Supercollider signals from gluino and squark decays to Higgs bosons

Howard Baer
Department of Physics, Florida State University, Tallahassee, Florida 32306

Mike Bisset and Xerxes Tata
Department of Physics and Astronomy, University of Hawaii, Honolulu, Hawaii 96822

Jeffrey Woodside
Department of Physics, Iowa State University and Ames Laboratory, Ames, Iowa 50011
(Received 5 March 1992)

If the mass of the charged Higgs boson of the minimal supersymmetric model (MSSM) is smaller than about 150 GeV, the branching fraction for heavy gluinos and left-handed squarks to cascade decay to the heavier Higgs bosons H_h, H_p, and $H^\pm$ of the MSSM may be as large as 50–60 % for values of supersymmetric parameters consistent with experimental data. These decays, which have been assumed to be kinematically inaccessible in earlier analyses, can potentially lead to significant modification of the cross section for missing E_T ($\not{E}_T$), same-sign dilepton, and multilepton events from squarks and gluinos. We find that the $\not{E}_T$, same-sign dilepton, and trilepton production rates are relatively insensitive to low values of m_{H^+}, so that these remain viable signals for the identification of gluinos and squarks at the Superconducting Super Collider or the CERN Large Hadron Collider. Finally, our exploratory study shows that substantial production of H_h and H_p ($H^\pm$) in gluino and squark pair events can lead to $\not{E}_T$ events with anomalously large numbers of b quarks (τ leptons). There also exist small regions of parameter space where the H_l and H_h may be identifiable via the presence of $\gamma\gamma$ in $\not{E}_T$ events.

PACS number(s): 14.80.Ly, 12.15.Cc, 13.85.Qk, 14.80.Gt

I. INTRODUCTION

It is by now well known that the cascade decays [1] of squarks ($\tilde{q}$) and gluinos ($\tilde{g}$) lead to a variety of signals by which they may be detected at hadron supercolliders. Although their production cross sections are fixed by QCD, the decay patterns of squarks and gluinos which determine the experimental signatures are somewhat sensitive to the model-dependent mixing patterns of those charginos ($\tilde{W}_i$) and neutralinos ($\tilde{Z}_i$) that are accessible in these decays. Most detailed studies [2–8] of signatures via which squarks and gluinos may be detected at the Superconducting Super Collider (SSC) or CERN Large Hadron Collider (LHC) have been carried out within the framework of the minimal supersymmetric model (MSSM) [9], which is the simplest supersymmetric model in that it contains the minimum number of new particles and new interactions.

Within this framework, the Higgs sector consists of two SU(2) Higgs supermultiplets. After SU(2)×U(1) breaking, the gauginos and Higgsinos mix to form two Dirac charginos and four Majorana neutralinos, whose mass matrices are determined in terms of just three parameters which we may take to be (i) the gluino mass $m_{\tilde{g}}$, (ii) the supersymmetric Higgsino mixing mass $\mu = -2m_1$, and (iii) the ratio $\tan\beta = \frac{v}{v'}$ of the vacuum expectation values (VEV's) v and v' of the Higgs fields h and h' that couple to the $T_3 = \frac{1}{2}$ and $T_3 = -\frac{1}{2}$ fermions, respectively. Here, we have made the usual assumption [9] that the supersymmetry (SUSY) breaking masses of the SU(3), SU(2), and U(1) gauginos are related to a common gaugino mass by grand unification. Since charginos and neutralinos can decay into Higgs bosons provided that the $\tilde{W}_i$ and $\tilde{Z}_i$ are heavy enough, their decay patterns also depend on the scalar Higgs sector. This sector is very tightly constrained by SUSY [10], so that, even allowing for soft SUSY breaking scalar masses, it is completely fixed (at tree level) by just one additional parameter which we may take to be the charged-Higgs-boson mass (m_{H^+}). As in any two-doublet model, the physical particles consist of two neutral scalars (H_l and H_h, where the subscripts denote light and heavy), a neutral pseudoscalar (H_p) (the terms scalar and pseudoscalar refer to the couplings of these particles to fermions), and a charged spin-zero particle ($H^\pm$). Neglecting t-squark mixing and assuming that the squarks are approximately degenerate, the cross sections for the cascade decay topologies from gluino and squark production are fixed in terms of the five SUSY parameters, ($m_{\tilde{q}}, m_{\tilde{g}}, \mu, \tan\beta, m_{H^+}$) together with the top-quark mass (m_t) which enters via the top-quark Yukawa coupling, as is discussed, for instance, in Ref. [11].

The production of charginos and neutralinos via the decays of very heavy squarks and gluinos leads to many promising signatures via which it may be possible to search for supersymmetry. Aside from the classic missing transverse momentum ($\not{p}_T$) signal, these include same-sign dilepton $+\not{p}_T$ events [4, 6, 8], events with n (≥ 3) high-p_T, isolated leptons produced in association with jets and $\not{p}_T$ [8], and events with one or two high-p_T Z bosons [2, 4, 8] (identified via their e or μ decays) possibly accompanied by an additional lepton together with jets and $\not{p}_T$. In a recent paper [8], we studied the rates for these signals both at the SSC and at the LHC and also estimated the corresponding backgrounds from standard-model (SM) sources. As mentioned above, the decay patterns of the various particles depend on their masses and mixing angles, so that the signals are sensitive to the values of model parameters.

In order to keep the analysis of the signals in the six-dimensional (6D) parameter space tractable, most SUSY analyses [2–8] assume that m_{H^+} is rather large ($\gg M_W$). In this case, all the Higgs scalars other than H_l are heavy and decouple from the vector bosons, whereas H_l remains light and has the couplings of the SM Higgs boson. Thus, the signatures of squarks and gluinos are insensitive to the precise value of m_{H^+} as long as it exceeds about 200–250 GeV [12]. With this assumption, it was shown[8] that it should be possible to identify SUSY signals in several channels, both at the SSC and at the LHC.

If, however, m_{H^+} happens to be $100-160$ GeV, it is possible that all the MSSM Higgs bosons (including H_l) are lighter than about 200 GeV but heavier than 90 GeV (so that they will not be accessible at the CERN e^+e^- collider LEP 200). In this case, the daughter charginos and neutralinos produced in squark and gluino decays may also decay [13] via two-body modes into H_p, H_h, and $H^\pm$ [we will refer to these as non-standard-model (NSM) Higgs bosons], so that the branching fractions for $\tilde{W}_i$ and $\tilde{Z}_i$ decays into real W and Z bosons are correspondingly reduced. Since Higgs bosons with masses smaller than $2M_W$ will decay almost entirely into jets, this will lead to a corresponding reduction of the multilepton and high-p_T Z-boson cross sections from gluino and squark production. One purpose of this paper is to study whether or not the various signatures discussed in Ref. [8] remain viable even when the NSM Higgs bosons are relatively light.

A related issue is the detectability of the NSM Higgs bosons produced in SUSY events. The fact that these are produced in squark and gluino decays necessarily implies that these are often accompanied by $\not{E}_T$ and/or two (or more) hard (and possibly same sign) isolated leptons together with several very hard jets. As we have already shown [8], there is a judicious choice of cuts which makes the SUSY signal stand out above the background. It is, therefore, interesting to ask whether it is possible to detect the presence of NSM Higgs bosons in these SUSY events, even if these dominantly decay into heavy quarks (b or c) and/or tau leptons. The prospects for using the SUSY characteristics as a trigger for NSM Higgs events is the other issue studied in this paper. Since the efficiency for identification of heavy flavors and tau leptons is sensitively dependent on the details of the detector, we can only address this in a qualitative way. Our study should, therefore, be regarded as exploratory, and the results viewed in the proper perspective.

The rest of this paper is organized as follows. In Sec. II, after a quick review of the Higgs sector of the MSSM, we delineate the region of the SUSY parameter space excluded by the nonobservation [14] of Higgs signals by the experiments at LEP. We then study how the gluino and squark decays into the NSM Higgs bosons depend on the model parameters. We find, for example, that the gluinos may decay into NSM Higgs bosons with a branching fraction as high as 60% for values of parameters not excluded by the LEP data. This obviously makes it imperative to study the effects of these decays on the squark and gluino signals at supercolliders. This is done in Sec. III. We have improved upon our previous analysis [8] by incorporating the radiative corrections [15] arising from the t-quark Yukawa coupling that have recently been shown to have a substantial effect on the mass spectrum and mixing patterns of the neutral scalar Higgs bosons. We find that although several signals are altered if the NSM Higgs bosons are relatively light, the qualitative conclusions of Ref. [8] remain valid. In Sec. IV, we explore several strategies for identifying the NSM Higgs bosons in SUSY events. These include a high multiplicity of b quarks in $\not{E}_T$ events, a difference between the τ lepton and e or μ multiplicities, and $\gamma\gamma$ mass bumps (from the two-photon decays of the neutral Higgs bosons) in SUSY events.

II. GLUINO AND SQUARK DECAYS TO NSM HIGGS BOSONS

The only quartic interactions of the MSSM Higgs bosons that are allowed by supersymmetry are gauge interactions arising from D terms. Thus, unlike as in the SM, the quartic coupling constant of the MSSM is not a free parameter, but is determined in terms of the gauge couplings of the electroweak symmetry group. This results in the well known tree-level bounds [10], $m_{H_l} < M_Z|\cos 2\beta|$, $m_{H^+} > M_W$, and $m_{H_h} > M_Z$.

