New precision electroweak tests of SU(5)×U(1) supergravity

Jorge L. Lopez,[1,2] D. V. Nanopoulos,[1-3] Gye T. Park,[1,2] and A. Zichichi[4]
[1]Center for Theoretical Physics, Department of Physics, Texas A&M University, College Station, Texas 77843-4242
[2]Astroparticle Physics Group, Houston Advanced Research Center (HARC), The Mitchell Campus, The Woodlands, Texas 77381
[3]CERN, Theory Division, 1211 Geneva 23, Switzerland
[4]CERN, 1211 Geneva 23, Switzerland
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We explore the one-loop electroweak radiative corrections in SU(5)×U(1) supergravity via explicit calculation of vacuum-polarization and vertex-correction contributions to the ϵ_1 and ϵ_b parameters. Experimentally, these parameters are obtained from a global fit to the set of observables Γ_l, Γ_b, A^l_{FB}, and M_W/M_Z. We include q^2-dependent effects, which induce a large systematic negative shift on ϵ_1 for light chargino masses ($m_{\chi^\pm_1} \lesssim 70$ GeV). The (nonoblique) supersymmetric vertex corrections to $Z \to b\bar{b}$, which define the ϵ_b parameter, show a significant positive shift for light chargino masses, which for $\tan\beta \approx 2$ can be nearly compensated by a negative shift from the charged Higgs contribution. We conclude that, at the 90% C.L., for $m_t \lesssim 160$ GeV the present experimental values of ϵ_1 and ϵ_b do not constrain in any way SU(5)×U(1) supergravity in both no-scale and dilaton scenarios. On the other hand, for $m_t \gtrsim 160$ GeV the constraints on the parameter space become increasingly more strict. We demonstrate this trend with a study of the $m_t = 170$ GeV case, where only a small region of parameter space, with $\tan\beta \gtrsim 4$, remains allowed and corresponds to light chargino masses ($m_{\chi^\pm_1} \lesssim 70$ GeV). Thus SU(5)×U(1) supergravity combined with high-precision CERN LEP data would suggest the presence of light charginos if the top quark is not detected at the Fermilab Tevatron.

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I. INTRODUCTION

Since the advent of the CERN e^+e^- collider LEP, precision electroweak tests have become rather deep probes of the standard model of electroweak interactions and its challengers. These tests have demonstrated the internal consistency of the standard model, as long as the yet-to-be-measured top-quark mass (m_t) is within certain limits, which depend on the value assumed for the Higgs-boson mass (m_H): $m_t = 135 \pm 18$ GeV for $m_H \sim 60$ GeV and $m_t = 174 \pm 15$ GeV for $m_H \sim 1$ TeV (for a recent review see, e.g., Ref. [1]). In the context of supersymmetry, such tests have been performed throughout the years within the minimal supersymmetric standard model (MSSM) [2–5]. The problem with such calculations is well known but usually ignored—there are too many parameters in the MSSM (at least twenty)—and therefore it is not possible to obtain precise predictions for the observables of interest.

In the context of supergravity models, on the other hand, any observable can be computed in terms of at most five parameters: the top-quark mass, the ratio of Higgs vacuum expectation values ($\tan\beta$), and three universal soft-supersymmetry-breaking parameters ($m_{1/2}$, m_0, A) [6]. This implies much sharper predictions for the various quantities of interest, as well as numerous correlations among them. Of even more experimental interest is SU(5)×U(1) supergravity where string-inspired *Ansätze* for the soft-supersymmetry-breaking parameters allow the theory to be described in terms of only three parameters: m_t, $\tan\beta$, and $m_{\tilde{g}}$ [7]. Precision electroweak tests in the no-scale [8] and dilaton [9] scenarios for SU(5)×U(1) supergravity have been performed in Refs. [10,11], using the description in terms of the $\epsilon_{1,2,3}$ parameters introduced in Refs. [12,13]. In this paper we extend these tests in two ways: first, we include for the first time the ϵ_b parameter [4] which encodes the one-loop corrections to the $Z \to b\bar{b}$ vertex, and second, we perform the calculation of the ϵ_1 parameter in a new scheme [4], which takes full advantage of the latest experimental data.

