

**Z → bbbb in the light gluino and light sbottom scenario**

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The light gluino (12 ~ 16 GeV) and light sbottom (2 ~ 6 GeV) scenario has been used to explain the apparent overproduction of b-quarks at the Tevatron. This scenario also predicts the decay $Z → bar{b}gar{g}$ where the gluinos subsequently decay into b-quarks and sbottoms. We show that this can contribute to $\Gamma_{bb} = \Gamma(Z → bbbb)$ since most of the sbottoms and b-quarks arising from gluino decay have a small angular separation. We find that while no excess in $\Gamma_{bb}$ is observable due to large uncertainties in experimental measurements, the ratio $\Gamma(Z → bar{b}gar{g})/\Gamma(Z → bbbb)$ can be large due to sensitivity to b-quark mass, the sbottom mixing angle and the gluino mass. We calculate it to be in the range $0.05 - 0.41$ inclusive of the entire parameter space.

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**I. INTRODUCTION**

The Standard Model (SM) has been successful in explaining a host of experimental observations on electroweak and QCD phenomenon at LEP as well as hadron colliders. But it is generally believed that the SM is an effective theory valid at the electroweak energy scale with some new physics lying beyond it. Among the leading candidates for a theory beyond the SM is the Minimal Supersymmetric Standard Model (MSSM) which has been extensively studied in the past few decades.

The MSSM predicts the existence of SUSY partners of quarks, gluons and other known particles of the Standard Model. These so-called “sparticles” have not been observed which has led to speculation that they might be too heavy to have observable production rates at present collider energies. However, it has been suggested in [2] that a light sbottom ($b_1$) with a mass of $\mathcal{O}(5 \text{ GeV})$ 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 Tevatron [4]. In this model, gluinos of mass 12 – 16 GeV are produced in pairs in $pp$ collisions and decay almost immediately into a sbottom ($2 – 6 \text{ GeV}$) and a b-quark each. The sbottom manages to evade direct detection via $R$-parity violating decays into soft jets of light quarks around the cone of the b-jet. This mechanism is shown to successfully fit the b-quark transverse momentum distribution at NLO level. Alternatively it has been suggested that using the latest b-quark fragmentation functions reduces the discrepancy at the Tevatron [5]. In this report however we will work in the LSLG scenario.

Recently, there has been some careful re-examination of Z-pole precision data in this scenario. QCD corrections to the Zbb vertex with sbottom and gluino loops have been calculated [6]. They contribute negatively to $R_b$ and increase in magnitude with the mass of the other eigenstate of the sbottom ($b_2$). To maintain consistency with data, $b_2$ must be lighter than 125 (195) GeV at 2σ (3σ) level. An extension of that analysis to the entire range of electroweak precision data finds that $b_2$ must be lighter than 180 GeV at the 5σ level [7]. A $b_2$ in such a mass range would have been produced in association with a $b_1$ at LEPII energies (upto 209 GeV) via the couplings $Zb_1\bar{b}_2$ and $Zb_2\bar{b}_1$. Since such a $b_2$ has not been observed it would seem that LEP data disfavours the LSLG scenario.

However, these constraints can be relaxed because (i) a subsequent study of the decay $Z → b_1\bar{b}_2 + b_1\bar{b}_2$ has shown that it can contribute positively to $R_b$ and therefore should overcome at least some of the negative loop effects, (ii) a heavier $b_2 (> 200 \text{ GeV})$ might be allowed if large CP-violating phases are present in the model [7] and (iii) experimental searches for SUSY particles are heavily model-dependent and, to our knowledge, an exhaustive search of LEPII data for a $b_2$ in this particular scenario has not been done.

