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Invisible decays of Higgs bosons in supersymmetric models

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We point out that the dominant decay of the light scalar Higgs boson in a supersymmetric model may be into a pair of the lightest neutralinos (assumed to be the lightest supersymmetric particles), which would result in an invisible final state. Thus, in the search at the Stanford Linear Collider and the CERN collider LEP for a Higgs scalar produced in association with a real or virtual Z boson, it is important not to cut out events with significant missing energy recoiling against the Z.

I. INTRODUCTION

The search for a Higgs boson will be an important part of the experimental program at the Stanford Linear Collider (SLC) and the CERN collider LEP. At present, the experimental bounds on the existence of Higgs scalars is rather meager. Taking all theoretical uncertainties into account, one can only conclude at present[1] that the Higgs boson must have a mass larger than about 15 MeV. Recent results from the CLEO Collaboration[2] at the Cornell Electron Storage Ring (CESR) suggest that the Higgs-boson mass must be larger than 3.6 GeV, although this conclusion is based on the assumed knowledge of various B-meson branching ratios[3] (involving the Higgs boson). In principle, additional B-meson data (and additional data on radiative Υ decays) from CESR and the DESY storage ring DORIS will lead to a Higgs-boson mass bound of order 4 GeV. Further improvement of the situation must await e^+e^- colliders with $\sqrt{s} \geq m_Z$, and/or a very-high-luminosity pp supercollider. By running on the Z pole, SLC and LEP (at design luminosity) will be sensitive to Higgs-boson masses up to about 40 GeV (Refs. 4 and 5). When LEP is finally upgraded to a center-of-mass energy of 200 GeV, it will be sensitive to Higgs-boson masses as high as 80 GeV (Ref. 5).

Many theoretical arguments have been made which suggest that the standard model with one physical elementary Higgs boson is an incomplete theory. The only known theory in which scalar particles are elementary and which possesses a mechanism for understanding the large hierarchy between the electroweak scale and the Planck scale is supersymmetry. In this view, the discovery of a Higgs boson at SLC and/or LEP could be interpreted as the first evidence for supersymmetry. This would be a theoretical argument based on the fact that we know of no other sensible theoretical framework which contains light Higgs scalars with a mass less than that of the Z boson. It is important to reconsider the search for Higgs scalars at SLC and LEP in light of these remarks. In the supersymmetric framework, the Higgs sector is more complicated than in the standard model,[6,7] so one needs to examine whether the Higgs phenomenology is any different (as compared with the standard model) and determine the implications for the Higgs-boson searches at SLC and LEP.

In Sec. II, we review the basic properties of Higgs bosons in the minimal supersymmetric extension of the standard model. In Sec. III, we present formulas for the decay width of the lightest Higgs scalar and pseudoscalar into a pair of neutralinos. If the final-state neutralinos are identical and are the lightest supersymmetric particles, then this decay mode will be invisible. Section IV contains the main results of this paper. We have surveyed the supersymmetric parameter space in order to determine where the branching ratio for invisible Higgs-boson decay can be large. Our conclusions are summarized in Sec. V.

II. HIGGS BOSONS IN THE MINIMAL SUPERSYMMETRIC EXTENSION OF THE STANDARD MODEL

For simplicity, we will consider the minimal supersymmetric extension of the standard model.[8] This model contains two Higgs doublets (required to give mass to both up- and down-type quarks, consistent with the supersymmetric constraints). After spontaneous symmetry breaking, five physical Higgs bosons remain: a charged-Higgs-boson pair ($H^{\pm}$), a neutral pseudoscalar (H_3^0), and two neutral scalars (H_1^0 and H_2^0). The notation used here is that of Ref. 7; by convention, we shall take $m_{H_1^0} \geq m_{H_2^0}$. Apart from the masses of the physical Higgs particles, the model depends on two additional parameters: a mixing angle α which results when one diagonalizes the neutral scalar mass matrix, and the ratio of vacuum expectation values:

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

where v_2 is the vacuum expectation value of the Higgs doublet which couples to the up-type quarks. Supersymmetry imposes strong constraints on the parameters of the Higgs sector. For example, given the Higgs-pseudoscalar mass ($m_{H_3^0}$) and $\tan\beta$, we may compute the mixing angle α (Ref. 9) and the other Higgs-boson masses as follows:

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

$$m_{H_1^0,H_2^0}^2 = \tfrac{1}{2}\{m_{H_3^0}^2 + m_Z^2 \pm [(m_{H_3^0}^2 + m_Z^2)^2 - 4m_Z^2 m_{H_3^0}^2 \cos^2 2\beta]^{1/2}\} , \tag{3}$$

$$\cos 2\alpha = -\cos 2\beta \left[\frac{m_{H_3^0}^2 - m_Z^2}{m_{H_1^0}^2 - m_{H_2^0}^2} \right] , \tag{4}$$

$$\sin 2\alpha = -\sin 2\beta \left[\frac{m_{H_1^0}^2 + m_{H_2^0}^2}{m_{H_1^0}^2 - m_{H_2^0}^2} \right] . \tag{5}$$

These relations imply that the other masses are restricted such that (i) $m_{H_1^0} \geq m_Z$, (ii) $m_{H_2^0} \leq m_{H_3^0}$, (iii) $m_{H_2^0} \leq m_Z \mid \cos 2\beta \mid \leq m_Z$, and (iv) $m_{H^+} \geq m_W$. Furthermore, the phases of the Higgs fields can be chosen such that $0 \leq \beta \leq \pi/2$, which implies that $-\pi/2 \leq \alpha \leq 0$.

The implications for the detection of Higgs bosons at SLC and LEP are clear: H_2^0 is almost certainly light enough to be observable, while H_1^0 and $H^\pm$ are too heavy to be observable. The fate of H_3^0 is less certain, as its mass is unconstrained. To make the discussion more precise, we must consider both production mechanisms and modes of detection. There are two basis mechanisms which may be responsible for Higgs-boson production at SLC and LEP. The first, shown in Fig. 1(a), is the process $e^+e^- \to H_2^0 f\bar{f}$, which proceeds via the $H_2^0 ZZ$ coupling in which one of the two Z's is on shell and the other Z is virtual. Normally, the associated fermion pair ($f\bar{f}$) produced is e^+e^- or $\mu^+\mu^-$, although $\nu\bar{\nu}$ has also been considered in order to enhance the raw rate.[10] The second mechanism, shown in Fig. 1(b), would be relevant only if the top quark is not too heavy so that toponium is produced as a real bound state. Note that in Fig. 1(a), only the scalar H_2^0 can be produced, since there is no $H_3^0 ZZ$ coupling at the tree level. In Fig. 1(b), both the scalar and pseudoscalar Higgs bosons can be produced.

We will for the most part be concerned with the production of H_2^0 via the $H_2^0 ZZ$ coupling. In the two-Higgs-doublet model, this coupling is reduced by a factor of $\sin(\beta-\alpha)$ in amplitude compared to the standard model with one Higgs doublet.[7,9] However, as emphasized in Ref. 9, over nearly all of the parameter space of the supersymmetric model, $\sin(\beta-\alpha)$ is close to unity, implying the $H_2^0 ZZ$ coupling is nearly equal to its standard-model value. Thus, the predicted production cross section for Fig. 1(a) is close to the value found in the standard model.

