Supersymmetry, Supergravity and R_b Revisited in the Light of LEP 2

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Abstract

A previous study of supersymmetric models has indicated that they are unlikely to make a large contribution to $R_b \equiv \Gamma(Z^0 \to \bar{b}b)/\Gamma(Z^0 \to \text{hadrons})$. We revisit this analysis, taking into account the improved lower limits on sparticle masses provided recently by LEP 2 and the Tevatron, finding that a generic supersymmetric model cannot contribute more than about one-and-a-half current experimental standard deviations to R_b. We then specialize this analysis to minimal supergravity models with universal high-energy boundary conditions, and find a much more stringent upper bound $R_b^{\text{susy}} < 0.0003$. We discuss in detail why such models can only attain values of R_b^{susy} that are considerably smaller than those obtainable in more general supersymmetric models.

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There has been considerable interest during the recent past in $R_b \equiv \Gamma(Z^0 \to \bar{b}b)/\Gamma(Z^0 \to \text{hadrons})$, which has been the only observable at the Z^0 whose measurements appeared for some time to be in significant disagreement with the Standard Model. This discrepancy triggered great theoretical interest in the possibility that some aspect of physics beyond the Standard Model might be playing a rôle, in particular supersymmetry [1]. It was pointed out that supersymmetric radiative corrections to R_b would be largest, and potentially of significant magnitude, either if the lighter chargino $\chi^\pm$ and the lighter top-squark $\tilde{t}_1$ were light and the ratio $\tan\beta$ of supersymmetric higgs vacuum expectation values were near unity [2, 3], or if the neutral CP-odd supersymmetric higgs mass m_A were small and $\tan\beta$ were very large [4]. In particular, considerable interest centred on the light $\chi^\pm, \tilde{t}_1$ scenario [5, 6], which offered the possibility of removing the apparent R_b discrepancy if the $\chi^\pm$ and $\tilde{t}_1$ were light enough to be discovered at LEP 2 or at the Tevatron, making the scenario particularly attractive.

Around a year ago, the first preliminary results from the running of LEP at energies between 130 and 140 GeV (LEP 1.5) were announced, and indicated that the $\chi^\pm$ was unlikely to weigh less than about 65 GeV [7], and Tevatron searches also imposed significant constraints on $m_{\tilde{t}_1}$ [8]. In a previous paper [9], we combined these limits with a number of other phenomenological contraints, including the CLEO measurement of $B(b \to s\gamma)$, and found the upper limit $R_b^{\text{susy}} < 0.0017$. At the time, this was comparable with the experimental error, while the apparent discrepancy between the Standard Model and the reported measurements was 3.7 standard deviations. Accordingly, we concluded that supersymmetry was unable to explain the apparent experimental discrepancy, and we suggested that a re-evaluation of the data in the context of the Standard Model was desirable.

The experimental situation has changed significantly subsequently, with the appearance of four new measurements of R_b (as compiled in Ref. [10]), none of which disagrees significantly with the Standard Model prediction. Indeed, the measurement with the smallest reported error (from ALEPH) agrees with the Standard Model within a fraction of a standard deviation. However, if one combines the newer measurements with the older ones that are not superseded, the world experimental average and the Standard Model still differ by about 2 standard deviations [10]. This is not significant in itself, but it does leave open the possibility of a non-negligible contribution from physics beyond the Standard Model, such as supersymmetry. If this were the case, it would not be justified to include R_b in global electroweak fits to the Standard Model, and indications about the mass of the Higgs boson inferred from such analyses would require revision. In particular, it has been argued that dropping R_b from the global fit would tend to increase the preferred range of M_H [11].

Recently, further updates on supersymmetric searches at LEP have been made available, with published [12, 13, 14] and preliminary [15] limits from LEP 2W running at the W^+W^- threshold energy of 161 GeV, and higher-energy LEP 2 running at 172 GeV [16]. These indicate in particular a lower limit $m_{\chi^\pm} > 83$ GeV, unless $m_{\chi^\pm} - (m_{\tilde{\nu}}$ or $m_\chi) < 3$ GeV, where degenerate sneutrinos $\tilde{\nu}$ are assumed, and χ denotes the lightest neutralino. There are also improved lower limits on $m_{\tilde{t}_1}$ [13],

which also depend on its difference from m_χ. It seems opportune to re-examine our previous upper bound on R_b^{susy} in the light of these improved lower limits. We also examine the extent to which the absolute upper bound in a general supersymmetric model can be approached in supergravity models in which the different soft supersymmetry-breaking masses are assumed to be universal at the input scale, and dynamical electroweak symmetry breaking is driven by the Yukawa coupling of the top quark.

