Observability of $\gamma\gamma$ decays of Higgs bosons from supersymmetry at hadron supercolliders

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Motivated by the recent discovery that radiative corrections can cause the mass of the lightest scalar Higgs boson H_l of the minimal supersymmetric model (MSSM) to be in the intermediate-mass range, we assess the prospects for discovering the MSSM Higgs bosons via their $\gamma\gamma$ decay modes at the Superconducting Super Collider (SSC) and at the CERN Large Hadron Collider (LHC). We find that if the charged Higgs boson is not too light, it is possible to discover at least one of the Higgs bosons via this mode within a few years of operation of the SSC, provided the detector has the resolution to identify a standard model Higgs boson in the intermediate-mass range via its $\gamma\gamma$ decay. Similar conclusions hold at the LHC provided the luminosity is higher by a factor of about 4. In the case where m_{H^+}, and hence m_{H_p}, is somewhat smaller than 200 GeV, we find there are regions of parameter space where all three Higgs bosons are in the intermediate-mass range, and none of them lead to an observable signal. Thus, new strategies may be needed to identify the Higgs bosons of the MSSM.

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I. INTRODUCTION

The need for the elucidation of the mechanism of spontaneous symmetry breakdown is one of the main reasons for the construction of supercolliders designed to explore elementary-particle collisions at TeV energies. Within the standard model (SM), electroweak symmetry breaking is realized via a vacuum expectation value (VEV) of an elementary doublet of scalars that has to be introduced for just this reason. A neutral, spin-0 particle, the Higgs boson, is the relic of this mechanism of gauge symmetry breakdown. The introduction of elementary scalar fields makes the SM technically unnatural and necessitates severe fine-tuning of parameters in order to keep the Higgs-boson mass below the unitarity limit [1]. Supersymmetry (SUSY) leads to an elegant solution to the fine-tuning problem [2] provided only that the SUSY partners of known particles are all lighter than ~ 1TeV [3].

The symmetry-breaking sector of even the minimal supersymmetric model (MSSM) [4], to be consistent with phenomenology, requires the introduction of at least two sets of SU(2) Higgs doublets h and h' whose VEV's give rise to masses for the $T_3 = \frac{1}{2}$ and $T_3 = -\frac{1}{2}$ fermions, respectively. As a result, instead of just a single Higgs boson as in the SM, the observable spectrum of the Higgs sector of the MSSM is much richer and consists of two neutral scalars H_l and H_h (the subscripts denote light and heavy), a pseudoscalar H_p, and a pair of charged scalars $H^\pm$. The fact that the only allowed quartic interactions of these scalars are gauge interactions from the D terms leads to the restrictions [5]

$$m_{H_l} \le \min(M_Z, m_{H_p})|\cos 2\beta| \le M_Z \ , \tag{1a}$$

$$m_{H^+} \ge M_W \ , \tag{1b}$$

$$m_{H_h} \ge M_Z \ , \tag{1c}$$

which are valid at the tree level. In Eq. (1), $\tan\beta = v/v'$ is preferably greater than 1 in all known models, primarily because the t quark is much heavier than the b quark. The bound (1a) on the mass of H_l has led several authors [6] to argue that it should be possible to discover H_l via the Bjorken process at the CERN e^+e^- collider LEP 200 even if it is degenerate with the Z, thus providing a crucial test of the MSSM.

It has, however, recently been pointed out [7] that if the top quark is heavy, as it now appears [8] to be, radiative corrections due to the large top-quark Yukawa coupling invalidate the tree-level relations (1), so that H_l may well be heavier than M_Z. An electron-positron collider with a center-of-mass energy of several hundred GeV and a luminosity of ~ 10 fb^{-1}/yr is the optimal facility to search for a Higgs boson in this mass range [5]. The construction of such a collider is well beyond the reach of present technology. This has led many groups to study the feasibility of detecting heavier Higgs bosons at hadron supercolliders such as the Superconducting Super Collider (SSC) in the USA and the Large Hadron Collider (LHC) at CERN.

The identification of a Higgs boson in the intermediate-mass range $M_Z < m_H < 2M_W$ is extremely difficult at hadron colliders. As several studies [9] have shown, the SM Higgs boson in the intermediate-mass region can be detected via its decay $H \to \gamma\gamma$, both at the SSC and at the LHC, provided the detector includes excellent electromagnetic calorimetry capable of measuring the two-photon mass with a precision of 1–2 %. The SM Higgs-boson peak can then be detected above the two-photon continuum background from $q\bar{q} \to \gamma\gamma$ and $gg \to \gamma\gamma$ (via box diagrams) [10] using a suitable set of cuts described below. Our main purpose is to evaluate whether $\gamma\gamma$ decay remains a viable signal for the Higgs bosons of the MSSM when the changes in their couplings and decay patterns (from the SM expectation), including the effects of radiative corrections [7] due to the top-quark Yukawa coupling, are incorporated in the analysis. The necessity of such an analysis is highlighted by the fact that it is possible for all the three Higgs bosons of the MSSM to have masses in the intermediate-mass range.