The calculation of ϵ_b is of particular importance, since in the standard model, of the four parameters $\epsilon_{1,2,3,b}$ at present only ϵ_b falls outside the 1σ experimental error (for $m_t > 120$ GeV [4,14]). This discrepancy is not of great statistical significance, although the trend should not be overlooked, especially in the light of the much better statistical agreement for the other three parameters. Within the context of the standard model, another reason for focusing attention on the ϵ_b parameter is that, unlike the ϵ_1 parameter, ϵ_b provides a constraint on the top-quark mass which is *practically independent* of the Higgs-boson mass. Indeed, at the 95% C.L., the limits on ϵ_b require $m_t < 185$ GeV, whereas those from ϵ_1 require $m_t < 177-198$ GeV for $m_H \sim 100-1000$ GeV [14].

In supersymmetric models, the weakening of the ϵ_1-deduced m_t upper bound for large Higgs-boson masses does not occur (since the Higgs boson must be light) and both ϵ_1 and ϵ_b are expected to yield comparable constraints. In this context, it has been pointed out [5] that if certain mass correlations in the MSSM are satisfied, then the prediction for ϵ_b will be in better agreement with the data than the standard model prediction is. However, the opposite situation could also occur (i.e., worse agreement), as well as negligible change relative to the standard model prediction (when all supersymmetric particles are heavy enough). We show that this three-way ambiguity in the MSSM prediction for ϵ_b disappears when one considers SU(5)×U(1) supergravity in both no-scale and dilaton scenarios. The SU(5)×U(1) supergravity prediction is practically always in better statistical agreement with the data (compared with the standard model one).

This study shows that at the 90% C.L., for $m_t \lesssim 160$ GeV the present experimental values of ϵ_1 and ϵ_b do not constrain SU(5)×U(1) supergravity in any way. On the other hand, for $m_t \gtrsim 160$ GeV the constraints on the parameter space become increasingly more strict. We demonstrate this trend with a study of the $m_t = 170$ GeV case, where only a small region of parameter space, with $\tan\beta \gtrsim 4$, remains allowed and corresponds to a light supersymmetric spectrum, and in particular light chargino masses ($m_{\chi_1^\pm} \lesssim 70$ GeV). Thus SU(5)×U(1) supergravity combined with high-precision LEP data would suggest the presence of light charginos if the top quark is not detected at the Fermilab Tevatron.

II. SU(5)×U(1) SUPERGRAVITY

Our study of one-loop electroweak radiative corrections is performed within the context of SU(5)×U(1) supergravity [7]. In addition to the several theoretical string-inspired motivations that underlie this theory, of great practical importance is the fact that only three parameters are needed to describe all their possible predictions. This fact has been used in the recent past to perform a series of calculations for collider [15,16] and rare [17,10,11] processes within this theory. The constraints obtained from all these analyses should help sharpen even more the experimental predictions for the remaining allowed points in parameter space.

In SU(5)×U(1) supergravity, gauge coupling unification occurs at the string scale $\underline{10}^{18}$ GeV [7], because of the presence of a pair of $\mathbf{10}, \overline{\mathbf{10}}$ representations with intermediate-scale masses. The three parameters alluded to above are: (i) the top-quark mass (m_t), (ii) the ratio of Higgs vacuum expectation values ($\tan\beta$), which satisfies $1 \lesssim \tan\beta \lesssim 40$, and (iii) the gluino mass, which is cut off at 1 TeV. This simplification in the number of input parameters is possible because of specific string-inspired scenarios for the universal soft-supersymmetry-breaking parameters $(m_0, m_{1/2}, A)$ at the unification scale. These three parameters can be computed in specific string models in terms of just one of them [18]. In the *no-scale* scenario one obtains $m_0 = A = 0$, whereas in the *dilaton* scenario the result is $m_0 = (1/\sqrt{3}) m_{1/2}$, $A = -m_{1/2}$. After running the renormalization group equations from high to low energies, at the low-energy scale the requirement of radiative electroweak symmetry breaking introduces two further constraints which determine the magnitude of the Higgs mixing term μ, although its sign remains undetermined. Finally, all the known phenomenological constraints on the sparticle masses are imposed (most importantly, the chargino, slepton, and Higgs-boson mass bounds). This procedure is well documented in the literature [19] and yields the allowed parameter spaces for the no-scale [8] and dilaton [9] scenarios.

TABLE I. The approximate proportionality coefficients to the gluino mass for the various sparticle masses in the two supersymmetry-breaking scenarios considered.

