DETECTING THE SUPERSYMMETRIC HIGGS BOSONS: AN OVERVIEW AND THE ROLE OF $\gamma\gamma$ COLLISIONS

JOHN F. GUNION
Davis Institute for High Energy Physics, Department of Physics
University of California at Davis, Davis, CA, 95616, U.S.A.

ABSTRACT

I summarize the abilities of LEP-II, the SSC/LHC hadron colliders, and a future high energy $e^+e^-$ collider (NLC) to detect the Higgs bosons of the Minimal Supersymmetric Model (MSSM). In the case of LEP-II, I emphasize the importance of having as large a value of $\sqrt{s}$ as possible in order to guarantee discovery of the light CP-even MSSM Higgs boson ($h^0$) regardless of the top quark and stop squark masses. For the SSC/LHC particular emphasis is placed upon the comparison between results for large supersymmetric particle mass scales as opposed to smaller mass scales for which radiative corrections to the MSSM Higgs sector are smaller and neutralino-chargino pair decays of the MSSM Higgs bosons are kinematically allowed. I then focus on the unique capabilities of a back-scattered laser beam facility (BSLBF) at the NLC for detecting the heavier neutral Higgs bosons ($H^0$ and $A^0$) of the MSSM. In particular, I emphasize that typical GUT scenarios predict that the $H^0$ and $A^0$ are likely to be very difficult to detect at the SSC and LHC, and that $m_{H^0}$ and $m_{A^0}$ can easily be too large to allow their discovery at a $\sqrt{s} \sim 500$ GeV NLC. In contrast, I show that a BSLBF could well allow $H^0$ and $A^0$ discovery via inclusive $\gamma\gamma \rightarrow H^0, A^0$ production out to masses of order $0.8\sqrt{s}$, i.e. roughly 400 GeV, at such an NLC. In addition, a BSLBF allows one to check for CP violation in the neutral Higgs sector; such CP violation is predicted to be absent in the MSSM.

1. Introduction

Despite the enormous success of the Standard Model (SM) of strong and electroweak interactions, the mechanism responsible for mass generation/electroweak symmetry breaking (EWSB) remains uncertain. The naturalness and hierarchy problems of the minimal Standard Model Higgs sector mechanism are well-known. Fully consistent models employing the general concept of technicolor/compositeness remain elusive, and phenomenological constraints on technicolor from precision LEP data are very restrictive. Currently, supersymmetric models appear to be substantially more attractive. First, supersymmetry \cite{1} is the only known theoretical framework that resolves the naturalness/hierarchy problems while maintaining the elementarity of Higgs bosons. (A detailed review of Higgs bosons in supersymmetric models is contained
in Ref. [2].) Further, most supersymmetric models can be consistently incorporated into a simple grand unification scenario while maintaining perfect agreement with the LEP data. Indeed, the very simplest Minimal Supersymmetric Model (MSSM) is completely successful in all these respects, even requiring no intermediate mass scale(s) for grand unification.\[^{[3,4,5]}\]

Because of its consistency and simplicity, it is not unreasonable to consider the MSSM as a real candidate theory appropriate for describing physics between the electroweak scale and the grand unification scale. Thus, it is important to determine whether the experimental information required to either rule out or confirm the model can be obtained at present and future accelerators. Experimental signatures for supersymmetry, deriving from the many superpartner particles (such as the gluino, squarks, neutralinos and charginos) are plentiful, both at $e^+e^-$ and hadronic supercolliders. However, the MSSM in its most general form has many parameters. Consequently, even if all of these superpartners are discovered a full test of the MSSM will be impossible without detecting its Higgs bosons. Indeed, only by verifying the Higgs structure predicted by the model can we be certain that the theoretical difficulties associated with EWSB in the SM are fully resolved in the manner predicted by minimal supersymmetry. Further, the Higgs sector of the MSSM is so highly constrained that even rather limited information about the Higgs sector could rule out the model, and at the very least require consideration of non-minimal supersymmetric models. Or conversely, verification of a few of the very specific predictions for the Higgs sector could provide the first convincing evidence in favor of the MSSM. Much effort has gone into developing techniques for detecting the Higgs bosons of the MSSM in recent years. I will review the substantial progress that has been made and discuss the possibly crucial role that could be played by a back-scattered laser beam facility (BSLBF) at a future $e^+e^-$ linear collider.

2. Scenarios

Before proceeding with our detailed discussion, it is perhaps useful to elaborate upon some of the possible experimental scenarios that could arise. First, let us recall\[^2\] that the MSSM contains exactly two Higgs doublets and therefore predicts the existence of five physical Higgs bosons, the CP-even $h^0$ and $H^0$ (with $m_{h^0} < m_{H^0}$), the CP-odd $A^0$, and a charged pair $H^\pm$. It also requires that there be a gluino ($\tilde{g}$), squark partners for all the quarks ($\tilde{q}$’s), two charginos ($\tilde{\chi}^+_1,2$), and four neutralinos ($\tilde{\chi}^0_{1,2,3,4}$) with $\tilde{\chi}^0_1$ being the lightest supersymmetric particle. At tree-level, the Higgs sector is completely determined by two basic parameters, normally taken to be $\tan \beta = v_2/v_1$ (the ratio of the vacuum expectation value for the neutral member of the Higgs doublet, $\phi^0_2$, coupling to up quarks to that of the doublet, $\phi^0_1$, coupling

\[^*\] Classification of the neutral Higgs bosons by CP properties is possible in the MSSM because the Higgs sector is automatically CP conserving.
to down quarks) and the mass of the CP-odd scalar, \( m_{A^0} \). However, the masses and couplings of the Higgs bosons are strongly influenced by one-loop radiative corrections that depend upon the top quark mass, \( m_t \), and the masses of the top squarks, \( M_{\tilde{t}_1} \) and \( M_{\tilde{t}_2} \) (and, to a much weaker extent, on other MSSM parameters). A complete review of radiative corrections was given in earlier talks and can also be found in Ref. [6]. The results for Higgs masses, couplings, and branching ratios have already been discussed in the earlier talks and only the most important points will be repeated here. Reviews can be found in Refs. [6] and [7]. Taking \( M_{\tilde{t}_1} = M_{\tilde{t}_2} \equiv M_{\tilde{t}} \), the most crucial result obtained after radiative corrections is that, for fixed \( m_{A^0} \) and \( \tan \beta \), the mass of the lightest CP-even Higgs boson increases significantly with \( m_t \) and \( M_{\tilde{t}}/m_t \) (the most important term in the one-loop radiative correction to \( m_{h^0} \) is proportional to \( m_t^4 \ln(M_{\tilde{t}}/m_t) \)). For given values of \( M_{\tilde{t}} \) and \( m_t \), the maximum value of \( m_{h^0} \) occurs for large \( m_{A^0} \) and large \( \tan \beta \). For large \( m_{A^0} \), the \( h^0 \) has couplings that approach those of the SM Higgs boson and the \( H^0 \), \( A^0 \) and \( H^\pm \) all become rather degenerate in mass. It is in this region of parameter space that a back-scattered laser beam facility is likely to play a most crucial role.

Particularly important unknowns in determining the ability of LEP-II, the NLC and the SSC/LHC to discover the Higgs bosons of the MSSM relevance are: the mass scale for the superpartner particles; and, the Higgs sector parameters \( m_{A^0} \) and \( \tan \beta \). (The top quark will presumably be discovered before long, and \( m_t \) will be known.) One scenario is illustrated by taking GUT schemes seriously. Typically (see, for example, Ref. [4]) correct predictions for \( m_W \) and \( m_t \) at low energy, starting from simple boundary conditions at the GUT scale \( M_X \), can only be obtained without fine-tuning if the soft supersymmetry breaking mass scales are modest in size. This would imply that the gluino, the squarks, and the neutralinos and charginos are all relatively light. In addition, the \( h^0 \) typically has a mass \( \gtrsim 100 \text{ GeV} \) (after radiative corrections) and \( m_{H^0} \sim m_{H^\pm} \sim m_{A^0} \gtrsim 250 \text{ GeV} \). (If certain \( M_X \) boundary conditions are relaxed, the superpartner particles would remain relatively light, but the \( H^0 \), \( A^0 \) and \( H^\pm \) masses could be even larger.) In such a case, LEP-II, unless it has energy somewhat above 200 GeV, would not be able to detect any of these new particles. At a new \( e^+e^- \) collider with energy of order 500 GeV (dubbed the NLC), the \( h^0 \) would be discovered, and the neutralinos and charginos could be studied. But, in the scenario being considered the \( ZZH^0 \) and \( Zh^0A^0 \) couplings are suppressed, implying that the only production mode for the \( H^0 \) and \( A^0 \) with good coupling strength would be \( Z^* \to H^0A^0 \). However, this mode would not be kinematically allowed. Similarly, the main mode for charged Higgs detection, \( Z^* \to H^+H^- \) pair production, would not be kinematically allowed. At the NLC, the only possibility for detecting any of the Higgs bosons other than the \( h^0 \) would be to produce the \( H^0 \) and \( A^0 \) singly using back-scattered laser beams. As described later, prospects for their detection in this manner are reasonable for \( m_{A^0} \) and \( m_{H^0} \) up to \( \sim 300-400 \text{ GeV} \) (depending on \( \tan \beta \)).

At the SSC or LHC, the above scenario would yield a plentiful array of signals for the gluino and the squarks, and large numbers of all of the Higgs bosons would be produced. The \( h^0 \) would again most probably be detectable (if not already found
at LEP-II); it would be quite similar in properties to a SM Higgs boson of the same mass. However, detection of both the $A^0$ and $H^0$ would be very difficult since they would tend to decay to two-body neutralino-neutralino or chargino-chargino channels, which would have large backgrounds and missing energy. Meanwhile, the $H^+$ would be too heavy to appear in $t \to H^+b$ decays (the only case for which it has been clearly demonstrated that detection of the $H^+$ would be possible). Indeed, the $H^+$ would decay to a combination of $\tilde{t}\tilde{b}$ and chargino-neutralino channels, both of which have large backgrounds.

Thus, if the typical mass scale of the superpartner particles (denoted generically by $M_{SUSY}$) is relatively low, it could happen that many of the superpartner particles could be studied at the NLC and/or SSC/LHC, but that only the SM-like $h^0$ of the Higgs sector could be found.

However, without the restriction on fine-tuning, the GUT schemes are all in agreement that $M_{SUSY}$ could be large. Although the original motivation for SUSY based on naturalness and hierarchy considerations would begin to be lost if $M_{SUSY}$ were so large that the superpartner particles could not be found at the NLC or SSC/LHC, we certainly should allow for the possibility that their masses (in particular those of the squarks and the gluino) could be of order 1 TeV. In such a scenario, the first direct indications and the most definitive tests of the MSSM could arise via its Higgs sector. As for the previous scenario, the $h^0$ would be found, if not at LEP-II then certainly at the NLC and most probably at the SSC/LHC. However, detection of the $A^0$, $H^0$ and $H^+$ would remain quite problematic at the SSC or LHC, while at the NLC the largest mass reach would be afforded by a BSLBF.

With these scenarios in mind, it is perhaps useful to give a few explicit examples of how even very limited knowledge of the Higgs sector could either rule out the MSSM or provide strong evidence in its favor. The theory and phenomenology behind these examples has been given in earlier talks and is reviewed in Ref. [7]. Disproofs of the MSSM which would be possible if only the $h^0$ were detected or excluded include the following observations.

Failure to detect the $h^0$ with $m_{h^0} \leq 160$ GeV (assuming $m_t < 200$ GeV and $M_{\tilde{t}_1}, M_{\tilde{t}_2} < 2$ TeV); LEP-II with energy $> 240$ GeV, or the NLC and/or SSC/LHC would be needed to fully cover this $m_{h^0}$ range.

Detection of an $h^0$ with a value for $m_{h^0}$ that is too small or otherwise inconsistent with the observed value of $m_t$ and established lower bounds on $M_{\tilde{t}_1}, M_{\tilde{t}_2}$ and $m_{A^0}$.

Detection of an $h^0$ with $m_{h^0}$ larger than the maximum allowed for large $m_{A^0}$ and large tan $\beta$ and observed values for $M_{\tilde{t}_1}, M_{\tilde{t}_2}$ and $m_t$; determination of the stop squark masses would require their detection at SSC/LHC.

Detection of an $h^0$ with inconsistent values for or ratios between its coupling constants; e.g. if the $h^0ZZ$ coupling is SM-like, the $h^0tt$ coupling should also have a SM-like value in the MSSM.
If more than one Higgs boson is detected, additional possible means for ruling out the MSSM arise. These include:

Detection of the $h^0$ and $A^0$ with $m_{A^0} > 2m_Z$ but couplings for the $h^0$ that are not SM-like.

Detection of the $h^0$ and $A^0$ with masses $m_{h^0}$ and $m_{A^0}$ that are inconsistent with the observed $m_t$ and $M_{\tilde{t}_1}, M_{\tilde{t}_2}$ values for all $\tan \beta$ choices.

Two or more of the $A^0$, $H^0$ and $H^\pm$ found with masses that are large but not approximately degenerate.

The following observations would also contradict the MSSM.

Detection of a neutral Higgs boson with mass larger than $2m_W$ and a large width associated with $WW/ZZ$ decays.

Detection of CP violation in the Higgs sector.

The general point should now be clear. The Higgs sector of the MSSM is so constrained that there are many precise relations and predictions that can be checked, especially once $m_t$ and the masses of the stop squarks have been measured (so as to determine the most important radiative corrections to the Higgs boson masses.) Of course, if results for any of the preceding consistency checks were positive, this would constitute considerable support for the MSSM. Certainly, the relative simplicity and cleanliness of such tests should provide more than enough motivation for finding means for detecting the MSSM Higgs bosons for as large a range of parameter space as possible.