Recent calculations [15] have shown that the radiative corrections due to top-quark Yukawa interactions can significantly alter the masses and mixings of the scalar Higgs bosons from their tree level values. We have independently computed these corrections in a recent paper [16]. In order to avoid a proliferation of SUSY parameters in our phenomenological analysis, we have neglected any t-squark mixing and also assumed that all the squarks are degenerate. For simplicity, we have also neglected b quark and τ-lepton Yukawa couplings, which should be valid unless [17] $\tan\beta$ becomes as large as m_t/m_b. The resulting formulas for the masses and mixing angle of the scalar Higgs bosons are given in Ref. [16] in our notation, and will not be reproduced here. We note that the tree-level relation between m_{H_p} and m_{H^+} is unaltered (so that the lower bound of M_W on the charged-Higgs-boson mass remains valid) only because of the simplifying assumptions that we have made in deriving these formulas [18, 19]. It has been shown in Ref. [18] that $m_{H^+} < M_W$ is possible but always in those regions of parameter space where $m_{H_l} > m_{H_p}$ or where the decay $Z^0 \to H_l + H_p$ is kinematically accessible (this is already excluded by LEP experiments [14]). Drees and Nojiri [19] have shown that for values of m_t consistent with perturbative grand unification, $m_{H_l} > m_{H_p}$ cannot occur in supergravity models (where a common supersymmetry-breaking mass is assumed for all scalars at the unification scale) so that the charged-Higgs-boson mass is bounded below by M_W.

Before turning to the decays of gluinos and squarks into NSM Higgs bosons, we evaluate the constraints on the parameters of the MSSM Higgs sector that arise from the experiments at LEP where MSSM Higgs bosons can be produced via either

$$Z \to Z^* + H_l \tag{2.1a}$$

or

$$Z \to H_l + H_p. \tag{2.1b}$$

The partial width for the decay (2.1a) is given by

$$\Gamma(Z \to Z^* + H_l) = \sin^2(\alpha+\beta)\Gamma(Z \to Z^* + H_{SM}), \tag{2.2a}$$

whereas that for the decay (2.2b) is

$$\Gamma(Z \to H_l + H_p) = \frac{g^2\cos^2(\alpha+\beta)}{192\pi\cos^2\theta_W}M_Z \times\lambda^{\frac{3}{2}}\left(1, \frac{m_{H_p}^2}{M_Z^2}, \frac{m_{H_l}^2}{M_Z^2}\right). \tag{2.2b}$$

Assuming that the SUSY decay channels of H_l are kinematically forbidden if its mass is in the range accessible at LEP, (2.1a) leads to the same experimental signature as a SM Higgs boson (H_{SM}). Thus, the region of the $\tan\beta - m_{H^+}$ plane where the width (2.2a) exceeds the corresponding width for the decay into a SM Higgs boson of mass 57 GeV is excluded by the same analysis [20] that leads to the bound $m_{H_{SM}} > 57$ GeV. In view of the fact that the four experiments have collectively accumulated around 2×10^6 Z events, we have further required the branching fraction for the decay (2.1b) to be smaller than 2×10^{-6}. The region of parameter space excluded by these constraints depends somewhat on the t-quark mass (which enters via radiative corrections to m_{H_l} [15]) and is shown in Fig. 1 for (a) $m_t = 140$ GeV, and (b) $m_t = 200$ GeV. We note the following.

(1) The mass of H_l must exceed about 45 GeV independent of the MSSM parameters.

(2) The constraint on the branching fraction for the decay $Z \to H_l + H_p$ essentially coincides with the kinematic limit for this decay, so that the accumulation of more Z events will not strengthen this any further.

(3) Unlike its tree-level value which vanishes when $\tan\beta = 1$, the mass of H_l can be quite large [15] when radiative corrections are incorporated. As a result, the data do not lead to any constraint on $\tan\beta$. We see that although values of $m_{H^+} \leq 160$ GeV are excluded if $\tan\beta$ is close to unity and $m_t = 140$ GeV (the central value obtained from a global fit to all data in the SM), m_{H^+} may be much lighter if the t quark is very heavy.

(4) Even LEP 200, which should be able to probe a neutral-Higgs-boson mass up to about 90 GeV [21], will not be able to exclude $\tan\beta = 1$ if the t-quark mass is large. For $m_t \leq 140$ GeV, nonobservation of any Higgs-boson signal will, however, imply that $\tan\beta \geq 1.9$.

We now turn to a study of the decays of gluinos and squarks to NSM Higgs bosons. These occur via gluino (or squark) decays into heavy charginos and neutralinos and the subsequent decays of these into Higgs bosons and lighter $\tilde{W}_i$ and $\tilde{Z}_i$. The relevant formulas for the computation of the branching fractions for gluino decays may be found in the literature [1,3,7,8,11] whereas those for the two-body decays of the charginos and neutralinos are given in Ref. [13].

The μ dependence of the branching fraction for the decay of a gluino into any of H_p, H_h, or $H^\pm$ is illustrated in Fig. 2 for several values of (a) $m_{\tilde{g}}$, (b) $\tan\beta$, and (c) m_{H^+}. In these figures, we have fixed $m_t = 140$ GeV, $m_{\tilde{q}} = 1000$ GeV and (except where their explicit variation is shown) the other parameters are fixed at their default values, $m_{\tilde{g}} = 1000$ GeV, $m_{H^+} = 150$ GeV, and $\tan\beta = 4$. The branching fractions shown are somewhat underestimated because the contributions from Higgs bosons produced by the decays of heavier Higgs bosons or secondary decays of charginos and neutralinos are not included. In order to avoid a proliferation of figures, we have only shown the sum of the branching fractions into the H_h, H_p, and $H^\pm$ rather than the individual compo-

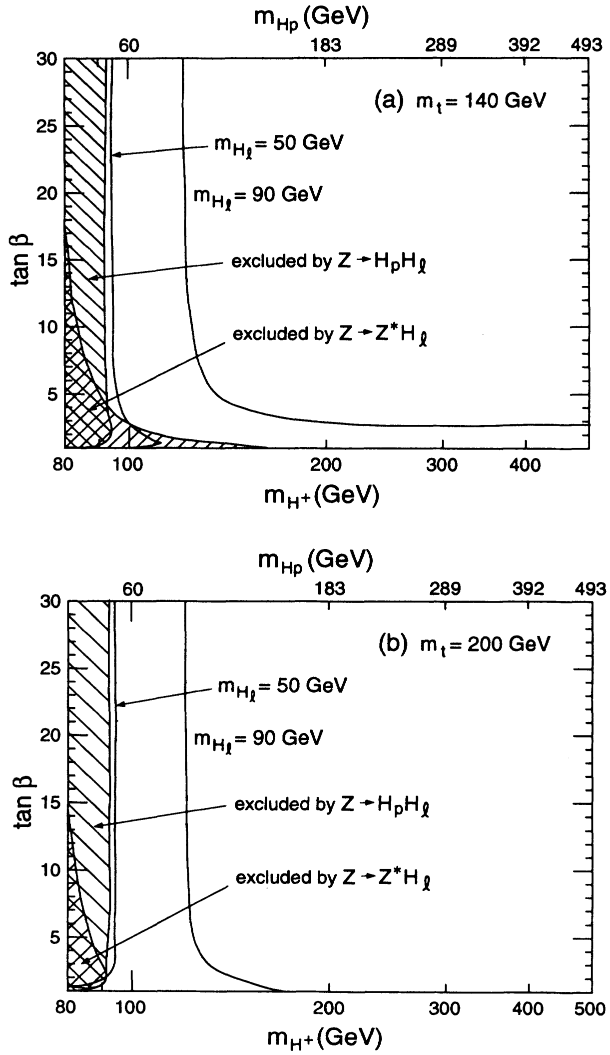

FIG. 1. Regions in the $m_{H^+} - \tan\beta$ plane which are excluded by Higgs-boson searches at LEP, for the decays $Z \to H_pH_l$ and $Z \to Z^*H_l$. We also show the mass contours for $m_{H_l} = 50$ and 90 GeV. The top scale shows corresponding values of m_{H_p}. We show excluded regions for (a) $m_t = 140$ GeV and (b) $m_t = 200$ GeV.

nents. This gives a measure of how much earlier analyses, [2–8] would be affected if the NSM Higgs bosons are kinematically accessible in gluino decays. We have left blank the region of parameters where either the lighter chargino mass is smaller than 45 GeV [22] or, where $m_{\tilde{W}_1} < m_{\tilde{Z}_1}$ [9]. Essentially all of the remaining range in Fig. 2 is allowed. We observe the following.

(i) If m_{H^+} is small, NSM Higgs-boson decays of the gluino can be very frequent for Higgs-boson masses consistent with LEP data (see Fig. 1); this branching fraction may be as high as 60% if the gluino mass is in the TeV range.

(ii) The branching fraction into NSM Higgs bosons exceeds 20–25% for a wide range of parameters, which implies that almost half the gluino pair events at a supercollider contain a NSM Higgs boson if the parameters are indeed in this range.

