R_b in supergravity grand unification with nonuniversal soft supersymmetry breaking

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An analysis of supersymmetric contributions to R_b in supergravity grand unification with nonuniversal boundary conditions on soft supersymmetry breaking in the scalar sector is given. Effects on R_b of Planck scale corrections on gaugino masses are also analyzed. It is found that there exist regions of the parameter space where positive corrections to R_b of size $\sim 1\sigma$ can be gotten. The region of the parameter space where enhancement of R_b occurs is identified. Predictions of sparticle masses for the maximal R_b case are given. The analysis has implications for the discovery of supersymmetric particles at colliders. [S0556-2821(97)00719-4]

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The standard model (SM) predicts a value of R_b of

$$R_b^{\rm SM}=0.2159, \quad m_t=175 \text{ GeV} \tag{1}$$

with $\delta R_b/\delta m_t=-0.0002$. The experimental value of R_b has been in a state of flux over the past couple of years. The experimental analyses in 1994–1995 indicated $R_b=0.2208\pm 0.0024$. However, more recently $R_b^{\rm expt}$ has drifted downwards, and currently, assuming the value of R_c at its SM value of $R_c=0.172$, one finds [1]

$$R_b^{\rm expt}=0.2178\pm 0.0011, \tag{2}$$

which is about 1.8σ higher than the SM value. (We note that in the most recent analysis of data three of the four CERN e^+e^- collider LEP detectors observe a significant R_b anomaly and ALEPH alone does not show any deviation from the SM results [2].) The possibility of a discrepancy between $R_b^{\rm expt}$ and the SM value has aroused much interest, since if valid the result would signal the onset of new physics beyond the SM. There have been several analyses recently to understand the possible origin of potentially large R_b corrections. Specifically supersymmetric contributions to this process have been analyzed within minimal supersymmetric standard model (MSSM) [3–7]. A variety of other suggestions have also been made, such as corrections from additional Z' and from additional fermion generations.

In this work we give the first analysis of the maximal supersymmetry (SUSY) corrections within supergravity unification [8,9] with radiative breaking of the electroweak symmetry with non-universal boundary conditions [10–13] including Planck scale corrections to the gauge kinetic energy function in supergravity [14]. For comparison with the previous work we also give results for the maximum SUSY corrections in MSSM, and in minimal supergravity. One defines $R_b=\Gamma(Z\to b\bar{b})/\Gamma(Z\to \text{hadrons})$ and the supersymmetric corrections to R_b by $R_b=R_b^{\rm SM}(m_t,m_b)+\Delta R_b^{\rm SUSY}$, where $\Delta R_b^{\rm SUSY}$ can be written in the form [3]

$$\Delta R_b^{\rm SUSY}=R_b^{\rm SM}(0,0)[1-R_b^{\rm SM}(0,0)][\nabla_b^{\rm SUSY}(m_t,m_b) - \nabla_b^{\rm SUSY}(0,0)]. \tag{3}$$

Numerically $R_b^{\rm SM}(0,0)=0.2196$ and $\nabla_b^{\rm SUSY}(m_t,m_b)$ is given by

$$\nabla_b^{\rm SUSY}(m_t,m_b)=\frac{\alpha}{2\pi\sin^2\theta_W}\left(\frac{v_L F_L+v_R F_R}{(v_L)^2+(v_R)^2}\right), \tag{4}$$

where v_L is defined by $v_L=-\frac{1}{2}+\frac{1}{3}\sin^2\theta_W$, and v_R by $v_R=\frac{1}{3}\sin^2\theta_W$. In supersymmetric models the quantities $F_{L,R}$ receive one-loop contributions from the charged Higgs, the chargino, the neutralinos, and the gluino. The most dominant terms are those arising from the chargino exchange and we exhibit these below [3]:

