Higgs boson decay into hadronic jets

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The remarkable agreement of electroweak data with standard model (SM) predictions motivates the study of extensions of the SM in which the Higgs boson is light and couples in a standard way to the weak gauge bosons. Postulated new light particles should have small couplings to the gauge bosons. Within this context it is natural to assume that the branching fractions of the light SM-like Higgs boson mimic those in the standard model. This assumption may be unwarranted, however, if there are nonstandard light particles coupled weakly to the gauge bosons but strongly to the Higgs field. In particular, the Higgs boson may effectively decay into hadronic jets, possibly without important bottom or charm flavor content. As an example, we present a simple extension of the SM, in which the predominant decay of the Higgs boson occurs into a pair of light bottom squarks that, in turn, manifest themselves as hadronic jets. Discovery of the Higgs boson remains possible at an electron-positron linear collider, but prospects at hadron colliders are diminished substantially.

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I. INTRODUCTION

In the standard model (SM) of elementary particle interactions, breaking of electroweak symmetry is achieved through the Higgs mechanism. The simplest realization is provided by the introduction of a complex Higgs doublet, which leads to the presence of a neutral CP-even Higgs boson H^0 in the physical spectrum. This state has not been observed, but a good theoretical description of the precision electroweak data [1] within the SM requires the Higgs boson to be lighter than about 200 GeV [2]. Although it can be argued that there are internal inconsistencies in the data [3] that may demand the presence of new physics [4,5], the SM with a light Higgs boson provides a surprisingly good description of the data. This success has induced an overwhelming preference for weakly interacting extensions of the SM, incorporating a light Higgs boson in a natural way, in comparison with heavy Higgs boson models in which the effect of the large Higgs boson mass in the oblique corrections is compensated by new physics contributions [6–8].

Among the possible extensions of the SM, the minimal supersymmetric standard model (MSSM) has been considered most seriously. The minimal realization of the Higgs mechanism within supersymmetric extensions of the standard model requires the presence of two Higgs doublets at low energies. In most regions of the supersymmetry (SUSY) breaking parameter space, the lightest neutral CP-even Higgs particle h resembles the SM Higgs boson in many of its properties [9]. Searches for experimental manifestations of the Higgs states are a central motivation for the experimental programs at the Fermilab Tevatron and the CERN Large Hadron Collider (LHC), with experimental detection techniques guided by theoretical expectations about the anticipated properties of these states.

Within the MSSM, the upper bound on the mass of the lightest Higgs state is roughly 135 GeV [10]. For Higgs boson masses m_h between 115 and 135 GeV, the total SM decay width is predicted to grow from about 3 to about 6 MeV [11]. At $m_h = 120$ GeV, the principal decay mode is into a pair of bottom quarks $b\bar{b}$, with about 69% branching fraction; this SM branching fraction drops to about 34% at $m_h = 140$ GeV while branching fractions into weak boson decays increase. In weakly interacting extensions of the SM, it is natural to assume that the light SM-like Higgs boson state has decay branching ratios similar to those in the SM. This expectation may be modified easily under the presence of light particles, weakly coupled to the weak gauge bosons, but strongly coupled to the Higgs field. The resulting Higgs boson decay properties will depend on the rates for decay to these new particles. For instance, the possible decay of the Higgs boson into stable neutral particles, such as neutralinos in the MSSM or neutrinos within models of extra dimensions, may lead to a Higgs particle with mainly invisible decays [12]. Alternatively, the Higgs boson may decay predominantly into hadronic jets, without any particular bottom or charm content. In this article, we consider scenarios which lead to this latter possibility.

Direct experimental searches at the CERN Large Electron Positron Collider (LEP) place the mass of a SM-like Higgs state, with a significant decay branching ratio into bottom (b) quarks, above approximately 115 GeV [2]. An alternative analysis, based only on the assumption of Higgs boson decay into hadronic jets, without b-tagging, leads to a bound of about 113 GeV [13]. In this article, we explore in detail the possible detection of such a Higgs boson at future hadron and lepton colliders.

A Higgs boson with a dominant effective decay branching ratio into jets may be obtained within the MSSM, under the assumption of the presence of light bottom squarks in the spectrum. The possible existence of bottom squarks $\tilde{b}$ with

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low masses is advanced in several recent papers [14,15]. Bottom squarks are the spin-0, charge -1/3, and color triplet supersymmetric partners of bottom quarks. Interestingly, very small $\tilde{b}$ masses on the order of 10 GeV may be compatible with existing measurements [14–25]. Within SUSY theories, a light bottom squark is obtained most readily for large values of $\tan\beta$ [14], the ratio of neutral Higgs field vacuum expectation values, and we work in this limit. Moderate to high values of $\tan\beta$ are further motivated by the fact that experiments at LEP II did not find conclusive evidence of the light SUSY Higgs boson; such values are favored in order that the predicted mass of the Higgs boson remain above the value excluded experimentally [10]. We restrict $\tan\beta \lesssim 50$, as for larger values the bottom quark couplings to some of the Higgs particles can be strong enough that perturbation theory breaks down.

We work in the the decoupling limit in which the mass of the pseudoscalar Higgs boson (m_A) is large compared to m_Z and the couplings of h with SM particles approach their SM values. In particular, even for large values of $\tan\beta$, the coupling of the light scalar Higgs boson h to bottom quarks is not enhanced. Within the light bottom squark scenario, the dominant Higgs decay is into a pair of bottom squarks $\tilde{b}\tilde{b}^*$ [14] that, in turn, manifest themselves as jets of hadrons. The total width is predicted to increase by a factor of ten to several hundred, depending upon the value of $\tan\beta$. Since the couplings to SM particles remain approximately unchanged, the upshot is that branching fractions into conventional decay modes ($b\bar{b}$, WW^*, ZZ^*, gg, $\tau\bar{\tau}$, $\gamma\gamma, \ldots$) are all reduced by a corresponding factor.

In order to fix the framework, we concentrate for the most part on the particular example of a light bottom squark. While details of our approach depend on the existence of low mass $\tilde{b}$'s, the principal conclusions are illustrative of the challenges to be faced if the dominant decays of a light Higgs state, with $m_H < 135$ GeV, are into hadronic jets without specific flavor tags. In Sec. II, we summarize salient aspects of the phenomenology of bottom squarks, including constraints on their couplings, and we review available experimental bounds. In Sec. III, we compute the Higgs boson width for decay into a pair of bottom squarks as well as the influence of bottom squarks in loop processes that describe decay into other final states. The decay width into the gluon-gluon gg final state is enhanced as is the partonic production cross section $gg \to h$. We show that decay to a pair of bottom squarks is by far the dominant decay mode of the Higgs boson for large values of $\tan\beta$. Since the SM decay couplings are essentially unaffected, the total decay width of the Higgs boson is increased and the branching fractions into the SM decay modes are decreased accordingly. Except for the gluon fusion process, the Higgs boson production rates are not enhanced in hadron collisions and in electron-positron annihilation processes. As we discuss in Sec. IV, dominant decay into bottom squarks that materialize as hadronic jets makes it much more difficult, if not impossible, to discover the Higgs boson at a hadron collider. The possibilities at an electron-positron linear colliders are examined in Sec. V where we demonstrate that it remains possible to discover the Higgs boson and to measure its mass and several of its coupling strengths.

II. LOW MASS BOTTOM SQUARKS

Light bottom squarks are discussed in Ref. [15] in the context of an explanation for the large bottom quark production cross section at hadron colliders. In that work, a light gluino is also postulated with 100% branching fraction into a bottom quark and a bottom squark. In this discussion of Higgs boson decay, we need not assume a light gluino since there is a direct coupling of the Higgs boson to a pair of bottom squarks. The bottom squark is the LSP, the SUSY particle with lowest mass. It may decay promptly through baryon-number and R-parity violating interactions into light quarks [26], or it could be stable on collider time scales [27]. The least model-dependent statement one can make is that at high energies the $\tilde{b}$ is likely to manifest itself experimentally as a jet of hadrons in the detector. If we introduce somewhat more model-dependent assumptions about decay modes of the $\tilde{b}$, identification of the Higgs boson at hadron colliders could be facilitated if jets containing charm and/or leading baryons can be identified cleanly.