	No scale	Dilaton
$\tilde{e}_R, \tilde{\mu}_R$	0.18	0.33
$\tilde{\nu}$	0.18–0.30	0.33–0.41
$2\chi_1^0, \chi_2^0, \chi_1^\pm$	0.28	0.28
$\tilde{e}_L, \tilde{\mu}_L$	0.30	0.41
$\tilde{q}$	0.97	1.01
$\tilde{g}$	1.00	1.00

These allowed parameter spaces in the three defining variables $(m_t, \tan\beta, m_{\tilde{g}})$ consist of a discrete set of points for three values of m_t ($m_t = 130, 150, 170$ GeV), and a discrete set of allowed values for $\tan\beta$, starting at 2 and running (in steps of two) up to 32 (46) for the no-scale (dilaton) scenario. The chosen lower bound on $\tan\beta$ follows from the requirement by the radiative breaking mechanism of $\tan\beta > 1$, and because the LEP lower bound on the lightest Higgs-boson mass ($m_h \gtrsim 60$ GeV [16]) is quite constraining for $1 < \tan\beta < 2$.

In the models we consider all sparticle masses scale with the gluino mass, with a mild $\tan\beta$ dependence (except for the third-generation squark and slepton masses). In Table I we give the approximate proportionality coefficient (to the gluino mass) for each sparticle mass. Note that the relation $2m_{\chi_1^0} \approx m_{\chi_2^0} \approx m_{\chi_1^\pm}$ holds to good approximation. The third-generation squark and slepton masses also scale with $m_{\tilde{g}}$, but the relationships are smeared by a strong $\tan\beta$ dependence. From Table I one can (approximately) translate any bounds on a given sparticle mass on bounds on all the other sparticle masses.

III. ONE-LOOP ELECTROWEAK RADIATIVE CORRECTIONS AND THE NEW ϵ PARAMETERS

There are different schemes to parametrize the electroweak (EW) vacuum polarization corrections [20–22,12]. It can be shown, by expanding the vacuum polarization tensors to order q^2, that one obtains three independent physical parameters. Alternatively, one can show that upon symmetry breaking three additional terms appear in the effective Lagrangian [22]. In the (S,T,U) scheme [21], the deviations of the model predictions from the SM predictions (with fixed SM values for $m_t, m_{H_{\rm SM}}$) are considered as the effects from "new physics." This scheme is only valid to the lowest order in q^2, and is therefore not applicable to a theory with new, light ($\sim M_Z$) particles. In the ϵ scheme [13,4], on the other hand, the model predictions are absolute and also valid up to higher orders in q^2, and therefore this scheme is more applicable to the EW precision tests of the MSSM

[3] and a class of supergravity models [10].

There are two different ϵ schemes. The original scheme [13] was considered in our previous analyses [10,11], where $\epsilon_{1,2,3}$ are defined from a basic set of observables Γ_l, $A^l_{\rm FB}$ and M_W/M_Z. Because of the large m_t-dependent vertex corrections to Γ_b, the $\epsilon_{1,2,3}$ parameters and Γ_b can be correlated only for a fixed value of m_t. Therefore, $\Gamma_{\rm tot}$, $\Gamma_{\rm hadron}$, and Γ_b were not included in Ref. [13]. However, in the new ϵ scheme, introduced recently in Ref. [4], the above difficulties are overcome by introducing a new parameter ϵ_b to encode the $Z\to b\bar{b}$ vertex corrections. The four ϵ's are now defined from an enlarged set of Γ_l, Γ_b, $A^l_{\rm FB}$, and M_W/M_Z without even specifying m_t. In this work we use this new ϵ scheme. Experimentally, including all LEP data allows one to determine the allowed ranges for these parameters [1]:

$$\epsilon_1^{\rm expt}=(-0.3\pm3.2)\times10^{-3}\ ,\quad \epsilon_b^{\rm expt}=(3.1\pm5.5)\times10^{-3}\ . \tag{1}$$

Since among $\epsilon_{1,2,3}$ only ϵ_1 provides constraints in supersymmetric models at the 90% C.L. [10,5], we discuss below only ϵ_1 and ϵ_b.

