Light Gluinos and $\Gamma(Z \to b\bar{b})$

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Abstract

We discuss the anomaly in the $b$ branching ratio of the $Z$ in the context of the light gluino scenario.

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Recently, some attention [1] has been given to a possible deviation from the standard model in the $b\bar{b}$ decay rate of the $Z$. The discrepancy may be discussed in terms of the ratio

$$R_b \equiv \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to \text{hadrons})}$$

(1)

where the current experimental results and theoretical expectations are [2–4]

$$R_{b}^{\text{exp}} = 0.2192 \pm 0.0018$$

(2)

$$R_{b}^{\text{th}} = \begin{cases} 
0.2157 \pm 0.0004 & (\text{for } M_t = 174 \text{GeV}) \\
0.2165 \pm 0.0004 & (\text{for } M_t = 150 \text{GeV}) 
\end{cases}$$

(3)

Over the relevant range of $M_t$, $R_{b}^{\text{th}}$ is approximately linear [3] so we may parametrize the anomaly as

$$\delta R_b \equiv R_{b}^{\text{exp}} - R_{b}^{\text{th}} = \left(18 \pm 18 + \left(\frac{M_t - 123}{3}\right)\right) \cdot 10^{-4}$$

(4)

Thus the anomaly disappears at the one standard deviation level if $M_t \approx 123$. This however is below the lower limit of 131 GeV quoted by the $D\emptyset$ collaboration for the top mass and is inconsistent with the top interpretation of the $CDF$ results suggesting $M_t \approx 174$.

The anomaly may disappear with further statistics or may be due to a theoretical underestimate of the $b$ production from gluon hadronization. On the other hand, it is attractive to examine each discrepancy from the standard model in terms of a possible explanation in supersymmetry ($SUSY$). In particular it has been pointed out that an enhanced $b\bar{b}$ production at the $Z$ could be a signal for low lying stop quarks, charginos, or neutralinos due to loop effects [7–9]. Such explanations require stop quarks, charginos, or neutralinos below $M_Z$. In the standard $SUSY$ model with heavy squarks and gluinos an explanation of the anomaly requires abandoning the conventional supergravity (SUGRA) inspired model for $SUSY$ breaking [9]. On the other hand, in the light gluino scenario, the SUGRA inspired breaking leads automatically to charginos and neutralinos in the required mass region. There
are three scenarios associated with light gluinos which could separately or together explain
the excess bottom production at LEP. These are

- 1. The top quark might be light (on the order of 123 GeV) thus reconciling the data
   through $\frac{M_Z}{2}$. This is ruled out by the $D\emptyset$ and $CDF$ experiments if the gluino is heavy
   but is allowed in the light gluino case as discussed below.

- 2. The $Z$ branching ratio into $b$'s could be enhanced by loop effects with virtual stop
   quarks and charginos and/or charged Higgs as, for example, in fig.1. This has been
   discussed by several authors and might (marginally) explain the effect if the stop quarks
   and charginos are light. This is natural in the light gluino scenario but otherwise re-
   quires abandoning the current ideas about supergravity related $SU(5)$ breaking.

- 3. The $Z$ could be decaying into on-shell neutralinos or charginos which would give
   some preference in their decay to bottom quarks through their higgsino components.
   In the light gluino case these particles decay predominantly into $q\bar{q}$. In the heavy
   gluino case these particles are expected to decay down into the lightest neutralino
   which will then escape the detector leading to an appreciable missing energy. This
   latter possibility is ruled out if the gauginos are below $M_Z/2$ due to the $LEP$
   experiments. We reserve a quantitative discussion of this possibility to a later paper.

