Implications for Supersymmetry of the Reported Deviations from the Standard Model for $\Gamma(Z \to b\overline{b})$ and $\alpha_s(m_Z^2)$

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If the reported excess (over the standard model prediction) for $Z \to b\overline{b}$ from LEP persists, and is explained by supersymmetric particles in loops, then we show that (1) a superpartner (chargino and/or stop) will be detected at LEP2, and probably at intermediate energy upgrades, (2) the basic parameter $\tan\beta$ is at its lower perturbative limit, (3) $\mathrm{BR}(t \to \tilde{t}_1 + \tilde{\chi}^0)$ is at or above 0.4, (4) the upper limit on m_h is considerably reduced, and (5) several important consequences arise for the form of a unified supersymmetric theory. Our analysis is done in terms of a general weak scale Lagrangian and does not depend on assumptions about SUSY breaking.

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For a year or so evidence has been getting stronger for two deviations from the standard model. One is an excess of about $(2.1 \pm 0.7)\%$ in the Z decays to $b\overline{b}$ (using the value reported [1] when the charm quark width is fixed at its standard model value, for reasons explained below) denoted by R_b, and the second that the $\alpha_s(m_Z^2)$ measured from the Z linewidth at CERN LEP differs from that determined other ways [2]. For the first, the effect is even larger [1] if one uses constrained data $[(2.73 \pm 0.79)\%]$. Also, these numbers are for $m_t = 170$ GeV; the deviation between theory and experiment increases as m_t^2 if one uses larger m_t. Experimentally these are logically independent deviations—for example, if the excess $b\overline{b}$ were due to including charm decays in the b sample, there would be no effect on $\alpha_s(m_Z^2)$ since the total hadronic width would be unchanged. Theoretically they are also logically independent. For example, if the predicted α_s in a model were lowered by high scale threshold effects or intermediate scale matter multiplets, there would be no necessary increase in R_b. If these are true deviations, they are the long-awaited clues to physics beyond the standard model.

From a supersymmetric view these two deviations are natural and expected. The standard model value for R_b is the tree value minus about a 2% effect from the t-W^+ loop (proportional to m_t^2). The corresponding supersymmetric (SUSY) stop-chargino loop naturally has the opposite sign of the t-W^+ loop, and approximately cancels it if the stop and chargino are light enough. Further, if the excess Z decays are due to a new mechanism such as a stop-chargino loop, then this contribution must be included when the increase in the Z width is used to determine α_s; when that is done the α_s deviation also goes away, and α_s from the Z linewidth decreases to about 0.112, consistent with its determination other ways [2–4]. Thus the existence of the α_s deviation considerably strengthens one's confidence that both deviations are real, and also that the SUSY explanation is perhaps correct. It has been confirmed with global fits to all the precision data [3,4] that including the SUSY contributions does not lead to disagreement with any observable, and indeed that SUSY gives a better global fit to the data than the standard model.

In this paper we argue that if the R_b deviation is indeed real, then several consequences follow. (1) Most important, stop and chargino must be light enough to be detected when the energy of LEP is increased to over 140 GeV, as expected during 1995, if sufficient luminosity is obtained (over about 5 pb^{-1}). To put it differently, if a stop or chargino is not found, then either the R_b excess will go away, or if it persists the SUSY explanation is not relevant and there are different effects that change R_b. (2) By combining the R_b effects with other data we can show that R_b can be explained in SUSY only if $\tan\beta$ is of order 1. Earlier arguments [4–6] that perhaps large $\tan\beta$ and an $A - h$ loop with small m_A could also explain R_b can be excluded. (3) Since the stop is lighter than the top, there will be a decay of top to stop plus the lightest superpartner (LSP). We show the branching ratio for this decay must be large, about 0.4. (4) The upper limit on m_h decreases considerably, making its detection at LEP and/or Fermilab more probable.

All of this analysis is essentially model and parameter independent. While many of the relevant quantities depend on masses and couplings, we vary them over all values allowed by constraints, and make no assumptions about them. The only assumption is that there are no other contributions except those coming from standard model particles and their superpartners. There is no dependence on the form of the theory at a high scale, on supersymmetry breaking, etc., and no assumption of a MSSM (minimal supersymmetric standard model) [7]. Also, we have not included gluino (sbottom) diagrams [8] in our calculations since we expect these to be well below the neutralino (sbottom) and chargino (stop) contributions.

The results do have implications for the form that models and the high scale theory can take, and a fifth consequence (in addition to the four above) is that there

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are at least three independent ways in which the high scale theory must differ from the MSSM. The MSSM is excluded if the R_b excess is true.