The expression for ϵ_1 is given as [3]

$$\epsilon_1=e_1-e_5-\frac{\delta G_{V,B}}{G}-4\delta g_A\ , \tag{2}$$

where $e_{1,5}$ are the combinations of vacuum polarization amplitudes,

$$e_1=\frac{\alpha}{4\pi\sin^2\theta_W M_W^2}[\Pi_T^{33}(0)-\Pi_T^{11}(0)]\ , \tag{3}$$

$$e_5=M_Z^2F'_{ZZ}(M_Z^2)\ , \tag{4}$$

and the $q^2\neq0$ contributions $F_{ij}(q^2)$ are defined by

$$\Pi_T^{ij}(q^2)=\Pi_T^{ij}(0)+q^2F_{ij}(q^2)\ . \tag{5}$$

The δg_A in Eq. (2) is the contribution to the axial-vector form factor at $q^2=M_Z^2$ in the $Z\to l^+l^-$ vertex from proper vertex diagrams and fermion self-energies, and

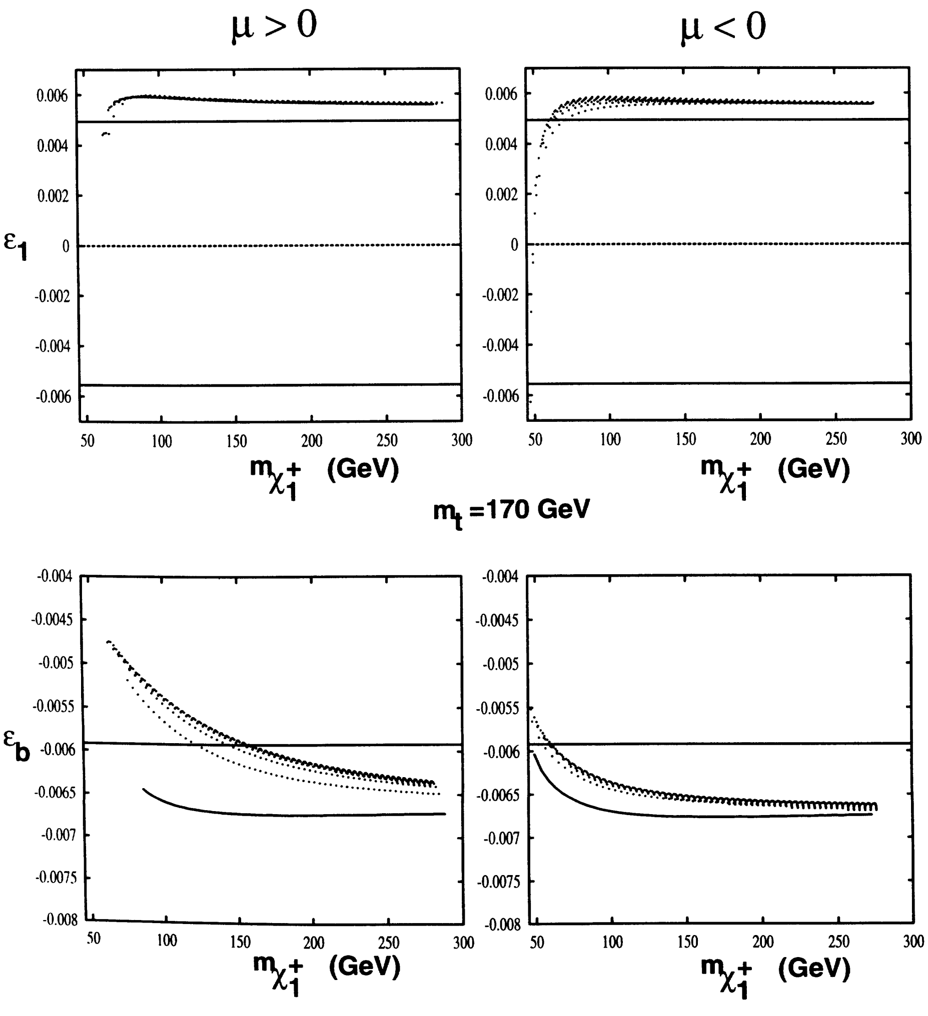

FIG 1. The predictions for the ϵ_1 (top row) and ϵ_b (bottom row) parameters versus the chargino mass in the no scale SU(5)×U(1) supergravity scenario for $m_t=170$ GeV. In the top (bottom) row, points between (above) the horizontal line(s) are allowed at the 90% C.L. The solid curve (bottom row) represents the $\tan\beta=2$ line.

