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## THE FINE-TUNING PRICE OF LEP

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### ABSTRACT

We quantify the amount of fine tuning of input parameters of the Minimal Supersymmetric Extension of the Standard Model (MSSM) that is needed to respect the lower limits on sparticle and Higgs masses imposed by precision electroweak measurements at LEP, measurements of  $b \rightarrow X_s \gamma$ , and searches at LEP 2. If universal input scalar masses are assumed in a gravity-mediated scenario, a factor of  $\gtrsim 180$  is required at  $\tan \beta \sim 1.65$ , decreasing to  $\sim 20$  at  $\tan \beta \sim 10$ . The amount of fine tuning is not greatly reduced if non-universal input scalar Higgs masses are allowed, but may be significantly reduced if some theoretical relations between MSSM parameters are assumed.

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The measured magnitudes of the gauge coupling strengths are consistent with the presence of light sparticles within a supersymmetric GUT model [1], - for a recent updated analysis see [2] - and precision electroweak data are also consistent with a relatively light Higgs boson [3, 4] as predicted in the MSSM, but other *ad hoc* interpretations of these pieces of circumstantial evidence for low-energy supersymmetry are also possible. The primary phenomenological motivation for observable supersymmetric particles with masses  $\lesssim 1$  TeV is that they render  $M_W \ll M_{Pl}$  natural and thereby alleviate the fine tuning of input parameters required to keep  $M_W$  small. Some time ago, it was proposed [5, 6] that the amount of fine tuning be measured by the logarithmic sensitivity  $\Delta$  of  $M_Z$  to input model parameters  $a$ :  $\Delta \equiv |(a/M_Z^2)(\partial M_Z^2/\partial a)|$ , and the requirement that  $\Delta$  be not too large was used to motivate numerically the lightness of sparticles [5, 6, 7, 8].

This argument offered hope that some sparticles might be detected at LEP 2. At the time of writing, no such sparticles have been seen, nor have any Higgs bosons [9, 10], and precision electroweak measurements [11] and observations of  $b \rightarrow X_s \gamma$  decay [12] are consistent with the Standard Model. This depressing lack of evidence for supersymmetry is in *prima facie* disagreement with some of the previous optimistic suggestions [6, 8] motivated by the absence of fine tuning. How much should one worry about this apparent disappointment? The answer is necessarily subjective, since the fine-tuning argument is not a rigorous mathematical statement, but rather an intuitive physical preference. However, it is possible to make an objective contribution to the debate by quantifying the amount of fine tuning that is required by the data. The reader may then reach her/his own judgement how seriously to take the continued absence of supersymmetry.

This paper describes a first attempt to formulate the fine-tuning problem in this way. Our theoretical framework is that of supergravity with gravity-mediated supersymmetry breaking and universal gaugino masses  $M_{1/2}$  and trilinear (bilinear) supersymmetry-breaking parameters  $A_0$  ( $B_0$ ) at the input supergravity scale <sup>1</sup>. We shall for the most part assume universality also for the input scalar masses  $m_0$ , but shall also discuss the implications of relaxing this assumption for the Higgs scalar masses. The data we take into account include the latest set of precision electroweak data reported at the Jerusalem conference [11], which are dominated by those from LEP 1, the latest measurement of  $B(b \rightarrow X_s \gamma)$  by the CLEO collaboration [12], and the lower limits on sparticle and Higgs boson masses from LEP 2. For the latter, we again base ourselves on the data reported in Jerusalem [9], but also comment on the impact of more recent limits from LEP running at 183 GeV [10]. To set our results in context, we also remark on the inflation in the price of fine tuning since the initial LEP runs in 1990, and mention the potential implications of non-observation of supersymmetry when LEP 2 running is completed, and if no sparticles appear during Run II of the Tevatron.

At the present time, we find that a fine-tuning price  $\Delta \gtrsim 180$  must be paid if  $\tan \beta$  is close to its infra-red fixed-point value and universal boundary conditions are chosen for the input scalar masses  $m_0$ . This price is reduced to  $\Delta \simeq 60$  for  $\tan \beta = 2.5$ , and  $\Delta \simeq 20$  for  $\tan \beta = 10$ . The fine-tuning price is not decreased significantly if one allows the input scalar Higgs masses

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<sup>1</sup>Similar considerations may also be applied to gauge-mediated models, but lie beyond the scope of this paper.

to be non-universal, because there are additional parameters whose fine tuning must be taken into account in evaluating  $\Delta$ . In the absence of an objective criterion for interpreting  $\Delta$ , we observe that  $\Delta \sim 3$  was possible before LEP started setting limits on supersymmetry, and that if the remaining stages of LEP 2 do not find the lightest supersymmetric Higgs boson with a mass below 95 MeV, there will be lower bound  $\Delta \gtrsim 1000$  for  $\tan\beta \simeq 1.65$  and  $\Delta \gtrsim 130$  for  $\tan\beta = 2.5$ , though the impact will be less severe for larger values of  $\tan\beta$ . For higher values of  $\tan\beta$  ( $\sim 10$ ), the minimal amount of fine tuning is for  $M_h \approx 105$  GeV. The non-observation of gluinos and squarks at the FNAL Tevatron collider during Run II would not increase the fine-tuning price much further. Non-universal boundary conditions for the Higgs scalar masses do not reduce greatly the fine-tuning price, but it could be reduced significantly if there was some theoretical relation between the input MSSM parameters.

