Can there be a heavy sbottom hidden in three-jet data at CERN LEP?

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A low-energy supersymmetry scenario with a light gluino of mass 12–16 GeV and light sbottom ($\tilde{b}_1$) of mass 2–6 GeV has been used to explain the apparent overproduction of b quarks at the fermilab Tevatron. In this scenario the other mass eigenstate of the sbottom, i.e., $\tilde{b}_2$, is favored to be lighter than 180 GeV due to constraints from electroweak precision data. We survey its decay modes in this scenario and show that decay into a b quark and gluino should be dominant. Associated sbottom production at CERN LEP via $e^+e^-\to Z^*\to\tilde{b}_1\tilde{b}_2^*+\tilde{b}_1^*\tilde{b}_2$ is studied and we show that it is naturally a three-jet process with a small cross section, increasingly obscured by a large standard model background for heavier $\tilde{b}_2$. However we find that direct observation of a $\tilde{b}_2$ at the 5σ level is possible if it is lighter than 110–129 GeV, depending on the sbottom mixing angle $|\cos\theta_b|=0.30$–0.45. We also show that $\tilde{b}_2$-pair production can be mistaken for production of neutral minimal supersymmetric standard model Higgs bosons in the channel $e^+e^-\to h^0A^0\to b\bar{b}b\bar{b}$. Using searches for the latter we place a lower mass limit of 90 GeV on $\tilde{b}_2$.

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I. INTRODUCTION

The standard model (SM) has been very successful in explaining a range of observations at hadron colliders and the CERN e^+e^- collider LEP. But it is still widely believed to be an effective theory valid at the electroweak scale, with new physics lying beyond it. The minimal supersymmetric standard model (MSSM) [1] is widely considered to be the most promising candidate for physics beyond the SM.

The MSSM contains supersymmetric (SUSY) partners of quarks, gluons, and other SM particles that have not been observed, leading to speculation that they might be too heavy to have observable production rates at present collider energies. However, it has been suggested in Ref. [2] that a light sbottom ($\tilde{b}_1$) with mass O(5 GeV) is not ruled out by electroweak precision data if its coupling to the Z boson is tuned to be small in the MSSM. Recently Berger *et al.* [3] have also proposed a light sbottom and light gluino (LSLG) model to explain the long-standing puzzle of overproduction of b quarks at the fermilab Tevatron [4]. In this model gluinos of mass 12–16 GeV are produced in pairs in $p\bar{p}$ collisions and decay quickly into a b quark and light sbottom (2–6 GeV) each. The sbottom evades direct detection by quickly undergoing R-parity-violating decays into soft dijets of light quarks around the cone of the accompanying b jet. The extra b quarks so produced result in a remarkably good fit to the measured transverse momentum distribution $\sigma_b(p_T>p_T^{min})$ at the next leading order (NLO) level, including data enhancement in the $p_T^{min}\sim m_{\tilde{g}}$ region.

Some independent explanations within the SM have also been proposed to resolve the discrepancy. These include unknown NNLO QCD effects, updated b-quark fragmentation functions [5], and effects from changing the renormalization scale [6]. But, without an unambiguous reduction in theoretical and experimental errors, the LSLG scenario cannot be ruled out. It is also interesting in its own right even if not solely responsible for the Tevatron discrepancy. For example, a light $\tilde{b}_1$ is more natural if the gluino is also light [7]. Experimental bounds on light gluinos do not apply here as either the mass range or the decay channel is different: only gluinos lighter than 6.3 GeV [8] are absolutely ruled out. Very recently ALEPH [9] has ruled out stable sbottoms with lifetime $\gtrsim 1$ ns and mass <92 GeV. However, using formulas in Ref. [10] we calculate that even minimal R-parity-violating couplings, as small as 10^{-6} times experimental limits, would leave $\tilde{b}_1$ with a lifetime shorter than 1 ns. Light gluino and sbottom contributions to the running strong coupling constant $\alpha_S(Q)$ have also been calculated and found to be small [3,11]. New phenomena such as SUSY Z decays [12–14] and gluon splitting into gluinos [15] are predicted in this scenario, but the rates are either too small or require more careful study of LEP data.

The sbottoms and light gluinos also affect electroweak precision observables through virtual loops. In this case, serious constraints arise on the heavier eigenstate of the sbottom, i.e., $\tilde{b}_2$. According to Ref. [16], corrections to R_b are increasingly negative as $\tilde{b}_2$ becomes heavier and it has to be lighter than 125 (195) GeV at the 2σ (3σ) level. An extension of this analysis to the entire range of electroweak precision data [17] yields that $\tilde{b}_2$ must be lighter than 180 GeV at 5σ level. However, it has been suggested that the SUSY decay $Z\to\tilde{b}_1\overline{b\tilde{g}}+$H.c. can contribute positively to R_b [13], reducing some of the negative loop effects, and possibly allowing higher $\tilde{b}_2$ masses [12,18]. Independently, if large CP-violating phases are present in the model a $\tilde{b}_2$ with mass $\gtrsim 200$ GeV is possible [19]. Still, it is fair to say that in the face of electroweak constraints the LSLG model at least favors a $\tilde{b}_2$ lighter than 200 GeV or so.