We find a general upper bound $R_b^{\mathrm{susy}} < 0.0017$, which is intermediate between the present experimental error and the present apparent experimental discrepancy with the Standard Model. It would therefore seem that supersymmetry might be able to make a contribution to the resolution of this residual discrepancy, though at the price of fine-tuning the model parameters. We find, moreover, that supergravity models can make at best a contribution $R_b^{\mathrm{susy}} \simeq 0.0003$, which is negligible compared with the present experimental errors (as was already pointed out in Ref. [3]). As we discuss in more detail later in this paper, this is because their highly-constrained nature prevents supergravity models from reaching the values of μ and M_2, and of $m_{\tilde{t}_1}$ and θ_t, where general supersymmetry models are able to make their largest contributions to R_b.

As has already been mentioned, four new experimental measurements of R_b have recently been announced: 0.2158 ± 0.0009 from ALEPH [17], $0.2176 \pm 0.0028 \pm 0.0027$ from DELPHI [18], 0.2149 ± 0.0032 from SLD [19], and $0.2175 \pm 0.0014 \pm 0.0017$ from OPAL [20]. None of these differs significantly from the Standard Model, and the first one, which has the smallest errors, agrees with the Standard Model ($R_b^{\mathrm{SM}} = 0.2157$) within a fraction of a standard deviation. This result supersedes previous ALEPH measurements, whilst the DELPHI collaboration suggests that its new and older results should be combined to obtain $R_b = 0.2205 \pm 0.0014 \pm 0.0018$ [18]. The relatively large errors of the SLD and OPAL measurements are each compatible individually with the Standard Model. Combining all the old and new measurements, the LEP Electroweak Working Group recommends 0.2178 ± 0.0011 [10]. It is clear that the definitive result for R_b is still to come, since the SLD continues to take data at the Z^0 peak, and not all the LEP collaborations have arrived at their final results. Accordingly, it is possible that the central experimental value of R_b will evolve further, for example as the full LEP data is re-analyzed with the most up-to-date values of the auxiliary experimental input parameters that are needed for the extraction of R_b. *Ad interim*, we use the number recommended by the LEP Electroweak group as the basis for our subsequent discussion.

Direct searches for supersymmetric particles have also advanced significantly in recent months. Data from LEP 2W running during the summer of 1996 have been analyzed and presented by all four LEP collaborations [15, 16], and limits published by OPAL on charginos and neutralinos [12], on top squarks [13] and on sleptons [14]. In the case of the chargino $\chi^\pm$, the available limits reach almost the kinematic limit for $m_{\chi^\pm}$, unless its decay products are too soft to be detected with high efficiency.

Thus these new limits on $m_{\chi^\pm}$ generally apply as long as

$$m_{\chi^\pm} - (m_\chi \text{ or } m_{\tilde{\nu}}) \gtrsim 3\,\text{GeV} \tag{1}$$

In the case of smaller mass differences, which clearly involve some special choice of parameters, one reverts to the absolute LEP 1 limit $m_{\chi^\pm} > 47$ GeV. In the case of the more recent LEP 2 run at 172 GeV, only preliminary analyses have been reported, but it seems that charginos can again be excluded almost up to the kinematic limit, as long as the condition (1) is satisfied. On the other hand, the LEP 2W and LEP 2 limits on neutralinos and sleptons are not by themselves restrictive on supersymmetric models. Updated limits on the mass of the lighter top squark $\tilde{t}_1$ from LEP [13] and the Tevatron [8] have also been provided recently. These share the features that no limit can be established if $m_{\tilde{t}_1} - m_\chi$ is so small that detection efficiency is lost. The LEP limit is currently sensitive to smaller values of this mass difference, but the D0 limit extends up to higher values of $m_{\tilde{t}_1}$.

