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Naturalness and superpartner masses or when to give up on weak scale supersymmetry

Greg W. Anderson* and Diego J. Castaño†
Center for Theoretical Physics, Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
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Superpartner masses cannot be arbitrarily heavy if supersymmetric extensions of the standard model explain the stability of the gauge hierarchy. This ancient and hallowed motivation for weak scale supersymmetry is often quoted, yet no reliable determination of this upper limit on superpartner masses exists. In this paper we compute upper bounds on superpartner masses in the minimal supersymmetric model, and we identify which values of the superpartner masses correspond to the most natural explanation of the hierarchy stability. We compare the most natural value of these masses and their upper limits to the physics reach of current and future colliders. As a result, we find that supersymmetry could explain weak scale stability naturally even if no superpartners are discovered at the CERN LEP II or the Fermilab Tevatron (even with the Main Injector upgrade). However, we find that supersymmetry cannot provide a complete explanation of weak scale stability, if squarks and gluinos have masses beyond the physics reach of the CERN LHC. Moreover, in the most natural scenarios, many sparticles, for example, charginos, squarks, and gluinos, lie within the physics reach of either LEP II or the Tevatron. Our analysis determines the most natural value of the chargino (squark) [(gluino)] mass consistent with current experimental constraints is ~ 50 (250) [(250)] GeV and the corresponding theoretical upper bound is ~ 250 (700) [(800)] GeV.

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I. INTRODUCTION

As a candidate for physics beyond the standard model, weak scale supersymmetry has several appealing features: It provides an understanding of why a light weak scale is stable, it successfully predicts the value of $\sin^2\theta_W$ assuming gauge unification, it predicts a top quark Yukawa coupling of order one, leading to a heavy M_t (assuming τ lepton and bottom quark Yukawa coupling unification), and it provides a natural cold dark matter candidate in the form of the lightest superpartner.

Despite these circumstantial arguments for weak scale supersymmetry, there is not a shred of *direct* experimental evidence to support it. Should we be surprised or discouraged that we have not yet found any supersymmetric partners to the standard model particles? To date, of the particles we believe to be fundamental, all those observed would be massless if the gauge symmetries of the standard model were unbroken.[1] Because the current, experimental probes only reach up through the lower fringes of the weak scale, it is not surprising that the fundamental particles discovered so far obtain masses as a consequence of spontaneously broken gauge symmetries. Their superpartners, by contrast, can have gauge-invariant mass terms, provided supersymmetry is broken. Although they are not required to be light by gauge symmetries, there is a theoretical upper limit on their masses above which the weak scale does not arise naturally. As the scale of supersymmetry breaking is increased, the weak scale can only remain light by virtue of an increasingly delicate cancellation. Requiring that the weak scale arises naturally places an upper bound on superpartner masses.

In this paper, we attempt to quantify the relationship between naturalness and superpartner masses. Using recently formulated naturalness measures we compute the most natural value of the superpartner masses, the extent to which naturalness is lost as experimental bounds on superpartner masses increase, and a theoretical upper limit to the masses of superparticles.

In Sec. II we review the naturalness measures used in our study. Section III is devoted to a discussion of radiative electroweak symmetry breaking in the minimal supersymmetric extension of the standard model (MSSM) and to details of the numerical methods we employed in our analysis. The results, presented in Sec. IV, demonstrate that the MSSM cannot accommodate the weak scale naturally if superpartner masses lie beyond the reach of the CERN Large Hadron Collider (LHC). Moreover, in the most natural cases, physics beyond the standard model has a good chance of being discovered at the CERN e^+e^- collider LEP II or the Fermilab Tevatron.

II. MEASURING FINE TUNING

In this section we review the recently formulated naturalness measures we use in our analysis. A more detailed

*Electronic address: anderson@mitlns.mit.edu
†Electronic address: castano@mitlns.mit.edu

[1] Only quite recently has there been experimental evidence for the top quark.

motivation and derivation of these criteria can be found in Ref. [1]. Any measure of naturalness contains assumptions about how the fundamental parameters of a Lagrangian are distributed. If we parametrize these assumptions, a quantitative measure of naturalness follows directly. Consider a Lagrangian density written in terms of fundamental couplings specified at the high energy boundary of the effective theory: $\mathcal{L}(a_1, a_2, ..., a_n)$. At a low energy scale, we can write the Lagrangian in terms of physical observables X (e.g., $X = M_Z^2$). These observables will depend on the a_i through the renormalization group and possibly on a set of minimization conditions: $X = X(a)$. If we assume the probability distribution of a fundamental Lagrangian parameter a is given by

$$dP(a) = \frac{f(a)da}{\int f(a)da}, \tag{2.1}$$

a likelihood distribution for the low energy observable X follows:

$$\int_{a_-}^{a_+} f(a)da = \int_{X(a_-)}^{X(a_+)} \rho(X)\, dX \ . \tag{2.2}$$

The value of an observable X is unnatural if it is relatively unlikely to end up in an interval $u(X)$ about X compared to similarly defined intervals around other values of X. The probability that X lies within an interval $u(X)$ about X has weight $u\rho$. So we define our quantitative measure of naturalness as