In this article we study production and decay of such a heavy sbottom at LEPII. Available channels are (i) pair pro-

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duction, $e^+e^- \to \tilde{b}_2\tilde{b}_2^*$, and (ii) associated production, $e^+e^- \to \tilde{b}_1^*\tilde{b}_2 + \tilde{b}_1\tilde{b}_2^*$. With LEPII center-of-mass energies ranging up to $\sqrt{s} = 209$ GeV, the second channel should have produced heavy sbottoms with masses as high as ~ 200 GeV. Since they have not been observed, it has been commented that the LSLG scenario is disfavored [16,17].

However, searches for unstable sbottoms at LEPII have not been done for the decay $\tilde{b}_2 \to b\tilde{g}$, which should dominate in this scenario as squarks, quarks, and gluinos have strong trilinear couplings in the MSSM. In that case, the fast-moving gluino emitted by $\tilde{b}_2$ would decay quickly into a b quark and $\tilde{b}_1$ that are nearly collinear, with $\tilde{b}_1$ subsequently undergoing R-parity-violating decays into light quarks around the cone of the accompanying b jet. Unless the jet resolution is set very high, the gluino should look like a fused b flavored jet. Overall $\tilde{b}_2$ should appear as a heavy particle decaying into b flavored dijets. On the other hand, the highly boosted prompt $\tilde{b}_1$ produced in the associated process would decay into nearly collinear light quarks and appear as a single hadronic jet. Pair and associated productions are therefore naturally described as 4-jet and 3-jet processes, respectively, at leading order. Pair production in particular should be similar to neutral MSSM Higgs production in the channel $e^+e^- \to h^0A^0 \to b\bar{b}b\bar{b}$ if h^0 and A^0 have approximately equal masses.

The article is organized as follows: $\tilde{b}_2$ decays are studied in Sec. II and $\tilde{b}_2 \to b\tilde{g}$ is found to be dominant; cross sections and event topology are studied in Sec. III, and the corresponding SM 3-jet background for associated production is studied in Sec. IV. In Sec. V, LEP searches for neutral Higgs bosons are used to derive a lower bound on the $\tilde{b}_2$ mass. Conclusions are drawn in Sec. VI.

II. HEAVY SBOTTOM DECAY

Sbottom decays in MSSM scenarios with large mass splitting between $\tilde{b}_2$ and $\tilde{b}_1$ have been investigated before; see Ref. [20] for example. However, the scenario where the gluino is also light has not received much attention.

The direct decay products can be purely fermionic (1) or bosonic (2):

$$\tilde{b}_2 \to b\tilde{g}, b\chi_k^0, t\chi^-, \tag{1}$$

$$\tilde{b}_2 \to \tilde{b}_1 Z, \tilde{t}W^-, \tilde{b}_1 h^0, \tilde{b}_1 A^0, \tilde{b}_1 H^0, \tilde{t}H^-, \tag{2}$$

where χ_k^0 ($k=1,..,4$) and $\chi^\pm$ are neutralinos and charginos respectively, t is the top quark, $\tilde{t}$ are stops, h^0 and H^0 are neutral CP-even Higgs bosons, A^0 is the CP-odd Higgs boson, and $H^\pm$ are charged Higgs bosons.

The individual widths depend on masses of above particles, but available experimental constraints [21] are model dependent and might not all be applicable in the LSLG scenario. However, precision Z-width measurements can be used to apply some basic constraints on masses and the sbottom mixing angle.

A. Couplings and mass constraints

In the MSSM, Z-boson couplings to sbottom pairs are given by

$$Z\tilde{b}_1\tilde{b}_1 \propto \frac{1}{2}\cos^2\theta_b - \frac{1}{3}\sin^2\theta_W, \tag{3}$$

$$Z\tilde{b}_1\tilde{b}_2 \propto -\frac{1}{2}\sin\theta_b\cos\theta_b, \tag{4}$$

$$Z\tilde{b}_2\tilde{b}_2 \propto \frac{1}{2}\sin^2\theta_b - \frac{1}{3}\sin^2\theta_W, \tag{5}$$

where θ_b is the mixing angle between left and right-handed states:

$$\begin{pmatrix}\tilde{b}_1\\ \tilde{b}_2\end{pmatrix} = \begin{pmatrix}\cos\theta_b & \sin\theta_b\\ -\sin\theta_b & \cos\theta_b\end{pmatrix}\begin{pmatrix}\tilde{b}_L\\ \tilde{b}_R\end{pmatrix}. \tag{6}$$

The light sbottom should have a vanishingly small coupling in Eq. (3) as the $Z \to \tilde{b}_1\tilde{b}_1^*$ decay does not occur to high accuracy. This is achieved with the choice

$$\cos\theta_b \approx \pm\sqrt{\frac{2}{3}}\sin\theta_W = \pm 0.39. \tag{7}$$

The narrow range $|c_b| = 0.30$–0.45 ($c_b \equiv \cos\theta_b$) is allowed [2], which we use at times to obtain upper and lower bounds.

Given that $m_{\tilde{b}_1} = 2-6$ GeV, the decay $Z \to \tilde{b}_1\tilde{b}_2^* + \text{H.c.}$ might also take place if $\tilde{b}_2$ is lighter than ~ 89 GeV. However, this decay is suppressed both kinematically and by the factor $\sin^2 2\theta_b$. Even for the higher value $|c_b| = 0.45$ we calculate $\Gamma(Z \to \tilde{b}_1\tilde{b}_2^* + \text{H.c.}) \leqslant 10$ MeV for $m_{\tilde{b}_2} \geqslant 55$ GeV and $m_{\tilde{b}_1} \geqslant 2$ GeV. With the full Z width having a 1σ error of 2.3 MeV and a 0.6σ pull from the theoretical SM calculation [21], a lower limit of 55 GeV on the $\tilde{b}_2$ mass can be set at the $\sim 4\sigma$ level without a detailed analysis.