Before discussing our analysis in more detail, we first specify more precisely the fine-tuning criterion we use. Following [5, 6, 8], we consider the logarithmic sensitivities of  $M_Z$  with respect to variations in input parameters  $a_i$ :

$$\Delta_i = \left| \frac{a_i}{M_Z^2} \frac{\partial M_Z^2}{\partial a_i} \right| \quad (1)$$

and then define

$$\Delta = \max_i \Delta_i \quad (2)$$

In the specific case of the MSSM with universal gaugino and scalar masses ( $M_{1/2}, m_0$ ) at the input supergravity scale and a universal trilinear (bilinear) supersymmetry-breaking parameter  $A_0$  ( $B_0$ ), we consider the following input parameters  $a_i$ :

$$(M_{1/2}, m_0, \mu_0, A_0, B_0) \quad (3)$$

and we use the tree level formula for the scalar Higgs potential, with parameters renormalized at the electroweak scale <sup>2</sup>. The  $\Delta_i$  are calculated as in ref. [8], with the dependence of  $\tan\beta$  on the input parameters taken into account, from the master formula

$$\Delta_i = \left| \frac{2a_i}{(\tan^2\beta - 1)M_Z^2} \left\{ \frac{\partial m_1^2}{\partial a_i} - \tan^2\beta \frac{\partial m_2^2}{\partial a_i} - \frac{\tan\beta}{\cos 2\beta} \times \left( 1 + \frac{M_Z^2}{m_1^2 + m_2^2} \right) \left[ 2 \frac{\partial m_3^2}{\partial a_i} - \sin 2\beta \left( \frac{\partial m_1^2}{\partial a_i} + \frac{\partial m_2^2}{\partial a_i} \right) \right] \right\} \right| \quad (4)$$

where the  $m_i^2$  are the mass parameters of the Higgs potential of the MSSM.

We now review in more detail the data set used in our analysis. As already mentioned, we use the precision electroweak data set reported at the Jerusalem conference [11, 4]. As is well known, the data set are fitted well by the Standard Model with a value of the Higgs mass compatible with MSSM predictions, and measurements of  $Z^0 \rightarrow \bar{b}b, \bar{c}c$  decays no longer give any hint of new physics beyond the Standard Model. We constrain MSSM parameters by requiring

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<sup>2</sup>The full one-loop corrections to the scalar potential relax the degree of fine tuning by 20-30% [13]. We ignore this effect here, since it is inessential for our conclusions.

that  $\Delta\chi^2 < 4$  in a global MSSM fit [14]. The main effect of this constraint is a lower bound on the left-handed stop,  $M_{\tilde{t}_L} \gtrsim 300 - 400$  GeV [15, 16]. We also take into account the direct LEP 2 lower limits on the masses of sparticles and Higgs bosons that were also reported at Jerusalem. Qualitatively, these impose  $M_{1/2} \gtrsim 100$  GeV but still allow  $m_0 \rightarrow 0$  in the absence of other constraints. As we shall see, an important rôle can be played by searches for MSSM Higgs bosons. However, the preliminary results from data taken around 183 GeV in centre-of-mass energy, although representing a significant advance on the Jerusalem data by imposing  $M_h \gtrsim 75$  GeV, are still insufficient to increase the fine tuning price beyond that already required by the rest of the constraints. For that, one must wait for further upgrades of the LEP 2 energy.

The final accelerator constraint we use is the measured value of  $1 \times 10^{-4} < B(b \rightarrow X_s \gamma) < 4.2 \times 10^{-4}$  at 95% C.L. [12]. The interpretation of this measurement in the MSSM is still subject to some uncertainty, because not all the  $\mathcal{O}(\alpha_s)$  corrections have yet been calculated. Resumming large QCD logarithms up to next-to-leading order (NLO) accuracy has been recently accomplished in the SM [17]. All these calculations are identical in the SM and the MSSM except for that the initial numerical values of the Wilson coefficients at the scale  $\mu \approx M_W$  are different. In our analysis we have used for them only the leading order results available in the MSSM. The uncertainty due to order  $\alpha_s/\pi$  corrections to them has been, however, included as in ref. [18, 16]. Those references also contain extensive discussion of the role played by the  $b \rightarrow s\gamma$  measurement in constraining the parameter space of the MSSM.

An important rôle may also be played by non-accelerator constraints, in particular the relic cosmological density of neutralinos  $\chi$ , if these are assumed to be the lightest supersymmetric particles, and if  $R$  parity is absolutely conserved. Both of these assumptions may be disputed, and a complete investigation of astrophysical and cosmological constraints is beyond the scope of this analysis. We limit ourselves to a qualitative discussion based on the requirement that  $0.1 \leq \Omega_\chi h^2 \leq 0.3$ , where  $\Omega_\chi$  is the density of neutralinos relative to the critical density, and  $h$  is the present Hubble expansion rate in units of  $100 \text{ kms}^{-1} \text{ Mpc}^{-1}$ . Previous discussions [19] have indicated that this requirement can be satisfied for some parameter choices in the ranges  $0.2 \lesssim m_0/M_{1/2} \lesssim 1$  and  $M_{1/2} \lesssim 450$  GeV. We comment later on the potential impact of these constraints.

