Extended Anomaly Mediation and New Physics at 10 TeV

Ann E. Nelson and Neal J. Weiner

Department of Physics, Box 1560, University of Washington, Seattle, WA 98195-1560, USA

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In the MSSM, an unfortunate prediction of minimal anomaly mediated supersymmetry breaking is that the slepton masses squared are negative. This problem is particularly intractable because of the insensitivity of anomaly mediation to ultraviolet physics. In this paper we note that tree level couplings to the conformal compensator in the Kähler potential give 10 TeV as a natural mass scale for physics beyond the MSSM, and, moreover, that the SUSY breaking effects from physics at this scale do not generically decouple from the low-energy spectrum. We consider particular extensions, including the effects of vector-like matter at 10 TeV, and a specific model in which the leptons are placed in a triplet of an asymptotically free SU(3). We find that the features of minimal anomaly mediation are not a robust prediction of the general framework, and that the problem of negative slepton masses squared can easily be avoided.

I. INTRODUCTION: THE SUPERSYMMETRIC FLAVOR PROBLEM, AND ANOMALY MEDIATION

Extending the standard model of particle physics into a supersymmetric theory is attractive for many reasons, most notably stabilization of the electroweak scale against radiative corrections, and coupling constant unification. A significant drawback to supersymmetric theories is our lack of understanding of supersymmetry breaking. A phenomenological parametrization of the soft supersymmetry breaking effects in the minimal supersymmetric extension leads to 104 new free parameters. Most of this parameter space is ruled out by low energy constraints on flavor changing neutral currents, lepton number violation, and CP violation. The supersymmetric flavor problem is how to explain the absence of indirect evidence for supersymmetry via flavor changing neutral currents and lepton flavor violation. The supersymmetric CP problem is why virtual superpartner exchange has not led to CP violation in conflict with experiment.

In the simplest solutions to the supersymmetric flavor and CP problems the superpartner masses are insensitive to Planck scale physics, and can be predicted. Such UV insensitivity can arise if the supersymmetry breaking scale is low, as in low energy gauge mediation, where the fundamental supersymmetry breaking scale is between 10 TeV and $10^9$ GeV and the gravitino mass $m_{3/2}$ is between $10^{-3}$ eV and 1 GeV. Typically Planck scale physics gives contributions to soft supersymmetry breaking masses of order $m_{3/2}$, and so with a low gravitino mass the effects from the Planck scale are negligible. This line of reasoning implies that the gravitino should be the lightest superpartner (LSP), and the LSP would not be a candidate for cold dark matter.

Recently there have been several interesting proposals for UV insensitivity of superpartner masses with $m_{3/2}$ as high as 10 TeV, or even higher. Randall and Sundrum proposed that the hidden supersymmetry breaking sector and the visible supersymmetric extension of the standard model should live in separate (3+1) dimensional subspaces (known as 3-branes) embedded in extra dimensions. They also proposed that if the bulk contains only supergravity, and the 3-branes are far apart in units of the Planck length, then the visible sector learns about supersymmetry breaking only via the breaking of conformal invariance. In this “anomaly mediated supersymmetry breaking” (AMSB) scenario, the susy breaking parameters at any given scale can be found from an exact solution to the renormalization group equations, known as the anomaly mediated trajectory. Heavy particle threshold corrections will maintain the soft masses and couplings on this trajectory, provided the masses of the heavy particles come from supersymmetric terms. Since the superpartner masses are a loop factor below $m_{3/2}$, and since the weak scale can be determined from the effective supersymmetry breaking scale in the MSSM, a gravitino mass of order 10 TeV will give the weak scale to be of order 100 GeV. Thus to leading order in supersymmetry breaking, all the soft supersymmetry breaking parameters at any scale can be computed in terms of the gravitino mass, tree level violation of conformal invariance, and the beta functions and anomalous dimensions, and is insensitive to UV physics.

This predictive scenario would be extremely attractive were it not for the fact that in the Minimal Supersymmetric Standard Model (MSSM), the slepton masses squared are predicted to be negative. Another potential problem with AMSB is that it is not known how to realize this scenario from string theory, and generic extra dimensional models do not realize its predictions—simply separating the 3-branes is insufficient. However, recently, Luty and Sundrum have shown that AMSB may be obtained from four dimensional theories with a supersymmetry breaking sector which is embedded in a superconformal sector with certain properties, so a special extra dimensional set up is unnecessary for AMSB.

One appealing solution to the negative slepton mass squared problem is “deflected anomaly mediation” (DAM), in which some particles with nontrivial stan-
dard model charges obtain large masses from additional light \(< m_{3/2}/2\) singlets with large vevs. Integrating out heavy fields leads to a “deflection” from the trajectory at a high energy scale. DAM typically retains some UV sensitivity as it requires running the soft parameters from the threshold to the weak scale. Flavor violation below the threshold would generically reintroduce the flavor problem. There are a number of other viable solutions to the flavor problem with a gravitino which is heavier than 100 GeV. Most refs. \([12, 13, 14, 15, 16, 17, 18, 19]\) are sensitive to physics up to some high scale, but not to the Planck scale.