Similarly, decays into pairs of neutralinos, charginos, and stops might contribute unacceptably to the Z width and it seems safe enough to apply a lower mass limit of $M_Z/2$ to them for calculation purposes. With the observed top quark mass of ~ 175 GeV, this rules out the chargino channel $\tilde{b}_2 \to t\chi^-$ as $\tilde{b}_2$ masses $\lesssim 200$ GeV are being considered.

B. Calculations

The decay width for $\tilde{b}_2 \to b\tilde{g}$ is easily calculated at tree level using Feynman rules for the MSSM given in Ref. [22]:

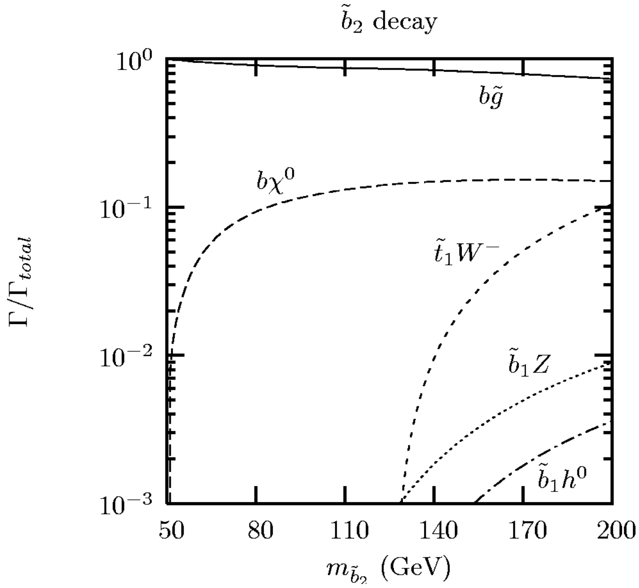

FIG. 1. Branching ratios for $\tilde{b}_2$ with $\tan\beta = 30$. Masses are set as $m_{\chi_k^0}, m_{\tilde{t}_1} = M_Z/2\ \forall\ \chi_k^0$ and $m_{h^0} = 114.4$ GeV. The Higgs width is calculated in the decoupling limit.

$$\Gamma(\tilde{b}_2 \to b\tilde{g}) = \frac{g_s^2 m_{\tilde{b}_2} \kappa A}{6\pi},$$

$$A = 1 - x_b^2 - x_{\tilde{g}}^2 - 2x_b x_{\tilde{g}} \sin 2\theta_b, \tag{8}$$

where $x_i = m_i/m_{\tilde{b}_2}$, $\kappa^2 = \Sigma_i x_i^4 - \Sigma_{i \neq j} x_i^2 x_j^2$ (summing over all particles involved in the decay) is the usual kinematic factor, and g_s is the strong coupling evaluated at $Q = m_{\tilde{b}_2}$. The canonical strong coupling value $\alpha_S(M_Z) = 0.118$ is used here. Other parameters used in this section are $m_b = 4.5$ GeV, $m_{\tilde{b}_1} = 4$ GeV, $m_{\tilde{g}} = 14$ GeV, and $c_b = +0.39$.

The remaining widths in Eqs. (1) and (2) are calculated using tree-level formulas given in Ref. [20]. Figure 1 shows the branching ratios versus $\tilde{b}_2$ mass. The $b\tilde{g}$ width is large, varying between 3.9 and 13.8 GeV for $m_{\tilde{b}_2} = 55$–200 GeV. It has the maximum amount of available phase space and proceeds via the strong coupling, while the other widths are $\propto g_w^2$ where $g_w = e/\sin\theta_W$ is the usual weak coupling.

The width shown for $\tilde{b}_2 \to b\chi^0$ is the summed width over all 4 neutralinos (χ_k^0). This value scales approximately as $m_b^2 \tan^2\beta$ for large $\tan\beta$. Here $\tan\beta = v_2/v_1$ where v_i are the vacuum expectation values of the two Higgs doublets. Our calculation is most likely an overestimate as mixing angles are ignored and all neutralinos are prescribed the same mass. This channel has been extensively searched for at LEP [23], but seems to be at most 10–15% of the full width in the LSLG scenario.

Bosonic decays with W, Z in the final state are also found to be small. We show $\Gamma(\tilde{b}_2 \to \tilde{t}_1 W^-)$ is correct up to an unknown factor $\sin^2\theta_t \leq 1$ where $\sin\theta_t$ is the stop mixing angle. For $\tilde{t}_2$ the factor would be $\cos^2\theta_t$. Because of the unnaturally low value of the $\tilde{t}_1$ mass chosen here, this width rises significantly as $m_{\tilde{b}_2}$ approaches 200 GeV.

