Abstract

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1. Introduction

The production of a heavy quark-antiquark pair in Z-decay can be mediated by a light quark-antiquark pair in the final state. This process is

\[ Z \rightarrow q\bar{q}'q'\bar{q} \]

where \( q \) and \( q' \) are heavy quarks (e.g., c and b). The rates for this process can be calculated using perturbative QCD (pQCD) and

\[ \Gamma_{Z\rightarrow q\bar{q}'q'\bar{q}} = \frac{\alpha_s^2}{4\pi^3} \frac{m_Z^5}{m_{q\bar{q}}^3} \]

where \( \alpha_s \) is the strong coupling constant and \( m_Z \) and \( m_{q\bar{q}} \) are the masses of the Z boson and the heavy quark pair, respectively.

2. Results

The predicted cross section for this process is

\[ \sigma_{Z\rightarrow q\bar{q}'q'\bar{q}} = \frac{\alpha_s^2}{4\pi^3} \frac{m_Z^5}{m_{q\bar{q}}^3} \]

and can be compared to data from experiments such as CDF, D0, and others.

3. Conclusion

The measured rates for this process can be compared to the calculated rates using pQCD to test the validity of the theoretical predictions.
I. INTRODUCTION

There has been a persisting discrepancy that the measured cross section of hadronic production of $b$ quarks measured by both CDF and DØ collaborations [1] is about a factor of two larger than the prediction in perturbative QCD with the most optimal choice of parameters, such as $b$-quark mass ($m_b$) and the factorization scale $\mu$, tuned to maximize the calculated rate. \footnote{Refs. [2, 3] argued that if the most up-to-date $B$ fragmentation function is used the observed excess can be reduced to an acceptable level. Fields [4] interestingly pointed out that correlations between the $b$ and $\bar{b}$ can be used to isolate various sources of production, especially, in his study he included the fragmentation of gluon and light quarks.} Recently, Berger et al. [5] interpreted the discrepancy in the scenario of light gluinos and light sbottoms. Light gluinos of mass between $12 - 16$ GeV are pair-produced by QCD $q\bar{q}$ and $gg$ fusion processes, followed by subsequent decays of gluinos, $\tilde{g} \rightarrow b\tilde{b}_1^* \rightarrow b\bar{b}_1$, where the sbottom has a mass $2 - 5.5$ GeV. Therefore, in the final state there are $\tilde{b}\tilde{b} + \tilde{b}_1\bar{b}_1$, and the sbottoms either remain stable or decay into other light hadrons (e.g. via $R$-parity violating couplings) and go into the $b$-jets. Gluino-pair production thus gives rise to inclusive $b$-quark cross section. The mass range of gluino is $m_{\tilde{g}} = 12 - 16$ GeV and sbottom $m_{\tilde{b}_1} = 2 - 5.5$ GeV. Such masses are chosen so that both the total cross section and the transverse momentum spectrum of the $b$-quark are reproduced. Before Berger et al.'s work, there have been some studies in the light sbottom and/or light gluino scenario [6]. However, such a scenario cannot be ruled out, unless there exists a sneutrino of at most 1–2 GeV.

Such a scenario easily contradicts other experiments, especially, the $Z^0$-pole data because of the light sbottom. However, it can avoid the $Z$-pole constraints by tuning the coupling of $Z\tilde{b}_1\tilde{b}_1^*$ to zero by choosing a specific mixing angle $\theta_b$ of $\tilde{b}_L$ and $\tilde{b}_R$: $\sin^2 \theta_b = \frac{2}{3} \sin^2 \theta_W$, where $\theta_W$ is the Weinberg mixing angle. In spite of this, subsequent studies [7, 8, 9] showed that such light gluino and sbottom will still contribute significantly to $R_b$ via one-loop gluino-sbottom diagrams. In order to suppress such contributions, the second $\tilde{b}_1$ has to be lighter than about 180 GeV (at 5\sigma level) with the corresponding mixing angle in order to cancel the contribution of $\tilde{b}_1$ in the gluino-sbottom loop contributions to $R_b$. Although Berger et al.'s scenario is not ruled out, it certainly needs a lot of fine tuning in the model. In other words, instead of saying this scenario is fine-tuned, we can say that so far the light gluino...
and light sbottom scenario is not ruled out. It definitely deserves more studies, no matter whether it was used to explain the excess in hadronic bottom-quark production or not.