Greater than 2σ deviations from the standard model have been reported for R_c and for A_b $[\equiv (g_L^2 - g_R^2)/(g_L^2 + g_R^2)]$. Supersymmetry has no natural way to explain these, and the SUSY prediction is that they will go away. Lest the reader think we are arbitrarily choosing our deviations, we note that for R_c the reported deviation is over a 10% effect (compared to about 2% for R_b where the m_t^2 dependence leads one to expect a large effect), and we are confident that no mechanism could give such a huge effect without being detected other ways. R_c has no significant m_t^2 contribution. Thus any effect for R_c should be well within its current reported 4% errors, and that is why we quote the data with R_c constrained to its standard model value above (which is conservative in any case). For A_b the errors are a few % while the size of the expected effects in SUSY is less than 1%. Also, contributions to R_b are sensitive to the left-handed couplings of b to Z, while the asymmetry is most sensitive to the right-handed coupling, which will be smaller. In both cases the present errors are well above any possible loop effect.

Stop and chargino at LEP.—Figure 1 shows the region of stop and chargino masses where a δR_b of 0.003 or more can be obtained. We think 0.003 is a good value to use as a criterion to explain δR_b. The standard model gives $R_b = 0.216$ ($m_t = 170$), and the reported R_b value for charm constrained to its standard model value is 0.2205 ± 0.0016 [1], so the 1σ lower limit is 0.003 above the standard model. Also, the effect on the LEP α_s is about $-4\delta R_b$, so a change of 0.003 in R_b would yield a change of -0.012 in α_s. This is exactly what is needed to get the $\alpha_s(m_Z^2)$ extracted using the Z line shape down to about 0.112 (from 0.124) where other ways of determining α_s lead us to expect it. The line in Fig. 1 is plotted for $m_t = 170$ GeV and for $\tan\beta = 1.1$. A rule is given in the caption for scaling to other m_t and $\tan\beta$. This region is obtained by varying all parameters over values that do not lead to a contradiction with theory or data, for each combination of stop and chargino masses. A point inside the region $\delta R_b > 0.003$ gives $\delta R_b > 0.003$ for some values of other parameters, though not necessarily for all. A point outside does not give $\delta R_b \geq 0.003$ for any parameter values.

The chargino cross section is large enough at LEP so chargino pairs could be copiously produced nearly up to the kinematic limit [9] with several pb^{-1} of integrated luminosity regardless of the values of other parameters. Note that if the chargino is not detected below about 70 GeV, then the stop mass should be lighter than 60 GeV. Stop cross sections are smaller, but with over 5 pb^{-1} perhaps a few stop events could be detected [9]. Thus if the R_b excess is real and LEP takes data at or above 140 GeV and over about 5 pb^{-1}, charginos and/or stops can be detected if SUSY is relevant to understanding R_b. However, it is possible that the luminosity or center of mass energy will be too low to detect them in some portions of parameter space. Then LEP2 would be required.

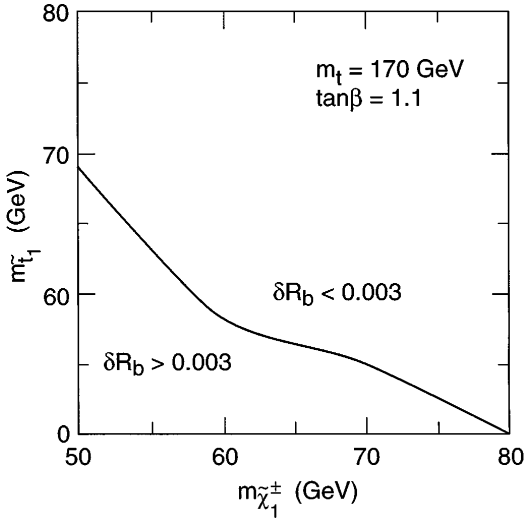

FIG. 1. Contour of $\delta R_b = 0.003$ in the $m_{\chi_1^\pm}$-$m_{\tilde t_1}$ plane with $m_t = 170$ GeV and $\tan\beta = 1.1$. Above the contour no solution exists which yields $\delta R_b > 0.003$. Below the contour solutions do exist with $\delta R_b > 0.003$ for appropriate choices of parameters. The numerical value of this contour is enhanced (or diminished) by about $(0.4/\sin\beta)^2(m_t/m_Z)^2$ for different choices of m_t and $\tan\beta$.