Our analysis follows the methodology of our previous paper [9]. That is, we consider the set of supersymmetric parameters that determine the value of R_b, namely $\{\mu, M_2, \tan\beta, m_{\tilde{t}_1}, m_{\tilde{t}_2}, \theta_t\}$, and generate a Monte Carlo sample of models in this six-dimensional space that is so large that 10,000 of the sampled points yield $R_b^{\text{susy}} > 0.0020$. The ranges of dimensionful parameters are all restricted to the interval 0–250 GeV, while $\tan\beta$ is allowed to range from 1 to 5, and θ_t from 0 to π[1]. The complete sample of 484,000 models is then subjected to a series of phenomenological and experimental constraints:

1. From LEP 1: $\Gamma(Z \to \chi\chi) < 3.9$ MeV, $B(Z \to \chi\chi') < 10^{-4}$.

2. From CLEO: $B(b \to s\gamma) = (1 - 4) \times 10^{-4}$.

3. From the agreement between Tevatron top-quark mass and cross section measurements: $B(t \to \text{new}) < 0.45$.

4. From OPAL: the lower limit on $m_{\tilde{t}_1}$ obtained at LEP 2W, as a function of θ_t and dependent on $\Delta m = m_{\tilde{t}_1} - m_\chi$.

5. From D0: the lower limit on $m_{\tilde{t}_1}$ obtained with Run IA data on possible $\tilde{t}_1 \to c\chi$ decays, as a function of m_χ.

6. From LEP172: the lower limit $m_{\chi^\pm} > 83$ GeV, unless $m_{\chi^\pm} - (m_{\tilde{\nu}} \text{ or } m_\chi) < 3$ GeV, where degenerate sneutrinos $\tilde{\nu}$ are assumed.

We also require that neither $\tilde{t}_1$ nor $\chi^\pm$ be lighter than the lightest neutralino, which is not a very restrictive constraint. In contrast to Ref. [9], this time we do not enforce *a priori* the current experimental lower limit on the lightest Higgs boson mass. This constraint is hard to satisfy in the region of parameter space where R_b^{susy} is enhanced,

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[1]This angle is defined such that $\tilde{t}_1 = \cos\theta_t \tilde{t}_L + \sin\theta_t \tilde{t}_R$ corresponds to the lighter eigenvalue of the top-squark mass matrix.

though it may be satisfied more easily if the heavier top-squark mass $m_{\tilde{t}_2}$ is allowed to have a sufficiently large value. However, this corresponds to a special choice of parameters, as we discuss later.

After all the above constraints have been applied, the remaining set of still-allowed points in parameter space is reduced to 41K, or 8.5% of the total sample. In what follows, we consider the subset of these points which have relatively large values of $R_b^{\text{susy}} > 0.0010$, about 210 points or 0.04%, from which we obtain the absolute upper bound[2]

$$R_b^{\text{susy}} < 0.0017 \ . \tag{2}$$

All of these points correspond to $\mu < 0$. We display in Fig. 1 the still-allowed set of models with $R_b^{\text{susy}} > 0.0010$, projected onto the (M_2, μ) plane. The resulting "globular cluster" of models gives a good idea of the actual extent of the allowed region. We remark that our restriction on the dimensionful parameters to the interval 0–250 GeV is not restrictive, and that our values of R_b^{susy} in this region of the (M_2, μ) plane agree well with those obtained in Ref. [6]. However, the region in (M_2, μ) space that is still allowed after we implement the constraints in our analysis is significantly more restrictive than that considered in Ref. [6], leading to the more stringent upper bound on R_b^{susy} (2) that we obtain.

To gain more insight into the multi-dimensional nature of our "globular cluster" of still-allowed models with relatively large values of R_b^{susy}, we next consider in Fig. 2 the projection of the "globular cluster" onto the $(m_{\tilde{t}_1}, \theta_t)$ plane. In this case, we have also indicated the lower bound on $m_{\tilde{t}_1}$ as a function of θ_t obtained by OPAL at LEP 2W. Note the different sensitivities for the different cases: $\Delta m = m_{\tilde{t}_1} - m_\chi = 5\,(10)$ GeV. The points below both dashed lines are allowed because $\Delta m < 5$ GeV in these particular models. This figure makes apparent the significant contribution to a more stringent upper limit on R_b^{susy} that LEP experiments will be able to make if they refine their analyses to be sensitive to smaller values of $m_{\tilde{t}_1} - m_\chi$.

