Collider discovery limits for supersymmetric Higgs bosons

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ABSTRACT

The prospects for discovery of the five Higgs bosons of the minimal supersymmetric standard model are assessed for existing and planned future colliders, including LEP I, LEP II, LHC and SSC. As a benchmark for comparisons, we take a top-quark mass $m_t = 150 \text{ GeV}$ and squark mass parameter $\tilde{m} = 1 \text{ TeV}$ in evaluating one-loop radiative corrections; some results for other $m_t$ values are also given. Searches based on the most promising production and decay channels are taken into account. For large regions in parameter space, detectable signals are predicted for one or more of the Higgs bosons, but there remains a region for which no signals would be visible at the above colliders.
I. INTRODUCTION

The nature of the electroweak symmetry-breaking (EWSB) sector is the outstanding unresolved issue of contemporary particle physics. The Standard Model (SM) mechanism with a single scalar doublet and one physical Higgs boson has been subject to extensive experimental and phenomenological scrutiny [1]. Experiments at LEP I [2,3,4,5] exclude a SM Higgs boson ($H_{SM}$) with mass $m(H_{SM}) < 57$ GeV [6] and future measurements at LEP II are expected to explore the range $m(H_{SM}) \lesssim 80$ GeV [7]. A higher-mass SM Higgs boson will be detectable [8] at the $pp$ supercolliders LHC (15.4 TeV) and SSC (40 TeV). For intermediate masses between 80 GeV and $2M_W$, searches can utilize the $H_{SM} \to \gamma\gamma$ and $H_{SM} \to ZZ^* \to 4\ell$ decay channels, with high-resolution photon and lepton detection. Above the $H \to ZZ, WW$ thresholds, the purely leptonic decays $Z \to \ell^+\ell^-$, $\nu\bar{\nu}$ and $W \to \ell\nu$ give reasonable signatures up to masses of order 0.8–1.0 TeV, where some other EWSB mechanism must take effect to preserve unitarity. Thus the SM Higgs boson is detectable throughout the range of its relevance.

The minimal supersymmetric extension [1] of the Standard Model (MSSM), which solves the problem of large radiative corrections to the EWSB Higgs boson associated with the grand unified scale, has a richer Higgs boson spectrum with five physical states $h, H, A, H^\pm$. Recently it has been shown that one-loop radiative corrections can produce important shifts in both masses and couplings of these MSSM Higgs bosons, provided that the top quark is heavy ($m_t \sim 150$ GeV) and the squark masses are somewhat heavier [9]. Increased phenomenological attention is now focussed on the discovery potential for these scalar states at present and possible future colliders. [10,11,12,13,14,15,16,17,18,19]

The purpose of the present paper is to discuss systematically the potential of different colliders to discover these MSSM Higgs bosons, using the most promising production and decay channels, but restricting consideration to the presently existing or planned colliders LEP I, LEP II, LHC and SSC. As a benchmark for comparison, we take a top-quark mass $m_t = 150$ GeV and a common supersymmetry (SUSY) mass scale $\tilde{m} = 1$ TeV, following
the analysis of Ref. [14]; some results for $m_t = 100, 120$ and $200 \text{ GeV}$ will be compared. Following renormalization-group arguments for no-scale models (e.g. Ref. [18]) we consider the ratio of vacuum expectation values $\tan \beta = v_2/v_1$ to be in the range $1 \lesssim \tan \beta \lesssim m_t/m_b$.

In subsequent Sections, we first describe the MSSM parameters and then consider searches at each collider in turn. Discovery criteria are necessarily approximate, since they depend on assumptions about future detector performance and achievable luminosity, so the conclusions that can be reached are tentative; in this sense our present analysis should therefore be viewed as indicative rather than definitive.

II. HIGGS SECTOR OF THE MSSM

At tree level, the masses of the five Higgs bosons in the MSSM are determined by two parameters, conveniently chosen to be $m_A$ and $\tan \beta$, where $m_A$ is the mass of the CP-odd neutral boson and $\tan \beta = v_2/v_1$ is the ratio of the vacuum expectation values that give masses to up-quarks ($v_2$) and down-quarks ($v_1$). When one-loop radiative corrections are included, a number of additional mass parameters enter through the loops. It is still convenient to take $m_A$ and $\tan \beta$ (evaluated at one-loop order) as independent parameters together with the top-quark mass $m_t$, and squark-sector mass parameters: the latter are the soft SUSY-breaking squark masses $m_Q$, $m_U$, $m_D$, the coefficient $\mu$ of the $H_1 H_2$ mixing term in the superpotential, and the coefficients $A_t$ and $A_b$ of trilinear $\tilde{t}_L \tilde{t}_R H_2$ and $\tilde{b}_L \tilde{b}_R H_1$ soft SUSY-breaking terms (in the notation of Refs. [10,14]). In our later quantitative analysis we choose a common SUSY mass scale

$$m_Q = m_U = m_D = \tilde{m} = 1 \text{ TeV}$$

(1a)

and set

$$A_t = A_b = 2\mu = \tilde{m}/2$$

(1b)

such that squark mixing effects are present but not overwhelming, following Ref. [14]. As previously indicated, we also generally choose the top quark mass to be
\[ m_t = 150 \text{ GeV} \, . \] (1c)

The qualitative features of the one-loop corrections to the Higgs boson masses can, however, be explored in terms of \( m_t \) and a common squark mass scale \( \tilde{m} \), neglecting the smaller effects from \( A_t, A_b, \mu \) and the \( b \)-quark mass \( m_b \). In this approximation the mass-squared matrix for the neutral CP-even neutral Higgs bosons is

\[
\begin{pmatrix}
    m_A^2 \sin^2 \beta + M_Z^2 \cos^2 \beta & -(m_A^2 + M_Z^2) \sin \beta \cos \beta \\
    -(m_A^2 + M_Z^2) \sin \beta \cos \beta & m_A^2 \cos^2 \beta + M_Z^2 \sin^2 \beta + \epsilon / \sin^2 \beta
\end{pmatrix}, \tag{2}
\]

where the modification due to radiative corrections is given by

\[
\epsilon = \frac{3g^2}{8\pi^2 M_W^2} m_t^4 \ln \left( 1 + \frac{\tilde{m}^2}{m_t^2} \right), \tag{3}
\]

with \( g \) the SU(2) electroweak gauge coupling. Here the corrections are controlled by a single parameter \( \epsilon \); thus a change in \( \tilde{m} \) has the same effect as a much smaller change in \( m_t \).