$\tan\beta$ is near 1.—Earlier studies of R_b [4–6,10,11] have sometimes argued that a SUSY loop containing the pseudoscalar (A) and scalar Higgs bosons (h and H) could, if $\tan\beta$ were sufficiently large, give a large contribution to R_b. And when the contributions due to chargino (stop) and neutralino (sbottom) loops are added, a significant enhancement of R_b is possible. However, there are constraints. These include the decay $Z \to b\bar{b}(A \to b\bar{b})$ [12] since the strength of the $Ab\bar{b}$ vertex is proportional to $\tan\beta$, so if $\tan\beta > 60$ the rate is enhanced by over 3600; $b \to c\tau\nu_\tau$ [13,14]; and $Z \to \tau^+\tau^-$, $t \to H^+ + b$, $Z \to A + \gamma$, $b \to s + \gamma$. It turns out that at the present time the first two of these give the strongest constraints, and are probably sufficient to exclude the large $\tan\beta$ + small m_A solution. The others may in the future strengthen this case, and data on all of these should be improved.

Figure 2 shows these constraints. The approximately vertical lines are shown labeled by the numbers of $Z \to b\bar{b}(A \to b\bar{b})$ events that would have been produced out of 10×10^6 Z's at LEP. We are not yet aware of published data on this, but we think that if many such events had been produced it is likely to have been noticed, so we assume the allowed region in the $\tan\beta$-m_A plane is to the right of an appropriate one of those lines. To say it differently, if $m_A < 60$ GeV and $\tan\beta > 60$, then over

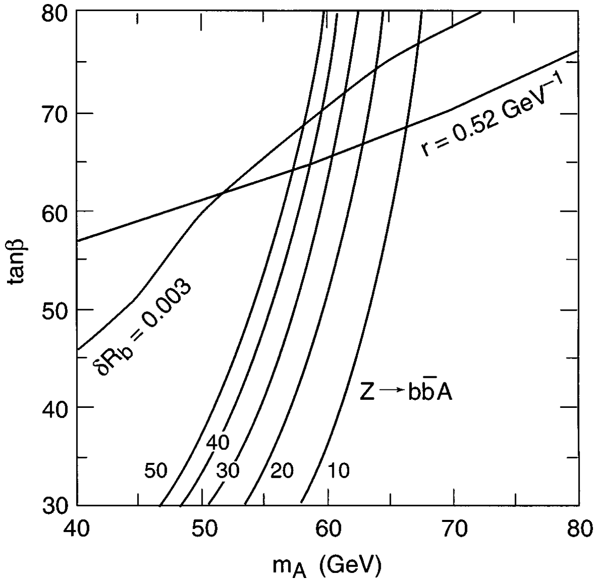

FIG. 2. The high $\tan\beta$ exclusion plot. The $\delta R_b = 0.003$ contour is plotted such that no supersymmetric solution below the contour can provide $\delta R_b \geq 0.003$. The region above the $r = \tan\beta/m_{H^+} = 0.52\ \mathrm{GeV}^{-1}$ contour is excluded by $b \to c\tau\nu_\tau$ decay data. The region to the left of the vertical lines, which indicate contours of $Z \to b\bar{b}A$ events (out of 10×10^6 Z's), is probably also excluded. Therefore, if we require $\delta R_b > 0.003$, which we argue for in the text, then no region of parameter space is simultaneously consistent with the $b \to c\tau\nu_\tau$ and $Z \to b\bar{b}A$ decay constraints. At the point where the $r = 0.52\ \mathrm{GeV}^{-1}$ line and the $\delta R_b = 0.003$ line cross, about 160 $Z \to b\bar{b}A$ events are produced for 10×10^6 Z's.

150 $Z \to b\bar{b}A$ events have been produced at LEP, and we hope someone would soon report on such a signal. The calculation of [14] shows that the observed rate for $b \to c\tau\nu_\tau$ requires that $\tan\beta/M_{H^+} < 0.52\ \mathrm{GeV}^{-1}$. This gives a constraint on m_A—note that some model dependence enters into this constraint that could be changed if the Higgs sector were nonminimal in an unexpected way. The tree level constraint follows from the sum rule $m_{H^+}^2 = m_A^2 + m_W^2$. This relation must be radiatively corrected by loop effects, and the corrections are large if $\tan\beta$ is large [15]. The results are shown as the approximately horizontal line in the figure; the region above the line is excluded. But to explain δR_b the parameters must be in the region above the 0.003 line, which does not overlap with the allowed region. It was shown previously [4,6] that to explain δR_b required either $\tan\beta \simeq 1$ or very large. Therefore SUSY can explain δR_b only for $\tan\beta$ about 1.