The light gluino and light sbottom scenario will possibly give rise to other interesting signatures, e.g., decay of \( \chi \) into the light sbottom \([10]\), enhancement of \( t\bar{t}b\bar{b} \) production at hadron colliders \([11]\), decay of \( \Upsilon \) into a pair of light sbottoms \([12]\), and affecting the Higgs decay \([13]\). In a previous work \([14]\), we calculated the associated production of a gluino-pair with a \( q\bar{q} \) pair and compared to the standard model (SM) prediction of \( q\bar{q}b\bar{b} \) at both LEPI and LEPII (here \( q \) refers to the sum over \( u, d, c, s, b \)). We found that at LEPII the \( q\bar{q}g\bar{g} \) production cross section is about \( 40 - 20 \% \) of the SM production of \( q\bar{q}b\bar{b} \), which may be large enough to produce an observable excess in \( q\bar{q}b\bar{b} \) events \([14]\). This is rather model-independent, independent of the mixing angle in the sbottom, and is a QCD process.

In this work, we present another interesting channel in \( Z \) decay in the light gluino and light sbottom scenario:

\[
Z \to \tilde{b}_1\tilde{g} + \tilde{b}_1\tilde{g}; \quad \text{followed by} \quad \tilde{g} \to \tilde{b}_1\tilde{g} / \tilde{b}_1. \tag{1}
\]

Since the gluino is a Majorana particle, so it can decay either into \( \tilde{b}_1\tilde{g} \) or \( \tilde{b}_1 \). The final state can be \( \bar{b}_1\tilde{b}_1\tilde{g}, \bar{b}_1\tilde{b}_1\tilde{g}, \text{or} \bar{b}_1\tilde{b}_1\tilde{g} \). This channel, unlike the one mentioned in the previous paragraph, depends on the mixing angle of \( \tilde{b}_1 \) and \( \tilde{b}_1 \) in the \( \tilde{b}_1\tilde{g} \) coupling.

The hadronic branching ratio of this channel will be shown to be \((3.4 - 2.5) \times 10^{-3}\) for \( \sin 2\theta_b > 0 \) and \((1.4 - 1.1) \times 10^{-3}\) for \( \sin 2\theta_b < 0 \), and for \( m_{\tilde{b}_1} = 12 - 16 \text{ GeV} \) and \( m_{\tilde{g}} = 3 \text{ GeV} \), which is of order of the size of the uncertainty in \( R_b \). The process is the supersymmetric analog of \( Z \to bbq \), but kinematically they are very different because of the finite mass of the gluino and sbottom. A typical event consists of an energetic prompt bottom-jet back-to-back with a “fat” bottom-jet, which consists of a bottom quark and two bottom squarks. If such events cannot be distinguished from the prompt \( bb \) events, they may increase the \( R_b \) measurement (\( R^{\text{exp}}_b = 0.21646 \pm 0.00065 \) \([15]\)) with a hadronic branching ratio of \((1 - 3) \times 10^{-3}\). If the “fat” bottom jet can be distinguished from the ordinary bottom jet, then this kind of events would be very interesting on their own. It is a verification of the light gluino and light sbottom scenario. Furthermore, if the flavor of the bottom quarks can be identified, the ratio of \( bb : \bar{b}\bar{b} : bb \) events can be tested (theoretically it is 1 : 1 : 2) \([5]\).