Another projection of the globular cluster is shown in Fig. 3, where we display the $(m_\chi, m_{\tilde{t}_1})$ plane, indicating this time the lower bound on top squarks from D0. Note again the significant contribution that D0 will be able to make once its analysis of searches for top squarks is completed with the full Run IB luminosity, which is about 10 times the data used to obtain the current excluded region, and if the efficiency for small $m_{\tilde{t}_1} - m_\chi$ differences can be improved. We observe that many points in the "globular cluster" concentrate near the $\Delta m = 0$ line, escaping detection with a relatively special choice of parameters.

To be more specific, in Fig. 4 we display the distributions of models with enhanced R_b^{susy} values as functions of the chargino and top-squark masses. This figure displays the impact on the density of the allowed points in parameter space of the chargino mass limits from LEP 2. We see in the top panel that the run of LEP at

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[2]This upper limit happens to coincide with that found previously in Ref. [9], although we use here a somewhat different set of experimental constraints, including relaxation of the Higgs mass constraint and strengthening of the sparticle mass constraints. We have also corrected a calculational error in Ref. [9].

172 GeV has already eliminated many models with large R_b^{susy}, although the absolute upper limit has not been reduced. The same point is also made in the lower panel of Fig. 4, where we see that the models which survive LEP 1.5 constraints are further decimated by LEP 172.

To exemplify the point that models with relatively large values of R_b^{susy} represent relatively special choices in supersymmetric parameter space, we now specialize the above analysis to the subspace spanned by supergravity models with universal soft supersymmetry breaking parameters at the unification scale and radiative electroweak symmetry breaking driven by the top-quark Yukawa coupling. In this class of models, one needs to specify four parameters $\{m_{1/2}, m_0, A_0, \tan\beta\}$. The solid lines shown in Figs. 1, 2, and 3 are obtained by varying $m_{1/2}$, fixing $\tan\beta = 2$,[3] fixing $\xi_0 = m_0/m_{1/2}$ and $\xi_A = A_0/m_{1/2}$ to the representative values of $(1, -6)$ and $(1, 0)$, and applying all the experimental constraints discussed above. The $(1, -6)$ case has the virtue of allowing rather light $m_{\tilde{t}_1}$, whereas the $(1, 0)$ case does not require such large values of A_0, which may be questionable from the point of view of vacuum stability. We also exhibit a class of models with $\tan\beta = 1.84$, $\xi_0 = 0.89$, and $\xi_A = -4.88$. These particular values were chosen because they yield a rather large value of $R_b^{\mathrm{susy}} \simeq 0.0015$ prior to the application of the LEP 2 constraints. We note that, once these constraints are imposed, none of the lines shown reach the globular cluster. Specifically, we see in Fig. 1 that these supergravity models cannot attain small enough values of $|\mu|$, in Fig. 2 that they yield values of θ_t that are too small for the relevant values of $m_{\tilde{t}_1}$, and in Fig. 3 that they tend to have uninterestingly large $m_{\tilde{t}_1}$ for allowed values of m_χ. These observations are confirmed by a general Monte Carlo simulation of 10,000 supergravity models with parameters taking values in the ranges: $\tan\beta = 1 \to 5$, $\xi_0 = 0 \to 1$, $\xi_A = -5 \to 5$, and $m_{1/2} = (50 \to 200)$ GeV. We obtain

$$R_b^{\mathrm{sugra}} < 0.0003, \tag{3}$$

representing a negligible contribution to R_b.

We have emphasized at several points in the text that the available LEP and Tevatron limits on supersymmetric particles have loopholes associated with small mass differences, and that models with large values of R_b^{susy} often exploit these loopholes. Thus, improvements in the LEP and Tevatron sensitivities to events with small differences between sparticle masses would help to thin out such models and improve the current absolute upper limit on R_b^{susy}. For example, as an exercise, we have considered the impact on the model sample described in this paper of establishing the absolute lower limits $m_{\chi^\pm} > 85$ GeV and $m_{\tilde{t}_1} > 60, 70, 80$ GeV (see Fig. 4). The 41K points that satisfy the constraints listed above are thereby reduced to 39K,37K,34K points, of which 104,51,16 have $R_b^{\mathrm{susy}} > 0.0010$ (compared with the previous 210), and the absolute upper limit becomes $R_b^{\mathrm{susy}} < 0.0017, 0.0014, 0.0012$ in the general

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[3]This choice is close to the smallest value of $\tan\beta$ (needed to maximize R_b^{susy}) allowed by the radiative electroweak symmetry breaking mechanism, the constraint on the Higgs boson mass, and the perturbativity of the top-quark Yukawa coupling up to the unification scale.

supersymmetry case.[4] Note that the upper bound on R_b^{susy} would not decrease significantly, but the amount of fine-tuning required to obtain such enhanced values would increase considerably.