It is generally recognized that there are one or more low mass gluino windows consistent
with current experimental limits [10]. for an update on these windows see [11,12]. However,
perhaps because these windows are small compared with the unbounded region above 150
GeV, most theoretical and experimental analyses on squark and gluino mass limits assume
that the gluino mass is not in the low energy windows. If, on the other hand, the gluino is
light (which we will take in this article to mean below 5 GeV), most of the limits quoted on the other SUSY particles and the top quark are also voided. Such a light gluino will decay into a $q\bar{q}\gamma$ without an appreciable missing energy. Therefore the squarks decaying into $q\bar{g}$ would also not produce enough missing energy to make the collider experiments sensitive to them. Similarly, in the light gluino scenario with a SUSY scale below approximately 570 GeV, one of the stop quarks is typically lighter than the top in which case the top decays through the chain

\[ t \rightarrow \tilde{t}g \]
\[ \tilde{t} \rightarrow \tilde{W}b \]
\[ \tilde{W} \rightarrow q\bar{q}g \quad (5) \]

Such a decay chain involves no high $P_T$ leptons and would make the top quark invisible to the current FNAL searches. It could therefore lie considerably lower than the 131 GeV lower limit for a top with a standard model decay chain. In the light gluino scenario with radiative electroweak symmetry breaking as currently understood, the running top quark mass is predicted to be about 114 GeV [14]. This corresponds to a physical top quark mass of about 124 GeV [15]. Such a light top quark mass could by itself resolve the $R_b$ anomaly as can be seen in [4]. However as mentioned above there are other features of the light gluino scenario which lead naturally to an enhanced $R_b$. Any one of these, or all of them together, could explain the discrepancy.

An enhancement in $\Gamma(Z \rightarrow b\bar{b})$ is naturally coupled to a higher apparent $\alpha_3$ from the $Z$ width. Assuming that only the $b$ channel is enhanced leads to the relation

\[ \delta\alpha_3 = \pi\delta R_b \frac{1 + \alpha_3/\pi}{1 - R_b} \quad (6) \]

The LEP result from the $Z$ width assuming a nominal top quark mass of 174 GeV, namely $\alpha_3(M_Z) = 0.125 \pm 0.005 [1]$ correlates well with the observed enhancement in $R_b$ and the value $\alpha_3(M_Z) \approx 0.11 [16]$ found by extrapolating from low energy data assuming a light gluino. In references [17][8] an attempt was made to explain the $\alpha_3$ discrepancy by a light gluino and
squarks below the $Z$ (but above $M_Z/2$ of course) through the $t\bar{t}g\bar{g}$ decays of the $Z$. In the SUGRA model it is not possible to have $b$ squarks significantly below the other squarks and sleptons and hence a low $SUSY$ scale with a light gluino will not selectively enhance $R_b$ through this mechanism. In view of the current data on $R_b$, the universal scalar mass must therefore be at least $80 \, GeV$. The lightest $SUSY$ scalar apart (possibly) from one of the stop quarks is then the sneutrino with a mass above $62 \, GeV$.

In reference [18] it was noted that in the light gluino scenario with a universal gaugino mass $M_{1/2}$ set to zero, there is a stringent limitation on the possible values of $\tan(\beta)$. These come from the theoretical expression for the chargino masses [19]

$$M_{\chi^\pm_2} = \frac{1}{2} \left( 2M_W^2 + \mu^2 \pm \sqrt{\mu^2 + 4M_W^2\mu^2 + 4M_W^4\cos^2(2\beta)} \right)$$ (7)

together with the experimental requirement that these masses be greater than (or almost equal to) half the $Z$ mass. Assuming $\tan(\beta) > 1$ as required in the model of radiative electroweak symmetry breaking and taking the experimental lower limit on the light Higgs boson to be $42 \, GeV$ [20] yields a possible range for $\tan(\beta)$ of

$$1.5 < \tan(\beta) < 2.266 \quad (8)$$

In reference [14] it was argued that, in the light gluino scenario, the lower limit on the light Higgs is actually $60 \, GeV$ which then, at the current level of theoretical analysis, requires, assuming also radiative electroweak breaking, that $\tan(\beta)$ be restricted to a very tiny window around the center of the above range. We are reluctant to attribute such precision to the current perturbative arguments so we will, in the present article, explore the already narrow range of [8]. In ref. [9] it was found that the $\delta R_b$ discussed above could be brought to within one standard deviation of zero with a top mass of $174 \pm 15$ if the lightest chargino was below $60 \, GeV$ and $\tan(\beta)$ were below 1.8 (See their $fig.2$). Such a situation is not expected in the usual treatment of the $MSSM$ with a supergravity inspired
SUSY breaking and a heavy gluino. On the other hand exactly this situation is predicted in the light gluino scenario. To see this we run over the allowed tan(β) range of $\tan(\beta)$ and the full range of $\mu^2$ allowed by the experimental limits on the light chargino mass in $\mu$. In addition we require that the next-to-lightest neutralino, $\chi_1$ have a mass consistent with limits from the $Z$ width. The lightest neutralino in this scenario is the photino, which decouples from the mixing matrix of the remaining three. The mass term in the Lagrangian for these states can be obtained from \cite{19} by putting $M_{1/2}$ to zero. It takes the form