The lighter bottom squark is a mixture of the scalar partners of the left- and right-chiral bottom quarks. After SUSY breaking and electroweak symmetry breaking, the mass matrix for bottom squarks in the weak eigenstate basis is

$$\begin{pmatrix} m_{\tilde{Q}}^2 + m_b^2 + D_L & m_b[A_b - \mu\tan\beta] \\ m_b[A_b - \mu\tan\beta] & m_{\tilde{b}}^2 + m_b^2 + D_R \end{pmatrix}, \tag{1}$$

where $m_{\tilde{Q}}^2$ and $m_{\tilde{b}}^2$ are the SUSY-breaking masses for the third family squark doublet and down-type singlet, respectively, A_b is the SUSY-breaking interaction term for the Higgs boson and bottom squarks, m_b is the bottom quark mass, μ is the Higgsino mass parameter, and D_L and D_R are the D terms for the bottom quark sector, given by $m_Z^2 \cos 2\beta(-1/2 + \sin^2\theta_W/3)$ and $-m_Z^2 \cos 2\beta/3$, respectively. The mass eigenstates are two complex scalars ($\tilde{b}_1$ and $\tilde{b}_2$) with masses and mixing parameter ($\sin\theta_b$) determined by diagonalizing the matrix, Eq. (1). These mass eigenstates are expressed in terms of left-handed (L) and right-handed (R) bottom squarks, $\tilde{b}_L$ and $\tilde{b}_R$, as

$$|\tilde{b}_1\rangle = \sin\theta_b|\tilde{b}_L\rangle + \cos\theta_b|\tilde{b}_R\rangle, \tag{2}$$

$$|\tilde{b}_2\rangle = \cos\theta_b|\tilde{b}_L\rangle - \sin\theta_b|\tilde{b}_R\rangle. \tag{3}$$

The diagonalization of Eq. (1) provides expressions for the squares of the masses of the two bottom squarks. The value of $\sin 2\theta_b$ can then be expressed in terms of the difference of the eigenvalues and the off-diagonal terms:

$$\sin 2\theta_b = \frac{2m_b(A_b - \mu\tan\beta)}{m_{\tilde{b}_1}^2 - m_{\tilde{b}_2}^2}. \tag{4}$$

Taking $\tilde{b}_1$ to be the lighter bottom squark, we obtain the condition $\sin 2\theta_b(A_b-\mu\tan\beta)\leqslant 0$. In the limit in which we retain only terms enhanced by large $\tan\beta$, we determine that $\mu\sin 2\theta_b \geqslant 0$.

There are important constraints on couplings of the bottom squarks from precise measurements of Z^0 decays. A light $\tilde{b}$ would be ruled out unless its coupling to the Z^0 is very small. The squark couplings to the Z^0 depend on the mixing angle θ_b. As described in Ref. [14], the lowest-order (tree-level) coupling of $\tilde{b}_1$ to the Z^0 can be arranged to vanish when $\sin^2\theta_b \sim 1/6$. An interesting conclusion of Ref. [14] is that in order to obtain appropriately small oblique corrections, in addition to a light bottom squark, a light top squark with mass $\lesssim 250$ GeV is required. In the remainder of this paper, we use $\tilde{b}$ without a subscript to denote the lighter bottom squark.

Bottom squarks make a small contribution to the inclusive cross section for $e^+e^- \to$ hadrons, in comparison to the contributions from quark production, and $\tilde{b}\tilde{b}^*$ resonances are difficult to extract from backgrounds in e^+e^- annihilation [23]. The angular distribution of hadronic jets produced in e^+e^- annihilation can be examined in order to bound the contribution of scalar-quark production. Spin-1/2 quarks and spin-0 squarks emerge with different distributions, $(1\pm\cos^2\theta)$, respectively. Within the limits of current experimental sensitivity, the angular distribution measured by the CELLO Collaboration [24] is consistent with the production of a single pair of charge 1/3 squarks along with five flavors of quark-antiquark pairs.

The presence of a light bottom squark slows the running of the strong coupling strength $\alpha_s(\mu)$. Below the gluino threshold, but above the bottom squark threshold, the β function of SUSY QCD is

$$\beta(\alpha_S)=\frac{\alpha_S^2}{2\pi}\left(-11+\frac{2}{3}n_f+\frac{1}{6}n_s\right), \tag{5}$$

where n_f is the number of Dirac quark flavors, and n_s is the number of left or right squark flavors active at the scale in question. The $\tilde{b}$ (as a color triplet scalar) contributes little to the running, equivalent to one quarter of a new flavor of quark and cannot be excluded with the current data [28]. The exclusion by the CLEO Collaboration [25] of a $\tilde{b}$ with mass 3.5 to 4.5 GeV does not apply since their analysis focuses only on the decays $\tilde{b}\to c\ell\tilde{\nu}$ and $\tilde{b}\to c\ell$. The $\tilde{b}$ need not decay leptonically nor into charm.

III. HIGGS BOSON DECAY RATES

In the standard model, a Higgs boson of mass below $\sim$135 GeV, as is always the case for the lightest Higgs boson in the MSSM, decays predominantly into pairs of bottom quarks, $H^0\to b\bar{b}$. The tree-level SM prediction for the partial width is

$$\Gamma_b=\frac{3g^2m_b^2m_h}{32\pi m_W^2}, \tag{6}$$

where m_b is the modified mimimal subtraction scheme ($\overline{\rm MS}$) bottom quark mass, evaluated at the mass m_h of the Higgs boson, m_W is the mass of the W boson, and g is the $SU(2)_W$ coupling strength. We neglect the $\mathcal{O}(10^{-3})$ correction from the finite bottom quark mass in the decay phase space. This formula is also valid for the light SUSY Higgs boson h in the decoupling limit in which the mass of the pseudoscalar Higgs boson (m_A) is large compared to m_Z and the couplings of h with SM particles approach their SM values.

The tree-level expression for the coupling of the lighter CP-even Higgs scalar h to the lighter bottom squark $\tilde{b}$ is [9,29]

$$\frac{gm_Z}{\cos\theta_W}\Bigg[-\frac{1}{2}\sin(\alpha+\beta)\left(\cos^2\theta_b-\frac{2}{3}\sin^2\theta_W\cos 2\theta_b\right) + \frac{m_b^2}{m_Z^2}\frac{\sin\alpha}{\cos\beta}+\frac{1}{2}\sin 2\theta_b\frac{m_b(A_b\sin\alpha+\mu\cos\alpha)}{m_Z^2\cos\beta}\Bigg]. \tag{7}$$

In this expression, α is the CP even Higgs mixing angle. In the decoupling regime, $\cos\alpha\to\sin\beta$, $\sin\alpha\to-\cos\beta$, and the term in Eq. (7) proportional to μ effectively grows with $\tan\beta$, unlike the coupling of h to bottom quarks in the decoupling limit. It is this feature that enhances the decay $h\to\tilde{b}\tilde{b}^*$ compared to the dominant SM decay, $h\to b\bar{b}$ [14].

In SUSY theories at large values of $\tan\beta$, there can be important loop effects (enhanced by $\tan\beta$) that affect the couplings of the bottom quark to the Higgs bosons [30]. The couplings to the Higgs boson mass eigenstates may be determined from the couplings to the weak eigenstates. These couplings are y_b, the tree level coupling of the bottom quark to the real part of the neutral component of the down-type Higgs field H_d^0 [31], and Δy_b, the effective coupling of the bottom quark to the neutral component of the up-type Higgs field H_u^0, which can be computed from the corresponding three-point Green function at the one-loop level. The one-loop effects modify the relation between the bottom quark mass and y_b by a factor potentially as large as order one [30]:

$$y_b=\frac{gm_b}{\sqrt{2}m_W\cos\beta(1+\Delta_b)}. \tag{8}$$

As shown in Ref. [32], when the masses of all supersymmetric particles are much larger than the weak scale, the corrections to the bottom quark mass are related to the vertex corrections obtained from the $H_u^0b\bar{b}$ three-point Green function, and Δ_b is equal to $\bar{\Delta}_b=\Delta y_b\tan\beta/y_b$. However, in the presence of light sparticles, there are additional contributions to the three-point function Δy_b, not related to the mass correction parameter Δ_b.

When only the terms enhanced by $\tan\beta$ factors are kept, the expressions for Δ_b and $\bar{\Delta}_b$ are [32]

$$\Delta_b = \frac{32\pi\alpha_s}{3}\int \frac{d^4k}{(2\pi)^4}\frac{i\mu m_{\tilde g}\tan\beta}{(k^2-m_{\tilde g}^2+i\epsilon)(k^2-m_{\tilde b_1}^2+i\epsilon)(k^2-m_{\tilde b_2}^2+i\epsilon)}, \tag{9}$$

$$\overline{\Delta}_b = \Delta_b + \frac{64\pi\alpha_s}{3}(m_b\mu\tan\beta)^2\int \frac{d^4k}{(2\pi)^4}\frac{i\mu m_{\tilde g}\tan\beta}{(k^2-m_{\tilde g}^2+i\epsilon)(k^2-m_{\tilde b_1}^2+i\epsilon)^2(k^2-m_{\tilde b_2}^2+i\epsilon)^2}. \tag{10}$$

In these expressions, $m_{\tilde g}$ denotes the mass of the gluino. The factor $m_b\mu\tan\beta$ may also be written in terms of the mixing angle and the bottom squark mass eigenvalues as $\sin\theta_b\cos\theta_b(m_{\tilde b_2}^2-m_{\tilde b_1}^2)$. The above expressions show that if all soft supersymmetry breaking masses are of the same order of magnitude and become much larger than the weak scale, then Δ_b and $\overline{\Delta}_b$ tend to a common value, apart from corrections that are suppressed by powers of the ratio of the weak scale divided by the supersymmetry breaking scale. In the presence of a light bottom squark and nonvanishing mixing angles, however, there is a finite difference between Δ_b and $\overline{\Delta}_b$.