$$\begin{aligned}F_{L,R}^{\tilde{W}}=&\left(B_1^{\alpha i}v_{L,R}-\frac{4}{3}\sin^2\theta_W C_{24}^{i\alpha i}\right)\Lambda_{i\alpha}^{L,R}\Lambda_{i\alpha}^{*L,R}\\&+C_{24}^{i\alpha j}T_{i1}^*T_{j1}\Lambda_{i\alpha}^{L,R}\Lambda_{j\alpha}^{*L,R}\\&+M_{\tilde{W}_\alpha}M_{\tilde{W}_\beta}C_0^{\alpha i\beta}O_{\alpha\beta}^{L,R}\Lambda_{i\alpha}^{L,R}\Lambda_{i\beta}^{*L,R}+\Bigg(2C_{24}^{\alpha i\beta}\\&-M_Z^2(C_{12}^{\alpha i\beta}+C_{23}^{\alpha i\beta})-\frac{1}{2}\Bigg)O_{\alpha\beta}^{R,L}\Lambda_{i\alpha}^{L,R}\Lambda_{i\beta}^{*L,R},\end{aligned} \tag{5}$$

where α,β (i,j) are the chargino (stop) indices. B_1,C_0,C_{12}, etc., are given in terms of the Passarino-Veltman functions [15] and $\Lambda_{i\alpha}^{L,R}$ are given by

$$\Lambda_{i\alpha}^L=T_{i1}V_{\alpha1}^*-\frac{m_t}{\sqrt{2}M_W\sin\beta}T_{i2}V_{\alpha2}^*, \tag{6}$$

$$\Lambda_{i\alpha}^R=-\frac{m_b}{\sqrt{2}M_W\cos\beta}T_{i1}U_{\alpha2}^*, \tag{7}$$

where $\tan\beta=\langle H_2\rangle/\langle H_1\rangle$ is the ratio of the Higgs vacuum expectation values (VEV's), $O_{\alpha\beta}^{L,R}$ are defined by $O_{\alpha\beta}^L=-\cos^2\theta_W\delta_{\alpha\beta}+\frac{1}{2}U_{\alpha2}^*U_{\beta2}$ and $O_{\alpha\beta}^R=-\cos^2\theta_W\delta_{\alpha\beta}+\frac{1}{2}V_{\alpha2}^*V_{\beta2}$, where $U_{\alpha\beta}$, $V_{\alpha\beta}$ are the matrices that diagonalize the chargino mass matrix and T_{ij} is the matrix that diagonalizes the stop mass^2 matrix: i.e.,

$$\begin{pmatrix} \tilde{t}_2 \\ \tilde{t}_1 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{t}} & \sin\theta_{\tilde{t}} \\ -\sin\theta_{\tilde{t}} & \cos\theta_{\tilde{t}} \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}. \tag{8}$$

To set the stage for the analysis in supergravity unification we discuss first the general features that lead to a large ΔR_b contribution in SUSY models. The maximum contribution to $\Delta R_b^{\rm SUSY}$ comes from the terms involving light masses in Eq. (5). So a large $\Delta R_b^{\rm SUSY}$ will require light $\tilde{\chi}_1^{\pm}$, $\tilde{t}_1$ and specific mixings requiring the stop which is mostly right handed and charginos which have significant Higgsino components. An effect of these constraints is to optimize the contributions of the top Yukawa couplings in the vertices involving the stop loops [3–7]. For low $\tan\beta$ we find $M_{\tilde{\chi}_2^{\pm}} \approx M_{\tilde{\chi}_1^{\pm}}$ [6] which is possible for $M_2 \approx -\mu$, where M_2 is the SU(2) gaugino mass and μ is the Higgs mixing parameter (for an overview of large $\tan\beta$ case see Ref. [6]). Further, Λ_{ij}^L's and $O_{ij}^{L,R}$'s that give large weights to the dominant terms in Eq. (5) lead to a large $\Delta R_b^{\rm SUSY}$. Large weights for the dominant terms require a large Λ_{11}^L (Λ_{12}^L) and a large negative $O_{11}^{L,R}$ $(O_{22}^{L,R})$ implying a large T_{12}, V_{12} (V_{22}) and a small U_{12} (U_{22}) for $\tan\beta<1$ $(\tan\beta>1)$. We find that for $\tan\beta>1$ $\Delta R_b^{\rm SUSY}$ is maximum for $\theta_{\tilde{t}} \simeq -9°$ and a $\tilde{\chi}_2^{\pm}$ which is mixture of a large up Higgsino and a gaugino state $(|V_{22}|>0.9,\ |U_{22}|<0.1)$. Our results are in accord with the analysis of Ref. [6] except for $\theta_{\tilde{t}}^{\rm opt}$ where our value supports the result of Ref. [3]. Our best value of ΔR_b in MSSM then is $\Delta R_b^{\rm SUSY} \leqslant 0.0028$ for $\tan\beta \geqslant 1.16$, comparable with previous determinations [4–7].