This has a number of important consequences. It allows b-τ unification, but excludes b-τ-t unification of Yukawa couplings. The large top mass must be due to a large top Yukawa coupling. It is consistent with an interesting explanation for the μ parameter [16]. It lowers the upper limit on the mass of the lightest Higgs boson (see below). It allows the LSP to have a large Higgsino component (as needed for R_b [6]) without disagreeing with the invisible width of the Z.

Light stop and top physics.—Given our results, there can be little kinematic suppression for $t \to \tilde{t}_1 + \tilde{\chi}^0$. As discussed in Ref. [6] the lightest stop must be mostly the superpartner of the right-handed top, and the light chargino and neutralinos must be mostly Higgsino-like. This, together with the requirement that $\tan\beta \sim 1$, largely determines the couplings between the light stop and Higgsinos. We find that the branching ratio for $t \to \tilde{t}_1 + \tilde{\chi}_i^0$ ($\tilde{\chi}_i^0$ is mostly LSP) is larger than 0.4 for all allowed choices of parameters, so it should be seen at Fermilab once it is looked for.

If stop is heavier than chargino it will decay to $\tilde{\chi}^+ + b$; if not, to $c + \tilde{\chi}^0$. We do not have room here to go through signatures and a detailed analysis, but we note several points. CDF has published a branching ratio of $0.87^{+0.18}_{-0.32}$ [17] for $t \to W^+ b$. But that analysis was for a sample with a W leptonic decay trigger, so it does not apply to some events with a decay to $c + \tilde{\chi}^0$, and without detailed analysis it is not clear what fraction of decays to stop could pass if $\tilde{t}_1 \to \tilde{\chi}^+ \to$ "W" + LSP. In any case, we think a branching ratio of 0.4 is not excluded [18]. We are aware that a smaller branching ratio for $W^+ b$ implies a larger production cross section for top, and therefore a smaller mass. This situation is interesting, and we are not quite sure about its implications. We note that if stop decays to $c + \tilde{\chi}^0$ then the $t\bar{t}$ final state will often have $t(\to W + b) + \bar{t}(\to \tilde{t}_1(\to c + \tilde{\chi}^0) + \tilde{\chi}^0)$ so it will have extra Wjj events. A mild indication of such an effect has been reported [19].

D0 has reported [20] some limits on light stops. It is difficult to show the impact of this on Fig. 1 without model dependence since one has to relate charginos and neutralinos. For stops above about 60 GeV it constrains possible solutions, but has little impact below that. This could be interpreted as an argument for lighter stops, but is not conclusive.

Prediction for m_h.—In SUSY the value of the lightest Higgs boson mass can be calculated, but it depends on other parameters. There is an upper limit, independent of models, of about 150 GeV [21]. The MSSM gives upper limits of about 130 GeV. In all cases m_h has a tree level value plus a large contribution mainly from top dependent one-loop corrections. The tree level limit is $m_Z|\cos 2\beta|$, so for $\tan\beta$ near 1 this is very small, and the upper limit on m_h is considerably reduced. In the minimal model it is then well below 100 GeV. The loop contributions are also reduced when the stop mass is small. Therefore it is nearly certain that LEP will find h (if δR_b is real and explained by SUSY) if a total energy over 190 GeV and 500 pb^{-1} are obtained. With $\tan\beta$ near 1 the light Higgs is rather standard-model-like, but even if the Zh cross section were suppressed the Ah cross section should be large enough.

Consequences for theory.—There are at least three major consequences of these arguments for the form a supersymmetric unified theory can take. Two of them have been remarked on before [3] and we only briefly comment on them here. Each of the three excludes the MSSM. It is exciting that data at the electroweak scale may be constraining the theory at the unification scale—if it is, once we have information on superpartner properties it may be possible to determine much of the effective Lagrangian at the unification scale from experiments at the electroweak scale.

It is well known that in order to have light superpartners in the MSSM it is necessary to have $\alpha_s(m_Z^2) > 0.126$ [22], while we see here that $\alpha_s(m_Z^2)$ is about 0.112. Thus the theory must have some additional structure in order to lower $\alpha_s(m_Z^2)$.

Second, the light chargino must be largely Higgsino and the light stop mainly right handed. That cannot happen in the MSSM when one looks carefully at the conditions [6].

Third, we have seen here that we require a value of $\tan\beta$ lower than the minimal model perturbative lower limit given approximately by $\sin\beta > m_t/200$ GeV [23]. One could view that as evidence against a SUSY explanation of δR_b, but we think that is premature, because the form of a more complete supersymmetric theory can affect the running of the top Yukawa potential, thus lowering the allowed $\tan\beta$. We prefer to view it as a constraint on the form of a satisfactory unified supersymmetric theory, a constraint that the MSSM fails.

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