As emphasized above, in this paper we work in the decoupling limit, in which the mass of the CP-odd Higgs boson is much larger than the weak scale. In the absence of light sparticles, one recovers the SM as an effective theory at the weak scale, as well as the standard values of the Higgs couplings to quarks and leptons. In the presence of light sparticles, however, these couplings may differ from their standard model values. For instance, due to the difference between the one-loop vertex correction, $\overline{\Delta}_b$, and the bottom quark mass correction, Δ_b, the effective coupling of the bottom quark to the Higgs boson in the decoupling limit reads

$$g_{hb\bar b} = \frac{g m_b(m_h)}{2m_W}\frac{1+\overline{\Delta}_b}{1+\Delta_b}, \tag{11}$$

differing from the standard model coupling by a factor of order one. If $\Delta_b = \overline{\Delta}_b$, one recovers the standard model coupling.

On the other hand, for large values of $\tan\beta$, the coupling of light bottom squarks to the light Higgs boson in the decoupling limit is governed by the presence of a tree-level coupling of the bottom squarks to H_u,

$$g_{h\tilde b\tilde b^*} \simeq \frac{g\mu m_b(m_h)\tan\beta}{2m_W(1+\Delta_b)}\sin 2\theta_b, \tag{12}$$

where we have neglected subdominant terms in $\tan\beta$. Therefore, for large values of $\tan\beta$, the width for Higgs boson decay into light bottom squarks may become much larger than the width for decay into bottom quarks. The precise relation between these decay widths depends not only on $\tan\beta$ but also on the values of the one-loop correction factors Δ_b and $\overline{\Delta}_b$. Because the values of Δ_b and $\overline{\Delta}_b$ depend sensitively on the masses of other super-particles such as the gluino, we do not attempt to include them in our results, but instead treat them as an order-one model-dependence on our prediction for the ratio of the partial widths into bottom squarks and bottom quarks, $\Gamma_{\tilde b}/\Gamma_b$.

The tree-level partial width for h decay to a pair of $\tilde b$'s is

$$\Gamma_{\tilde b} = \frac{3g^2m_b^2\mu^2\tan^2\beta}{64\pi m_h m_W^2}\sin^2 2\theta_b(\mu\tan\beta)^2 \times\left(1-4\frac{m_{\tilde b}^2}{m_h^2}\right)^{1/2}, \tag{13}$$

and the ratio of partial widths is

$$\frac{\Gamma_{\tilde b}}{\Gamma_b} = \frac{(\mu\tan\beta)^2}{2m_h^2}\sin^2 2\theta_b\left(1-4\frac{m_{\tilde b}^2}{m_h^2}\right)^{1/2}. \tag{14}$$

Equation (14) indicates that $(\mu\tan\beta/m_h)$ is the relevant quantity that determines the extent to which decays into bottom squarks dominate the decay process. The ratio as a function of $\mu\tan\beta/m_h$ is shown in Fig. 1. We choose $m_b(m_h)=3$ GeV, as is appropriate in the SM, $\sin^2\theta_b=1/6$, and we neglect the dependence on the bottom squark mass. As stated earlier, our analysis is valid in the region of large

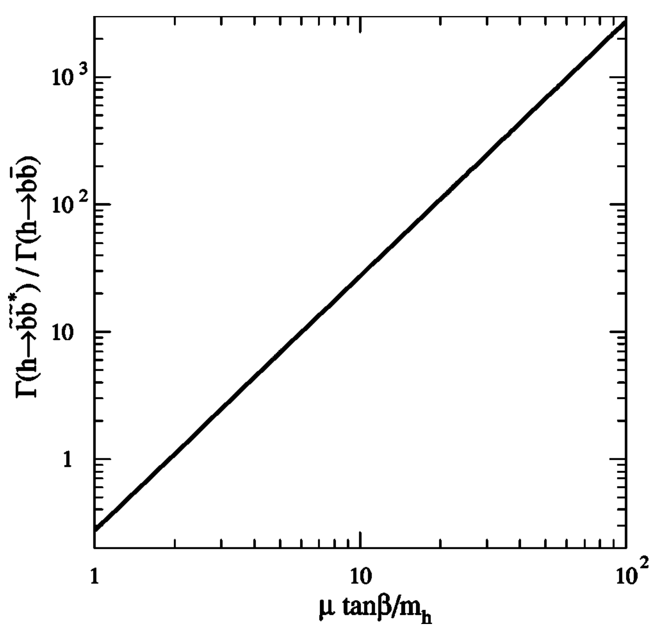

FIG. 1. Ratio of partial decay widths $\Gamma(h\to\tilde b\tilde b^*)/\Gamma(h\to b\bar b)$ is plotted against $\mu\tan\beta/m_h$ in the limit in which $m_{\tilde b}\ll m_h$.

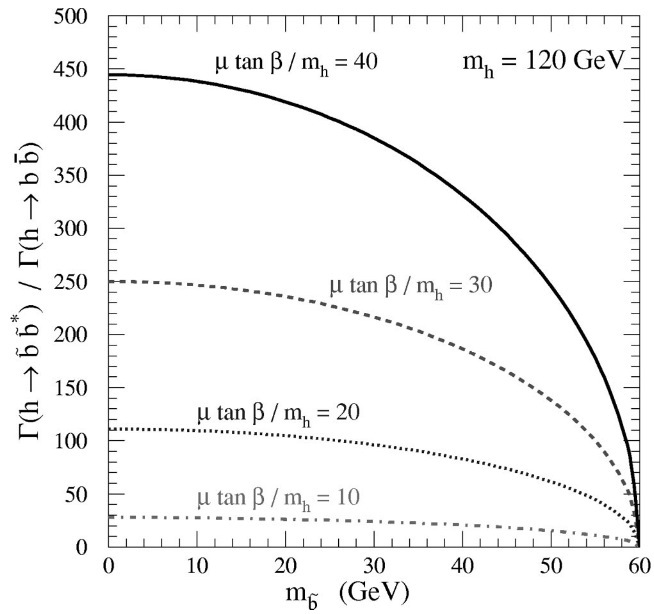

FIG. 2. Ratio of partial decay widths $\Gamma(h\to\tilde{b}\tilde{b}^*)/\Gamma(h\to b\bar{b})$ is plotted against the bottom squark mass $m_{\tilde{b}}$. From bottom to top, the curves correspond to choices of $\mu\tan\beta/m_h = 10$, 20, 30 and 40, respectively.

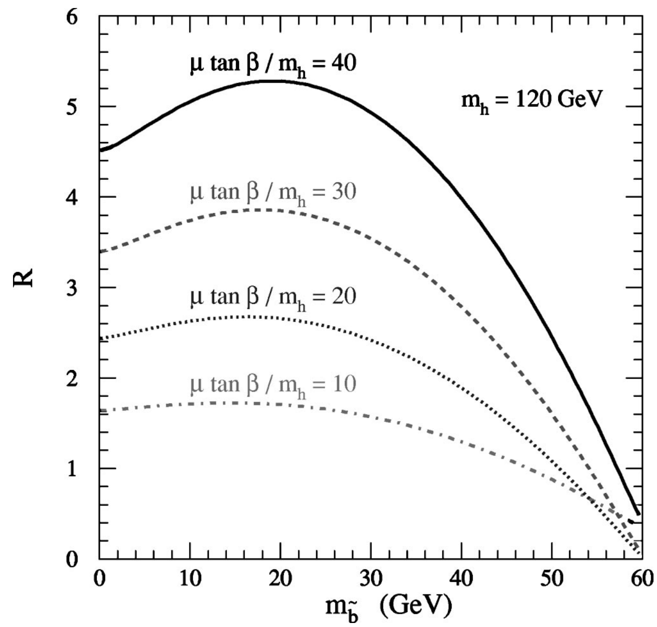

FIG. 3. The ratio R of the Higgs boson decay width into gluons divided by its SM value is plotted against $m_{\tilde{b}}$ for (from bottom left to top left) $\mu\tan\beta/m_h = 10$, 30, and 40, respectively.

$\mu\tan\beta/m_h$. Nevertheless, we provide numerical results in Fig. 1 and subsequently for values of $\mu\tan\beta/m_h$ that extend down to 1. Our reason is that we take $\mu\tan\beta/m_h$ as a parametrization of the jet-jet rate, represented in our example by the $\tilde{b}\tilde{b}^*$ rate. We show the ratio as a function of $m_{\tilde{b}}$ and for a few values of $\mu\tan\beta/m_h$ in Fig. 2. Evident in Figs. 1 and 2 is that decay to a pair of bottom squarks is much more important than decay into bottom quarks for $\mu\tan\beta/m_h > 10$, so long as $m_{\tilde{b}} < m_h/2$.