Even in the absence of these possible improvements in the present experimental limits, it seems to us unlikely that supersymmetry is making a significant contribution to R_b. We recall that only 0.04% of the general model sample that we studied yielded $R_b^{\text{susy}} > 0.0010$, and that all supergravity model contributions fell below 0.0003. In our view, it is reasonable to ignore the possibility of a supersymmetric contribution to R_b [1] when making global fits to the available electroweak data. Since adding such a contribution decreases the weight of R_b in such fits, and since fits that include R_b tend to yield lower preferred ranges for the Higgs mass, the neglect of the possible supersymmetry contribution to R_b tends to sharpen the present indications from the precision electroweak data in favour of a relatively light Higgs boson [11], as itself mandated by supersymmetry.

Acknowledgements

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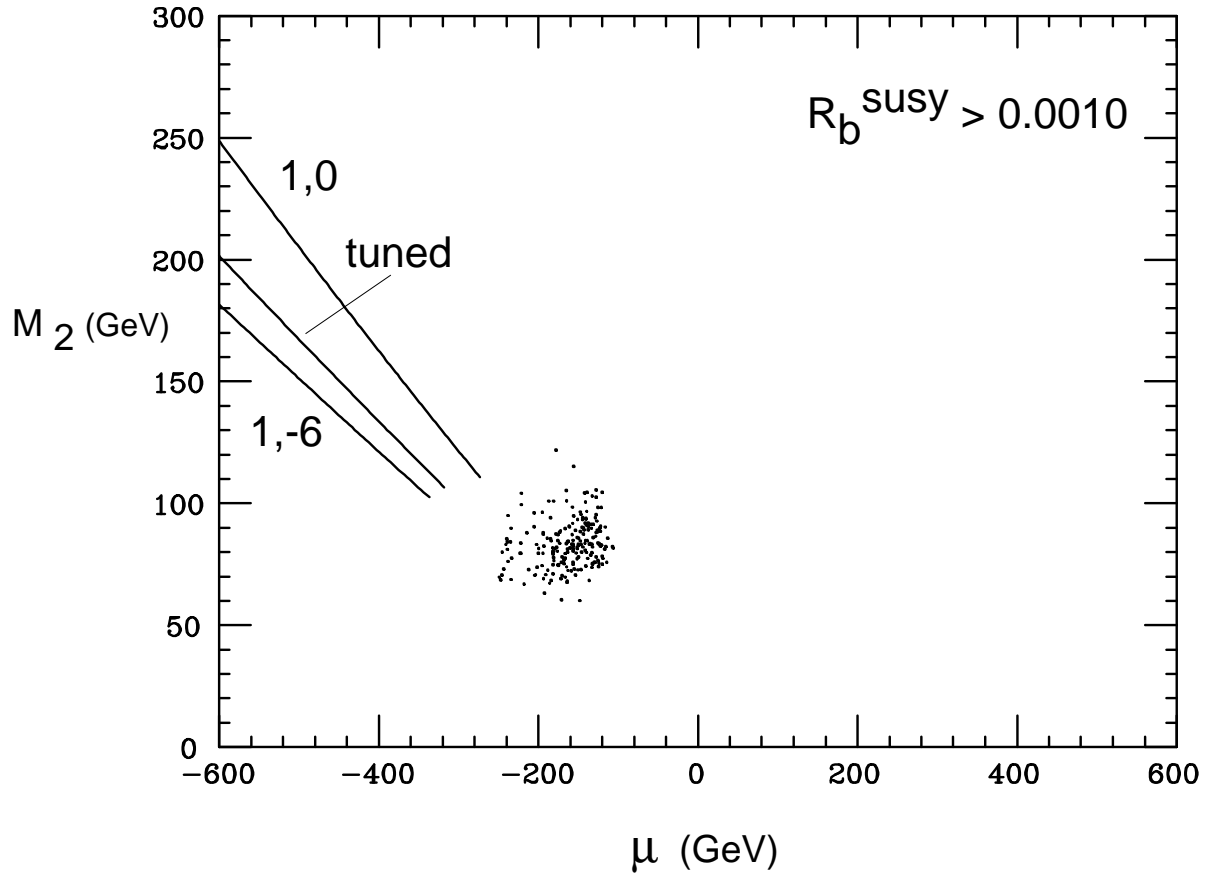[20] K. Ackerstaff, *et. al.* (OPAL Collaboration), CERN-PPE-96-167.

