New Bounds on Slepton and Wino Masses in Anomaly Mediated Supersymmetry Breaking Models

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We show how the spectrum of the minimal anomaly-mediated supersymmetry breaking model can be constrained from the condition that the electroweak symmetry breaking minimum of the scalar potential is the deepest point in the field space. Applying the current experimental bounds and scanning over the whole parameter space, we rule out selectrons below 378 GeV and staus below 269 GeV, the numbers having a modest uncertainty. We also find a new upper bound on the wino-like chargino mass for a given slepton mass. This rules out the possibility of slepton pair production at ongoing or upcoming colliders like the Tevatron or the Next Linear Collider at $\sqrt{s} = 500$ GeV, where pair production of charginos may be the only available signal.

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Supersymmetry (SUSY), if it exists, must be broken, and this breaking cannot take place in the observable sector (OS). Thus one envisages a hidden sector (HS), whose fields are all singlets under the SM gauge group, where SUSY is broken. The key question is how to convey the breaking to the OS. One option is to consider a contact interaction between the HS and the OS fields in the Kahler potential, suppressed by the Planck mass squared. This tree-level interaction induces SUSY breaking in the OS; such models are generically known as supergravity (SUGRA) type models, where the gravitino mass is of the order of 1 TeV.

Recently, one came to note that if the OS and the HS live in two distinct 3-branes separated by a finite distance along a fifth compactified dimension, there is no tree-level term in the Kahler potential that transmit SUSY breaking from the HS to the OS. However, a superconformal anomaly may induce the SUSY breaking in the OS (this term is present in the SUGRA type models too, but is suppressed in comparison to the usual soft-breaking terms). To generate the weak scale masses of the sparticles, the gravitino mass must be of the order of tens of TeV. Such models are generically known as anomaly-mediated SUSY breaking (AMSB) models [5,6].

AMSB, alongwith the radiative electroweak symmetry breaking condition, should fix the sparticle spectrum completely in terms of three parameters: $m_{3/2}$ (the mass of the fermionic component of the compensator superfield, and equal to the gravitino mass), $\tan\beta$ (ratio of the vacuum expectation values (VEV) of the two Higgs fields), and $sign(\mu)$. The gaugino masses M_1, M_2 and M_3, and the trilinear couplings (generically denoted by A) can be obtained from the relevant renormalization group (RG) β-functions and anomalous dimensions. The sfermion masses, as well as the Higgs mass parameters, are also determined by $m_{3/2}$; unfortunately, for sfermions that do not couple to asymptotically free gauge groups (*i.e.*, both right and left sleptons), the masses come out to be tachyonic. The remedy is sought by putting a positive definite mass squared term m_0^2 in the GUT scale boundary conditions. This is not exactly an *ad hoc* prescription; there are a number of physical motivations for the introduction of such a term, mostly related to the presence of extra field(s) in the bulk. Such models with a universal m_0 for all scalars are called the minimal AMSB (mAMSB) models [5,6]. The phenomenology of such models has been at the focus of attention of many recent works [7–12], and we also confine our discussions within the scope of mAMSB models.

With four free parameters in the model, one can determine the complete particle spectrum. A few key observations can be immediately made [5–9]:

(i) The lighter chargino $\tilde{\chi}^{\pm}$ is almost degenerate with the lightest neutralino $\tilde{\chi}_1^0$, which we assume to be the lightest supersymmetric particle (LSP). Both of them are heavily dominated by the wino component. The near degeneracy leads to the most striking experimental signature of AMSB models, based on the "nearly invisible" decay of the relatively long lived $\tilde{\chi}^{\pm}$ to the LSP and a soft charged pion [13]. A heavily ionizing charged track in the vertex detector ending in a soft pion is taken to be the smoking gun of such models.

(ii) M_1, M_2 and M_3 increase with $m_{3/2}$ but are insensitive to m_0 for all practical purpose.

(iii) Sfermion masses increase linearly with m_0, but also depend on the precise value of $m_{3/2}$.

(iv) Right and left sleptons of the first two generations are highly degenerate. Stau is the lightest slepton.

