|$ range as possible (say, $|\eta|_{max} \approx 5$), so that missing p_T of $\mathcal{O}(70 - 80\ GeV)$ can be measured.

Hadron-Calorimeter

(1) Energy resolution: $\Delta E/E \approx 0.5/\sqrt{E(GeV)} \oplus 0.02$ is sufficient.

(2) Segmentation: The lateral segmentation of the electromagmetic and hadronic parts of the calorimeter should be matched. Therefore, a lateral cell size of $\Delta\eta \times \Delta\phi$ of 0.03×0.03 is required for the first few layers of the hadronic calorimeter. The longitudinal segmentation must be designed to have good μ-identification.

(3) Hermeticity: The hadronic calorimeter should be hermetic over as large an $|\eta|$ range as possible (say, $|\eta|_{max} \approx 5$), in order to measure missing p_T over the same region as the electromagnetic calorimeter.

3. Lepton identification efficiencies and hadron rejection factors

We have not evaluated the necessary lepton identification efficiency and the hadron rejection factor for electrons and muons. In any case, compared with the requirements for particle searches with good signal to background ratio, we need even better identification efficiency for isolated leptons and greater hadron rejection power. Charged pions (associated with π^0's) from isolated taus must be distinguished from isolated electrons and muons.

E. The Supersymmetric Two-Higgs-Doublet Model and Beyond

In this report, we have endeavored to discuss the consequences of a non-minimal Higgs sector, in the framework of the Standard Model, without further theoretical assumptions. However, as stressed in the Introduction, the number of new parameters increases rapidly as additional Higgs doublets are added. In this section, we wish to examine briefly the consequences of "low-energy" supersymmetry for the phenomenology of the Higgs sector. The advantages of imposing such a theoretical framework are twofold. First, supersymmetry imposes strong constraints on the form of the Higgs potential, thereby reducing the number of free parameters and providing more predictive power. Second, supersymmetry may be the only consistent theory which contains weakly coupled Higgs bosons (with mass of order m_Z) and can explain the origin of the electroweak scale.

We shall briefly describe the main features of the Higgs sector in the minimal supersymmetric extension of the Standard Model. Details of the model can be found in refs. 17 and 18. [Many of our conclusions below continue to hold in non-minimal supersymmetric models; see ref. 6.] The notation for the Higgs bosons will be the same as introduced earlier. The effect of the supersymmetry is to introduce relations between the various parameters; the end result is that two parameters suffice to determine all Higgs masses and nearly all of their couplings. Here, we shall take $\tan\beta$ and $m_{H_3^0}$ as the free parameters. The minimal supersymmetric model also has the property that the Higgs potential is automatically CP invariant. Furthermore, we are free to choose the phases of the scalar fields so that the vacuum expectation values are real and positive. Hence, we will choose $0 \leq \beta \leq \pi/2$. The other (tree-level) masses are then given by:

$$m_{H^+}^2 = m_{H_3^0}^2 + m_W^2 \tag{12}$$

$$m_{H_1^0,H_2^0}^2 = \frac{1}{2}\left[m_{H_3^0}^2 + m_Z^2 \pm \sqrt{(m_{H_3^0}^2 + m_Z^2)^2 - 4m_Z^2 m_{H_3^0}^2 \cos^2 2\beta}\right], \tag{13}$$

where, by definition, $m_{H_2^0} \leq m_{H_1^0}$. Note that eqs. (12) and (13) imply that $m_{H^+} \geq m_W$, $m_{H_1^0} \geq m_Z$, and

$$m_{H_2^0} \leq m_Z \cos 2\beta \leq m_Z. \tag{14}$$

The result of eq. (14) is remarkable, in that it guarantees that the theory must possess at least one light Higgs boson. Unless $\cos 2\beta$ is near its maximum of 1, this relation implies that the lightest scalar Higgs will be observable at SLC, LEP or LEP-II.