Decays into Higgs bosons are more complex, as besides Higgs masses, the widths depend on unknown soft SUSY-breaking mass terms A_b and μ. The only available mass constraint is $m_{h^0} \lesssim 130$ GeV at two-loop level in the MSSM. However, the excellent agreement between electroweak precision measurements and theoretical predictions with a single SM Higgs boson has led to a preference for the "decoupling limit" of the MSSM Higgs sector. In this limit, Yukawa couplings of h^0 to quarks and leptons are nearly identical to those of the standard model Higgs bosons. At the same time $A^0, H^0, H^\pm$ have almost degenerate masses $\gg M_Z$. Therefore, with $\tilde{b}_2$ lighter than 200 GeV, only $\tilde{b}_2 \to \tilde{b}_1 h^0$ is likely to be significant while other decays would be kinematically impossible or heavily suppressed. The width is then given by

$$\Gamma(\tilde{b}_2 \to \tilde{b}_1 h^0) = \frac{g_w^2 \kappa B^2}{64\pi m_{\tilde{b}_2}},$$

$$B = -\frac{m_b \cos 2\theta_b}{m_W}(A_b - \mu \tan\beta) + \frac{m_Z \sin 2\theta_b}{\cos\theta_W}\left(-\frac{1}{2} + \frac{2}{3}\sin^2\theta_W\right)\cos 2\beta. \tag{9}$$

We choose $m_{h^0} = 114.4$ GeV in our calculation as LEP data has ruled out SM Higgs bosons lighter than this value [24].

In the decoupling limit, arbitrary variation over A_b, μ in calculating B is not required as the factor $A_b - \mu\tan\beta$ can be expressed in terms of sbottom masses and θ_b:

$$\sin 2\theta_b = \frac{2m_b(A_b - \mu\tan\beta)}{m_{\tilde{b}_1}^2 - m_{\tilde{b}_2}^2} \tag{10}$$

with θ_b given by Eq. (7). This is a common relation that arises when the sbottom mass matrix (see Ref. [25] for example) is diagonalized with the mixing matrix in Eq. (6).

Though theoretically and experimentally attractive, if the decoupling limit does not hold, then other Higgs particles might also be light. The most general lower mass limits from LEP on neutral MSSM Higgs bosons are about 90 GeV [26]. Then, the $\tilde{b}_2 \to \tilde{b}_1 A^0$ width (say) can become larger than 10% of $\tilde{b}_2 \to b\tilde{g}$ due to the coupling

$$A^0 \tilde{b}_1 \tilde{b}_2 \propto -\frac{g_w m_b \cos 2\theta_b}{2m_W}(\mu + A_b \tan\beta). \tag{11}$$

This happens if $A_b \tan\beta$ is larger than ~ 10 TeV. Though the possibility is there, we consider it less likely and do not pursue it further. In any event such a decay would be more important for higher $\tilde{b}_2$ masses, and we show in Sec. III that $\tilde{b}_2$ production at LEPII falls rapidly as its mass nears 200 GeV. We therefore conclude that the strong decay $\tilde{b}_2 \to b\tilde{g}$ is dominant and other decays are unlikely to be of more than marginal importance at LEPII.

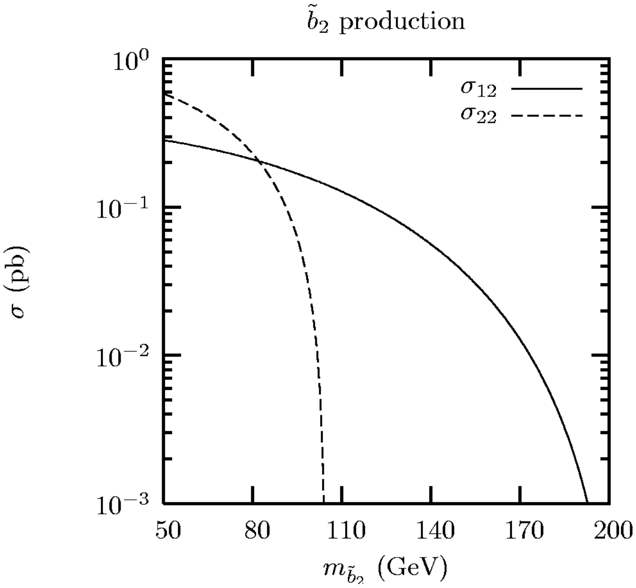

FIG. 2. The $\tilde{b}_2$ production cross section for $\sqrt{s}=207$ GeV, $|c_b|=0.39$ as a function of mass.

III. PRODUCTION AT LEP

Cross sections for $\tilde{b}_2$ production are defined as follows: $\sigma_{22}=\sigma(e^+e^-\to\tilde{b}_2\tilde{b}_2^*)$ and $\sigma_{12}=\sigma(e^+e^-\to\tilde{b}_1\tilde{b}_2^*+\text{H.c.})$. For completeness production of $\tilde{b}_1\tilde{b}_1^*$ pairs is referred to as σ_{11}. The σ_{ij} are readily calculated at tree level,

$$\sigma_{ij}=\frac{g_w^4\sin^4\theta_W\beta_{ij}^3}{16\pi s}f_{ij}, \tag{12}$$

$$f_{ij}=\left(\frac{1}{9}-\frac{2c_V\lambda_{ij}}{3\beta_Z^2\sin^2 2\theta_W}\right)\delta_{ij}+\frac{(c_V^2+c_A^2)\lambda_{ij}^2}{\beta_Z^4\sin^4 2\theta_W}, \tag{13}$$

where $\lambda_{11}\approx 0$, $\lambda_{12}=(1/\sqrt{2})\sin 2\theta_b$, $\lambda_{22}=\sin^2\theta_b-\frac{2}{3}\sin^2\theta_w$, $\beta_{ij}^2=[1-(m_{\tilde{b}_i}+m_{\tilde{b}_j})^2/s][1-(m_{\tilde{b}_i}-m_{\tilde{b}_j})^2/s]$, $\beta_Z^2=1-M_Z^2/s$, and $c_{V,A}$ are electron vector and axial couplings that equal $-\frac{1}{2}+2\sin^2\theta_W$ and $\frac{1}{2}$, respectively. The λ factors are proportional to sbottom-Z couplings in Eqs. (3)–(5). We use the same parameters here as used earlier for width calculations.