The paper is organized as follows. In the next section, we present the calculation, including the decay of the gluino into \( \tilde{b}_1\tilde{g} \) or \( \tilde{b}_1 \). In Sec. III, we show the results and various
distributions that verify the “fat” bottom jet. We conclude in Sec. IV. There is an analog
in hadronic collisions, \( p\bar{p} \rightarrow b\bar{b}_1\tilde{g} \) followed by \( \tilde{g} \rightarrow b\bar{b}_1^* / \bar{b}\bar{b}_1 \). Thus, it also gives rise to two
hadronic bottom jets. However, in hadronic environment it is very difficult to identify the
“fat” bottom jet. We believe it only gives a small correction to the inclusive bottom cross
section.

II. FORMALISM

The interaction Lagrangian among the bottom quark, sbottom, and gluino is given by

\[
\mathcal{L} \supset \sqrt{2} g_s [\tilde{b}_1^\dagger \tilde{g}^\ast (\sin \theta_b P_L + \cos \theta_b P_R) T_{ij}^g \tilde{b}_j + \text{h.c.} ] ,
\]

(2)

where the lighter sbottom \( \tilde{b}_1 \) is a superposition \( \tilde{b}_1 = \sin \theta_b \tilde{b}_L + \cos \theta_b \tilde{b}_R \) of the left- and
right-handed states via the mixing angle \( \theta_b \). As mentioned above, the vanishing of the \( Z\tilde{b}_1\tilde{b}_1^* \)
coupling requires \( g_L \sin^2 \theta_b + g_R \cos^2 \theta_b = 0 \), where \( g_L = -\frac{1}{2} + \frac{1}{3} \sin^2 \theta_W \) and
\( g_R = \frac{1}{3} \sin^2 \theta_W \). It implies \( \sin^2 \theta_b = \frac{2}{3} \sin^2 \theta_W \).

A. Primary Production

Even a perfect cancellation in the amplitude \( Z \rightarrow \tilde{b}_1\tilde{b}_1^* \), the \( Z \) boson can still decay at
tree level into \( b\tilde{b}_1^* \tilde{g} \) (or its conjugated channel) as shown in Fig. 1. The Feynman amplitude

\[
\text{FIG. 1: The Feynman diagram for the process } Z \rightarrow b\tilde{b}_1^* \tilde{g}.
\]

is

\[
\mathcal{M} = \sqrt{2} g_s g_Z \bar{u}(b) f_Z (g_L P_L + g_R P_R) \frac{-\not{p} + m_b}{p^2 - m_b^2} (\sin \theta_b P_R + \cos \theta_b P_L) T_{ij}^g v(\tilde{g}) ,
\]

(3)

where \( P_{L,R} = (1 \mp \gamma^5)/2 \), \( g_Z = g_2 / \cos \theta_W \), and \( i, j, a \) correspond to the color indices of
the final-state particles \( b, \tilde{b}_1^* \) and \( \tilde{g} \), respectively. We can tabulate the complete formula of
the transitional probability, summing over the initial- and final-state spin polarizations or helicities, and colors, as

$$\sum |M|^2 = \frac{16g_s^2g_{\tau}^2}{(p^2 - m_b^2)^2}(N_0 + m_b m_{\bar{b}} N_1 \sin 2\theta_b + m_{\bar{b}}^2 N_2), \quad (4)$$

$$N_0 = (g_{\tau}^2 \sin^2 \theta_b + g_{\tau}^2 \cos^2 \theta_b)[4\hat{g} \cdot p \cdot b \cdot \hat{\sigma} + p^2 \hat{g} \cdot \hat{\sigma} (p^2 - m_b^2 - 2s)/s + 2\hat{g} \cdot p \cdot Z m_{\bar{b}}^2/s]$$

$$N_1 = 3(p^2 + m_b^2)g_{\tau}g_{\tau}R + (g_{\tau}^2 + g_{\tau}^2)(p^2 + 2p \cdot Z b \cdot Z/s) \quad (5)$$

$$N_2 = 6g_{\tau}g_{\tau}R \hat{g} \cdot p + (g_{\tau}^2 \sin^2 \theta_b + g_{\tau}^2 \cos^2 \theta_b)(\hat{g} \cdot b + 2\hat{g} \cdot Z b \cdot Z/s),$$

where $s = M_{\bar{b}}^2$. Here the momenta of the particles are denoted by their corresponding symbols. We use $p$ to denote the momentum of the virtual $\hat{b}$, which turns into $\hat{g}$ and $\hat{b}_1^\ast$ (i.e. $p = \hat{g} + \hat{b}_1^\ast$).