The one additional parameter which is determined is the scalar Higgs mixing angle α. Using the definition given in ref. 17, it turns out that α is constrained to lie in the range $-\pi/2 \le \alpha \le 0$. Explicitly, we have:

$$\cos 2\alpha = -\cos 2\beta \left(\frac{m^2_{H^0_3} - m^2_Z}{m^2_{H^0_1} - m^2_{H^0_2}} \right) ; \tag{15}$$

$$\sin 2\alpha = -\sin 2\beta \left(\frac{m^2_{H^0_1} + m^2_{H^0_2}}{m^2_{H^0_1} - m^2_{H^0_2}} \right) . \tag{16}$$

Probably one of the most interesting implications of the minimal supersymmetric model is obtained by examining the coupling of the heavy Higgs scalar (H^0_1) to vector boson pairs. We already know from eq. (3) that this coupling will be suppressed compared to the minimal Higgs model coupling. In fact, in a general two-Higgs doublet model, the suppression factor turns out to be $\cos(\beta - \alpha)$. In the minimal supersymmetric model, this factor is given by:

$$|\cos(\beta - \alpha)| = \left[\frac{m^2_{H^0_2}(m^2_Z - m^2_{H^0_2})}{(m^2_{H^0_1} - m^2_{H^0_2})(m^2_{H^0_1} + m^2_{H^0_2} - m^2_Z)} \right]^{\frac{1}{2}} . \tag{17}$$

If one computes $|\cos(\beta - \alpha)|$ over the allowed range of parameters, one quickly sees that it is a very small number, except for a small range where $m_{H^0_1} \to m_Z$. In particular, for the so-called "heavy" Higgs range ($m_{H^0_1} \ge 2m_W$), we find that $|\cos(\beta - \alpha)|$ never exceeds 0.15; and for heavier masses, it goes to zero like $1/m^2_{H^0_1}$. Thus, in the supersymmetric model, the H^0_1 totally decouples from the theory in the limit that its mass gets large, and H^0_2 becomes identical to the minimal Standard Model Higgs (as is evident from eq. (3)). It is this same suppression factor that also enters the $H^+ \to W^+ H^0_2$ and $H^+ \to W^+ H^0_2 \gamma$ modes discussed earlier.

Based on the discussion above, the consequences for the search for neutral Higgs bosons at the SSC are twofold. First, a light Higgs scalar may already have been discovered before the SSC turns on. (We would argue that such a discovery would be the first experimental evidence for supersymmetry!) Second, the heavy Higgs scalar will be extremely difficult to observe, due to its suppressed decay rate into vector boson pairs. (The pseudoscalar has no tree-level couplings to vector boson pairs, and is therefore just as hard to detect.) Assuming that the dominant decay of such heavy Higgses is into $t\bar{t}$ pairs, we know of no technique for observing these Higgs at the SSC, either through their $t\bar{t}$ decays or through rare decays into non-supersymmetric particles. The decays $H^0_1 \to H^0_3 Z^0$ and $H^0_3 \to H^0_1 Z^0$ are kinematically forbidden (see eq. (13)), whereas the production of $H^0_3 H^0_2$ by virtual Z^* exchange and the decay $H^0_3 \to H^0_2 Z^0$ are suppressed in amplitude by $\cos(\beta-\alpha)$. The latter decay rate, and branching ratios into $\gamma\gamma$, γZ^0, and $\gamma\Theta$ are too small to be viable signatures.[3] (Of course, if $m_{H_3^0}$ or $m_{H_1^0}$ happens to be smaller than $2m_t$, then detection in the $\gamma\gamma$ mode is likely to be possible.) The difficulty of charged Higgs detection is already apparent before the introduction of supersymmetry. As discussed in Section B, in the minimal supersymmetric model, certain rare decay modes which might have provided a useful signature are even further reduced due to the appearence of suppression factors like $\cos(\beta-\alpha)$ (*e.g.*, see eq. (8)).

However, before concluding that the picture is totally bleak, it is important to realize that a new feature is present. Because we are discussing a supersymmetric theory, there are new supersymmetric particles in the spectrum, which can couple to the Higgs bosons. In particular, it is possible that new Higgs decay modes into supersymmetric final states will be available which will radically alter Higgs phenomenology at the SSC. In a supersymmetric model, Higgs bosons can decay either into squark and slepton pairs, or into charginos and neutralinos (these are the mass eigenstates comprising the gauginos and higgsinos). If the relevant decays are kinematically allowed, then the corresponding branching ratios can be large. Indeed, over a fairly large region of the supersymmetric model parameter space, one finds total branching ratios into supersymmetric final states which are larger than 10%, and can easily approach 100%. As an example, we show the Higgs branching ratios into chargino and neutralino final states as a function of the supersymmetric parameters, taken from ref. 19. in fig. 4. For reasonable choices of certain supersymmetric model parameters, M and μ, described in detail in refs. 17, 18, and 19, we see in fig. 4 that a charged Higgs with mass of order 500 GeV can decay more than 80% of the time into chargino and neutralino modes, even when the tb decay channel is kinematically allowed.

