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$\mathbf{R}_b$ in supergravity models

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Abstract

We compute the supersymmetric contribution to $R_b \equiv \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$ in a variety of supergravity models. We find $R_b^{\rm susy} \lesssim 0.0004$, which does not shift significantly the Standard Model prediction ($R_b^{\rm SM} = 0.2162$ for $m_t = 160\,{\rm GeV}$). An improvement in experimental precision by a factor of four would be required to be sensitive to such an effect.

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Precision tests of the electroweak interactions at LEP have provided the most sensitive checks of the Standard Model of particle physics. The pattern that has emerged is that of consistent agreement with the Standard Model predictions. This pattern seems to have so far only one apparently dissonant note, namely in the measurement of the ratio $R_b \equiv \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$, where the latest global fit to the LEP data (0.2192 ± 0.0018 [1]) lies about two standard deviations above the one-loop Standard Model prediction [2] for all preferred values of the top-quark mass (*e.g.*, $R_b^{\rm SM} = 0.2162$ for $m_t = 160\,{\rm GeV}$). Further experimental statistics will reveal whether this is indeed a breakdown of the Standard Model. In the meantime, it is important to explore what new contributions to R_b are expected in models of new physics, such as supersymmetry.

The study of supersymmetric contributions to $\Gamma(Z \to b\bar{b})$ has proceeded in two phases. Originally the quantity ϵ_b [3] was defined as an extension of the $\epsilon_{1,2,3}$ scheme [4] for model-independent fits to the electroweak data. More recently it has become apparent that the ratio R_b is more directly calculable [5, 6] and readily measurable. It has been made apparent [6] that supersymmetric contributions to R_b are not likely to increase the total predicted value for R_b in any significant manner, as long as typical assumptions about unified supergravity models are made. On the other hand, if these assumptions are relaxed, it is possible for supersymmetry to make a significant contribution to R_b, if certain conditions on the low-energy supersymmetric spectrum are satisfied: the lightest chargino and lightest top-squark should be below 100 GeV, with the chargino being mostly Higgsino and the top-squark mostly right-handed. One should keep in mind that novel supersymmetry breaking scenarios, such as those arising from string models, may provide such otherwise ad-hoc conditions. In any event, for the purposes of this paper we assume that the experimental data will settle at values for R_b which do not require extreme choices of the supersymmetry parameters for its explanation, and yet still allow for a discrimination among the various supergravity models on the basis of their prediction for R_b. If this assumption turns out to be invalid, all models discussed in this paper (as well as the Standard Model) would be seriously disfavored.

We consider unified supergravity models with universal soft supersymmetry breaking at the unification scale, and radiative electroweak symmetry breaking (enforced using the one-loop effective potential) at the weak scale [7]. These constraints reduce the number of parameters needed to describe the models to four, which can be taken to be $m_{\chi_1^\pm}, \xi_0 \equiv m_0/m_{1/2}, \xi_A \equiv A/m_{1/2}, \tan\beta$, with a specified value for the top-quark mass (m_t). In what follows we take $m_t^{\rm pole} = 160\,{\rm GeV}$ which is the central value obtained in fits to all electroweak and Tevatron data in the context of supersymmetric models [8]. Among these four-parameter supersymmetric models we consider generic models with continuous values of $m_{\chi_1^\pm}$ and discrete choices for the other three parameters:

$$\tan\beta = 2, 10, 20\ ; \qquad \xi_0 = 0, 1, 2, 5\ ; \qquad \xi_A = 0\ . \tag{1}$$

The choices of $\tan\beta$ are representative; higher values of $\tan\beta$ are likely to yield values of $B(b \to s\gamma)$ in conflict with present experimental limits [9]. The choices of ξ_0 correspond to $m_{\tilde{q}} \approx (0.8, 0.9, 1.1, 1.9) m_{\tilde{g}}$. The choice of A has little impact on the results. We also consider the case of no-scale $SU(5) \times U(1)$ supergravity [7]. In this class of models the supersymmetry breaking parameters are related in a string-inspired way. In the two-parameter *moduli* scenario $\xi_0 = \xi_A = 0$ [10], whereas in the *dilaton* scenario $\xi_0 = \frac{1}{\sqrt{3}}$, $\xi_A = -1$ [11]. A series of experimental constraints and predictions for these models have been given in Ref. [12]. In particular, the issue of precision electroweak tests in this class of models has been addressed in Refs. [13, 14].