$$L = N_3^\dagger M N_3$$  \hspace{1cm} (9)

$$N_3 = \begin{pmatrix} \tilde{Z} \\ \tilde{H}_1^0 \\ \tilde{H}_2^0 \end{pmatrix}$$  \hspace{1cm} (10)

$$M = M_Z \begin{pmatrix} 0 & s_\beta & c_\beta \\ s_\beta & 0 & -\tilde{\mu} \\ c_\beta & -\tilde{\mu} & 0 \end{pmatrix}$$  \hspace{1cm} (11)

where $\tilde{\mu} \equiv \mu/M_Z$ and $s_\beta$ and $c_\beta$ are the sine and cosine of $\beta$ respectively. The eigenvalues of $M$ are written in terms of the quantities

$$b = \tilde{\mu} \sin 2\beta$$  \hspace{1cm} (12)

$$a = 1 + \tilde{\mu}^2$$  \hspace{1cm} (13)

$$\cos \phi \equiv -\frac{b}{2} \left(\frac{a}{3}\right)^{-3/2}$$  \hspace{1cm} (14)

The three neutralino eigenstates have masses

$$M_n = 2M_Z \sqrt{\frac{a}{3}} \left| \cos \frac{\phi + 2\pi n}{3} \right| \quad n = 1, 2, 3$$  \hspace{1cm} (15)

However we relabel the eigenstates according to the definition $M_1 < M_2 < M_3$ so that $\chi_1$ corresponds to the lightest neutralino apart from the photino. This lightest neutralino is a mixture of the form
\[ \chi_1 = \alpha_1 \tilde{Z} + \beta_1 \tilde{H}_1^0 + \gamma_1 \tilde{H}_2^0 \] (16)

with \(|\alpha_1|^2 + |\beta_1|^2 + |\gamma_1|^2 = 1\). The \(\chi_1\) will decay through its \(\tilde{Z}\) component into \(q\bar{q}\tilde{g}\) where the \(q\) and \(q\) should be bottom quarks with the same probability as in standard model \(Z\) decay. Through its Higgsino components the \(\chi_1\) will decay primarily into \(b\bar{b}\tilde{g}\). Hence it is possible, if \(\alpha_1\) is small enough, that the \(b\) excess at the \(Z\) could be due to a production of \(\chi_1\) pairs near threshold. The experimental mass limits on neutralinos that are usually quoted \([21]\) do not take into account possible decays into such states containing a light gluino. In the light gluino scenario \(\chi_1\) masses near \(M_Z/2\) are in fact required in the \(SUGRA\) inspired model. 