We illustrate our discussion of fine tuning by discussing three specific choices of  $\tan\beta$ : 1.65, which is favoured by an infra-red fixed-point analysis and on the verge of being excluded by a more detailed analysis of the compatibility between accelerator and astrophysical constraints, an intermediate choice  $\tan\beta = 2.5$ , and a higher value  $\tan\beta = 10$ . The discussion of larger values of  $\tan\beta$  requires a more complete treatment of the renormalization-group equations below the supergravity scale, which is beyond the scope of this paper.

The case  $\tan\beta = 1.65$  with universal input scalar masses is displayed in Fig. 1. Panel (a) shows the  $(\mu, M_2)$  plane, including the boundaries of the regions excluded by direct LEP searches for charginos and neutralinos now and at LEP 1. We see that the combination of the requirement of the proper electroweak breaking (which is possible only for  $\mu > M_{1/2}, m_0$ ), precision electroweak data and the  $b \rightarrow X_s \gamma$  constraint disallow regions of low  $\mu$  and  $M_2$  that were not excluded by the direct searches, particularly for  $\mu < 0$ . Panel (b) exhibits a strong

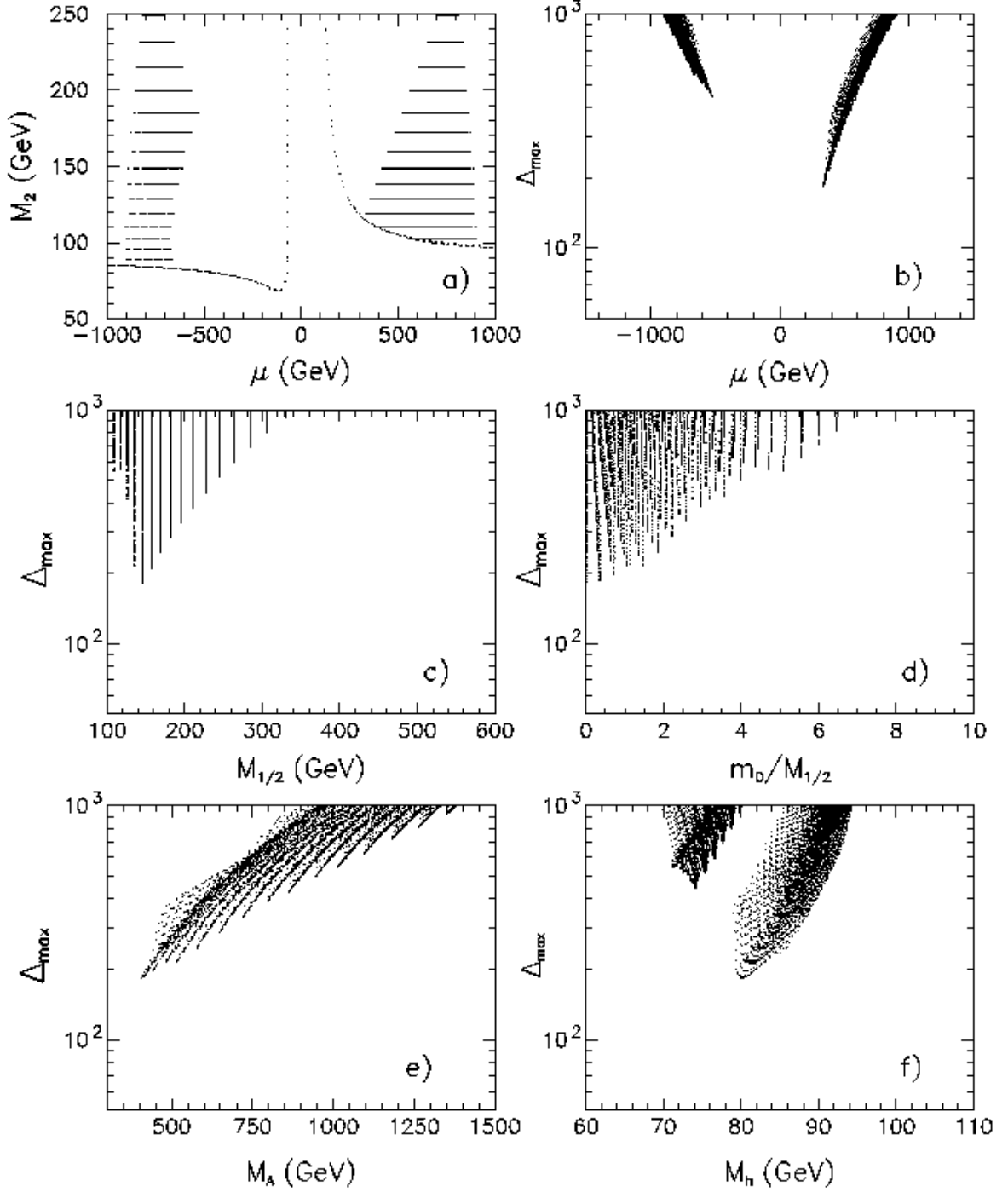


Figure 1: The price of fine tuning for  $\tan\beta = 1.65$ , assuming universal input scalar masses at the supergravity scale. Panel (a) displays the regions of the  $(\mu, M_2)$  plane that are allowed by LEP 2, and the restricted regions permitted when the other constraints discussed in the text are implemented. The other panels display the ranges of the fine-tuning parameter  $\Delta$  obtained as functions of (b) the Higgs mixing parameter  $\mu$ , (c) the input gaugino mass parameter  $M_{1/2}$ , (d) the ratio of the universal scalar mass  $m_0$  to  $M_{1/2}$ , (e) the CP-odd neutral Higgs mass  $M_A$ , and (f) the lightest neutral Higgs mass  $M_h$ .

correlation between  $\Delta$  and  $|\mu|$ , that  $\Delta$  increases as  $|\mu|$  increases, and that more fine tuning is required for negative values of  $\mu$ . Panel (c) displays possible values of  $\Delta$  versus values of  $M_{1/2}$ . We see that the minimal values of  $\Delta$  are for  $M_{1/2} \approx 140$  GeV, and that they increase rapidly for smaller or larger  $M_{1/2}$ . The increase for increasing  $M_{1/2}$  has an obvious reason, whereas that at low values of  $M_{1/2}$  is due to the constraints discussed above, which in that case require a larger value of  $m_0$ . Panel (d) displays values of  $\Delta$  versus the ratio  $m_0/M_{1/2}$ , where we see little dependence for  $m_0/M_{1/2} < 2$ , whilst the fine-tuning price increases for larger values of this ratio. Panel (e) shows a correlation of  $\Delta$  with the CP-odd neutral Higgs mass  $M_A$ : lower values of  $M_A$  are disallowed by the  $b \rightarrow X_s \gamma$  constraint. Finally, panel (f) shows the variation of  $\Delta$  with the mass of the lightest MSSM Higgs boson  $M_h$ . The two populated regions correspond to the different signs of  $\mu$ : since  $A_t$  is essentially determined by  $M_{1/2}$  in the neighbourhood of the fixed point, these different signs correspond to different amounts of  $\tilde{t}$  mixing, and hence different ranges of  $M_h$ . We see that  $\Delta$  increases with  $M_h$ , as might be expected from the sensitivity of  $M_h$  to  $m_0$  and  $M_{1/2}$  via radiative corrections, and the dependences of  $\Delta$  on  $M_{1/2}$  and  $m_0$  seen in panels (c) and (d). As the LEP 2 energy increases, and correspondingly the experimental sensitivity to  $M_h$ , continued non-observation of the lightest MSSM Higgs boson would increase significantly the fine-tuning price imposed by LEP.

Figure 2 displays corresponding panels for the choice  $\tan\beta = 2.5$ . Panel (a) shows that the non-LEP constraints exclude a smaller region of the  $\mu, M_{1/2}$  plane for negative  $\mu$  than was the case for smaller  $\tan\beta$ . This is reflected in a reduction in the minimum fine-tuning price to  $\Delta \simeq 60$ , as we see in the other panels. We see that this is attained when  $M_{1/2} \sim 100 - 140$  GeV [panel (c)] and also  $m_0 \sim 300 - 400$  GeV corresponding to a relatively large value of  $m_0/M_{1/2} \sim 3 - 4$  [panel (d)]. Finally, we note in panel (f) that the minimum value of  $\Delta$  is attained when  $M_h \sim 85$  GeV, beyond the current reach of LEP but accessible to future LEP 2 upgrades. Beyond this value of  $M_h$ , the fine-tuning price increases significantly, though it is always less than for  $\tan\beta = 1.65$ , reflecting less need for large values of  $m_0$  and  $M_{1/2}$  to yield the same value of  $M_h$  via radiative corrections.

The corresponding analysis for  $\tan\beta = 10$  is displayed in Fig. 3. We see in panel (b) that the correlation between  $\Delta$  and  $\mu$  has now become very tight, and note in panel (c) a familiar tendency for  $\Delta$  to increase with  $M_{1/2}$ , once a minimum around 140 GeV has been passed. The minimum in panel (d) is for  $m_0/M_{1/2} \sim 2$  to 5 and it is somewhat more pronounced than for smaller  $\tan\beta$ . Panel (b) shows the same correlation between  $\Delta$  and  $\mu$  as for other values of  $\tan\beta$ . Finally, we see in panel (f) that  $\Delta$  is minimized when  $M_h \sim 105$  to 110 GeV, which is probably beyond the reach of LEP 2.