In addition to $Z$-precision data, production of $bb$-pairs at the Z-pole via gluon splitting has been re-examined recently by Cheung and Keung [10]. They calculate the contribution of $Z → q\bar{q}g$ to the process $Z → q\bar{q}g^* → bb$ ($q = u,d,c,s,b$) in the massless $g$ approximation and find that the former is only around 4 – 15% of the latter. They do not go further and consider the ratio $\Gamma(Z → b\bar{b}g)/\Gamma(Z → bbbb)$ as they expect it to be very similar. Like them we note that the process $Z → b\bar{b}g$ can contribute to $\Gamma(Z → bbbb)$ via the final states $bb\bar{b}_1\bar{b}_1$, $bb\bar{b}_1\bar{b}_1$ and $bbb\bar{b}_1\bar{b}_1$ which have four $b$-quarks and two sbottoms arising from the gluino decays $\tilde{g} → b\bar{b}_1\bar{b}_1$. This can happen if the $b$-quark and sbottom arising from gluino decay prefer a small angular separation, so that a typical event looks like $Z → bbbb$. But $Z → b\bar{b}g$ can arise not only from the gluon splitting diagrams in Fig. 1(b) but also from “sbottom splitting” diagrams in Fig. 1(c). We show that the net SUSY process should indeed contribute to $Z → bbbb$ and the latter diagrams significantly enhance the width for this process. We also calculate $\Gamma(Z → bbbb)$ to leading order in the SM over a

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range of \( b \)-quark masses. The final result is a wide theoretical range for the ratio \( \Gamma(Z \rightarrow b\bar{b}g\bar{g})/\Gamma(Z \rightarrow b\bar{b}b\bar{b}) \) of 5% to 41% inclusive of the entire parameter space.

II. CALCULATIONS

The tree level diagrams for evaluating \( \Gamma_{4b} = \Gamma(Z \rightarrow b\bar{b}b\bar{b}) \) and \( \Gamma_{b\bar{g}} = \Gamma(Z \rightarrow b\bar{b}g\bar{g}) \) are shown in Fig. 1(a).

\[
\text{FIG. 1: Feynman diagrams contributing to (a) } Z \rightarrow b\bar{b}b\bar{b} \text{ and (b),(c) } Z \rightarrow b\bar{b}g\bar{g}. \text{ Diagrams with gluon/gluino emission off the } b \text{-leg and the crossing of identical particles are not shown.}
\]

Feynman rules for the MSSM given by Rosiek [11] are used to evaluate these diagrams. Their formalism allows us to write the lighter sbottom mass eigenstate as a superposition \( \bar{b}_1 = \sin \theta_b \, \bar{b}_L + \cos \theta_b \, \bar{b}_R \) of the left and right-handed states where \( \theta_b \) is the sbottom mixing angle. This angle appears in the coupling:

\[
Z\bar{b}_1\bar{b}_1 \propto (\frac{1}{2}\sin^2 \theta_b - \frac{1}{3}\sin^2 \theta_W)
\]

where \( \theta_W \) is the Weinberg angle. However since electroweak data excludes the process \( Z \rightarrow \bar{b}_1\bar{b}_1 \) to a high precision, the mixing angle must be fine-tuned to make the coupling small i.e., \( s_b = \frac{1}{2}\sin \theta_W \), \( |s_b| \approx 0.38 \) [2] where the short-hand notation \( s_b \equiv \sin \theta_b \) is used. We vary \( |s_b| \) in the narrow range 0.30 – 0.45.

At constant scale we find that the diagrams in Fig. 1(c) enhance the width for \( Z \rightarrow b\bar{b}g\bar{g} \) by 10 – 60%. The lower limit is obtained for \( s_b = -0.30 \), \( m_{\tilde{b}} = 12 \text{ GeV} \) and the upper for \( s_b = +0.45 \), \( m_{\tilde{b}} = 16 \text{ GeV} \). Default values of \( m_{\tilde{b}} = 4.5 \text{ GeV} \), \( m_{\tilde{b}} = 4 \text{ GeV} \) are used in this analysis and variation of these within \( m_{\tilde{b}} = 4 - 5.25 \text{ GeV} \) and \( m_{\tilde{b}} = 2 - 6 \text{ GeV} \) has little effect. We also verify that as \( m_{\tilde{b}} \) becomes large, the contribution of Fig. 1(c) diminishes, and vanishes in the limit \( m_{\tilde{b}} \rightarrow \infty \). We therefore choose the invariant mass of the two gluinos, \( m_{\tilde{g}\tilde{g}} \), as the running scale \( Q \) since the diagrams in Fig. 1(b) are still dominant. Using a different invariant mass such as \( Q = m_{b\bar{g}} \) only changes \( \Gamma_{b\bar{g}} \) by 2 – 3%.