3. Masses, Coupling Constants and Branching Ratios

It will be useful to recall some of the more important results. As already noted, at tree level all the masses and couplings of the Higgs bosons are determined by just two parameters, conventionally chosen to be $m_{A^0}$ and $\tan \beta = v_2/v_1$. All other Higgs boson masses as well as the neutral sector mixing angle, $\alpha$, and all couplings to quarks and vector bosons can be expressed in terms of these parameters. In particular, one finds $m_{h^0} < \text{Min}\{m_Z, m_{A^0}\} |\cos 2\beta|$, $m_{H^0} \geq m_Z$, and $m_{H^\pm} \geq m_W$. Further, for large $m_{A^0}$, $m_{H^0} \simeq m_{A^0} \simeq m_{H^\pm}$. However, at one loop, additional parameters are required to fully determine the masses and couplings of all the Higgs bosons. Aside from $m_{A^0}$ and $\tan \beta$, values for $m_t$ and a number of supersymmetric model parameters (squark masses, $\mu$ and the $A_{b,t}$) must be specified. In much of what follows, we shall simplify the discussion by neglecting squark mixing and assuming the squarks to be degenerate. In this case, the only important parameter other than $m_t$ for determining radiative corrections to the Higgs sector is the common squark mass, typified by that of the stop squark, $M_{\tilde{t}}$.

Perhaps the most important impact of the radiative corrections is that as $m_t$ increases so does the upper bound on $m_{h^0}$; and, at the same time, the lower bound
on $m_{H^0}$ gets larger. The largest $m_{h^0}$ values are attained in the large $\tan \beta$, large $m_{A^0}$ corner of parameter space. For $m_t = 150$ GeV the largest value is slightly in excess of 108 GeV, while for $m_t = 200$ GeV the upper limit on $m_{h^0}$ is about 138 GeV. Meanwhile, in the large $\tan \beta$, small $m_{A^0}$ corner of parameter space are found the minimum $m_{H^0}$ values, $\sim 110$ GeV ($\sim 141$ GeV) for $m_t = 150$ GeV ($m_t = 200$ GeV). For $m_t = 100$ GeV the upper bound on $m_{h^0}$ and lower bound on $m_{H^0}$ are both near $m_Z$, as predicted at tree level. Note also that at large $m_{A^0}$ the approximate degeneracy $m_{A^0} \simeq m_{H^0} \simeq m_{H^\pm}$ continues to hold after including radiative corrections.

Next, let us recall that some of the most crucial couplings of the MSSM Higgs bosons are directly determined by $\cos^2(\beta - \alpha)$. A remarkable feature of the MSSM is that $\cos^2(\beta - \alpha)$ decreases very rapidly with increasing $m_{A^0}$, and in fact is highly suppressed over all of parameter space, except in the moderate to large $\tan \beta$, small $m_{A^0}$ corner. These features were first observed at tree-level, and continue to pertain after radiative corrections, although radiative corrections do decrease the suppression somewhat at every $\tan \beta$, $m_{A^0}$ parameter choice. (More details can be found in, for instance, Refs. [9-10].) The importance of $\cos^2(\beta - \alpha)$ becomes apparent by recalling the pattern of the couplings of the $h^0$ and $H^0$ to $VV$ ($V = Z$ or $W$) and $ZA^0$. The squares of these couplings at tree-level are given by:

$$
\begin{align*}
    h^0VV & : \quad f_W^2 \sin^2(\beta - \alpha) \\
    H^0VV & : \quad f_V^2 \cos^2(\beta - \alpha)
\end{align*}
\begin{align*}
    h^0A^0Z & : \quad g^2 \frac{\cos^2(\beta - \alpha)}{4 \cos^2 \theta_W} \\
    H^0A^0Z & : \quad g^2 \frac{\sin^2(\beta - \alpha)}{4 \cos^2 \theta_W},
\end{align*}
$$

(1)

where $f_W = g m_W$ and $f_Z = g m_Z / \cos \theta_W$. (Of course, the $A^0$ has no $VV$ coupling at tree-level.) Note the complementarity of the $ZZ$ and $A^0Z$ couplings for the $h^0$ and $H^0$ — in particular, if $m_{A^0}$ is large, so that $\cos^2(\beta - \alpha)$ is small, the $h^0$ has large coupling to $ZZ$ while the $H^0$ has large coupling to $A^0Z$. If the angle $\alpha$ is computed by diagonalizing the radiatively corrected CP-even sector mass matrix, these results for the couplings remain valid to order $g^4$. The one-loop corrections to the vertices themselves first generate corrections to these squared couplings at order $g^6$. [10,11] We have not included the latter corrections in the numerical work to be discussed later; they would not alter the basic phenomenology.

Regarding quark couplings, the $t\bar{t}$ ($b\bar{b}$) couplings of the $H^0$ and $A^0$ tend to be suppressed (enhanced) at large $\tan \beta$, while those of the $h^0$ become SM-like at large $m_{A^0}$. The most important radiative corrections to these couplings are automatically included by using their tree-level forms as a function of $\alpha$ and $\beta$, but with $\alpha$ determined by diagonalizing the radiatively corrected CP-even mass matrix. The

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* These results, and those of later plots, are obtained using the complete leading-log radiative corrections to the MSSM Higgs masses and couplings given in Ref. [8].
coupling of the charged Higgs boson to $t\bar{t}$ is such that the potentially large $m_t$ term is suppressed for large $\tan\beta$.

We note here one important impact of the suppression of the $WW, ZZ$ couplings of the $H^0$ and $A^0$. This suppression implies that the $VV$ decays of the $H^0$ and $A^0$ generally have quite small partial widths. This, in turn, implies that even when heavy these Higgs bosons are generally quite narrow resonances ($\Gamma < 5$ GeV).

The only situations for which the $H^0$ width becomes large are two: if $\tan\beta < \sim 1$, implying a large $t\bar{t}$ coupling for the $H^0$, and $m_{H^0}$ is above $t\bar{t}$ threshold; or if $\tan\beta > 20$, in which case the $b\bar{b}$ coupling and, hence, decay width of the $H^0$ is very enhanced. The behavior of the $A^0$ width is very similar. Of course, the $h^0$, which is strongly coupled to $VV$ channels, cannot be heavy enough (for $m_t \lesssim 200$ GeV and $M_{\tilde{t}} \lesssim 2$ TeV) to decay to $VV$ pairs, and thus will also be a narrow resonance.

Should the $H^0$ or $A^0$ be discovered, their narrow width will be immediately apparent. (Indeed, the SSC/LHC detection techniques for these Higgs bosons rely on their having a narrow width.) If, in addition, the observed state has mass above $2m_W$, it will be obvious that it cannot be the SM Higgs boson; the latter is expected to rapidly develop a broad width in $VV$ decay channels for $m_{h^0} > 2m_W$. Conversely, discovery of a neutral scalar with a large decay width to $VV$ channels would immediately contradict the predictions of the MSSM.

The branching ratios clearly play a crucial role in understanding how to detect the Higgs bosons of the MSSM. It is a straightforward, if tedious exercise to compute the branching ratios. This has been carried out by a number of groups, with consistent results. Typical results were illustrated in earlier talks. We first summarize crucial features of these results assuming that neutralino and chargino pair decay modes of the Higgs bosons are forbidden.

For $m_{h^0}$ near its maximum value, it has SM-like couplings. This means that it can have a significant $\gamma\gamma$ branching ratio, and that the $ZZ^*$ branching ratio can become significant if $m_{h^0}^{max}$ is large enough (which requires large $m_t$ and $M_{\tilde{t}}$). Note that the $\tau^+\tau^-$ branching ratio is typically of order 10%.

Branching ratios (in the case of large SUSY mass scales) for the $H^0$ are illustrated in the top half of Fig. 1. Note that the $ZZ^*$ and $ZZ$ branching ratios are not necessarily suppressed despite the smaller-than-SM width for decays to these channels. If $m_{H^0} < 2m_t$ and $\tan\beta$ is not too large, $\Gamma(H^0 \rightarrow ZZ) > \Gamma(H^0 \rightarrow b\bar{b})$ and the $ZZ$ branching ratio is substantial. This means that the $l^+l^-l^+l^-$ detection mode at the SSC/LHC could be viable. A particularly interesting decay of the $H^0$ is $H^0 \rightarrow h^0h^0$; this mode has a large branching ratio for small to moderate $\tan\beta$. Of course, for large $\tan\beta$ the $b\bar{b}$ and $\tau^+\tau^-$ modes are dominant, with the latter branching ratio being of order 10%. For moderate to large $\tan\beta$, there is a narrow window of $m_{H^0}$ for which $BR(H^0 \rightarrow \gamma\gamma)$ is reasonable.

The general pattern for the $A^0$ is similar, except for the severe suppression of $VV$ decays (which are not present at tree-level, first occurring at one-loop level). In
Figure 1: We plot branching ratios for $H^0$ decays for $\tan \beta = 2$ and 20 (at $m_t = 150$) as a function of $m_{H^0}$. We have taken $M_{\tilde{t}} = 1$ TeV and neglected squark mixing. In the top half of the figure, ino masses are large and ino-pair channels are forbidden. In the bottom graphs, ino masses are determined by $M = 200$ GeV and $\mu = 100$ GeV. In the latter case only the more important decay channels are shown.
addition, $b\bar{b}$ and $\tau^+\tau^-$ branching fractions at $\tan \beta = 2$ are larger than in the case of the $H^0$. Also of interest is the $A^0 \to Zh^0$ decay that can have a large branching ratio for moderate $\tan \beta$ if $m_{A^0} < 2m_t$. The $\gamma\gamma$ branching ratio of the $A^0$ is only significant near its peak value at $m_{A^0} = 2m_t$, unless $\tan \beta \lesssim 1$.

Turning to the $H^+$, we will only be concerned with the situation where $m_t > m_{H^+} + m_b$, and $H^+ \to t\bar{b}$ decays are forbidden. Except in a small window of parameter space where $H^+ \to W^+h^0$ decays are allowed and would dominate, the primary decay of the $H^+$ for $\tan \beta \gtrsim 1.5$ will be to $\tau^+\nu_\tau$ ($BR$ near 100\% for $\tan \beta \gtrsim 2.5$). This mode might play a crucial role at the SSC/LHC. For plots see Ref. [17]. Of course, in the alternative case where $H^+ \to t\bar{b}$ decays are allowed, they will be dominant.

Of course, if ino-pair channels are kinematically allowed they can be quite important. This is because the Higgs bosons have couplings to charginos and neutralinos that are proportional to $g$, rather than $gm/(2m_W)$ (as would be typical of a quark or lepton of mass $m$). Indeed, when allowed, the ino-pair channels can easily dominate the decays of a Higgs boson. To illustrate this point, I compare the $H^0$ branching ratios when ino decay channels are forbidden to those found when the ino’s are relatively light, determined by taking the $SU(2)$ gaugino mass $M$ to be 200 GeV (corresponding in the standard GUT approach to $m_\tilde{g} \sim 600$ GeV) and the higgsino mixing parameter $\mu$ to be 100 GeV. (For this choice of parameters the neutralino masses at $\tan \beta = 2$ are 39, 103, 119 and 245 GeV, while the chargino masses are 61 and 243 GeV.) Results for $m_t = 150$ GeV and $\tan \beta = 2$ and 20 are illustrated in Fig. 1. Note that the $\chi^0$ pair modes dominate below $2m_t$. The $h^0h^0$ mode branching ratio remains large, but the $ZZ$ branching ratio is substantially suppressed in comparison to the case where ino decays are forbidden. At large $\tan \beta$, ino-pair modes continue to be significant, but the $b\bar{b}$ mode is still dominant. The primary result is that $H^0$ detection at the SSC or LHC in the $H^0 \to ZZ \to 4l$ mode becomes essentially impossible, whereas without ino decays this mode would be useful for moderate to small $\tan \beta$ when $m_{H^0} \lesssim 2m_t$.

The impact of ino decays on the $A^0$ branching ratios is quite similar in nature to that found in the case of the $H^0$. The $h^0$ decays are also affected; the $b\bar{b}$ is often dominated by ino-pair modes for $h^0$ masses such that the latter are kinematically allowed. Even the $H^+$ decays are significantly altered when $\tan \beta \lesssim 2$; for such $\tan \beta$, the $H^+ \to \tau^+\nu_\tau$ width (proportional to the square of $m_t \tan \beta$) is not especially enhanced and neutralino-chargino pair channels can dominate.

Clearly, allowing for decays of the MSSM Higgs bosons to ino-pair channels can significantly reduce their detectability in the even R-parity channels involving SM particles and other Higgs bosons. This fact will have its largest impact at the SSC/LHC, where the only thoroughly established detection techniques rely on these modes. At an $e^+e^-$ collider, we expect that all decay channels, including the odd R-parity channels, can be used to isolate a Higgs signal using relatively efficient cuts to reduce backgrounds. Thus, we will outline the detectability of the MSSM Higgs
bosons at $e^+e^-$ colliders primarily on the basis of their production rates.