Diagonalization leads to the masses

\[
m_{h,H}^2 = \frac{1}{2} \left[ m_A^2 + M_Z^2 + \epsilon / \sin^2 \beta \right] \pm \frac{1}{2} \left\{ \left[ (m_A^2 - M_Z^2) \cos 2\beta + \epsilon / \sin^2 \beta \right]^2 + (m_A^2 + M_Z^2)^2 \sin^2 2\beta \right\}^{1/2}. \tag{4}
\]

For \( \tan \beta \geq 1 \) these mass eigenvalues increase monotonically with \( m_A \); the upper bound on the mass of the lighter scalar boson \( h \) is

\[
m_h^2 < M_Z^2 \cos^2 2\beta + \epsilon \, , \tag{5}
\]

\[
< M_Z^2 + \epsilon \, .
\]

For \( m_t = 150 \text{ GeV} \) and \( \tilde{m} = 1 \text{ TeV} \), this gives \( m_h < 115 \text{ GeV} \). There is a corresponding lower bound on the heavier mass \( m_H \),

\[
m_H^2 > \frac{1}{2} \left[ M_Z^2 + \epsilon / \sin^2 \beta \right] + \frac{1}{2} \left[ (M_Z^2 - \epsilon / \sin^2 \beta)^2 + 4M_Z^2 \epsilon \right]^{1/2} \, , \tag{6}
\]

\[
> M_Z^2 + \epsilon \, .
\]

We note that the bounds are more stringent when \( \tan \beta \) is specified.
The mixing angle $\alpha$ in the CP-even sector, determined from the diagonalization of the above mass-squared matrix, is
\[
\tan 2\alpha = \frac{(m_A^2 + M_Z^2) \sin 2\beta}{(m_A^2 - M_Z^2) \cos 2\beta + \epsilon / \sin^2 \beta}.
\] (7)

The one-loop corrections to the masses and mixing angle can be large if $\tilde{m}$ is well above $m_t$ and $m_t$ is well above $M_W$. The radiative corrections to $m_h^2$ and $M_H^2$ are proportional to $m_t^4/M_W^2$, whereas the leading corrections to the charged Higgs mass squared are proportional to $m_t^2$ and are considerably smaller.

Figure 1 shows contour plots of $m_h$, $m_H$ and $m_{H^\pm}$ in the $(m_A, \tan \beta)$ plane, for $m_t = 150$ GeV or 200 GeV and the SUSY parameters in Eq. (1). The exact CP-even Higgs boson mass limits here are $m_h < 116(149)$ GeV < $m_H$ for $m_t = 150(200)$ GeV.

The couplings of the MSSM Higgs bosons depend on $\alpha$ and $\beta$ through the following factors:

\[
\begin{array}{cccc}
  h & H & A \\
  t\bar{t} & \cos \alpha / \sin \beta & \sin \alpha / \sin \beta & \gamma_5 \cot \beta \\
  b\bar{b}, \tau\bar{\tau} & -\sin \alpha / \cos \beta & \cos \alpha / \cos \beta & \gamma_5 \tan \beta \\
  WW, ZZ & \sin(\beta - \alpha) & \cos(\beta - \alpha) & 0 \\
  ZA & \cos(\beta - \alpha) & \sin(\beta - \alpha) & 0 \\
  H^+ & & & \\
  \bar{t}b & m_t \cot \beta (1 - \gamma_5) + m_b \tan \beta (1 + \gamma_5) \\
  \nu\bar{\tau} & m_\tau \tan \beta (1 + \gamma_5) \\
  ZH^+ & (1 - 2 \sin^2 \theta_W) & &
\end{array}
\] (8)

There is no tree-level $WZH$ vertex. In the standard convention, $0 \leq \beta \leq \pi/2$ and $-\pi/2 \leq \alpha \leq 0$.

The factors in Eqs. (8) and (9) determine the $\alpha, \beta$ dependences of the Higgs boson production and decay vertices that enter in the various measurable subprocesses. For a given $\tan \beta$, $\alpha \rightarrow \beta - \pi/2$ as $m_A \rightarrow \infty$; in this limit $A$, $H$ and $H^\pm$ become approximately
degenerate and physically irrelevant, while the \( h \) couplings approach those of the SM Higgs boson. Figure 2 shows the regions where the \( W, t, b \) couplings of \( h \) are within 10% of the corresponding \( H_{SM} \) couplings. We see that the MSSM would be almost indistinguishable from the SM (with \( h \) in the role of \( H_{SM} \)) for \( m_A \gtrsim 200 \text{ GeV} \) and \( \tan \beta > 1 \) unless some of the additional particles \( A, H \) or \( H^\pm \) could be discovered.

The decays of an off-shell \( Z^* \) to \( Zh \) and \( Ah \) are complementary in the sense that \( \sin^2(\beta - \alpha) + \cos^2(\beta - \alpha) = 1 \); thus any suppression in one coupling is accompanied by an enhancement in the complementary coupling. Similarly, the decays of \( h \) (or \( H \)) to \( WW, ZZ \) and \( ZA \) are complementary. Figure 2 shows a contour plot of \( \sin(\beta - \alpha) \) in the \((m_A, \tan \beta)\) plane; it also shows contour plots of the quantities \( \cos \alpha / \sin \beta \) and \( \sin \alpha / \sin \beta \) that govern the strength of \( h \) and \( H \) couplings to \( \bar{t}t \) and the quantities \( -\sin \alpha / \cos \beta \) and \( \cos \alpha / \cos \beta \) that govern couplings to \( \bar{b}b \). These five factors control the \( W, t \) and \( b \) loop contributions for \( h \) and \( H \) decays into two photons; we see that they vary strongly across the parameter space.