Although, as discussed above, one can generate a significant $\Delta R_b^{\rm SUSY}$ correction in MSSM, it is not *a priori* clear what part of the parameter space, if any, which gives large corrections is compatible with the constraints of grand unification and radiative breaking of the electroweak symmetry. This is the issue we address in this work. The analysis we carry out includes radiative breaking of the electroweak symmetry, constraints to avoid color and charge breaking, experimental constraints on the superparticle spectrum, and the $b \to s + \gamma$ experimental constraint as given by the CLEO Collaboration [16]. We also include the constraint arising from the decay $t \to \tilde{t}_1 \tilde{\chi}_i^0$ and assume that the branching ratio of the top decay into stops satisfies $B(t \to \tilde{t}_1 \tilde{\chi}_i^0) < 0.4$. We discuss first the minimal supergravity case which is parametrized by m_0, $m_{1/2}$, A_0, and $\tan\beta$, where m_0 is the universal scalar mass, $m_{1/2}$ is the universal gaugino mass, and A_0 is the universal trilinear coupling. We find that the maximal supersymmetric contribution to R_b is $\Delta R_b^{\rm SUSY} = 0.0002$ over the entire parameter space investigated. Our result is in accord with previous analyses [7] where it was also found that the minimal supergravity grand unification does not produce a significant correction to R_b.

The rest of this work is devoted to a discussion of R_b in supergravity unification with nonuniversal soft SUSY breaking. While the simplest supergravity models are based on universal soft SUSY breaking, the general framework of the theory [8,9] allows for the existence of nonuniversalities via a generational dependent Kähler potential [10]. The nonuniversalities that affect R_b most sensitively are the nonuniversalities in the Higgs sector and in the third-generation sector. For this reason we shall focus in the present analysis on the nonuniversalities in these sectors and assume universality in the remaining sectors. It has recently been shown that the nonuniversalities in the Higgs sector and in the third-generation sector are strongly coupled because of the large top Yukawa coupling [13]. This phenomenon will play an important role in our analysis. It is convenient to parametrize the nonuniversalities in the Higgs sector by $\delta_{H_1}, \delta_{H_2}$ where $m_{H_1}^2(0) = m_0^2(1+\delta_{H_1})$, and $m_{H_2}^2(0) = m_0^2(1+\delta_{H_2})$. Similarly we parametrize the nonuniversalities in the third-generation sector by $\delta_{\tilde{t}_L}$ and $\delta_{\tilde{t}_R}$ where $m_{\tilde{t}_L}^2(0) = m_0^2(1+\delta_{\tilde{t}_L})$, and $m_{\tilde{t}_R}^2(0) = m_0^2(1+\delta_{\tilde{t}_R})$. We also include in the analysis Planck scale corrections which arise via corrections to the gauge kinetic energy, i.e., $-\frac{1}{4} f_{\alpha\beta} F_{\mu\nu}^{\alpha} F^{\beta\mu\nu}$, where $f_{\alpha\beta}$ contains the corrections from the Planck scale. Planck corrections in $f_{\alpha\beta}$ contribute to gauge coupling unification in supergravity grand unified theory (GUT) [14] and also generate corrections to the gaugino masses which can be parametrized by $M_i = (\alpha_i/\alpha_G)[1 + c'(M/M_P)n_i]m_{1/2}$, where M is the GUT mass, M_P is the Planck mass, c' parametrizes the Planck scale correction, and $n_i = (-1,-3,-2)$ [14]. Thus for the nonminimal model we have the set of parameters c', δ_{H_1}, δ_{H_2}, $\delta_{\tilde{t}_L}$, and $\delta_{\tilde{t}_R}$, in addition to the parameters of the minimal model.