Besides the one-loop Standard Model contributions to R_b, in supersymmetric models there are four new diagrams, as follows:

- The charged-Higgs–top-quark loop, depends on the charged Higgs mass and the $t - b - H^{\pm}$ coupling. For a left-handed b quark the coupling is $\propto m_t / \tan\beta$ whereas for a right-handed b quark it is $\propto m_b \tan\beta$. Therefore, for small[1] (large) $\tan\beta$ left- (right)-handed b-quark production is dominant. (For $\tan\beta \gg 1$, the value of m_b impacts the contribution significantly.) It has been shown that the $H^{\pm} - t$ contribution is always negative [15], a fact which makes the prediction for R_b in two Higgs-doublet models always in worse agreement with experiment.

- The chargino–stop loop, is the supersymmetric counterpart of the $H^{\pm}$–t loop discussed above. The chargino mass eigenstate is a mixture of (charged) Higgsino and wino, and the coupling strength is a complicated matter now because it involves the stop mixing matrix and the chargino mixing matrix. However, because only the Higgsino admixture in the chargino eigenstate has a Yukawa coupling to the t–b doublet, generally speaking a light chargino with a significant Higgsino component, and a light stop with a significant right-handed component are required for this diagram to make a non-negligible contribution to R_b, as pointed out in Ref. [6].

- The neutralino–sbottom loop, is the supersymmetric counterpart of the neutral-Higgs–bottom-quark loop. The coupling strength of $\chi_1^0 - \tilde{b} - b$ is also rather complicated, since it involves the sbottom mixing, the neutralino mixing, and their masses. However, it can be non-negligible since it is proportional to $m_b \tan\beta$ for the left-handed b-quark. Therefore in the high $\tan\beta$ region we have to include this contribution.[2]

- The neutral-Higgs–bottom-quark loop, involves the three neutral scalars, two CP-even (h, H) and one CP-odd (A). For the $h\,(H)$ neutral Higgs boson the coupling to the bottom quark is $\propto m_b \sin\alpha (\cos\alpha)$ which in the absence of a $\tan\beta$ enhancement makes its contribution negligible. For the A Higgs boson, the coupling to $b\bar{b}$ is $\propto \tan\beta$ and the A-dependent contribution can be large and positive if $m_A \lesssim 90\,\mathrm{GeV}$ and $\tan\beta \gtrsim 30$ [15]. Since we restrict ourselves to

[1] The radiative electroweak symmetry breaking mechanism requires $\tan\beta > 1$.

[2] This term was not included in our previous study in terms of the parameter ϵ_b [14], although it was pointed out that its effects were non-negligible for $\tan\beta \gg 1$.

$\tan\beta \lesssim 20$, and $m_A \gtrsim 100\,\mathrm{GeV}$ in these models, this contribution is neglected in what follows.

Our computations of $R_b^{\rm susy}$ have been performed using the expressions given in Ref. [6]. Even though these formulas are given explicitly, the details are quite complicated by the presence of various Passarino-Veltman loop functions. As a check of our calculations, we have verified numerically that the results are independent of the unphysical renormalization scale that appears in the formulas. The predictions for $R_b^{\rm susy}$ in the generic supergravity models are shown in Fig. 1. Only curves for $\tan\beta = 2, 10$ are shown, since the corresponding sets of curves for other values of $\tan\beta$ fall between these two sets of curves. Moreover, in the interest of brevity we do not show explictly the results in $SU(5)\times U(1)$ supergravity since for the same values of the parameters the predictions differ little from those in the generic models.

In almost all cases the largest positive contribution to $R_b^{\rm susy}$ comes from the chargino–stop loop. As expected, the largest contribution from this diagram happens for points with the lightest chargino masses (which correspond to the lightest $\tilde{t}_1$ masses) since supersymmetry is a decoupling theory. However, even the largest value ($\approx 10^{-4}$) is still very small compared with the largest possible result in a generic low-energy supersymmetric model [6]. The reason for this is that while the smallest possible chargino and a stop masses are required for an enhanced contribution, it is also necessary that the chargino has a significant Higgsino component and that the stop be mostly right-handed. The latter requirement is in fact attainable in these models (*i.e.*, the stop mixing angle is not small), but the former is not. Indeed, $R_b^{\rm susy} \propto |V_{12}|^2$, where V_{12} is the (12) element of the chargino mixing matrix V, which does not exceed ≈ 0.3, since for light charginos $|\mu| \gg M_2$ which makes the lightest chargino mainly a wino instead of a Higgsino. The charged-Higgs–top-quark loop is always negative, and is enhanced for either small or large values of $\tan\beta$. The neutralino–sbottom contribution is almost always smaller than the chargino–stop contribution and not of definite sign.