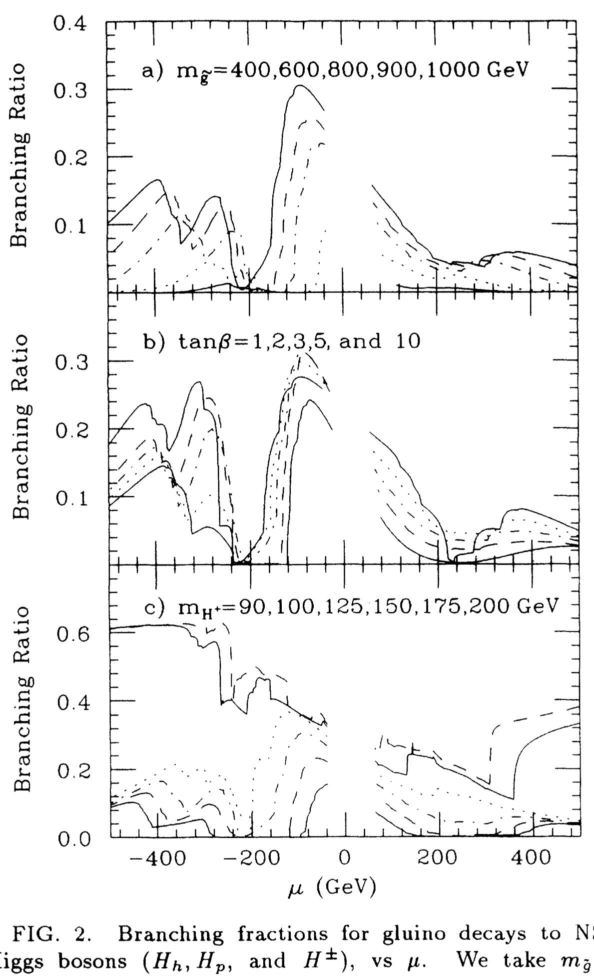

FIG. 2. Branching fractions for gluino decays to NSM Higgs bosons (H_h, H_p, and $H^{\pm}$), vs μ. We take $m_{\tilde{g}}$ = 1000 GeV, $m_{\tilde{q}}$ = 1000 GeV, m_{H^+} = 150 GeV, $\tan\beta = 4$ and m_t = 140 GeV, unless otherwise noted. In (a), we show plots for $m_{\tilde{g}}$ = 400 GeV (lower solid), 600 GeV (dots), 800 GeV (dot-dash), 900 GeV (dashes) and 1000 GeV (upper solid). In (b), we show $\tan\beta = 1$ (solid-largest for $\mu \sim -500$ GeV, smallest for $\mu \sim 500$ GeV), 2 (dashes), 3 (dot-dash), 5 (dots), and 10 (other solid). In (c), we show m_{H^+} = 90 GeV (upper dashes), 100 GeV (upper solid), 125 GeV (dots), 150 GeV (dot-dash), 175 GeV (lower dashes), and 200 GeV (lower solid).

(iii) As expected, decays to NSM Higgs bosons become less important with decreasing values of $m_{\tilde{g}}$; their branching fraction is smaller than about 5% for $m_{\tilde{g}} <$ 600 GeV. The branching fraction for these decays is very sensitive to both μ as well as $\tan\beta$ as can be seen from Fig. 2(b). Notice also that while the branching ratio to the NSM Higgs bosons is largest when $\tan\beta = 1$ for $\mu < 0$, exactly the opposite is true for positive values of μ.

In order to give the reader some idea of the breakup between the various NSM Higgs bosons in gluino decays we have shown in Table I the maximum branching fraction for the decays of the gluino into the different Higgs bosons of the MSSM for various ranges of SUSY parameters. The maximum for the summed branching fraction into NSM Higgs bosons is shown in column 2, whereas the remaining columns denote the maximum into a particular Higgs boson. Since the various maxima occur at different values of SUSY parameters, columns 3–5 do not add up to column 2. In scanning the parameter space to obtain the maxima, we have allowed $m_{\tilde{g}}$ to vary between its Collider Detector at Fermilab (CDF) bound [23] of 150 GeV to 1 TeV, -500 GeV $< \mu <$ 500 GeV, $1.05 < \tan\beta < 20$, $130 < m_t < 200$ GeV and further required, $m_{\tilde{W}} >$ 45 GeV, $m_{\tilde{W}} > m_{\tilde{Z}_1}$ [9] and finally, $m_{H_l} >$ 45 GeV (see Fig. 1), which also ensures that the decay (2.1b) is kinematically forbidden. We have checked that the maxima occur when the gluino is heavy and the squark mass is just above $m_{\tilde{g}}$. In Table I we have, therefore, taken $m_{\tilde{q}}$ = 1 TeV. Finally, we mention that, as in Fig. 2, we have only counted "primary" Higgs bosons in this table; i.e., if, for example, H_p or H_l is produced via the decay of H_h or $H^{\pm}$, it is not counted in column 4 or column 6, so that each event is counted just once. We have checked that this makes only a small difference, and then only for smaller values of m_{H^+}.

We see from the table that NSM Higgs-boson decays of the gluino (which can exceed 60% for small values of m_{H^+}) are quite significant for m_{H^+} as large as about 200–250 GeV. It is interesting to see that while the decays to H_p and $H^{\pm}$ can range up to $\sim$ 50%, the decays to a heavy scalar never exceed about 15%. Unless H_p and $H^{\pm}$ are heavy enough to decay to vector bosons and/or H_l [10], H_p dominantly decays to $b\bar{b}$ pairs whereas the charged Higgs boson dominantly decays via $H^+ \to \tau\nu$ (for $\tan\beta > 1$), provided that SUSY particles are too heavy to be produced in their decays. We will see in Sec. IV that this may have interesting implications for the prospects of discovering MSSM Higgs bosons produced in gluino pair events.

The branching fractions for NSM Higgs decays of squarks are shown in Fig. 3, assuming the decay $\tilde{q} \to q\tilde{g}$ is kinematically forbidden. Again, only "primary" Higgs bosons are counted. Since the decay pattern is different for each of the four types of squarks ($\tilde{u}_{L,R}, \tilde{d}_{L,R}$), we have, for brevity, fixed $m_{\tilde{q}} = m_{\tilde{g}}$ = 1 TeV, m_t = 140 GeV, and $\tan\beta = 4$ in this figure. Of course, the decays to NSM Higgs bosons become less important if the squarks are light. We have also checked that in the region of small values of $|\mu|$ where the NSM decays of $\tilde{u}_L$ and $\tilde{d}_L$ squarks are significant, the branching fraction is usually within a

TABLE I. Maximum branching fractions for gluino decays to Higgs bosons of the MSSM. We have scanned over the following parameters: $m_{\tilde{g}}$: 150 → 1000 GeV, μ : −500 → 500 GeV, m_t : 130 → 200 GeV, $\tan\beta$: 1.05 → 20. Furthermore, we have restricted $m_{\tilde{W}_1} > 45$ GeV, $m_{\tilde{W}_1} > m_{\tilde{Z}_1}$ and $m_{H_l} > 45$ GeV. We have set $m_{\tilde{q}} = 1000$ GeV.

	Maximum branching fractions				
m_{H^+} mass range (GeV)	$H_h+H_p+H^\pm$	H_h	H_p	$H^+ + H^-$	H_ℓ
$90 \leq M_{H^+} \leq 100$	0.65	0.12	0.49	0.54	0.42
$100 \leq M_{H^+} \leq 110$	0.63	0.12	0.44	0.52	0.50
$110 \leq M_{H^+} \leq 120$	0.61	0.11	0.34	0.51	0.50
$120 \leq M_{H^+} \leq 140$	0.50	0.14	0.23	0.42	0.51
$140 \leq M_{H^+} \leq 160$	0.31	0.09	0.14	0.22	0.51
$160 \leq M_{H^+} \leq 180$	0.27	0.07	0.11	0.20	0.51
$180 \leq M_{H^+} \leq 200$	0.21	0.05	0.08	0.16	0.51
$200 \leq M_{H^+} \leq 250$	0.17	0.04	0.08	0.11	0.51
$250 \leq M_{H^+} \leq 300$	0.09	0.02	0.04	0.06	0.51
$300 \leq M_{H^+} \leq 350$	0.04	6.0×10^{-3}	4.2×10^{-3}	0.036	0.51
$350 \leq M_{H^+} \leq 400$	0.02	1.6×10^{-3}	2.0×10^{-3}	0.016	0.51
$400 \leq M_{H^+} \leq 450$	2.9×10^{-4}	7.1×10^{-5}	2.8×10^{-4}	9.3×10^{-5}	0.51
$450 \leq M_{H^+} \leq 500$	5.8×10^{-8}	0	5.8×10^{-8}	0	0.51
$500 \leq M_{H^+} \leq 600$	0	0	0	0	0.51

factor 2 of the value shown in the figure when $\tan\beta$ is varied between 1 and 30.

We see that while $\tilde{u}_L$ and $\tilde{d}_L$ squarks can have very substantial branching fractions into NSM Higgs bosons, the corresponding branching fractions for right-handed squarks are $\lesssim 1\%$ except for a very limited region of parameters. This is easy to understand if we recall that the coupling of the heaviest neutralino to $\tilde{q}_R$ tends to be small: if $m_{\tilde{g}}$ [and hence the soft SUSY breaking SU(2) and U(1) gaugino masses, μ_2 and μ_1] is large compared to $|\mu|$, $\tilde{Z}_4$ is dominantly the SU(2) gaugino [and hence, does not couple to the SU(2) singlet $\tilde{q}_R$] since $\mu_2 \simeq 2\mu_1$, whereas in the other case, $\tilde{Z}_4$ is mainly Higgsino-like so that it can couple only via its small gaugino components. Further, charginos couple to $\tilde{q}_R$ only via very suppressed Yukawa interactions which we have neglected

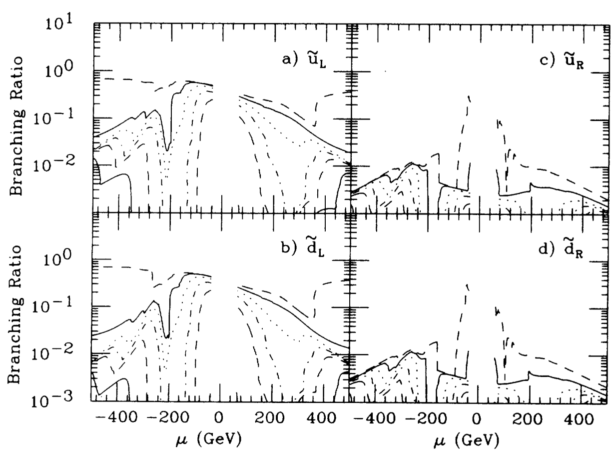

FIG. 3. Branching fractions for various squark types to NSM Higgs bosons, vs μ. We take $m_{\tilde{g}} = 1000$ GeV, $m_{\tilde{q}} = 1000$ GeV, $\tan\beta = 4$ and $m_t = 140$ GeV. The different textures denote $m_{H^+} = 100$ GeV (upper dashes), 125 GeV (upper solid), 150 GeV (dots), 175 GeV (dot-dash), 200 GeV (lower dashes), and 250 GeV (lower solid).

in our computations of squark decays, so that decays of right-handed squarks to $\tilde{Z}_4$ and $\tilde{W}_2$ are suppressed [1]. In contrast, the left-handed squarks preferentially decay into $\tilde{W}_2$ and $\tilde{Z}_4$ [1] if the gluino is heavy. Finally, for heavy gluinos, the masses of $\tilde{Z}_3$ and $\tilde{W}_1$ are considerably smaller than $m_{\tilde{Z}_4}$, so that their decays into NSM Higgs bosons are often kinematically forbidden, which explains why decays of $\tilde{q}_R$ into NSM Higgs bosons are so strongly suppressed. For large values of $|\mu|$ the decays of $\tilde{q}_L$ into NSM Higgs bosons are suppressed because the heavier $\tilde{W}_i$ and $\tilde{Z}_i$ tend to be dominantly Higgsino-like. The suppression is not as severe in the case of gluino decays in Fig. 2, because gluino decays to Higgsino-like $\tilde{W}_i$ and $\tilde{Z}_i$ mediated by virtual $\tilde{t}$ squarks proceed via large t-quark Yukawa interactions [7, 11]. Thus gluino events which lead to NSM Higgs bosons must be rich in t quarks.