We now turn to the detection of the Higgs boson via the process shown in Fig. 1(a). In principle, the produced Higgs boson and its decay products can be simply ignored (assuming that the Higgs boson is produced in association with an e^+e^- or $\mu^+\mu^-$ pair). One simply measures the invariant mass recoiling against the charged-lepton pair and by using the beam energy constraint, one observes a peak at the Higgs-boson mass. In practice, one may be tempted to make some assumptions about the Higgs-boson decay product. This information could be used as part of the trigger for the desired events. In the standard model, the dominant decay of a Higgs boson heavier than 10 GeV is expected to be into $b\bar{b}$ pairs, so one might be tempted to cut away events with either little hadronic activity or with large missing energy. However, consider the decay of the scalar Higgs boson H_2^0 in the supersymmetric model. We shall show below that over a region of supersymmetric parameter space, the dominant decay of H_2^0 is into a pair of the lightest neutralinos. Assuming that these are the lightest supersymmetric particles, the result will be that the Higgs will decay invisibly. Therefore, any cut or trigger which eliminates events with a significant amount of missing energy may be throwing away a large part of the Higgs signal.

III. DECAY OF THE HIGGS BOSON INTO NEUTRALINOS—FORMULAS

In the supersymmetric model, the decay of H_2^0 into quark pairs and lepton pairs may be enhanced or suppressed compared with the standard-model expectations depending on whether $\tan\beta$ is above or below 1. In addition, a new feature is the possible decay into supersymmetric final states. Decays into squark and slepton pairs are possible, but are most likely kinematically forbidden, given the recent bounds on squark masses ($M_{\tilde{q}} \gtrsim 50$ GeV) reported by the UA1 Collaboration.[11] The Higgs boson can also decay into neutralino and chargino pairs. Here, the experimental mass bounds are less stringent. There are no constraints on the lightest neutralino, which we assume to be the lightest supersymmetric particle. For charginos, the mass limits found at the DESY storage ring PETRA are around 23 GeV (Ref. 12).

In order to calculate the decay rate of the Higgs boson into neutralino pairs, we must diagonalize the neutralino mass matrix. The resulting mass eigenstates will be

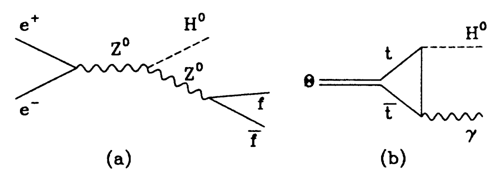

FIG. 1. Mechanisms for Higgs-boson production in e^+e^- collisions. In (a), one of the Z's is on mass shell and the other one is virtual. The corresponding Higgs boson must be a scalar. In (b), either scalar or pseudoscalar Higgs boson can be produced in heavy-quarkonium (Θ) decay.

denoted by $\tilde{\chi}_i^0$, where the neutralinos are labeled such that their masses *increase* with the subscript which labels the particle. (For example, $\tilde{\chi}_1^0$ is the lightest neutralino.) The parameters of the mass matrix are $\tan\beta$, the gaugino Majorana mass parameters M and M', and the supersymmetric Higgs-boson mass parameter μ. If we assume that the gaugino masses are unified at the grand unification scale, then we can relate M and M' (viz., $M'=\frac{5}{3}\tan^2\theta_W M$), which reduces the number of free parameters. Using the Feynman rules of Ref. 7, the decay rate of the neutral Higgs boson into neutralino pairs is given by

$$\Gamma(H_k^0\to\tilde{\chi}_i^0\tilde{\chi}_j^0)=\frac{g^2\lambda^{1/2}[(F_{ijk}^2+F_{jik}^2)(m_H^2-M_i^2-M_j^2)-4F_{ijk}F_{jik}\epsilon_i\epsilon_j\eta_k M_i M_j]}{16\pi m_H^3(1+\delta_{ij})}\ , \tag{6}$$

where the factor of η_k is equal to 1 for the Higgs scalar ($k=2$), and is equal to -1 for the Higgs pseudoscalar ($k=3$). The factor $1+\delta_{ij}$ is inserted to allow for the case in which two identical Majorana neutralinos appear in the final state. The kinematical factor λ is given by

$$\lambda=(M_i^2+M_j^2-m_H^2)^2-4M_i^2M_j^2\ , \tag{7}$$

where the (positive) mass of the neutralino $\tilde{\chi}_i^0$ is denoted by M_i. The factor ϵ_i stands for the sign of the neutralino mass. When the neutralino mass matrix is diagonalized, we allow the sign of the ith eigenvalue (ϵ_i) to be either positive or negative. The factors F_{ijk} are given in terms of the elements of the diagonalizing matrix for the neutralinos, Z, which is defined in the $(\tilde{B},\tilde{W}_3,\tilde{H}_1,\tilde{H}_2)$ basis (where H_2 is the doublet that couples to the top quark). We assume *CP*-invariant couplings, in which case Z is a real orthogonal matrix. The factors F_{ijk} appearing in Eq. (6) are given by

$$F_{ijk}=\frac{1}{\sin\beta}\left[c_k Q_{ij}+d_k\left[R_{ij}-\frac{\epsilon_i M_i}{2m_W}\delta_{ij}\right]\right]\ , \tag{8}$$

where Q_{ij} and R_{ij} are defined by

$$Q_{ij}=\tfrac{1}{2}[Z_{i3}Z_{j2}+Z_{j3}Z_{i2}-\tan\theta_W(Z_{i3}Z_{j1}+Z_{j3}Z_{i1})]\ , \tag{9}$$

$$R_{ij}=\frac{1}{2m_W}[MZ_{i2}Z_{j2}+M'Z_{i1}Z_{j1}-\mu(Z_{i3}Z_{j4}+Z_{i4}Z_{j3})-\epsilon_i M_i\delta_{ij}]\ , \tag{10}$$

and the constants c_k and d_k are given by

$$c_k=\begin{cases}\cos(\beta-\alpha), & k=2\ ,\\ \cos2\beta, & k=3\ ,\end{cases} \tag{11}$$

and

$$d_k=\begin{cases}\cos\alpha, & k=2\ ,\\ \cos\beta, & k=3\ .\end{cases} \tag{12}$$

The expression for F_{ijk} given by Eq. (8) may be misleading in one respect due to the appearance of the factor $\sin\beta$ in the denominator. This might lead one to believe that the Higgs-boson decay rate into neutralinos is enhanced as $\beta\to 0$ (i.e., for $v_1 \gg v_2$). This effect is illusory; in fact this decay rate [Eq. (6)] is invariant under the interchange of v_1 and v_2. In order to demonstrate this fact, we first define

$$S_{ij}=\tfrac{1}{2}[Z_{i4}Z_{j2}+Z_{i2}Z_{j4}-\tan\theta_W(Z_{i4}Z_{j1}+Z_{i1}Z_{j4})]\ . \tag{13}$$

It is easy to show that

$$\frac{\epsilon_i M_i\delta_{ij}}{2m_W}=Q_{ij}\cos\beta-S_{ij}\sin\beta+R_{ij} \tag{14}$$

which implies that

$$F_{ijk}=e_k Q_{ij}+d_k S_{ij}\ , \tag{15}$$

where

$$e_k=\begin{cases}\sin\alpha, & k=2\ ,\\ -\sin\beta, & k=3\ .\end{cases} \tag{16}$$

Thus, we see explicitly that the factor of $\sin\beta$ in the denominator of Eq. (8) has canceled out. Furthermore, under $\beta\to\pi/2-\beta$, we note that the neutralino masses and the mixing elements Z_{i1} and Z_{i2} remain unchanged, whereas $Z_{i3}\to -Z_{i4}$ and $Z_{i4}\to -Z_{i3}$. This implies that $|F_{ijk}|$ is unchanged under the interchange of v_1 and v_2; hence, the Higgs-boson decay rate into neutralinos is invariant.