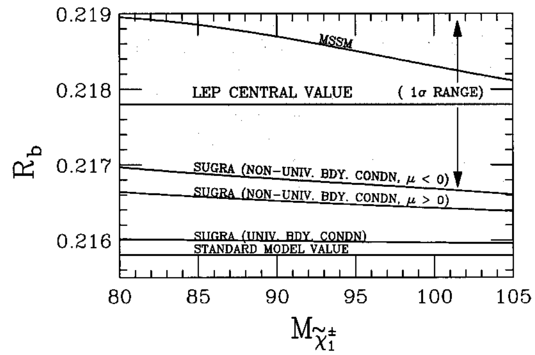

FIG. 1. Maximum R_b for various models as a function of the light $m_{\tilde{\chi}_1^{\pm}}$.

In Fig. 1 we display R_b in the standard model and the maximal R_b that can be achieved in MSSM and supergravity models with universal and nonuniversal boundary conditions. As discussed above the supersymmetric contributions for the universal case are always small, maximally $\Delta R_b^{\rm SUSY} = 0.0002$. However, for the nonuniversal case one can get much larger contributions. Thus for $\mu<0$ the maximal $\Delta R_b^{\rm SUSY}$ is 0.0011, and for $\mu>0$ the maximal $\Delta R_b^{\rm SUSY}$ is 0.0008. As discussed earlier the maximal $\Delta R_b^{\rm SUSY}$ is associated with a relatively light chargino $\tilde{\chi}^{\pm}{}_1$ and a relatively light top squark $\tilde{t}_1$. In Fig. 2 we display the correlation between the light chargino mass and the light top squark mass for the maximal $\Delta R_b^{\rm SUSY}$ for the case $\mu<0$ and a similar analysis holds for the case $\mu>0$. We find that the maximal $\Delta R_b^{\rm SUSY}$ decreases systematically with increasing mass of the light top squark and the light chargino, and one cannot maintain a $\sim 1\sigma$ correction to the SM value with both the

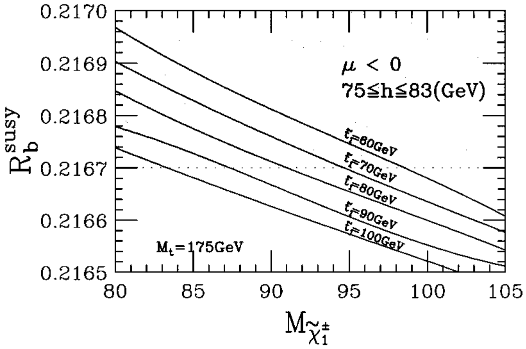

FIG. 2. Maximum R_b as a function of $m_{\tilde{\chi}_1^{\pm}}$ for different $m_{\tilde{t}_1}$ with nonuniversalities.

light top squark and the light chargino above 100 GeV. Thus if the experimental lower limits on the light chargino and the light top squark exceed 100 GeV, then the maximal $\Delta R_b^{\rm SUSY}$ in supergravity grand unification with inclusion of nonuniversalities is not in excess of 0.0006. Further, if both the chargino and the light Higgs boson lie above 100 GeV, then $\Delta R_b^{\rm SUSY}$ reduces to a value similar to what one has in the minimal case.