Both virtual photon (γ^*) and virtual $Z(Z^*)$ channels are available for σ_{22} while only Z^* is available for σ_{12}. The latter falls by a factor of 2 in going from $|c_b|=0.45$ to 0.30. Pair production rises in the same range by a smaller factor of 1.3 at $\sqrt{s}=207$ GeV. Variation of the $\tilde{b}_1$ mass between 2 and 6 GeV has a negligible effect on σ_{12}.

Figure 2 shows σ_{ij} versus the $\tilde{b}_2$ mass at $\sqrt{s}=207$ GeV. Both cross sections are suppressed due to the β^3 kinematic factor for scalar particle production. However, asymmetry between sbottom masses causes additional kinematic suppression of σ_{12} as $\beta_{12}\approx\beta_{22}^2$ for the same total rest mass of final products, $m_{\tilde{b}_i}+m_{\tilde{b}_j}$. The missing photon channel and smaller λ factor, $\lambda_{22}^2/\lambda_{12}^2\approx 1.8$, reduces the cross section further. Therefore associated production is generally small and falls rapidly as $\tilde{b}_2$ gets heavier.

TABLE I. Expected number of raw LEPII events for the combined luminosity recorded in the entire run. We show the $\tilde{b}_2$ masses beyond which event counts fall below rough benchmark levels.

Number of events at LEPII	Maximum $\tilde{b}_2$ mass (GeV)	
	Associated production	Pair production
1000	59	71
100	147	94
10	177	101
1	192	103

The LEPII operation covered a range of center-of-mass energies from 130 to 209 GeV with maximum data collected at $\sqrt{s}=189$ GeV and 205–207 GeV. Table I shows the expected number of raw events. We use an approximate luminosity distribution provided in Ref. [27] counting the combined integrated luminosity recorded by all four LEP experiments. The number of events for associated production falls below $\sim$100 for $m_{\tilde{b}_2}>147$ GeV at $|c_b|=0.39$. It is therefore possible that sufficient statistics might not be available to explore sbottom masses above this value.

We now discuss the event topology in order to identify important backgrounds. As shown in Sec. II the decay $\tilde{b}_2\to b\tilde{g}$ is dominant, which results in the states $\tilde{b}_1\overline{b\tilde{g}}+\text{H.c.}$ and $b\bar{b}\tilde{g}\tilde{g}$ for associated and pair processes, respectively. We decay the gluinos into $b\tilde{b}_1^*/\bar{b}\tilde{b}_1$ pairs and show the opening angles between final products for some representative $\tilde{b}_2$ masses in Fig. 3. The b quark and $\tilde{b}_1$ arising from gluino decay overwhelmingly prefer a small angular separation with a sharp peak at $\cos\theta\gtrsim 0.9$. The other particles tend to be well separated.

Through R-parity- and baryon-number-violating couplings λ''_{ij3}, $\tilde{b}_1$ can decay into pairs of light quarks: $\tilde{b}_1^*\to u+s;c+d;c+s$. A detailed discussion of such decays is given in Ref. [10]. In that case, the $\tilde{b}_1$ arising from gluino decay would further decay hadronically in and around the cone of the accompanying b jet. In practice it would be difficult to distinguish between the overlapping jets, unless a very fine jet resolution is used. The gluino should then appear for the most part as a single fused b-flavored jet with perhaps some extra activity around the cone.

The prompt $\tilde{b}_1$ from the associated production is highly boosted for most $\tilde{b}_2$ masses within range. This should result in a very small angular separation between its decay products. If it decays into pairs of light quarks, we calculate that at $\sqrt{s}=207$ GeV, $m_{\tilde{b}_1}=4$ GeV, and $m_{\tilde{b}_2}\lesssim 170$ GeV, at least 90% of these would have an opening angle $<30°$. At any rate a $\tilde{b}_2$ as heavy as 170 GeV is unlikely to be observable because of low event counts and would be obscured by the