For completeness, we give the Higgs-boson decay rate into quark pairs:

$$\Gamma(H_k^0\to u\bar{u})=\frac{3g^2m_u^2d_k^2(m_H^2-4m_u^2)^p}{32\pi m_W^2 m_H^2\sin^2\beta}\ , \tag{17}$$

$$\Gamma(H_k^0\to d\bar{d})=\frac{3g^2m_d^2e_k^2(m_H^2-4m_d^2)^p}{32\pi m_W^2 m_H^2\cos^2\beta}\ , \tag{18}$$

where d_k and e_k are given by Eqs. (12) and (16), respectively, and the power p is

$$p=\begin{cases}\frac{3}{2}, & k=2\ ,\\ \frac{1}{2}, & k=3\ .\end{cases} \tag{19}$$

Equations (17) and (18) are valid for any up- or down-type quark. For leptonic final states, the same two equations apply if one removes the color factor of 3.

IV. BRANCHING RATIO FOR INVISIBLE HIGGS-BOSON DECAY—A SURVEY OF PARAMETER SPACE

Our strategy now is as follows. We survey the supersymmetric parameter space by varying M, μ, and $\tan\beta$. (We have assumed the unification relation $M'=\frac{5}{3}\tan^2\theta_W M$, which removes a fourth possible degree of freedom.) We then compute the corresponding chargino and neutralino masses and the decay rates of H_2^0 and H_3^0 using Eqs. (6)–(12). To compute the branching ratios of the supersymmetric modes, we also must compute the Higgs-boson decay rate into ordinary fermion pairs. (To a good approximation, we can neglect the Higgs-boson decays into gluons, photons, electrons, muons, and the three lightest quark flavors, in computing the total widths.) Since $\tilde{\chi}_1^0$ is assumed to be the lightest supersymmetric particle, $\tilde{\chi}_1^0\tilde{\chi}_1^0$ is the only supersymmetric final state which leads to an invisible Higgs-boson decay. Other supersymmetric states such as $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^+$ may be light enough to be produced; but these decay quickly into $\tilde{\chi}_1^0$ plus quark or lepton pairs. Of course, if these decays are allowed, then they must be included in the computation of the total Higgs-boson width.

In order to understand why the branching ratio into the lightest neutralino pair may be dominant, consider the plot of the lightest neutralino mass as a function of M and μ, at fixed $\tan\beta$, shown in Fig. 2. A striking feature of this three-dimensional plot is the small mountain in a region of moderate M and μ, followed by a deep valley at the base of a towering wall. The explanation of this picture is quite simple. When the neutralino mass matrix is diagonalized, its eigenvalues may be either positive or negative. The lightest neutralino corresponds to the state whose eigenvalue has the smallest absolute value. The deep valley corresponds to one of the negative eigenvalues going through zero and then becoming positive. Thus, as an example, for $\tan\beta=2$ and $M=\mu=100$ GeV, we find that $M_{\tilde{\chi}_1^0}=5.9$ GeV. Normally, one expects the decay rate of the Higgs boson into fermion pairs to be proportional to m_f^2/m_W^2. By examining Eqs. (6)–(12), one sees immediately that this expectation is too naive in the case of the neutralino decay mode. In addition to terms proportional to $M_{\tilde{\chi}_i^0}^2/m_W^2$, one finds terms which go like M^2/m_W^2 and μ^2/m_W^2 [see Eq. (10)]. Thus, it is possible for the decay into neutralino pairs to be dominant, *even if the lightest neutralino is no heavier than the b quark.* In the example quoted above, the decay branching ratio of a 40-GeV Higgs boson into the lightest neutralino pair is about 90%, even though the lightest neutralino has a mass less than 6 GeV. Note that the branching ratio to $\tilde{\chi}_1^0\tilde{\chi}_1^0$ will be largest when other supersymmetric final states are kinematically forbidden. In the example just given, $M_{\tilde{\chi}_1^+}=26$ GeV and $M_{\tilde{\chi}_2^0}=64$ GeV, so that for any Higgs boson of mass below 52 GeV, the $\tilde{\chi}_1^0\tilde{\chi}_1^0$ mode is the only supersymmetric channel open.

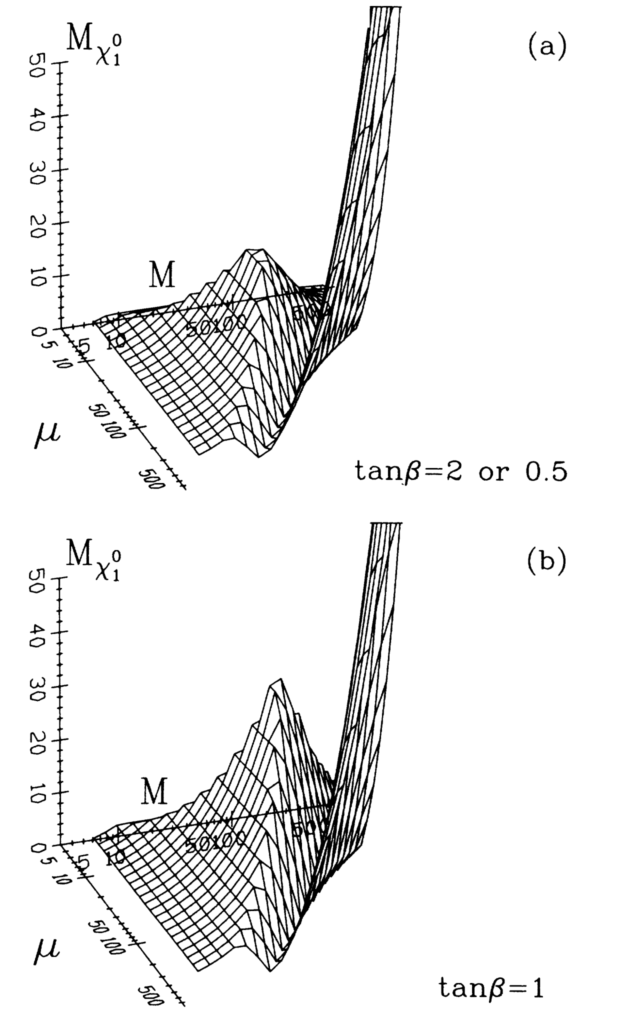

FIG. 2. Three-dimensional plot of the lightest neutralino mass (in GeV) as a function of M and μ, for (a) $\tan\beta=2$ or 0.5, and (b) $\tan\beta=1$. M and μ are each plotted on a logarithmic scale, with $5\le M,\mu\le 500$ GeV. See discussion above Eq. (6) for the definition of the supersymmetric parameters.