We note here that our conclusions about squark decays are sensitive to our assumption of mass degeneracy of the squarks. If there are substantial mass splittings between the squarks, two-body decays into a lighter squark and a neutral or charged Higgs boson may be possible. These would be particularly important for third generation squarks since these have large Yukawa couplings.

To summarize, we have seen that if the charged-Higgs-boson mass is not very large ($\lesssim 200$ GeV), the cascade decays of gluinos and left squarks result in the production of the NSM Higgs bosons, H_p, H_h, and $H^\pm$ with a branching fraction that can be as high as 60% for ranges of SUSY parameters not yet excluded by any data. A branching fraction of 25% implies that, on an average, there is a NSM Higgs boson in half of the gluino or squark pair events. Thus previous analyses of squark and gluino signals at supercolliders in which it was assumed that all the NSM Higgs bosons were too heavy to be produced in gluino or squark decays need to be reexamined. In particular, it is important to check whether the multilepton signatures continue to remain viable even when the decays of MSSM bosons to isolated e and μ are strongly suppressed.

III. DEPENDENCE OF GLUINO AND SQUARK SIGNALS ON THE MSSM HIGGS SECTOR

In this section, we study how the various signatures via which squarks and gluinos might be detected at the SSC or the LHC are modified if the NSM Higgs bosons are relatively light. Specifically, we focus on the various event topologies discussed in Ref. [8] for which the signal cross sections were found to be above SM background for a wide range of SUSY parameters but with m_{H^+} fixed to be 500 GeV. These include (1) events with $\not{E}_T > 150$ GeV $+n \geq 4$ jets, (2) events with hard ($p_T > 20$ GeV), isolated like-sign dileptons (e or μ) $+\not{E}_T > 100$ GeV, (3) events with $n = 3, 4, 5$ isolated leptons (e or μ)$+\not{E}_T > 100$ GeV, (4) events with high-p_T Z bosons (reconstructed via their decays to e or μ pairs) $+\not{E}_T > 100$ GeV, and possibly accompanied by additional leptons, and (5) events with two high-p_T Z bosons $+\not{E}_T > 100$ GeV.

In order to incorporate the experimental cuts and detector resolutions, we have used the Monte Carlo program SUSYSM to simulate events containing squarks and gluinos at hadron colliders. For any set of MSSM input parameters, SUSYSM generates final states from $\tilde{q}\tilde{q}$, $\tilde{g}\tilde{q}$, and $\tilde{g}\tilde{g}$ production at hadron colliders, incorporating their cascade decay patterns as given by the MSSM. Effects of final-state string hadronization of quarks and gluons as well as those of the fragmentation and decay of heavy quark flavors are included. We refer the reader to Ref. [8] where SUSYSM has been described in some detail, and mention here only the improvements that we have made on it.

First, we have incorporated the radiative corrections [15] to the masses and mixing angle for the Higgs bosons using the formulas given in Ref. [16]. Further, we have developed a program HIGSBF to compute the branching fractions for all tree-level two-body decays of all the Higgs bosons of the MSSM, including also decays to supersymmetric particles. Toward this end, we have independently computed all the relevant couplings of the Higgs bosons (those to charginos and neutralinos are given in Baer *et al.* Ref. [13]) and confirmed (at least in the limit of negligible mixing between sfermions) that we agree with the couplings as given by Gunion and Haber [10] with the replacement $\alpha \rightarrow -\alpha$ (due to a difference in choice of convention). HIGSBF also includes the computation of the branching fraction for the $\gamma\gamma$ decay [16, 24] of the neutral Higgs bosons. HIGSBF has been incorporated into SUSYSM, so that our simulation of squark and gluino events now also includes all the cascade decays of the MSSM Higgs bosons.

In our simulation of the signal, we have used the cuts of Ref. [8] which were inspired by the Solenoidal Detector Collaboration (SDC) [25]. We model the SDC calorimeter by cells of size 0.05 in both $\Delta\eta$ and $\Delta\phi$, and extending out to $|\eta| = 4.5$. We assume a hadronic energy resolution of $50\%/\sqrt{E_T}$(GeV). We further require (1) E_T(jet) > 50 GeV, (2) p_T(lepton) > 20 GeV, $|\eta_{\text{lepton}}| < 2.5$, with the additional requirement that there is less than 5 GeV of hadronic activity in a cone with $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.3$ about the lepton direction, (3) for the $\not{E}_T$ signal, we veto events with isolated leptons to reduce backgrounds from W and heavy-flavor production, and further require that the transverse sphericity $S_T > 0.2$ and, finally (4) for the like-sign dilepton signal we veto events with additional leptons. We further assume that the Z boson is always identifiable via its decay into e or μ.

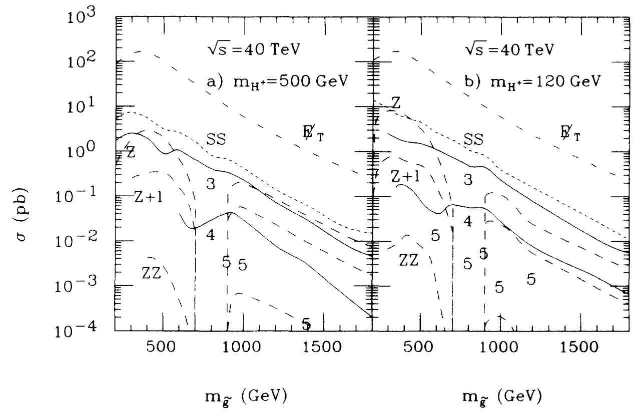

FIG. 4. Cross sections after cuts specified in the text vs $m_{\tilde{g}}$, for various event topologies. We take $\mu = -150$ GeV, $m_{\tilde{q}} = 2m_{\tilde{g}}$, $\tan\beta = 2$, and $m_t = 140$ GeV. In (a), $m_{H^+} = 500$ GeV, while in (b) $m_{H^+} = 120$ GeV.

We now turn to a study of how the various signals alter when m_{H^+} is lowered from 500 GeV, the value at which it was fixed in our previous analysis [8]. Since differences are expected mainly from $\tilde{g}$ and $\tilde{q}$ decays to NSM Higgs bosons, our analysis of Sec. II strongly suggests that these will be large only when $m_{H^+} \lesssim 150 - 200$ GeV. The variation of the cross sections for various event topologies with $m_{\tilde{g}}$ and μ is shown in Figs. 4 and 5, respectively. We have fixed $m_{\tilde{q}} = 2m_{\tilde{g}}$, $m_t = 140$ GeV and $\tan\beta = 2$ and illustrated the cross sections for (a) $m_{H^+} = 500$ GeV, and (b) $m_{H^+} = 120$ GeV. Following Ref. [8], we have fixed $\mu = -150$ GeV in Fig. 4 and $m_{\tilde{g}} = 750$ GeV in Fig. 5.

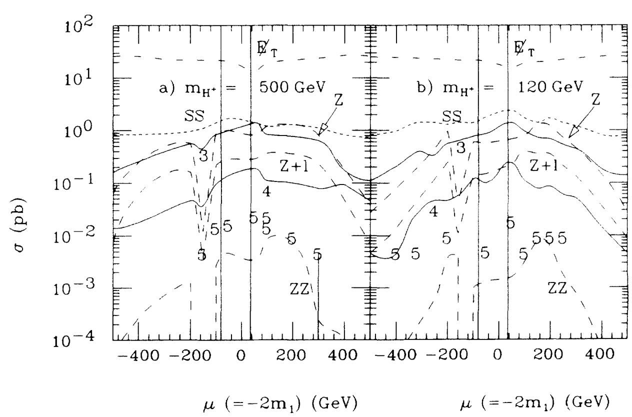

FIG. 5. Cross sections after cuts specified in Sec. III of the text vs μ, for the same event topologies as in Fig. 4. We take $m_{\tilde{g}} = 750$ GeV, $m_{\tilde{q}} = 2m_{\tilde{g}}$, $\tan\beta = 2$, and $m_t = 140$ GeV. In (a), $m_{H^+} = 500$ GeV, while in (b) $m_{H^+} = 120$ GeV. The region between the vertical bars is excluded by LEP data [22].

We have not done a new calculation of the signals for the $m_{H^+} = 500$ GeV cases shown in Fig. 4(a) and Fig. 5(a), but have reproduced these figures from Ref. [8], where radiative corrections to the Higgs-boson masses and mixing angles were ignored. We have explicitly checked that for $m_t = 140$ GeV and $m_{H^+} = 500$ GeV, these corrections have a negligible effect on the Higgs-boson mixing angle α which determined the couplings of H_l. This is to be expected since, in the limit $m_{H^+} \to \infty$, couplings of H_l to SM fermions and vector bosons become identical to those of the SM Higgs boson. The main effect of the radiative corrections is to increase m_{H_l} by up to 25 GeV. Thus, aside from threshold effects, we expect the results of Ref. [8] to remain valid if the NSM Higgs bosons are heavy.