We have also computed the supersymmetric spectrum in the range where $\Delta R_b^{\rm SUSY}$ is large. We find that for R_b in the supergravity model with nonuniversalities to lie in the LEP 1σ range one must have $80<M_{\chi_1^{\pm}}<105$, $M_h\leqslant 83$, $156<M_{\chi_2^{\pm}}<213$, $60<M_{\tilde{t}_1}<100$, $353<M_{\tilde{t}_2}<470$, $317<M_{\tilde{b}_L}<445$, $58<M_{\chi_1^0}<79$, $156<M_{\chi_2^0}<213$, $152<M_{\chi_3^0}<213$, $114<M_{\chi_4^0}<136$, $434<M_{H^{\pm}}<562$, $430<M_H<558$, and $427<M_A<556$ (all masses are in GeV). We find that in all cases $\delta_{H_2}\sim-\delta_{H_1}=1.15-1.17$ and $\delta_{\tilde{t}_L}\simeq-\delta_{\tilde{t}_R}=0.25-0.35$. The relative signs of the nonuniversalities, i.e., opposite signs for δ_{H_1} and δ_{H_2} and for $\delta_{\tilde{t}_L}$ and $\delta_{\tilde{t}_R}$ can be easily understood by looking at the nonuniversality correction to μ^2 and to the stop masses. The correction to μ^2 is given by [13]

$$\Delta\mu^2=m_0(t^2-1)^{-1}\left[\delta_{H_1}-\left(\delta_{H_2}+\frac{D_0-1}{2}\delta\right)t^2\right],$$

where $t=\tan\beta,\delta=\delta_{H_2}+\delta_{\tilde{t}_L}+\delta_{\tilde{t}_R}$, and D_0 is defined by $D_0=1-m_t^2/m_f^2$ where m_t is the top mass and $m_f\simeq 200\sin\beta$ GeV. For $m_t=175$ GeV, $M_G=10^{16.2}$ GeV, one has $D_0=0.27$. One finds then that a $\delta_{H_1}<0$ and a $\delta_{H_2}>0$ gives a negative contribution to μ^2 and makes $|\mu|$ small, which is what is needed to obtain a large $\Delta R_b^{\rm SUSY}$. The corrections to $m_{\tilde{t}_L}^2$ and $m_{\tilde{t}_R}^2$ are given by [13] $\Delta m_{\tilde{t}_L}^2=m_0^2\{\delta_{\tilde{t}_L}+[(D_0-1)/6]\delta\}$, and $\Delta m_{\tilde{t}_R}^2=m_0^2\{\delta_{\tilde{t}_R}+[(D_0-1)/3]\delta\}$. Here for values of δ_{H_2}, $\delta_{\tilde{t}_L}$, and $\delta_{\tilde{t}_R}$ indicated, e.g., for $\delta_{H_2}=1.15$, $\delta_{\tilde{t}_L}=-\delta_{t_R}=0.25$, one finds $\Delta m_{\tilde{t}_L}^2=0.11m_0^2$ and $\Delta m_{\tilde{t}_R}^2=-0.53\ m_0^2$. Since $\tilde{t}_1\approx\tilde{t}_R$, one finds then that the sign of the nonuniversalities is such as to split the $\tilde{t}_1-\tilde{t}_2$ masses, making $\tilde{t}_1$ lighter and $\tilde{t}_2$ heavier. This effect enhances the value of R_b. The analysis shows that most of the corrections to R_b come from the nonuniversalities in the scalar sector, and c' is seen not to play a significant role, i.e., the effect of c' on $\Delta R_b^{\rm SUSY}$ is less than 5%. This is not unexpected as one is in a region where the Higgsino contributions are dominant. Numerical results for $m_t=175$ GeV are summarized in Table I. We note that the upper limit of $R_b^{\rm SUSY}\leqslant 0.0011$ in the nonuniversal case is mostly due to the fact that one needs a high value of $\tan\beta$ to obtain low values of $M_{\tilde{t}_1},\mu$, and $M_{\tilde{\chi}_1^{\pm}}$ using radiative breaking.

TABLE I. Maximal $\Delta R_b^{\rm SUSY}$ in models versus experiment. The last four entries are from this analysis. For other determinations of $\Delta R_b^{\rm SUSY}$ in MSSM see Refs. [4,5,7].