In the course of the analysis, one must check a number of things. First, since we have assumed that $\tilde{\chi}_1^0$ is the lightest supersymmetric particle, we must reject the small region of parameter space where the lightest chargino is lighter than $\tilde{\chi}_1^0$. Second, one notices that in the example cited above, the lightest chargino is rather light. A number of experimental groups at PETRA have[12] presented analyses which claim to rule out charginos lighter than 23 GeV. These analyses are quite complex, and the results depend somewhat on the gaugino/Higgsino content and the mass of the lightest neutralino. Nevertheless, we shall take this bound seriously, and impose it as a condition on our analysis. This will have the effect of ruling out certain regions of M and μ where the chargino is too light.

There have also been a number of discussions in the literature by theorists concerning possible limits on chargino masses which can be obtained from data collected at the CERN $\bar{p}p$ collider. Chamseddine *et al.* [13] have argued that the UA1 monojet data[14,15] could be used to imply that $M_{\tilde{\chi}_1^+} \gtrsim 35$ GeV. Similar bounds were obtained by Baer *et al.*[16] by considering various types of event topologies with substantial missing transverse energy in association with hadronic jets and/or isolated leptons. Such events could be generated by the decay of W and Z bosons into neutralinos and charginos. (Similar signatures have also been discussed in Refs. 17 and 18.) Thus it appears that the experimental absence of anomalous W decays would provide stronger constraints on chargino masses than those obtained by PETRA. However, we believe that the claims of a chargino mass limit beyond those obtained by PETRA are probably premature. The theoretical work referred to above is suggestive, but it should not be regarded as providing a definitive experimental limit. The only experimental result from the CERN collider regarding charginos which we are aware of concerns the chargino limits quoted by the UA2 Collaboration.[19] However, their results depend on the assumption of a light sneutrino and are therefore not relevant if $M_{\tilde{\nu}} > M_{\tilde{\chi}_1^+}$. One may be tempted to invoke the UA1 limit on heavy leptons from W decay[15] ($m_L > 41$ GeV) obtained from the analysis of the monojet data, in order to derive similar limits on chargino masses due to the nonobservation of $W^+ \to \tilde{\chi}_1^+ \tilde{\chi}_1^0$. However, the UA1 heavy-lepton mass limit assumes an associated zero-mass neutrino. Calculations performed in Ref. 20 indicate that the heavy-lepton mass limit would disappear entirely if $m_{\nu_L} \gtrsim 8$ GeV. Clearly, any chargino mass limit derived from observations of W decay depends on the mass and mixing angles of $\tilde{\chi}_1^0$ and hence will be rather model dependent. (This point has also been recently emphasized in Ref. 21.) Thus, we believe that it is reasonable to present results here assuming that only the PETRA chargino mass limits are

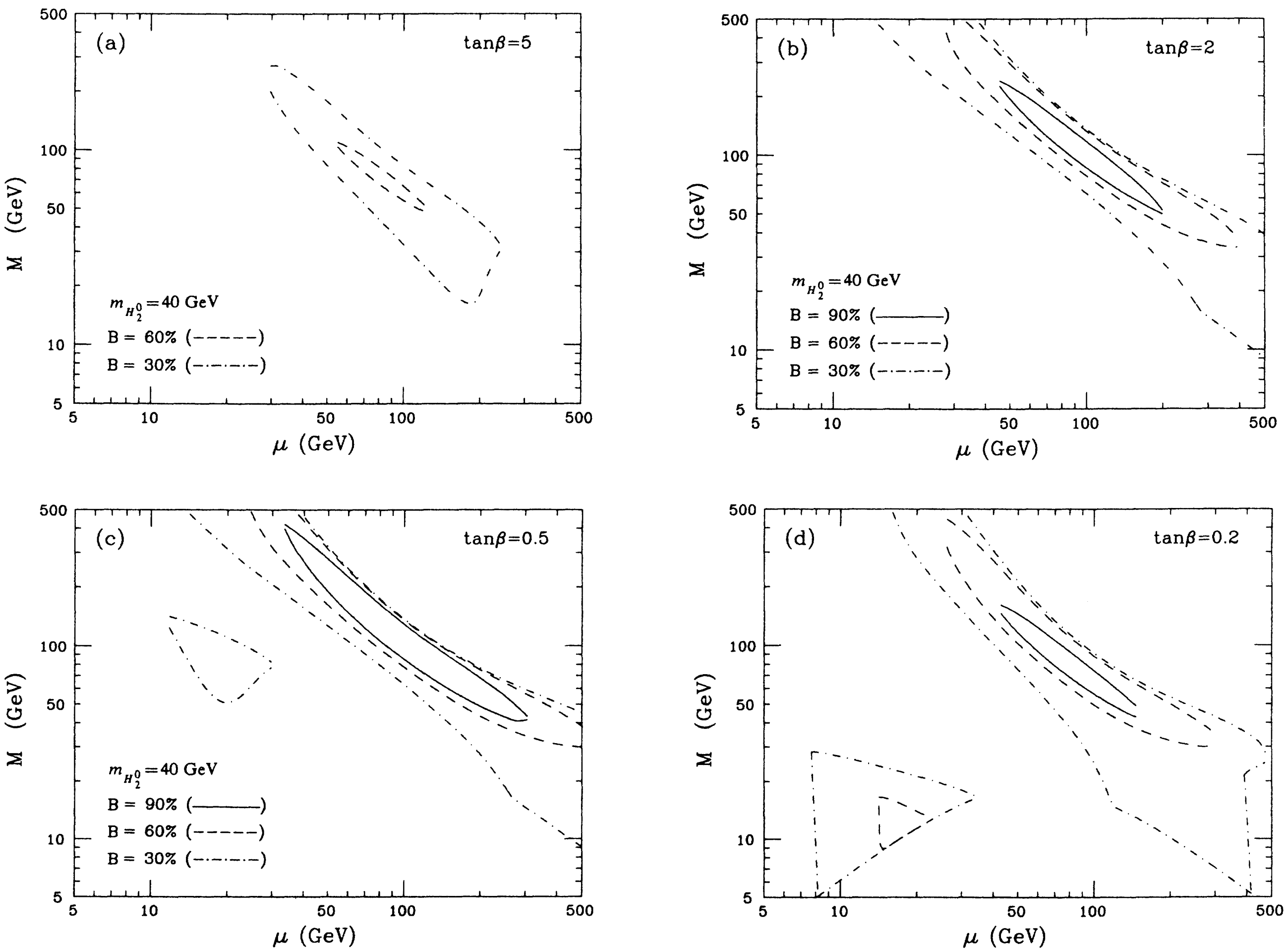

FIG. 3. Branching ratio contours for invisible Higgs-boson decay. We display the branching ratio of the lightest Higgs scalar to decay into a pair of the lightest neutralinos ($H_2^0 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$). The contours displayed correspond to branching ratios of 30% (dotted-dashed line), 60% (dashed line), and 90% (solid line). We take $m_{H_2^0} = 40$ GeV, and show plots for various possible tanβ.

operative. Of course, we expect to have improved mass bounds from the $p\bar{p}$ colliders and from SLC and LEP in the next few years. As a result, we shall also present curves corresponding to chargino mass limits of 30 and 40 GeV, in order to indicate how our conclusions would change if the chargino mass limits were improved.