Since $m_{H^+} = 120$ GeV is close to the lowest value of m_{H^+} allowed in Fig. 1 for this choice of parameters, we expect that the difference between cases (a) and (b) (in Figs. 4 and 5) reflects the maximum variation of the signal on the Higgs sector if the other parameters are fixed at the chosen values. We observe the following.

(i) The $\not{E}_T$, like-sign dilepton and the trilepton signals are not significantly altered when m_{H^+} is changed from 500 to 120 GeV, over the entire range of $m_{\tilde{g}}$ and μ.

(ii) The cross sections for those topologies containing Z bosons in the final state are 2–4 times larger for $m_{H^+} = 120$ GeV as compared with $m_{H^+} = 500$ GeV if gluinos are not too heavy ($m_{\tilde{g}} \simeq 400$ GeV). This is somewhat surprising, since one may expect that heavier charginos and neutralinos would decay into NSM Higgs bosons if these are light, thereby leading to a reduced rate for decays into Z bosons. We have also checked that this increase for the small m_{H^+} case is not due to the decays $H_h \to Z + H_p$ and $H_p \to H_l + Z$ which are kinematically forbidden. We have traced the enhancement in the rate for Z production to a threefold increase in the branching fraction for the decay, $\tilde{Z}_3 \to \tilde{Z}_1 + Z$, which, in turn, results from a reduction of the $\tilde{Z}_3 H_l \tilde{Z}_1$ coupling because of the change in the Higgs-boson mixing angle α. This illustrates the complicated interplay between the various parameters of the model. For very heavy gluinos, the decays of the heavier charginos and neutralinos into NSM Higgs bosons suppresses the cross section into real Z bosons when NSM bosons are light and their decays to Z are kinematically forbidden.

(iii) Some caution should be exercised in drawing conclusions about topologies with $n \geq 4$ isolated leptons for which the cross sections are very small. For instance, in our Monte Carlo simulation of 20000 events for each 100 GeV bin, a cross section of 0.01 pb corresponds to just 2.35 events for the $m_{\tilde{g}} = 750$ GeV case shown in Fig. 5, so that the differences between the 4-lepton cross sections for large negative values of μ as well as between the 5-lepton cross sections could just be statistical fluctuations. These cross sections should be observable at the SSC for a large range of SUSY parameters, and, as we have shown in Ref. [8], should stand out over backgrounds from SM sources. We also remark that for very heavy gluinos ($m_{\tilde{g}} > 1.3$ TeV), the $n \geq 4$ lepton cross sections are considerably larger for smaller values of m_{H^+}.

Up to now, we have only considered $\tan\beta = 2$. The branching fraction for decays into NSM Higgs bosons is somewhat sensitive to this parameter. In order to check that the conclusions that we have drawn from Figs. 4 and 5 are not qualitatively altered, we have shown the variation of the cross sections for the same set of signals with m_{H^+}, but for $\tan\beta = 5$ in Table II. Here, we have fixed $m_{\tilde{g}} = 1$ TeV, $m_{\tilde{q}} = 1.1$ TeV and the other parameters as in Fig. 4. We see, once again, that it is the signals involving Z bosons that are altered by the largest amount, whereas the $\not{E}_T$ and the like-sign dilepton signals are almost independent of the Higgs sector. In this case, there are far fewer Z bosons produced via gaugino decay. Finally, we remark that the cross sections in Table II are larger than those in Fig. 4 because the contribution from $\tilde{q}\tilde{g}$ production is quite significant as squarks and gluinos have comparable masses.

The main conclusion of Sec. III is that the $\not{E}_T$, like-sign dilepton and trilepton signals from squark and gluino production at hadron colliders are not very sensitive to the details of the Higgs sector of the MSSM. As the parameters of the Higgs sector are varied over the range allowed by the LEP data, these cross sections are not substantially altered from their values in Ref. [8], where it was shown that the signals should be detectable above SM backgrounds for a wide range of SUSY parameters. The cross sections for event topologies containing Z bosons, on the other hand, show considerable dependence on m_{H^+}. Nevertheless, these events, as well as those with $n \geq 4$ isolated leptons, do occur at observable rates, and so could provide a striking confirmation of a SUSY signal first observed in another channel.

TABLE II. Cross sections in pb for various signals after cuts from $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, and $\tilde{q}\tilde{q}$ production at $\sqrt{s} = 40$ TeV for different values of m_{H_p} (m_{H^+}). We take $m_{\tilde{g}} = 1000$ GeV, $m_{\tilde{q}} = 1100$ GeV, $\mu = -150$ GeV, $\tan\beta = 5$, and $m_t = 140$ GeV.

m_{H_p} (m_{H^+})	$\not{E}_T$	SS	$3L$	$4L$	$5L$	Z	ZZ
50 (94.3)	10.4	0.69	0.31	3.3×10^{-2}	2.0×10^{-2}	0.13	2.1×10^{-4}
100 (128.1)	10.7	0.73	0.37	3.6×10^{-2}	9.9×10^{-3}	0.23	3.6×10^{-4}
150 (170.0)	9.7	0.74	0.59	9.8×10^{-2}	9.4×10^{-3}	0.44	1.9×10^{-3}
200 (215.4)	10.3	0.71	0.54	8.1×10^{-2}	1.4×10^{-2}	0.47	2.0×10^{-3}
300 (310.5)	10.1	0.71	0.51	1.1×10^{-1}	1.2×10^{-2}	0.45	1.9×10^{-3}
400 (407.9)	10.1	0.71	0.54	6.5×10^{-2}	9.8×10^{-3}	0.44	1.9×10^{-3}
500 (506.4)	10.3	0.76	0.52	8.6×10^{-2}	1.2×10^{-2}	0.45	1.9×10^{-3}

IV. LOOKING FOR MSSM HIGGS BOSONS IN GLUINO AND SQUARK EVENTS

As we saw in Sec. II, the production of NSM Higgs bosons via the decays of gluinos and squarks can be quite substantial if $m_{H^+} \lesssim 150 - 200$ GeV. While these decays do not affect our conclusions about the detectability of squarks and gluinos produced at hadron supercolliders in an essential way, the (possibly) large rate for the production of NSM Higgs bosons makes it interesting to ask whether these might be detectable in events from gluino and squark production. In a previous analysis [8], we have shown that, with appropriate cuts, the SUSY signal stands out over SM backgrounds. We therefore wish to ascertain whether there exist features of the SUSY events which would also indicate the presence or lack of NSM Higgs bosons.

NSM Higgs bosons in the mass range of interest ($\lesssim$ 150 GeV) are most likely to decay into b quarks and τ leptons unless their decays to supersymmetric particles are accessible. Their production via the cascade decays of squarks and gluinos is, therefore, signaled by an excess of b quarks and τ leptons in the SUSY event sample identified in the previous section. Since the efficiency for identification of b's and τ's is sensitively dependent on the detailed properties of the detector (and detector simulation is beyond the scope of this paper), our study of the prospects for identifying NSM Higgs bosons in $\tilde{g}$ and $\tilde{q}$ events is necessarily qualitative and should only be regarded as a guide for future analyses.

A. *B* multiplicity in SUSY events

We begin by considering the multiplicity of b quarks in SUSY events, signaled by their hadronization into high-p_T B mesons in the central region. Whether these can be identified is an experimental issue. While b tagging is very difficult along the beam direction, it is conceivable that high-p_T B mesons may be identified by a search for displaced vertices using a microvertex detector in the central region. The B multiplicity in SUSY $\not{E}_T$ events was first studied in Ref. [8] where it was pointed out that SUSY events are likely to be B rich compared to the SM background. This is because (i) the rate for the decays of heavy gluinos, charginos and neutralinos to b quarks is comparable to that for other flavors, and (ii) the heavier neutralinos often exclusively decay to $\tilde{Z}_1$ and an H_l (which then decays to $b\bar{b}$). It was also pointed out that although the multiple B production occurs at a large rate via QCD processes, these events are unlikely to be confused with SUSY events. This is because the B mesons are mainly produced in the beam directions, and further, that only a small fraction of QCD events would have very large $\not{E}_T$ [26].

Unless $\tan\beta$ is close to or smaller than unity, the charged Higgs boson dominantly decays via $H^+ \to \tau\nu_\tau$ (if its decays into WH_l and tb as well as those into SUSY particles are kinematically forbidden); hence H^+ will not likely be a major source of b's. However, the production of H_p and H_h via $\tilde{q}$ and $\tilde{g}$ production would lead to yet a further increase in the B multiplicity in SUSY events. We have illustrated this in Fig. 6 where we have plotted the fractional b multiplicity for (a) $\not{E}_T > 150$ GeV events and (b) the sample of same-sign dilepton (e and μ) events passing the cuts discussed in Sec. III. In addition we have assumed an efficiency of 50% for the identification of each b quark, i.e., an efficency of $(\frac{1}{2})^n$ for n b quarks to be identified. We have illustrated this only for the case of heavy gluinos and squarks, since as we saw in Fig. 2(a), the branching fraction for the decays of the gluino into NSM Higgs bosons falls to $\leq 5\%$ if $m_{\tilde{g}} < 600$ GeV. In this figure, we have fixed $m_{\tilde{g}} = 900$ GeV, $m_{\tilde{q}} = 1000$ GeV, $m_t = 140$ GeV, $\mu = -150$ GeV, and $\tan\beta = 2$ and compared the results for the extreme case $m_{H^+} = 100$ GeV with that for $m_{H^+} = 500$ GeV (for which the production of NSM Higgs bosons is zero). Although $m_{H^+} = 100$ GeV is excluded for $\tan\beta = 2$ (see Fig. 1), we expect that our results are insensitive to $\tan\beta$ so that the difference between the solid and dashed curves in Fig. 6 indeed represents the maximum variation of the b fraction since $m_{H^+} = 100$ GeV is allowed if $\tan\beta > 3$. We see that the