$\delta G_{V,B}$ comes from the one-loop box, vertex, and fermion self-energy corrections to the μ-decay amplitude at zero external momentum. These nonoblique SM corrections are non-negligible, and must be included in order to obtain an accurate SM prediction. As is well known, the SM contribution to ϵ_1 depends quadratically on m_t but only logarithmically on the SM Higgs-boson mass (m_H). In this fashion upper bounds on m_t can be obtained which have a non-negligible m_H dependence: up to 20 GeV stronger when going from a heavy (≈ 1 TeV) to a light (≈ 100 GeV) Higgs boson. It is also known (in the MSSM) that the largest supersymmetric contributions to ϵ_1 are expected to arise from the $\tilde{t}$-$\tilde{b}$ sector, and in the limiting case of a very light top squark, the contribution is comparable to that of the t-b sector. The remaining squark, slepton, chargino, neutralino, and Higgs sectors all typically contribute considerably less. For increasing sparticle masses, the heavy sector of the theory decouples, and only SM effects with a *light* Higgs boson survive. (This entails stricter upper bounds on m_t than in the SM, since there the Higgs boson does not need to be light.) However, for a light chargino ($m_{\chi_1^\pm} \to \frac{1}{2}M_Z$), a Z-wave-function renormalization threshold effect can introduce a substantial q^2-dependence in the calculation, i.e., the presence of e_5 in Eq. (2) [3]. The complete vacuum polarization contributions from the Higgs sector, the supersymmetric chargino-neutralino and sfermion sectors, and also the corresponding contributions in the SM have been included in our calculations [10].

Following Ref. [4], ϵ_b is defined from Γ_b, the inclusive partial width for $Z \to b\bar{b}$, as

$$\Gamma_b = 3R_{\rm QCD}\frac{G_F M_Z^3}{6\pi\sqrt{2}}\left[1+\frac{\alpha}{12\pi}\right] \times \left[\beta_b \frac{3-\beta_b^2}{2}(g_V^b)^2 + \beta_b^3 (g_A^b)^2\right], \tag{6}$$

with

$$R_{\rm QCD} \cong \left[1 + 1.2\frac{\alpha_S(M_Z)}{\pi} - 1.1\left[\frac{\alpha_S(M_Z)}{\pi}\right]^2 - 12.8\left[\frac{\alpha_S(M_Z)}{\pi}\right]^3\right], \tag{7}$$

$$\beta_b = \left[1 - \frac{4m_b^2}{M_Z^2}\right]^{1/2}, \tag{8}$$

$$g_A^b = -\frac{1}{2}\left[1+\frac{\epsilon_1}{2}\right](1+\epsilon_b), \tag{9}$$

$$\frac{g_V^b}{g_A^b} = \frac{1 - \frac{4}{3}\bar{s}_W^2 + \epsilon_b}{1+\epsilon_b}. \tag{10}$$

Here $\bar{s}_W^2$ is an effective $\sin^2\theta_W$ for on-shell Z, and ϵ_b is closely related to the real part of the vertex correction to $Z \to b\bar{b}$, denoted in the literature by ∇_b and defined explicitly in Ref. [23]. In the SM, the diagrams for ∇_b involve top quarks and $W^\pm$ bosons [24], and the contribution to ϵ_b depends quadratically on m_t. In supersymmetric models there are additional diagrams involving Higgs bosons and supersymmetric particles. The charged Higgs contributions have been calculated in Refs. [25–27] in the context of a nonsupersymmetric two Higgs doublet model, and the contributions involving supersymmetric particles in Refs. [23,28]. Moreover, ϵ_b itself has been calculated in Ref. [27]. The additional supersymmetric contributions are: (i) a negative contribution from charged-Higgs-boson–top-quark exchange which grows as $m_t^2/\tan^2\beta$ for $\tan\beta \ll m_t/m_b$; (ii) a positive contribution from chargino–top-squark exchange which in this case grows as $m_t^2/\sin^2\beta$; and (iii) a contribution from neutralino(neutral-Higgs-boson)–bottom-quark exchange which grows as $m_b^2\tan^2\beta$ and is negligible ex-