4. The MSSM Higgs Bosons at $e^+e^-$ Colliders

4.1. LEP and LEP-II

In the context of the MSSM, the decays $Z \rightarrow Z^*h^0$ and $Z \rightarrow h^0A^0$ will take place if the couplings are adequate and they are kinematically allowed. Failure to detect these signals at LEP with the integrated luminosity accumulated to date indicates that $m_{h^0} \gtrsim 40$ GeV, $m_{A^0} \gtrsim 20$ GeV, $m_{H^\pm} \gtrsim 40$ GeV; no restriction on $\tan \beta$ is obtained.\footnote{For $m_t = 150$ GeV and $\sqrt{s} = 200$ GeV, the region is also very sensitive to the precise value of $m_t$. This is because $m_Z + m_{h^0}^{\max}$ is fairly close to $\sqrt{s}$, and small changes in $m_t$ cause significant shifts in $m_{h^0}$.} These lower bounds will be pushed to near $m_Z$ after LEP-II completes its experimental search for $e^+e^- \rightarrow Z^* \rightarrow h^0A^0$ or $Zh^0$. In particular, an $h^0$ with $m_{h^0} \sim m_Z$ can be seen at LEP-II provided that $\sqrt{s} > \sim 200$ GeV, $L \sim 500$ pb$^{-1}$ can be achieved, and that efficient $b$-tagging is possible.\footnote{For instance, if 10 observed events are sufficient or $L$ a factor of 2.5 larger, $h^0$ detection would be possible at LEP-200 for $m_t = 150$ GeV in all but the large $\tan \beta$, large $m_{A^0}$ corner of parameter space. For $m_t = 200$ GeV, the boundary line for $h^0$ detection is rather insensitive to precise experimental efficiencies; the $h^0$ is simply too heavy to be produced in the $m_{A^0} > \sim 140$ GeV and $\tan \beta > \sim 2$ portion of parameter space.} Unfortunately, after radiative corrections $m_{h^0}$ could be larger than $m_Z$ if $m_t$ and $M_{\tilde{t}}$ are large.

The impact of radiative corrections on the potential of LEP-II for detection of the neutral Higgs bosons of the MSSM was first considered in Refs. [21] and [22]. Consider, for example, $\sqrt{s} = 200$ GeV and $L = 500$ pb$^{-1}$. If one assumes an overall detection efficiency of 25% and that 25 observed events are needed for discovery, then at $m_t = 150$ GeV there are already substantial portions of $m_{A^0}$–$\tan \beta$ parameter space (at moderate to large $m_{A^0}$ and $\tan \beta$) for which discovery of the $h^0$ is not possible using either $h^0Z$ or $h^0A^0$ associated production. The precise region is sensitive to the integrated luminosity and analysis efficiencies.\* For instance, if 10 observed events are sufficient or $L$ a factor of 2.5 larger, $h^0$ detection would be possible at LEP-200 for $m_t = 150$ GeV in all but the large $\tan \beta$, large $m_{A^0}$ corner of parameter space. For $m_t = 200$ GeV, the boundary line for $h^0$ detection is rather insensitive to precise experimental efficiencies; the $h^0$ is simply too heavy to be produced in the $m_{A^0} > \sim 140$ GeV and $\tan \beta > \sim 2$ portion of parameter space.

Of course, the ability of LEP-II to detect the $h^0$ is also strongly dependent upon the actual $\sqrt{s}$ that can be achieved and upon the unknown value of $M_{\tilde{t}}$ (and, to a lesser degree, the parameters that control squark mixing). This issue is studied in Refs. [23] and [24]. In Fig. 2 the contours for 100 total $h^0Z$ events (no efficiencies included) are given for large $m_{A^0}$ ($m_{A^0} \gg m_Z$) in $m_t$–$M_{\tilde{t}}$ parameter space for a selection of ($\sqrt{s}$, $\tan \beta$) values, assuming $L = 500$ pb$^{-1}$. Once $m_{h^0}$ is larger than about 100 GeV this number of events should prove marginally adequate to observe the Higgs signal above the background coming from continuum $e^+e^- \rightarrow ZZ$ production.\footnote{100 $h^0Z$ events would, for instance, yield $\sim 7$ events in which the $Z$ decays to $l^+l^-$.}
Figure 2: The discovery boundaries for the $h^0$ at LEP-II in $m_t-M_\tau$ parameter space assuming that $m_A^0$ is large ($m_A^0 = 1$ TeV was used) for a variety of $(\sqrt{s}, \tan \beta)$ values. We assume that $L = 500$ pb$^{-1}$ and require 100 total $h^0Z$ events (before efficiencies). We have neglected squark mixing. The region where discovery is possible lies to the left and below the boundary curves. 

$(l = e, \mu)$ and the $h^0$ would be seen as a bump in the $(p_{e^+} + p_{e^-} - p_Z)^2$ spectrum. For most $(\sqrt{s}, \tan \beta)$ choices this criterion turns out to be quite close to the criteria specified in the detailed experimental treatment of Ref. [25]. (The only exception is for $(190 \text{ GeV}, 20)$, where the criteria of Ref. [25] yield a significantly more pessimistic contour than that plotted in Fig. 2.) Of course, for $m_{h^0}$ near to $m_Z$, $b$ tagging would be needed to eliminate the $ZZ$ continuum; $\tau$ pair final states would also help to isolate the Higgs boson. (See, for instance, Refs. [23] and [25].)
The figure makes it quite apparent that the $\sqrt{s} = 175$ GeV option for LEP-II (more or less the minimum that is anticipated) is far less desirable than the somewhat more expensive $\sqrt{s} = 200$ GeV possibility. Pushing to the technically feasible $\sqrt{s} = 240$ GeV energy would be highly desirable since the $h^0$ would be detectable for all but the very largest top and stop masses. Of course, it can be hoped that the top quark will be found at the Fermilab Tevatron in the near future. This would provide crucial guidance in setting the maximum LEP-II machine energy for which we should strive. For instance, if it is found that $m_t \approx 140$ GeV, then Fig. 2 shows that discovery of the $h^0$ at LEP-II would be possible for all of the most interesting region of parameter space ($M_{\tilde{t}} \lesssim 1$ TeV and $\tan \beta \lesssim 20$) for a machine energy of $\sqrt{s} = 200$ GeV. In contrast, for this value of $m_t$ even a small decrease in energy to $\sqrt{s} = 190$ GeV would greatly worsen the prospects; detection of the $h^0$ would not be possible for high values of $\tan \beta$ if $M_{\tilde{t}} > \sim 350$ GeV. Even a lower bound placed on $m_t$ by the Tevatron would be helpful. For example, if it is determined that $m_t > 160$ GeV, the most reasonable procedure might be to first push LEP-II to an energy of 200 GeV, thereby allowing a significant possibility for $h^0$ detection according to Fig. 2. But, if the $h^0$ were not discovered at this energy, pushing slowly to $\sqrt{s} = 240$ GeV would rapidly open up the possibility for $h^0$ detection in the regions of parameter space corresponding to the higher values of $m_t$, $M_{\tilde{t}}$ and $\tan \beta$.

4.2 The Next Linear $e^+e^-$ Collider

As we have just seen, if the MSSM model is correct, the $h^0$ may or may not be discovered at LEP-II, depending upon $m_t$, the precise machine parameters, in particular $\sqrt{s}$, and the MSSM model parameters, especially $M_{\tilde{t}}$. In the event that the $h^0$ is not observed, because $M_{\tilde{t}}$ is large and/or the $\sqrt{s}$ achieved is small, a higher energy $e^+e^-$ collider would clearly be required in order to detect any of the MSSM Higgs bosons. Even if the $h^0$ is found at LEP-II, as discussed earlier the $h^0$ will have couplings to quarks and vector bosons that are quite similar to those of a SM Higgs boson of the same mass should it happen that $m_{A^0} \gtrsim 2m_Z$. In this a priori rather likely case, discrimination between the Higgs sectors of the SM and the MSSM requires detection of one or more of the additional MSSM Higgs bosons, i.e. the $A^0$, $H^0$ and/or $H^\pm$. Not surprisingly, an $e^+e^-$ collider of sufficient energy and luminosity would be an ideal machine for this purpose. An overview of this subject is given in Ref. [2]. For an early tree-level survey of relevant production mechanisms and strategies see Ref. [26]. These early surveys were updated to include radiative corrections to masses and coupling constants in Ref. [27]. (See also, Refs. [28] and [16].)

Detection of the $H^\pm$ is most easily discussed. For $\sqrt{s} \gg m_Z, 2m_{H^\pm}$, one finds (in units of the standard $R$ — one unit of $R$ at $\sqrt{s} = 500$ GeV corresponds to 0.347 pb)

$$\frac{\sigma(e^+e^- \rightarrow \gamma^*, Z^* \rightarrow H^+H^-)}{\sigma(e^+e^- \rightarrow \gamma^* \rightarrow \mu^+\mu^-)} = \frac{1 + 4 \sin^4 \theta_W}{8 \sin^4 2\theta_W} \approx 0.308.$$ (2)
Figure 3: Event number contours for an NLC with $\sqrt{s} = 500$ GeV and $L = 10 \text{ fb}^{-1}$. We have taken $m_t = 150$ GeV, $M_{\tilde{t}} = 1$ TeV and have neglected squark mixing. We display contours for 30 and 100 total events (no detection efficiencies included) for the six most important processes at an NLC: $Z^* \to h^0, H^0 + Z$, $Z^* \to h^0, H^0 + A^0$, and $e^+ e^- \to \nu\bar{\nu}W^+W^- \to h^0, H^0 + X$.

Including effects of threshold suppression, and analyzing the various different final state channels, it is found that charged Higgs masses up to about $0.4\sqrt{s}$ will be detectable with an integrated luminosity of $10^3$ inverse units of $R$. Of course, if $t \to H^+ b$ decays are allowed, $BR(t \to H^+ b)$ can be substantial and detection of the
$H^+$ and $H^-$ in $e^+e^- \to t\bar{t}$ events could also be possible, but the $m_{H^+}$ values accessible in this way would probably be smaller than $0.4\sqrt{s}$. For higher $m_{H^+}$, one is forced to consider $e^+e^- \to t\bar{t}H^+$ production, via radiation of the $H^+$ off a virtual $b$ or $t$ quark. This process could easily have a lower threshold than $H^+H^-$ pair production. However, the cross section is not large; only for $\tan\beta > 1$ are kinematically allowed. If $Hdots t$ exceed 2 fb even for the smallest allowed value of $m_{H^+}$ ($\gtrsim m_W$).

As already described, the dominant decay modes of the $H^+$ depend very much on what channels are kinematically allowed. If $H^+ \to t\bar{b}$ decays are forbidden, then the $H^+ \to \tau^+\nu$ mode is dominant for $\tan\beta \gtrsim 2$, unless $H^+ \to W^+h^0$ is allowed. When allowed, the $t\bar{b}$ decay mode will generally dominate. None of these decay channels should present any particular difficulty for detection of the $H^+$ at an $e^+e^-$ machine provided the production rate is reasonable.

Let us now turn to the neutral Higgs bosons. The discussion presented here will be largely based on the work of Ref. [27]. The most important processes for production and detection of the neutral Higgs bosons, $h^0$, $H^0$ and $A^0$, are six: $e^+e^- \to Z^* \to h^0$, $H^0 + Z$, $e^+e^- \to Z^* \to h^0$, $H^0 + A^0$, and $e^+e^- \to \nu\bar{\nu} + W^+W^- \to \nu\bar{\nu} + h^0$, $H^0$ (the latter is conventionally referred to as $WW$ fusion). There is considerable complementarity among the first four processes, and the $WW$ fusion processes are also complementary to one another and to the first four. If $m_{A^0} \gtrsim m_Z$, so that $\cos^2(\beta - \alpha)$ is small, then $Z^* \to h^0Z$, $Z^* \to H^0A^0$, and $WW \to h^0$ are all maximal, and the other three small. The first three processes provide a reasonable event rate so long as $\sqrt{s}$ is not too near the relevant threshold. Typically, for $\sqrt{s} = 500$ GeV and the $m_{h^0}$ range of interest, $WW \to h^0$ is comparable to $Z^* \to h^0Z$, both having cross sections $\gtrsim 0.1$ units of $R$. Away from threshold, the cross section for $Z^* \to H^0A^0$ is at most about 0.1 units of $R$. (Precise cross section formulae appear in Ref. [2].) Consequently, detection of the $H^0$ and $A^0$ will only be possible in such a scenario if $\sqrt{s}$ is significantly larger than $m_{A^0} + m_{H^0}$ (i.e. $\gtrsim 2m_{A^0}$ for large $m_{A^0}$ where $m_{H^0} \simeq m_{A^0}$). To illustrate more precisely the expectations, we give event number contours for all six processes in Fig. 3 for an NLC with $\sqrt{s} = 500$ GeV and $L = 10$ fb$^{-1}$ in the case where $m_t = 150$ GeV and $M_{\tilde{t}} = 1$ TeV (squark mixing is neglected). Our estimate is that if more than 100 total events (before efficiencies) are obtained for a given process, then it will be detectable. Contours for 30 events are also shown, but detection of any of the processes with so few events would require very high experimental and analysis efficiencies. The most important conclusion from this figure is that detection of all of the neutral Higgs bosons will be possible at $\sqrt{s} = 500$ GeV if $m_{A^0} \lesssim 200 - 220$ GeV. Detection of the $H^0$ and $A^0$ would require higher machine energy for larger $m_{A^0}$ values.

While the above processes are certainly the most important ones for detecting the MSSM Higgs bosons at the NLC, there are other reactions that have been studied. These include: radiation of Higgs bosons off of top quarks or bottom quarks; $H^0$ and $h^0$ production via $ZZ$ fusion; $A^0$, $H^0$ and $h^0$ production via the $\gamma\gamma$ collisions.
arising from bremsstrahlung and beamsstrahlung radiation;[26,27] and production of pairs of Higgs bosons or a vector boson plus a Higgs boson.[26,27] Generally speaking, the cross sections for these processes are substantially smaller than those discussed earlier. However, they could provide important complementary information under some circumstances.