$$\gamma = \frac{\langle u\rho\rangle}{u(X)\rho(X)}, \tag{2.3}$$

where

$$\langle u\rho\rangle = \frac{\int u\rho\, da}{\int da}. \tag{2.4}$$

The conventional sense of naturalness for hierarchy problems corresponds to an interval[2] $u = X$. With this prescription, fine-tuning corresponds to $\gamma \gg 1$. The γ defined in Eq. (2.3) is proportional to the Barbieri-Giudice sensitivity parameter $c(X, a) = |(a/X)(\partial X/\partial a)|$ [2]. We can use Eqs. (2.3) and (2.4) to define an average sensitivity $\bar{c}$ through the relation

$$\gamma = c/\bar{c} \ . \tag{2.5}$$

This definition of $\bar{c}$ gives

$$1/\bar{c} = \frac{\int da\, af(a)\, c(X;a)^{-1}}{af(a)\int da}. \tag{2.6}$$

The naturalness measures defined by Eqs. (2.5) and (2.6) are a refinement of Susskind's description of Wilson's naturalness criteria [3]: Observable properties of a system, i.e., X, should not be unusually unstable with respect to minute variations in the fundamental parameters, a. In other words, $X(a)$ is fine-tuned if the values of the fundamental parameters a are chosen so that X depends on the a in an *unusually* sensitive manner when compared to other values of the fundamental parameters a. Sensitivity in this case is understood to mean that a small *fractional* change in a leads to a large *fractional* change in[3] X.

Returning to Eqs. (2.4)–(2.6), we see that three choices need to be specified before we can make practical use of this prescription. First, the choice of $f(a)$ reflects our theoretical prejudice about what constitutes a natural value of the Lagrangian parameter a. We will make two different choices for $f(a)$ as an aid in determining how sensitively the bounds we derive depend on this theoretical prejudice: $f(a) = 1$ and $f(a) = 1/a$. We denote the corresponding naturalness measures by γ_1 and γ_2, respectively. The bounds we derive on superpartner masses in Sec. IV are fairly insensitive to this choice. Second, the conventional notion of naturalness for hierarchy problems is $u(X) = X$ [1]. This choice has already been made in Eq. (2.6), and it is implicit in the qualitative statement of naturalness written above. Finally, the range of integration (a_-, a_+) for the averaging must be chosen. This range will be discussed in Sec. IV.

III. THE MSSM

All the chiral interactions of the MSSM are described by its superpotential

$$W = \hat{\bar{u}}\mathbf{Y}_u\hat{\Phi}_u\hat{Q} + \hat{\bar{d}}\mathbf{Y}_d\hat{\Phi}_d\hat{Q} + \hat{\bar{e}}\mathbf{Y}_e\hat{\Phi}_d\hat{L} + \mu\hat{\Phi}_u\hat{\Phi}_d \ . \tag{3.1}$$

The μ term explicitly breaks the Peccei-Quinn symmetry and avoids a phenomenologically disastrous axion. In addition to all the particles of the SM, there are 31 new ones including three new Higgs bosons.

Supersymmetry (SUSY) is explicitly broken in the MSSM using soft terms derived from the low energy limit of supergravity (SUGRA) theory. The form of the soft SUSY-breaking potential in the MSSM includes mass terms for all the scalars and for the gauginos as well as bilinear and trilinear terms following from the Kähler potential of the SUGRA theory in the low energy limit.

A generic feature of minimal low energy SUGRA models is universality of the soft terms. Universality implies that all the scalar mass parameters are equal to the gravitino mass m_0 at some high energy scale which we take to be the scale of gauge coupling unification, $M_X = 10^{16}$

[2]For example, in a theory of fundamental scalars, the scalar mass is related to the cutoff Λ and the bare term m_0 by $m_s^2 = g^2\Lambda^2 - m_0^2$. In this theory we must adjust g^2 with the same precision to place the scalar mass squared in a 1 (GeV)^2 window whether the scalar mass is $\sim \Lambda$ or $\sim 10^{-14}\Lambda$. A small mass for the scalar is unnatural in the sense that a small change in g^2 leads to a large *fractional* change in m_s^2 [1].

[3]In deriving the naturalness criteria Eqs. (2.3)–(2.6), we have attempted to make explicit the discretionary choices inherent in any quantitative measure of naturalness. In any particular application, in order to obtain a reliable measure of naturalness, these choices must be made sensibly.

GeV. All soft trilinear couplings share a common value A_0 that can be related to the soft bilinear coupling B_0, depending on the form of the Kähler potential. To some extent, universality in the soft breaking terms is required in order to avoid unwanted flavor-changing neutral current effects. Since the gauge couplings unify, the gaugino mass parameters are assumed equal to a common value $m_{1/2}$ at M_X. Consequently, the minimal model introduces five new parameters: m_0, A_0, $m_{1/2}$, B_0, and μ_0. However, it is very predictive since these account for the masses of 31 new particles [4].