Figure 1: Scatter plot showing the projection on the (M_2, μ) plane of models with $R_b^{\mathrm{susy}} > 0.0010$ which also satisfy LEP 2 limits on charginos and top squarks, D0 limits on top squarks, and other constraints discussed in the text. The lines correspond to representative supergravity models with universal boundary conditions at the unification scale, which are seen not to reach the region of enhanced R_b^{susy}.
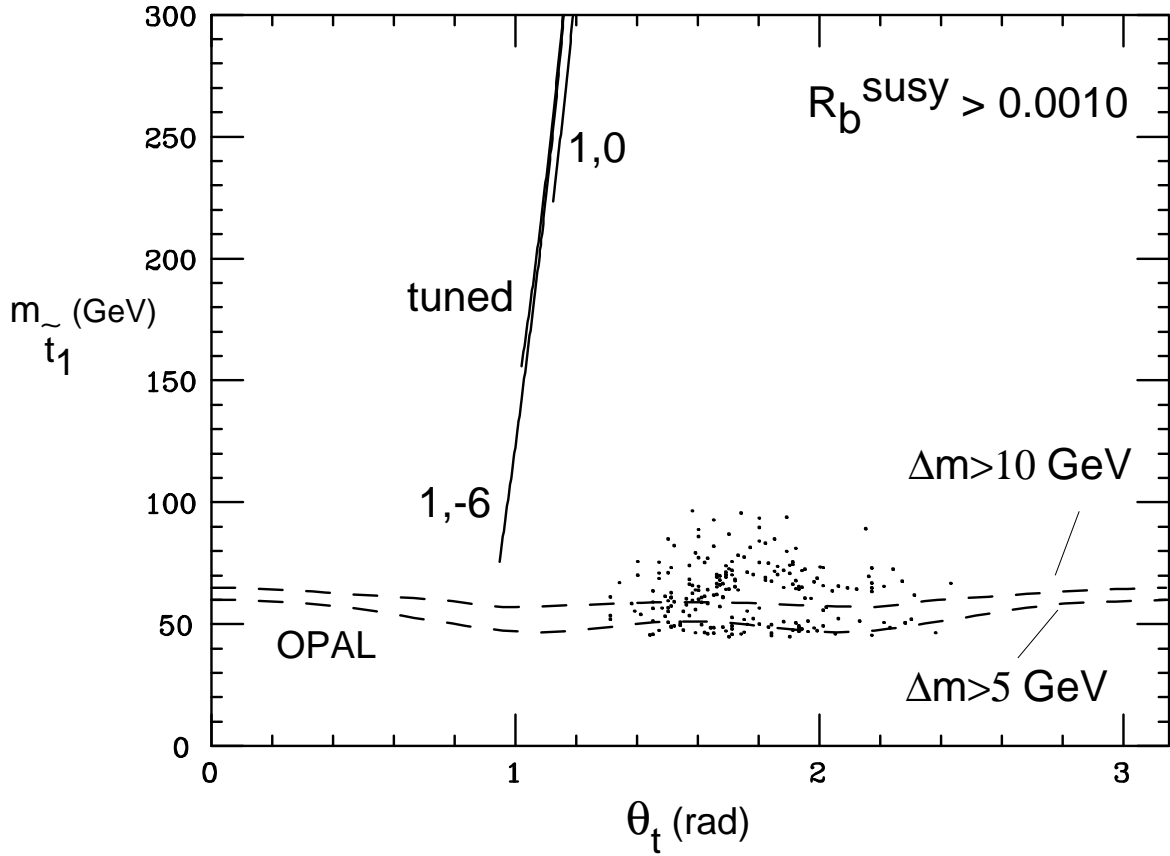
Figure 2: Scatter plot showing the projection on the $(m_{\tilde{t}_1}, \theta_t)$ plane of models with $R_b^{\text{susy}} > 0.0010$ which also satisfy LEP 2 limits on charginos