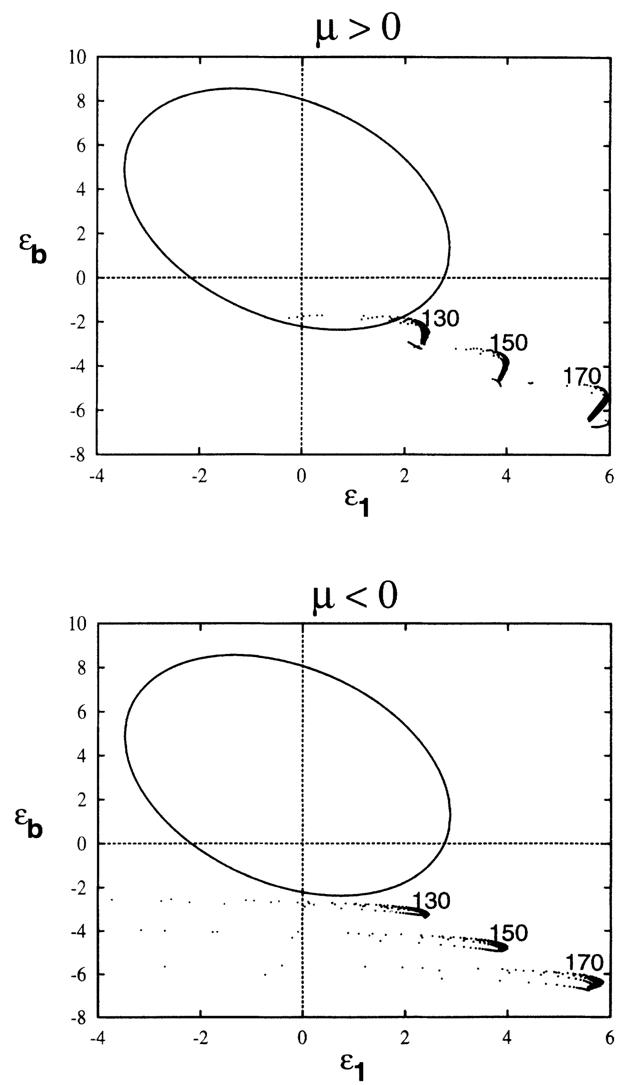

FIG. 2. The correlated predictions for the ϵ_1 and ϵ_b parameters in units of 10^{-3} in the no scale SU(5)×U(1) supergravity scenario. The ellipse represents the 1σ contour obtained from all LEP data. The values of m_t are as indicated.

cept for large values of $\tan\beta$ (i.e., $\tan\beta \gtrsim m_t/m_b$) [the contribution (iii) has been neglected in our analysis].

IV. RESULTS AND DISCUSSION

In Figs. 1–4 we show the results of the calculation of ϵ_1 and ϵ_b (as described above) for all the allowed points in SU(5)×U(1) supergravity in both no-scale and dilaton scenarios. Since all sparticle masses nearly scale with the gluino mass (or the chargino mass), it suffices to show the dependences of these parameters on, for example, the chargino mass. Table I can be used to deduce the dependences on any of the other masses. We only show the explicit dependence on the chargino mass (in Figs. 1 and 3) for the case $m_t = 170$ GeV, since for $m_t = 130$, 150 GeV there are no constraints at the 90% C.L. However, in the correlated (ϵ_1, ϵ_b) plots (Figs. 2 and 4) we show the results for all three values of m_t.

The qualitative results for ϵ_1 are similar to those obtained in Refs. [10,11] using the old definition of ϵ_1. That is, for light chargino masses there is a large negative shift due to a threshold effect in the Z-wave-function renormalization for $m_{\chi_1^\pm} \to \frac{1}{2} M_Z$ (as first noticed in Ref. [3]). As soon as the sparticle masses exceed ~ 100 GeV the result quickly asymptotes to the standard model value for a light Higgs-boson mass ($\lesssim 100$ GeV). Quantitatively, the enlarged set of observables in the new ϵ scheme shifts the experimentally allowed range somewhat, and the bounds become slightly weaker than in Refs. [10,11]. These remarks apply to both no-scale and dilaton scenarios.

In the case of ϵ_b, the results also asymptote to the standard model values for large sparticle masses as they should. Two competing effects are seen to occur: (i) a positive shift for light chargino masses, and (ii) a negative shift for light charged-Higgs-boson masses and small values of $\tan\beta$. In fact, the latter effect becomes evident in Figs. 1 and 3 (bottom rows) as the solid curve corresponding to $\tan\beta = 2$. What happens here is that the charged Higgs contribution nearly cancels the chargino contribution [23], making ϵ_b asymptote much faster to the SM value.

We also notice from Fig. 3 (bottom row) that there are lines of points far below the solid curve corresponding to $\tan\beta = 2$ in the dilaton scenario. These correspond to