In the MSSM, the electroweak symmetry is broken radiatively [5–8]. In our analysis, we use the one-loop effective Higgs potential

$$V_{1\ \mathrm{loop}} = V_0 + \Delta V_1 \ , \tag{3.2}$$

where the expression for the one-loop correction is given by

$$\Delta V_1 = \frac{1}{64\pi^2} \sum_i (-1)^{2s_i}(2s_i+1) m_i^4 \left(\ln\frac{m_i^2}{Q^2} - \frac{3}{2} \right) \ . \tag{3.3}$$

The m_i represent the field-dependent masses of the particles of the model and the s_i the associated spins. We include the contributions of all the MSSM particles in the one-loop correction.

Using the renormalization group, the parameters are evolved to low energies where the potential attains validity. This RG improvement uncovers electroweak symmetry breaking. The exact low energy scale at which to minimize is unimportant as long as the one-loop effective potential is used and the scale is in the expected electroweak range. The minimization scale will arbitrarily be taken to be M_Z. If the electroweak symmetry is broken, minimization yields nonzero values for the vacuum expectation values (VEV's) of the two Higgs fields v_u and v_d, or equivalently $v = \sqrt{v_u^2 + v_d^2}$ and $\tan\beta = v_u/v_d$. The two minimization conditions may be expressed as

$$\mu^2(M_Z) = \frac{\overline{m}^2_{\Phi_d} - \overline{m}^2_{\Phi_u}\tan^2\beta}{\tan^2\beta - 1} - \frac{1}{2}m_Z^2 \ , \tag{3.4}$$

$$B(M_Z) = \frac{(\overline{m}^2_{\Phi_u} + \overline{m}^2_{\Phi_d} + 2\mu^2)\sin 2\beta}{2\mu(M_Z)} \ , \tag{3.5}$$

where $\overline{m}^2_{\Phi_{u,d}} = m^2_{\Phi_{u,d}} + \partial\Delta V_1/\partial v^2_{u,d}$. In the process of integrating the two-loop renormalization group equations, the threshold corrections due to all the light particles are implemented as step functions [9].

The procedure we follow to analyze the MSSM assumes the following 4+1 free input parameters: A_0, m_0, $m_{1/2}$, $\tan\beta_0$, and $\mathrm{sgn}(\mu)$ since it is undetermined from Eq. (3.4). The other parameters of the MSSM are fixed using the following constraints: Electroweak breaking in the form of two minimization conditions at M_Z, the physical masses of the bottom quark and τ lepton, and the value of the strong coupling at M_Z. Therefore, solutions for B_0, μ_0, $y_\tau(M_X)$, $\alpha_3(M_X)$, and M_t are found consistent with the renormalization group (RG), the above constraints, and specified values for the free input parameters. We take the value of the strong coupling at M_Z to be $\alpha_3(M_Z) = 0.118$. The corresponding value of the strong coupling at M_X is determined based on this low energy constraint. The values of $\alpha_1(M_X)$ and $\alpha_2(M_X)$ are set equal and fixed at 1/25.3. This constant value for $\alpha_{1,2}$ at M_X never leads to more than about 1% and 3% error in α_{em} and $\sin^2\theta_W$, respectively. The difference in $\alpha_3(M_X)$ and $\alpha_{1,2}(M_X)$ is at most 3% and can be accommodated using grand unified theory (GUT) thresholds.

Not all input values for the free parameters will yield adequate solutions, and the (4 + 1)-dimensional parameter space must be explored and restricted using various criteria. Cases are rejected based on the existence of color- and/or charge-breaking vacua or a charged lightest supersymmetric particle (LSP). In arriving at the superpartner mass bounds, the fine-tuning prescription, Eq. (2.3), is applied to all solutions found in a grid of approximately 2000 points bounded as follows: $|A_0| \leq 400$ GeV, $0 \leq m_0 \leq 400$ GeV, $|m_{1/2}| \leq 500$ GeV, $1 \leq \tan\beta(M_X) \leq 15$, and $\mathrm{sgn}(\mu) = \pm$.

IV. ANALYSIS

The essential, novel feature of the fine-tuning measure γ is to evaluate the sensitivity c of a physical quantity relative to a benchmark $\bar{c}$. We have derived a formula for this benchmark in Sec. III and in Ref. [1]. This prescription for calculating $\bar{c}$ requires us to choose a range of integration (a_-, a_+). We use two conditions to define a suitable range of integration. First, we integrate over the all values of a where SU(3) $\times$ SU(2) $\times$ U(1) is broken to SU(3) $\times$ U(1)$_{\mathrm{em}}$. The resulting limits on the range of integration generally come from two conditions on the value of M_Z. The minimum value of M_Z