In addition to the direct tree level decay into bottom squark jets, light bottom squarks may affect Higgs boson decay rates into SM particles at the loop level. Decay into two gluons occurs through loops of colored (s)particles that couple to the Higgs boson and to gluons. In the SM, the only relevant contribution is from a loop of top quarks, with small corrections from the bottom quarks. (We remark here, again, that in the decoupling limit in which m_A is large compared to m_Z, the couplings of h with SM particles approach their SM values even for large $\tan\beta$.) In the MSSM, contributions from loops of light bottom squarks may also play an important role. The amplitude for $h\to gg$ is proportional to the sum $T_{SM}+T_{SUSY}$ where

$$T_{SM} = -\frac{1}{\eta_t} f(\eta_t), \tag{15}$$

$$T_{SUSY} = -\frac{m_b\mu}{m_h^2}\sin 2\theta_b \tan\beta\, g(\eta_{\tilde{b}}), \tag{16}$$

and

$$f(x) = 1 + \frac{x-1}{x} h(x), \tag{17}$$

$$g(x) = 1 - \frac{1}{x} h(x), \tag{18}$$

where

$$h(x) = \begin{cases} \arcsin^2\sqrt{x}, & x \leqslant 1, \\ -\dfrac{1}{4}\left[\log\dfrac{1+\sqrt{1-x^{-1}}}{1-\sqrt{1-x^{-1}}} - i\pi\right]^2, & x > 1. \end{cases} \tag{19}$$

In Eqs. (15) and (16), $\eta_i = m_h^2/4m_i^2$. Note that $\eta_t < 1$ and $\eta_{\tilde{b}} > 1$, making T_{SM} real but T_{SUSY} complex. Equation (16) shows that the sign of the SUSY contribution depends on the sign of the product of μ and $\sin 2\theta_b$. As explained after Eq. (4), the sign is positive.

The ratio of the total rate into the gg final state, including the SUSY contribution, and the pure SM rate is

$$R = \frac{|T_{SM}+T_{SUSY}|^2}{|T_{SM}|^2}. \tag{20}$$

In Fig. 3, we show the dependence of R on $m_{\tilde{b}}$ and $\tan\beta$. In this calculation, for completeness we include in the SM piece the (relatively small) contribution of the bottom quark loop along with that of the top quark loop. We use $m_t(m_h) = 170$ GeV for the $\overline{\rm MS}$ top quark mass at the Higgs mass scale. The relative plus sign between Eqs. (15) and (16) leads to constructive interference between the real parts of T_{SM} and T_{SUSY}. If $\mu\tan\beta/m_h = 20$, the constructive interference yields the ratio $R > 2$ for $m_{\tilde{b}} \lesssim 40$ GeV. This effect is magnified for larger values of $\mu\tan\beta/m_h$. The ratio $R > 1$ for a wide range of $m_{\tilde{b}} \lesssim 50$ GeV. The influence of the top squark loop may be modest. We find that the ratio of rates for the top squark and bottom squark loops is less than 3%, for $5 < m_{\tilde{b}} < 60$ GeV (and fixed $\mu \tan\beta/m_h = 20$, $m_{\tilde{t}} = 200$ GeV, $m_h = 120$ GeV, $A_t = 500$ GeV, and $\sin 2\theta_{\tilde{t}} = -1$). However, the real part of top squark contribution is destructive with T_{SM}. Inclusion of the top squark contribution reduces the ratio R in Fig. 3 by about 10%. The essential content of Fig. 3 is that for small $m_{\tilde{b}}$ the bottom squark loop can have a substantial effect on the expected rate for Higgs boson decay into a pair of gluons. Although the rate is enhanced, the partial width is not magnified as much as for the $\tilde{b}\tilde{b}^*$ mode since the gg decay mode is loop suppressed. As shown quantitatively below, the gg branching fraction decreases as $\mu \tan\beta/m_h$ is increased, albeit less quickly than the $b\bar{b}$ branching fraction.

For Higgs boson decay into $\gamma\gamma$, a W loop contribution dominates the SM prediction, and this remains true after SUSY contributions are included [33]. The contributions of the top squark, bottom squark, and chargino are all of similar size, with specific values that depend on the choice of parameters. In particular, a kinematic enhancement from the small $\tilde{b}$ mass is mitigated by the small charge of the $\tilde{b}$, $-1/3$. The SUSY contributions lead to a small destructive interference with the SM loop effect in the region of bottom squark masses of interest to us, reducing the decay rate (or the production rate in $\gamma\gamma \to h$) by less than 10% for $m_{\tilde{b}} < 30$ GeV, $20 < \mu \tan\beta/m_h < 40$, and the same parameters for the top squark contribution mentioned in the previous paragraph.

To summarize, a light bottom squark combined with moderate to large $\mu \tan\beta/m_h$ leads the light Higgs boson of the MSSM to decay dominantly into bottom squarks. In contrast to the growth with $\mu \tan\beta/m_h$ of the partial width into bottom squarks, the partial width into bottom quarks is affected at order one, that into gluons is enhanced with respect to the SM, and that into photons is relatively insensitive, being dominated by the contributions of the W. If there is a light gluino $\tilde{g}$ with mass $m_{\tilde{g}} < m_h/2$, the channel $h \to \tilde{g}\tilde{g}$ is open [34]. Its amplitude is provided by a loop diagram, proportional in our scenario to the $h\tilde{b}\tilde{b}^*$ coupling and therefore enhanced by $\tan\beta$. However, a factor of α_s and the usual loop suppression factors render the final contribution small, with a branching fraction typically orders of magnitude below that for the $\tilde{b}\tilde{b}^*$ final state. The top-squark loop contribution may also be significant for appropriate parameters.

Since the SM decay couplings are essentially unaffected, the total decay width of the Higgs boson is increased and the branching fractions into the SM decay modes are decreased accordingly. We obtain the new total width of the Higgs boson by adding the SM widths (except in the gg and $\gamma\gamma$ cases where we include the SUSY loop modifications) and the partial width into $\tilde{b}\tilde{b}^*$. The total width and the $\tilde{b}\tilde{b}^*$ partial width are shown in Fig. 4. For $m_h \simeq 120$ GeV, we predict a total width of about 250 MeV for $\mu \tan\beta/m_h = 20$, and about 1.6 GeV for $\mu \tan\beta/m_h = 50$. Although the branching fraction into bottom squarks and the total width of the Higgs boson are enhanced in proportion to the square of

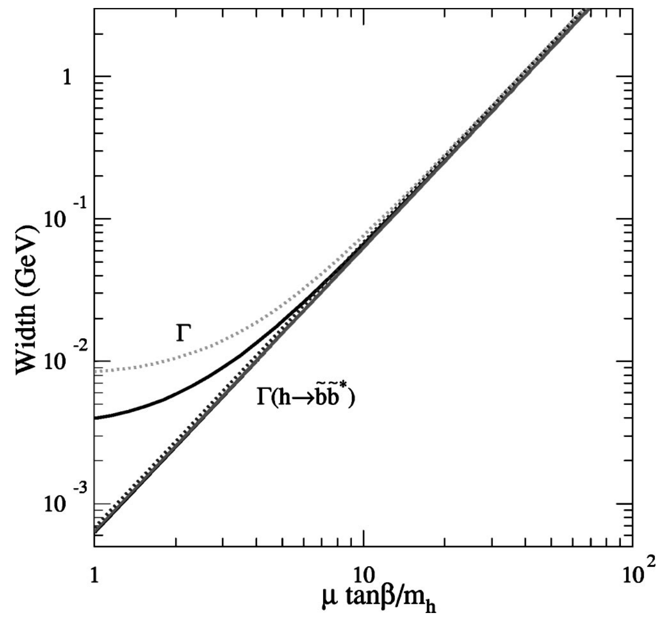

FIG. 4. Total width of the Higgs boson and the partial width into a pair of bottom squarks as a function of the ratio $\mu \tan\beta/m_h$, with $m_h = 120$ GeV and $m_h = 140$ GeV. We take $m_h \gg m_{\tilde{b}}$. For each pair of curves, the solid represents $m_h = 120$ GeV and the dotted $m_h = 140$ GeV.

$\mu \tan\beta/m_h$, there is no corresponding enhancement of the Higgs boson production rates in hadron collisions and in electron-positron annihilation processes, as discussed in more detail in Secs. IV and V.

A compilation of branching fractions is presented in Fig. 5 and in Table I as a function of $\mu \tan\beta/m_h$. In this table, we also provide values of the total width, obtained after SUSY effects in the $\tilde{b}\tilde{b}^*$, gg, and $\gamma\gamma$ cases are taken into account. We begin from the SM values of the branching fractions [35]. We assume that there are no SUSY corrections to the partial widths of the $b\bar{b}$, WW^*, ZZ^*, $\tau^+\tau^-$, and $c\bar{c}$ modes so that the branching fractions in these cases are obtained from the SM values of the partial widths divided by the new total width of the Higgs boson. In the gg and $\gamma\gamma$ cases, we include the SUSY loops effects described above in the computation of the partial widths. At $m_h = 120$ GeV, the $b\bar{b}$ and $\tilde{b}\tilde{b}^*$ branching fractions cross each other for $\mu \tan\beta/m_h \simeq 1.9$, where the two branching fractions are each about 0.4. At $m_h = 140$ GeV, the WW^* and $\tilde{b}\tilde{b}^*$ branching fractions cross each other for $\mu \tan\beta/m_h \simeq 2.3$, where the two branching fractions are each about 0.34. While $m_h = 140$ GeV cannot be obtained in the usual MSSM, we provide branching ratios at this value of mass, only slightly above that achievable in the minimal framework.