We conclude that the presently known supersymmetry breaking scenarios in the context of supergravity shift only slightly the Standard Model prediction for R_b, and would require an improvement in experimental sensitivity by a factor of four to be observable. Also, if the experimental value of R_b remains essentially unchanged over time, the models explored in this paper and the Standard Model as well, would fall into disfavor. If the experimental value changes in the direction of the Standard Model prediction, our calculations should help in discriminating among the various supergravity models on the basis of their prediction for R_b. It is also possible that new scenarios for supersymmetry breaking may entail low-energy spectra which satisfy the necessary conditions for an enhanced supersymmetric contribution to R_b.

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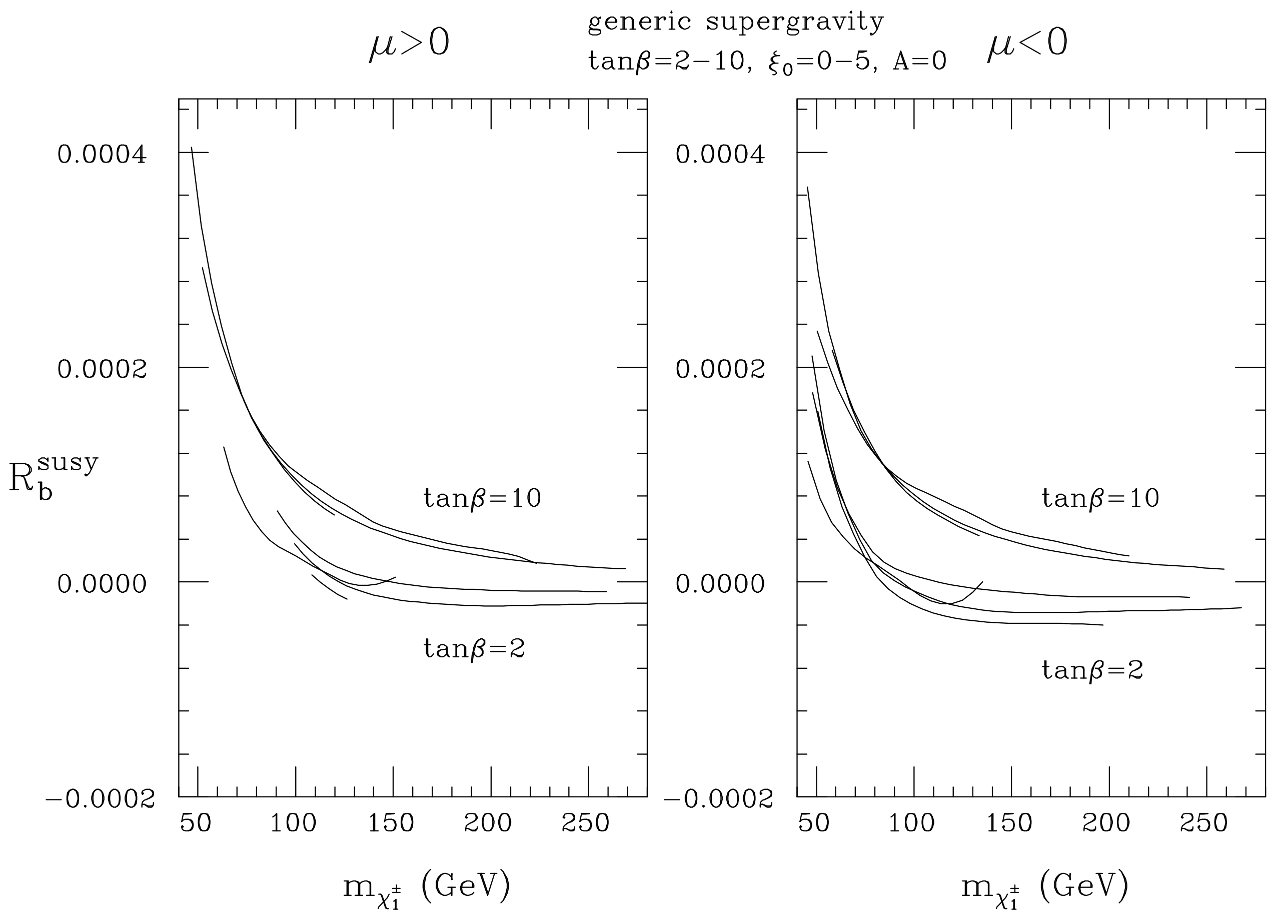

Figure 1: The supersymmetric contribution to R_b as a function of the chargino mass in generic supergravity models with $\tan\beta = 2, 10$, $\xi_0 = 0 - 5$, and $A = 0$. Curves for other values of $\tan\beta$ fall between the two sets shown.