The relatively large branching ratios into charginos and neutralinos can be explained by the fact that the relevant mass parameter which scales the Higgs couplings to these particles is m_W, m_Z, and the parameters of the neutralino and chargino mass matrices, which are presumably of the same order. However, unlike the coupling of H_1^0 to WW and ZZ, the Higgs couplings to the neutralinos and charginos are not suppressed, in general. As a result, it is not surprising that these final states can be dominant. The decay into squarks and sleptons can, in principle, also be an important fraction of the total Higgs widths. In evaluating various possible scenarios, we note that it seems more probable that some light charginos or neutralinos exist which would be accessible to Higgs decay. On the other hand, the general mass scale which controls the squark and slepton masses (and is *a priori* unrelated to the neutralino and chargino parameters) may be large enough so that Higgs decay into squark and sleptons would be forbidden. Clearly, no one can definitively predict, at present, which supersymmetric final states (if any) will dominate.

Supersymmetric decays of the Higgs present the possibility of completely novel signatures for Higgs searches. In particular, events with substantial missing transverse energy will now play an important role in the search for Higgs bosons. Previously, missing transverse energy was relevant in Higgs searches only in the search for W bosons in the final state which decayed leptonically or Z bosons

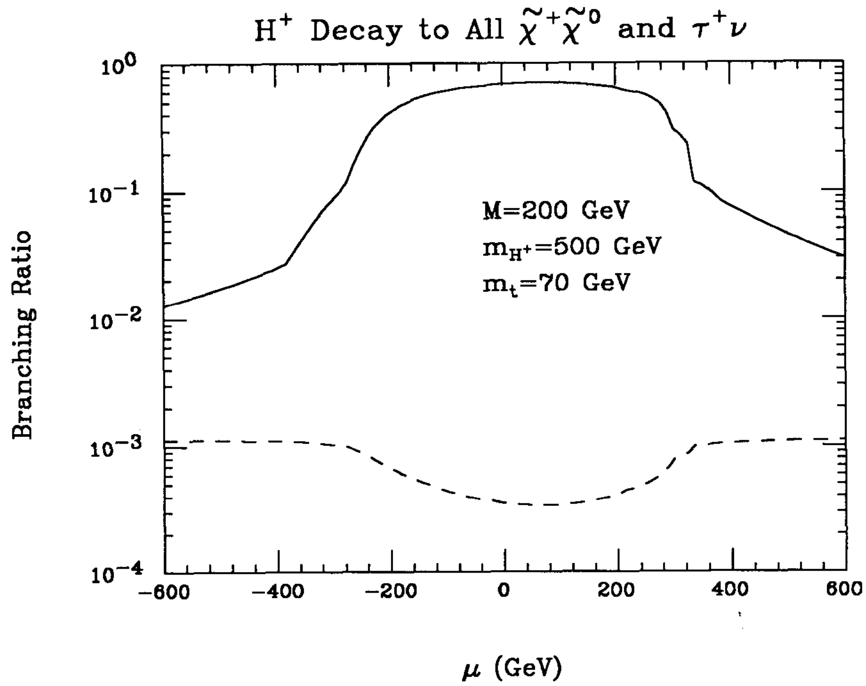

Figure 4: The branching ratio for $H^\pm$ to decay to any channel containing a neutralino-chargino pair, compared to the $\tau\nu$ branching ratio. We take $m_t = 70\ GeV$, $\tan\beta = 1.5$ and $m_{H^\pm} = 500\ GeV$, and have chosen a reasonable value of $M = 200\ GeV$ for the gaugino mass parameter of the model. We plot the branching ratio as a function of the higgsino mass parameter, μ. The curves are: solid, sum over all neutralino+chargino channels; and dashes, $\tau\nu$.

which decayed to $\nu\bar{\nu}$. In supersymmetric decays, it is very easy to generate large missing transverse energy without having a high-p_T lepton in the event. To fully assess the possibility of detecting various supersymmetric final states of the Higgs will require a substantial Monte Carlo effort. A sample study [20] was performed at Snowmass 1986, for a specific choice of parameters for which the neutralinos are very light, with encouraging conclusions. However, a systematic survey of the minimal supersymmetric model parameter space, along with appropriate Monte Carlo studies, is highly desirable. This is work which we hope will be undertaken in the near future. Clearly, if low-energy supersymmetry is correct, Higgs physics will become a branch of supersymmetry phenomenology.