For example, Higgs radiation off of the top quark would probe the $t\bar{t}$ Higgs coupling that does not enter directly into the production processes considered earlier. At $\sqrt{s} = 500$ GeV, the $h^0t\bar{t}$ cross section is of order $1 - 3$ fb for $m_{h^0}$ near its upper limit (i.e. for large $m_{A^0}$) where it has SM–like couplings. Detection of the process in several 10 fb$^{-1}$ years might prove possible. For small $m_{A^0}$, where $m_{h^0}$ is significantly below its maximum, the $h^0t\bar{t}$ cross section declines rapidly. The behavior of the $H^0t\bar{t}$ cross section is complementary. For small $m_{A^0}$, where $m_{H^0}$ is near its lower limit, and the $H^0$ couplings become SM–like, $\sigma(H^0t\bar{t})$ reaches the $1 - 2$ fb range and a viable signal might emerge. As $\tan\beta$ increases, the $h^0$ ($H^0$) mass regions for which they have SM–like couplings and for which $h^0(H^0)t\bar{t}$ could be detected become increasingly smaller. Finally, the $A^0t\bar{t}$ event rate is never large enough for detection for $\tan\beta > \sim 1$.

Radiation of $h^0$, $H^0$ or $A^0$ off of a bottom quark could be useful at very large $\tan\beta$ where the $b\bar{b}$ Higgs couplings are highly enhanced. For example, the $A^0t\bar{t}$ cross section is in the $1 - 3$ fb range for $m_{A^0} \lesssim 120$ GeV if $\tan\beta \gtrsim 40$. Unfortunately, for larger $m_{A^0}$ values ($\gtrsim 200$ GeV) such that $A^0, H^0$ discovery via $Z^* \to H^0A^0$ fails, the $A^0t\bar{t}$ process also becomes undetectable (even though phase-space-allowed) unless $\tan\beta \gtrsim 200$.

5. Detecting MSSM Higgs Boson at Hadron Super Colliders

Detection of the MSSM Higgs bosons at a hadron super collider is a much trickier subject, but a very important one since both the SSC (with $\sqrt{s} = 40$ TeV) and the LHC (with $\sqrt{s} \sim 16$ TeV) will almost certainly be constructed prior to a high energy linear $e^+e^-$ collider. Much work in this area has appeared recently and has been reviewed in earlier talks. A comprehensive review can also be found in Ref. [7]. Overall, one can come close to establishing a no-lose theorem according to which one or more of the MSSM Higgs bosons will be detected either at LEP-200 (if LEP-II only reaches $\sqrt{s} = 175$ GeV the theorem is greatly weakened) or at the SSC/LHC hadron super colliders. To a significant extent, the same modes that have proven critical to detecting the SM Higgs boson ($\phi^0$) can be employed for the MSSM Higgs bosons, provided that the decays of the MSSM Higgs bosons are primarily to SM particle channels. However, should the decays of a given MSSM Higgs bosons be dominated by supersymmetric particle pair channels, detection in the latter modes is likely to be necessary. The degree to which this is possible is not currently known. However, since a particularly important component of the no-lose theorem involves discovery of the relatively light $h^0$, and supersymmetric partners are less likely to dominate its decays, we shall see that the no-lose theorem is not dramatically weakened even
when detection of the \( H^0 \) and \( A^0 \) in even R-parity channels becomes impossible due to their having large branching ratios to odd R-parity channels.

Before summarizing the situation, it is necessary to briefly review the basic modes for discovery of a SM Higgs boson with \( m_Z \lesssim m_{\phi^0} \lesssim 800 \text{ GeV} \) at the SSC./LHC.\(^{[35]}\)

5.1. Techniques for Detecting the SM Higgs Boson and Application to the MSSM

Certainly one of the most difficult mass regions is \( 80 \lesssim m_{\phi^0} \lesssim 135 \text{ GeV} \). In this region \( \phi^0 \to b\bar{b} \) decays dominate, but have very large backgrounds. Rare decay modes have long appeared to provide the best hope.\(^{[36]}\) A viable signal in inclusive production, followed by \( \phi^0 \to \gamma\gamma \), emerges only if very excellent \( \gamma\gamma \) mass resolution and \( \gamma - \text{jet} \) rejection is possible. While the required mass resolution may be achieved by some detectors, jet rejection remains an issue. Further, not all detectors will have the required resolution. Thus, it has been important to develop an alternative approach to the \( 80 \text{ GeV} \lesssim m_{\phi^0} \lesssim 135 \text{ GeV} \) mass region between the lower limit of the \( ZZ^* \to 4l \) channel (to be reviewed shortly) and the approximate upper limit for \( \phi^0 \) discovery at LEP-II. The most promising (because of low backgrounds) appears to be \( W\phi^0 \) associated production, followed by \( W \to l\nu \) and \( \phi^0 \to \gamma\gamma \). The two processes leading to such a final state are: \( W^* \to W\phi^0 \) production\(^{[37, 38, 39]} \) and \( gg \to t\bar{t}\phi^0 \) production, with one of the \( t \)'s decaying to the observed \( W^* \).\(^{[40, 41]} \) At the SSC the latter has a much higher event rate than the former. Backgrounds have been investigated and found to be sufficiently small for reasonably good \( \gamma\gamma \) mass resolution and easily-achieved \( \gamma - \text{jet} \) discrimination factors. One obtains a viable \( \phi^0 \) signal at the SSC throughout the \( 80 \text{ GeV} \lesssim m_{\phi^0} \lesssim 135 \text{ GeV} \) mass region for the canonical \( L = 10 \text{ fb}^{-1} \) of integrated luminosity. (At the LHC, \( L \) substantially above \( 10 \text{ fb}^{-1} \) is required, but the full \( 100 \text{ fb}^{-1} \) enhanced luminosity is not necessary.) Since \( S/\sqrt{B} \) values are generally quite healthy for the SM Higgs boson, the \( l\gamma\gamma \) final state remains practical even for an MSSM Higgs boson with \( \gamma\gamma \) branching ratio somewhat below the SM-like value.

In practice, it is primarily the \( h^0 \) which might be detected in \( \gamma\gamma \) or \( l\gamma\gamma \) final states. As the \( h^0 \) couplings become SM-like, its \( \gamma\gamma \) and \( l\gamma\gamma \) phenomenology will become extremely similar to that of a \( \phi^0 \) of the same mass. Thus, it will mainly be a question of the region of parameter space for which the \( h^0 \) has couplings that are close to SM values. As we shall see, the \( A^0 \) and \( H^0 \) can also be detected in the \( \gamma\gamma \) and \( l\gamma\gamma \) modes, but only in very limited regions of MSSM parameter space.

In actual fact, the \( l\gamma\gamma \) (and possibly \( \gamma\gamma \)) mode continues to be useful for \( \phi^0 \) discovery up to \( \sim 150 \text{ GeV} \). However, above \( \sim 135 \text{ GeV} \) (but \( \lesssim 2m_Z \)) an even cleaner mode becomes available as well, namely \( gg \) fusion production of the \( \phi^0 \) followed by \( \phi^0 \to ZZ^* \to l^+l^-l^+l^- \) (4l for short, \( l = e \) or \( \mu \)).\(^{[36]} \) (For a sample experimental study, see Ref. [42].) With appropriate cuts on the \( Z^* \) mass, the only background of any
significance at all is that from continuum $ZZ^*$ production, and the level of this latter background is extremely tiny. Detection of the $\phi^0$ in this mass region becomes purely a matter of event rate.

Once $m_{\phi^0} > 2m_Z$, $\phi^0 \to ZZ$ double-on-shell decay becomes possible, and it is well-known that detection of the $\phi^0$ in the gold-plated $4l$ mode is possible up to masses of order $600 – 800$ GeV, depending upon the strength of the $gg$ fusion mechanism as determined by $m_t$. For masses below this, the $ZZ$ continuum background is significantly smaller than the Higgs resonance bump.

The $4l$ mode is clearly extremely useful for the MSSM Higgs bosons. As we have already emphasized, the $h^0$ behaves very much like a SM $\phi^0$ of the same mass once $m_{A^0}$ is sufficiently above $m_Z$ that its couplings become SM-like. Thus, if $m_{h^0} \gtrsim 135$ GeV and $m_{A^0}$ is relatively large, the $h^0$ will be detectable in the $4l$ mode. In the case of the $H^0$, it might be mistakenly concluded that the suppression of the $H^0 ZZ$ coupling would make detection in the $4l$ mode quite difficult. However, two very important counter-acting effects must be recognized. First, as noted earlier, the $H^0$ becomes quite narrow. This means that one is looking for a very narrow resonance above the $ZZ$ continuum background, in contrast to the SM case where the $\phi^0$ is a relatively broad resonance and a much larger mass interval must be considered in computing the background. Second, even if $\Gamma(H^0 \to ZZ)$ is suppressed, it can still be larger than or, at least, comparable to $\Gamma(H^0 \to Q\overline{Q})$ ($\Gamma(H^0 \to h^0 h^0)$ also plays an important role). If this is the case, then the $H^0 \to 4l$ branching ratio is not particularly suppressed. In practice, this favorable situation applies for $m_{H^0} < 2m_t$ so long as $\tan\beta$ is not so large that $b\bar{b}$ decays of the $H^0$ become highly enhanced. However, once $H^0 \to t\bar{t}$ decays are allowed, the $4l$ decays have too small a branching ratio for this to be a useful channel.

5.2. SSC/LHC MSSM Cross Sections

Of course, an important ingredient in the detectability of the MSSM Higgs boson is their production cross sections. In the case of the $H^+$ we have already noted that only $gg \to t\bar{t}$ production followed by $t \to H^+b$ (or the charge conjugate) will allow for $H^+$ detection. The $t\bar{t}$ cross sections are well-known. In the case of the neutral Higgs bosons, aside from the $W^* \to W + Higgs$ contribution to the $l\gamma\gamma$ final state mode, the only cross sections of importance are all induced by $gg$ collisions: $gg \to h$, $gg \to b\bar{b}h$ and $gg \to t\bar{t}h$ ($h = h^0, H^0, A^0$). Of these, the $t\bar{t}h$ process is only important for the $l\gamma\gamma$ final state mode. As reviewed elsewhere, $WW$ fusion does not make a significant contribution to the relevant production rates.

The $gg \to b\bar{b}h^0$ process could possibly be of importance for $h^0$ detection in the inclusive $\tau^+\tau^-$ decay mode; at large $\tan\beta$ both it and $gg \to h^0$ are greatly enhanced with respect to the corresponding SM Higgs cross sections when $m_{h^0}$ is not near its maximum. Note, however, that as $m_{h^0}$ approaches its maximum value the $h^0$ couplings become SM-like, and the $gg \to b\bar{b}h^0$ cross section does not play a significant role in contributing to $h^0$ detection in the $4l$ mode.
Clearly $gg \rightarrow H^0$ is crucial for $H^0$ discovery in the $4l$ mode, and, it turns out, so is $gg \rightarrow b\bar{b}H^0$ (especially in the $ZZ^* \rightarrow 4l$ mass region). Indeed, for $m_{H^0}$ of moderate size the latter can become so enhanced at large $\tan \beta$ as to dominate the $gg \rightarrow H^0$ inclusive mechanism. In fact, for large enough $\tan \beta$ the $gg \rightarrow b\bar{b}H^0$ cross section can be far larger than that for any mechanism for producing a SM Higgs boson of similar mass. This last remark also applies to $gg \rightarrow b\bar{b}A^0$. Thus, at large $\tan \beta$, it is possible that the very large cross sections for $H^0$ and $A^0$ production, coupled with their $\lesssim 10\%$ branching ratios to $\tau^+\tau^-$, could allow their detection in the $\tau^+\tau^-$ final state, despite the impossibility of using this mode for the SM $\phi^0$.

5.3. SSC/LHC MSSM Higgs Detection Phenomenology

Some examination of the relevant issues at tree level appeared early on in Refs. [2, 39, 44] (see also references therein) and related experimental studies for the SSC, and in Ref. [45] and related experimental studies for the LHC. Recently, the phenomenology of the MSSM Higgs bosons at the LHC and SSC has been re-examined after including radiative corrections. Here, I will summarize the results obtained in Refs. [9, 10, 46], where the last-noted reference contains the basic surveys discussed below. Overlapping work appears in Refs. [13-15, 47]; there is general agreement on the conclusions.

We shall consider $m_{A^0}$ and $\tan \beta$ as our fundamental Higgs sector parameters, but, as noted earlier, to determine one-loop leading-log radiative corrections we must also specify $m_t$, the squark masses, and other parameters that determine the amount of squark mixing. Although LEP provides the lower bound of $\gtrsim 20$ GeV for $m_{A^0}$ noted earlier, there are currently no experimental constraints on $\tan \beta$. On the basis of renormalization group arguments it is generally expected that $1 \lesssim \tan \beta \lesssim m_t/m_b$.[2] Thus, we have considered the range $0.5 \leq \tan \beta \leq 20$. In addition, we must specify the chargino and neutralino masses. These particles would dominate Higgs decays and strongly affect one-loop induced processes (such as $\gamma\gamma$ decays of neutral Higgs) if sufficiently light. In this subsection we shall take $M_{\tilde{q}} = 1$ TeV and neglect squark mixing. We shall also assume that the ino masses are all greater than 200 GeV (implying, in the minimal no-intermediate-scale GUT unification scheme, a gluino mass somewhat in excess of 1 TeV). This will be termed scenario (A).[4] In this case, we can explore $m_{A^0} \lesssim 400$ GeV without including the ino’s in the Higgs decays. In addition, as we noted earlier, if the charginos are more massive than about 200 GeV, then they essentially decouple from one-loop contributions to the $\gamma\gamma$ couplings of the neutral Higgs bosons. We also note that, for the squark mass assumed, squark loop contributions to the $gg$ and $\gamma\gamma$ couplings of the neutral Higgs bosons are small.