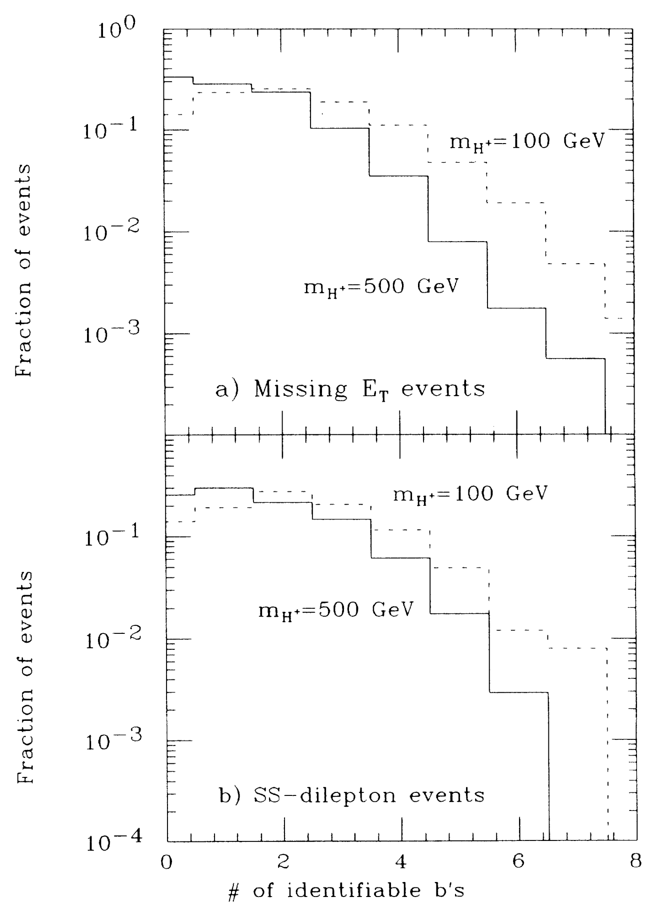

FIG. 6. Histograms of fraction of (a) $\not{E}_T$ events and (b) same-sign dilepton events from SUSY at the SSC containing n identifiable B mesons. We have assumed 50% detection efficiency for identifying a displaced B decay vertex. We take $(m_{\tilde{g}}, m_{\tilde{q}}, m_t, \mu, \tan\beta)$=(900 GeV, 1000 GeV, 140 GeV, −150 GeV, 2). We show plots for $m_{H^+} = 500$ GeV (solid), and 100 GeV (dashed).

fraction of $n_b \geq 6$ events increases by an order of magnitude in the $\not{E}_T$ sample, while the corresponding increase is about a factor of 3 for the same-sign dilepton sample if $n_b \geq 5$. Since the $\not{E}_T$ (same-sign dilepton) cross section for this set of parameters is ~ 10 pb (~ 1 pb) we expect about 200 $\not{E}_T$ events with $n_b \geq 6$ and a similar number of same-sign dilepton events with $n_b \geq 5$ annually at the SSC if there is no NSM Higgs-boson production. For $m_{H^+} = 100$ GeV, this increases to 2000 $\not{E}_T$ and 600 same-sign dilepton events with the same high b multiplicity.

We note here that for the case of heavy gluinos and squarks, the b fraction is relatively insensitive to the values of other SUSY parameters if m_{H^+} is heavy. To see this, we first note that if phase-space effects are negligible, the decay branching fraction for $\tilde{g} \to b$ decays is not very sensitive to the chargino and neutralino mixing parameters. Further, for heavy squarks, $\tilde{W}_i$ and $\tilde{Z}_i$ dominantly decay via (possibly virtual) W and Z decays, so that the branching fractions for their decays to b's are also independent of the details of gaugino-Higgsino mixing. Finally, H_l, the remaining source of b's, is essentially the SM Higgs boson, so that its decays are also insensitive to μ and $\tan\beta$. We are, therefore, led to attribute deviations from the solid histogram in Fig. 6 to variations of the MSSM Higgs sector. We have explicitly checked that changing $\tan\beta$ from 2 to 10 reduces the b fraction by a factor of ≤ 2 (for large n_b) whereas changing μ to -500 GeV leaves it essentially unaltered. In principle, the b multiplicity can also be sensitive to m_t, primarily because the decays $\tilde{g} \to t\bar{t}\tilde{Z}_i$ and $tb\tilde{W}_i$ can also be mediated by t-quark Yukawa interactions [7, 11]. We find that changing m_t to 190 GeV slightly softens the b-fraction distribution. This is not very relevant, however, since m_t will presumably be measured by the time the SSC and LHC are operational. We, therefore, conclude that the observation of a large deviation from the solid histogram in Fig. 6 is likely to be due to the production of H_p and H_h in gluino or squark decays.

B. τ multiplicity in SUSY events

Next, we turn to the prospects for finding evidence for the charged Higgs boson in SUSY events. A relatively light charged Higgs boson decays dominantly via $H^+ \to \tau\nu$ unless $\tan\beta \lesssim (3m_c^2/m_\tau^2)^{1/4} \sim 1.2$, in which case its major decay mode will be $H^+ \to c\bar{s}$. Since $\tan\beta > 1$ is the favored [9] range of this parameter, we are led to consider whether the observation of an excess of τ leptons relative to e and μ in SUSY multilepton events could serve as a signal for the production of H^+ via the cascade decays of gluinos and squarks. Of course, in principle, the neutral Higgs bosons can also lead to such an excess. Their branching ratio into τ pairs, however, is at most about 5%, to be compared with almost 90% for the decay $H^+ \to \tau\nu$ for $\tan\beta = 2$, assuming, of course, that H^+ cannot decay into t quarks or SUSY particles. We stress that within the framework of the MSSM, there are no other sources of violation of lepton universality. The decays of supersymmetric particles dominantly occur via gauge interactions [27] and so do not lead to any excess of τ leptons.

To illustrate just how much this excess could be, we have shown the "τ fraction" in single lepton events, same-flavor dilepton events and $ll l'$ events (where the third lepton l' can be any of e, μ, or τ) in Table III for (a) $m_{H^+} = 100$ GeV [28], (b) $m_{H^+} = 140$ GeV, and (c) $m_{H^+} = 500$ GeV. Here, we have taken $m_{\tilde{g}} = 1000$ GeV, $m_{\tilde{q}} = 1100$ GeV, $\mu = -150$ GeV, $\tan\beta = 5$, and $m_t = 140$ GeV, and have imposed the multilepton SUSY cuts discussed in Sec. III on these events. Notice that in case (a) m_{H^+} is just allowed by the LEP bound in Fig. 1 while in case (b) the top decay of H^+ is just inaccessible. We see that in both these cases, the τ fraction is significantly larger than the e or μ fractions which are essentially equal, aside from statistical fluctuations. In case (c), however, where NSM Higgs bosons are not produced in squark and gluino cascades, we see that the τ excess is much smaller. Even for the maximum case of 38% for $\tau\tau l'$ events, it is about a 2.6 sigma effect in our simulation. In contrast, for the $m_{H^+} = 140$ GeV case, we have 190, 175, and 275 $ll l'$ events for $l = e$, μ, and τ, respectively, in our simulation. This clearly shows that the cross sections for eel' and $\mu\mu l'$ events are essentially equal, whereas the number of $\tau\tau l'$ events exceed these by six standard deviations. The statistical significance of the other cases is higher because there are a larger number of events in our simulation. We have also checked trilep-

TABLE III. Cross section for $\not{E}_T$ events from SUSY containing one, two, or three leptons. We assume the lepton isolation cuts of Sec. III. We take $(m_{\tilde{g}}, m_{\tilde{q}}, m_t, \mu, \tan\beta)$=(1000 GeV, 1100 GeV, 140 GeV, -150 GeV, 5).

l	$\sigma(l)$ pb	$\sigma(ll)$ pb	$\sigma(ll l')$ pb
	(a) $m_{H^+} = 100$ GeV		
e	3.9 (19%)	0.43 (8%)	0.18 (18%)
μ	3.8 (18%)	0.47 (9%)	0.15 (15%)
τ	13.0 (63%)	4.3 (83%)	0.69 (67%)
	(b) $m_{H^+} = 140$ GeV		
e	5.1 (29%)	0.71 (27%)	0.19 (30%)
μ	5.2 (29%)	0.69 (26%)	0.17 (27%)
τ	7.4 (42%)	1.3 (48%)	0.27 (43%)
	(c) $m_{H^+} = 500$ GeV		
e	5.7 (33%)	0.88 (32%)	0.19 (32%)
μ	5.6 (33%)	0.90 (33%)	0.18 (30%)
τ	5.9 (34%)	0.95 (35%)	0.23 (38%)

ton cross sections where all the leptons were required to have the same flavor and found larger τ fractions than in the $ll l'$ case shown. Since the number of such events in our simulation was not very large, we have chosen not to show these cross sections here.

The fact that the τ excess is rather small for the $m_{H^+} = 500$ GeV case suggests that the light Higgs bosons make only a small contribution to this as might be expected since the neutral bosons dominantly decay to $b\bar{b}$ pairs. We have verified this by checking that in one run which resulted in 2164 $\tau\tau$ events, 942 were same-sign τ's: since H^+ and H^- can be produced with equal likelihood, τ pairs from charged Higgs sources are as likely to be like sign as opposite sign. We attribute the small excess of opposite-sign τ pairs to neutralino, Z boson, and neutral-Higgs-boson decays. We also note that the huge production rate of τ's from H^+ decays will likely mask any excess from the decay of neutral Higgs bosons. For the case in Table III(c) where only H_l can be produced, we have already seen that the τ excess is a small effect.