We now turn to the main results of this paper. In Fig. 3, we plot branching-ratio contours (corresponding to the decay $H_0^2 \to \widetilde{\chi}_1^0 \widetilde{\chi}_1^0$) for a 40-GeV Higgs scalar as a function of M and μ for various choices of $\tan\beta$. As shown, there are regions where the branching ratio exceeds 90%. Such a choice of parameters would truly correspond to an invisible Higgs boson. The trend as $\tan\beta$ changes is easily understood. As discussed below Eq. (16), the decay rate of the Higgs boson into neutralino pairs is unchanged when $\tan\beta$ is replaced by $1/\tan\beta$. However, the decay rates of the Higgs boson into ordinary fermions do change [see Eqs. (17) and (18)]. For small $\tan\beta$ the decay rate into up-type quarks is enhanced and the decay rate into down-type quarks is suppressed. But, the b quark is the heaviest quark available, so that the total rate into ordinary fermions is suppressed as compared with the case of large $\tan\beta$. As a result, the branching ratio into neutralinos will be larger for $\tan\beta < 1$ compared with $\tan\beta > 1$, as is seen in Fig. 3. In order to get a completely honest appraisal of the available supersymmetric parameter space, one must fold in the constraint that the lightest chargino mass is greater than 23 GeV. This constraint is shown in Fig. 4, and indicates the region of μ and M (for a given $\tan\beta$) which is excluded by the PETRA limits. The chargino mass constraints eliminate some of the interesting region where the invisible Higgs-boson decays have a branching ratio larger than 30%. But, keeping in mind that we are displaying our results as log-log plots, one sees that most of the interesting region of parameter space in Fig. 3 is still allowed. We also show in Fig. 4 contours corresponding to chargino masses of 30 and 40 GeV. The latter value would correspond to a limit that should be easily achievable at SLC and LEP I. We note that if charginos were heavier than 40 GeV, nearly the entire interesting area of parameter space referred to above would be ruled out. On the other hand, if charginos were discovered at SLC or LEP in Z decay, the possibility of invisible Higgs-boson decay becomes more likely. We may conclude that if invisible Higgs-boson decays are "observed," then charginos must be (or have been) discovered in Z decays. Thus, the supersymmetric model possesses an important consistency requirement which is testable in experiment.

In the calculation of the branching ratio for invisible Higgs-boson decay, we included all possible supersymmetric decays[22] (including, e.g., $\widetilde{\chi}_1^+\widetilde{\chi}_1^-$ and $\widetilde{\chi}_1^0\widetilde{\chi}_2^0$) which are kinematically allowed. Of course, for the case of a 40-GeV Higgs boson, $\widetilde{\chi}_1^+\widetilde{\chi}_1^-$ will not contribute in regions which satisfy the PETRA chargino mass limits. Nevertheless, other neutralino channels may contribute, and for heavier Higgs bosons which could only be studied at LEP II, the chargino decay modes may be allowed. A typical plot of contours of the total branching ratio into all neutralino and chargino final states is

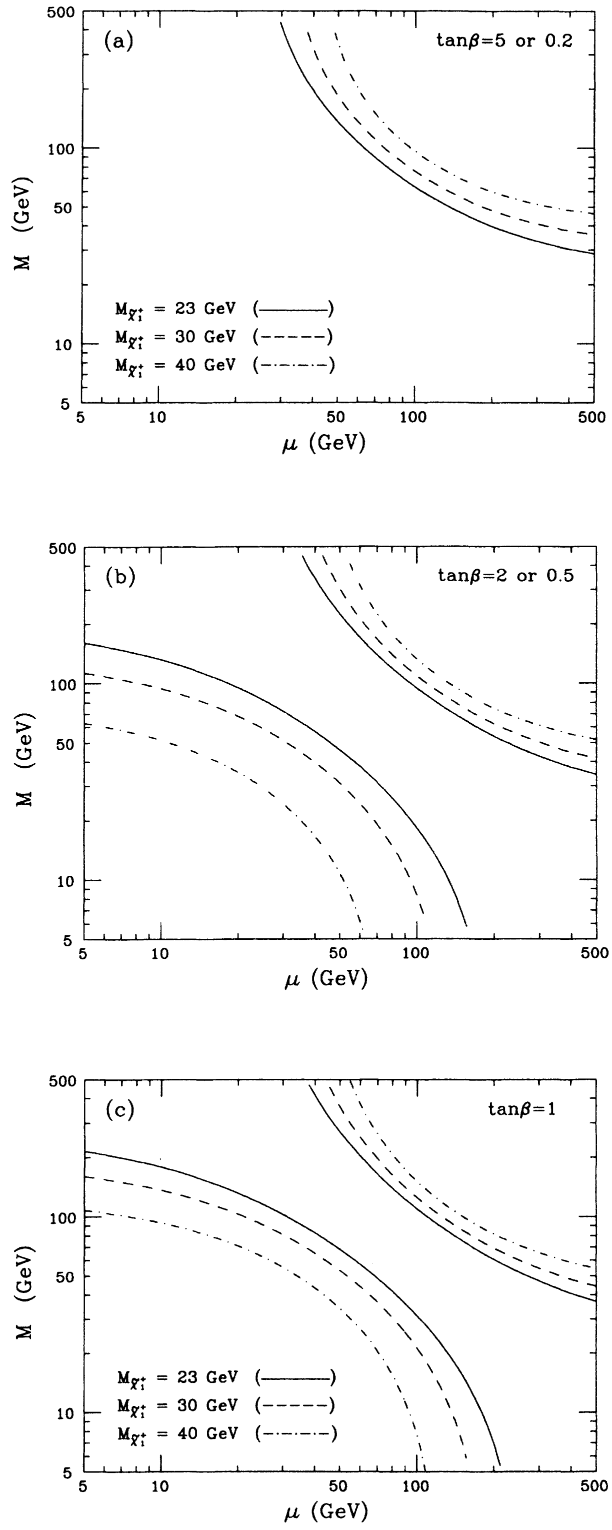

FIG. 4. Lightest chargino mass contours of 23, 30, and 40 GeV are shown as a function of M and μ. The plots are invariant under $\tan\beta \to 1/\tan\beta$, so we show (a) $\tan\beta = 5$, (b) $\tan\beta = 2$, and (c) $\tan\beta = 1$. In (b) and (c), regions between the two solid contours [and in (a) below the solid contour] correspond to chargino masses less than 23 GeV, and are excluded by data from PETRA.