IV. HADRON COLLIDER PHENOMENOLOGY

At the LHC, a SM-like Higgs boson of mass less than ~ 135 GeV is expected to be discovered through a variety of production processes and decay modes [36],
$gg \to h$, with $h \to \gamma\gamma$, $h \to W^+W^-$, or $h \to ZZ$;

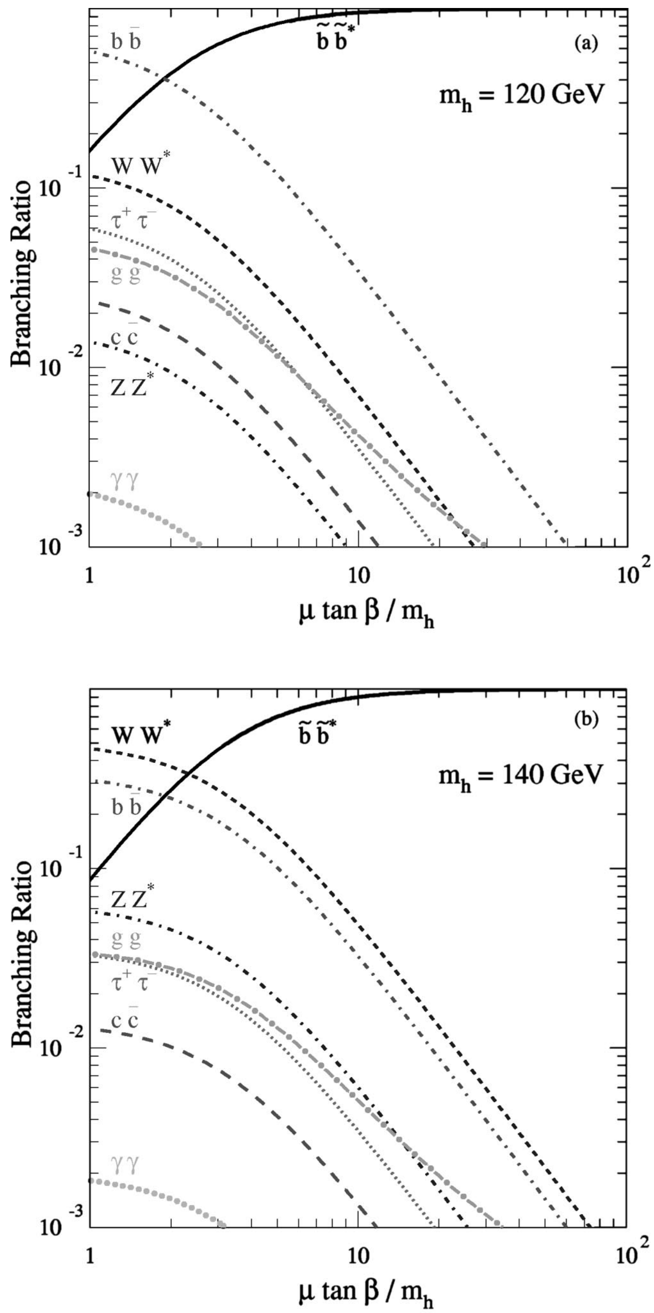

FIG. 5. Branching fractions for various Higgs boson decay channels as a function of the ratio $\mu \tan\beta/m_h$, with (a) $m_h = 120$ GeV and (b) $m_h = 140$ GeV. We fix $m_{\tilde{b}} = 5$ GeV in obtaining these values.

$t\bar{t}h$, with $h \to b\bar{b}$ or $h \to \gamma\gamma$;
$W^+W^-(ZZ) \to h$, with $h \to W^+W^-$, $h \to \gamma\gamma$, or $h \to \tau^+\tau^-$.

These standard searches look for Higgs boson decays into SM particles. As indicated in Fig. 5, the presence of the light bottom squark suppresses the branching ratios of these decay modes by a factor of order of ten to several hundred, depending somewhat on $m_{\tilde{b}}$ and to large degree on μ and $\tan\beta$. This reduction raises serious questions as to the capability of experiments at the LHC to discover a Higgs boson. The more standard decays are suppressed, and the principal decay mode into jets suffers from enormous QCD backgrounds. In the analysis below, we assume the LHC is a $\sqrt{s} = 14$ TeV pp collider with a total integrated luminosity of 100 fb^{-1}.

The gluon-gluon fusion process, $gg \to h$ [37], is a copious production mechanism mediated by the same loops that contribute to $h \to gg$ described above. In the narrow width approximation, the partonic production cross section may be related to the decay width at leading order by the expression

$$\sigma(gg \to h) = \frac{\pi^2}{8m_h^3}\Gamma(h \to gg)\,\delta(\hat{s} - m_h^2), \qquad (21)$$

and the ratio R of Fig. 3 is also the ratio of the hadronic cross sections from this production mode in the SUSY model to that in the SM. We mention that next-to-leading order contributions are known to be important for $gg \to h$ [38]. Next-to-leading order QCD effects for the bottom squark loop cannot be treated in analogous fashion owing to the small mass of the bottom squark. We restrict ourselves to a leading order treatment in this paper. As was the case for $\Gamma(h \to gg)$, we conclude from Eq. (21) that the gg fusion production rate is enhanced by the contribution from the bottom squark loop. The large backgrounds from hadronic production of jets make discovery of a SM Higgs boson possible only in the distinct decay modes $h \to \gamma\gamma$, $h \to ZZ$, and $h \to W^+W^-$, where here and elsewhere in our discussion, both of the final weak vector bosons are not on the mass shell. In the Higgs boson mass range 120 to 140 GeV, the significance for observation at the LHC (signal divided by the square root of background, $S/\sqrt{B}$) of a SM Higgs boson is 8.1 to 8.4, 5.3 to 22.1, and 4.8 to 17.7 standard deviations (σ's), respectively. A decrease in the branching fraction of any of these processes by a factor of 2 to 5 renders them ineffective for discovery of the h. It may be impossible to extract the new decay mode $h \to \tilde{b}\tilde{b}^*$ from the large QCD 2-jet background, unless the $\tilde{b}$ has very special decay signatures. For $m_h \geqslant 150$ GeV, which cannot be realized in the MSSM but could occur in a more general theory, decays into W's and Z's can dominate over the bottom squark decays, and a high significance could be restored.

If there are light bottom squarks, the parton density of $\tilde{b}$ in the proton may be significant at high energies, and due to their strong coupling to the Higgs, the partonic process $\tilde{b}\tilde{b}^* \to h$ would be competitive with the glue-glue production rate, for large enough $\tan\beta$. This production mode has the same experimental signature as the $gg \to h$ mode discussed above, and thus all of the comments regarding its observability apply to this process as well. In fact, one should combine the two processes and consider one "inclusive" Higgs production process. If one assumes that the $\tilde{b}$ content in the proton is comparable with the bottom content for comparable bottom quark and squark masses, the $\tilde{b}\tilde{b}^* \to h$ rate can be estimated from the $b\bar{b} \to h$ rate [39] with an appropriate replacement of the Higgs coupling to b with the coupling to $\tilde{b}$, and the rates at the LHC are of order 0.955 to 0.576 $\mathrm{pb} \times (\mu \tan\beta/m_h)^2$. This enhancement of the inclusive Higgs production, while growing with $(\mu \tan\beta)^2$ is compen-

TABLE I. Branching ratios and total widths of the Higgs boson for masses of 120 and 140 GeV and $\mu\tan\beta/m_h=10,20,50$. We fix $m_{\tilde{b}}=5$ GeV in obtaining these values.

m_h	BR×10^2 120 GeV				140 GeV			
$\mu\tan\beta/m_h$	SM	10	20	50	SM	10	20	50
$\tilde{b}\tilde{b}^*$	0	94.9	98.6	99.7	0	90.3	97.3	99.5
$b\bar{b}$	69	3.4	0.89	0.14	34	3.3	0.88	0.14
WW^*	14	0.69	0.18	0.029	51	4.9	1.3	0.21
ZZ^*	1.66	0.082	0.021	0.003	6.3	0.60	0.16	0.027
$\tau^+\tau^-$	7.1	0.35	0.091	0.015	3.6	0.34	0.093	0.015
gg	5.2	0.42	0.16	0.061	3.5	0.51	0.19	0.069
$c\bar{c}$	2.8	0.14	0.036	0.006	1.4	0.13	0.036	0.006
$\gamma\gamma$	0.24	0.011	0.003	0.0004	0.20	0.019	0.005	0.0007
Γ_{total} (MeV)	3.3	67	257	1585	7.8	82	303	1850

sated by the depression of the branching fractions into observable modes, which fall as $(\mu\tan\beta/m_h)^{-2}$. Thus, the rate into observable decay modes remains of the same order as in the SM. One might worry that the subprocess $\tilde{b}\tilde{b}^*\to h$ overestimates this contribution to inclusive Higgs production. However, since we conclude that the inclusive process is unobservable at sufficiently high $\mu\tan\beta/m_h$, a smaller expected contribution from $\tilde{b}\tilde{b}^*\to h$ only strengthens the result.