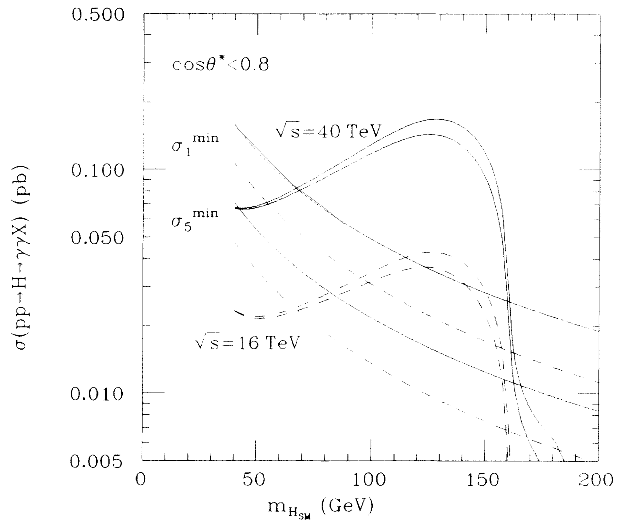

FIG. 1. The total cross section for $pp \to H_{SM} \to \gamma\gamma$ with $\cos\theta^* < 0.8$ at $\sqrt{s} = 40$ TeV (solid) and $\sqrt{s} = 16$ TeV (dashed). The upper (lower) curves correspond to $m_t = 100$ GeV ($m_t = 200$ GeV). The minimum observable signal cross section as given by Eq. (3) for integrated luminosities 10^4 pb^{-1} (upper) and 5×10^4 pb^{-1} (lower) is also shown for the SSC (solid) and the LHC (dashed) by the curves labeled $\sigma_1^{\min}$ and $\sigma_5^{\min}$, respectively.

II. DETECTABILITY OF THE STANDARD-MODEL HIGGS BOSON

At hadron supercolliders, Higgs bosons in the intermediate-mass range are dominantly produced via gluon fusion which occurs via a quark (and in the case of the scalars of the MSSM, also a squark) loop with a cross section given by

$$\sigma(pp \to H \to \gamma\gamma X) = \Gamma(H \to gg) \frac{\pi^2}{8m_H^3} \tau \int_\tau^1 \frac{dx}{x} g(x, m_H^2) g\left[\frac{\tau}{x}, m_H^2\right] \times B(H \to \gamma\gamma) , \quad (2)$$

where $\tau = m_H^2/s$ and $g(x, Q^2)$ is the gluon distribution function. The partial widths for the decays $H \to gg$ and $H \to \gamma\gamma$ that enter into Eq. (2) may be found, for example, in Ref. [5] for both the SM and the MSSM Higgs bosons. In order to facilitate the comparison of our results with other analyses, we have shown in Fig. 1 the total cross section for the production of a photon pair from the production and subsequent decay of a SM Higgs boson at the SSC (solid) and the LHC (dashed). A cut $\cos\theta^* < 0.8$, designed to reduce the background (discussed below), has been imposed on the photon scattering angle θ^* in the rest frame of the Higgs boson. The upper (lower) curves in each set correspond to $m_t = 100$ GeV (200 GeV). The branching fraction to two photons, and hence the cross section in Fig. 1, begins decreasing as the modes $H \to WW^*$ and ZZ^* become significant. In our computations we have used the updated structure functions of Owens [11] and have included leading QCD corrections [12] to $\Gamma(H \to q\bar{q})$ using the interpolation formula given in Ref. [13]. For the range of m_H shown in Fig. 1, these corrections reduce $\Gamma(H \to b\bar{b})$ by as much as a factor of 2, so that the branching fraction for the decays $H \to \gamma\gamma$, and hence, the signal cross section, is enhanced by the same factor.

The dominant QCD subprocesses for pair production of high p_T isolated photon pairs are $q\bar{q} \to \gamma\gamma$ and $gg \to \gamma\gamma$. Unlike the signal, which is isotropic in the center-of-mass frame of the two photons, most of the background photons are produced along the beam direction and can be removed by a cut, $\cos\theta^* < 0.8$, on the center-of-mass scattering angle [10] with just a 20% reduction in the signal. Because of the large gluon luminosity at hadron supercolliders, the cross section from $gg \to \gamma\gamma$ (which proceeds via the quark box diagram) is actually larger than the contribution from $q\bar{q}$ annihilation for large-angle photon pairs [10]. For the gg contribution to the $\gamma\gamma$ background, we have used the squared-matrix elements as given in Ref. [14] and assumed that the top loop makes a negligible contribution, which is justified [10] for $m(\gamma\gamma) < 2m_t$. We neglect contributions to the background from processes where either or both photons are radiated off jets and carry a substantial fraction of the jet energy, since these can be greatly reduced [15] by suitable isolation cuts without significant loss of signal. A Higgs boson in the intermediate-mass range is extremely narrow, so that the two-photon mass from its decay will fall in a narrow mass bin of width δm centered at m_H. The size of the background thus crucially depends on the experimental resolution of the measurement of the invariant mass of the $\gamma\gamma$. We have assumed $\delta m = 0.02 m_{\gamma\gamma}$, which assumes a detector with excellent capabilities for electromagnetic calorimetry [9].

The smallest signal cross section σ_s that will be observable above the background (cross section σ_b in the $\pm 1\%$

mass bin centered at m_H) for an integrated luminosity L, which we take to be 10^4 pb^{-1} (upper curve) (corresponding to a year's running at the SSC) and 5×10^4 pb^{-1} (lower curve), is shown by the remaining hyperbola-shaped curves in Fig. 1, labeled $\sigma_1^{\min}$ and $\sigma_5^{\min}$, respectively. We obtain the lower limit on σ_s by requiring that the 99%-confidence-level upper limit on the background is smaller than the 99%-confidence-level lower limit on the signal plus background (the rate for $\gamma\gamma$ events in each mass bin is at least $\sim(100)$ at the SSC so that the Gaussian approximation to the probability distribution is valid. Hence

$$L(\sigma_s+\sigma_b)-2.32\sqrt{L(\sigma_s+\sigma_b)}>L\sigma_b+2.32\sqrt{L\sigma_b}\ , \tag{3a}$$

or, equivalently,

$$\sigma_s>\frac{2.32^2}{L}\left[1+\frac{2\sqrt{L\sigma_b}}{2.32}\right] . \tag{3b}$$

We see that the $\gamma\gamma$ signal is visible over almost the entire intermediate-mass range at both the SSC and the LHC after just one year of running, provided only that the 2% mass resolution is achieved. The reason that our conclusion is somewhat more optimistic than earlier analyses [9] is that the signal is enhanced by the incorporation of QCD radiative corrections as mentioned above. We also note that the $\gamma\gamma$ pairs from $q\bar{q}$ and gg fusion form a smooth continuum (with small statistical fluctuations) which can be used to calibrate the expected background in the mass bin centered at $m(\gamma\gamma)=m_H$. Thus, uncertainties in the calculation of the background arising due to unknown QCD corrections or imperfect knowledge of structure functions will not be relevant since the data on photon pairs will be available. We now turn to the analysis of the prospects for detection of the Higgs bosons of the MSSM via their $\gamma\gamma$ decay modes.