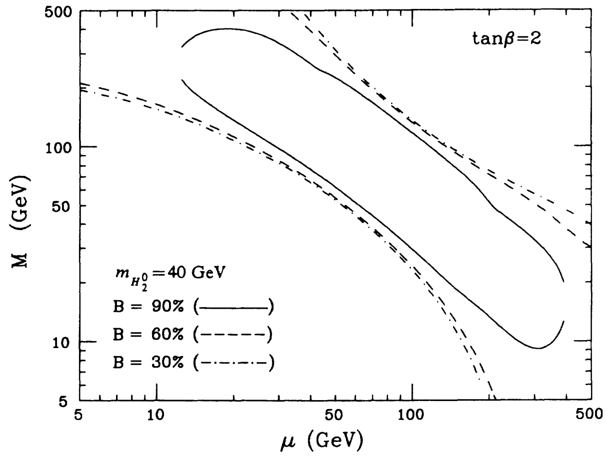

FIG. 5. Branching-ratio contours for the decay of the lightest Higgs scalar into neutralino and chargino pairs. All combinations which are kinematically accessible are included. We take $m_{H_2^0}=40$ GeV and $\tan\beta=2$.

shown in Fig. 5. The region of large branching ratios is clearly bigger than the one shown in Fig. 3. For larger Higgs-boson masses, the interesting region of large supersymmetric decay modes expands, as discussed in Ref. 22. These decay modes would also lead to missing energy signatures, and would be fundamentally different from standard-model modes.

For completeness, in Figs. 6 and 7 we show invisible decay branching ratio contours for three different Higgs-boson masses. In the case of the lighter Higgs-boson masses, the area of large branching ratio shrinks due to the kinematics; the final-state neutralinos must be very light. Furthermore, imposing the chargino mass limits is more stringent here in removing the interesting region of parameter space. The reason is clear: a lighter Higgs boson with invisible decays requires lighter neutralinos; hence the corresponding charginos will also be lighter. For the heavier Higgs-boson mass, one must recall the constraint that $m_{H_2^0} \le m_Z \, |\cos 2\beta|$. Thus, for $m_{H_2^0}=60$ GeV, $\tan\beta=2$ (or 0.5) is not allowed, and we only show results for $\tan\beta=5$ (and 0.2). As expected, the interesting region expands with the increasing

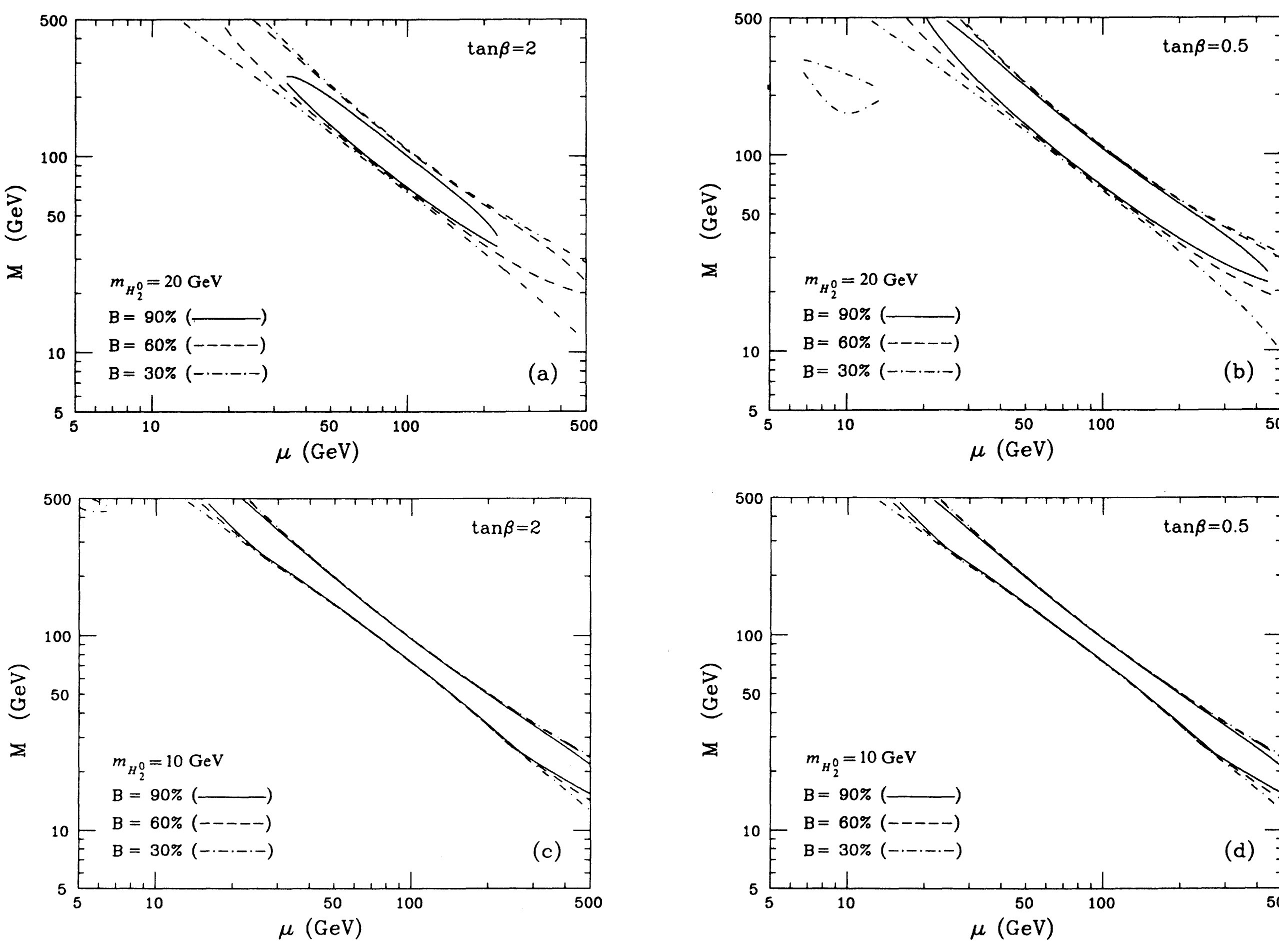

FIG. 6. Branching ratio contours for invisible Higgs-boson decay. We display the branching ratio of the lightest Higgs scalar to decay into a pair of the lightest neutralinos $(H_2^0 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0)$. We compare graphs with $m_{H_2^0}=20$ GeV [shown in (a) and (b)] and graphs with $m_{H_2^0}=10$ GeV [shown in (c) and (d)], for two choices of $\tan\beta$. The region with branching ratio larger than 30% becomes narrower as the Higgs-boson decreases.