The partial widths for neutral Higgs to \( \gamma \gamma \) transitions have the form

\[
\Gamma(X \rightarrow \gamma \gamma) = \Gamma_0(X)(\alpha/\pi)^2|I(X \rightarrow \gamma \gamma)|^2 ,
\]

where \( I(X \rightarrow \gamma \gamma) \) represents the loop integral contributions and

\[
\Gamma_0(X) = G_F m_X^3 \left/ \left(128\pi\sqrt{2}\right) \right. .
\]

The \( b \)-loop, \( t \)-loop and \( W \)-loop contributions have the following forms:

\[
I(h \rightarrow \gamma \gamma) = \frac{4}{9} I_b \frac{\sin \alpha}{\cos \beta} - \frac{16}{9} I_t \frac{\cos \alpha}{\sin \beta} + 7I_W \sin(\beta - \alpha) ,
\]

\[
I(H \rightarrow \gamma \gamma) = -\frac{4}{9} I_b \frac{\cos \alpha}{\cos \beta} - \frac{16}{9} I_t \frac{\sin \alpha}{\sin \beta} + 7I_W \cos(\beta - \alpha) ,
\]

\[
I(A \rightarrow \gamma \gamma) = \frac{2}{3} I'_b \tan \beta + \frac{8}{3} I'_t \cot \beta .
\]

Here the integrals \( I_q, I_W, I'_q \) are real and positive for \( m_X \leq 2m_q, 2M_W, 2m_q \) respectively. In the regime where \( m_X < M_W, m_q \) the integrals all approach unity. The quantities \( -\frac{4}{9} I_b, -\frac{16}{9} I_t \) and \( 7I_W \) are shown as functions of \( m_X \) in Fig. 3. For an intermediate mass \( h \) or \( H \), the \( W \)-loop contribution dominates unless the factor \( \sin(\beta - \alpha) \) or \( \cos(\beta - \alpha) \) becomes very small.
Although the $b$-loop contributions are usually negligible, they can become significant at large $\tan\beta$. These two-photon widths may be directly measurable in the future at a $\gamma\gamma$ collider [20]; Fig. 4 shows their dependences on the Higgs mass for $\tan\beta = 2, 5$ and 30, with the parameter choices of Eq. (1).

The partial widths for neutral Higgs to $gg$ transitions have the form [1]

$$\Gamma(X \to gg) = \frac{9}{8} \Gamma_0(X)(\alpha_s/\pi)^2|I(X \to gg)|^2,$$

(13)

where $I(X \to gg)$ represents the loop contributions. The formulas for $I(X \to gg)$ are obtained from those for $I(X \to \gamma\gamma)$ by simply setting $I_W = 0$ in Eqs. (12a)–(12c).

The cross-sections for Higgs boson production via $\gamma\gamma$ fusion or $gg$ fusion are directly proportional to the corresponding partial widths above.

In addition to the conventional Higgs boson decays into fermions and gauge bosons, the MSSM allows the decays

$$h \to AA; \ H \to hh, AA, AZ; \ A \to Zh$$

(14)

into other Higgs bosons, when the kinematics permits; these new decays modes usually dominate over decays into fermions and weak bosons in the regions where they are allowed, unless there is an accidental suppression of the coupling for particular $\alpha, \beta$ values. Figure 5 shows the allowed regions for these decays in the $(m_A, \tan\beta)$ plane. We see that one or more of these decays are allowed over a large part of the parameter space; in particular $H \to hh$ can occur widely, although there is a forbidden region (shaded in Fig. 5) and also a suppressed band in the neighborhood of a zero of the $Hhh$ coupling

$$f_h = \cos 2\alpha \cos(\beta + \alpha) - 2 \sin 2\alpha \sin(\beta + \alpha),$$

(15)

shown by a dashed curve in Fig. 5. The new decay modes such as $H \to hh$ lead to higher-multiplicity final states, but if the $H$ can be produced in conjunction with $Z$, through $e^+e^- \to Z^* \to ZH$, this is not necessarily a major liability. In fact, the possibility that one might eventually be able to measure such decays would offer extra tests of the Higgs sector couplings.
Figure 6 illustrates the total widths of the MSSM Higgs bosons versus mass compared to the SM value. Alternatively, Fig. 7 shows contour plots of these MSSM total widths in the $(m_A, \tan \beta)$ plane. Figure 8 illustrates the branching fractions for the dominant modes and the most detectable modes.

III. LEP I and LEP II $e^+e^-$ COLLIDERS

At the LEP I $Z$ factory with $\sqrt{s} \simeq M_Z$, the channels

$$e^+e^- \to Z \to Z^*h, \; Ah$$

(16)

are accessible if $h$ and $A$ are sufficiently light. These channels are complementary in the sense that the $Z^*h$, $Ah$ cross sections are proportional to $\sin^2(\beta - \alpha)$, $\cos^2(\beta - \alpha)$ respectively, and therefore cannot be simultaneously suppressed by these coupling factors.

Comprehensive searches for these Higgs boson signals have been made at LEP I, covering many decay channels (e.g. $h, A \to \tau^+\tau^-, \text{jet} + \text{jet}, \mu^+\mu^-, \pi^+\pi^-$). The null results of the ALEPH searches for $Z^*h$ and $Ah$ signals exclude the regions of the $(m_A, \tan \beta)$ plane shown in Fig. 9 for our SUSY parameter choices and $m_t = 100, 120, 150$ or 200 GeV (deduced from the corresponding ALEPH bounds on $\sin^2(\beta - \alpha)$ and $\cos^2(\beta - \alpha)$). We see that the excluded regions depend considerably on the value of $m_t$ (other inputs being held fixed). Accumulating higher statistics and combining the results from all four LEP detectors will tighten these parameter bounds in the future.