III. HIGGS BOSONS OF THE MINIMAL SUPERSYMMETRIC MODEL

Unlike the Higgs sector of a general two-doublet model, the symmetry-breaking sector of the MSSM is strongly constrained by supersymmetry and is completely determined [5] by just two parameters, which we may take to be $\tan\beta$ and the charged-Higgs-boson mass m_{H^+}. At tree level, the masses and mixings which determine the couplings of the three Higgs particles H_l, H_h, and H_p are completely fixed in terms of these two parameters, resulting in the bounds given in (1).

As noted in Sec. I, the masses and mixing patterns are considerably altered from their tree-level expectation if the top-quark Yukawa coupling ($f_t=gm_t/\sqrt{2}M_W\sin\beta$) is large. These modifications, which become important if $m_t\gtrsim100$ GeV, can be obtained by minimizing the one-loop effective potential which includes corrections arising from this large t-quark Yukawa coupling. Other corrections, e.g., due to gaugino-Higgsino loops are known to be small [16]. The calculation of the Yukawa-coupling contributions to the one-loop effective potential entails a knowledge of the field-dependent mass matrix for the third generation sfermions. As is well known [4], trilinear soft supersymmetry-breaking terms proportional to the A parameter lead to significant mixing between $\tilde{t}_L$ and $\tilde{t}_R$, so that the resulting masses and mixing patterns of the physical Higgs bosons are also A dependent. We have independently computed these radiative corrections. In order to avoid the proliferation of free parameters in our phenomenological analysis, we have neglected any $\tilde{t}_L$-$\tilde{t}_R$ mixing and assumed that all the squarks are degenerate [17]. We then find that the scalar-boson masses are given in terms of the diagonal soft breaking masses $m_{\tilde{L}}$ and $m_{\tilde{t}_R}$ of the third-generation doublet and singlet squarks by

$$m^2_{H^l_h}=\frac{m^2_{H_p}+M_Z^2+\delta\mp\xi^{1/2}}{2}\ , \tag{4a}$$

where

$$\xi=[(m^2_{H_p}-M_Z^2)\cos2\beta+\delta]^2+\sin^22\beta(m^2_{H_p}+M_Z^2)^2 \tag{4b}$$

and

$$\delta=\frac{3g^2m_t^4}{16\pi^2M_W^2\sin^2\beta}\ln\left[\left[1+\frac{m^2_{\tilde{t}_R}}{m_t^2}\right]\left[1+\frac{m^2_{\tilde{L}}}{m_t^2}\right]\right] . \tag{4c}$$

The relation between m_{H^+} and m_{H_p} is unaltered from its tree-level form

$$m^2_{H^+}=m^2_{H_p}+M_W^2 \tag{4d}$$

as long as the bottom-quark Yukawa coupling is negligible [18]. Finally, the angle α that determines the mixing between the neutral scalars is given in the convention of Ref. [19] (this differs in sign from that used in Ref. [5]) by

$$\tan\alpha=\frac{(m^2_{H_p}-M_Z^2)\cos2\beta+\delta+\xi^{1/2}}{\sin2\beta(m^2_{H_p}+M_Z^2)} . \tag{4e}$$

The couplings of all three Higgs bosons can now be readily obtained using Eq. (4).

In order to compute the cross section for the $\gamma\gamma$ signal from the production and subsequent decays of the Higgs bosons of the MSSM, we have computed the partial widths for all their two-body decays, as this is necessary to obtain the branching fraction for the $\gamma\gamma$ decay that enters via Eq. (2). All three particles can decay into fermion, sfermion (the pseudoscalar only via Yukawa couplings), chargino, or neutralino pairs, whereas at tree level only the scalars can decay via WW, ZZ, H_lH_l, H_pH_p, or ZH_p modes. In contrast, only H_p can decay into H_lZ. Notice that the decays $H_h\to ZH_p$, $H_l\to H_pH_p$, and $H_h\to H^+H^-$ are kinematically forbidden unless the radiative corrections (4) to the masses are incorporated. We have checked that for $m_{\tilde{t}}\lesssim1000$ GeV these additional decays are open only when $M_Z>m_{H_p}+m_{H_l}$ if $m_t=150$ GeV, i.e., in a region essentially excluded by the LEP searches [20] for the Higgs bosons of the MSSM. For heavier top-quark masses, the decay $H_h\to Z+H_p$ is allowed in a region not accessible to LEP, whereas for a very heavy top-quark masses ($m_t > 200$ GeV, which, we recognize, may well be on the verge of being excluded by global fits of the MSSM to all available data), even the decays $H_l \to H_p H_p$ and $H_h \to H^+ H^-$ may be accessible.

Within the framework of SUSY, the partial widths for the two-photon decays of scalar and pseudoscalar Higgs bosons were first computed by Kalyniak, Bates, and Ng [21]. The corresponding decay rates, with masses and mixings as given by the MSSM, have subsequently been computed [22,23]. The width for the decays into gluons can be simply obtained from the contributions of quark and squark loops to the $\gamma\gamma$ decay width by obvious changes of coupling constant and color factors. We have independently computed these widths using the expressions in Eq. (4). We agree with the formula for the $\gamma\gamma$ partial width as given in Ref. [22] (and, except for a typographical error, with that in Ref. [5]), but differ with the corresponding expressions as given in Ref. [23]. We do not present our formulas her for the sake of brevity.