Figure 4 assembles our information on the minimum value of  $\Delta$  as a function of  $\tan\beta$ . The current lower limit, assuming universal input scalar masses and the current data set reviewed earlier, is shown in the left panel as a solid line. The fine-tuning price is not strongly dependent on  $\tan\beta$ , except for  $\tan\beta \lesssim 3$ . Also shown in Fig. 4 as a dashed line is the fine-tuning price that was imposed by the first round of direct searches at LEP 1, which we model crudely by the requirement that all charged and strongly-interacting sparticles weigh  $\gtrsim 45$  GeV. Since these early were much less constraining, they corresponded to a much smaller fine-tuning price, and we see that  $\Delta \lesssim 30$  was possible for all the values of  $\tan\beta$  above the infra-red fixed point. The

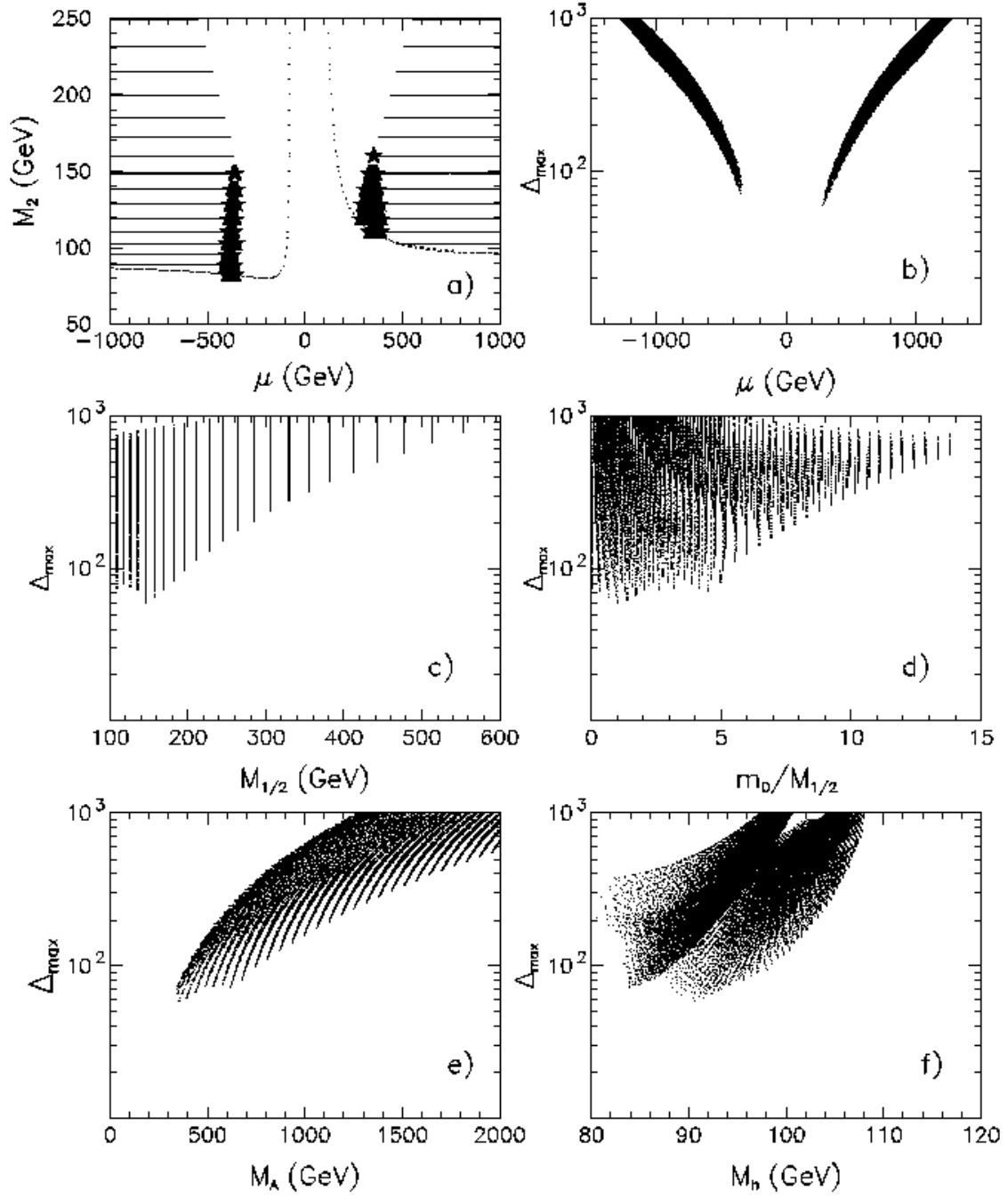


Figure 2: As for Fig. 1, but for the value  $\tan\beta = 2.5$ . Black stars in panel (a) correspond to points with  $\Delta < 100$ .