With the planned upgrade to LEP II at CM energy $\sqrt{s} \simeq 200$ GeV, the possible MSSM Higgs production channels will be

$$e^+e^- \to Z^* \to Zh, \; Ah, \; AH$$

(17)

$ZH$ production is either kinematically forbidden or highly suppressed for our parameter range. After decays these channels can yield the final states $\ell^+\ell^-jj, \nu\bar{\nu}jj, \tau\bar{\tau}jj$ and $jjjj$ (where $j$ denotes a hadronic jet).
Simulations of SM Higgs boson signals and backgrounds in the three channels $e^+e^- \rightarrow \nu\bar{\nu}jj, \ell^+\ell^-jj, jjjj$ have been presented for LEP II in Ref. [7]; the results show that $H_{SM}$ can be detected at least up to 80 GeV in the $\nu\bar{\nu}jj$ and $\ell^+\ell^-jj$ channels and at least up to 60 GeV in the $jjjj$ channel with integrated luminosity 500 pb$^{-1}$ per detector. The limited sensitivity in the $jjjj$ channel is due to combinatorial problems and large $e^+e^- \rightarrow W^+W^-(ZZ) \rightarrow jjjj$ backgrounds that obscure any Higgs mass peaks near $M_W$ or $M_Z$. These SM simulations can be rescaled approximately to estimate the detectability of the MSSM $e^+e^- \rightarrow Zh$ signals, that differ from the SM signals essentially by the cross-section factor $\sin^2(\beta - \alpha)$. Figure 10 shows the limits of detectability for the $Zh$ signals, defined by the requirement

$$S/\sqrt{B} = \text{number of signal events}/\sqrt{\text{number of background events}} \geq 4,$$

for an integrated luminosity $\mathcal{L} = 500$ pb$^{-1}$, obtained by rescaling the simulations of Ref. [7]. This luminosity corresponds approximately to 2 years LEP II running at one intersection. We here add the significance $S/\sqrt{B}$ of the three channels $Zh \rightarrow \ell^+\ell^-jj, \nu\bar{\nu}jj, jjjj$ in quadrature, considering only channels containing four or more events. The four standard deviation significance required in Eq. (18) implies a higher level of confidence for big signals (where gaussian statistics apply) than for smaller signals (with Poisson statistics); however, requiring a minimum signal $S > 4$ events per included channel ensures that a reasonable level of confidence is maintained.

The $e^+e^- \rightarrow Ah, AH$ channels lead to $\tau\tau jj$ and $jjjj$ signals; however the $jjjj$ simulations of Ref. [7] cannot be used to estimate the acceptances and backgrounds in these cases, since the cuts imposed include an explicit fit to an $e^+e^- \rightarrow ZH_{SM}$ hypothesis. The $\tau\tau jj$ channel was not addressed in Ref. [7] but has been used at LEP I [2][4][5] and advocated for higher energy $e^+e^-$ colliders [17]; it has the advantage that the background from $e^+e^- \rightarrow ZZ$ is relatively small, compared to the $W^+W^-$ and QCD backgrounds in the $4j$ channel, and it escapes the combinatorial problem of the $4j$ case. The missing neutrinos from the $\tau$ decays are approximately collinear with the observed $\tau$ decay products; the magnitude of these two missing momenta can therefore be reconstructed from energy-momentum constraints (there
is a 1C fit, allowing for initial-state radiation of a hard photon along a beam direction). In the distributions of the reconstructed invariant masses $m(\tau\tau)$ and $m(jj)$, the Higgs boson signals appear as narrow peaks with widths determined by the experimental resolution; it is advantageous to add these $m(\tau\tau)$ and $m(jj)$ signals to improve statistics in the peaks. The most serious $\tau\tau jj$ background is that from $e^+e^- \to ZZ$; all other backgrounds can be reduced to insignificance by suitable cuts, as demonstrated in Ref. [17] for a possible future linear collider with $\sqrt{s} = 500$ GeV.

In our present studies of $\tau\tau jj$ signals at LEP II, we assume that the irreducible $ZZ$ background can be estimated directly from the work of Ref. [17], rescaled to take account of the higher $ZZ$ production cross section and lower luminosity expected at LEP II. This background contains smearing from experimental resolution and the uncertainties of tau reconstruction. We assume that the MSSM signals have approximately 50% detection efficiency (as in Ref. [17]) and have the same smearing as the background. For an isolated Higgs boson peak, we define the signal strength $S$ to be the total number of Higgs-decay counts in a 10 GeV mass bin centered at the peak. The background strength $B$ is taken to be the total number of $Z$-decay counts (both from $ZZ$ and from $Zh, ZH$ production with the resolution of Ref. [17]) falling in the same mass bin. When two Higgs peaks approach within 10 GeV we combine them; the signal strength $S$ is then the number of Higgs counts expected in a 10 GeV bin centered at the weighted mean mass. If the signal bin center is separated by more than 5 GeV from $M_Z$, our discovery criteria are $S/\sqrt{B} > 4$ with $S > 4$, for integrated luminosity 500 pb$^{-1}$. With such a signal, we expect that a distinct Higgs peak will be seen or that a recognizable distortion of the $Z$ peak will be evident. But if the separation from $M_Z$ is less than 5 GeV, we can only infer the presence of a new signal if the height of the supposed $Z$ peak differs substantially from the expected $ZZ$ background contribution. In this latter case we rely entirely on normalization and therefore require a higher degree of significance. Here the signal $S$ is defined to be the sum of all MSSM ($h, H, A$ and $Z$) contributions falling in a 10 GeV bin centered at $M_Z$, and $B$ is the expected $ZZ$ background in the same bin; in this case we define a discoverable signal to have $S/\sqrt{B} > 6$ with $S > 5$ counts.
Figure 11 shows the regions in the \((m_A, \tan \beta)\) plane where a \(\tau \tau jj\) Higgs signal would be detectable at LEP II with the criteria above and the parameters of Eq. (1) with \(m_t = 120, 150\) or 200 GeV. The inaccessible regions at lower left occur because \(h \to AA\) decay dominates here (see Figure 3) and the \(\tau \tau jj\) signals are consequently suppressed. Through most of the discovery region just one new peak (corresponding to \(h\) alone or to overlapping \(h, A\) peaks) would be discernible; at small \(m_A\) there are regions where distinct \(h\) and \(A\) peaks would be predicted, but these regions are already excluded by the LEP I searches [2] (see Fig. 9).