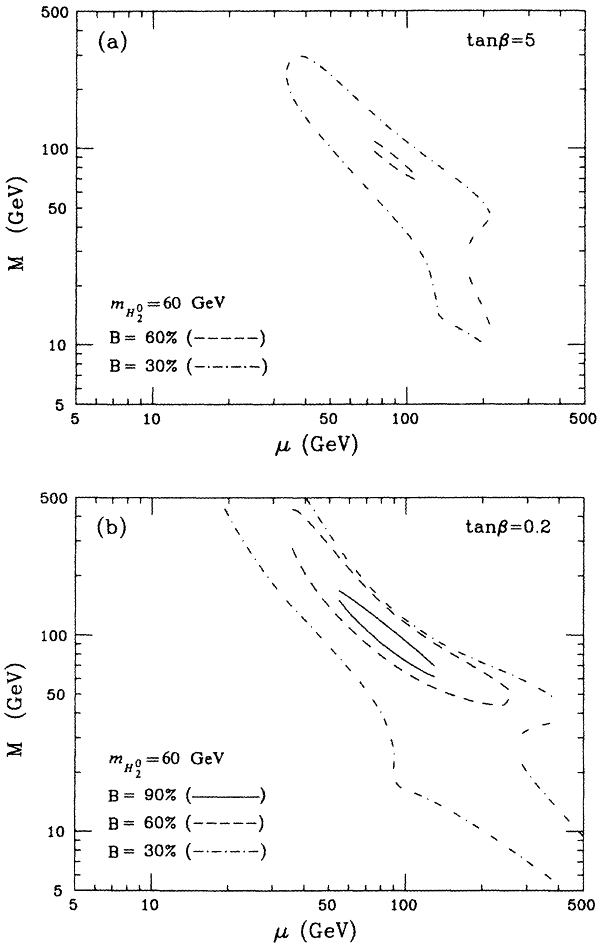

FIG. 7. Branching-ratio contours for invisible Higgs-boson decay. We display the branching ratio of the lightest Higgs scalar to decay into a pair of the lightest neutralinos ($H_2^0 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$). We take $m_{H_2^0}=60$ GeV, and show plots for $\tan\beta=5$ and 0.2.

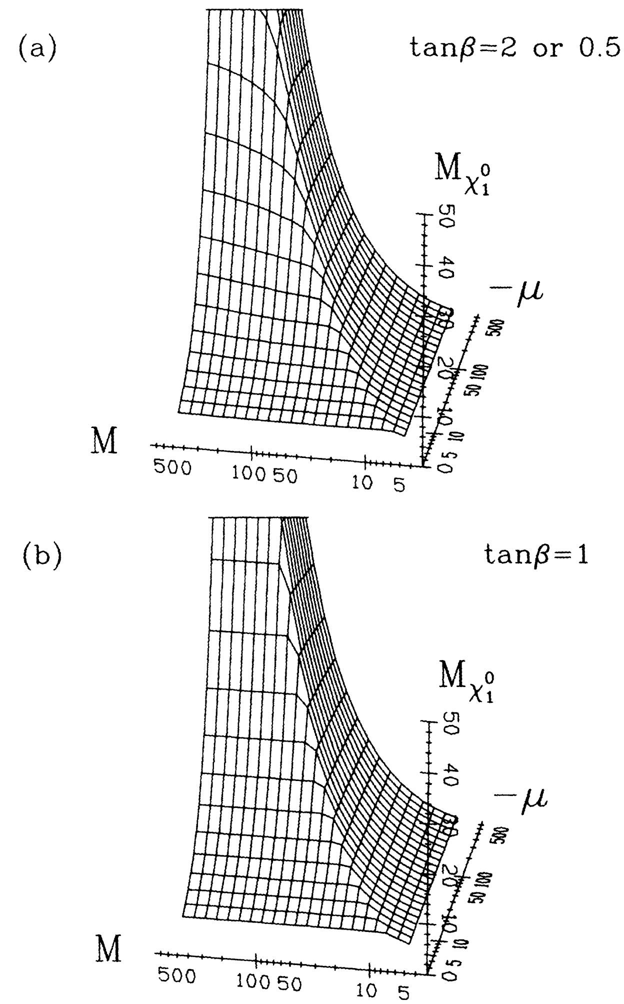

FIG. 8. Three-dimensional plot of the lightest neutralino mass (in GeV) as a function of M and μ, where μ is negative, for (a) $\tan\beta=2$ or 0.5, and (b) $\tan\beta=1$. M and μ are each plotted on a log scale, with $5 \leq M, |\mu| \leq 500$ GeV. See discussion above Eq. (6) for the definition of the supersymmetric parameters.

Higgs-boson mass, even after imposing the chargino mass constraints.

In the analysis above, M and μ were taken to be positive. One gets qualitatively different results if $M\mu < 0$. (Without loss of generality, we may define M to be positive and consider the possibility of negative μ.) In Fig. 8, we show the three-dimensional plot of the lightest neutralino mass in the case of negative μ. The results are quite different as compared to Fig. 2; in particular, the valley in front of the wall has vanished. A similarity between the two cases is that the ridge in the vicinity of $\mu \approx M$ is most pronounced for $\tan\beta=1$. As a result, for moderate values of M and $|\mu|$ with μ negative, one does *not* get particularly light neutralino masses. Thus, we do not expect especially large Higgs-boson branching ratios into light neutralino pairs in this case. As an example, we have computed the branching ratio for invisible Higgs-boson decay for a 40-GeV scalar as a function of the supersymmetric parameters, with μ taken negative. We never found a region of parameter space where the branching ratio was as large as 70%. Branching ratios of reasonable size were found only over a very small range of parameter space, where $0.1 \lesssim \tan\beta \lesssim 0.3$, as shown in Fig. 9(a). The constraint that the chargino mass be heavier than 23 GeV introduces no further constraint in this case, as seen in Fig. 9(b). However, as before, if the chargino were to be heavier than 40 GeV, the region of parameter space with large branching ratio would be eliminated.

So far, our discussion has concentrated on the decay of the *scalar* Higgs boson, H_2^0. One can repeat the calculations for the decay of the Higgs pseudoscalar H_3^0. Note that we are free to choose any value of $m_{H_3^0}$, regardless of the value of $\tan\beta$. Using Eq. (3), it follows that $m_{H_2^0} \leq m_{H_3^0}$; thus, a light pseudoscalar implies even a lighter scalar. However, one should keep in mind that detection of the pseudoscalar is likely to be rather difficult in general, since H_3^0 has no tree-level couplings to ZZ or W^+W^-. Hence, the standard mechanism for