In our calculation of the $\gamma\gamma$ cross section, we have ignored the interference between $gg \to H \to \gamma\gamma$ and $gg \to \gamma\gamma$ (via box) amplitudes. This is a valid approximation for Higgs scalars (pseudoscalar) with $m_H < 2M_W$ ($2m_t$) for which we find an observable signal. To see this, note that the interference can only be large when the loop amplitudes for Higgs-boson decay develop large imaginary parts [10], in which case the corresponding tree-level two-body decay width also becomes large, so that the $\gamma\gamma$ branching fraction, and hence, the signal is strongly suppressed.

The cross section for the production of $\gamma\gamma$ pairs via the decay of any of the three neutral Higgs bosons at the SSC is shown in Fig. 2 versus m_{H^+}. On the upper scale, we have marked some corresponding values of m_{H_p} to aid the reader. The three curves correspond to H_l (solid), H_h (long-dashed), and H_p (short-dashed). In order to fix the chargino sector which enters also via its loop contribution to the $\gamma\gamma$ partial width, we have nominally chosen $m_{\tilde{g}} = 500$ GeV and $\mu = -200$ GeV and illustrated the cross sections for (a) $\tan\beta = 1$, (b) $\tan\beta = 3$, and (c) $\tan\beta = 10$. In these figures, we have fixed $m_t = 150$ GeV and taken the squarks to be degenerate with a mass of 1 TeV. The numbers on the solid and long-dashed curves denote the masses of the light and heavy scalars, respectively. The following points are worthy of note.

(i) The cross section for $\gamma\gamma$ production from H_l exceeds $\sim 10^{-2}$ pb over almost the whole mass range, so that in excess of ~ 100 events may be expected annually at the SSC. For $\tan\beta = 1$, the light Higgs boson is always lighter than M_Z, but for $\tan\beta \gtrsim 2.5$, it is in the intermediate-mass range over a large range of m_{H^+} values. For a Higgs-boson mass of 100 GeV, we see from Fig. 1 that the signal is observable after one (five) year(s) of running at the SSC if the cross section exceeds 0.05 pb (0.02 pb). We will return to the observability of the cross section below.

(ii) The cross section for $\gamma\gamma$ production by the decay of H_p is generally large only when $\tan\beta$ is close to unity. As $\tan\beta$ moves away from unity, the coupling of the boson to the top loop, being proportional to $\cot\beta$, decreases while that to the bottom quarks increases. Thus, the partial widths for the decay $H_p \to gg$ or $H_p \to \gamma\gamma$ are each reduced by a factor of $\tan^2\beta$ (assuming the $\gamma\gamma$ decay is dominated by top loops), while the total width, which is dominated by $H_p \to b\bar{b}$ unless decays to neutralinos are kinematically accessible, increases as $\tan\beta$. From (2) we thus expect a $\cot^6\beta$ dependence of the cross section at least in the neighborhood of $\tan\beta = 1$ where top quarks dominate the loop decays. This is the basic reason why the cross section for $\gamma\gamma$ production from H_p decays drops so sharply as $\tan\beta$ moves away from 1. The actual behavior is complicated by the fact that chargino loops may interfere constructively or destructively with the t-quark loop, depending on the sign of μ, and for very large values of $\tan\beta$, bottom-quark- and τ-loop contributions are not negligible. However, although it may be possible to enhance the cross section by an order of magnitude over the values shown in Fig. 2 by varying μ, we have verified that this enhancement is not sufficient to give an observable signal when $\tan\beta > 2$. It is, however, interesting to note from Fig. 2(a) that there is an observable rate for H_p even when its mass exceeds $2M_W$, since there is no tree-level coupling of H_p to a W pair.

(iii) We see that the cross sections for producing $\gamma\gamma$ pairs via the decay of the heavier Higgs scalar are generally very small unless the charged-Higgs-boson mass is smaller than about 150 GeV. This is because if the H_h is heavy, then two-body tree-level decays other than $H_h \to b\bar{b}$ are kinematically accessible; this, of course, reduces the fraction of $H_h \to \gamma\gamma$ decays. The thresholds for vector-boson decays of the H_h are seen as kinks in the long-dashed curves. For the small values of m_{H^+} in Figs. 2(b) and 2(c), the cross section decreases because the decay $H_h \to H_l H_l$ becomes accessible. In contrast, the reason for the drop in Fig. 2(a) is the accessibility of the decay $H_h \to H_p Z$, which has a relatively large width even if the available phase space is quite small. Finally, we note that the dip at $m_{H^+} = 120$ GeV in Fig. 2(a) is due to cancellations between W and t-quark loops in the $H_h \to \gamma\gamma$ amplitude.

(iv) We have checked that the qualitative features of Fig. 2 discussed above are independent of the precise value of μ or m_t, although, as discussed in (ii), some cross sections may be altered by even an order of magnitude in specific regions of the parameter space. We have also checked that the general features of Fig. 2 do not change when m_t is varied between 100 and 200 GeV. The most notable change is that for a very heavy top quark the decay $H_h \to H_p Z$, which has a large branching fraction when it is allowed, remains accessible even when m_{H^+} is as heavy as 135 GeV if $\tan\beta$ is close to 1 ($m_{H^+} = 95$ GeV for all values of $\tan\beta$). The decay $H_h \to H^+ H^-$ is also accessible when $m_{H^+} < 90$ GeV. These decays obviously lead to a reduction of the signal if they are kinematically allowed.