The above LEP analyses do not rely on \(b\)-jet identification. The inclusion of \(b\)-tagging with vertex detection will expand the Higgs boson discovery limit since the \(Z\)-decay background has contributions from all quark flavors while the Higgs boson contribution is mainly from \(b\bar{b}\). Present \(b\)-tagging at LEP typically has efficiency of order 0.38 for \(b\bar{b}\) states compared to 0.11 for the average \(Z \to jj\) decays. Then if we adopt these efficiencies and consider for example the \(Z \to \ell^+\ell^- jj, \nu\bar{\nu}jj\) and \(Ah \to \tau \tau jj\) signals, where the Higgs signals all have \(b\bar{b}\) jets and the backgrounds come mainly from \(ZZ\) production, the significance \(S/\sqrt{B}\) of a tagged Higgs signal would be enhanced above that of the corresponding untagged signal by approximately a factor \(0.34/\sqrt{0.11} = 1.14\), a helpful but not dramatic improvement. For the present we conservatively neglect such developments.

Searches for charged Higgs bosons at LEP I [22] have excluded various ranges of \(m_{H^+}\) below 43 GeV, but such values are well below the expected MSSM range (see Fig. 1). Future searches at LEP II will be sensitive to \(H^+H^-\) production up to perhaps 70 GeV mass (the much larger \(WW\) background making higher masses hard to detect); the corresponding MSSM parameter region is marginal in our present discussion and appears to be excluded already by the LEP I \(h\) and \(A\) searches (see Fig. 3). Charged Higgs searches at LEP are therefore not likely to affect the MSSM discovery limits.
Extensive analyses have concluded that a SM Higgs boson in the intermediate or high mass ranges can be detected at the LHC ($\sqrt{s} = 15.4$ TeV) and the SSC ($\sqrt{s} = 40$ TeV) pp supercolliders [8]. However, in the MSSM the situation may be very different [13,14,15,16]; there are many more Higgs boson states to consider, the couplings may differ markedly from the SM values and new decay channels may be present. In the following we focus attention on the most promising signals. Since the LHC with a factor of 10 higher luminosity can cover about the same ground as the SSC [8], except at high Higgs boson mass values, we illustrate with results obtainable at the SSC. The discussion below considers the individual production subprocesses with decays that yield viable signals.

**A. $gg \rightarrow h, H, A \rightarrow \gamma\gamma$**

The largest neutral Higgs boson production cross sections are due to gluon-gluon fusion, and for Higgs masses in the intermediate range the $\gamma\gamma$ decay mode gives a viable signal provided that excellent $m(\gamma\gamma)$ mass resolution can be achieved. The proposed GEM detector [21] at the SSC is capable of mass resolution $\Delta m/m(\gamma\gamma) \leq 1\%$, that gives sufficient background suppression to detect the inclusive $H_{\text{SM}} \rightarrow \gamma\gamma$ signal through the mass range 80–160 GeV. We use the GEM simulations of the background with a liquid argon calorimeter and their minimal 55% signal efficiency after cuts [21] to determine the significance $S/\sqrt{B}$ of signal versus background in ±1% mass intervals at the Higgs boson masses (i.e. a bin width of twice the expected experimental resolution of 1%). Figure 12 gives the raw $pp \rightarrow gg \rightarrow h, H, A \rightarrow \gamma\gamma$ cross sections times branching fractions as contour plots in the $(m_A, \tan\beta)$ plane; the $H \rightarrow \gamma\gamma$ signals are essentially restricted to the region where $H \rightarrow hh$ is forbidden or suppressed (compare Fig. 5). Figure 13 gives the corresponding potential discovery regions for $h, H$ or $A$ for luminosity $\mathcal{L} = 20$ fb$^{-1}$ (corresponding approximately to 2 years SSC running at one intersection). The light areas show where $S/\sqrt{B}$ exceeds 4.
standard deviations. We note that the region where $h \to \gamma\gamma$ signals are detectable is also the region where $h$ masquerades as the SM Higgs boson (see Fig. 2(a)).

**B. $q\bar{q} \to (h,H)W \to \gamma\gamma\ell\nu$; $gg,q\bar{q} \to (h,H,A)t\bar{t} \to \gamma\gamma\ell\nu$ jets**

The presence of a lepton tag from $W \to \ell\nu$ or $t \to bW \to b\ell\nu$ decay leads to a cleaner signal that can be identified in the SDC detector \[\text{with } m(\gamma\gamma) \text{ resolution } \lesssim 3 \text{ GeV.}\] Simulations show that the SM Higgs boson signal can be detected above the backgrounds (of which $t\bar{t}\gamma\gamma$ production is the most important) through the intermediate mass range up to 140 GeV \[8,23,24\]. Figure 14 shows the raw signal cross sections from the $t\bar{t}$ Higgs process (for the parameters of Eq. 1) as contour plots, summing over lepton flavors $\ell = e, \mu$. In the following discussion we focus on detection in SDC.

The $W$–Higgs signals are calculated including an order $\alpha_s$ QCD enhancement factor \[25\]. The $t\bar{t}$-Higgs signal is evaluated as in Ref. \[26\] using the scale $Q = [m_T(t) + m_T(\bar{t}) + m_T(h)]/3$ where $m_T = \sqrt{m^2 + p_T^2}$. Final leptons and photons are required to satisfy realistic acceptance cuts on transverse momentum $p_T$, pseudo-rapidity $\eta$ and separation $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$

\[
p_T > 20 \text{ GeV} , \quad |\eta| < 2.5 , \quad \Delta R_{\ell\gamma} > 0.4 , \quad \Delta R_{\gamma\gamma} > 0.4 ,
\]

where $\phi$ denotes azimuthal angle.