From these observations one can understand the currently available bounds on the mAMSB spectrum and the correlations among them. They are summarized in the following (see Figure 1):

(a) There is a lower limit on $m_{3/2}$ coming from the lower bound $m_{\tilde{\chi}^{\pm}}^{min} = 86$ GeV [14] on charginos decaying through the soft pion mode from direct searches at LEP. This limit depends on a number of uncertainties to be elaborated below, but is $\sim$ 28-32 TeV. Region III of Fig. 1 is ruled out by this constraint.

(b) For a given $m_{3/2}$, there is a lower bound on m_0 below which either lighter stau($\tilde{\tau}_1$) is the LSP or sleptons

would have been observable at present-day colliders. This is shown as the boundary between regions II and IV in Fig. 1.

(c) For a very limited region of the parameter space with $\tan\beta \approx 3$ and relatively small $m_{3/2}$, a further region is ruled out [12] from the bound on neutral Higgs mass from LEP (106 GeV for small $\tan\beta$ and 88 GeV for large $\tan\beta$) [15]. The limit disappears for larger $m_{3/2}$ and/or large $\tan\beta$. Thus over a significant region of the currently available allowed parameter space (APS), sleptons as light as 150 GeV cannot be ruled out.

The main result of this letter is that over the whole APS there is a rather stringent lower bound on the slepton mass with important bearings on the search prospects at present or future colliders. An interesting upper bound on the wino mass also emerges. The main ingredient of our analysis is the so-called "unbounded from below" (UFB) directions of the scalar potential.

The real minimum of the SUSY scalar potential occurs along the direction where only the neutral components of two Higgs fields acquire nonzero VEVs. However, with a number of other scalar fields in the theory carrying charge and/or color, it may be possible to find some other direction(s) where nonzero VEVs to the corresponding scalar fields make the potential deeper than the real minimum, or even unbounded from below.

It is well known that the determination of these dangerous direction from the tree-level potential alone may not be reliable [16], and at least one-loop corrections should be included to get approximately reliable results. The addition of such terms on the other hand makes the minimization program rather involved and practically undoable when a large region of the parameter space has to be scanned. As a compromise the tree-level potential is analyzed at an optimum mass scale where the one-loop corrections are estimated to be small. If for a particular choice of the SUSY parameters, one gets even one such UFB direction, that set is not allowed.

UFB directions were classified in broadly three categories in a model independent way by Casas *et al* [17]. They are chosen in such a way that the F terms are zero and the D terms either vanish or are kept under control. These directions, known as UFB-1,2 and 3 (eqs. (20), (26) and (33) of [17]), are characterized by nonzero VEVs of the Higgs fields as well as of various slepton and/or squark fields.

Casas *et al* illustrated the constraints emerging from various UFB conditions numerically in the context of SUGRA models with a common scalar mass (m_0) and low values of $\tan\beta$ only. This work was supplemented by considering large values of $\tan\beta$ motivated by possible b-τ and t-b-τ Yukawa unification scenarios in context of SO(10) GUTs [18]. However, in such models, the common trilinear coupling at the GUT scale, A_0, is a free parameter, and the applicability of the UFB conditions depend crucially on the value of A_0. For example, they

are quite restrictive for negative A_0 but loses their constraining power for $A_0 > 0$ [18].

It is precisely here that the AMSB models score over the SUGRA ones. For, in AMSB models, A-terms at the GUT scale (they do not unify, by the way) are not free parameters but are completely determined by the other four free parameters of the theory. Thus, the constraints that one may obtain on the APS are independent of one major source of uncertainty in the SUGRA models.