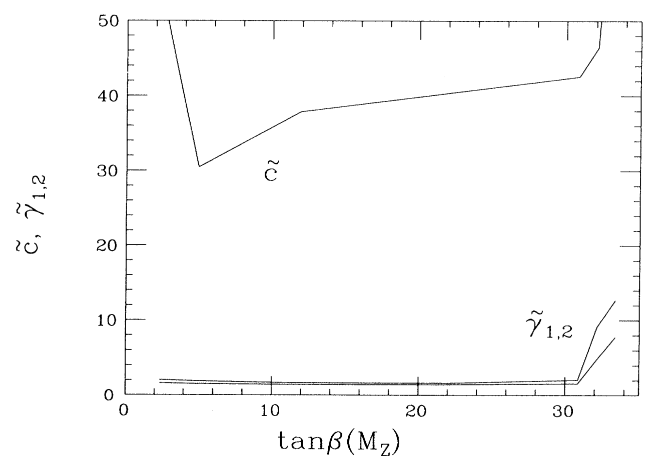

FIG. 1. Curves representing the lower envelope of regions defined by $\tilde{c} = \max\{c(m_{1/2}), c(m_0), c(y_t), c(g_3)\}$ and $\tilde{\gamma}_{1,2} = \max\{\gamma_{1,2}(m_{1/2}), \gamma_{1,2}c(m_0), \gamma_{1,2}(y_t), \gamma_{1,2}(g_3)\}$ plotted as a function of $\tan\beta$. The upper curve represents the amount of sensitivity required by current experimental superpartner limits, and the lower curves display the amount of fine-tuning.

cannot be less than 0, and its maximum value cannot exceed some upper bound, often set by the requirement that sneutrino squared masses be positive. Second, in our analysis we only consider points where we are able to find a significantly large range of integration. If the range of integration is not suitably large, we will fail in our attempt to compare the sensitivity of M_Z, when a is chosen so that the value of M_Z is 91.2 GeV, to the average sensitivity. Inspection of Eq. (2.6) shows that in the limit of vanishing $(a_+ - a_-)$, $\bar{c}$ approaches c, and γ tends to one. To eliminate spurious calculations of γ, we only consider cases were $\delta a = a_+ - a_-$ exceeds $a/4$ or $a/8$ for $M_Z(a) = 91.2$ GeV. We find that typically this has the effect of removing points where SU(3) only remains unbroken as the result of a fine tuning.

Figures 2–9 display correlations between the superpartner masses and fine-tuning. For each solution point, we computed the fine-tuning with respect to the common scalar mass, the top quark Yukawa coupling, and the common gaugino mass. Then, for each individual solution, we define $\tilde{\gamma}$ as the largest of these fine-tunings. Many earlier studies of naturalness, as well as employing measures of sensitivity instead of fine-tuning, considered the naturalness of the Z mass with respect to individual parameters separately. This separation can lead to a significant underestimate of fine-tuning.[4] In particular, we have compared the lower envelopes defined by scatter plots, and we find explicitly that, if fine-tuning is plotted as a function of a particular coupling or mass, the envelope defined by $\tilde{\gamma}$ cannot in general be constructed from the individual envelopes[5] for $\gamma(m_0)$, $\gamma(m_{1/2})$, and $\gamma(y_t)$. Figures 2–9 display the fine-tuning measure $\tilde{\gamma}$ plotted against selected superpartner masses. The individual points shown in these figures correspond to the grid of

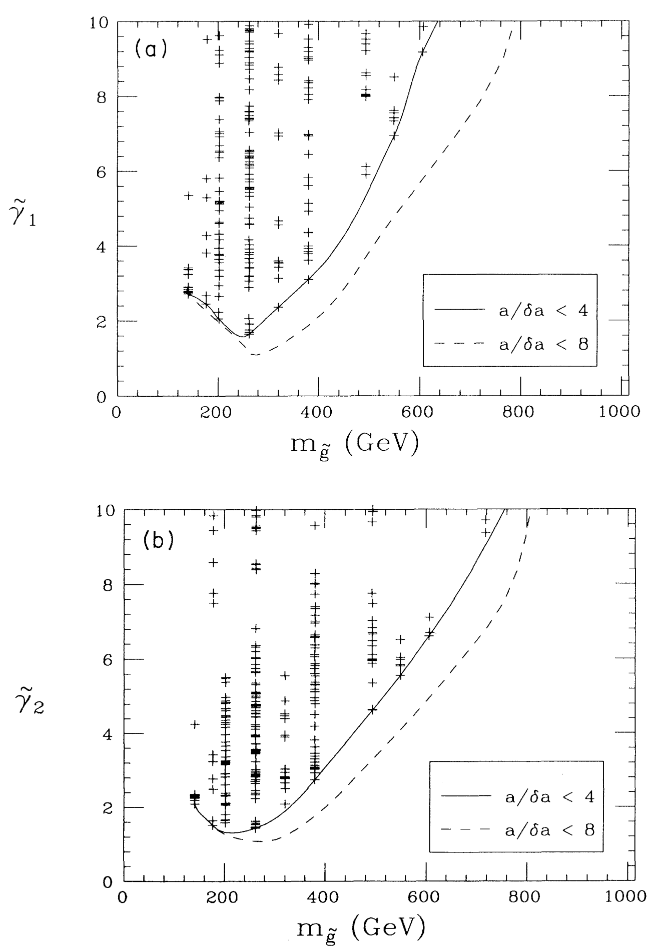

FIG. 2. (a,b) The fine-tuning measures $\gamma_{1,2}$ as a function of the gluino mass.