The cross sections are multiplied by $(0.85)^3$ for the detection efficiency \[23\] and an additional factor of 0.93 in the $W$-Higgs events and 0.73 in the $t\bar{t}$-Higgs events for isolation (excess $\sum E_T < 10 \text{ GeV}$ in a cone $\Delta R < 0.3$) as determined in SDC simulations.

The Gaussian resolution $\sigma_{\gamma\gamma}$ is taken from the baseline detector results in Table 3-3 of Ref. \[23\] (e.g. $\sigma_{\gamma\gamma} = 2 \text{ GeV}$ for $m_H = 160 \text{ GeV}$). The $b\bar{b}\gamma\gamma$ and $W\gamma\gamma$ backgrounds are also taken from Ref. \[23\]. The $t\bar{t}\gamma\gamma$ background is evaluated from the formulas for $t\bar{t}ZZ$ production in Ref. \[26\], with appropriate replacement of masses and couplings. The signals and backgrounds are integrated over an interval $m_H \pm 2\sigma_{\gamma\gamma}$. Figure 15 gives the contours of significance $S/\sqrt{B} = 4$ for the combined $t\bar{t}$ Higgs plus $W$ Higgs lepton-tagged signals.
for luminosity 20 fb$^{-1}$. Light areas show the potential discovery regions for $h$ or $H$ where the significance exceeds 4 standard deviations; there are no tagged-$A$ discovery regions. We see that the use of lepton-tagged two-photon channels substantially increases the discovery regions (compare Fig. 13 for untagged cases).

C. $gg \rightarrow H \rightarrow ZZ \rightarrow 4\ell$

Previous studies [13,14,16] have found that four-lepton decays are only useful as a signal for $H$; the $h \rightarrow ZZ$ branching fraction is kinematically suppressed and $A \rightarrow ZZ$ is absent at tree level. Figure 16 displays the $\sigma B$ contours for $pp \rightarrow H \rightarrow 4\ell$ at $\sqrt{s} = 40$ TeV for the parameters of Eq. (1), summed over lepton flavors $\ell = e, \mu$.

The principal background to this process is $q\bar{q} \rightarrow ZZ \rightarrow 4\ell$. We multiply the cross-section for this process by 1.65 to approximate the contributions of higher order QCD corrections and $gg \rightarrow ZZ$ [16,27,28]. Backgrounds from $t\bar{t}, Zb\bar{b}$ and $Zt\bar{t}$ production are essentially eliminated by our choice of cuts and the requirement that the four leptons be isolated. We require that each of the four leptons satisfy

$$p_T \ell > 20 \text{ GeV} \quad |\eta_\ell| < 2.5.$$  \hspace{1cm} (20)

In addition a separation $\Delta R > 0.4$ is required between all lepton pairs and an invariant mass restriction

$$|M_Z - M_{\ell\ell}| \leq 10 \text{ GeV}$$  \hspace{1cm} (21)

is imposed on one $\ell^+\ell^-$ pair in the event as expected for one on-shell $Z$-boson. We multiply the calculated cross section by $(0.9)^4$ to include SDC estimates of lepton isolation (excess $\sum E_T < 5$ GeV in a cone $\Delta R < 0.4$) and multiply by $[(0.85)(0.95)]^2$ to include the efficiency for the detection of lepton pairs from $Z$-bosons.

The mass resolution $\sigma_4\ell$ of the Higgs boson peak is estimated using the SDC electromagnetic single particle resolution.
\[
\frac{\sigma(E)}{E} = \left( \frac{0.14}{\sqrt{E}} \right)^2 + 0.01^2 \right)^{1/2}.
\]  
(22)

We find that \(\sigma_{4\ell}\) ranges from \(\approx 2\) GeV for \(m_H = 140\) GeV to \(\approx 6\) GeV for \(m_H = 1000\) GeV. This resolution is folded in quadrature with the Higgs boson decay width \(\Gamma_H\) to find an effective Gaussian resolution

\[
\sigma_{\text{eff}} = \left[ \sigma_{4\ell}^2 + \left( \frac{\Gamma_H}{2} \right)^2 \right]^{1/2}.
\]  
(23)

The signal and backgrounds are integrated over the interval \(m_h \pm 2\sigma_{\text{eff}}\) in our analysis.

Figure 17 gives the resulting contours of \(S/\sqrt{B} = 4\) for \(L = 20\ f_{b^{-1}}\) in the \((m_A, \tan \beta)\) plane. The potential discovery regions with \(S/\sqrt{B} \geq 4\) and \(S \geq 10\) events are unshaded. As previously remarked [13,14,16], this canonical “gold-plated” SM signature for a heavy Higgs boson can only be detected in a limited region of MSSM parameter space; this is due to competing \(H \rightarrow hh\) and other decay modes, not present in the SM (cf. Fig. 3), and reduced \(HZZ\) coupling strength. The boundary at \(m_A \approx 300\) GeV is associated with the kinematic threshold for \(H \rightarrow t\bar{t}\) decay. Our realistic calculations including explicit lepton cuts lead to a smaller potential discovery region than other recent analyses [13,16] that assumed an \(m_H\)-independent detector acceptance.