In this letter we find strong limits on m_0 for various values of $m_{3/2}$, $\tan\beta$ and $sign(\mu)$. The physical spectrum as well as the values of the running masses at different energy scales are determined with the ISAJET 7.51 code [11]. We demand the tree-level minima of the potential along an UFB direction (evaluated at a properly chosen scale Q_c as discussed above), to be always shallower than the true minimum evaluated at a scale $Q_r = \sqrt{m_{\tilde{t}_L} m_{\tilde{t}_R}}$. In presenting our results (fig. 1 and the tables) we follow the prescription laid down by Casas *et al* in choosing the scale Q_c (eq. 33 of [17]). This prescription, however, gives an order of magnitude estimate of Q_c rather than a precise value. Therefore, to check the robustness of our limits, we enforce the condition $V_{UFB}(Q_{UFB}) < V_{realmin}(Q_r)$ for Q_{UFB} varying from $10Q_c$ to $Q_c/10$. This, we think, is rather conservative and shall quote below the possible relaxation of our limits.

The allowed and ruled out regions of the parameter space are shown in Fig. 1 for $\tan\beta = 5$ and the choice of Q_c as stated above. μ is taken to be negative, but the bounds are not very sensitive on the sign of μ (see below). The main characteristics that follow from the figure are as follows:

(i) There is a lower bound on m_0 for a particular value of $m_{3/2}$, and this bound increases almost linearly with increasing $m_{3/2}$. This is because for low m_0, the sum of the Higgs mass parameter squared $m_{H_2}^2$ and the left-handed slepton mass squared $m_{L_i}^2$ (see eq. (33) of [17]) becomes so negative as to violate the UFB-3 constraint. Thus, there exists a minimum value of m_0 (indicated by the boundary between regions I and II in Fig. 1) above which the real minimum of the scalar potential is the deepest point in the field space. This strong lower bound comes for $m_{3/2}$ corresponding to $m_{\tilde{\chi}^\pm}^{min}$. Translated into slepton masses, the bound reads $m_{\tilde{e}} \geq 425$ GeV and $m_{\tilde{\tau}_1} \geq 416$ GeV.

(ii) For a given $m_{3/2}$, larger $\tan\beta$ leads to stronger lower bounds on m_0 (see Table 1). This is due to the fact that the stau becomes lighter as $\tan\beta$ increases which makes the UFB-3 condition more restrictive.

(iii) For a given slepton mass, there exists both lower and upper limits on the chargino mass. The lower limit comes from $m_{\tilde{\chi}^\pm}^{min}$. We find a strong upper limit too on $m_{\tilde{\chi}^\pm}$; above this, the UFB conditions are violated (see Table 2).

(iv) The UFB-3 constraint, by itself, ensures a neutralino LSP; one need not separately impose the condition that slepton/sneutrino should not be the LSP. In other words, region IV of Fig. 1 is actually a subset of region II.

The variations in the limit on m_0, for various choices of $sign(\mu)$ and $\tan\beta$, are shown in Table 1. However, these bounds depend crucially on the experimental bound on the mass of this type of chargino and will get much stronger if this bound improves.

A theoretical uncertainty in our limits arises due to the following reason. The running chargino mass at a given scale is related to $m_{3/2}$. When this mass is compared with the chargino mass bound it should be translated to the corresponding pole mass which is related to the running mass via certain weak threshold corrections [7] (see in particular eqs. (16) and (18)). These corrections are not incorporated in ISAJET 7.51. On the other hand the corrections are non-negligible. After including this correction our strongest bound (Table 1) on $m_{\tilde{e}}$ is relaxed to 361 GeV. We have checked that for other points in the APS this relaxation amounts to 20-25 GeV at the most for $m_{\tilde{e}}$ and $m_{\tilde{\tau}_1}$.

The uncertainty in the scale Q_{UFB} as discussed above may also relax our limits. For example, at a scale $10Q_c$ our strongest bounds (Table 1, set marked by an asterisk) on slepton masses are relaxed by about 25 GeV. Using both the weak threshold corrections and the modified scale we obtain $m_{\tilde{e}} \geq 335$ GeV. This, we believe, is the *most conservative* statement where allowance has been made for all possible conspiracies to weaken the bound.

In Table 2 we have similarly illustrated the variations in the upper limit on $m_{\tilde{\chi}^\pm}$ for given values of m_0. Inclusion of weak threshold corrections, however, modestly weakens this bound ($\sim 20\%$ [7]). The only other upper bound available in the literature is $M_2 < 200$ GeV, which comes from naturalness arguments [8]. We wish to stress that the requirement of no finetuning, though intuitively appealing, is difficult to quantify. It is gratifying to note that we are getting similar or even stronger limits from a well defined physical principle.