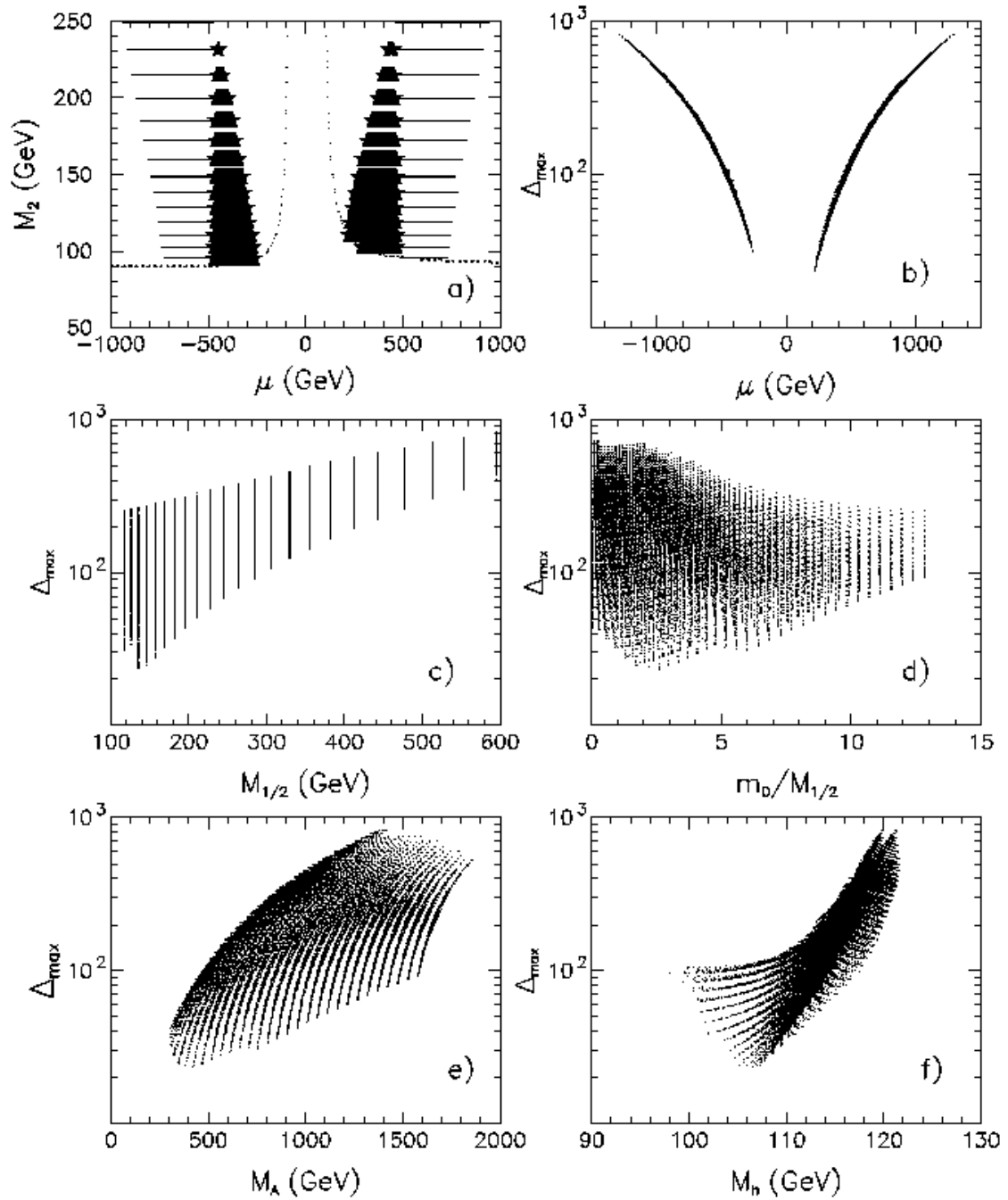


Figure 3: As for Figs. 1 and 2, but for the value  $\tan\beta = 10$ . Black stars in panel (a) again correspond to points with  $\Delta < 100$ .



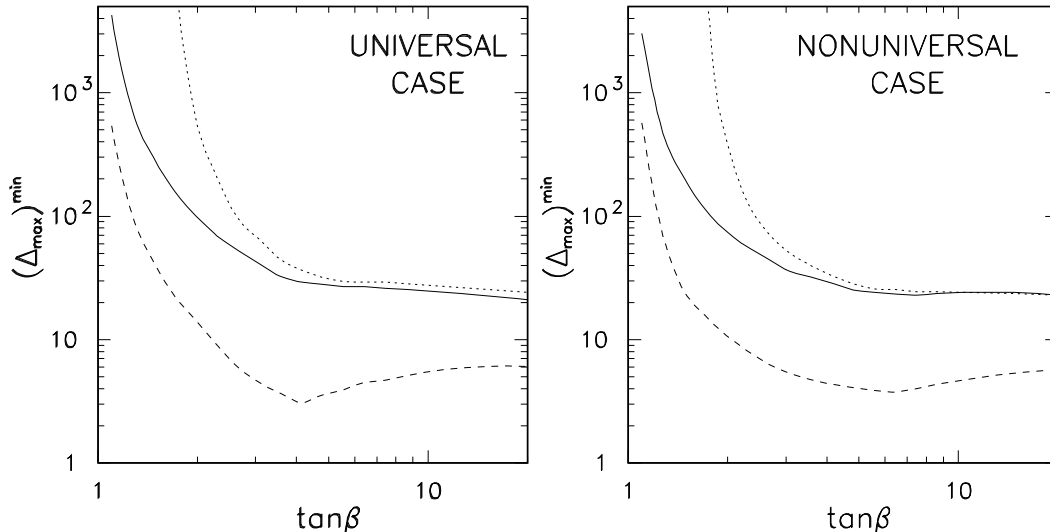


Figure 4: Compilation of the minimal values of the fine-tuning parameter  $\Delta$  as a function of  $\tan\beta$ . The left panel is for the case of universal scalar masses, with the current constraints from LEP,  $b \rightarrow X_s \gamma$ , etc., shown as a solid line. The dashed line is for the constraints that were available after the initial runs of LEP 1, and the dotted line indicates what might be the situation if no evidence for sparticles or MSSM Higgs bosons is found with future upgrades of LEP 2. The right panel shows the corresponding lower limits on  $\Delta$  for the case of non-universal Higgs masses, using the same conventions for the lines.