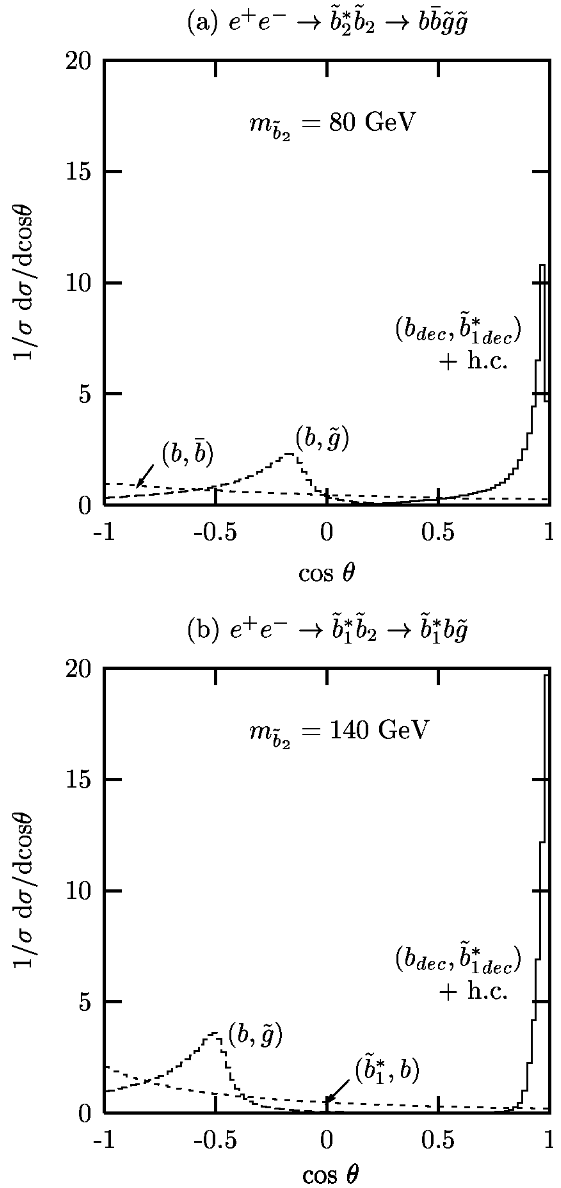

FIG. 3. Opening angles between particle pairs in (a) pair production and (b) associated production at $\sqrt{s}=207$ GeV. Particles marked with "*dec*" are gluino decay products. In (a) the $(b,\tilde{g})$ distribution shown is for *b* quarks and gluinos arising from the same $\tilde{b}_2$. $(b,\tilde{g})$ arising from different $\tilde{b}_2$ and $(\tilde{g},\tilde{g})$ have an identical distribution to that shown for $(b,\bar{b})$. In (b), $(\tilde{b}_1^*,\tilde{g})$ is not shown as it is the same as $(\tilde{b}_1^*,b)$.

large 3-jet SM background (Sec. IV). Therefore in the observable range $\tilde{b}_1$ should show up as a single hadronic jet.

At leading order then, associated production is best described as a 3-jet process, with 2 jets that can be tagged as *b* quarks and a hadronic jet from $\tilde{b}_1$. The relevant background for this would be SM 3-jet events, which we discuss in Sec. IV. On the other hand, pair production is naturally a 4-jet process where each jet can be tagged as a *b* quark. This would have a significant background from *any other* heavy particles produced in pairs and decaying into dijets of *b* quarks. Searches for neutral Higgs bosons h^0 and A^0 that can satisfy this criteria have been done, and we discuss them in Sec. V.

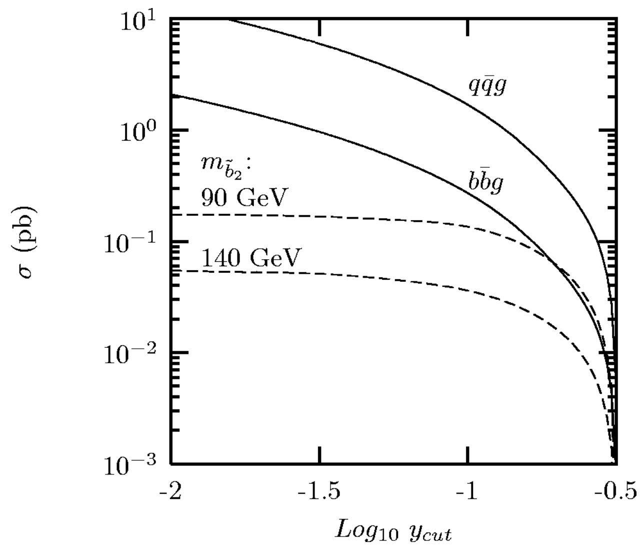

FIG. 4. Associated production (dashed lines) compared to SM 3-jet cross-sections versus y_{cut} at $\sqrt{s}=207$ GeV.

IV. THREE-JET BACKGROUND

The SM gluon radiation process $e^+e^-\to q\bar{q}g$, $q=u,d,s,c,b$, constitutes the main 3-jet background for associated production. In particular, $e^+e^-\to b\bar{b}g$ could be an irreducible background as gluon jets and jets from light sbottoms might not be distinguishable on a case-by-case basis.

We compare this background with associated production using the JADE jet-clustering algorithm [28]:

$$\min_{i\neq j}(p_i+p_j)^2 \geqslant y_{cut}s, \tag{14}$$

where p_i are the momenta of the final state partons and $0<y_{cut}<1$ is the jet resolution parameter. As long as $y_{cut}>m_{\tilde{g}}^2/s\approx(3.4\text{–}5.9)\times10^{-3}$ for $\sqrt{s}=207$ GeV and $m_{\tilde{g}}=12\text{–}16$ GeV, the hadronic decay products of $\tilde{g}$ and $\tilde{b}_1$ are clustered into single jets. We evaluate matrix elements at leading order and do not consider contributions to the SM 3-jet cross section from final states with more than three partons. The renormalization scale is set at $Q=\sqrt{s}/2$ with $\alpha_S(M_Z)=0.118$.

Figure 4 shows that σ_{12} is a small fraction of the total SM 3-jet cross section, though it increases in proportion as y_{cut} increases and the jets are required to be well separated. It is unlikely to be visible as a generic excess in 3-jet production given that measurements of hadronic cross sections at LEPII have errors of at least ±0.2 pb [27]. However, if at least one jet is *b*-tagged and $\sigma(e^+e^-\to b\bar{b}g)$ is measured very accurately, then for $\tilde{b}_2$ lighter than $\sim$140 GeV an excess might be observable at higher y_{cut} values.