Production in association with top quarks, $t\bar{t}h$, has a relatively low rate because of the large masses in the final state. In the decoupling limit, the coupling of h to top quarks is approximately standard, so the production rate is unaffected by the presence of a light bottom squark in the spectrum. The expected significances for $h\to b\bar{b}$ and $h\to\gamma\gamma$ in the SM are approximately 9.3 to 5.6σ [40] and 4.3σ [36], respectively, in the mass range of interest, and the conclusion is that a suppression by slightly more than a factor of two of the branching ratio $h\to b\bar{b}$ will exclude discovery of h in this mode. Production of $t\bar{t}h$ followed by the principal decay mode $h\to\tilde{b}\tilde{b}^*$ is expected to be difficult to observe at the LHC because of the $t\bar{t}+2$ jet background. We estimate this situation by considering the $h\to b\bar{b}$ analysis of Ref. [40] and removing the two b-tags from the Higgs decay products as estimated in Ref. [36]. The result is that for 100 fb^{-1} we have a significance of about 0.9σ, indicating that $t\bar{t}h, h\to$ jets is very difficult at the LHC.

The weak boson fusion modes [41] can be an effective means to search for the decays $h\to W^+W^-$ and $h\to\tau^+\tau^-$. As in the case of $t\bar{t}h$, because the couplings of h to W and Z are approximately standard in the decoupling limit, the production cross sections are basically the same as in the SM, and the primary influence of the light bottom squark is to depress the branching ratios into the distinctive decay modes in favor of decay into jets. The significances in the SM into the two decay modes are 3.3 to 13.2σ and 10.4 to 8.2σ respectively [40], for m_h in the range 120 to 140 GeV. A reduction of these branching fractions by a factor of 2 would prevent discovery of the Higgs in these channels. Weak boson fusion into a Higgs boson followed by the decay $h\to\tilde{b}\tilde{b}^*$ would be overwhelmed by the large QCD 4-jet backgrounds. For m_h larger than the upper limit in the MSSM, the decay mode into weak bosons may dominate, and discovery at the LHC would be possible with a relatively small data sample.

In Fig. 6, for $m_h=120$ and 140 GeV, we show the accuracies that we expect could be achieved at the LHC for measurements of the rates (cross sections times branching ratios) of gluon fusion into a Higgs boson followed by $h\to\gamma\gamma$, W^+W^-, and ZZ, and for weak boson fusion into a Higgs boson followed by the decays $h\to WW$ and $h\to\tau^+\tau^-$. The accuracies are shown as a function of the ratio of the jet-jet and the $b\bar{b}$ widths. The jet-jet width is the sum of the partial widths into $\tilde{b}\tilde{b}^*$, $b\bar{b}$, $c\bar{c}$, and gg. Note that this ratio is approximately 1.12 in the SM, and thus the left-most edge of the plot $(\Gamma(h\to\text{jets})/\Gamma(h\to b\bar{b})=1)$ corresponds to the case in which decay to bottom quarks is the only hadronic decay mode of the Higgs boson. The relative uncertainties contain only statistical effects, $\sqrt{S+B}/S$, where we use estimates of the backgrounds and SM signal rates presented in Refs. [40] and [42].

At the LHC, it is difficult to obtain information about the Higgs boson couplings in a model-independent way because it is impossible to observe all possible decays in a single production mode. One must be content with measurements of cross sections times branching ratios and cannot make definitive statements about the couplings themselves. In obtaining our estimates, we do not upgrade the glue-glue production cross section σ_{gg} by the SUSY bottom squark loop effects discussed in Sec. III and shown in Fig. 3. We prefer to show the relative uncertainties as a function of the ratio of the jet-jet and $b\bar{b}$ widths in a way that is as model-independent as possible.

Experiments at the LHC can still search for the heavy SUSY Higgs bosons, H, A, and $H^{\pm}$. For example, when $\tan\beta$ is large, radiation of A and H from bottom quarks is enhanced because these states couple to the bottom quark

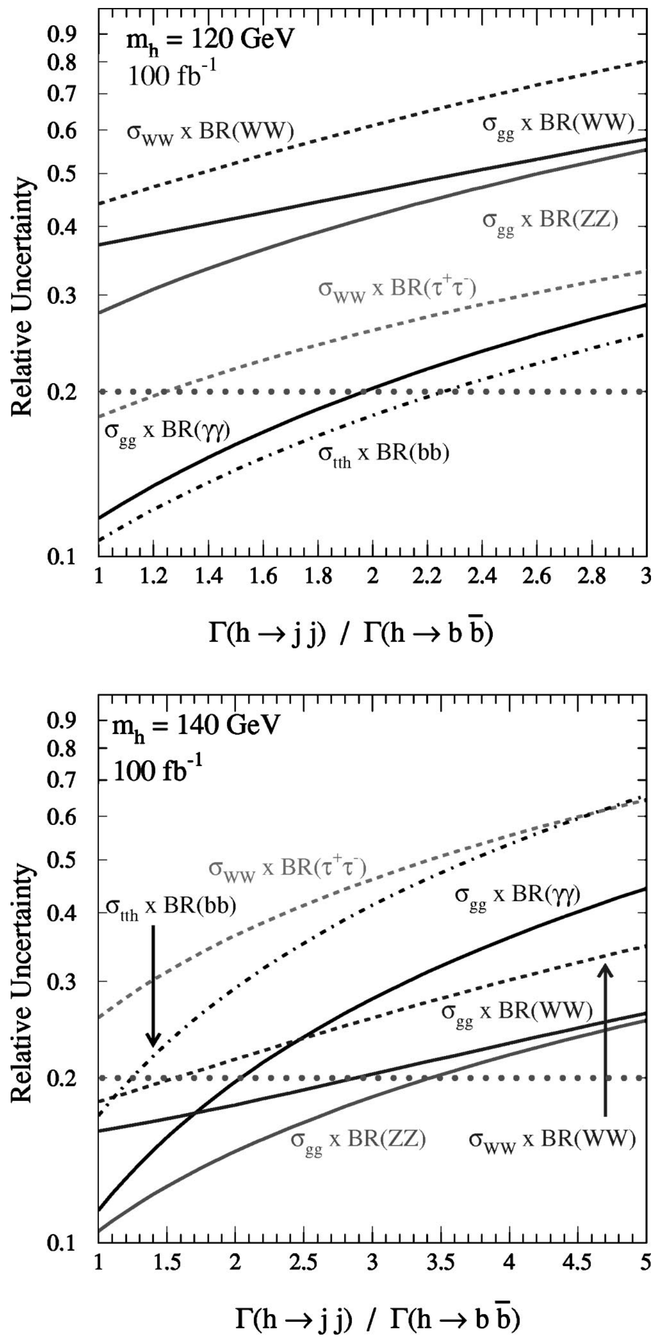

FIG. 6. Expected accuracy in LHC measurements of the product of production cross sections and branching ratios for the WW, ZZ, $b\bar{b}$, $\gamma\gamma$, and $\tau^+\tau^-$ decay modes of a Higgs boson with masses 120 GeV and 140 GeV, as a function of the ratio of the jet-jet and the $b\bar{b}$ widths. The horizontal dotted line at 0.2 indicates the 5σ discovery reach under the assumption $B \gg S$. The partial widths for decay into WW, ZZ, $b\bar{b}$, $\gamma\gamma$, and $\tau^+\tau^-$ and the production cross sections are assumed to be standard.

proportionally to $\tan\beta$, even in the decoupling limit [30,43]. This enhanced coupling further insures that the branching ratio of these states into $b\bar{b}$ may remain competitive with the decay into $\tilde{b}\tilde{b}^*$. The masses and properties of the heavy Higgs states are highly model-dependent, depending on many more of the SUSY-breaking parameters than $m_{\tilde{b}}$, μ, and $\tan\beta$, and thus it is difficult to draw firm conclusions. However, it is likely at least one of them could be identified at the LHC with 100 fb^{-1}. In this interesting situation, LHC experiments would discover several elements of the Higgs sector without actually discovering the boson responsible for the electroweak symmetry breaking.

For Higgs boson masses between 120 and 135 GeV, searches at the Tevatron rely on associated production of the Higgs boson with weak bosons, W and Z, and the decay mode $h \to b\bar{b}$. Discovery at the level of 5σ of a SM-like Higgs boson in this mass range is expected for integrated luminosities greater than 20 to 60 fb^{-1} [44]. Depression of the Higgs boson branching ratio into $b\bar{b}$ will raise the required luminosities by the corresponding factor. Discovery of the Higgs boson at the Tevatron would become very difficult under these circumstances.

Recognizing that a relatively long-lived bottom squark may pick up an antiquark and form a mesino, the supersymmetric partner of the B meson, we might expect that bottom squarks will produce hadronic jets with leading (anti-)baryons. R-parity violating decays of the $\tilde{b}^*$ may result in jets that are potentially rich in charm content. At hadron colliders, the relatively small SM $c\bar{c}$ branching fraction, along with substantial backgrounds expected from hadronic production of gluons, followed by $g \to c\bar{c}$, and backgrounds from b decays, $b \to cX$, have discouraged searches for $h \to c\bar{c}$. New efforts to simulate the Higgs boson signal and backgrounds in the $c\bar{c}$ channel might be warranted in view of a possibly enhanced $c\bar{c}$ branching fraction.