dotted line in Fig. 4 shows the fine-tuning price that may need to be paid if LEP 2 does not find any sparticles or a MSSM Higgs boson in future runs at centre-of-mass energies  $\lesssim 200$  GeV. We see that  $\Delta$  could be increased significantly at low  $\tan\beta$ , principally as a result of the increase in the LEP 2 reach in  $M_h$  to about 100 GeV. LEP 2 has already raised significantly the price of fine tuning, particularly at low  $\tan\beta$ , and the price for  $\tan\beta \lesssim 2$  could become exorbitant if no discovery is made with the remaining LEP 2 energy upgrades. If one assumes that the principal constraint imposed by the FNAL Tevatron Run II will be  $M_{1/2} \gtrsim 150$  GeV and that, for example, the reach in  $M_h$  will not greatly exceed that of LEP 2, the fine-tuning price would not increase at small values of  $\tan\beta$ , but there could be a marginally increased price at intermediate  $\tan\beta$ .

We have not included in the above analysis the requirement that the relic neutralino density fall in the range  $0.1 < \Omega_\chi h^2 < 0.3$ . As already mentioned, this may occur for  $0.2 \lesssim m_0/M_{1/2} \lesssim 1$ , with larger values of  $m_0/M_{1/2}$  corresponding to unacceptably large values of  $\Omega_\chi h^2$ . Looking at panels (d) of Figs. 1,2 and 3 we see that this restriction on  $m_0/M_{1/2}$  increases the fine-tuning price noticeably only when  $\tan\beta \sim 10$ , resulting in a small increase in the global minimum value of  $\Delta$ . A complete implementation of the relic-density constraint could only increase still further the fine-tuning price, but such an analysis is beyond the scope of this paper.

We comment now on the possibility of non-universal input scalar masses for the Higgs mul-

triplets  $m_{H_i}^2 \neq m_0^2$ ,  $i = 1, 2$ . One would think that the introduction of the two new parameters  $m_{H_i}^2$  must enable one to find parameter sets that require less fine tuning. However, the appearance of the  $m_{H_i}^2$  is accompanied by two additional sensitivity parameters  $a_i$  which must also be taken into account when evaluating  $\Delta$ . We recall that  $\Delta$  is defined as the *maximum* of the sensitivities  $|(a_i/M_Z^2)(\partial M_Z^2/\partial a_i)|$  (2). This means that  $\Delta$  could in principle even be *increased* by the introduction of the  $m_{H_i}^2$ . Fig. 5 shows our results for  $\tan\beta = 1.65$  with non-universal boundary conditions: after all cuts, the results are similar to those for universal scalar masses, though with a slight decrease in the minimal  $\Delta$ . The most interesting point about non-universal Higgs boson masses is that the region of small  $M_{1/2}$  and small, negative  $\mu$  is consistent with the requirement of the proper electroweak breaking but not with the experimental cuts other than the limit on the chargino mass. After the cut  $\Delta\chi^2 < 4$  and/or  $M_h > 75$  this region is disallowed as for the universal case. It would be allowed by all the cuts only after radical departure from the universality among the squark masses [20], which would increase the fine-tuning price.

Results for  $\Delta$  for other values of  $\tan\beta$  and choices of data sets are shown in the right panel of Fig. 4. Although there are differences in detail, the general trends are similar to those for the universal case shown in the left panel. We conclude that increasing the number of parameters in this way does not reduce significantly the fine-tuning price.

We have stressed already that fine tuning is a subjective issue: there is no unambiguous method for evaluating it, and there is no objective criterion for deciding when the price is too high. Moreover, if one or more of the parameters  $a_i$  is fixed by some external condition such as some more sophisticated theoretical assumption,  $\Delta$  may well be reduced. We can illustrate this point by calculating  $\Delta$  under the hypothetical assumption that some theory predicts a relation between a pair of the five parameters, so that we have now only four independent input parameters. For example, if there is a linear relation<sup>3</sup> between  $\mu$  and  $M_{1/2}$ , we find results that are qualitatively similar to those shown in Fig. 1 for  $\tan\beta = 1.65$ , but with the minimum value of  $\Delta$  reduced by a factor  $\sim 4$ . We have also found that  $\Delta$  could be reduced by postulating a linear relation between  $\mu$  and  $B_0$ , but this is mainly for low values of  $M_h$  that are apparently excluded by the latest LEP 2 limits [10].