In calculating \( \Gamma_{4b} \) the \( b\bar{b} \)-pair produced by gluon splitting cannot be isolated due to interference terms between crossed diagrams in Fig. 1(a), making the off-shellness of the virtual gluon indeterminate. This is in contrast to the gluon splitting processes \( Z \rightarrow q\bar{q}g^* \rightarrow b\bar{b} \) and \( Z \rightarrow b\bar{b}g^* \rightarrow q\bar{q} \), \( q \neq b \), where the secondary production of \( b \)-quarks does not interfere with primary production at leading order [12]. Therefore to calculate \( \Gamma_{4b} \) we first find the ratio \( \Gamma_{4b}/\Gamma(Z \rightarrow q\bar{q}g^* \rightarrow b\bar{b}) \) at constant \( Q \)-scale, summing the denominator over \( q = u, d, s, c, b \) in the massless \( q \) approximation. Then \( \Gamma_{4b} \) is evaluated over a running \( Q \)-scale as follows:

\[
\Gamma_{4b} = \frac{\Gamma(Z \rightarrow q\bar{q}g^* \rightarrow b\bar{b})}{\Gamma(Z \rightarrow q\bar{q}g^* \rightarrow b\bar{b})} \times \Gamma(Z \rightarrow q\bar{q}g^* \rightarrow b\bar{b}) \quad (1)
\]

The gluon-splitting process has been studied up to next-to-leading logarithm (NLL) level in the past and is known to be sensitive to the \( b \)-quark mass. Values ranging from \( m_b = 4.25 \text{ GeV} \) to variation between the pole mass and the \( B \)-meson mass i.e. \( m_b = 4.75 - 5.25 \text{ GeV} \) have been used [13, 14]. DELPHI and OPAL [15, 16] have measured \( \Gamma_{4b} \) and they use \( m_b = 4.5 - 5.25 \text{ GeV} \) in their analysis. Clearly, in the absence of a higher order calculation there is no choice but to vary \( m_b \) over a wide range. We vary it from the lower limit of the \( \overline{\text{MS}} \) value \( m_b(\overline{m}_b) = 4 \text{ GeV} \) to the \( B \)-meson mass \( m_B = 5.25 \text{ GeV} \).

The canonical strong coupling value \( \alpha_s(M_Z) = 0.118 \) is used as changes to the running of \( \alpha_s \) have been shown to be small [3, 13] even in light of the various new effects on the hadronic width of the \( Z \) in this scenario [2, 4, 8, 10, 12].

Results are given in terms of the ratios:

\[
R_{4b} \equiv \frac{\Gamma_{4b}}{\Gamma(Z \rightarrow \text{hadrons})}_{SM} \quad R_{b\bar{g}} \equiv \frac{\Gamma_{b\bar{g}}}{\Gamma(Z \rightarrow \text{hadrons})}
\]

The total hadronic width of the \( Z \) is taken to be \( \Gamma(Z \rightarrow \text{hadrons}) = 1.744 \text{ GeV} \).