F. Conclusions of the Non-Standard Higgs Working Group

In summary, we have examined the phenomenological consequences of the two Higgs doublet model relevant for the SSC. In the framework of the Standard Model, we have come to the conclusion that it may be very difficult to find evidence for a non-minimal Higgs sector. Among the neutral scalar Higgs, only those which couple strongly to WW and ZZ can be easily discovered. The techniques for discovery are identical to those used to detect the minimal Higgs. The neutral pseudoscalar Higgs does not couple to vector boson pairs at tree level. Thus its detection presents problems analogous to those encountered when looking for the "intermediate mass" minimal Higgs. In general, no "general purpose" strategy exists at present for such Higgses at a hadron collider. Only if the t quark is heavy, and the $t\bar{t}$ decay mode is forbidden, is there some hope for detection via rare decay modes. Primary among these is the the $\gamma\gamma$ mode discussed at length in ref. 3. For neutral Higgs bosons that have weak or vanishing couplings to vector boson pairs, the $\gamma\gamma$ mode should be usable for any Higgs boson with mass $\gtrsim 100\ GeV$ and $\leq 2m_t$. The general problem of detecting such neutral Higgs has much overlap with the work of the Intermediate Mass Higgs Working Group.[5] When a neutral Higgs has mass above $2m_t$, and its decay is dominated by the $t\bar{t}$ channel, we have been unable to develop a technique for discovering it at the SSC. The charged Higgs boson presents similar problems to those encountered for the neutral Higgs. Again, the t-quark mass is crucial. If $m_t > m_{H^\pm} + m_b$, then t-quark decays will provide a copious source of charged Higgs, and the $\tau\nu$ decays of the $H^\pm$ will have substantial branching ratio. We have seen that charged Higgs detection is possible in this case. But, if $m_{H^\pm} > m_t + m_b$, then the $H^\pm$ has a smaller production cross section and its decays will be dominated by the tb final state. The possibility of using rare decays to reduce the large backgrounds can still be considered; again, the most plausible decay of this type which might be observable at the SSC is the decay $H^+ \to \tau\nu$. Our Monte Carlo analysis of this scenario is not encouraging.

However, it is natural to go beyond the Standard Model framework when considering an extended Higgs sector. Indeed, it is probably true that the only sensible theoretical framework in which weakly coupled elementary Higgses can exist is "low-energy" supersymmetry. We have examined the consequences of the supersymmetric two-Higgs-doublet model. There are three general predictions. First, a neutral scalar Higgs boson with mass less than $\mathcal{O}(m_Z)$ almost certainly exists. Second, the heavy scalar neutral Higgs couples very weakly to vector boson pairs; in the absence of non-Standard Model decay modes this implies that its observability at the SSC is problematical. Finally, the widths of the charged and the heavy neutral Higgses may be dominated by the decay into supersymmetric final states. Large regions of the supersymmetric parameter space exist where the decays into neutralinos and charginos are dominant. This presents us with the possibility of new search strategies, involving missing transverse energy signatures, for the heavy Higgses at the SSC. A detailed appraisal and Monte Carlo study of such scenarios awaits future work.

Acknowledgements

This work was partially supported by the Department of Energy, including contract numbers DE-AS03-76ER70191 and DE-AC03-76SF00515. We would like to thank the members of the Madison conference working group (see ref. 6) who participated in the earlier stages of this effort.