In order to assess the prospects for the detection of intermediate-mass MSSM Higgs bosons at the SSC, we have delineated in Figs. 3(a)–3(c) the regions of the

m_{H_+}-tanβ plane where the $\gamma\gamma$ signal is observable with the 99%-confidence-level criterion [Eq. (3)]. For the purpose of illustration we have taken all squarks to be degenerate with $m_{\tilde{q}}=2m_{\tilde{g}}=1$ TeV and fixed $m_t=150$ GeV, $\mu=-200$ GeV in Fig. 3(a). In order to illustrate the dependence of this region on μ and m_t, we have also shown the regions where the signal is observable when μ is changed to 200 GeV, or when the top-quark mass is taken to be 200 GeV in Fig. 3(b) and Fig. 3(c), respectively. Also shown in Fig. 3 is the boundary of the region

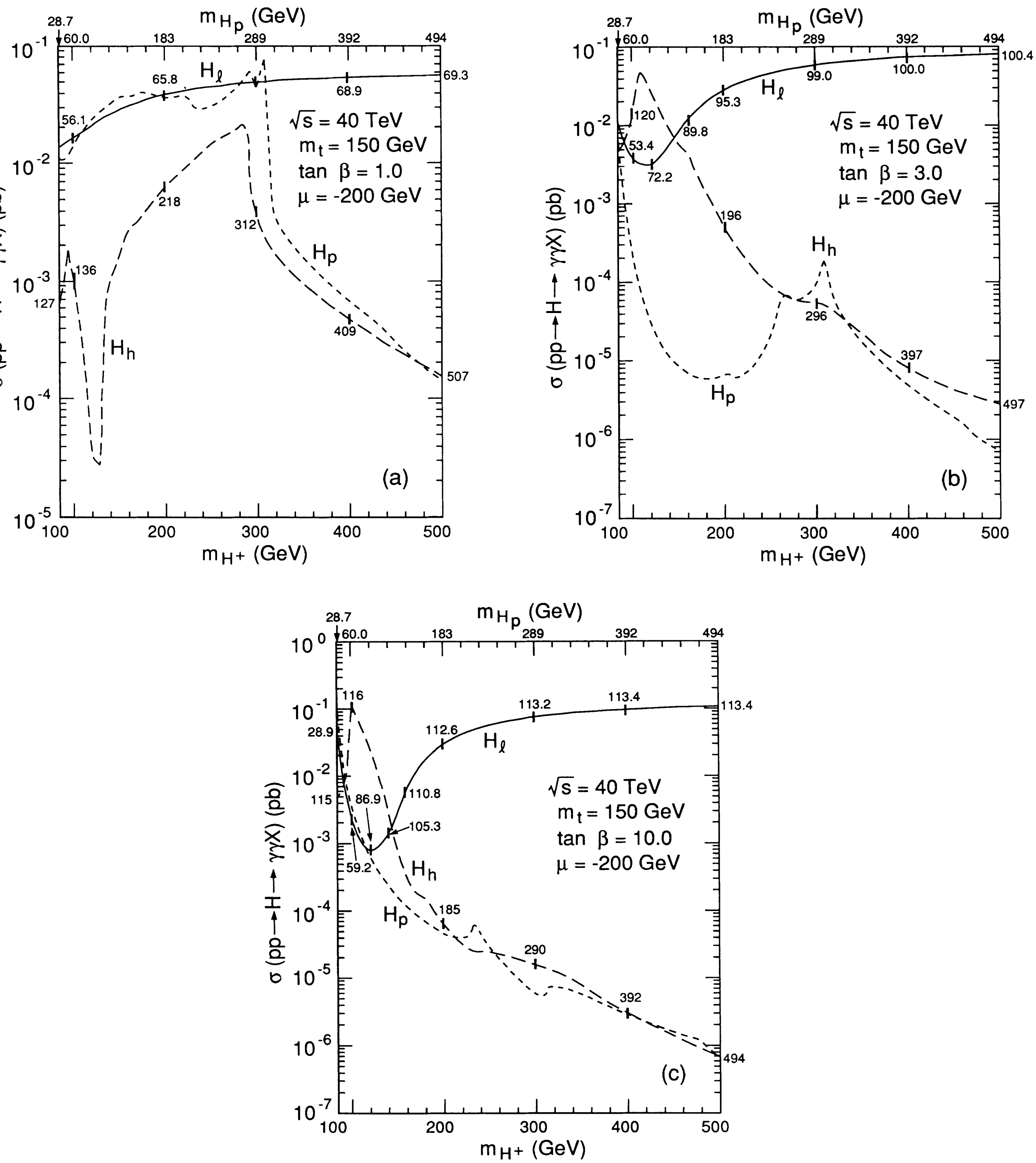

FIG. 2. (a) The total cross section for $pp\to H_{\rm SUSY}\to\gamma\gamma$ vs m_{H^+} at $\sqrt{s}=40$ TeV, with $m_t=150$ GeV, $\mu=-200$ GeV, $m_{\tilde{q}}=2m_{\tilde{g}}=1000$ GeV and (a) tan$\beta=1$, (b) tan$\beta=3$, and (c) tan$\beta=10$. The various curves are denoted by H_l (solid), H_h (long-dashed), and H_p (short-dashed). The numbers on the H_l and H_h curves denote their masses for the corresponding value of m_{H^+}, while corresponding values of m_{H_p} are indicated on the top scale.

where $m_{H_l} < 90$ GeV, i.e., to the left of this boundary it should be possible to search for H_l at LEP 200, except in a region where $\tan\beta$ is large [6]. The remaining solid (dashed) lines mark the boundaries of the regions where the $\gamma\gamma$ signal for the corresponding Higgs boson is expected to be visible at the SSC after one year (five years) of running, assuming as in Sec. II that the detector is capable of a mass resolution of $\pm 1\%$. We have checked that there is little overlap between the region of parameter space that can be searched at the SSC and that which is currently excluded by experiments at LEP [20]. We observe the following.