In the following we wish to determine the extent to which one or more of the Higgs bosons of the MSSM can be detected throughout all of $m_{A^0}$–$\tan \beta$ parameter

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* In this next subsection we shall consider the impact of lowering these two SUSY mass scales.
space at either LEP-II or the SSC/LHC hadron colliders. Let us list and label the most relevant discovery channels. For LEP-II we determine the parameter regions over which the a) $Z^* \to Zh^0$ and b) $Z^* \to h^0 A^0$ processes should provide a viable signal — our discovery criterion will be to require 25 events, assuming $\sqrt{s} = 200$ GeV, $L = 500$ pb$^{-1}$ and an overall detection efficiency of 25% (i.e. $0.2 \text{ pb}$ of cross section is demanded). For the SSC and LHC, we considered, in Refs. [46,9,10], only the cleanest and least controversial detection modes for the MSSM Higgs bosons. We adopted an integrated luminosity of $L = 30$ fb$^{-1}$ — a reasonably achievable goal for both colliders.

To recapitulate, in the case of the neutral Higgs bosons the clean modes are the same as employed for the SM $\phi^0$: c),d) detection of the $h^0, H^0 \to ZZ, ZZ^* \to 4l$ decay modes; and e),f) detection in the $W h^0 X, W H^0 X \to l\gamma\gamma X$ final state. In the case of the $ZZ^* \to 4l$ mode, where backgrounds are negligible, we required 15 events after a factor of $\epsilon = 35\%$ reduction for cuts and efficiencies. For the $ZZ \to 4l$ and the $l\gamma\gamma$ cases, we required $S/\sqrt{B} \geq 4$ after cuts and efficiencies. (The same $\epsilon = 35\%$ reduction as above was used for the $4l$ mode; a more sophisticated treatment is employed for the $l\gamma\gamma$ mode.$^\dagger$)

Not listed above and not included in the contour plots to presented later is the $W A^0 X \to l\gamma\gamma X$ detection mode for the $A^0$. It would be of considerable use if $\tan\beta < \sim 1.5$. In the case of the charged Higgs boson, the only detection mode considered is g) $t \to H^+b$ where the $H^\pm$ is detected via an excess of $\tau\nu$ events over universality expectations. This is an excellent technique so long as $\tan\beta \gtrsim 0.5$ so that the branching ratio for $H^+ \to \tau^+\nu$ is not severely suppressed.$^\dagger$ Our specific criterion is derived from the detailed studies$^{[48]}$ that have shown that the high rate of $t\bar{t}$ production at the SSC allows detection of $t \to H^+b$ decays unless $BR(t \to H^+b)$ is quite small. Typically, a very significant effect in the $H^+ \to \tau^+\nu$ decay mode can be observed at the SSC for $L = 30$ fb$^{-1}$ so long as $BR(t \to H^+b) \times BR(H^+ \to \tau^+\nu_\tau) \gtrsim 0.003$, even if single $b$-tagging is required to isolate the $t\bar{t}$ events of interest from background. We employ this $BR$ lower bound as our discovery criterion.

As a final note, it should be remarked that if very excellent $\gamma\gamma$ mass resolution and $\gamma$–jet rejection can both be achieved, inclusive production of the $h^0, A^0$ and $H^0$ followed by detection in $\gamma\gamma$ decays will supplement the $l\gamma\gamma$ detection technique. This was studied in Refs. [46] and [14], where it was shown that the regions of parameter space for which the inclusive $\gamma\gamma$ mode might allow Higgs boson discovery are very similar to those where the $l\gamma\gamma$ mode is viable. The potential advantage of being able to confirm a signal found in the $l\gamma\gamma$ using the inclusive $\gamma\gamma$ channel, or vice versa, is apparent.

Before presenting a representative summary graph, some additional discussion should prove useful. We first briefly recapitulate the discovery abilities of LEP-II (with $\tan\beta < \sim 1.5$, the $H^+ \to cs$ mode is also useful. In terms of the graphical contours to be presented later, its impact is relatively small. It is included in the $H^+$ detection contours presented in Ref. [7].

$^\dagger$ For values of $\tan\beta \lesssim 1.5$, the $H^+ \to cs$ mode is also useful. In terms of the graphical contours to be presented later, its impact is relatively small. It is included in the $H^+$ detection contours presented in Ref. [7].
$\sqrt{s} = 200$ GeV and $L = 500$ pb$^{-1}$). Consider first the $Z^* \to Zh^0$ production channel. Our earlier discussion showed that it will be viable so long as it is kinematically allowed and one is not in the small $m_{A^0}$, large $\tan \beta$ parameter space corner, where the $h^0ZZ$ coupling is suppressed. For $m_t = 100$ GeV the $h^0$ never gets so heavy that $Zh^0$ production is forbidden, and, therefore, this mode is visible everywhere except in the above-noted parameter space corner. For $m_t = 150$ GeV, the $h^0$ becomes too heavy when $m_{A^0} \gtrsim 100$ GeV and $\tan \beta \gtrsim 7 - 10$ (depending on $m_{A^0}$). For $m_t = 200$ GeV, the $h^0$ becomes too heavy over most of parameter space except for moderate $m_{A^0}$ and $\tan \beta \lesssim 3$. Consider next the $Z^* \to h^0A^0$ detection mode. It is essentially always viable for parameter choices in the small $m_{A^0}$, large $\tan \beta$ corner, whatever the value of $m_t$ ($\lesssim 200$ GeV). This is simply because not only is the required coupling substantial, but also the $h^0$ and $A^0$ both have small enough masses that the process is well below kinematic threshold. In actual fact, at $m_t = 100$ GeV, there is a very narrow region centered about $m_{A^0} \sim 65$ GeV with $\tan \beta \gtrsim 6$ where neither the $h^0Z$ nor the $h^0A^0$ reaction satisfies the strict discovery criterion of 25 events for a 25% detection efficiency. However, in this region one does obtain at least 15 events in one reaction or the other for $L = 500$ pb$^{-1}$. Obviously, this region would be filled in after a couple of years of running.

We next give an overview of the expectations for the SSC/LHC hadron collider detection modes. Consider first the $4l$ mode. For $m_t \leq 150$ GeV, the $h^0$ is never sufficiently heavy ($m_{h^0} \gtrsim 130$ GeV is required) that it could (even with full strength coupling) have an observable $4l$ decay rate. By $m_t = 200$, if $m_{A^0}$ is large enough (roughly $m_{A^0} \gtrsim 150$ GeV) the $h^0$ becomes heavy enough and has a sufficient fraction of the full SM-like $ZZ$ coupling that its $ZZ^* \to 4l$ event rate exceeds the 15 event requirement. The detectability of the $H^0 \to 4l$ decays is equally sensitive to $m_t$. For $m_t = 100$ GeV, there is essentially no mass range for which the suppressed $H^0 \to ZZ \to 4l$ decays are not swamped by $H^0 \to t\bar{t}$. By $m_t = 150$ GeV, $H^0 \to 4l$ can be detected for $m_Z \lesssim m_{A^0} \lesssim 2m_t$ so long as $\tan \beta$ is not so big that the $4l$ mode is overwhelmed by $H^0 \to b\bar{b}$ decays. The upper mass limit above is, of course, fixed by the $t\bar{t}$ threshold, while the lower limit is determined by when $m_{H^0}$ falls too far below the $ZZ$ threshold (roughly $m_{H^0} \lesssim 130$ GeV). By $m_t = 200$ GeV, for small $m_{A^0}$ the $H^0$ is heavier than the critical 130 GeV, and, in addition, has sufficiently substantial $ZZ$ coupling that the $4l$ mode is visible. At larger $m_{A^0}$ (but $m_{H^0} \lesssim 2m_t$ still), this coupling becomes progressively more suppressed, and at higher values of $\tan \beta$ the $4l$ decay is swamped by the $H^0 \to b\bar{b}$ decays. Once $m_{H^0} \geq 2m_t$, $t\bar{t}$ decays are dominant and the $H^0 \to 4l$ decays cannot be seen for any $\tan \beta$. Finally, we note that the region over which the $4l$ channel can be seen is not very strongly dependent upon the resolution.

With regard to the $l\gamma\gamma$ mode, there is only the tiniest region of parameter space (in the vicinity of $m_{A^0} \sim 80 - 90$ GeV and with $\tan \beta \gtrsim 4$) for which the $W$ loop (generally suppressed) and quark loops combine to yield a $H^0\gamma\gamma$ coupling and, hence, $BR(H^0 \to \gamma\gamma)$ that is large enough for the $H^0$ to be visible in this channel.
once cross sections and backgrounds are taken into account. In the case of the $A^0$, a significant $\gamma\gamma$ coupling must derive from the top quark loop and is only possible if $\tan \beta < 1$ so that the $A^0 t\bar{t}$ coupling is not suppressed. Thus, the $t\gamma\gamma$ mode is generally viable for the $A^0$ if $\tan \beta \lesssim 1$ and $m_{A^0} < 2m_t$. In the case of the $h^0$, the $t\gamma\gamma$ mode is always visible if the $h^0$ has sufficiently SM-like couplings that its $\gamma\gamma$ branching ratio is similar to that of a $\phi^0$ of the same mass, and if it is sufficiently heavy ($m_{h^0} \gtrsim 80 \text{ GeV}$) that $\gamma\gamma$ decays are not suppressed and backgrounds not too large. These criteria are satisfied, more or less independently of $\tan \beta$, so long as $m_{A^0}$ is large enough. For $m_t = 200 \text{ GeV}$, the radiative corrections cause $m_{h^0}$ to reach the required mass region for smaller $m_{A^0}$ than for $m_t = 150 \text{ GeV}$, while at $m_t = 100 \text{ GeV}$, $m_{h^0}$ is large enough only at quite large $m_{A^0}$. For instance, at $m_t = 200 \text{ GeV}$, as $m_{h^0}$ approaches its maximum value for large $m_{A^0}$ and the $h^0$ couplings become SM-like, the event rate is several times the minimum required in order to achieve a $4\sigma$ signal. Thus, a reduction in the $h^0$ rate as its couplings move away from the SM-like limit with declining $m_{A^0}$ can be afforded.

We are now in a position to present a sample summary graph. In Fig. 4 we give discovery contours for LEP-200 and the SSC, for the case of $m_t = 150 \text{ GeV}$. Integrated luminosities for LEP-200 and the SSC of $500 \text{ pb}^{-1}$ and $30 \text{ fb}^{-1}$, respectively, are assumed. The figure displays the regions in $m_{A^0}$-$\tan \beta$ parameter space for which discovery of one of the MSSM Higgs bosons using the reactions a)-g) listed earlier will be possible. Discovery criteria are as motivated and stated earlier: $\geq 25$ events (after including a detection efficiency of $\epsilon = 0.25$) for reactions a) or b) at LEP-200; $S/\sqrt{B} \geq 4$ for Higgs masses above $2m_Z$, or 15 events (after efficiencies) for Higgs masses below $2m_Z$, for reactions c)-d); $S/\sqrt{B} \geq 4$ for reactions e)-f); and $BR(t \to H^+ b) \times BR(H^+ \to \tau^+ \nu_\tau) \geq 0.003$ for the charged Higgs detection mode g).

In the following, we briefly summarize the most important conclusions that can be reached from this and similar figures for other $m_t$ values.

Fig. 4 shows that in the case of $m_t = 150 \text{ GeV}$ detection of one or more of the MSSM Higgs bosons will be possible either at LEP-200, or at the SSC, except in a window (indicated by the ? mark on the figure) with $m_{A^0} \sim 120 - 150 \text{ GeV}$ and $\tan \beta \gtrsim 8 - 10$. For large $m_{A^0} \gtrsim 200 \text{ GeV}$ and $\tan \beta \gtrsim 4$, only the $h^0$ will be detectable. For this same $m_{A^0}$ range and $\tan \beta$ between $\sim 4$ and $\sim 8$ the $h^0$ will be found at both LEP-200 and the SSC. But once $\tan \beta \gtrsim 8$ only the SSC can detect the $h^0$. Note that detection of the $h^0$ at the SSC is only possible in the $t\gamma\gamma$ final state channel (e) — $m_{h^0}$ is never large enough for the $ZZ^* \to 4l$ mode to have significant branching ratio. Once $m_{A^0} \lesssim 150 \text{ GeV}$, detection of the $h^0$ will not be possible at the SSC, but discovery at LEP-200 (a,b) will be possible over a significant fraction of this portion of parameter space. Detection of the $H^0$ in the $4l$ mode (d) at the SSC is confined to small to moderate $\tan \beta$ and $m_{A^0}$ between $\sim 60$ and $\sim 300 \text{ GeV}$.

* In the following discussion, parenthetical letters refer to the process labels appearing on the figures.
Figure 4: Discovery contours in $m_{A^0}$–tan$\beta$ parameter space for the SSC with $L = 30$ fb$^{-1}$ and LEP-200 with $L = 500$ pb$^{-1}$ for the reactions: a) $e^+e^- \to h^0Z$ at LEP-200; b) $e^+e^- \to h^0A^0$ at LEP-200; c) $h^0 \to 4l$; d) $H^0 \to 4l$; e) $Wh^0X \to l\gamma\gamma X$; f) $WH^0X \to l\gamma\gamma X$; g) $t \to H^+b$. The contour corresponding to a given reaction is labelled by the letter assigned to the reaction above. In each case, the letter appears on the side of the contour for which detection of the particular reaction is possible. We have taken $m_t = 150$ GeV, $M_{\tilde{t}} = 1$ TeV and neglected squark mixing.

(decreasing as tan$\beta$ increases). Detection of the $H^0$ in the $l\gamma\gamma$ mode (f) is confined to a very narrow region of parameter space centered on $m_{A^0} \sim 60$ GeV with tan$\beta \gtrsim 5$. Detection of the $H^+$ in $t$ decays (g) at the SSC will be possible if $m_{A^0} \lesssim 115$ GeV.