We stress that the results shown in Table III are greatly idealized since we have assumed that a τ is always identifiable if it passes the cuts discussed in Sec. III. A leptonically decaying τ may often be difficult to identify as the daughter lepton is likely to be soft. Although jet cross sections are very large, it may be possible to tag the τ (with some efficiency) as one can use the $\not{E}_T$ or the additional hard lepton (in the case of $ll l'$ events) as a trigger for this class of events. Identification of the τ may then be possible via its 1 and 3 charged prong hadronic decays, which occur with a branching fraction of 63%. Microvertex detectors may further facilitate the identification of τ events. Finally, the fact that τ pairs from charged-Higgs-boson decays have a 50% probability to be of the same sign provides an additional handle on the signal.

It is impossible for us to assess the viability of leptonic nonuniversality as a signal for the charged Higgs boson of the MSSM without a more detailed analysis that includes a complete detector simulation. However, several analyses entailing the identification of τ leptons at hadron colliders already exist in the literature [29]. We believe that the magnitude of the τ excess for $m_{H^+} < m_t$ shown in Table III makes it worthy of further investigation.

C. $\gamma\gamma$ and ZZ decays of Higgs bosons in SUSY events

The $\gamma\gamma$ and ZZ decays of the MSSM Higgs bosons lead to a promising method for their identification at hadron colliders [16, 24]. It is therefore natural to study whether one can see these decay modes for Higgs bosons produced in SUSY events.

We show in Fig. 7 the branching fraction for the decay chain $\tilde{g} \rightarrow \tilde{W}_i$ or $\tilde{Z}_i \rightarrow H_j \rightarrow \gamma\gamma$ ($j = l$, p, or h) for all three neutral Higgs bosons of the MSSM. The branching fractions shown are somewhat underestimated because we have not included a multiplicity factor when more than one Higgs boson is present. For instance, the $\gamma\gamma$ branching fraction from the chain, $\tilde{g} \rightarrow q\bar{q}\tilde{Z}_4$, $\tilde{Z}_4 \rightarrow \tilde{Z}_2 + H_l$, $\tilde{Z}_2 \rightarrow \tilde{Z}_1 + H_l$ is underestimated by a factor 2. Since most gluino decays contain at most one H_l, we estimate that the error thus introduced, is no more than a factor 2, and often smaller. In Fig. 7, we have fixed $m_{\tilde{g}} = 900$ GeV, $m_{\tilde{q}} = 1000$ GeV, $\tan\beta = 4$ and $m_t = 140$ GeV. We have shown the branching fraction versus μ for several values of m_{H^+} ranging from 100 GeV (close to the bound in Fig. 1) upwards. We observe the following features.

(i) H_l decays lead to a branching fraction in excess of 10^{-5} for a wide range of parameters. The branching fraction is largest for large values of m_{H^+} (when H_l resembles the SM Higgs boson) and drops off rapidly for $m_{H^+} \lesssim 150$ GeV unless $|\mu|$ is very large. As expected, the contribution from H_h shows the complementary behavior in that it is largest for smaller values of m_{H^+} when H_h is kinematically accessible (see Fig. 2). However, its contribution to the branching fraction almost never exceeds 10^{-5}.

(ii) In order to get a rough idea of what this means for the SSC, we see from Fig. 4 that for $m_{\tilde{g}} = 900$ GeV, about 10^5 $\not{E}_T$ events are expected annually at the SSC. A $\gamma\gamma$ branching fraction of 10^{-4} in Fig. 7, therefore,

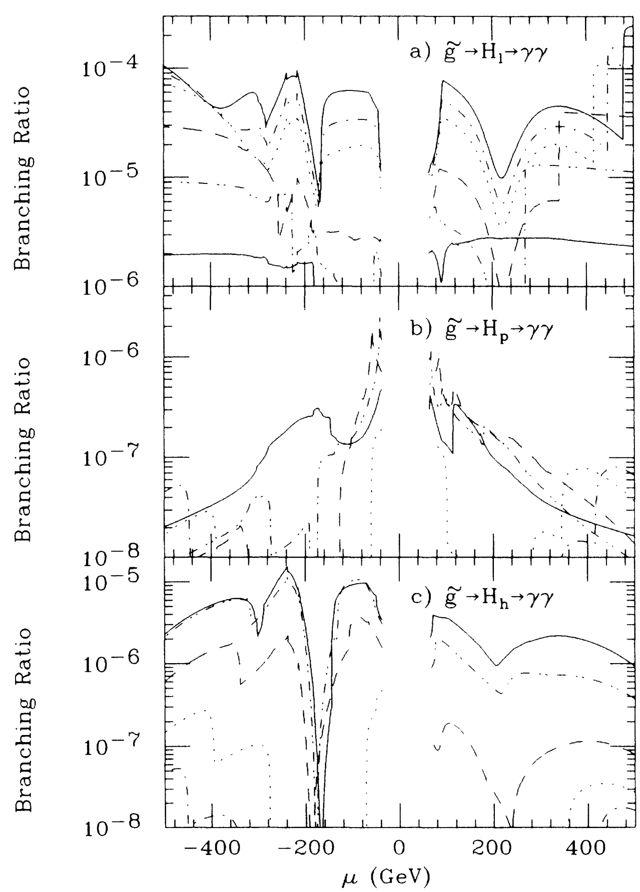

FIG. 7. Branching fraction for gluino decays to (a) light scalar, (b) pseudoscalar, and (c) heavy scalar Higgs bosons, followed by Higgs-boson decay to two photons, vs μ. We show curves for $m_{H^+} = 100$ GeV (solid), 125 GeV (double-dot-dash), 150 GeV (dashes), 200 GeV (dots), and 250 GeV (dot-dash). In (a) only, the upper solid curve is for $m_{H^+} = 500$ GeV.

corresponds to about 20 $\gamma\gamma$ + $\not{E}_T$+jets events annually at the SSC. If $m_{\tilde{q}} \simeq m_{\tilde{g}}$, $\tilde{g}\tilde{q}$ production can enhance the $\not{E}_T$ event rate so that at best 10–100 such events may be expected per year at the SSC.

(iii) We see that the contribution of H_p to the $\gamma\gamma$ branching fraction from gluinos is always small. This is not surprising since, as discussed in Ref. [16], the contribution of the t-quark loop to H_p decay is strongly suppressed when $\tan\beta$ is substantially larger than unity. This is essentially the reason why $H_p \to \gamma\gamma$ signals are observable only when $\tan\beta$ is close to unity [16,24]. Since $\tan\beta = 1$ maximizes this decay (remember we do not allow for $\tan\beta < 1$), we have computed this branching fraction for the smallest value of m_{H^+} (162 GeV) allowed by Fig. 1 for $m_t = 140$ GeV and $\tan\beta = 1$ and find a value of 4×10^{-5}. Increasing m_t to 200 GeV to allow $m_{H^+} = 110$ GeV results in a branching fraction of 2×10^{-5}. Since this branching fraction falls off rapidly with increase in $\tan\beta$ or m_{H^+} [see Fig. 7(c)], we conclude that it will be very difficult to observe $H_p \to \gamma\gamma$ in cascade decays of squarks and gluinos.

In order to see if the $\gamma\gamma$ decays of scalar Higgs bosons might lead to observable rates at the SSC, we have searched for parameter values where the branching fraction for the $\gamma\gamma$ decay chain of gluinos is maximized. We have done a parton level simulation of these events with complete cascade decays incorporated and required that the $p_T(\gamma) > 20$ GeV, and further, that they satisfy the same isolation requirement as the leptons. We find that for $m_{\tilde{q}} = m_{\tilde{g}}$, there may be as many as 86 (33) $\gamma\gamma + \not{E}_T > 100$ GeV events from H_l (H_h) decays per year at the SSC assuming an annual integrated luminosity of 10 fb^{-1}. In this calculation, we have included the contribution from squarks and included all (not just the primary decays) possible decay chains. Assuming that isolated photons can be discriminated from jets at a level of 5×10^{-4} [25], we do not expect a substantial background from jet misidentification. The physics background comes from the direct production of a pair of photons that accidently reconstruct the Higgs-boson mass. The presence of hard jets and substantial $\not{E}_T$ will serve to discriminate the SUSY signal from SM processes. Whether or not such a signal might be observable in a real detector will depend on its mass resolution and ability to identify isolated photons in events with large hadronic activity. This is beyond the scope of the present analysis. We should stress though that, at best, the signal may be identifiable only for a very limited range of SUSY parameters.

We have also considered the prospects for identifying H_h produced by cascade decays of squarks and gluinos via its $H_h \to ZZ$ signature. We have checked that for $m_t = 140$ GeV, $m_{\tilde{g}} = m_{\tilde{q}} = 1$ TeV, $|\mu| < 500$ GeV and $\tan\beta < 30$, the branching fraction for the decay chain, $\tilde{g} \to H_h \to ZZ$ is always smaller than 7.5×10^{-3} even for m_{H^+} as small as 200 GeV. If we also require that the Z bosons decay into e or μ pairs, the upper bound on the branching fraction is about 3×10^{-5}. Since this branching fraction is usually considerably smaller than this, it is unlikely that H_h can be detected in this way.