(i) If $m_{H_l} > 90$ GeV, the $\gamma\gamma$ decays of H_l lead to an observable signal at the SSC even after just one year of running unless the charged Higgs boson is relatively light. We see, however, that the region in which the signal is visible is somewhat sensitive to the choice of SUSY parameters; for instance, if $\mu = -200$ GeV, we see from Fig. 3(a) that the signal may be too small to be observable if $\tan\beta \lesssim 3-4$ even if m_{H^+} is relatively large. The dashed contour for H_l, however, illustrates that if the SSC is operated for over five years, the two-photon decays of H_l lead to an observable signal for the whole range of $\tan\beta$, provided $m_{H^+} \gtrsim 200$ GeV.

(ii) The $\gamma\gamma$ decays of the heavy Higgs scalar are generally visible only if m_{H^+} is rather small and $\tan\beta$ is not close to unity. This is completely in keeping with our earlier discussion of Fig. 2. Although we have not shown this, the size of the "H_h region" reduces if the top-quark mass is small. In this case, however, the radiative corrections to the Higgs sector from the top-quark Yukawa interactions are small, so that the prospects for discovering H_l at LEP 200 are greatly increased. Although we have included the three-body decays to WW^* and ZZ^* in our computation, we have checked that these do not greatly affect the results of Fig. 3 even though $\cos(\alpha+\beta)$, which enters the $H_h VV$ coupling, is not especially small for parameters near to the edge of the H_h region. The reason is that either the $H_h b\bar{b}$ coupling is enhanced for large values of $\tan\beta$, or decays of H_h into $H_p Z$ or H_l or H_p pairs become allowed. An increase of the two-body decay modes of H_h obviously reduces the importance of the three-body WW^* decays. Finally, H_l is generally too light for the WW^* decay of H_l to have a significant effect. It is important to notice that unless m_t is very large, H_h can be discovered by its $\gamma\gamma$ decays only if H_l is light enough to be discoverable at LEP 200. Discovery of H_l at LEP along with discovery of an intermediate-mass H_h is, however, very important since it could lead to direct evidence for a "beyond the SM" symmetry-breaking sector.

(iii) It is also interesting to observe that Fig. 3 implies that, if $m_t > 150$ GeV and $\tan\beta > 3$, a discovery of the light Higgs bosons at LEP 200 must be accompanied by the simultaneous discovery of either the charged Higgs boson at LEP 200 or the H_h at the SSC and/or LHC. One should, however, view such a strong conclusion, which could lead to a striking confirmation of the MSSM framework, with some caution. In our calculations of the

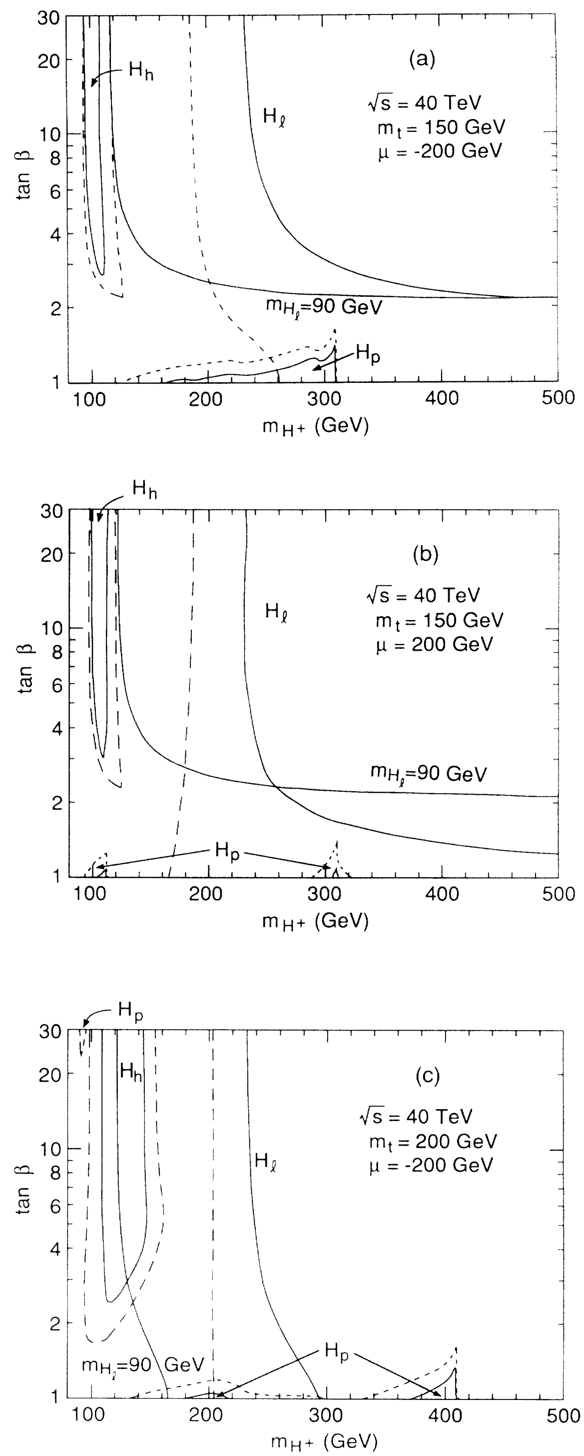

FIG. 3. (a) The regions in the m_{H^+}-$\tan\beta$ plane where $pp \to H_{\rm SUSY} \to \gamma\gamma$ is observable by the 99%-confidence-level criterion of Eq. (3) at a pp collider with $\sqrt{s} = 40$ TeV for $m_t = 150$ GeV, $\mu = -200$ GeV, and $m_{\tilde{q}} = 2m_{\tilde{g}} = 1000$ GeV. Integrated luminosity is 1×10^4 pb^{-1} (solid) and 5×10^4 pb^{-1} (dashed). The curve of $m_{H_l} = 90$ GeV is also shown by a solid line. (b) The same as in (a) except $\mu = +200$ GeV. (c) The same as in (a) except $m_t = 200$ GeV. The regions of favorable observability have the particle label located on the inside of the region or are marked by an arrow.

radiative corrections which lead to the formulas presented in Eq. (4), we have, as already mentioned, made two simplifying assumptions in neglecting (a) the bottom-quark Yukawa coupling f_b and (b) $\tilde{f}_L$-$\tilde{f}_R$ mixing. The neglect of the bottom-quark Yukawa coupling is justified as long as $\tan\beta \ll m_t/m_b$. Thus, for the very largest values of $\tan\beta$ shown in Fig. 3, our computation of the contours should be viewed with some caution. A nonzero value of f_b, or nonzero mixing between the sfermions, alters the mass formulas [7] in Eq. (4) [even (4d) may receive additional contributions [18]], so that our conclusions should be viewed in the proper perspective.