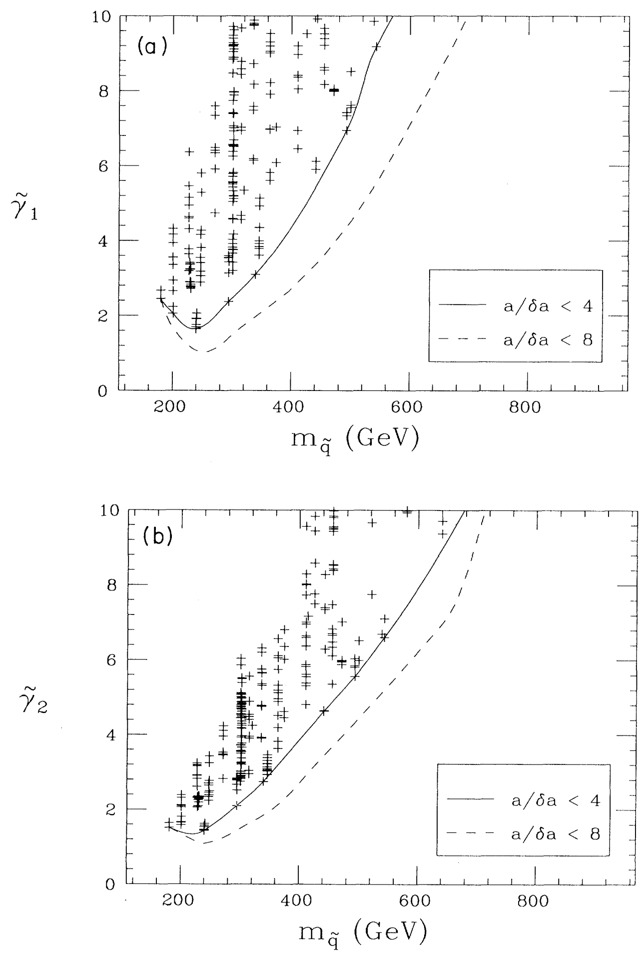

FIG. 3. (a,b) The fine-tuning measures $\gamma_{1,2}$ as a function of the lightest squark mass of the first two generations.

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[4]In fact, the original bound of $c < 10$ imposed by Barbieri and Giudice can no longer be satisfied. A calculation of the sensitivity of the Z mass with respect to m_0, $m_{1/2}$, y_t, and g_3 gives $\bar{c} > 30$ (see Fig. 1).

[5]This is a reflection of the fact that because the Z mass depends on several parameters, even if another variable is fixed, it is easy to find solutions where the Z boson's dependence on an isolated fundamental parameter is relatively insensitive.

approximately 2000 points discussed in Sec. III. We caution the reader that the density of these points is *not* an indication of how likely particular values of the superpartner masses or γ are. This is because the grid we have used is not completely uniform, and more importantly because the minimization conditions (3.4) and (3.5) have been used to determine the values of B_0 and μ_0. The dashed and dotted curves in these figures show the minimum fine-tuning necessary for a particular value of the superpartner mass. The likelihood or naturalness of a particular value of a superpartner mass scales like $1/\gamma$.

Figure 1 contrasts the sensitivity parameter c with our measure of fine-tuning γ. We see that currently viable solutions depend on at least one fundamental parameter in a fairly sensitive manner, however the fine-tuning curve, $\tilde{\gamma}$, shows that this sensitivity is not always unusual.

Figures 2(a) and 2(b) display the correlation between the gluino mass and the fine-tuning parameters $\tilde{\gamma}_1$ and $\tilde{\gamma}_2$. This plot and, unless otherwise noted, the following plots are constructed from solution points consistent with the current LEP limits on superpartner masses [10]. We have taken the limits on the sneutrino and the charged superpartner masses to be $M_Z/2$, and the lower limit on the light Higgs boson mass as 60 GeV. If no superpartner masses lie below these limits the most natural value of the gluino mass is about 260 GeV, above the published Collider Detector at Fermilab (CDF) limit of 141 GeV and also above the recently reported limit from DØ [11]. For potential, future search limits at the Tevatron see for example Ref. [12]. If we require that fine-tunings are at most a part in ten, the gluino mass should lie below $\sim 600-800$ GeV, a value that should be easily accessible at the LHC [13].