III. RESULTS

Using eqn. 11 we numerically calculate \( R_{4b} = (6.06 - 3.04) \times 10^{-4} \) for \( m_b = 4 - 5.25 \text{ GeV} \). Measurements of the same by DELPHI and OPAL yield \((6.0 \pm 1.9 \pm 1.4) \times 10^{-4} \) and \((3.6 \pm 1.7 \pm 2.7) \times 10^{-4} \) respectively and the uncorrelated average is given by the Particle Data Group to be \( R_{4b}^\text{exp} = (5.2 \pm 1.9) \times 10^{-4} \) [17]. Our entire calculated range is within 1.2\( \sigma \) of the experimental average.
Therefore, the lack of experimental precision does not allow us to fix the b-quark mass any further. The central value of $R_{bb}^{exp}$ is obtained for $m_b \sim 4.3$ GeV which agrees well with $m_b = 4.25$ GeV used in [10] to fit the full gluon-splitting process. In a similar fashion, $R_{b\tilde{b}}$ is very sensitive to the gluino mass $m_{\tilde{g}}$ showing a decrease by nearly a factor of 3.5 as $m_{\tilde{g}}$ varies from 12 to 16 GeV [Fig. 2(a)]. On the other hand, variations in $b$-quark mass and the sbottom mass (2–6 GeV) have very little effect (∼5%) [Fig. 2(b)]. The effect of varying $s_b$ within the range $|s_b| = 0.30 – 0.45$ is shown in Fig. 2(c) for $m_{\tilde{g}} = 12$ GeV. The variation is ≥30%, increasing with gluino mass. $R_{b\tilde{b}}$ is lower for negative values of $s_b$ but increases with $|s_b|$ due to constructive interference with the gluon-splitting diagrams. Including all parameters, we find $R_{b\tilde{b}} = (0.25 – 1.33) \times 10^{-4}$.

The total $R_{4bb} + R_{b\tilde{b}}$ equals $(3.3 – 7.3) \times 10^{-4}$ for the entire parameter space which is still within 1.2σ of the experimental value. However the ratio $r = R_{b\tilde{b}}/R_{4bb}$ can be quite large, varying from 5 – 41% [Fig. 3]. Thus the SUSY process can be a significant fraction (4 – 30%) of the total events if it cannot be distinguished from the SM $b\bar{b}b\bar{b}$ decay.

In this context we now study the structure of $Z \rightarrow b\bar{b}g\bar{g}$ events. The cumulative final state $q\bar{q}gg$ has been studied in $e^+e^-$ annihilation at $\sqrt{s} = 189$ GeV [11], and our results are similar. Fig. 4 shows the opening angle (cos $\theta$) between final state $b$-quarks, gluinos and gluino decay products. We see that the prompt $b$-quarks tend to be well-separated from each other and also from the gluinos. We decay a gluino into a $b\bar{b}$ pair and find that the decay products are rather close to each other, with cos $\theta$ peaking at around 0.8. The two gluinos on the other hand appear to have a more or less uniform cosine distribution with a slight preference for smaller angles. Therefore most events primarily consist of four jets containing $b$-quarks, with at least three of them well-separated, and two of them having sbottoms in or quite close to them. If the sbottom hadronizes completely in the detector and deposits its energy as a jet then it might be difficult to separate from the accompanying $b$-quark without a deliberate search. In that case the events would
look just like $Z \rightarrow bb\bar{b}$. However, if the sbottom-jet lies near the periphery of the $b$-jet then it might widen it somewhat. A similar situation could arise if the sbottoms deposit only a fraction of their energy in the detector and appear as missing energy. This energy is likely to be small enough that sbottoms arise from gluino decay and tend to be rather soft in comparison to prompt $b$-quarks. Events with missing energy can also arise from $Z \rightarrow bbb\bar{b}$ because of subsequent semileptonic decays $B \rightarrow X \ell \nu$. While a full detector simulation is beyond the scope of this report; given the experimental uncertainties and the absence of a deliberate search it is possible that sbottoms produced in this scenario escaped detection. The SUSY events might therefore lie hidden in data for $Z \rightarrow bbb\bar{b}$ and could be sufficient in number that a deliberate search might uncover them.

IV. CONCLUSIONS

We show that the light sbottom and light gluino scenario predicts the SUSY decay $Z \rightarrow \tilde{b}\tilde{g}$. We also show that this can contribute to the SM process $Z \rightarrow bbb\bar{b}$ because of gluino decay into pairs of proximate sbottoms and $b$-quarks. This scenario cannot be constrained by an excess in the measured rate $R_{bb}^{\exp}$ due to large experimental and theoretical uncertainties. However, the ratio between the SUSY and SM decays is shown to be significant, from 5% to 41% inclusive of the entire parameter space. A good fraction of events in the $R_{bb}^{\exp}$ sample might therefore arise from the SUSY process and contain sbottom signatures hidden in and around $b$-jets. We suggest a model-dependent search for sbottoms in existing LEP data in order to constrain this scenario.

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