Quantity	Numerical values
$R_b^{\rm expt}-R_b^{\rm SM}$	$0.0019\pm\ 0.0011$
$\Delta R_b^{\rm SUSY(max)}$ (MSSM)	0.0022 (Ref. [5])
$\Delta R_b^{\rm SUSY(max)}$ (MSSM)	0.0028
$\Delta R_b^{\rm SUSY(max)}$ (minimal SUGRA)	0.0002
$\Delta R_b^{\rm SUSY(max)}$ (nonuniv. SUGRA)	0.0011 ($\mu<0$)
$\Delta R_b^{\rm SUSY(max)}$ (nonuniv. SUGRA)	0.0008 ($\mu>0$)

Prediction of the sparticle spectrum in the nonuniversal supergravity model depends on the size of $\Delta R_b^{\rm SUSY}$ one assumes. If one requires a sizable $\Delta R_b^{\rm SUSY}$ correction, which we take here to imply a correction greater than 0.0006, i.e., greater than $\sim\frac{1}{2}\sigma$, then for both signs of μ the light Higgs boson will have a mass below 93 GeV, the light chargino and the light top squark will have masses around or below 100 GeV, and the gluino mass will lie below 450 GeV (525 GeV) for $\mu<0$ ($\mu>0$). Thus the entire range of the light chargino and the light stop masses will be fully accessible at the Tevatron in the Main Injector era. Since the light Higgs lies below 93 GeV in this case, it must be visible at LEP II if it achieves its optimum energy of $\sqrt{s}=192$ GeV and an integrated luminosity of 500 pb^{-1} or at TeV33 with 5–10 fb^{-1} of integrated luminosity [17]. Regarding the gluino essentially the entire gluino mass range for $\mu<0$ and the range up to 450 GeV for $\mu>0$ could be probed at TeV33 with an integrated luminosity of 100 fb^{-1} [17]. Thus the supergravity model with $\Delta R_b^{\rm SUSY}>0.0006$ can be completely tested in the Higgs boson, chargino and stop sectors for both signs of μ at LEP II and at TeV33. It can also be completely (partially) tested in the gluino sector for $\mu<0$ ($\mu>0$) at TeV33. If no SUSY particles are seen in the mass ranges indicated, then $\Delta R_b^{\rm SUSY}$ must lie below the level of 0.0006, i.e., below $\sim\frac{1}{2}\sigma$.

In this work we have given the first analysis of the maximal R_b that can be gotten in supergravity unification with nonuniversal boundary conditions on the soft SUSY breaking parameters. We find maximal $\Delta R_b^{\rm SUSY}\simeq 1\sigma$ (0.8σ) for $\mu<0$ (>0) which is significantly smaller than the maximum value one can get in MSSM but significantly larger than the maximum value achievable in minimal supergravity unification. Thus values of $\Delta R_b^{\rm SUSY}$ in MSSM in excess of 0.0011 (0.0008) for $\mu<0$ ($\mu>0$) are in conflict with the twin constraints of grand unification and radiative breaking of the electroweak symmetry. The ΔR_b supergravity correction gives a correction to the LEP value of α_s of $\Delta\alpha_s = -4\Delta R_b$ which amounts to a maximal correction of $\Delta\alpha_s = -0.0044$ (-0.0032) for $\mu < 0$ $(\mu > 0)$. Recalling the discrepancy between the LEP value of α_s and the DIS value of α_s [18,19], one finds that supergravity unification with nonuniversal soft SUSY breaking can bridge the gap maximally only half way between the LEP value of α_s (0.123 ± 0.006) and the DIS value of α_s (0.116 ± 0.005) [19]. The analysis makes several predictions on the sparticle spectra which can be tested at colliders in the near future. The analysis on maximal $\Delta R_b^{\mathrm{SUSY}}$ presented here is also applicable to the class of string models which have the SM gauge group and no extra generations below the GUT scale.

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