A similar graph for $m_t = 200$ GeV appears in Fig. 5. It shows that for large $m_t$ at least one MSSM Higgs boson can be found everywhere in $m_{A^0}$–tan$\beta$ parameter
space — there would be no ‘gap’. Indeed, the SSC alone can discover at least one of the MSSM Higgs bosons throughout all of parameter space (whereas the region of parameter space that is covered by LEP-200 is relatively limited for such a large $m_t$).

In particular, at the SSC the $H^0 \to 4l$ channel (d) becomes viable in all but the large $m_{A^0}$, large tan $\beta$ region of parameter space (where $b\bar{b}$ decays of the $H^0$ suppress the $4l$ decays of interest). Meanwhile, the $h^0$ can be discovered in both the $4l$ (c) and $l\gamma\gamma$ (e) modes for all $m_{A^0} \gtrsim 200$ and tan $\beta \gtrsim 2$, thereby allowing determination of both its $ZZ$ and its $t\bar{t}$ couplings. For $m_t = 200$ GeV and $m_{A^0} \lesssim 150$ GeV, the $h^0$ will not generally be detectable at the SSC, but both the $H^0 \to 4l$ (d) and $t \to H^+b$ (g) processes will be observable. Detection of the $H^0$ in the $l\gamma\gamma$ channel (f) even becomes
significant in a substantial wedge of parameter space with \( m_{A^0} \) between \( \sim 65 \) and \( \sim 105 \) GeV and \( \tan \beta > 2.5 \).

In contrast to these two larger \( m_t \) cases, at \( m_t = 100 \) GeV detection of the MSSM Higgs bosons at the SSC would be confined to a much more limited portion of parameter space. In this case, radiative corrections are small and \( m_{h^0} \) would never be significantly larger than \( m_Z \); indeed, \( m_{h^0} \) would be substantially smaller than \( m_Z \) in many regions of parameter space. Thus, the \( 4l \) channel would not be viable for the \( h^0 \) anywhere in parameter space. However, for \( m_{A^0} \gtrsim 250 \) GeV and \( \tan \beta > \sim 2 \) it can be demonstrated (see Ref. [46]) that the \( h^0 \) could be found via the \( l\gamma\gamma \) mode, the \( h^0 \) mass being \( \gtrsim 80 \) GeV. At low \( m_{A^0} \), \( t \to H^+b \) decays could be observed. A small region with \( m_{A^0} \lesssim 200 \) GeV and low to moderate \( \tan \beta \) where \( H^0 \to 4l \) decays could be observed would remain. Thus, at this small \( m_t \) LEP-200 would play a very prominent role. As already discussed, it is virtually certain that the \( h^0 \) could be detected. But, of course, the only other Higgs boson of the MSSM that might be found at LEP-200 would be the \( A^0 \) were it to have small enough mass that \( Z^* \to h^0 A^0 \) is kinematically allowed and \( \cos^2(\beta - \alpha) \) is large.

The above plots and discussion have omitted detection of the \( A^0 \) at the SSC. As already noted, and described in detail in Ref. [46], the \( A^0 \) can be detected at the SSC in the \( l\gamma\gamma \) (and, possibly, \( \gamma\gamma \)) mode if \( m_{A^0} \leq 2m_t \) and \( \tan \beta \leq 1 \). Thus, its discovery in such modes at the SSC would instantly place a strong upper limit on \( \tan \beta \).

A more complete discussion of the above outlined results and the corresponding results for the LHC can be found in Refs. [46,9,10] as well as the other earlier-referenced work by other authors. The LHC results are easily summarized: the LHC with \( L = 100 \) fb\(^{-1} \) gives very much the same discovery contours as the SSC with \( L = 30 \) fb\(^{-1} \).

5.4. Influence of Ino Decays and Effects of Low \( M_{\tilde{t}} \)

Of course, the results obtained above will be altered if the masses of supersymmetric partner particles are substantially lower than we have been assuming. First, radiative corrections to the MSSM Higgs boson masses and mixing angle \( \alpha \) become relatively small if \( M_{\tilde{t}} \) is substantially smaller than \( 1 \) TeV. In addition, relatively light neutralinos and charginos will become important for decays of the Higgs bosons, as illustrated earlier in Fig. 1. These two effects have a substantial impact on both LEP-200 and SSC phenomenology. To illustrate, I have considered several alternative scenarios.

(A) First, we have the case discussed above, with \( M_{\tilde{t}} = 1 \) TeV and neutralinos and charginos all heavier than \( 200 \) GeV.

(B) Second, I consider \( M_{\tilde{t}} = 1 \) TeV with neutralino and chargino masses set (as in Fig. 1) by \( M = \) 200 GeV and \( \mu = 100 \) GeV.
Third, I take squark masses as determined using the above $M$ and $\mu$ values, a low-energy soft-SUSY-breaking mass of $m_{\tilde{Q}} = m_{\tilde{U}} = m_{\tilde{D}} = 300$ GeV, and soft-SUSY-breaking “$A$” parameters of $A_t = A_b = 50$ GeV. Here, $\tilde{Q}$, $\tilde{U}$ and $\tilde{D}$ are the doublet, up-singlet and down-singlet squark states, respectively. The $m_{\tilde{Q}\tilde{U}\tilde{D}}$ are taken to be the same for all three generations. $A$ parameters for the first two families are taken to be the same as for the third family, but, in any case, have negligible effect. Full “$D$” and “$F$” term mass contributions are included, and mass matrix diagonalization performed.

In both (B) and (C), all allowed decays to ino pairs are incorporated (see Fig. 1 and associated discussion). (Squark pair channels are still above threshold for the $m_{A^0}$ range considered here.) Exact contributions to $\gamma\gamma$ and $gg$ couplings coming from chargino and/or squark loops are included for both decays and production. Work related to that discussed below has appeared in Ref. [49].

Of course, in most GUT scenarios $M_{\tilde{t}}$ would probably not be as large as 1 TeV if the neutralinos and charginos are light. Thus, scenario (B) might be regarded as somewhat adhoc; but, it presents a useful point of comparison. On the other hand, scenario (C) is not unrepresentative of results found in the specific grand unification analyses mentioned earlier. For the choice of $M_{\tilde{t}} \sim 300$ GeV, the radiative corrections to the $h^0$ mass are quite small, and Fig. 2 shows that LEP-II (with $\sqrt{s} = 200$ GeV) could detect at least the $h^0$ of the MSSM. With regard to the SSC, we can crudely anticipate that detection of the $A^0$, $H^0$ and $H^+$ will become more difficult. With this in mind, let us turn to specific results.

Results for scenarios (B) and (C) are presented in Figs. 6 and 7, respectively. The main effect in going from (A) to (B) is obviously the decrease in the $H^0 \rightarrow 4l$ viability region. This occurs due to the smaller size of $BR(H^0 \rightarrow ZZ)$ as depicted in Fig. 1. In going from (B) to (C) the $H^0 \rightarrow 4l$ region almost disappears. This is because $BR(H^0 \rightarrow ZZ)$ has declined further — partly due to the fact that the $H^0$ is less massive for low $m_{A^0}$ values when $M_{\tilde{t}}$ is small, and partly due to the fact that $\cos^2(\beta - \alpha)$ (which determines the $H^0ZZ$ coupling) decreases significantly as the radiative corrections to $\alpha$ decline with decreasing $M_{\tilde{t}}$. (See Refs. [9,10] for relevant graphs.) Meanwhile, the $h^0 \rightarrow t\gamma\gamma$ (and, for good $\gamma\gamma$ resolution, also the $\gamma\gamma$ channel) region remains relatively stable. The exception is the $\tan \beta \sim 1$ region. In going from (B) to (C) the radiative corrections to $m_{h^0}$ decrease to such an extent that for $\tan \beta$ near 1 $m_{h^0}$ falls below the $\sim 80$ GeV lower limit for which these modes are viable. The $t \rightarrow H^+b$ detection mode also remains relatively stable for $\tan \beta \gtrsim 4$ since $M_{\tilde{t}}$ does not greatly influence the $H^+$ mass and the $\tilde{\chi}^+\tilde{\chi}^0$ decay modes do not greatly decrease the $H^+ \rightarrow \tau^+\nu_\tau$ branching ratio. However, for $\tan \beta \lesssim 4$, the $\tau\nu$ decay channel width declines to a level such that the ino-pair modes do become important. Consequently, the maximum $m_{H^+}$ that can be detected in this way decreases significantly, which is reflected in the shift of the $H^+$ discovery contour to smaller $m_{A^0}$ values. Finally, as noted earlier, in going from (B) to (C) the coverage of parameter space by LEP-200
Figure 6: Discovery contours in $m_{A^0}$–$\tan \beta$ parameter space for scenario (B). Notation etc. as for Fig. 4.

becomes almost complete.

Changing $m_t$ does not greatly alter these trends. To illustrate, we present in Figs. 8 and 9 the contours for $m_t = 200$ GeV in scenarios (B) and (C), respectively. Consider first Fig. 8. The region for which $H^0 \rightarrow 4l$ detection is possible expands greatly compared to the corresponding $m_t = 150$ GeV case, Fig. 6, but is still somewhat reduced compared to scenario (A) at $m_t = 200$ GeV, Fig. 5. Compared to scenario (A) at $m_t = 200$ GeV, the $h^0 \rightarrow 4l$ detection region is decreased — keeping $M_{\tilde{t}}$ fixed leaves $m_{h^0}$ and, hence, $h^0 \rightarrow ZZ^*$ phase space unchanged, but ino-pair channels for the $h^0$ become important. Another significant difference between the
$m_t = 150$ GeV and 200 GeV scenario (B) cases arises from the fact that the larger $m_t$ value expands the region of viability for $t \rightarrow H^+ b$, to $m_{A^0} \lesssim 150$ GeV for all tan $\beta$ values. Let us now turn to the scenario (C) case, Fig. 9. Comparing Fig. 9 to Fig. 5, we see that the impact of taking both $M_{\tilde{t}}$ and the ino masses to be small instead of large is quite dramatic. Indeed, Fig. 9 is much more similar to Fig. 7 (the $m_t = 150$ GeV, scenario (C) figure). $h^0$ detection in the $4l$ mode has become impossible because of the much smaller radiative correction addition to $m_{h^0}$ when $M_{\tilde{t}}$ is small. $H^0 \rightarrow 4l$ has become impossible for most of parameter space, for exactly the same reasons outlined for $m_t = 150$ GeV. The $l\gamma\gamma$ (and $\gamma\gamma$) mode for the $h^0$ remains viable for $m_{A^0} \gtrsim 150$ GeV, except for tan $\beta \sim 1$. 
A particularly important point to note is the following: regardless of $m_t$, the SSC will have difficulty detecting the $H^0$ (and $A^0$) neutral MSSM Higgs bosons over most of parameter space if all SUSY mass scales are small, unless the neutralino-chargino-pair decay modes can be isolated from backgrounds. The authors of Ref. [49] have performed a first examination of such ino-pair modes and conclude that they could provide viable signals in rather limited regions of parameter space. But, even in these hopeful regions, the backgrounds are significant, especially those coming from continuum ino-pair production processes. To fully assess the possibilities, detailed detector-simulation studies of the ino-pair modes are needed.

5.5. The No-Lose Theorem and Overview
The above remarks and figures can be summarized by saying that the combination of LEP-II (with $\sqrt{s} = 200$ GeV, $L = 500$ pb$^{-1}$) and the SSC (with $L = 30$ fb$^{-1}$) comes close to providing a no-lose theorem: at least one of the MSSM Higgs bosons will be discovered in one of the very robust modes discussed at one or the other machine for any choice of the basic parameters $m_t$, $m_A$, and $\tan \beta$. In order for the coverage of the various detection channels to be sufficiently complete that one is equally close to a no-lose theorem at the LHC, the full enhanced luminosity of $L = 100$ fb$^{-1}$ will be required.

In scenario (A), with large SUSY masses, we have seen that LEP-II and the SSC are highly complementary at moderate $m_t \sim 150$ GeV. In contrast, at small $m_t$
LEP-II plays the major role, while at large $m_t$ LEP-II covers only a small fraction of parameter space whereas the SSC covers all of parameter space. Of course, if $m_t = 150$ GeV, the no-lose theorem is not actually quite complete for large $M_T$ values. Without considering additional channels, there is a gap for $m_{A^0} \sim 125$ to 160 GeV and $\tan \beta \gtrsim 10$ for which neither LEP-II nor the SSC can detect any of the MSSM Higgs bosons. A decrease in the LEP-II machine energy to a $\sqrt{s}$ value significantly below 200 GeV would increase the size of this gap. (This gap may be covered, at least in part, by other SSC discovery channels that we shall discuss below.)

The other natural extreme is that in which SUSY mass scales are all modest in size, scenario (C). We have seen that, regardless of the value of $m_t$, LEP-II will play the most crucial role. Low $M_T$ implies that radiative corrections to $m_{h^0}$ become small implying that LEP-II will be able to detect the $Z h^0$ process throughout much of parameter space. The SSC will provide complementary information on $h^0 \to \gamma\gamma$ for $m_{A^0} \gtrsim 150$ GeV. In addition, the SSC will always be able to detect $t \to H^+ b$ decays, if kinematically allowed. However, at the SSC detection of the $H^0$ (or $A^0$) in the $4l, \gamma\gamma$ or $l\gamma\gamma$ modes or of $h^0 \to 4l$ events will not be possible in most of parameter space. As already noted, scenario (C) is not atypical of that arising in a GUT study of the MSSM. Indeed, a typical GUT result predicts not only that the squark andino masses are modest in size, but also yields moderately large values for $m_{A^0}$ and $\tan \beta$. Typically, these latter parameters fall in the range $200 - 400$ GeV and $5 - 30$, respectively. As already noted, at the SSC only $h^0$ detection in the $l\gamma\gamma$ (and/or $\gamma\gamma$) mode will be viable for such parameter choices.