Figures 3(a) and (b) display the correlation between fine-tuning and the lightest squark mass of the first and second generation. The analogous plots for the top squark mass are shown in Figs. 4(a) and (b). The most natural value of the stop mass is around 220 GeV, and for the lightest of the remaining squarks it is about 240 GeV. This is close to the preliminary mass limit reported by DØ at Glasgow [11]. If we require that fine-tunings

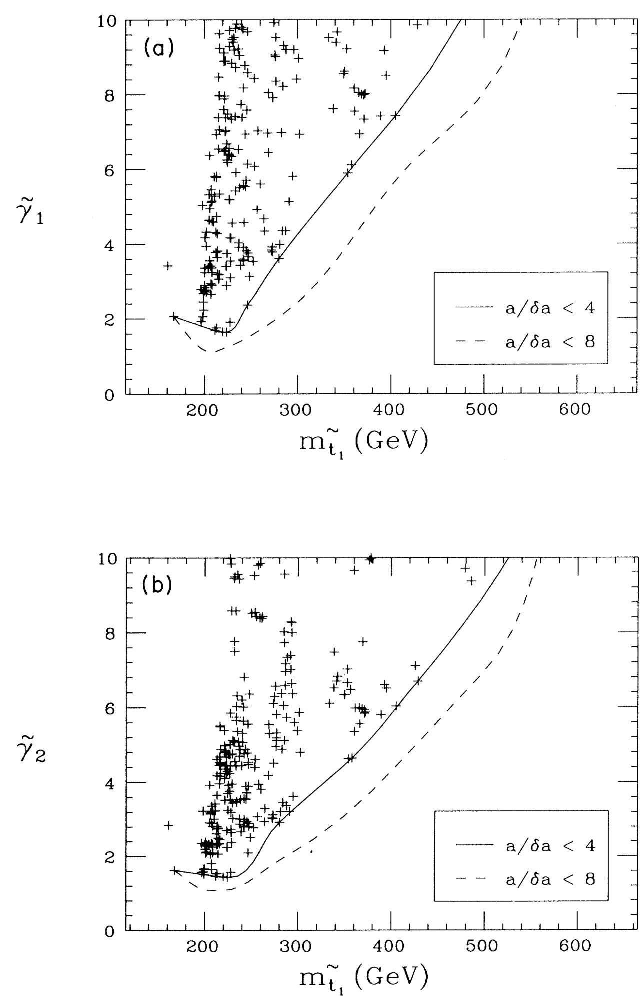

FIG. 4. (a,b) The fine-tuning measures $\gamma_{1,2}$ as a function of the lightest top squark mass.

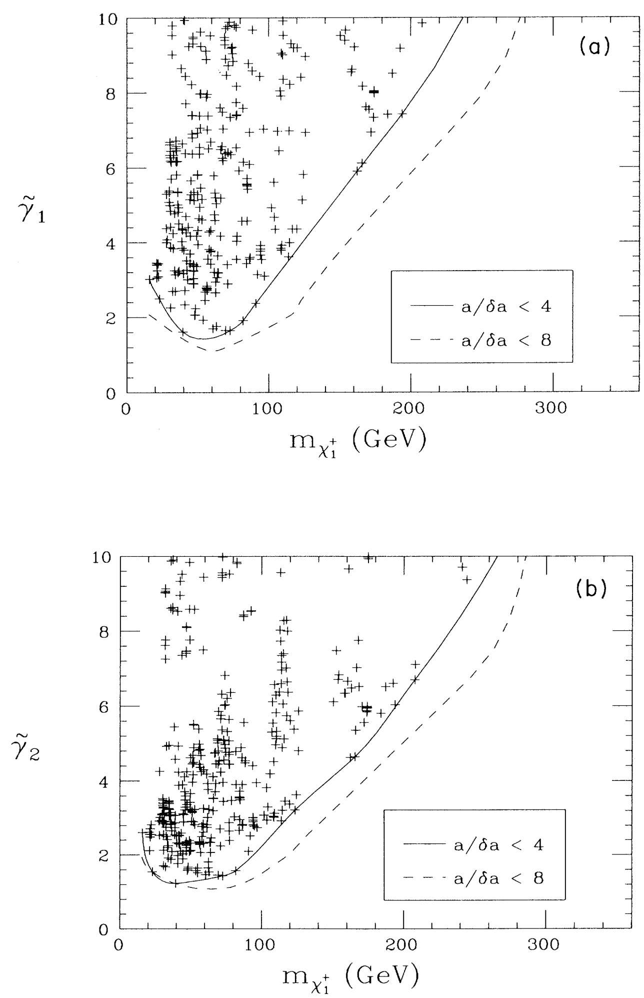

FIG. 5. (a,b) The fine-tuning measures $\gamma_{1,2}$ as a function of the lightest chargino mass.

are at most a part in ten, the stop mass should lie below $\sim 500-600$ GeV and the lightest of the remaining squark masses should lie below $\sim 600-800$ GeV.

Figures 5(a)–(b) display the correlation between fine-tuning and the lightest chargino mass. This plot displays solution points consistent with the LEP derived constraints on superpartner masses with the exception of the chargino mass. The most natural value of the lightest chargino mass, corresponding to the smallest $\tilde{\gamma}$, is around 50 GeV. Note that a significant region of the most natural solutions lie within the physics reach of LEP II, which should be able to search for charged particles up to the kinematic limit [14]. The lightest chargino mass should not exceed $\sim 200-300$ GeV if $\tilde{\gamma} < 10$.

Figures 6(a) and (b) display the correlation between fine-tuning and the mass of the lightest superpartner. The most natural value of the LSP mass appears to be around 42 GeV, and the theoretically favored values of the LSP mass are concentrated below 70 GeV. The LSP cannot be heavier than 150 GeV if $\tilde{\gamma} < 10$. This bound provides a more stringent limit than bounds set by the requirement that the LSP not overclose the Universe.