and top squarks, D0 limits on top squarks, and other constraints discussed in the text. The OPAL LEP 2 limits on top squarks are indicated by the dashed lines for two choices of $\Delta m \equiv m_{\tilde{t}_1} - m_\chi$. The lines correspond to representative supergravity models with universal boundary conditions at the unification scale, which are seen not to reach the region of enhanced R_b^{susy}.
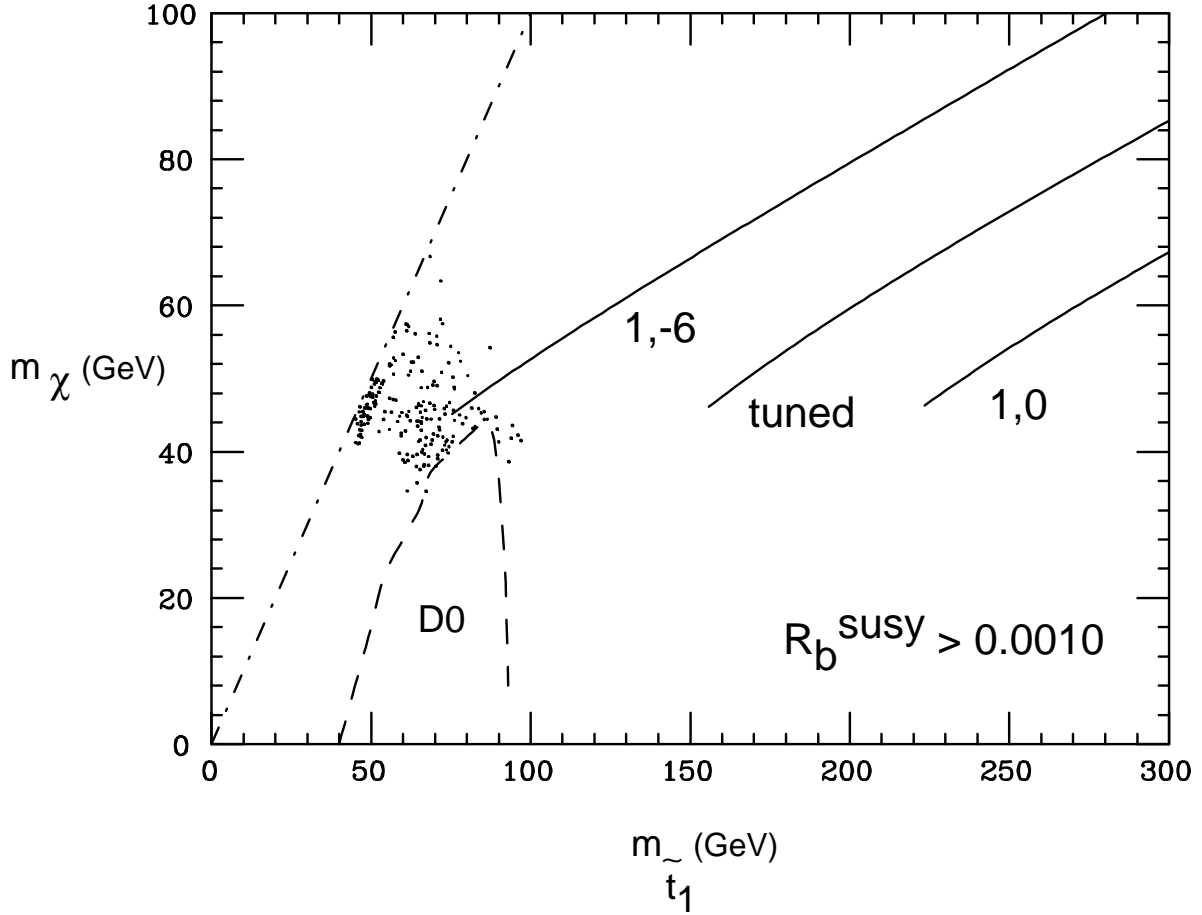
Figure 3: Scatter plot showing the projection on the $(m_\chi, m_{\tilde{t}_1})$ plane of models with $R_b^{\text{susy}} > 0.0010$ which also satisfy LEP 2 limits on charginos and top squarks, D0 limits