(iv) Finally, we see that the pseudoscalar bosons are observable via their $\gamma\gamma$ decays only when $\tan\beta$ is close to unity for reasons already mentioned in (ii) of our discussion of Fig. 2. Thus, unless the t quark is very heavy, the signal from $H_p \to \gamma\gamma$ decays is accessible only when H_l is also kinematically accessible at LEP 200. We see also that the region of observability of H_p is (a) rather sensitive to the SUSY parameter μ and (b) increases considerably if the machine can be run for a longer period.

In order to compare the capabilities of the LHC and the SSC for the observation for the $\gamma\gamma$ signal from the Higgs bosons for the MSSM, we have shown in Fig. 4 the regions where the signal is observable (at 99% C.L.) at the LHC for integrated luminosities of 10^4 pb^{-1} and 20×10^4 pb^{-1}. For brevity, we have only shown the results for $\mu=-200$ GeV and $m_t=150$ GeV, corresponding to Fig. 3(a) for the SSC. We see that, with just 10^4 pb^{-1} of integrated luminosity, the only observable signal comes from $H_p \to \gamma\gamma$ decays in a tiny region of parameter space. This should not be very surprising if we recall that H_l is lighter than 115 GeV over the whole range of parameters shown in the figure. We see from Fig. 1 that even a SM Higgs boson with a mass smaller than 100 GeV is unobservable after just one year of running at the LHC (recall that the coupling of SUSY scalars is usually suppressed by mixing factors from that of the SM Higgs-boson), and further that a Higgs boson with a mass of 115 GeV would be unobservable if its couplings are suppressed by just about 25%. Of course, if m_t is very large, it is possible that H_l is heavy enough for its signals to be observable even after just one year of operation of the LHC. Also shown in Fig. 4 are regions where the MSSM Higgs bosons can be searched for with an integrated luminosity of 2×10^5 pb^{-1}, which can be accumulated in two years if the LHC can be operated at a luminosity an order of magnitude greater than the design luminosity of the SSC. We then see that the region that can be probed at the LHC (at design luminosity) is comparable to the region that the SSC can probe after about five years of operation.

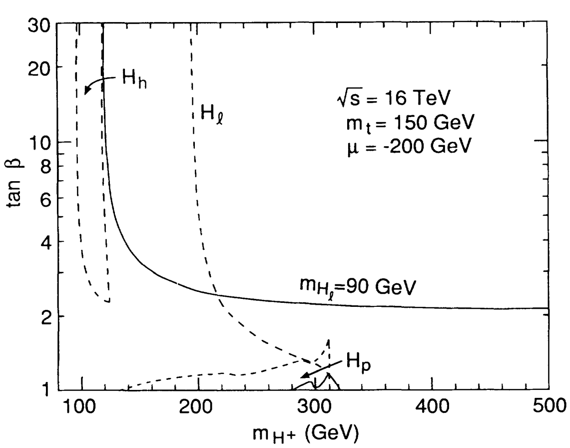

FIG. 4. The same as Fig. 3(a) except at $\sqrt{s}=16$ TeV. Here, the integrated luminosity is assumed to be 1×10^4 pb^{-1} (solid) and 20×10^4 pb^{-1} (dashed).

Our main conclusion from Fig. 3 and Fig. 4 is that even with our generous assumptions about the $\gamma\gamma$ mass resolution that may be achieved by future detectors, there are regions of parameter space where there are no observable $\gamma\gamma$ signals from any of the Higgs bosons and where all three Higgs bosons are in the intermediate-mass range. Further, if μ, $m_{\tilde{g}}$, $m_{\tilde{q}}$, and $m_{\tilde{l}}$ are all large, there are no SUSY decays of these Higgs bosons, so that it appears quite possible that their signals may be entirely unobservable even after several years of operation of a hadron supercollider. It is thus imperative that other strategies, probably involving the examination of other rare decay modes, be examined in the context of the MSSM.

IV. CONCLUDING REMARKS

We have studied the prospects for discovering the Higgs bosons of the minimal supersymmetric model via their $\gamma\gamma$ decays at hadron supercolliders. Our study was mainly motivated by the recent observation [7] that the expectations for the masses of these Higgs bosons are significantly altered from their tree-level values if the top quark is heavy as it now appears to be [8]. In particular, the bound (1a) on the mass of the lighter scalar H_l is no longer valid, so that earlier [6] analyses, which concluded that the signals from at least one of the Higgs bosons would be observable at LEP 200, are no longer tenable. For a wide range of parameters, m_{H_l} is expected to be in the intermediate-mass range, so that it would be inaccessible at LEP 200. It would then have to be searched for at the hadron supercolliders that have been proposed for construction during this decade. Many previous studies [5,9,10] of strategies to search for SM Higgs bosons at hadron colliders suggest that the decay $H\to\gamma\gamma$ provides one of the most promising signatures when $M_Z < m_H < 2M_W$. Furthermore, it is even possible that the pseudoscalar Higgs boson H_p as well as the heavier scalar boson H_h also have masses in this range, so that the signals from their dominant (hadronic) decays will be swamped by QCD backgrounds. The main purpose of this paper was to study whether the $\gamma\gamma$ decays of MSSM Higgs bosons can lead to an identifiable mass bump on top of the $\gamma\gamma$ continuum at either the SSC or the LHC.