Figures 7(a) and (b) summarizes the mass predictions for all the superpartners. The upper and lower ends of the bars correspond to $\tilde{\gamma} < 10$ and the current experimental limits, respectively. The diamond point represents the $\tilde{\gamma} < 5$ mass limit, and the square represents the most natural value for the respective sparticle mass.

Finally, for completeness we display the correlation between the lower bound on fine tuning and the fundamental parameters m_0 and $|\mu_0|$ in Figs. 8 and 9.

V. CONCLUSIONS

As the mass limits on superpartners increase, it becomes increasingly difficult to accommodate a light weak scale naturally. We have presented a detailed study of

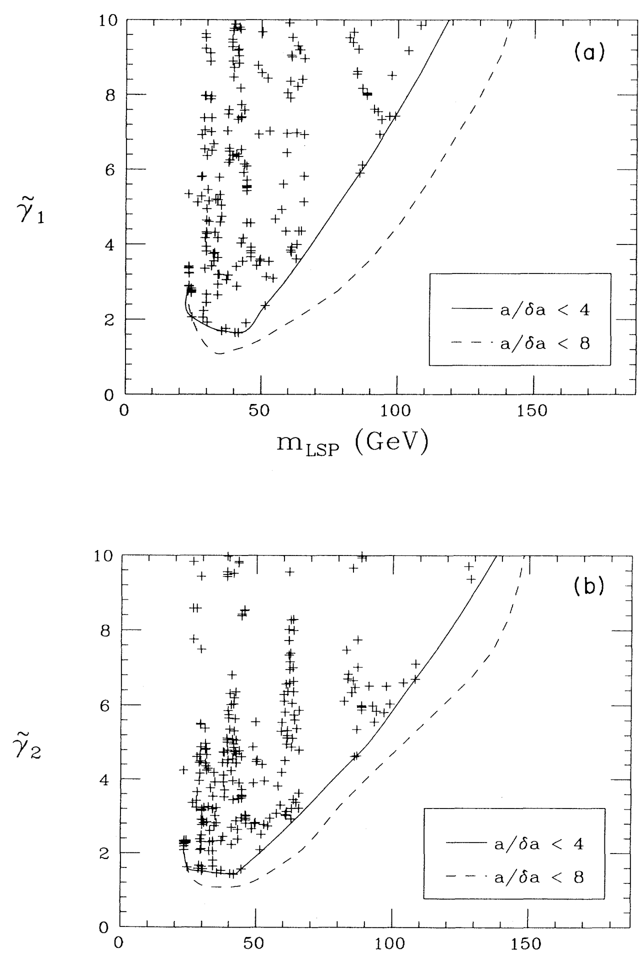

FIG. 6. (a,b) The fine-tuning measures $\gamma_{1,2}$ as a function of the lightest sparticle mass.

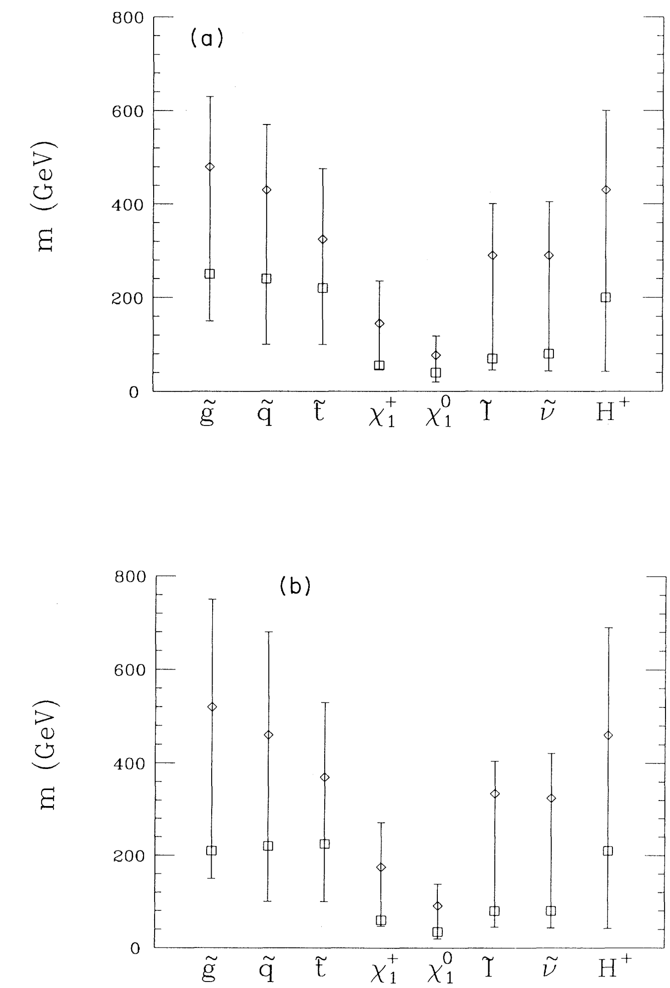

FIG. 7. (a,b) Superpartner mass ranges. The upper and lower ends of the bars correspond to $\tilde{\gamma} < 10$ and the current experimental limits, respectively. The diamond (square) represents the limit $\tilde{\gamma} < 5$ (the most natural value).