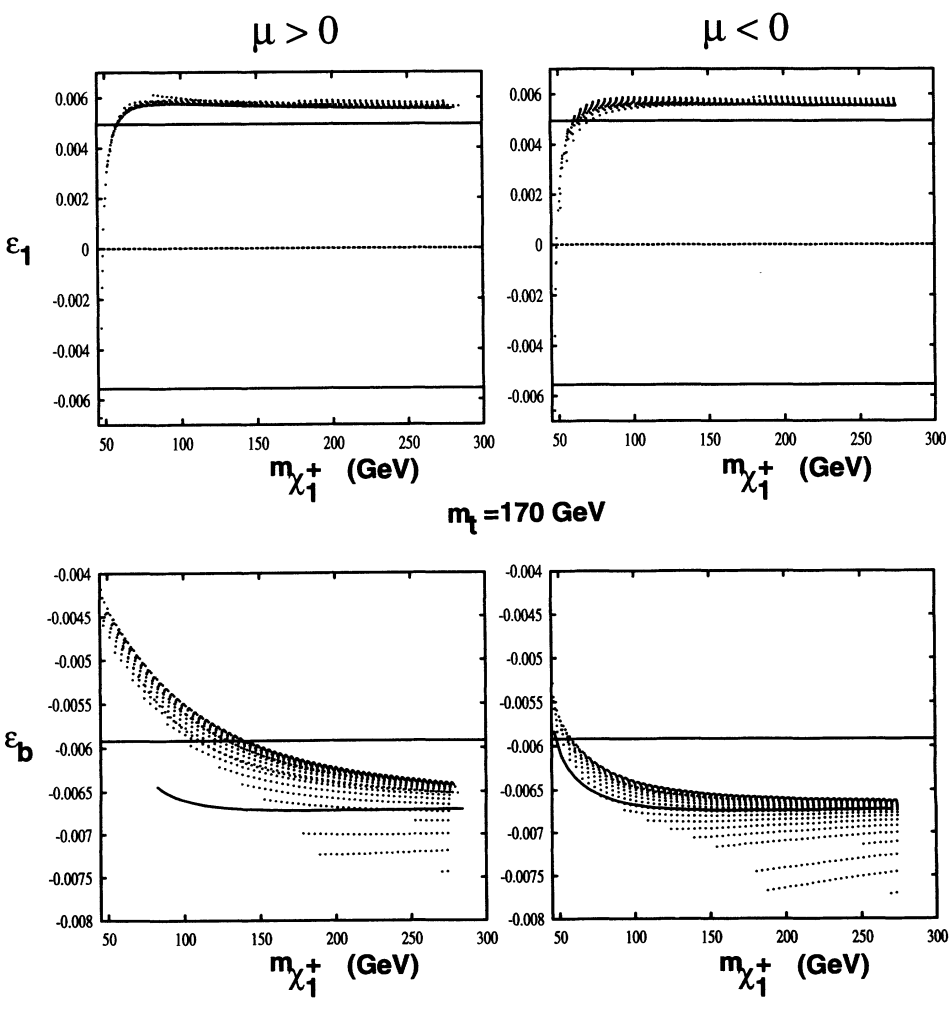

FIG. 3. The predictions for the ϵ_1 (top row) and ϵ_b (bottom row) parameters versus the chargino mass in dilaton SU(5)×U(1) supergravity scenario for $m_t = 170$ GeV. In the top (bottom row), points between (above) the horizontal line(s) are allowed at the 90% C.L. The solid curve (bottom row) represents the $\tan\beta = 2$ line.

large $\tan\beta$ ($\gtrsim m_t/m_b$) for which the charged Higgs diagram gets a significant contribution $\sim m_b^2\tan^2\beta$ coming from the charged Higgs coupling to b_R. Such large values of $\tan\beta$ are not allowed in the no-scale scenario. It must be emphasized that for such large values of $\tan\beta$, the neglected neutralino–neutral-Higgs-boson diagrams will also become significant [23], and since especially neutralino diagrams give a positive contribution, their effect could compensate the large negative charged Higgs contributions.

For $m_t = 170$ GeV at the 90% C.L., one can safely exclude values of $\tan\beta \lesssim 2$ in the no-scale and dilaton (except for just one point for $\mu < 0$) scenarios. Moreover, as Figs. 1 and 3 show, there are excluded points for all values of $\tan\beta$. In the dilaton scenario, large values of $\tan\beta$ (i.e., $\tan\beta \gtrsim 32$ for $\mu > 0$ and $\tan\beta \gtrsim 24$ for $\mu < 0$) are also constrained, and even perhaps excluded in the neutralino– neutral-Higgs-boson contributions are not large enough to compensate for these values.

It is seen that for light chargino masses and not too small values of $\tan\beta$, the fit to the ϵ_b data is better in SU(5)×U(1) supergravity than in the standard model, although only marginally so. To see the combined effect of $\epsilon_{1,b}$ for increasing values of m_t, in Figs. 2 and 4 we show the calculated values of these parameters for $m_t = 130, 150, 170$ GeV, as well as the 1σ experimental ellipse (from Ref. [5]). Clearly smaller values of m_t fit the data better.