D. \(gg, q\bar{q} \rightarrow t\bar{t}; t \rightarrow bH^+\)

There will be copious \(t\bar{t}\) production at the LHC and SSC that will allow non-standard top decays to be scrutinized by triggering on the \(t \rightarrow bW^+ \rightarrow b\ell\nu\) decay of one top quark \[29\]. Simulations [21,23,30] indicate that the decay \(t \rightarrow bH^+\) with subsequent \(H^+ \rightarrow \tau^+\nu\) and \(\tau^+ \rightarrow \bar{\nu}_\tau\pi^+\) decays will be detectable as a violation of lepton universality expected from \(W\)-decays in \(t\bar{t} \rightarrow W^+W^- \rightarrow \ell\nu\tau\nu\) events. In evaluating this signal we impose the SDC acceptance cuts and efficiencies [23], which include a cut \(p_T(\pi) > 100\) GeV. A significance \(S/\sqrt{S+B} > 5\) is required for discovery, where \(B\) is the number of background \(\ell\nu\tau\nu\) events from SM \(t\bar{t} \rightarrow b\bar{b}WW\) decays and \(S\) is the excess of such events due to the charged Higgs
decay mode of the top quark. Figure 18 displays the potential discovery regions in the
$(m_A, \tan \beta)$ plane for $m_t = 120, 150$ and $200$ GeV with $\mathcal{L} = 20$ fb$^{-1}$; the inaccessible region
for $m_t = 150$ GeV is shaded. Charged Higgs boson masses up to a few GeV below $m_t$ are
accessible (see Fig. 1). We note however that detecting an excess of $\ell \nu \tau \nu$ events would not
by itself measure the mass $m_{H^+}$, although it would constrain $m_A$ and $\tan \beta$.

V. SUMMARY AND CONCLUSIONS

The limits of detectability depend on several different factors: (a) the $\alpha$- and $\beta$-dependent
couplings governing the dynamics of production and decay, (b) the Higgs boson masses
that determine the regions of kinematical suppression, (c) the acceptance, luminosity and
background values that determine whether or not a signal can be extracted. Of these,
(a) and (b) vary strongly across the $(m_A, \tan \beta)$ parameter plane and we have evaluated
them exactly; (c) can only be estimated approximately, but moderate changes here will not
qualitatively alter our conclusions about discovery limits in the parameter space.

In the previous sections we have discussed the coverage of the $(m_A, \tan \beta)$ plane achiev-
able by different colliders, using the best signals in each case. We can now combine these
different discovery limits, to see how completely the parameter space can be explored.

We first discuss the potential for discovery of at least one of the MSSM Higgs bosons,
h, $H, A, H^\pm$. Figure 19 shows the combined coverage, assuming $m_t = 150$ GeV with the
SUSY mass scale around 1 TeV as in Eq. (1). Roughly speaking, LEPI and LEP II can
cover all areas except the region $m_A \gtrsim 80, \tan \beta \gtrsim 2$. The SSC/LHC searches for $h \to \gamma \gamma$
and $H \to \gamma \gamma$ (with or without a lepton tag) extend the coverage to include $m_A \gtrsim 180$ GeV
and $m_A \lesssim 100$ GeV respectively (any $\tan \beta$). Charged Higgs searches extend the discovery
region little for this $m_t$ value. The region $100 \lesssim m_A \lesssim 180$ GeV with $\tan \beta \gtrsim 2$ remains
largely inaccessible for the standard luminosities. However, a higher-energy $e^+e^-$ collider
could cover this remaining area [17,31]. The SSC/LHC searches for $H \to \ell \ell \ell \ell$ cover a region
already accessible to other searches ($Zh$ at LEP II, $h \to \gamma \gamma$ at SSC/LHC) but would discover
a different particle. Figure 20 presents an expanded view of the region of the \((m_A, \tan \beta)\) plane showing the Higgs boson masses that would not be ruled out by LEP II and SSC experiments, for the case \(m_t = 150\) GeV. Figures 21 and 22 map the discovery regions for the cases \(m_t = 120\) GeV and \(m_t = 200\) GeV, respectively. In the case \(m_t = 200\) GeV, the improvement in coverage is largely due to the wider range of \(H^+\) masses that become accessible through \(t \to bH^+\) decays.

Finding one MSSM Higgs boson is a minimum requirement. In some parts of the \((m_A, \tan \beta)\) plane, more than one of these Higgs bosons would be discoverable. This information is summarized in Fig. 23, for the case \(m_t = 150\) GeV.
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FIGURES

FIG. 1. Contour plots of MSSM Higgs boson masses in the \((m_A, \tan \beta)\) plane, for the SUSY parameters in Eq. (1): (a) \(m_h\) and \(m_H\) for \(m_t = 150\) GeV, (b) \(m_{H^+}\) for \(m_t = 150\) GeV, (c) \(m_h\) and \(m_H\) for \(m_t = 200\) GeV, (d) \(m_{H^+}\) for \(m_t = 200\) GeV. The \(m_h\) (\(m_H\)) curves are distinguished by solid (dashed) curves.

FIG. 2. Contours in the \((m_A, \tan \beta)\) plane of the \(\alpha\)-dependent factors that enter the \(h\) and \(H\) couplings to weak bosons and quarks: (a) boundaries, to the right of which the \(h\) couplings are within 10\% of the \(H_{SM}\) couplings; (b)–(f) contour plots of the individual coupling factors \(\sin(\beta - \alpha)\), \(\cos \alpha/\sin \beta\), \(\sin \alpha/\sin \beta\), \(-\sin \alpha/\cos \beta\), \(\cos \alpha/\cos \beta\), respectively. The \(h\) couplings approach the \(H_{SM}\) couplings at large \(m_A\).

FIG. 3. The \(b\)-loop \((-\frac{4}{9}I_b)\), \(t\)-loop \((-\frac{1}{6}/9I_t)\) and \(W\)-loop \((7I_W)\) factors contributing to the \(\gamma\gamma\) partial widths of the \(h\) and \(H\) Higgs bosons are shown versus mass \(m_X\).

FIG. 4. Two-photon partial widths for \(h, H, A\) decays versus Higgs boson mass for the parameters of Eq. (1) with (a) \(\tan \beta = 2\), (b) \(\tan \beta = 5\) and (c) \(\tan \beta = 30\).

FIG. 5. Kinematically allowed regions in the \((m_A, \tan \beta)\) plane for MSSM Higgs boson decays into other Higgs bosons; when allowed, these decays usually dominate over other decay modes. Shading shows the area where the new modes \(H \rightarrow hh, AA, AZ\) are all forbidden. A dashed curve shows the locus of zeros of the \(H \rightarrow hh\) coupling.