In the mAMSB model $\tilde{\chi}^\pm$ decays dominantly into a nearly degenerate $\tilde{\chi}_1^0$ and a soft π after travelling typically through a distance of a few cms [9] and traverses several layers of the vertex detector in the process. The signature of this $\tilde{\chi}^\pm$ and/or the soft π in the detector during the analysis stage may help to reduce the background to a negligible level. However, other particles in the final state in addition to the $\tilde{\chi}^\pm$s are needed to trigger the event. Various suggestions and their viability in the light of our bounds are summarized below.

In [7,10] the proposed signals were based on the decays $\tilde{e}_L \to e + \tilde{\chi}_1^0, \nu + \tilde{\chi}^\pm$ and $\tilde{\nu} \to \nu + \tilde{\chi}_1^0, e + \tilde{\chi}^\pm$. Thus a $\tilde{\nu}$-$\tilde{\ell}_L$ pair produced at hadron colliders, *e.g.*, would lead to a $2\ell + \tilde{\chi}^\pm + \tilde{\chi}_1^0$ where the hard leptons can be triggered on. It was estimated in [7] that a detectable signal can be found at the Tevatron for $m_{\tilde{\nu}} < 200$ GeV. In view of

the new bounds such signals are strongly disfavoured. A similar signal from $\tilde{\ell}_L$ pairs produced at the Next Linear Collider (NLC) [10] is also improbable at the early versions of the NLC, say at $\sqrt{s} = 500$ GeV. Thus a properly constrained mAMSB model leaves open the possibility of the Large Hadronic Collider (LHC) as the only source of slepton signals in the near future.

On the other hand, our upper bounds on $m_{\tilde{\chi}^\pm}$ as a function of m_0 reveal that the chargino will necessarily be in the striking range of the Tevatron for a wide range of slepton masses. The signal from chargino pair plus mono-jet, where the jet is essentially required for triggering, was recommended by Feng *et al* in [9]. It was further pointed out that typical discovery reaches are $m_{\tilde{\chi}^\pm} = 140, 210, 240$ GeV for $c\tau = 3, 10, 30$ cm, where τ is the mean lifetime of $\tilde{\chi}^\pm$. Our upper bounds on $m_{\tilde{\chi}^\pm}$ reinforces the prospect of this channel.

The signal $e^+e^- \to \tilde{\chi}^+\tilde{\chi}^-\gamma$ where the hard photon triggers the event [13], has also been proposed. Our bounds also strengthtens the possibility of observing this signal at an early version of the NLC. Moreover, if $m_{\tilde{\chi}^\pm}$ is not too close to the kinematic limit, one can determine $m_{\tilde{\chi}^\pm}$ from the distribution of $(p_{e^-} + p_{e^+} - p_\gamma)^2 > 4m_{\tilde{\chi}^\pm}^2$. In addition, if the $\tilde{\ell}_L$ is indeed light (say, 400-500 GeV), which is the case in mAMSB over a large region of the APS, some useful hints on $m_{\tilde{\ell}_L}$ may come as a bonus, from the size of the cross-section. Due to the destructive interference between the s-channel γ, Z mediated diagrams and the t-channel $\tilde{\nu}$ exchange diagram the cross-section will be smaller for lighter $\tilde{\ell}_L$ [19]. Competing models with nearly invisible $\tilde{\chi}^\pm$ like the string motivated model ($m_{\tilde{\ell}_L} \approx 1$ TeV) of [13] would yield much larger cross sections for comparable $\tilde{\chi}^\pm$ mass. Models with nearly degenerate Higgsino dominated chargino and LSP, on the other hand, can be distinguished from the AMSB model by measuring the cross-section with right polarized electrons.

The region of the $m_0 - m_{3/2}$ plane that can be probed at the LHC via the conventional m lepton $+$ n jets $+$ $\not{E}_T$ signals has been given in [12]. A significant part of this region is, however, ruled out by the new bounds presented in this paper.