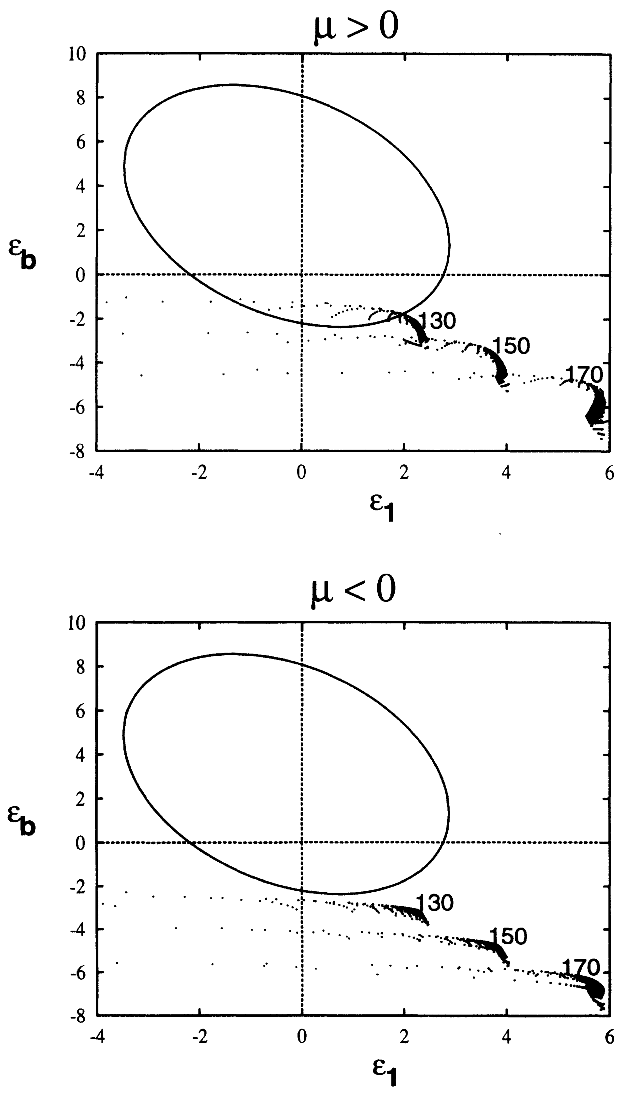

FIG. 4. The correlated predictions for the ϵ_1 and ϵ_b parameters in units of 10^{-3} in the dilaton SU(5)×U(1) supergravity scenario. The ellipse represents the 1σ contour obtained from all LEP data. The values of m_t are as indicated.

V. CONCLUSIONS

We have computed the one-loop electroweak corrections in the form of the ϵ_1 and ϵ_b parameters in the context of SU(5)×U(1) supergravity in both no-scale and dilaton scenarios. The new ϵ scheme used allows us to include in the experimental constraints all of the LEP data. In addition, the minimality of parameters in SU(5)×U(1) supergravity is such that rather precise predictions can be made for these observables, and this entails strict constraints on the parameter spaces of the two scenarios considered.

In agreement with our previous analysis, we find that for $m_t \lesssim 160$ GeV, at the 90% C.L. these constraints are not restricting at present. However, their quadratic dependence on m_t makes them quite severe for increasingly large values of m_t. We have studied explicitly the case of $m_t = 170$ GeV and shown that most points in parameter space are excluded. The exceptions occur for light chargino masses which shift ϵ_1 down and ϵ_b up. However, for $\tan\beta \lesssim 2$ the ϵ_b constraint is so strong that no points are allowed in the no-scale scenario.

In the near future, improved experimental sensitivity on the ϵ_b parameter is likely to be a decisive test of SU(5)×U(1) supergravity. In any rate, the trend is clear: lighter values of the top-quark mass fit the data much better than heavier ones do. In addition, supersymmetry seems to always help in this statistical agreement. Finally, if the top quark continues to remain undetected at the Tevatron, high-precision LEP data in the context of SU(5)×U(1) supergravity would suggest the presence of light charginos.

Note added in proof. Since the completion of this paper new LEP data have been released which shift the central values in Eq. (1) such that the 1σ ellipses in Figs. 2 and 4 now encompass all points for $m_t = 130$ and 150 GeV. See Ref. [29] for an updated analysis.

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