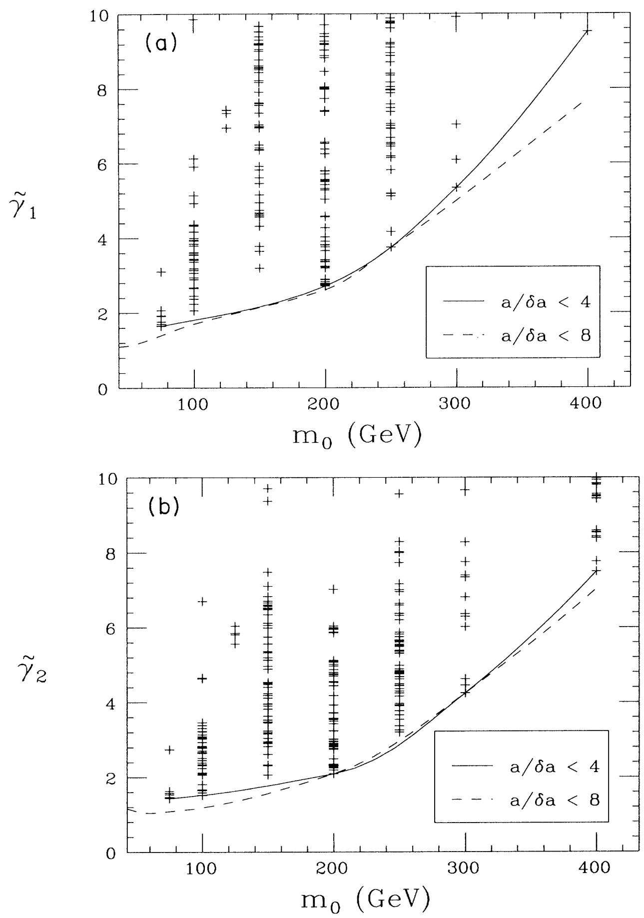

FIG. 8. (a,b) The fine-tuning measures $\gamma_{1,2}$ as a function of the common scalar mass m_0.

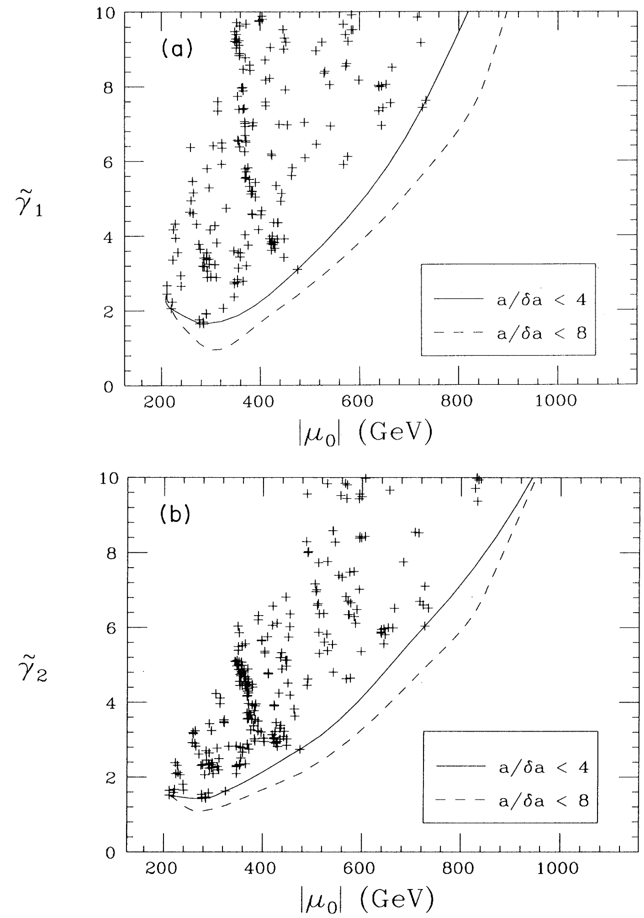

FIG. 9. (a,b) The fine-tuning measures $\gamma_{1,2}$ as a function of the mixing parameter $|\mu_0|$.

the relationship between superpartner masses and naturalness. This analysis demonstrates that supersymmetry cannot accommodate the weak scale without significant fine-tuning if superpartner masses lie beyond the physics reach of the LHC. In addition our analysis reveals that the most natural values of these masses often lie well below 1 TeV. We note that our limits are higher than those which would be obtained using conventional sensitivity criteria, but they lie below the bounds found in common folklore. In light of our results, we feel the potential for the discovery of physics beyond the standard model before the LHC is promising. However, this optimism should *not* be interpreted as a guarantee that LEP II or the Tevatron will see superpartners even in the case when supersymmetry is relevant to electroweak symmetry breaking.

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