on top squarks (indicated by the dashed line), and other constraints discussed in the text. The lines correspond to representative supergravity models with universal boundary conditions at the unification scale. Note that one case $(1, -6)$ appears to reach into the region of enhanced R_b^{susy} in this projection, but this is not so once one considers the multi-dimensional nature of the cluster of points.
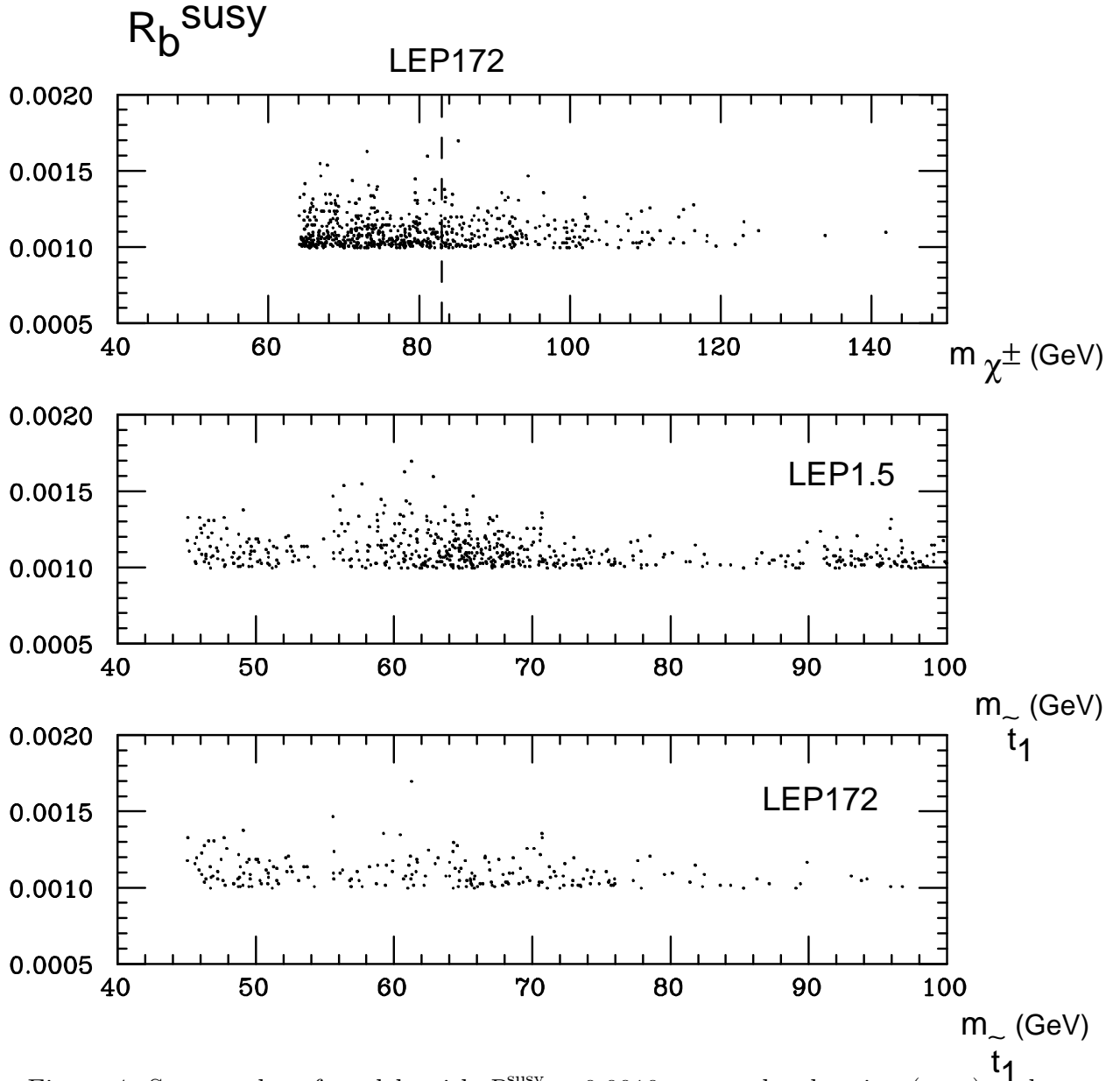
Figure 4: Scatter plot of models with $R_b^{\mathrm{susy}} > 0.0010$ versus the chargino ($m_{\chi^\pm}$) and top-squark ($m_{\tilde{t}_1}$) masses before and after imposing LEP 2 limits on charginos.