V. PHENOMENOLOGY AT e^+e^- LINEAR COLLIDERS

For a light Higgs boson the dominant production process at a lepton collider is $e^+e^- \to Z^0 h$ via an intermediate Z^0. Once the Z^0 is identified, the Higgs boson is discovered, independent of the Higgs boson decay modes, as a clean enhancement in the distribution of mass recoiling from the Z^0 [35], and the mass of the Higgs boson can be measured. The backgrounds from the W fusion and Z^0 fusion processes are small. Because the Zh cross section depends on the hZZ coupling strength, observation of the Higgs boson determines this coupling with an expected accuracy of $\sim 1.2\%$ [35] and can establish the Higgs boson as the principal scalar responsible for the electroweak symmetry breaking. These statements, true in the SM and MSSM, remain valid if the Higgs boson decays primarily into a pair of bottom squarks since the hZZ coupling is unaffected and the method does not depend on the Higgs boson decay products.

Measurement of the Higgs boson's branching ratios is essential to establish the properties of the boson. For a light Higgs boson, the largest of these in the SM is that for $h \to b\bar{b}$, with a value $\sim 69\%$ at $m_h = 120$ GeV. At this mass, simulations [35,45] show that the branching fraction can be determined to be $(69 \pm 2)\%$ based on an integrated luminosity of 500 fb^{-1} at 500 GeV. The next largest is the branching fraction for decay into WW^*, with an expected measured value of (14±1.3)%. As derived above, the presence of the light bottom squark decay mode reduces the SM branching fractions into $b\bar{b}$, WW^*, and other modes inversely with the square of $\mu \tan\beta/m_h$. These values are presented in Fig. 5. In all cases except $b\bar{b}$, the reduced branching fractions at $\mu \tan\beta/m_h = 10$ are below the experimental accuracies estimated for a sample of data accumulated after an integrated luminosity of 500 fb^{-1} at a linear collider operating at a center of mass energy of 500 GeV. At $m_h = 120$ GeV, the uncertainty on the branching fraction into the $b\bar{b}$ mode increases to 31% when $\mu \tan\beta/m_h = 10$. The branching fraction itself drops below the expected experimental sensitivity of ~2% for $\mu \tan\beta/m_h > 13$.

Determination of the hWW coupling allows an experimental test of the $SU(2)$ relationship between the hWW and hZZ couplings. The usual approach for determining the hWW coupling is based on measurement of the cross section for the WW fusion process, $e^+e^- \to \nu\bar{\nu}h$, plus knowledge of at least one branching fraction for h into an observed final state. A thorough analysis of the expected signal and backgrounds is presented in Ref. [46] for the $h \to b\bar{b}$ final state. At $\sqrt{s} = 500$ GeV and with an integrated luminosity of 500 fb^{-1}, a signal to background $S/B \simeq 5$ and $S/\sqrt{B} \simeq 200$ are expected. With the inclusion of light bottom squarks, the $b\bar{b}$ branching fraction drops inversely with the square of $\mu \tan\beta/m_h$, and the attendant signal rate falls. Beginning from the numbers quoted in Table 3 of Ref. [46], and decreasing the branching fraction $BR(h \to b\bar{b})$, we find that $S/\sqrt{B}$ drops below 5 for $\mu \tan\beta/m_h > 18$. The ratio $S/\sqrt{B}$ also drops to roughly 5 in the Higgsstrahlung process $e^+e^- \to hZ^0 \to b\bar{b}Z^0$ for $\mu \tan\beta/m_h \approx 8$. Just as in the SM, the anticipated uncertainty on the determination of $b\bar{b}$ branching fraction dominates the overall uncertainty. As $\mu \tan\beta/m_h$ is increased beyond 8, the uncertainty in the hWW coupling becomes greater than 10%. Extrapolating from the simulation results in Refs. [45,46], we expect that $\sigma(e^+e^- \to h\nu\bar{\nu})$ could be determined with an accuracy of ~36% at $\sqrt{s} = 350$ GeV and ~33% at $\sqrt{s} = 500$ GeV for $\mu \tan\beta/m_h = 10$, equivalent to accuracies of 18% and 17%, respectively, for the hWW coupling.

The analysis of Ref. [46] can be exploited also to show that the Higgs boson can be discovered in the $h \to$ jet-jet decay channel in $e^+e^- \to \nu\bar{\nu}h$, even at large $\mu \tan\beta/m_h$. The dominant reducible backgrounds are listed in Table 2 of that paper. After removing the "b-tag" requirement, we find that the dominant, and no-longer reducible backgrounds are from the processes $e^+e^- \to e\nu W$ and $e^+e^- \to eeZ$, where the W and Z decay to jets. Removing all requirements in Tables 2 and 3 of Ref. [46] that the Higgs boson signal and various backgrounds proceed via the $b\bar{b}$ mode, we determine $S/B \simeq 0.3$ and $S/\sqrt{B} \simeq 77$ at $\mu \tan\beta/m_h = 10$. The ratio $S/\sqrt{B}$ grows with $\mu \tan\beta/m_h$, but it saturates near 79 since the jet-jet branching fraction is already close to unity at $\mu \tan\beta/m_h = 10$.

In the weak boson fusion process, the jet-jet Higgs boson decay channel can also be used to determine the hWW coupling at large $\mu \tan\beta/m_h$ with significantly greater anticipated accuracy than from the $b\bar{b}$ channel [47]. In Fig. 7, we show the accuracies that we expect could be achieved in the measurements of the $b\bar{b}$ branching fraction, the hZZ and hWW coupling strengths, and the total width of the Higgs boson, all as a function of the ratio of the jet-jet and the $b\bar{b}$ widths. We distinguish the accuracies to be expected for the hWW coupling strength depending upon whether the $b\bar{b}$ or jet-jet decay mode of the Higgs boson is used. In this plot, the jet-jet width includes the partial widths into $\tilde{b}\tilde{b}^*$, $b\bar{b}$, $c\bar{c}$, and gg.

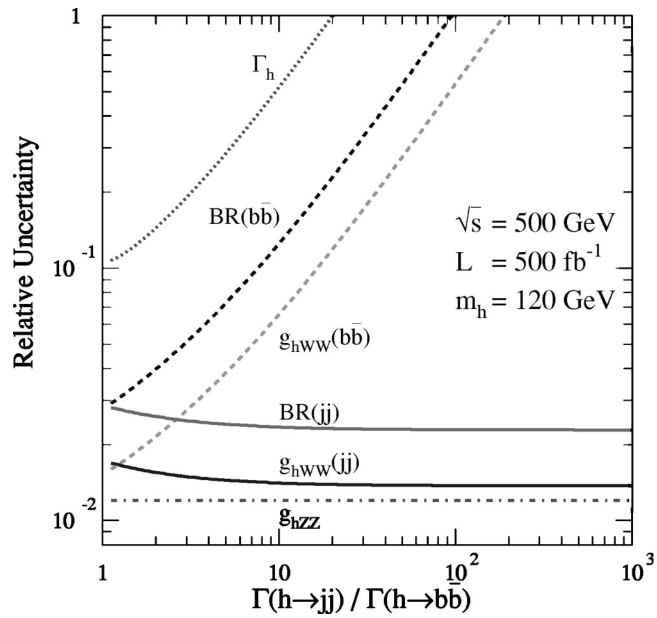

FIG. 7. Expected accuracy in the measurements of the $b\bar{b}$ and jet-jet branching fractions, the hZZ and hWW coupling strengths, and the total width of the Higgs boson, as a function of the ratio of the jet-jet and the $b\bar{b}$ widths. We assume the Higgs boson couplings to $b\bar{b}$, ZZ, and WW^* are standard.

Knowledge of the coupling strength of the Higgs boson to the W, combined with the measurement of the Higgs boson mass, allows one to compute the corresponding partial decay width for $h \to WW^*$ (Γ_W). If an independent measurement of the branching ratio $BR(h \to WW^*)$ is also available, one may obtain the Higgs boson total width (Γ_h) from the relation $\Gamma_h = \Gamma_W / BR(h \to WW^*)$. The accuracy on the total width is obtained from the expected accuracy on the determination of the branching fraction into WW^* along with the expected accuracy on the coupling strength g_{hWW}. The resulting uncertainty in Γ_h is presented as a function of the ratio of the jet-jet and the $b\bar{b}$ widths in Fig. 7.

It would be desirable to measure the total width of the Higgs boson *directly*. For $m_h < 135$ GeV, the total width Γ_h in the SM and conventional MSSM (at large m_A) is predicted to be less than 6 MeV, much too small for direct measurement at the LHC or at a lepton linear collider. The substantial increase in Γ_h arising from decays into bottom squarks may alter this expectation if $\mu \tan\beta/m_h$ is sufficiently large. At $m_h = 120$ GeV and $\mu \tan\beta/m_h = 10$ and 50, we expect Γ_h

$\sim$66 MeV and 1.6 GeV, respectively, both smaller than the best estimates of $\sim$2 GeV for the jet-jet invariant mass resolution at a linear collider [35]. The total width will exceed 2 GeV if $\mu \tan\beta/m_h > 56$, well within the range of values assumed in many MSSM investigations. The relatively large predicted width of the Higgs boson may help to motivate additional effort to improve the expected jet-jet invariant mass resolution in order that it may be measured directly.