Solutions to the negative slepton mass squared problem which retain UV insensitivity may be found in refs. \([20, 21, 22, 23]\). These models depart from the anomaly mediated framework by additional supersymmetry breaking effects which lie on a different, but UV insensitive, trajectory. Other UV insensitive solutions include \([24, 25]\). In this paper we will explore anomaly mediation in theories which go beyond the MSSM at the 10 TeV mass scale, where nondecoupling effects are important. We will argue that 10 TeV is a natural scale for physics beyond the MSSM. Since anomaly mediation is still the dominant contribution to supersymmetry breaking parameters, we dub this framework Extended Anomaly Mediation (EAM). In the EAM framework, for any given extension of the MSSM, all supersymmetry breaking parameters can be computed in terms of the gravitino mass and supersymmetric parameters.

\section{Extended Anomaly Mediation}

We start with the following assumptions about the effective theory of physics below the Planck scale:

- Anomaly mediation is the dominant source of supersymmetry breaking in the visible sector.
- Above 10 TeV all soft supersymmetry breaking terms are on the anomaly mediated trajectory.
- The visible sector is some general extension of the MSSM. Typically this will include some new fields charged under the SM gauge group whose masses are not prevented by a gauge symmetry, but which are nevertheless light.
- No additional mass scales in the vicinity of the weak scale other than \(m_{3/2}\) should be input by hand, as it would seem to be overly coincidental for a theory to produce several mass scales of disparate origin so close together.
- For at least some of the new fields, tree level Kähler potential terms are allowed which will generate masses of \(O(m_{3/2})\) from the coupling to \(\phi\), the conformal compensator \([4, 17, 29]\).

We shall see that the resulting low energy superpartner spectrum is not that of minimal anomaly mediation, and we can easily generate spectra with positive slepton mass squared. We begin by reviewing the manner in which fields can become massive with couplings to the conformal compensator \(S\). For instance, consider a chiral superfield \(S\) with a bilinear coupling in the Kähler potential.

\[
\int d^4x\ d^4\theta\ x^2 S^2. \tag{1}
\]

Upon rescaling by \(S \rightarrow \phi S\) we have

\[
\int d^4x\ d^4\theta\ \frac{\lambda^2}{\phi^2} S^2 \tag{2}
\]

Since \(S^2\) is a chiral superfield, only terms involving the \(F\)-component of the conformal compensator appear in the Lagrangian. In this example, assuming \(\phi = 1 + m_{3/2}/2\gamma[27]\), we are left with

\[
\int d^4x\ \left( \int d^2\theta\ \frac{\lambda^2}{2} m_{3/2}^2 S^2 + h.c. \right) + \frac{\lambda^2}{2} m_{3/2}^2 s^2. \tag{3}
\]

Since we roughly identify the weak scale with \(m_{3/2}/16\pi^2\), \(S\) naturally has a mass of order 10 TeV.

The low energy phenomena of the theory depend critically on the value of \(\lambda\). The scalar mass matrix for \(S\) is

\[
\frac{m_{3/2}^2}{2} \left( \frac{\lambda^2}{\lambda} \frac{\lambda}{\lambda^2} \right). \tag{4}
\]

For \(|\lambda| > 1\) the mass matrix has positive determinant, and the situation is straightforward. However, with \(|\lambda| < 1\), this matrix has a negative eigenvalue, and \(s\), the \(A\)-component of \(S\), will acquire a vev. The size of the vev will be determined by the presence of additional operators. If the superpotential contains a term \(O(m_{3/2})\) is quite natural, and hence upon integrating them out, one would be left with higher dimension operators suppressed by this mass scale. As a consequence, it is easy to find natural ways to stabilize the the vev of \(s\) at \(O(m_{3/2})\).

This is our main point: with a gravitino mass \(m_{3/2} \sim O(10 \text{ TeV}), a natural scale for physics beyond the MSSM is \(O(10 \text{ TeV})\). This physics could consist of new heavy particles, or a new symmetry breaking scale. Furthermore, in AMSB, threshold effects at 10 TeV or below do not decouple, and the low energy superpartner mass spectrum is significantly changed. We will now examine two attractive scenarios for physics at this scale. We find that AMSB need look very little like the minimal case. In some cases the spectrum is similar to a variant of gauge mediation.
A. N-viable Anomaly Mediation or Positive Deflection at 10 TeV

We begin with the simplest example of additional chiral superfields $\Xi, \overline{\Xi}$ in a nontrivial vector-like representation of the standard gauge group and the Kähler potential term

$$\int d^2\theta \lambda \phi^\dagger \phi \Xi \overline{\Xi} = \int d^2\theta \lambda m_{3/2} \phi \Xi \overline{\Xi} + h.c.$$ (5)

We assume $\lambda > 1$ to prevent color-charge breaking.