FIG. 6. Total widths of MSSM Higgs boson decays versus mass compared to the SM result, for (a) \(\tan \beta = 2\), (b) \(\tan \beta = 30\), with the parameters of Eq. (1).

FIG. 7. Contour plots of total widths of MSSM Higgs bosons in the \((m_A, \tan \beta)\) plane for (a) \(h\) decay, (b) \(H\) decay, (c) \(A\) decay, (d) \(H^+\) decay, with the parameters of Eq. (1).
FIG. 8. MSSM Higgs boson branching fractions for the dominant modes and the most detectable modes, taking the parameters of Eq. (1): (a) $h, H$ decays with $\tan \beta = 2$, (b) $h, H$ decays with $\tan \beta = 30$, (c) $A$ decays with $\tan \beta = 2$, (d) $A$ decays with $\tan \beta = 30$, (e) $H^+$ decays with $\tan \beta = 2$, (f) $H^+$ decays with $\tan \beta = 30$.

FIG. 9. Excluded regions of the $(m_A, \tan \beta)$ plane, from the ALEPH experiment [2] at LEP I, including electroweak radiative corrections with the SUSY parameters of Eq. (1) and $m_t = 100, 120, 150$ or 200 GeV: (a) $Z \to Z^* h$ searches, (b) $Z \to Ah$ searches. Areas below or to the left of the curves are excluded; the non-excluded regions for $m_t = 150$ GeV are shaded.

FIG. 10. Limits of detectability at LEP II for the $e^+e^- \to Zh$ signals obtained by rescaling the simulations of Ref. [7], for luminosity $0.5 \text{ fb}^{-1}$ and the SUSY parameters of Eq. (1) with $m_t = 100, 120, 150$ or 200 GeV. The inaccessible area for $m_t = 150$ GeV is shaded.

FIG. 11. Regions of the $(m_A, \tan \beta)$ plane where an MSSM Higgs boson signal would be detectable in the $\tau \tau jj$ channel at LEP II, for luminosity $0.5 \text{ fb}^{-1}$ and the SUSY parameters of Eq. (1) with $m_t = 120, 150$ or 200 GeV. Boundary curves are shown for different top masses; the area inaccessible with $m_t = 150$ GeV is shaded.

FIG. 12. Untagged two-photon signals at the SSC. Predicted cross sections times branching fraction in fb at $\sqrt{s} = 40$ TeV for $pp \to h, H, A \to \gamma\gamma$ signals are shown as contour plots in the $(m_A, \tan \beta)$ plane, for the parameter choices of Eq. (1): (a) $h$ signals, (b) $H$ signals, (c) $A$ signals.

FIG. 13. Contours of significance $S/\sqrt{B} = 4$ for the detection of the untagged two-photon signals in Fig. [12] based on a luminosity of $20 \text{ fb}^{-1}$ and the GEM estimates of backgrounds [21]. The light areas show potential discovery regions for $h, H$ or $A$, where the significance exceeds four standard deviations.
FIG. 14. Lepton-tagged two-photon signals at the SSC. The cross sections times branching fraction in fb at $\sqrt{s} = 40$ TeV for the process $pp \rightarrow gg, q\bar{q} \rightarrow (h, H, A)t\bar{t} \rightarrow \gamma\gamma\ell\nu$ jets are shown as contour plots in the $(m_A, \tan\beta)$ plane, for the parameter choices of Eq. (1): (a) $h$ signals, (b) $H$ signals, (c) $A$ signals.

FIG. 15. Contours of significance $S/\sqrt{B} = 4$ for detection of the combined $t\bar{t}$ Higgs and $W$ Higgs lepton-tagged two-photon signals in Fig. 14, based on luminosity $20$ fb$^{-1}$ with SDC estimates of $b\bar{b}\gamma\gamma$ and $W\gamma\gamma$ backgrounds and our calculations of the $t\bar{t}\gamma\gamma$ background, integrated over 3 GeV bins of $\gamma\gamma$ invariant mass. The light areas show potential discovery regions for $h$ and $H$.

FIG. 16. Four-lepton signals at the SSC. Cross sections times branching fraction $\sigma B(pp \rightarrow H \rightarrow 4\ell)$ at the SSC are shown in fb, as contours in the $(m_A, \tan\beta)$ plane, for the parameters of Eq. (1).

FIG. 17. Contours of significance $S/\sqrt{B} = 4$ for detection of the four-lepton signals in Fig. 16, based on luminosity $20$ fb$^{-1}$ and calculated $ZZ \rightarrow 4\ell$ background. The light areas show potential $H$ discovery regions.

FIG. 18. Potential discovery regions for the charged Higgs boson via the decays $t \rightarrow bH^+$, $H^+ \rightarrow \tau^+\nu$, $\tau^+ \rightarrow \pi^+\nu$, through lepton universality violation in $t\bar{t} \rightarrow W^+W^- \rightarrow \ell\nu\tau\nu$ events; the inaccessible region for $m_t = 150$ GeV is shaded.

FIG. 19. Combined potential discovery regions for at least one MSSM Higgs boson, with $m_t = 150$ GeV and the SUSY parameters of Eq. (1), are shown as an unshaded area in the $(m_A, \tan\beta)$ plane. Curves show the limits of various search possibilities, previously described in Figs. 9–18: (a) LEP I and LEP II limits, (b) SSC limits.
FIG. 20. Expanded view of the region of no coverage from Fig. 19, for $m_t = 150$ GeV, shown as a shaded area in the $(m_A, \tan \beta)$ plane. Contours of $m_h$ (solid), $m_H$ (dashed) and $m_{H^+}$ (dotted) are superposed.

FIG. 21. Similar to Fig. 19 with $m_t = 100$ GeV.

FIG. 22. Similar to Fig. 21 with $m_t = 200$ GeV.

FIG. 23. Potential discovery regions for more than one MSSM Higgs boson, with $m_t = 150$ GeV and the SUSY parameters of Eq. (1). The regions where no bosons, one boson and two or more bosons can be detected are distinguished by different levels of shading.