In Fig.-1 we show the range of allowed \(\mu\) and \(M_1\) values with the shape coding indicating the corresponding value of the lightest chargino mass. An approximately symmetric set of solutions not shown in Fig.-2 is found at negative values of \(\mu\). The points are plotted as squares, triangles, circles, and diamonds if the lightest chargino is in the 1st, 2nd, 3rd, or 4th quadrant of the total predicted range 45.5 \(GeV\) to 52.5 \(GeV\). This very narrow range overlaps with that required to bring the \(R_b\) values into 1\(\sigma\) agreement with theory. (see Fig.-2 of \([9]\)). Such values of the chargino mass will be definitively tested at \(LEP\ II\) and hence, if the chargino is not found there, either the light gluino scenario or the supergravity inspired model for \(SUSY\) mass splitting will be ruled out. The solutions in Fig.-2 with \(M_1\) below 45.6 correspond to on shell production of \(\chi_1\) pairs at \(LEP\ I\). In Fig.-3 we show the solution space projected onto the \(\tan(\beta) - \alpha_1^2\) plane with the shape coding indicating the quadrant values of \(M_1\) over its full range of 43 to 51 \(GeV\). The solutions allowing \(Z\) decay into on-shell \(\chi_1\)’s are indicated by squares. In the light gluino case such \(\chi_1\) production would appear in the hadronic branching ratio of the \(Z\) and would hence lead to an apparently enhanced value of the strong coupling constant \(\alpha_3(M_Z)\). In a future paper we will examine quantitatively how much such events might enhance \(R_b\). It is interesting to note from Fig.-3 that the solutions with low \(\alpha_1\) implying an enriched Higgsino content in \(\chi_1\) also have a low \(\chi_1\) mass. The narrow triangle near \(\alpha_1^2 \approx .46\) corresponds to negative values of the \(\mu\) parameter.
Let us return to the possibility of $R_b$ being related to light stop quarks and charginos. In the supergravity related SUSY breaking scheme, the diagonal terms in the sfermion mass matrices are related to a universal scalar mass $M_0$ and a universal gaugino mass $M_{1/2}$ by

\begin{align}
M_{\tilde{e}}^2 &= M_0^2 + C_{\nu}M_{1/2}^2 + \frac{1}{2}M_Z^2 \cos (2\beta) \\
M_{\tilde{t}}^2 &= M_t^2 + M_0^2 + C_{uL}M_{1/2}^2 + (-\frac{1}{2} + \sin \theta_W^2)M_Z^2 \cos (2\beta) \\
M_{\tilde{\nu}_{LR}}^2 &= M_{\nu}^2 + M_0^2 + C_{\ell}\nu M_{1/2}^2 - \sin \theta_W^2 M_Z^2 \cos (2\beta) \\
M_{\tilde{\nu}_{L}}^2 &= M_{\tilde{\nu}}^2 + M_0^2 + (\frac{1}{2} - \frac{2}{3} \sin^2 \theta_W)M_Z^2 \cos (2\beta) \\
M_{\tilde{\nu}_{R}}^2 &= M_{\tilde{\nu}}^2 + M_0^2 + C_{\ell}\nu M_{1/2}^2 + \frac{2}{3} \sin^2 \theta_W M_Z^2 \cos (2\beta) \\
M_{\tilde{d}_{LR}}^2 &= M_d^2 + M_0^2 + C_{dL}M_{1/2}^2 + (-\frac{1}{2} + \frac{1}{3} \sin^2 \theta_W)M_Z^2 \cos (2\beta) \\
M_{\tilde{d}_{R}}^2 &= M_d^2 + M_0^2 + C_{dR}M_{1/2}^2 + (-\frac{1}{3} \sin^2 \theta_W)M_Z^2 \cos (2\beta)
\end{align}

In addition there are off diagonal terms for each squark of the form

\[ M_{LR}^2 = A_q M_q M_0 \]  (24)

Arguments can be made that the constant $A_q$ should be $\leq 3$ [19]. Then this mixing is negligible except possibly in the case of the top quark. One sees that for sufficiently small $M_0$ and $M_{1/2}$ the stop quark could be lighter than the top quark. This occurs naturally in the light gluino case ($M_{1/2} \approx 0$) whenever $M_0 \leq 500 \text{ GeV}$. The lightest top quark partner has mass

\[ M_{\tilde{t}}^2 = M_0^2 + M_t^2 + \frac{1}{4}M_Z^2 \cos (2\beta) - \frac{1}{4}\left[(M_Z^2 \cos (2\beta) - \frac{8}{3} \sin^2 \theta_W) + 16M_t^2 M_0^2 A_t^2\right]^{1/2}. \]  (25)

Therefore in the monte-carlo described above which runs over all experimentally allowed values of $m$ and $\tan(\beta)$ we simultaneously run over values of $M_t$ between 110 and 200 $\text{GeV}$, over values of $A_t$ between 0 and 3 and over values of $M_0$ between 80 and 1000 $\text{GeV}$. In view of the CDF results we throw out solutions with $M_t < 158$ unless $M_{\tilde{\nu}} + M_b < M_t < M_t$. 