5.6. Alternative Detection Modes: A Brief Note

While the production/detection modes considered above potentially provide the cleanest signals for the MSSM Higgs bosons, there are a variety of other modes that clearly deserve consideration. Those with substantial promise in the case where neutralino/chargino pair decays are forbidden were reviewed in Ref. [7]. Full evaluation of the viability of all the modes will require detailed Monte Carlo assessment of mixed electroweak/QCD backgrounds. However, there is clear hope that the signatures discussed will provide at least weak signals at the SSC for the neutral Higgs bosons over important regions of parameter space. In particular, $H^0$ and $A^0$ detection in the $\tau^+\tau^-$ decay channel seems likely to be practicable at high enough $\tan \beta$ ($\gtrsim 15$?) in the moderate $m_{A^0}$ domain where the no-lose theorem as outlined earlier is incomplete. This is due to the large enhancement of the $gg \to H^0, A^0 + b\bar{b}$ cross sections at large $\tan \beta$.

6. A Back-Scattered Laser Beam Facility at the NLC

So far, we have seen that LEP-II, an NLC with $\sqrt{s} \sim 500$ GeV, and the SSC/LHC hadron colliders are guaranteed to detect at least the $h^0$ throughout all of parameter space. However, detection possibilities for the $H^0, A^0$ and $H^\pm$ are likely
to be very limited at the hadron colliders and even the NLC only has a guaranteed reach in mass to about $0.4\sqrt{s}$. The latter is restricted primarily by virtue of the fact that for large $m_{A^0}$ the only high rate reactions are $H^0 A^0$ and $H^+ H^-$ pair production. An extremely interesting possibility for extending the $m_{A^0}$ and $m_{H^0}$ mass reach of a high-luminosity NLC is to use collisions of two photons produced by back-scattering laser beams off of the incoming $e^+$ and $e^-$ beams at the NLC.\textsuperscript{[50,51]} Because the $A^0$ and $H^0$ would be produced singly, the kinematical limit placed on detectable $m_{A^0}, m_{H^0}$ values is of order $\sqrt{s}$. We shall see that there is a good possibility that in practice one can probe masses as high as $0.8\sqrt{s}$. In addition, production of the $h^0, A^0$, and $H^0$ in this way automatically provides a measure of their $\gamma\gamma$ couplings — couplings of great interest as a probe of new physics in the loop graphs from which they arise.

Detection of the SM Higgs boson and of the neutral Higgs bosons of the MSSM using back-scattered laser beam photons was first studied in Ref. \textsuperscript{[52]}. Monte Carlo results for a SM Higgs boson have appeared in Ref. \textsuperscript{[53]}. Here, we shall be summarizing the results of Ref. \textsuperscript{[52]}.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure11.png}
\caption{We plot rates for $\gamma\gamma \rightarrow A^0 \rightarrow Q\overline{Q}$ compared to the $\gamma\gamma \rightarrow Q\overline{Q}$ background ($Q = b$ or $t$) with the same conventions as for Fig. 10. The exotic $A^0 \rightarrow Zh^0$ decay mode event rate (computed with $\Gamma_{\text{res}} = \infty$) is also shown.}
\end{figure}
Figure 10: We plot rates for $\gamma\gamma \rightarrow H^0 \rightarrow Q\overline{Q}$ compared to the $\gamma\gamma \rightarrow Q\overline{Q}$ background ($Q = b$ or $t$) for $\gamma\gamma$ collisions produced by back-scattered laser beams at a linear $e^+e^-$ collider. We have required an angular cutoff of $z = \cos\theta < 0.5$ on the outgoing $Q$'s in the center of mass frame. An effective (see text) photon-photon luminosity of $L_{\text{eff}} = 20$ fb$^{-1}$ has been employed and it is assumed that mass resolution in the $Q\overline{Q}$ channel will be $\Gamma_{\text{exp}} \sim 5$ GeV. Finally, for incoming electrons and laser beams such that $2\lambda_e\lambda_\gamma \sim 1$ we have used the estimate of $\langle \lambda\lambda' \rangle \sim 0.8$, obtained after convolution over the two back-scattered photons, 1 and 2. The relatively background free $H^0 \rightarrow h^0h^0$ and $H^0 \rightarrow ZZ$ decay mode event rates (computed with $\Gamma_{\text{res}} = \infty$) are also shown (no $ZZ$ decay branching fraction included). It should be noted that in the region $165 < m_{h^0} < 220$ GeV, the decay $H^0 \rightarrow h^0h^0$ is kinematically forbidden for the MSSM parameters chosen. Supersymmetric partners are assumed to be sufficiently heavy that they do not influence the $H^0\gamma\gamma$ coupling or $H^0$ decays. Radiative corrections to the MSSM Higgs sector are incorporated with $M_{\text{SUSY}} = 1$ TeV and squark mixing neglected. Results for $m_t = 150$ GeV and $m_t = 200$ GeV are displayed for both $\tan\beta = 2$ and $\tan\beta = 20$.

The number of Higgs ($h$, $h = h^0$, $A^0$ or $H^0$) events in a given channel $X$ is given by
Figure 12: We plot rates for $\gamma\gamma \rightarrow h^0 \rightarrow b\bar{b}$ compared to the $\gamma\gamma \rightarrow b\bar{b}$ background for the same conditions as specified in Fig. 10.

$$N(\gamma\gamma \rightarrow h \rightarrow X) = \frac{8\pi BR(h \rightarrow X)}{E_{e^+e^-}m_h^2} \tan^{-1} \frac{\Gamma_{\text{res}}}{\Gamma_h} \Gamma(h \rightarrow \gamma\gamma) \times F(y_h)(1 + \langle \lambda\lambda' \rangle_{y_h})L_{e^+e^-},$$

(3)

where $y_h \equiv m_h/E_{e^+e^-}$. In Eq. (3), $F(y)$ is defined in terms of the differential $\gamma\gamma$ luminosity as $F(y) \equiv L_{e^+e^-}^{-1}(dL_{\gamma\gamma}/dy)$, and $\Gamma_{\text{res}} \equiv \max\{\Gamma_{\text{exp}}, \Gamma_h\}$; $\langle \lambda\lambda' \rangle_{y_h}$ is the average product of the polarizations of the colliding photons evaluated at $y_h$. For $Q\bar{Q}$ channels $\Gamma_{\text{exp}}$ is taken to be the mass resolution that can be achieved. Since both the $A^0$ and $H^0$ are generally narrower than a few GeV in the MSSM, optimal signal to background ratio is achieved by taking $\Gamma_{\text{exp}}$ as small as possible. We shall employ a relatively optimistic value of $\Gamma_{\text{exp}} \simeq 5$ GeV. In the limit where $\Gamma_{\text{exp}} \gg \Gamma_h$ the inverse tangent approaches $\pi/2$, and $N$ is independent of $\Gamma_{\text{res}}$. In channels $X$ that are free of background, $\Gamma_{\text{res}} = \infty$ is employed, which also results in replacing the inverse tangent by $\pi/2$.

For the MSSM Higgs bosons a variety of channels are important: these include $X = Q\bar{Q}$ for all the neutral Higgs bosons; $X = h^0h^0$ and, possibly, $X = ZZ$ for the
$H^0$; and $X = Zh^0$ for the $A^0$. (Recall that $VV$ decays are absent at tree-level for the $A^0$.) The analysis performed to date also assumes that two-body decays to supersymmetric particle pair channels are absent, i.e. that neutralinos and charginos are heavier than about half the Higgs boson mass. Studies\cite{50,51,53} of $F(y)$, as obtained by convoluting the spectra of the colliding back-scattered photons, indicate that $F \sim 1 - 2$ is not atypical. In detail, both $F(y)$ and $\langle \lambda \lambda' \rangle$ depend on the helicity of the incoming electron $\lambda_e$ and the polarization of the laser beam $\lambda_\gamma$ with which it collides, and on the corresponding parameters for the positron beam. If the incoming electron and associated laser beam are polarized so that $2\lambda_e - \lambda_\gamma \sim 1$ (and similarly for the positron and its associated laser beam) then values of $\langle \lambda \lambda' \rangle \approx 0.8$ can be achieved for a substantial range of $y_h$ values corresponding to $m_h$ below about 70% of $E_{e^+e^-}$. For $m_h$ values above this it is best to use $2\lambda_e \lambda_\gamma \sim -1$ so that $F(y)$ peaks for $m_h$ near $E_{e^+e^-}$. In this case, for $m_h$ in the vicinity of $E_{e^+e^-}$ one finds that $\langle \lambda \lambda' \rangle_{y_h}$ can again be large, but is rapidly varying and could also be small.

The background event rate for a $Q\overline{Q}$ final state is given by

$$N(\gamma\gamma \to Q\overline{Q}) = \frac{\Gamma_{\text{res}}}{E_{e^+e^-}} F(y_h) \mathcal{L}_{e^+e^-} \sigma_{Q\overline{Q}}(m_h^2, z_0). \quad (4)$$

In Eq. (4)

$$\sigma_{Q\overline{Q}}(s, z_0) = \frac{4\pi\alpha^2 e_Q^4 N_c}{s} \left\{ -\beta z_0 \left[ 1 + \frac{(1 - \beta^2)^2}{(1 - \beta^2 z_0^2)} \right] + \frac{1}{2} \left[ 3 - \beta^4 \right] \log \frac{1 + \beta z_0}{1 - \beta z_0} \right. \right.$$  

$$\left. + \lambda \lambda' \beta z_0 \left[ 1 + \frac{2(1 - \beta^2)}{1 - \beta^2 z_0^2} - \frac{1}{\beta z_0} \log \frac{1 + \beta z_0}{1 - \beta z_0} \right] \right\}. \quad (5)$$

where $\beta = \sqrt{1 - 4m_Q^2/m_h^2}$ and $z_0$ is the angular cutoff ($|\cos\theta_Q| \leq z_0$) on the $Q$ direction in the $\gamma\gamma$ center of mass. There are two important observations regarding $\sigma_{Q\overline{Q}}$. First, it is greatly suppressed by an angular cutoff of order $z_0 = 0.85$, especially for $m_h \gg 2m_Q$. (In contrast, the Higgs signal is isotropic.) Second, it is easily seen that $\sigma_{Q\overline{Q}} \propto [\lambda \lambda' - 1]$ if $\beta \approx 1$. Thus, for large $E_{e^+e^-}$ we can severely suppress the $b\overline{b}$ background in the region $m_h < 2m_t$ by polarizing the incoming electron and laser beams to achieve large $\langle \lambda \lambda' \rangle_{y_h}$. Once $m_h > 2m_t$ we must focus on the $t\overline{t}$ channel for which both techniques are somewhat less effective, but still of importance.

* Gluon radiation can allow the $Q\overline{Q}$ background to evade the $[\lambda \lambda' - 1]$ suppression factor if the gluon is hard and not collinear with either of the $Q$’s. However, an experimental limitation on such radiation can in principle preserve the background suppression.\cite{54}
In assessing backgrounds to the $h^0h^0$ and $Zh^0$ channels, we assume that the $h^0$ will already have been discovered and its mass fairly precisely determined. Its primary decay will be to $b\bar{b}$. Thus, it will be easy to eliminate backgrounds to these channels by tagging at least two $b$ quarks that reconstruct to the mass of the $h^0$ and requiring that the remaining jets reconstruct to the mass of the $h^0$ in the case of the $h^0h^0$ channel or to the mass of the $Z$ in the case of the $Zh^0$ channel (lepton pairs or large missing energy with appropriate Jacobian peak location can also be included in the latter case). Since $b$ tagging will be possible at the NLC with quite high efficiency and purity, we estimate that this procedure should have an overall efficiency of 20-30%. With regard to the $ZZ$ channel, there is no direct irreducible background from continuum $ZZ$ production (at tree-level), but continuum $W^+W^-$ production has a very large cross section. The ability to separate a $ZZ$ signal in a four-jet channel will depend upon the precise mass resolution that can be achieved in reconstructing two jets. To be conservative, one can require that one of the $Z$’s decay to $l^+l^- (l = e, \mu)$; summing over all possibilities for the second $Z$ yields a net effective branching ratio for such channels of $\sim 0.134$. The $W^+W^-$, and other smaller reducible backgrounds will then be effectively eliminated by requiring events with an $l^+l^-$ pair with mass near $m_Z$ and, on the opposite side, two jets or two leptons with mass near $m_Z$ or else large missing energy (with appropriate Jacobian peak location).

Our results are presented in Figs. 10, 11, and 12, for the $H^0$, $A^0$ and $h^0$, respectively. Event rates in a variety of channels are exhibited for $\tan \beta = 2$ and $\tan \beta = 20$ for both $m_t = 150$ GeV and $m_t = 200$ GeV. We have used a uniform value of $L_{eff} \equiv F(y_h)L_{e^+e^-} = 20$ fb$^{-1}$ in computing event rates and have taken $\langle \lambda\lambda' \rangle = 0.8$. Radiative corrections have been included in the computations of $\gamma\gamma$ couplings and $Q\bar{Q}$ decays using $M_t = 1$ TeV. The $z_0 = 0.85$ angular cut has been included in computing $Q\bar{Q}$ channel signal and background rates. Branching ratios and efficiencies for isolating the $h^0h^0$, $ZZ$, and $Zh^0$ final states have not been included. We briefly summarize the conclusions that can be drawn.