One could have evaded our bounds by assuming the universe to be in a standard model like false vacuum, separated from a charge and color breaking true vacuum by a barrier with a tunnelling time too large compared to the age of the universe [20]. The calculation, which is relatively straightforward for a single scalar field, is rather complicated and uncertain in SUSY models. Moreover, it cannot be checked against experimental data. Thus the false vacuum option is at best a theoretically interesting alternative to the much simpler true vacuum hypothesis favored by the principle of Occam's razor. We, however, wish to stress that even if the alternative scenario happens to be the correct one our bounds do not lose their

significance. If, *e.g.*, one discovers the AMSB spectrum (almost degenerate lowest-lying gauginos, maximal mixing between right-and left-handed smuons etc.) along-with sleptons violating our bounds, it may be the first indication that we are living in a false vacuum. This, we note, is experimentally a much simpler way to find out our precarious existence in a false vacuum, compared to what happens in the minimal SUGRA models, where, *e.g.*, one has to determine the trilinear A parameter precisely to get the same information.

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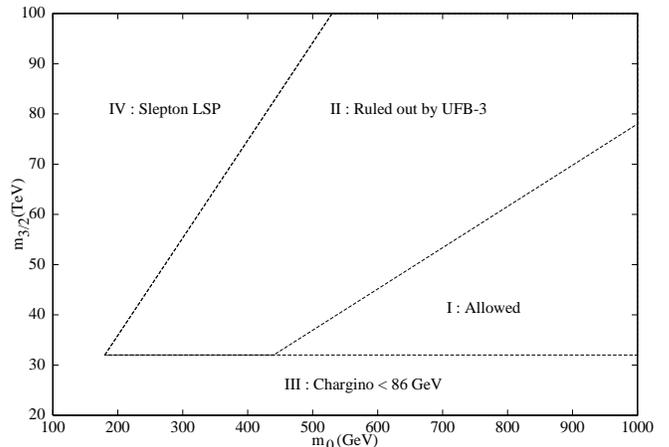
FIG. 1. Allowed parameter space for the mAMSB model for $\tan\beta = 5$ and $\mu < 0$. Already existing constraints are depicted as regions III and IV, while our constraints fall in region II. Only region I remains allowed.

TABLE I. *Lower bounds on m_0 and corresponding slepton masses for different sets of input parameters (see text). The limit $m_{\tilde{\chi}^{\pm}}^{min} = 86$ GeV has been used. The set marked by the asterisk corresponds to the minimum $m_{\tilde{e}}$ consistent with $m_{\tilde{\chi}^{\pm}}^{min}$ and the Higgs mass limit as discussed in the text. The set marked by the dagger corresponds to the minimum value of $m_{\tilde{\tau}_1}$.*

$\tan\beta$	sign(μ)	$m_{3/2}$ (TeV)	m_0 (GeV)	$m_{\tilde{e}}$ (GeV)	$m_{\tilde{\tau}_1}$ (GeV)
3.3 ($*$)	$+$	27.9	395	378	372
5	$+$	28.6	406	389	380
5	$-$	31.6	446	425	416
35	$+$	30.2	457	440	350
35	$-$	30.8	462	444	355
59 ($\dagger$)	$+$	30.4	484	468	269

TABLE II. *Upper bounds on $m_{3/2}$ and corresponding $m_{\tilde{\chi}^{\pm}}$ for given values of m_0. Weak threshold corrections (see text) weaken the bound by about 20%.*

$\tan\beta$	sign(μ)	m_0 (GeV)	$m_{3/2}$ (TeV)	$m_{\tilde{\chi}^{\pm}}$ (GeV)
5	$+ (-)$	500	35.8 (35.7)	106 (98)
5	$+ (-)$	700	51.6 (51.5)	150 (144)
5	$+ (-)$	1000	76.0 (75.9)	216 (212)
35	$+ (-)$	500	33.3 (33.5)	95 (94)
35	$+ (-)$	700	48.2 (48.5)	137 (136)
35	$+ (-)$	1000	71.1 (71.5)	200 (200)