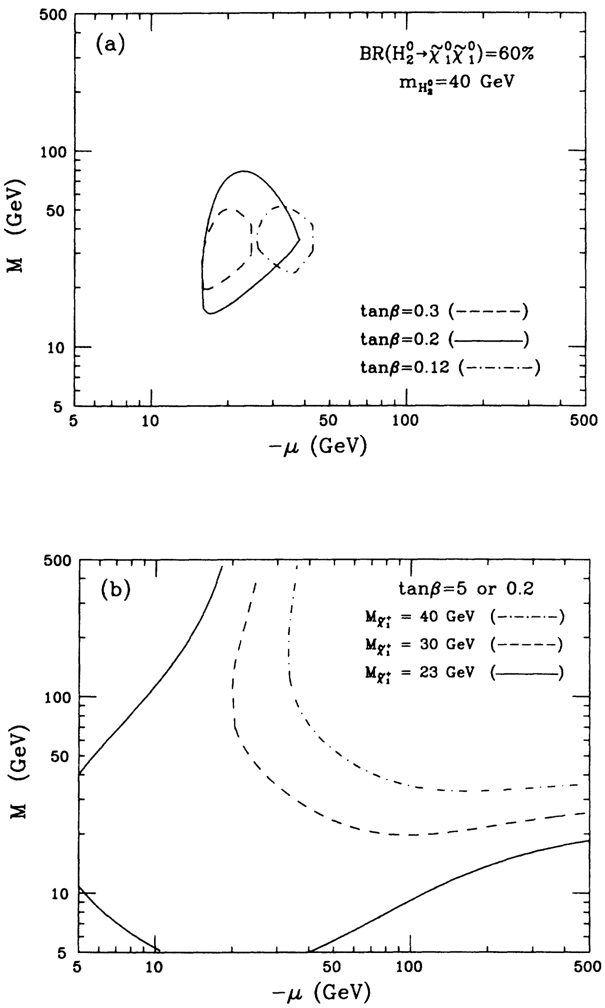

FIG. 9. In (a), we show contour plots for invisible Higgs-boson decay, with $m_{H_2^0}=40$ GeV. The parameter μ is taken to be negative. The contours represent fixed branching ratio equal to 60%; values of $\tan\beta=0.12, 0.2$, and 0.3 are shown. For larger or smaller values of $\tan\beta$ the branching ratio for invisible Higgs-boson decay is never as large as 60%. In (b), we show contours of fixed chargino masses, for $\tan\beta=5$ (or 0.2), with μ negative.

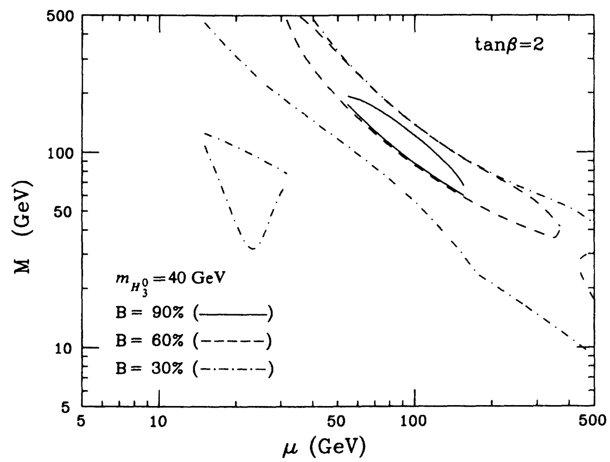

FIG. 10. Branching-ratio contours for invisible Higgs-pseudoscalar decay. We display the branching ratio of the Higgs pseudoscalar to decay into a pair of the lightest neutralinos. We take $m_{H_3^0}=40$ GeV and $\tan\beta=2$.

Higgs-boson production shown in Fig. 1(a) is not operative in this case. If one is fortunate to have a heavy-quarkonium system available, then it is possible to produce either a Higgs scalar or pseudoscalar via the $H\gamma$ final state [Fig. 1(b)]. The question of whether the invisible decay of the Higgs boson is a substantial fraction of all Higgs-boson decay would be a relevant consideration in the search for the Higgs boson in quarkonium decay.[23] The branching ratio for invisible Higgs-boson decay is fairly similar for the pseudoscalar as compared with the scalar. In Fig. 10, we show the contour plot for the branching ratio for invisible decay of H_3^0. Not surprisingly, the results are similar to the corresponding plot for H_2^0 decay shown in Fig. 3.

V. DISCUSSION AND CONCLUSIONS

We have studied in this paper the possibility that the dominant decay of the Higgs boson is into an invisible final state. Our theoretical framework is the minimal supersymmetric extension of the standard model, where supersymmetry is invoked to explain the origin of the weak scale and to guarantee the elementarity of the Higgs bosons needed for spontaneous symmetry breaking of SU(2)×U(1). By surveying the space of relevant supersymmetric model parameters, we uncovered a non-negligible region of parameter space in which the dominant decay of the Higgs boson was into a pair of the lightest neutralinos. In most approaches, these will be the lightest supersymmetric particles, weakly interacting and stable. Hence, the decay into the lightest neutralino pair would be interpreted as an invisible Higgs-boson decay. By imposing the requirement that the lightest chargino be heavier than 23 GeV (the lower bound as determined by PETRA experiments), we found that the region of parameter space corresponding to large branching ratio for invisible decay is slightly reduced. In future, this interesting region of parameter space may be eliminated entirely if chargino masses are heavier than $m_Z/2$. As a result, we have deduced an interesting consistency requirement on the model. If the Higgs boson is discovered at SLC and LEP in Z decays, and if invisible decays of the Higgs boson are an appreciable fraction of all Higgs-boson decays, then charginos must be light enough to be observed directly in Z decay.

The minimal supersymmetric extension of the standard model has a rather constrained Higgs sector. This is fortunate, since it suggests a number of other consistency tests which could either confirm or rule out the model. As mentioned in Sec. II, two parameters suffice to specify the Higgs-boson masses and its couplings to standard-model particles (gauge bosons and ordinary fermions). By measuring the Higgs-boson production cross section in $e^+e^- \to H_2^0 f\bar{f}$ [see Fig. 1(a)], one measures the $H_2^0 ZZ$ coupling. This allows one to measure the combination $\sin(\beta-\alpha)$. Measuring the H_2^0 mass then determines the Higgs sector parameters completely [see Eqs. (2)–(5)]. Thus, as an example, from Eqs. (17)–(19), it follows that

$$\frac{\Gamma(H_2^0 \to b\bar{b})}{\Gamma(H_2^0 \to c\bar{c})} = \frac{m_b^2}{m_c^2} \left[\frac{m_{H_2^0} - 4m_b^2}{m_{H_2^0} - 4m_c^2} \right]^{3/2} \tan^2\beta \tan^2\alpha \ . \quad (20)$$

Since the Higgs parameters are now fixed after the two measurements just described, α and β are now known, so that Eq. (20) is a nontrivial prediction of the model.

Throughout this paper, we have employed the minimal supersymmetric extension of the standard model. It is important to consider whether enlargements of the model will substantially effect our results. Certainly, with more free parameters at our disposal, the consistency checks of the minimal model just described will be considerably weakened. Nevertheless, we believe that the basic result of this paper is unaltered, namely, that invisible decays of the light Higgs boson can be important. First, it is important to note that in the "low-energy" supersymmetric approach, one is nearly guaranteed the existence of a light Higgs boson which cannot be heaver than $O(m_Z)$ (Ref. 24). Second, the couplings of the light Higgs boson to neutralinos and charginos have many similar features in all models. In nonminimal models, there can be more than four neutralinos and two charginos. This simply leads to larger mass matrices which must be diagonalized and more complicated mixing patterns. The general features are not likely to change,[25] and we expect that regions of parameter space exist in the nonminimal models with large invisible Higgs-boson decays.

The possibility of a substantial fraction of invisible Higgs-boson decay is an additional challenge to experimentalists who are devising experiments to search for Higgs bosons at SLC and LEP. We encourage them to be aware of nonstandard Higgs-boson decay patterns so as not to bias the Higgs-boson searches. Given that the maximum luminosity will be required to carry out the searches effectively, it is important to preserve as much of the Higgs signal as possible. Cuts and triggers which have the potential for eliminating a substantial fraction of the signal should be avoided. Since the prediction of a Higgs boson with mass $\lesssim m_Z$ is almost a model-independent prediction of the low-energy supersymmetry approach, the Higgs searches at SLC and LEP are especially important. Their results will have a profound effect on our understanding of the origins of the electroweak scale.

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