One can integrate the exact 3-body phase space to find the decay rate,

$$d\Gamma(Z \to \bar{b}\bar{b}_1\bar{g}) = \frac{1}{3} \sum |M|^2 \frac{\sqrt{s} dx_b dx_{\bar{b}}}{256}. \quad (6)$$

The scaling variables of the 3-body phase space are defined by

$$x_b = 2E_b/M_Z, \quad x_{\bar{b}} = 2E_{\bar{b}}/M_Z, \quad \text{and} \quad x_{\bar{g}} = 2E_{\bar{g}}/M_Z, \quad (7)$$

with the energies $E_i$ measured in the $Z$ rest frame, and $x_b + x_{\bar{b}} + x_{\bar{g}} = 2$. The ratios of the mass-squared are

$$\mu_b = m_b^2/M_Z^2, \quad \mu_{\bar{b}} = m_{\bar{b}}^2/M_Z^2, \quad \text{and} \quad \mu_{\bar{g}} = m_{\bar{g}}^2/M_Z^2. \quad (8)$$

The region of the phase space is limited by

$$2\sqrt{\mu_b} \leq x_b \leq 1 + \mu_b - \mu_{\bar{b}} - \mu_{\bar{g}} - 2\sqrt{\mu_{\bar{b}}\mu_{\bar{g}}}, \quad (9)$$

$$x_{\bar{b}} \leq (1 - x_b + \mu_b)^{-1}[2(2 - x_b)(1 + \mu_b + \mu_{\bar{b}} - \mu_{\bar{g}} - x_b) \pm \sqrt{(2 - x_b)^2 - 4 \mu_b} \sqrt{(1 + \mu_b - x_b, \mu_{\bar{b}}, \mu_{\bar{g}})}]$$

with the function $\lambda(a, b, c) = a^2 + b^2 + c^2 - 2ab - 2bc - 2ca$. The scalar dot-products can be expressed in terms of the scaling variables as

$$p^2 = s(1 + \mu_b - x_b), \quad \hat{g} \cdot b = \frac{1}{2} s(1 - x_b + \mu_b - \mu_{\bar{b}} - \mu_{\bar{g}})$$

$$b \cdot p = \frac{1}{2} s(x_b - 2\mu_b), \quad \hat{g} \cdot p = \frac{1}{2} s(1 - x_b - \mu_{\bar{b}} + \mu_{\bar{g}} + \mu_b)$$

The calculation for the charge-conjugated process $Z \to \bar{b}\bar{b}_1\bar{g}$ can be repeated in a straightforward manner. Eqs. (3) and (4) remain valid if we make the substitutions $b \leftrightarrow \bar{b}, \bar{b}_1^\ast \leftrightarrow \bar{b}_1$. 

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B. Decay of gluino

Since the gluino so produced will decay promptly into $\tilde{b}\tilde{b}^*_1$ or $\tilde{t}\tilde{b}$, the event ends up with the final states $bb\tilde{b}^*_1\tilde{b}^*_1$, $b\tilde{b}^*_1\tilde{t}$, or $\tilde{b}b\tilde{t}$. In the minimal hypothesis that the sbottom hadronizes completely in the detector, it behaves like a hadronic jet. The final configuration includes $bb + 2j$, $\tilde{b}b + 2j$, and $\tilde{b}b + 2j$ at the parton level. We will show below that the $2j$ most of the time goes together with the softer $b$, and therefore makes the $b$ look “fat”. The complete jet structure requires the full helicity calculation following the decay chain $Z \rightarrow \tilde{b}\tilde{b}^*_1\tilde{g}$ and $\tilde{g} \rightarrow \tilde{b}\tilde{b}^*_1$ or $\tilde{t}\tilde{b}$. Based on Feynman rules for the Majorana fermions, we replace $v(\tilde{g})$ in the above Eq. (3) by