In order to facilitate comparison with previous calculations [9] we have performed our own analysis of the $\gamma\gamma$ signal for the SM Higgs boson in Sec. II. We find that the signal is observable at the 99% C.L. over the whole intermediate-mass range with just one year of operation of the SSC at the design luminosity, and also at the LHC if the luminosity is larger by a factor of about 2. In arriving at this conclusion, we have assumed that the detector includes a hermetic electromagnetic calorimeter capable of a $\pm 1\%$ mass resolution.

Our main results are summarized in Fig. 3 (SSC) and Fig. 4 (LHC), where we have shown regions of the $\tan\beta$-m_{H^+} plane where the $\gamma\gamma$ decays of the Higgs bosons lead to an identifiable signal, assuming the same type of calorimeter and signal criteria as in Sec. II for the SM Higgs bosons. In these figures, we have taken $m_{\tilde{q}}=2m_{\tilde{g}}=1$ TeV. Our results are insensitive to the choice of $m_{\tilde{q}}$ as long as it is large, while $m_{\tilde{g}}$ essentially enters only by determining the chargino and neutralino masses which can, of course, affect the decay patterns of the Higgs bosons if they are sufficiently light.

We see from Fig. 3 that after just a few years of SSC operation, it should be possible to identify the lightest Higgs boson if it is in the intermediate-mass range, provided only that m_{H^+} is relatively heavy. The identification of H_h (H_p) via decay to $\gamma\gamma$ is possible only if m_{H^+} is very small ($\tan\beta$ is close to unity). The various supersymmetric Higgs bosons ought to be observable at the LHC in much the same regions of parameter space that are favorable for an SSC discovery, although higher integrated luminosities will be required for a similar detector.

We note here that our conclusions concerning the observability of the $\gamma\gamma$ decay mode of the Higgs bosons of supersymmetry are considerably more optimistic than the previous analysis of Gunion *et al.* [22]. The major difference in our present analysis from Ref. [22] is the incorporation of radiative corrections to the Higgs-boson masses, which allows the light scalar mass to significantly exceed the tree-level bound of M_Z. This results in a larger cross section for $pp \to H_l X \to \gamma\gamma X$, as well as a less severe SM background. Furthermore, incorporation of QCD corrections to Higgs-boson decays reduces $H \to b\bar{b}$, which enhances the $H \to \gamma\gamma$ branching fraction.

It is very important to observe that there are significant regions of the $\tan\beta$-m_{H^+} plane in Fig. 3 where the $\gamma\gamma$ signal from all the Higgs bosons is unobservable. Further, if m_t is indeed around 150 GeV, all three Higgs bosons may well be in the intermediate-mass range, so that the signals from their dominant decay modes will be obscured by QCD backgrounds. Our analysis shows that, despite our optimistic assumptions about the capabilities of the detector, there may be no observable signal from their production at supercolliders, even if the detector has the capability to identify a SM Higgs boson over the complete intermediate-mass range. It is, therefore, necessary to explore other avenues via which the Higgs bosons may be identified at hadron supercolliders.

For the SM Higgs boson in the intermediate-mass range, several rare decay modes have been assessed: the ZZ^* (WW^*) modes [9], or their doubly virtual counterparts, have been shown [24] to lead to observable signals if the Higgs-boson mass exceeds about 140–145 GeV. The production of a SM Higgs boson (which decays to a $\gamma\gamma$ pair) in association with a leptonically decaying W boson has been shown [9,25] to result in 6 (3) events/SSC year after experimental cuts for $m_H=75$ GeV (150 GeV), so that it may conceivably lead to an observable signal after the SSC is operated for a few years. Although it may be worth reexamining each of these signals for the case of MSSM Higgs bosons, it seems fair to point out the following. (i) Scalar mixing reduces the HWW and HZZ coupling from the SM values for both H_h and H_l, so that the MSSM cross sections will be generally smaller than the corresponding SM cross section. (ii) H_p, because it does not couple to vector bosons, cannot be detected via these processes. More recently, it has been suggested [26] that $Ht\bar{t}$ production, where $H \to \gamma\gamma$ (and a lepton from t decay is used as a tag), may lead to an observable signal for an intermediate-mass Higgs boson, at least at the SSC. We only note that the couplings of all three Higgs bosons to t-quarks may be smaller than the SM Higgs-boson coupling if $\tan\beta$ is large.

A completely different alternative may be to explore the signals from Higgs bosons produced via cascade decays of squarks and gluinos. As is well known, it is possible by suitable cuts to isolate a relatively clean sample of SUSY events. If $m_{H^+} < 150$–200 GeV, there is a significant branching fraction for the production of all three Higgs bosons in the decay cascades of squarks and gluinos. These signatures have been recently investigated in Ref. [27].

To summarize, we have explored the prospects for identifying the Higgs bosons of the MSSM via their two-photon decays. We have incorporated important radiative corrections to the Higgs-boson masses and mixings. It is possible to identify *each* of the neutral Higgs bosons via $\gamma\gamma$ decays in *some* region of parameter space. However, if $m_{H^+} < 200$ GeV [28], there exist regions of parameter space where *none* of the neutral Higgs bosons are visible via $\gamma\gamma$ decays. If that is the case, either new detection strategies will have to be developed at hadron supercolliders or a thorough exploration of the Higgs sector of the MSSM will have to await the construction of a high-luminosity e^+e^- collider operating at $\sqrt{s} \simeq 500$ GeV.

Note added. After completion of this manuscript, we received two papers where similar work was reported [29].

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