In this paper we have made a first attempt to pose the experimental constraints on fine tuning in an objective way. We have seen that LEP 2 has raised the fine-tuning price by a significant factor, particularly at low  $\tan\beta$  close to the infra-red fixed point. We have seen that important rôles in this price rise has been played by precision measurements, the observation of  $b \rightarrow X_s\gamma$  decay and to some degree the non-observation of the lightest MSSM Higgs boson. The price could rise again if the Higgs boson is not discovered with subsequent runs of LEP 2 at higher energies. Moreover, the price is not reduced by postulating non-universal boundary conditions for the Higgs scalar masses, and could be further increased if one imposes an astrophysical requirement on the relic neutralino density.

Personally, we do not find the present fine-tuning price too high, particularly for  $\tan\beta \gtrsim 2.5$ . The price rise at low  $\tan\beta$  does diminish somewhat the attraction of the infra-red fixed

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<sup>3</sup>The requirement of the electroweak symmetry breaking selects approximately such a subspace in the parameter space [21].

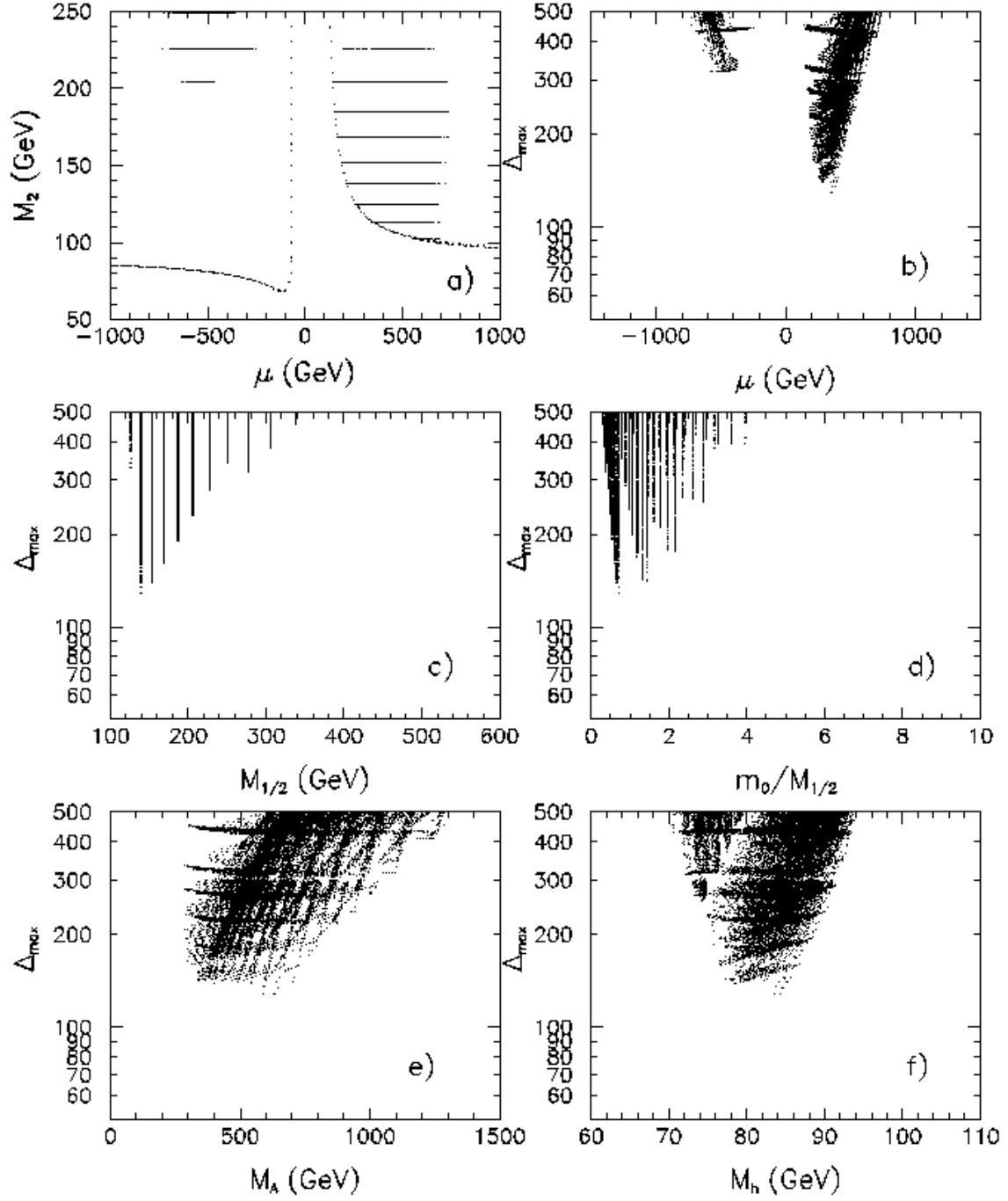


Figure 5: As for Fig. 1, but now with non-universal input scalar masses for the Higgs multiplets:  $m_{H_i}^2 \neq m_0^2$ ,  $i = 1, 2$ . In panel (a), only points with  $\Delta_{max} < 500$  are displayed.

point. However, this is a luxury model with added features, so the reader may be prepared to pay a higher price for it! Alternatively, some more predictive theory may correlate some of the five MSSM parameters that are currently regarded as independent, which may reduce  $\Delta$  significantly.

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