$$v(\tilde{g}) \rightarrow -\sqrt{2}g_s T^a \frac{-\tilde{g} + m_\tilde{g}}{\tilde{g}^2 - m_\tilde{g}^2 + i \Gamma_\tilde{g} m_\tilde{g}} (\sin \theta_b P_L + \cos \theta_b P_R) v(\tilde{b}),$$

for the process $\tilde{g} \rightarrow \tilde{t}\tilde{b}$. Similarly, we replace $v(\tilde{g})$ in Eq. (3) by

$$v(\tilde{g}) \rightarrow \sqrt{2}g_s T^a \frac{-\tilde{g} + m_\tilde{g}}{\tilde{g}^2 - m_\tilde{g}^2 + i \Gamma_\tilde{g} m_\tilde{g}} (\sin \theta_b P_L + \cos \theta_b P_R) v(\tilde{b}),$$

for the process $\tilde{g} \rightarrow \tilde{b}\tilde{b}^*_1$. We use the narrow-width approximation to calculate the on-shell gluino propagator

$$\frac{1}{(\tilde{g}^2 - m_\tilde{g}^2)^2 + \Gamma_\tilde{g}^2 m_\tilde{g}^2} \rightarrow \frac{\pi}{m_\tilde{g} \Gamma_\tilde{g}} \delta(\tilde{g}^2 - m_\tilde{g}^2),$$

where $\tilde{g} = b + \tilde{b}^*_1$ or $\tilde{t} + \tilde{b}_1$. Assuming the gluino only decays into $\tilde{b}\tilde{b}^*_1$ and $\tilde{b}\tilde{b}^*_1$, we find the decay width of the gluino is

$$\Gamma_\tilde{g} = \frac{1}{4}(\alpha_s / m_\tilde{g}) \lambda^2 (1, m_\tilde{b}_1^2 / m_\tilde{g}^2, m_\tilde{b}_1^2 / m_\tilde{g}^2) (m_\tilde{b}_1^2 + m_\tilde{b}_1^2 - m_\tilde{b}_1^2 + 2m_\tilde{b}_1 m_b \sin 2\theta_b).$$

Since we have already assumed CP invariance in Eq. (2), the event distributions of a pair of CP-conjugated variables are the same.

III. RESULTS

We first list the input parameters in our study

$$m_b = 4.5 \text{ GeV}, \quad m_{\tilde{b}_1} = 3 \text{ GeV}, \quad \sin \theta_b = \sqrt{\frac{2}{3}} \sin^2 \theta_W, \quad \cos \theta_b = \pm \sqrt{1 - \frac{2}{3} \sin^2 \theta_W}.$$
The scale $Q$ that we used in the running strong coupling constant is evaluated at $\alpha_s(Q = M_Z/2)$. \(^2\)

We show in Fig. 2 the partial width of the channel $Z \to b\bar{b}g + \bar{b}b\tilde{g}$ versus the gluino mass $m_\tilde{g}$ for two different sign choices $\sin 2\theta_b > 0$. Numerically, the effect of $m_\tilde{b}$ is not negligible at $\sqrt{s} = M_Z$. Given that the total hadronic width of the $Z$ boson is 1.745 GeV [15], the hadronic branching fraction of the process $Z \to b\bar{b}g + \bar{b}b\tilde{g}$ is $(3.4 \pm 2.5) \times 10^{-3}$ for $\sin 2\theta_b > 0$ and $(1.4 \pm 0.1) \times 10^{-3}$ for $\sin 2\theta_b < 0$, and $m_\tilde{g} = 12 - 16$ GeV. Thus, this hadronic branching ratio is at the level of, or even larger than, the uncertainty in the $R_b$ measurement ($R_b^\text{exp} = 0.21646 \pm 0.00065$). If it cannot be distinguished from the prompt $b\bar{b}$ events, it will affect the precision measurement on the $b\bar{b}$ yield at LEP 1.