If two jets out of three are required to have *b* tags then their total invariant mass can also be studied as in Fig. 5. The total invariant mass of the $b/\bar{b}$ quark and gluino (which ap-

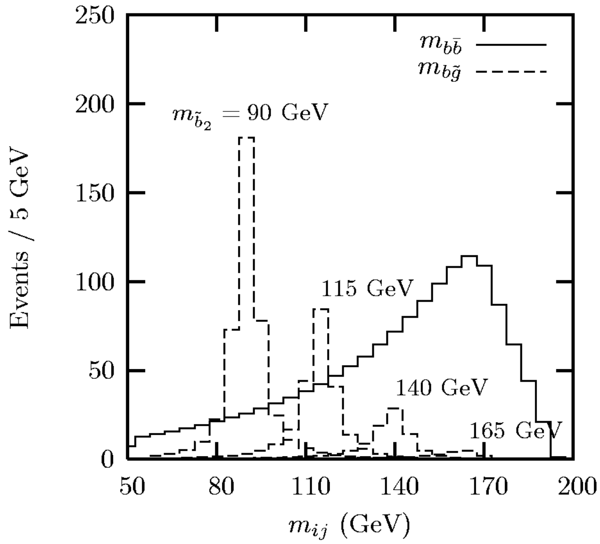

FIG. 5. The invariant mass of two b tagged jets can be reconstructed to observe excesses. Dashed lines show associated production and the solid line $b\bar{b}g$ for $\log_{10}y_{cut}=-1.2$. Tagging efficiencies for b quarks are not applied here. Events are shown for the total integrated luminosity recorded by the four LEP collaborations at $\sqrt{s}\geqslant 183$ GeV.

pears as a b-like jet) gives rise to a clear resonance around $m_{\tilde{b}_2}$. This would allow direct observation of a $\tilde{b}_2$, and should be the preferred method of study.

The differential cross section for $b\bar{b}g$ events increases with the invariant mass, $m_{b\bar{b}}$, while the resonance in σ_{12} rapidly gets smaller as $\tilde{b}_2$ gets heavier. This is natural as gluon radiation from quark pairs is higher for softer gluons, which in turn implies a higher total invariant mass for the $b\bar{b}$ pair. To estimate the discovery region we calculate both signal (S) and background (B) events in the mass window $M_{bb}=m_{\tilde{b}_2}\pm\Delta M$ where M_{bb} is the invariant mass of the b tagged jets and $\Delta M=\Gamma_{\tilde{b}_2}$. The b tagging efficiency ϵ_b is taken to be 65%, from R_b studies at LEPII [29]. Mistag probabilities are assumed to be small and not included in the analysis. We also use $\log_{10}y_{cut}=-1.2$, which is found to maximize the significance $S/\sqrt{(S+B)}$. The $N\sigma$ discovery region is defined as

$$\frac{S}{\sqrt{S+B}}\geqslant N. \tag{15}$$

Calculating events using the entire integrated luminosity recorded for $\sqrt{s}\geqslant 183$ GeV, we find that for $|c_b|=0.39$, $\tilde{b}_2$ masses up to 123 (136) GeV can be discovered at the 5σ (3σ) level. For $|c_b|=0.30$–0.45, the upper limits for discovery are $m_{\tilde{b}_2}=110$–129 GeV (5σ) and $m_{\tilde{b}_2}=125$–140 GeV (3σ). Since S and B are $\propto\epsilon_b^2$, the significance is $\propto\epsilon_b$ and better b tagging efficiencies can improve the upper limits. However, we have not included effects of Gaussian smearing of pair invariant mass measurements, which might reduce the significance.

We note that the associated process also receives an irreducible SUSY background as the $\tilde{b}_1^* b\tilde{g}+$H.c. final state is possible even if the heavy sbottom is absent. This has been studied in the context of Z decay [13]. However, its kinematics are very different from the same state produced by $\tilde{b}_2$ decay, and it should have little effect on the overall background. In Fig. 5 it would appear as an approximately uniform distribution of ~ 5 events/5 GeV, which is insignificant compared to the $b\bar{b}g$ background.

V. SEARCHES FOR $e^+e^-\rightarrow h^0A^0$

At leading order $e^+e^-\rightarrow h^0A^0$ proceeds only through the virtual Z channel. The relevant coupling is

$$Zh^0A^0\propto g_w\cos(\beta-\alpha), \tag{16}$$

where α is the mixing angle between neutral CP-even Higgs bosons. This is comparable to the heavy sbottom coupling $Z\tilde{b}_2\tilde{b}_2\propto g_w(\sin^2\theta_b-\frac{2}{3}\sin^2\theta_W)$ in Eq. (5). However, production of $\tilde{b}_2\tilde{b}_2^*$ pairs is somewhat higher as it also takes place through the γ^* channel and receives an extra factor of 3 from summing over final-state colors.

Being scalars, both pairs of particles are produced with the same angular distribution. Searches for h^0A^0 production [26] have been done along the diagonal $m_{h^0}=m_{A^0}$, which makes them kinematically identical to $\tilde{b}_2$ pair production. The final states searched for are $b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$, or $\tau^+\tau^-\tau^+\tau^-$ as h^0/A^0 decay mainly into b or τ pairs in the parameter space where they are approximately equimassive. Therefore, the 4b channel can be used to place limits on $\tilde{b}_2$ pair production as the latter leads to 4 b-flavored jets in the final state.