V. SUMMARY

In summary, we have seen that within the framework of the MSSM, the branching fractions for heavy squarks and gluinos to cascade decay to the Higgs bosons H_p, H_h, and $H^{\pm}$ can be very substantial if m_{H^+} is smaller than about 150 GeV. Since these decays can potentially alter the cross sections for $\not{E}_T$, same-sign dilepton and multilepton events which lead to promising signatures for supersymmetry at hadron supercolliders [8], we have studied their dependence on m_{H^+} in this paper. We find that for $\not{E}_T$, same-sign dilepton events and trilepton events the cross sections are relatively insensitive to m_{H^+}, so that these remain viable signals for the identification of SUSY at the SSC or the LHC. In Sec. IV, we have done exploratory studies of the prospects for identifying the NSM Higgs bosons produced via the cascade decays of 1 TeV squarks and gluinos. We find that if it is possible to identify b jets (within the experimental acceptance) with an efficiency of 50% per jet, the presence of relatively light neutral Higgs bosons (H_p and H_h allowed) is signaled by a significant increase in the multiplicity of B hadrons. We have checked that the increase in multiplicity when m_{H^+} is reduced from 500 to 100 GeV cannot be attributed to the variation of $\tan\beta$ or μ. We have also suggested that if it is possible to identify high-p_T isolated τ leptons in multijet $+\not{E}_T$ events, the presence of a light charged Higgs boson will be signaled by the observation of an excess of τ events relative to e and μ (after detection efficiency corrections, of course) in the sample of dilepton and trilepton events from squark and gluino sources. Furthermore, a large fraction of τ pairs will contain same-sign τ leptons. Finally, we have shown that the cascade decays of heavy squarks and gluinos lead to an observable rate for neutral Higgs bosons (identified via their $\gamma\gamma$ decays) produced in association with several jets and $\not{E}_T$, but only for a very limited range of SUSY parameters. We have also shown that the identification of H_h produced in SUSY events via its ZZ ($Z \to e\bar{e}$ or $\mu\bar{\mu}$) mode is probably impossible. We should stress here that our studies of the feasibility of identifying NSM Higgs bosons should be viewed as preliminary since the identification of B hadrons and τ leptons is very dependent on the details of the detector.

ACKNOWLEDGMENTS

We thank the organizers of the U.C. Davis Workshop on Higgs/EWSB Physics at Hadron Supercolliders, where part of this work was done. The authors wish to thank J. Gunion and R. Kaufman for useful discussions. This research was supported in part by the U.S. Department of Energy under Contracts Nos. DE-FG05-87-ER40319 and DE-AM03-76SF00235.

[1] H. Baer, V. Barger, D. Karatas, and X. Tata, Phys. Rev. D **36**, 96 (1987).

[2] H. Baer *et al.*, in *From Colliders to Supercolliders*, Proceedings of the Workshop, Madison, Wisconsin, 1987, edited by V. Barger and F. Halzen (World Scientific, Singapore, 1987), p. 241; M. Barnett *et al.*, in *Experiments, Detectors and Experimental Areas for the Supercollider*, Proceedings of the Workshop, Berkeley, California, 1987, edited by R. Donaldson and M. Gilchriese (World Scientific, Singapore, 1988), p. 178; H. Baer, M. Drees, D. Karatas, and X. Tata, *ibid.* p. 210; C. Albajar *et al.*, in *Proceeedings of the ECFA Large Hadron Collider Workshop*, Aachen, Germany, 1990, edited by G. Jarlskog and D. Rein (CERN Report No. 90-10, Geneva, Switzerland, 1990), Vol. II, p. 621.

[3] R. Barnett, J. Gunion, and H. Haber, Phys. Rev. D **37**, 1892 (1988).

[4] H. Baer *et al.*, in *Research Directions for the Decade*, Proceedings of the Workshop, Snowmass, Colorado, 1990, edited by E. L. Berger and I. Butler (Editions Frontières, Gif-sur-Yvette, 1991).

[5] R. Barnett and A. White, in *Research Directions for the Decade* [4]; V. Fonseca *et al.*, *ibid.*

[6] R. Barnett, J. Gunion, and H. Haber, in *High Energy Physics in the 1990's*, Proceedings of the Summer Study, Snowmass, Colorado, 1988, edited by S. Jensen (World Scientific, Singapore, 1989), p. 230.

[7] A. Bartl, W. Majerotto, B. Mosslacher, N. Oshimo, and S. Stippel, Phys. Rev. D **43**, 2214 (1991).

[8] H. Baer, X. Tata, and J. Woodside, Phys. Rev. D **45**, 142 (1992).

[9] For reviews of supersymmetry and the minimal model, see H. P. Nilles, Phys. Rep. **110**, 1 (1984); P. Nath, R.Arnowitt, and A. Chamseddine, *Applied $N = 1$ Supergravity*, ICTP Series in Theoretical Physics, Vol. I, (World Scientific, Singapore, 1984); H. Haber and G. Kane, Phys. Rep. **117**, 75 (1985); X. Tata, in *The Standard Model and Beyond*, edited by J. E. Kim (World Scientific, Singapore, 1991), p. 304.

[10] J. Gunion and H. Haber, Nucl. Phys. **B272**, 1 (1986); for a review, see J. Gunion, H. Haber, G. Kane, and S. Dawson, *The Higgs Hunter's Guide* (Addison-Wesley, Redwood City, CA, 1990).

[11] H. Baer, X. Tata, and J. Woodside, Phys. Rev. D **42**, 1568 (1990).

[12] Such a value of m_{H^+} is plausible (though not compulsory) in models with a common SUSY-breaking scalar mass at the unification scale if the sleptons are relatively heavy.

[13] H. Baer, A. Bartl, D. Karatas, W. Majerotto, and X. Tata, Int. J. Mod. Phys. A **4**, 4111 (1989); J. Gunion and H. Haber, Phys. Rev. D **37**, 2515 (1988).

[14] ALEPH Collaboration, D. Decamp *et al.*, Phys. Lett. B **241**, 141 (1990); **265**, 475 (1991); CERN Report No. PPE 91-149 1991 (unpublished); DELPHI Collaboration, P. Abreu *et al.*, *ibid.* **245**, 276 (1990); L3 Collaboration, B. Adeva *et al.*, *ibid.* **251**, 311 (1990); **252**, 511 (1990); OPAL Collaboration, M. Akrawy *et al.*, Z. Phys. C **49**, 1 (1991); P. D. Acton *et al.*, Phys. Lett. B **268**, 122 (1991).

[15] Y. Okada, M. Yamaguchi, and T. Yanagida, Phys. Lett. B **262**, 54 (1991); Prog. Theor. Phys. **85**, 1 (1991); H. Haber and R. Hempfling, Phys. Rev. Lett. **66**, 1815 (1991); J. Ellis, G. Ridolfi, and F. Zwirner, Phys. Lett. B **257**, 83 (1991); R. Barbieri, M. Frigeni, and F. Caravaglios, *ibid.* **258**, 167 (1991); A. Yamada, *ibid.* **263**, 233 (1991).

[16] H. Baer, M. Bisset, C. Kao, and X. Tata, Phys. Rev. D (to be published).

[17] M. Drees and N. Nojiri, Nucl. Phys. **B369**, 54 (1992).

[18] A. Brignole, J. Ellis, G. Ridolfi, and F. Zwirner, Phys. Lett. B **271**, 123 (1991).

[19] M. Drees and N. Nojiri, Phys. Rev. D **45**, 2482 (1992).

[20] S. L. Wu, in *The Vancouver Meeting — Particles and Fields '91*, Proceedings of the Joint Meeting of the Division of Particles and Fields of the American Physical Society and the Particle Physics Division of the Canadian Association of Physicists, Vancouver, 1991, edited by D. Axen, D. Bryman, and M. Comyn (World Scientific, Singapore, 1992).

[21] J. Gunion and L. Roszkowski, in *Research Directions for the Decade* [4]; Z. Kunszt and J. Stirling, Phys. Lett. B **242**, 507 (1990); V. Barger and K. Whisnant, Phys. Rev. D **43**, 1443 (1991); N. Brown, Z. Phys. C **49**, 657 (1991).

[22] See, e.g., F. Dydak, in *Proceedings of the 25th International Conference of High Energy Physics*, Singapore, 1990, edited by K. K. Phua and Y. Yamaguchi (World Scientific, Singapore, 1991); also, H. Baer, M. Drees, and X. Tata, Phys. Rev. D **41**, 3414 (1990); J. Ellis, G. Ridolfi, and F. Zwirner, Phys. Lett. B **237**, 423 (1990); M. Drees and X. Tata, Phys. Rev. D **43**, 2971 (1991).

[23] See contribution by A. Beretvas, in *Research Directions For the Decade* [4]; also, H. Baer, X. Tata, and J. Woodside, Phys. Rev. D **44**, 207 (1991).

[24] P. Kalyniak, R. Bates, and J. Ng, Phys. Rev. D **33**, 755 (1986); **34**, 172 (1986); J. Gunion, G. Gamberini, and S. Novaes, *ibid.* **38**, 3481 (1988); T. Weiler and T. C. Yuan, Nucl. Phys. **B318**, 337 (1989); J. Gunion and L. Orr, Report No. UCD-91-15, 1991 (unpublished); V. Barger, M. Berger, A. Stange, and R. Phillips, Phys. Rev. D **45**, 4128 (1992).

[25] SDC Collaboration, Letter of Intent, SDC-90-00151.

[26] V. Barger, R. Phillips, and A. Stange, Phys. Rev. D **44**, 1987 (1991); J. Gunion and Z. Kunszt, Phys. Lett. **159B**, 167 (1985); Phys. Lett. B **176**, 477 (1986); H. Baer, V. Barger, H. Goldberg, and R. Phillips, Phys. Rev. D **37**, 3152 (1988); R. Fletcher, F. Halzen, and C. S. Kim, Phys. Lett. B **209**, 351 (1988).

[27] Chargino and neutralino decays may violate lepton universality if these are mediated by a virtual Higgs boson, or if they occur via the Higgsino component of the $\tilde{W}_i$ or $\tilde{Z}_i$. In both cases the amplitude is proportional to the lepton Yukawa coupling and hence is negligible.

[28] If $m_t > m_{H^+}$, the production and subsequent decays of t-quark pairs can be an important source of H^+ in any two-Higgs-doublet model. The jet activity and $\not{E}_T$ characteristics of these events should, however, make it easy to distinguish H^+'s from SUSY sources from those produced via $t\bar{t}$ production.

[29] A. Savoy-Navarro, invited talk at Workshop on τ-lepton Physics, Orsay, France, Saclay, Report No. DPhPE 90-23, 1990 (unpublished); R. K. Ellis, I. Hinchliffe, M. Soldate, and J. van der Bij, Nucl. Phys. **B297**, 221 (1988); R. M. Godbole and D. P. Roy, Phys. Rev. D **43**, 3640 (1991).