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which would allow the non-standard top decay mode of $\bar{t}$ (neglecting the gluino mass). Fig.-4 shows the correlation between top mass and lighter stop quark mass for those solutions with $M_t < 195$. Only for low values of stop quark mass is $R_b$ enhanced through the mechanism 2 above. The solution is printed as a square, triangle, circle, or diamond respectively if $M_0$ is in the 1st, 2nd, 3rd, or 4th quadrant of the range from 80 GeV to 550 GeV. From the work of [7,9] we know that with a lighter chargino mass about 48 GeV as predicted here, the maximum lighter stop quark mass that will reconcile the $R_b$ data is a steeply falling function of $M_t$. The solutions with a sufficiently enhanced $R_b$ lie below and to the left of the hatched line in Fig.-4. All of these solutions lie in the region where the top quark has the anomalous decay mode of $\bar{t}$, and all of them have a low SUSY threshold ($M_0 < 400$ GeV).

In the $M_{1/2} = 0$ model, the gluino mass is determined through radiative corrections in terms of $M_0, A_t, M_t$, and $M_{\tilde{t}}$ [15]. In Fig.-5 we show the correlation between $M_0$ and $M_g$. The solutions with an adequately enhanced $R_b$ are plotted as $x$'s. Gluino masses up to 2 GeV are found but only a narrow band below 1.7 GeV is associated with an enhanced $R_b$.

Our conclusions are as follows:

• 1. If the enhancement of $R_b$ survives further experimentation and is due to SUSY then either the standard picture of soft SUSY breaking through universal scalar and gaugino masses is wrong or $M_{1/2} \approx 0$ and the gluino lies below 1.7 GeV.

In this article we have taken the universal gaugino mass, $M_{1/2}$, to be strictly zero so that all SUSY breaking originates in the scalar sector. If $M_{1/2}$ rises above 1 GeV the lightest neutralino acquires significant Higgsino components and the gaugino masses consistent with LEP limits rise rapidly. For this reason the $R_b$ enhancement is not consistent with the standard SUGRA inspired SUSY breaking in the heavy gluino.
• 2. If the $R_b$ enhancement survives and is due to light gluinos then the $SUSY$ scale is below 400 GeV, the lightest chargino has a mass below 52 GeV, and the lightest neutralino (apart from the photino) has a mass between 43 and 51 GeV. In this scenario, the $CDF$ events should not be attributable to top quark decay but instead to background or to $SUSY$ particle production since the top will decay through the decay chain $^3$

• 3. It is not ruled out that the $R_b$ enhancement could be at least partially due to on-shell gaugino production with non-negligible Higgsino components. We have not treated this quantitatively here and we leave a full combined treatment of the light gluino mechanisms for $b$ enhancement at the $Z$ to a later paper.

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FIGURES

FIG. 1. A typical Feynman diagram leading to enhanced b decay of the Z. Such contributions decouple if $M_{\tilde{W}}$ and $M_{\tilde{t}}$ are large compared to $M_Z$.

FIG. 2. Allowed values of the Higgs mixing parameter, $\mu$, and the second lightest neutralino mass $M_1$ in the light gluino scenario. Shape coding indicates the corresponding values of the lighter chargino mass. (See text.)

FIG. 3. Allowed values of the Higgs vev ration $\tan(\beta)$ and the Zino fraction in the second lightest neutralino, $\chi_1$, in the light gluino scenario. Shape coding indicates the value of the $\chi_1$ mass. (See text.)

FIG. 4. The correlation between lighter stop quark mass $M_{\tilde{t}}$ and the top mass $M_t$ for all possible values of the other parameters in the light gluino scenario. Solutions shown are all those with $M_{\tilde{t}}$ less than 195 GeV as is required in the light gluino scenario if the universal scalar mass $M_0$ is less than 550 GeV. Solutions leading to agreement between theory and experiment for $R_b$ are those to the left of the hatched curve. Shape coding indicates the value of the SUSY breaking parameter $M_0$. (See text.)

FIG. 5. Correlation between the gluino mass $M_{\tilde{g}}$ and the universal scalar mass $M_0$ in the $M_{1/2} = 0$ case. Solutions leading to a sufficiently enhanced value of $R_b$ are indicated by $x$’s.
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