The process $e^+e^- \to ht\bar{t}$ in which h is radiated from a top quark provides in principle the opportunity to measure the $ht\bar{t}$ coupling [48,49]. The cross section is less than 1 fb at $\sqrt{s}=500$ GeV but increases with energy and reaches a maximum in the $\sqrt{s}=700$ to 800 GeV range. Since $t\to bW$ occurs with approximately 100% branching fraction, the signal produces multijet final states with at least 2 b-jets. In the SM, with dominant decay of h into $b\bar{b}$, the relevant final states are $W^+W^-bb\overline{bb}$. The largest background results from gluonic radiation: $e^+e^-\to t\bar{t}\to gW^+W^-b\bar{b}$, with $g\to$ jet jet, and the largest electroweak background from $e^+e^-\to Z^0 t\bar{t} \to ZW^+W^-b\bar{b}$, with $Z\to$ jet jet. A 120 GeV SM Higgs boson produced at 800 GeV with an integrated luminosity of 1000 fb^{-1} is considered in Ref. [48]. The signal to background ratio is only $\sim$3%. After a neural net analysis, a potential accuracy of 5.5% is obtained in the determination of the $ht\bar{t}$ coupling. A decrease of the $b\bar{b}$ branching fraction by even a factor of 2 would seem to make prospects untenable. If Higgs boson decay into a pair of hadronic jets is considered, instead of decay to $b\bar{b}$, there will be a slight increase in the expected signal (from a branching fraction of $\sim$69% to $\sim$100%) but the backgrounds from g and Z decays will increase by a much greater factor. It seems unlikely that the $ht\bar{t}$ coupling could still be determined, but a full simulation of the larger signal and backgrounds would be required for a definitive answer.

One might hope to measure the Higgs boson coupling to squarks through the process $e^+e^-\to h\tilde{b}\tilde{b}^*$, in which h is radiated from one of the $\tilde{b}$'s, followed by the decay $h \to\tilde{b}\tilde{b}^*$. However, despite the $\tan\beta$ enhancement of the coupling, we compute a rate that remains less than 10^{-3} fb at all collider energies below 1 TeV, because of the small bottom squark charge and the suppressed P-wave coupling to the intermediate photon. (Recall that the light bottom squarks do not couple to the Z [14].) These rates are small enough to preclude a single event for anticipated integrated luminosities, even before efficiencies are taken into account. For reference, after reasonable acceptance cuts on the jets ($p_T \geqslant 10$, $|y|<2$, and $\Delta R>0.4$) and the requirement that two of them reconstruct an invariant mass within 5 GeV of the Higgs boson mass, the four jet background is on the order of 10^{-1} pb.

Baryon-number and R-parity violating decays of the $\tilde{b}^*$ into a pair of quarks, ud, cd, us, or cs [26], will result in jets that are potentially rich in charm content. Speculating that the probabilities could be equal for decay into these four channels, we suggest that the $c\bar{c}$ branching fraction of a light Higgs boson could be as great as 25%, roughly 10 times the SM value. Simulations for linear collider experiments indicate that the SM $h\to c\bar{c}$ branching fraction is expected to be determined at the level of $(2.8\pm1.1)\%$, implying that there should be no difficulty observing and establishing a much larger value.

In a $\gamma\gamma$ collider [50] with γ beams produced by lasers backscattered from incident high energy e^- beams, the coupling $g_{h\gamma\gamma}$ could be determined from the process $\gamma\gamma\to h$ [51]. Backgrounds from light quark ($q\bar{q}$) production, $\gamma\gamma \to q\bar{q}(g)$ are large, particularly if $q=u$ or c, and likely would make observation of the Higgs boson impossible in the jet jet decay channel. These backgrounds can be partially suppressed by selections on the polarizations of the colliding photons. In the case of identification through the $b\bar{b}$ decay mode, the hadronic backgrounds include $\gamma\gamma\to b\bar{b}(g)$ and $\gamma\gamma\to c\bar{c}(g)$. For $m_h=120$ GeV, with the SM decay branching fraction into $b\bar{b}$, a simulation shows an expected signal of 1450 events and a background of 335 events, leading to a measurement of $g^2_{h\gamma\gamma}BR(h\to b\bar{b})$ with an accuracy $\sqrt{S+B}/S\sim2.9\%$ [52]. This estimate is based on one 10^7 seconds year of operation and excellent b tagging. A value of $S/\sqrt{B}\sim5$ can be maintained if the signal is reduced by a factor of $\sim$16 ($S/B\simeq0.27$). These numbers suggest that even for $BR(h\to b\bar{b})\sim4.3\%$ ($\mu\tan\beta/m_h\sim9$), an MSSM Higgs boson with $m_h=120$ GeV and dominant decay to hadronic jets could be observed at a $\gamma\gamma$ collider, with an expected accuracy of $\sqrt{S+B}/S\sim23\%$ on the product $g^2_{h\gamma\gamma}BR(h\to b\bar{b})$.

VI. CONCLUSIONS

Discovery of the Higgs particle is essential to shed light on the mechanism of electroweak symmetry breaking. Current strategies for discovery and measurement of its properties in the mass range $m_h<135$ GeV rely heavily on the presumption that the principal branching fractions are close to those predicted in the SM or in the usual MSSM. For masses in this range, the decay width of the SM Higgs boson is dominated by its decay into bottom quarks, $b\bar{b}$. In this article, we emphasize that these assumptions are unwarranted if there are non-standard light particles that couple weakly to the gauge bosons but strongly to the Higgs field.

The small value of the bottom quark Yukawa coupling implies that the Higgs boson width may be modified significantly in the presence of light particles with relevant couplings to the Higgs boson. In the work reported here, we analyze the possibility that the Higgs boson decays into new particles that manifest themselves as hadronic jets without necessarily significant bottom or charm flavor content. As an example of this possibility, we present the case of a light scalar bottom quark, with mass smaller than about 10 GeV. While this sparticle has not been observed directly, its existence is consistent with all indirect experimental constraints. It may decay into a pair of quarks that might be detected as a single energetic jet due to the high boost in Higgs boson decay.

We work in the decoupling limit in which the mass of the pseudoscalar Higgs boson (m_A) is large compared to m_Z, and we assume that the ratio of Higgs vacuum expectation values $\tan\beta$ is large. Under these conditions, the dominant decay of the light scalar Higgs boson h is into a pair of light bottom squarks. The total decay width of the Higgs boson becomes several orders of magnitude larger than the width for decay into bottom quarks. For simplicity, we assume that the decay widths to standard model particles remain approximately constant (except in the gg and $\gamma\gamma$ cases) and that the variation of the Higgs boson decay properties arises from the addition of the extra decay channel. Branching fractions into standard model decay channels are reduced from their standard model values by a factor proportional to $\tan^{-2}\beta$. For $\mu \tan\beta/m_h \simeq 13$, the $b\bar{b}$ branching fraction is reduced to $\sim 2\%$.

Experiments at the LHC are capable of looking for a Higgs boson in a variety of channels. The Higgs boson will be found if its couplings to the W and Z gauge bosons and its branching ratios into bottom quarks, tau leptons, or electroweak gauge bosons do not differ significantly from those in the SM. These are the natural decay channels, provided there are only perturbative modifications of the theory and no new physics below the Higgs boson mass scale. We show in this paper that for values of the branching ratio $BR(h\to jj)$ larger than two to five times that into bottom quarks, the Tevatron and the LHC will encounter severe difficulties in finding the Higgs boson. The difficulty arises because the SM decay branching fractions are diminished and the principal decay mode into a pair of hadronic jets suffers from very large hadronic production of jet pairs. However, experiments at these colliders are likely to see clear evidence of low-energy supersymmetry, pointing towards the presence of an unseen light Higgs boson in the spectrum.

Because they rely principally on the production process $e^+e^-\to hZ^0$, experiments at proposed $\sqrt{s}=500$ GeV electron-positron linear colliders remain fully viable for direct observation of the Higgs boson and measurement of its mass. We demonstrate that this machine will discover the Higgs particle, determine its couplings to the weak gauge bosons, and possibly also measure the branching ratio into bottom quarks. The possibility of measuring the Higgs boson width, however, is diminished owing to the large suppression of the decay branching ratio into the weak gauge bosons. If the width exceeds about 2 GeV, a direct measurement should be possible from the invariant mass distribution in the jet-jet channel. If it is smaller, determination of the width may have to await a Higgs boson factory based on a muon collider [53].

In the general case considered here, the Higgs boson decays to a large extent into hadronic jets, possibly without definite flavor content. Measurements of various properties of the Higgs boson, such as its full width and branching fractions, may therefore require a substantial improvement in the experimental jet-jet invariant mass resolution and a more thorough understanding of backgrounds in the jet-jet channel. Full event and reconstruction studies done for the SM decay $h\to gg$ (where the SM branching fraction is $\sim 5\%$ for $m_h = 120$ GeV) should be pursued further to establish the extent to which properties of the Higgs boson can be determined solely from the jet-jet mode.

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arises from Z decay, the background is increased by $1/R_b \simeq 1/0.21$, where R_b is the measured fraction of the hadronic width of the Z into $b\bar{b}$.

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