In the following, we study the event topology to examine the difference from the prompt $b\bar{b}$ production, which essentially consists of two back-to-back clean bottom jets with energy equal to $M_Z/2$. In Fig. 3, we show the energy distributions, in terms of dimensionless variables $x_b$, $x_{\tilde{b}}$, $x_h$, of the prompt $b$, sbottom, and gluino, respectively. The prompt $b$ has a fast and sharp energy distribution as expected, but the gluino and the sbottom have slower and flatter energy spectra. We also note that the spectra are different between $\sin 2\theta_b > 0$ and $< 0$. These features are very different from the prompt $b\bar{b}$ production including QCD correction, in which both $b$ and $\bar{b}$ are very energetic and the gluon is quite soft.

In Fig. 4, we show the energy spectra for the decay products, $b_{\text{dec}}$ and $\bar{b}_{\text{dec}}$, of the gluino. Since gluino is a Majorana particle, it decays into either $b\bar{b}$ or $\bar{b}b$. Although there are some differences between these two decay modes because of the difference in the coupling, in both modes the $b_{\text{dec}}$ and $\bar{b}_{\text{dec}}$ are rather soft. We also note that the spectra are different between $\sin 2\theta_b > 0$ and $< 0$. Therefore, just by looking at the prompt $b$ and the secondary $b_{\text{dec}}$, the energy spectra are very different from the prompt $b\bar{b}$ production. However, if the first and the second sbottoms go very close with the secondary $b_{\text{dec}}$ and cannot be separated experimentally, and the sbottoms deposit all their energies in the detector, then the event will mimic the prompt $b\bar{b}$ event. Thus, it is important to look at the angular separation

\(^2\) The difference in $\alpha_s$ between including and not including the light gluino and sbottom in the running of $\alpha_s$ from $Q = M_Z$ to $M_Z/2$ is only 3%. Thus, we neglect the effect of light gluino and sbottom in the running of $\alpha_s$. Refs. [5, 12] also estimated the effect of including the light gluino in the running of $\alpha_s$ in their studies. A recent work [16] studied the running of $\alpha_s$ from low-energy scales such as $m_t$ to $M_Z$ including a light gluino and a light sbottom. However, it cannot rule out the existence of such light particles from current data.
among the final-state particles.

We show the cosine of the angles between the primary $b$ and the $\vec{b}_{\text{dec}}$, between $\vec{b}_{\text{dec}}$ and $\vec{b}'_1$, and between $\vec{b}_{\text{dec}}$ and $\vec{b}'_1$ in Fig. 5. Here we only show the spectra for the case $\sin 2\theta_b > 0$ and gluino decay Ch. 1, because for $\sin 2\theta_b > 0$ or $< 0$, Ch. 1 or Ch. 2, the spectra are very similar. We can immediately see that the primary $b$ is back-to-back with the secondary $\vec{b}_{\text{dec}}$ from gluino decay. The $\vec{b}_{\text{dec}}$ and $\vec{b}_{\text{dec}}$ are very much close to each other that the cosine of the angle between them is peaked at $0.8 - 0.9$. The cosine of the angle between $\vec{b}_{\text{dec}}$ and $\vec{b}'_1$ has a broader distribution, but still peaks in the $\cos \theta = 1$ region. Thus, we have the following picture. The decay products, $\vec{b}_{\text{dec}}$ and $\vec{b}_{\text{dec}}$, and the primary $\vec{b}'_1$ combine to form a wide or “fat” bottom-like jet. This “fat” bottom jet is back-to-back to the primary bottom jet, which has an energy close to $M_Z/2$.