Cross-sections for the two processes are compared in Fig. 6. The h^0A^0 cross section is called σ_{hA}. We simply maximize this by setting $\cos(\beta-\alpha)=1$ and the branching ratio $\mathrm{BR}(h^0/A^0\rightarrow b\bar{b})=1$. The parameters used in the experimental study were similar or lesser. We find that σ_{22} is 1.8–2.3 times higher than Higgs production for $|c_b|=0.45$–0.3. If the more typical branching ratios $\mathrm{BR}(h^0\rightarrow b\bar{b})=0.94$ and $\mathrm{BR}(A^0\rightarrow b\bar{b})=0.92$ are used, then σ_{22} is effectively 2.1 to 2.6 times higher. However, that could be offset if $\tilde{b}_2$ has a branching ratio into $b\tilde{g}$ near its lower limit of around 0.9 in this mass range (see Fig. 1).

Experimental searches for h^0A^0 have used approximately 870 pb^{-1} of combined integrated luminosity, with center-of-mass energies between 200 and 209 GeV. Only OPAL has seen a significant excess in the 4b-jet channel, which is at the 2σ level at $(m_{h^0},m_{A^0})\sim(93,93)$ GeV. This does not appear in other experiments, though it cannot be ruled out statistically. No excess in this channel seems to have been observed by any experiment below ~ 90 GeV, which is approximately the quoted lower limit at 95% confidence for Higgs masses. Since the pair cross section is higher than that for h^0A^0, this should simultaneously rule out heavy sbottoms lighter than 90 GeV in the LSLG scenario.

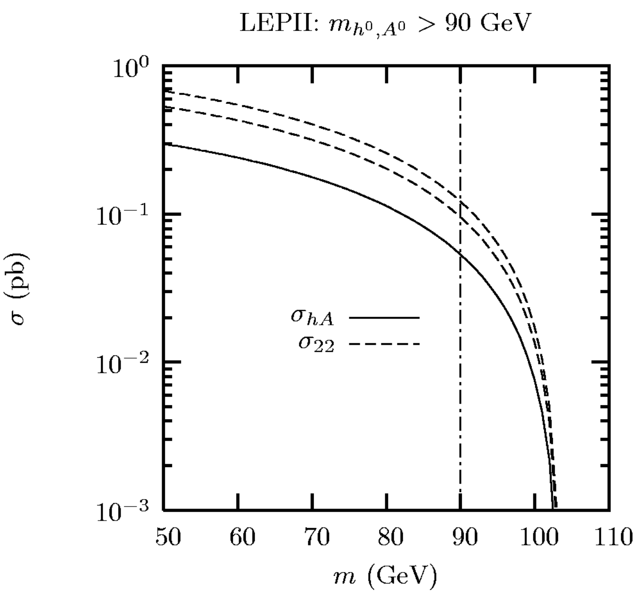

FIG. 6. Comparison between σ_{hA} and σ_{22} at $\sqrt{s}=207$ GeV versus $m=m_{h^0}=m_{A^0}=m_{\tilde{b}_2}$. Upper and lower limiting curves for σ_{22} are obtained for $|c_b|=0.30$ and 0.45, respectively.

There are some qualifications to this analysis. First, $\tilde{b}_2$ has a much larger width in absolute terms than h^0 or A^0, and that seems to have been a significant factor in the h^0A^0 searches at LEP. However, since σ_{22} is larger, it is likely that any excess would have been observed and the 90 GeV lower limit is approximately correct. Secondly, if very low values of y_{cut} (below $m_{\tilde{g}}^2/s$) were used in the LEP searches, then the above analysis might not hold.

VI. CONCLUSIONS

We have shown that the heavy sbottom eigenstate decays dominantly into $b\tilde{g}$ pairs in the light sbottom and light gluino scenario. The pair and associated production of $\tilde{b}_2$ at LEPII have been studied and found to be naturally described as 4-jet and 3-jet processes, respectively. Their cross-sections and raw event rates have been calculated and associated production is found to be small and obscured by the large SM 3-jet background for large values of $\tilde{b}_2$ mass. However, we find that 5σ discovery of a $\tilde{b}_2$ is possible using 3-jet data provided $m_{\tilde{b}_2}\leq 110$–129 GeV, for $|c_b|=0.30-0.45$. The corresponding 3σ limits are $m_{\tilde{b}_2}\leq 125$–140 GeV. We recommend a search as far as possible. While invariant masses reconstructed from b-tagged jet pairs might be the most direct way to do this, single b-tagged events can also be useful if the cross sections are measurable to a high accuracy.

We also find that $\tilde{b}_2$ pair production is similar to production of neutral MSSM Higgs bosons decaying into $b\bar{b}$ pairs, which have been extensively searched for by the four LEP collaborations. Minor excesses, though inconclusive, seen in the $4b$ jet channel for masses ~ 93 GeV provide further motivation for a detailed study of 3-jet events. We show that $\tilde{b}_2$ should be heavier than about 90 GeV as no excess has been reported below this value.

Note added. A paper by E.L. Berger, J. Lee, and T.M.P. Tait [30] that also covers associated production in this scenario, using the jet cone algorithm, recently appeared independently.

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