REFERENCES

1. S. Glashow and S. Weinberg, *Phys. Rev.* **D15**, 1958 (1977).
2. J.A. Grifols and A. Mendez, *Phys. Rev.* **D22**, 1725 (1980); G. Keller and D. Wyler, *Nucl. Phys.* **B274**, 410 (1986).
3. J. Gunion, G.L.Kane and J. Wudka, preprint UCD-87-28 (September, 1987).
4. R. Cahn, M. Chanowitz, M. Gilchriese, M. Golden, J. Gunion, M. Herrero, I. Hinchliffe, F. Paige, and E. Wang, to appear in *Proceedings of the 1987 Berkeley Workshop on "Experiments, Detectors and Experimental Areas for the Supercollider".*
5. D.M. Atwood, J.E. Brau, J.F. Gunion, G.L. Kane, R. Madaras, D.H. Miller, L.E. Price, and A.L. Spadafora, "Intermediate Mass Higgs Boson(s)", to appear in *Proceedings of the 1987 Berkeley Workshop on "Experiments, Detectors and Experimental Areas for the Supercollider".*
6. J.F. Gunion and H.E. Haber, "Probing the Higgs Sector at the SSC: the Standard Model and Beyond", *Proceedings of the 1987 Madison Workshop on "From Colliders to Supercolliders", Int. J. Mod. Phys.* **A2**, 957 (1987).
7. H.E. Haber, D.E. Soper and R.M. Barnett, in *Physics Simulations at High Energies*, Proceedings of the 1986 Madison Workshop, edited by V. Barger, T. Gottschalk, and F. Halzen (World Scientific, Singapore, 1987) p. 425, and Oregon preprint, OITS-365 (1987).
8. J.F. Gunion, H.E. Haber, F.E. Paige, Wu-Ki Tung, and S.S.D. Willenbrock, *Nucl. Phys.* **B294**, 621 (1987).
9. J.F. Gunion and D. Millers, work in progress.
10. J.A. Grifols, J.F. Gunion, and A. Mendez, *Phys. Lett.* **197B**, 266 (1987).
11. See the reports by: J.F. Gunion *et al.*, p. 103, *Proceedings of the 1984 Snowmass Workshop on the Design and Utilization of the Superconducting Super Collider,* edited by R. Donaldson and J. G. Morfin; F.J. Gilman and L. Price, in *Proceedings of the 1986 Snowmass Workshop on the Design and Utilization of the Superconducting Super Collider,* edited by R. Donaldson and J. Marx, p. 185; and the Intermediate Mass Higgs group, ref. 5.
12. H-U Bengtsson, S. Komamiya, and H. Yamamoto, preprint SLAC-PUB-5369 (1987), to appear in *Proceedings of the 1987 Madison Workshop on "From Colliders to Supercolliders".*
13. T. Barklow, in *Proceedings of the Second MARK-II Workshop on SLC Physics*, SLAC-Report-306 (1986), edited by G. Feldman, p. 189.
14. T. Sjostrand and M. Bengtsson, *Compt. Phys. Commun.* **43**, 367 (1987).
15. J.F. Gunion and H.E. Haber, 'τ Decay Spectra at the SSC', in *Proceedings of the 1984 Snowmass Workshop on the Design and Utilization of the Superconducting Super Collider,* edited by R. Donaldson and J. G. Morfin, p.150.

16. F. Halzen and C.S. Kim, *Proceedings of the 1987 Madison Workshop on "From Colliders to Supercolliders"*, have also computed the $gb \to W^{\pm}t$ cross section, including some QCD corrections.

17. J.F. Gunion and H.E. Haber, *Nucl. Phys.* **B272**, 1 (1986).

18. J.F. Gunion and H.E. Haber, *Nucl. Phys.* **B278**, 449 (1986).

19. J.F. Gunion, H.E. Haber, *et al.*, 'Decays of Higgs Bosons to Neutralinos and Charginos in the Minimal Supersymmetric Model: Calculation and Phenomenology', *Proceedings of the 1987 Madison Workshop on "From Colliders to Supercolliders"*, *Int. J. Mod. Phys.* **A2**, 1035 (1987); and J.F. Gunion and H.E. Haber, in preparation.

20. R.M. Barnett, J.A. Grifols, A. Mendez, J.F. Gunion, and J. Kalinowski, 'Detection of a Heavy Neutral Higgs Boson in a Higgsino-Neutralino Decay Mode', in *Proceedings of the 1986 Snowmass Workshop on the Design and Utilization of the Superconducting Super Collider,* edited by R. Donaldson and J. Marx, p. 188.