Here we comment on the possibility that the channel that we consider here may affect the $R_b$ measurement, based on two criteria. First, one of the bottom jet in the channel under consideration is “fat”. If the two sbottoms cannot be separated from the bottom, the resulting bottom jet will just look like a fat bottom jet and may affect $R_b$. Second, whether the energy in this fat bottom jet equals to half of the $Z$ mass or not. As mentioned by Berger et al. [5], the sbottom can either decay into light hadrons or escape unnoticed from the detector. If the sbottoms escape the detection (which means that they do not deposit enough kinetic energy in the detector material for detection), the fat bottom jet would have an energy much less than $M_Z/2$. The final-state would be two bottom jets (one energetic and one much less energetic) plus missing energy, and thus would not affect $R_b$. Nevertheless, this is a very interesting signal on its own. On the other hand, if the sbottoms deposit all their kinetic energy in the detector, the measured energy of the fat bottom jet would be close to $M_Z/2$. In this case, it may affect the measurement of $R_b$. In fact, it would increase $R_b$. But if the fat bottom jet could be distinguished from the normal bottom jet, the present channel is also interesting on its own. According to a study on the light gluino [17], a sbottom of mass $2-5.5$ GeV, if similar to gluino, will likely deposit most of its kinetic energy in the detector. If this is the case the signal would be two back-to-back bottom jets, one of which is “fat” or wide, with no or little missing energy.
IV. CONCLUSIONS

We show that the light-sbottom-gluino scenario predicts the production of $b\bar{b}l_1\tilde{l}_1$, $b\bar{b}l_1\tilde{l}_1$, and $b\bar{b}l_1\tilde{l}_1$ at the $Z$ pole, with a branching fraction of order of $10^{-3}$, depending on the gluino mass and the sign of the mixing angle. The event topology is very different from the prompt $b\bar{b}$ production. Depending on whether the sbottoms deposit little or almost all of their energies in the detector, the signal would be very different. If the sbottoms escape the detector unnoticed, the final-state would be two bottom jets (one energetic and one much less energetic) plus missing energy. On the other hand, if the sbottoms deposit all their kinetic energy in the detector, the final state will be two bottom jets, one of which is fat. In this case, it may increase the measurement of $R_\phi$. But if the fat bottom jet could be separated from the normal bottom jet, it is a distinct signal. These two kinds of signals may well be hidden in the LEP I data, waiting for deliberate search.

One special feature of the Majorana nature of the gluino predicts a ratio of 1:1:2 for the rates of $bb : \bar{b}\bar{b} : b\tilde{l}$ [5]. However, one needs to look for the charged modes $B^+B^+$ or $B^-B^-$ to avoid effects due to $B^0\bar{B}^0$ oscillation.

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FIG. 2: Partial width of $Z \rightarrow b\bar{b}_{1}\tilde{g} + \tilde{b}\bar{b}_{1}\tilde{g}$ versus $m_{\tilde{g}}$ for $m_{\tilde{b}_{1}} = 3$ GeV and $m_{\tilde{b}} = 4.5$ GeV.
FIG. 3: Normalized energy spectra of the $b$ ($x_b$), sbottom ($x_{\tilde{b}}$), and gluino ($x_{\tilde{g}}$) in the decay $Z \rightarrow \tilde{b}\tilde{g}$. (a) $\sin 2\theta_b > 0$ and (b) $\sin 2\theta_b < 0$. 

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FIG. 4: Normalized energy spectra $x_{\ell_{dec}}$ and $x_{\tilde{b}_{dec}}$, in which the bottom and sbottom are the subsequent decay products of the gluino. (a) $\sin 2\theta_{\tilde{b}} > 0$ and (b) $\sin 2\theta_{\tilde{b}} < 0$. Here “ch. 1” and “ch. 2” refer to the decay channels of the gluino in Eqs. (10) and (11), respectively.
FIG. 5: Normalized spectra of the cosine of the angles between various pairs of final-state partons in the decay process $Z \rightarrow b\tilde{b}\tilde{g} \rightarrow b\tilde{b}_{\text{dec}}\tilde{b}_{\text{dec}}$. Here $\tilde{b}_{\text{dec}}$ and $\tilde{b}_{\text{dec}}$ denote the decay products of the gluino.