We first discuss results obtained for $m_t = 150$ GeV and $\tan \beta = 2$. Focusing on the $H^0$, we see that if most of the $ZZ$ decay events could be employed without introducing backgrounds, then there is a region where this mode would be preferred over the $b\bar{b}$ mode which has a large irreducible background. However, it is also clear that the best means for detecting the $H^0$ when $m_H < 2m_t$ is in $H^0 \rightarrow h^0h^0$ decays. The event rate is quite large (even above $2m_t$) and, as discussed earlier, the backgrounds are small. Above $t\bar{t}$ threshold, $BR(H^0 \rightarrow t\bar{t})$ is close to 1, due to the suppressed couplings of the $H^0$ to other channels. Detection of the $H^0$ in its $t\bar{t}$ decay mode from $2m_t$ up to about 500 GeV should prove feasible.

In the case of the $A^0$, we see that the $b\bar{b}$ mode provides a viable signal for $120$ GeV $\lesssim m_{A^0} \lesssim 2m_t$. However, once the background-free $Zh^0$ mode becomes significant ($m_{A^0} \gtrsim 190$ GeV for $m_t = 150$ GeV) it provides almost as large an absolute event rate and might prove to be the preferable mode for detection. In any case, there is certainly a significant range of $m_{A^0} < 2m_t$ for which $A^0$ detection should
be possible in both the $b\bar{b}$ and the $Zh^0$ final states, thereby allowing one to confirm a signal for the $A^0$ seen in one channel by examining the alternative channel. For $m_{A^0} > 2m_t$, Fig. 11 makes it clear that the $A^0$ should be easily detectable in its $t\bar{t}$ decay mode.

Results for the $h^0$ are easily summarized. Since the $h^0$ never becomes very heavy, only the $b\bar{b}$ final state is relevant. The $h^0$ will be detectable in this mode for $m_{h^0} \gtrsim 60$ GeV. This corresponds to the parameter space region $m_{A^0} \gtrsim 70$ GeV. In fact, once $m_{A^0} \gtrsim 2m_Z$ the couplings of the $h^0$ approach their Standard Model values, and our ability to detect the $h^0$ will be exactly the same as our ability to find the $\phi^0$ at $m_{\phi^0} \simeq m_{h^0}$.

Let us now contrast the results obtained at $m_t = 150$ GeV for the MSSM Higgs bosons in the case of $\tan\beta = 2$ with those for the much larger value of $\tan\beta = 20$. Plots corresponding to the ones given at $\tan\beta = 2$ are presented in the second window of Figs. 10-12. As noted earlier, only the $b\bar{b}$ channel is relevant since this is the dominant decay mode for both the $H^0$ and $A^0$ for all but small $m_{A^0}$ values (already ruled out by LEP). In the case of the $H^0$, we see that detection in the $b\bar{b}$ channel should be possible for $m_{H^0} \lesssim 350$ GeV, except possibly in the region of $m_{H^0} \sim 2m_W$. For $m_{H^0}$ above 350 GeV, the $b\bar{b}$ event rate is not much smaller than the $\gamma\gamma \rightarrow b\bar{b}$ background, but the absolute event rate is simply not adequate. However, with four times the luminosity assumed, detection of the $H^0$ would be possible all the way out to $m_{H^0} \sim 400 - 500$ GeV. In the case of the $A^0$, detection in the $b\bar{b}$ mode should be possible from the lowest masses out to $m_{A^0} \lesssim 250$ GeV at which point $\Gamma(A^0 \rightarrow \gamma\gamma)$ has a large dip (leading to a large dip in event rate) due to cancellation between the $b$ and $t$ loop contributions to the $\gamma\gamma$ coupling of the $A^0$. For $m_{A^0} \gtrsim 350$ GeV, detection of the $A^0$ would again become possible if the luminosity were four-fold enhanced. Prospects for $h^0$ detection for $\tan\beta = 20$ are very good for all values of $m_{A^0}$. For the lowest $m_{h^0}$ masses (corresponding to small $m_{A^0}$), the $b\bar{b}$ background is of order $10^4$ events, but the $h^0 \rightarrow b\bar{b}$ signal yields about $10^3$ events, and is therefore easily observable. (This result presumes that the experimental resolution of $\sim 5$ GeV we have employed can be achieved.) The enhancement of the $h^0$ cross section at small $m_{h^0}$ when $\tan\beta$ is large, compared to values obtained for small $\tan\beta$, is due to the fact that large $\tan\beta$ implies an enhanced $h^0b\bar{b}$ coupling. This, in turn, leads to an enhanced magnitude of the $b$-loop contribution to the $\gamma\gamma$ coupling of the $h^0$. For the largest values of $m_{h^0}$ (corresponding to large $\tan\beta$ and large $m_{A^0}$), $m_{h^0}$ approaches 108 GeV. The signal, of order 500 events, is easily detectable above the smaller background, of order 80 events.

The detectability of the MSSM Higgs bosons is not greatly altered if $m_t = 200$ GeV instead of 150 GeV. Results for this choice of $m_t$ are presented in the third and fourth windows of Figs. 10-12. The results are summarized simply as follows. For the $H^0$, detection should be possible in two final state modes for nearly all values of $m_{H^0}$ for $\tan\beta = 2$. At large $\tan\beta = 20$, the $b\bar{b}$ final state is the only relevant one. The signal is never much lower than the background and detectability simply depends on
the number of accumulated events. For the $A^0$, detection is possible in at least one, and sometimes two, final state mode(s) for all $A^0$ masses considered, for tan $\beta = 2$. Detectability of the $A^0$ when tan $\beta = 20$ is much more limited; a sufficient number of signal events in the $b\bar{b}$ final state is only obtained for $m_{A^0} \lesssim 200$ GeV. Detecting the $h^0$ when $m_t = 200$ GeV should be quite straightforward for both moderate and large values of tan $\beta$.

Thus, the prospects for MSSM Higgs boson detection at a future $e^+e^-$ linear collider (with center of mass energy $E_{e^+e^-} = 500$ GeV) operating in a $\gamma\gamma$ collider mode are promising. Indeed, the $\gamma\gamma$ collider mode at the NLC proves to be an enormously powerful tool. For moderate tan $\beta$, detection of the $H^0$ and $A^0$ will be possible for all masses up to about $0.8\sqrt{s}$, i.e. roughly the $\gamma\gamma$ collider kinematical limit, and often in more than one final state mode. This represents a significant increase in Higgs mass reach as compared to a Higgs mass mass limit of roughly $0.4\sqrt{s}$ obtained by using the NLC in its conventional mode to search for $e^+e^- \rightarrow H^0 A^0$. In the case of the lighter CP-even Higgs scalar, detection of the $h^0$ will be possible for $m_{h^0} \gtrsim 60$ GeV. The ease of detection increases with increasing $m_t$. For large tan $\beta$, $h^0$ detection becomes possible for all $m_{h^0}$ values, but $H^0$ and $A^0$ detection would be confined to a low mass range (no larger than $200 - 300$ GeV, depending upon which Higgs is considered and the value of $m_t$). A four-fold increase in $\gamma\gamma$ luminosity beyond that assumed in this paper would allow $H^0$ detection for all masses up to the $E_{\gamma\gamma}$ kinematic limit when tan $\beta$ is large.

In reaching these optimistic conclusions, the ability to achieve substantial polarization for the colliding photon beams has been assumed. In Ref. [52], we have illustrated the fact that the mass ranges for which the MSSM Higgs bosons can be detected deteriorate significantly as the degree of polarization decreases, especially in the $b\bar{b}$ and $t\bar{t}$ channels. Every effort should be made to achieve as high a degree of polarization for the colliding photons as possible.

In our analysis, we have also assumed that the supersymmetric mass scale is sufficiently large that the Higgs bosons do not decay to superparticle final states and charged superpartners do not significantly contribute to the one-loop $\gamma\gamma$ coupling of the Higgs bosons. Should the supersymmetric mass scale be modest in size, then the phenomenology of the model in $\gamma\gamma$ collisions would be altered. In particular, once neutralino-chargino decays of the Higgs bosons are allowed, they generally dominate. However, we do not anticipate that it will be significantly more difficult to detect the Higgs bosons in such modes in $\gamma\gamma$ collisions. Indeed, the neutralino-pair channels will have no tree-level irreducible background, although one will have to deal with backgrounds from chargino-pair events which can be produced in continuum $\gamma\gamma$ collisions. However, the chargino-pair backgrounds should be no worse than the $Q\bar{Q}$ backgrounds discussed earlier. Neutralino and chargino pair events should be distinguishable from SM-particle final states by large missing energy. An investigation of these issues is presently in progress.

Probing the MSSM Higgs sector using back-scattered laser beams has one
other potential advantage. Using polarized electron and laser beams, various 
polarization asymmetries can be defined that could allow an experimental determination 
of the CP properties of any Higgs boson detected in $\gamma\gamma$ collisions. The most easily 
measured asymmetry is isolated by circularly polarizing the incoming laser beams. 
This asymmetry is only non-zero if the produced Higgs boson is a mixture of CP 
eigenstates. As noted earlier, there is no CP violation in the Higgs sector of the 
MSSM, which therefore predicts a null result. Another asymmetry can be defined using 
linear polarization for the initial laser beams; this latter asymmetry would be $+1$ 
for production of the CP-even $H^0$ and $-1$ in the case of $A^0$ production. Measurement 
of a value smaller than unity in absolute value would contradict the MSSM. Unfortu-
ately, an experimental determination of this asymmetry would require a somewhat 
larger number of events than obtained for $L_{eff} = 20 \text{ fb}^{-1}$ (due to the difficulty of 
achieving large average linear polarizations for the back-scattered photons). However, 
such a study would clearly become of prime importance once a Higgs boson (or two) 
is detected via back-scattered laser beams.

To summarize, there are three very important motivations for an intense ef-
fort towards developing a back-scattered laser beam facility at the NLC that has the 
capability for substantial polarizations of the colliding photons. First, such a facility 
provides the only viable means for measuring the crucial $\gamma\gamma$ Higgs coupling(s). Sec-
ond, $\gamma\gamma$ collisions can greatly extend the kinematic reach in detectable Higgs boson 
mass that can be achieved. Thirdly, (polarized) $\gamma\gamma$ collisions provide a beautifully 
clean technique for determining the CP properties of any Higgs boson that is observed.

7. Final Remarks

It is clear that LEP-II and the SSC combine to nearly guarantee that at least 
one of the Higgs bosons of the MSSM will be discovered at one or the other machine. 
If $m_t \gtrsim 140 \text{ GeV}$ (as preferred in current electroweak analyses at LEP) and $M_\tilde{t}$ is 
of order 1 TeV, the SSC will play an important role, allowing discovery of one or 
more of the MSSM Higgs over much, if not all, of the basic $m_{A^0}\tan\beta$ parameter 
space not covered by LEP-II. Perhaps most importantly, if LEP-II discovers the light 
scalar Higgs, the SSC will have a substantial chance of finding the heavy scalar, the 
pseudoscalar, and/or the charged Higgs boson. As the supersymmetric mass scales 
are decreased, charginos/neutralinos are more likely to appear in the decays of the 
$A^0$, $H^0$ and $H^+$ and their non-supersymmetric-particle SSC/LHC signals would be 
significantly weakened. Further study is required to firmly establish whether Higgs 
detection in the chargino/neutralino modes would be feasible in such a case, but 
preliminary studies allow for some optimism. Of course, as the supersymmetric mass 
scale decreases, radiative corrections to $m_h^0$ would be relatively smaller, and the 
probability of discovering the $h^0$ at LEP-II is substantially increased. In general, for 
a light top quark and/or light squarks, LEP-II will play the most important role, and 
sensitivity of the SSC to the MSSM Higgs bosons could be small. For this reason it 
is critical that the energy achieved by LEP-II be maximized.
Of course, we have also seen that a sufficiently energetic linear $e^+e^-$ collider with adequate luminosity would provide a fairly ideal machine for the detection of the MSSM Higgs bosons. Operating in the conventional $e^+e^-$ collision mode, detection of the $h^0$ would be certain and the $A^0$, $H^0$ and $H^+$ could be discovered for masses up to $m_{A^0} \sim m_{H^0} \sim m_{H^+} \sim 0.4\sqrt{s}$.

However, there seems to be a significant possibility that only the $h^0$ would be observed with the combination of an NLC and the SSC/LHC. Indeed, GUT scenarios suggest that SUSY mass scales (in particular $M_T$ and the ino masses) are not very large, but that $m_{A^0} \sim m_{H^0} \sim m_{H^+} \gtrsim 200$ GeV. In this case, discovery of the $A^0$, $H^0$, and $H^+$ at SSC/LHC could prove quite difficult, while the conventional $e^+e^- \rightarrow A^0H^0$ and $e^+e^- \rightarrow H^+H^-$ pair production processes would be either very close to or beyond the kinematic limit of a $\sqrt{s} = 500$ GeV NLC and could not be used to probe masses much beyond $\sim 0.4\sqrt{s} = 200$ GeV. Only a back-scattered laser beam facility at the NLC provides a clear-cut possibility of probing the higher $A^0, H^0, H^+$ masses found in many GUT scenarios. With good polarization for the colliding photon beams, $A^0$ and $H^0$ masses up to $\sim 0.8\sqrt{s}$ can be probed for moderate $\tan\beta$ at easily achieved effective $\gamma\gamma$ luminosities. (Full coverage of this mass range for large $\tan\beta$ requires about four times as much luminosity.) The roughly 400 GeV upper mass reach that could be achieved encompasses many of the GUT scenario predictions for $A^0$ and $H^0$ masses.

Overall, the various accelerators of the next decade will almost certainly unlock the secrets of a supersymmetric electroweak symmetry breaking sector, providing many possibilities for relatively detailed verification of its features. In conjunction with the probable discovery of supersymmetric partners, such as the gluino and squark, detailed consistency checks of the predictions (including radiative corrections) for masses and couplings of the Higgs bosons will become possible.

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