When we rescale the messenger fields $\phi \Xi \rightarrow \Xi$, the remaining superpotential term is

$$\int d^2\theta \frac{\lambda m_{3/2}}{\phi} \Xi \overline{\Xi}.$$ (6)

Notice that when we Taylor expand this in powers of $\theta$, the $B\mu$ term arising from the conformal compensator now has the opposite sign when compared with the usual anomaly mediated piece. These messengers will decouple in the usual fashion (up to higher powers in $F/m^2$) when considering only the scalar masses squared. However, their effects on the gaugino masses will remain. The gaugino masses at the threshold are

$$M_i = -\frac{b_i + 2n}{4\pi} \alpha_i m_{3/2} ,$$ (7)

where $n$ is the Dynkin index of the $\Xi$ fields and $b_i$ is the coefficient of the one loop beta function for $\alpha_i$.

Because the gaugino masses are no longer on the anomaly mediated trajectory, running from the threshold scale can change the masses of the sfermions considerably. Their soft masses at a scale $\mu < m_{\Xi}$ are given by

$$m_f^2 = m_{3/2}^2 \times$$ (8)

$$\sum_i -\frac{b_i c_{f,i} \alpha_i^2 (m_{\Xi})}{8\pi^2} + \frac{c_{f,i} (b_i + 2n)^2}{8\pi^2 b_i} (\alpha_i^2 (m_{\Xi}) - \alpha_i^2 (\mu)),$$

where $i$ indexes the gauge group, $f$ indexes the sfermion representation, and $c_{f,i}$ is the quadratic Casimir. For $n \geq 5$, we obtain positive slepton masses squared. Notice that the case $n = 0$ reproduces the ordinary anomaly mediated result.

B. $SU(3)$ Electroweak at 10 TeV

Possibly the most interesting way to solve the negative slepton mass squared problem is to change the gauge structure of the MSSM matter fields at the 10 TeV scale. For instance, if we can place all the MSSM fields into asymptotically free gauge groups, their soft masses at 10 TeV will be positive. In minimal anomaly mediation, enlarging the gauge group of the standard model above the scale $m_{3/2}$ is irrelevant due to decoupling, as only the gauge group structure at the weak scale determines the soft scalar masses at the weak scale. However in EAM, the gauge contributions occur at the scale $m_{3/2}$ and do not decouple.

It is interesting to extend the electroweak gauge group to include an additional $SU(3)_W$ factor, with all the leptons transforming as triplets $\mathbf{3}$. Dimopoulos and Kaplan [30] showed that this naturally gives a successful prediction for the weak angle when the extended gauge group is broken at a few TeV, and the $SU(2) \times U(1)$ couplings are fairly large. Such an extension is attractive for EAM, since with the leptons transforming under an asymptotically free group the anomaly mediated contribution to their masses squared is positive. Here we build an EAM model with positive slepton masses squared and weak gauge group $SU(3)_W \times SU(2) \times U(1)$, which breaks to $SU(2)_W \times U(1)_Y$ at a scale of order $m_{3/2} \sim 10$ TeV. The matter content is as follows.

### 3 3 2 1 model Chiral Superfields

**Quark, lepton and spectator sector (R parity odd)**

| $SU(3)_c$ | $SU(3)_W$ | $SU(2)$ | $U(1)$ |
|-----------|-----------|---------|--------|
| $\ell_i$ | 1 | 3 | 1 | 0 |
| $q_i$ | 3 | 1 | 2 | 1/6 |
| $a_i$ | 3 | 1 | 1 | -2/3 |
| $\bar{d}_i$ | 3 | 1 | 1 | 1/3 |
| $\chi_2$ | 1 | 3 | 2 | -1/2 |
| $\chi_1$ | 1 | 3 | 1 | 1 |

**Higgs sector (R parity even)**

| $SU(3)_c$ | $SU(3)_W$ | $SU(2)$ | $U(1)$ |
|-----------|-----------|---------|--------|
| $H$ | 1 | 1 | 2 | 1/2 |
| $\bar{H}$ | 1 | 1 | 2 | -1/2 |
| $\Sigma_2$ | 1 | 3 | 2 | -1/2 |
| $\Sigma_1$ | 1 | 3 | 1 | +1 |
| $\Sigma_2$ | 1 | 3 | 2 | +1/2 |
| $\Sigma_1$ | 1 | 3 | 1 | -1 |

Note that $i = 1, 2, 3$ is a generation index. The $\chi_{1,2}$ are spectators which obtain mass at the scale $m_{3/2}$, and for three generations, cancel the triangle gauge anomalies from the quarks and leptons.

We include superpotential terms

$$\phi^\dagger (g \Sigma_2^2 \Sigma_1 + \bar{g} \Sigma_2^2 \bar{\Sigma}_1)$$ (11)

and Kähler terms

$$\phi^\dagger (\lambda_1 \Sigma_1 \bar{\Sigma}_1 + \lambda_2 \Sigma_2 \bar{\Sigma}_2)$$ (12)

For simplicity, we set $\lambda_1 = \lambda_2 = \lambda$ and assume all couplings to be real. For $|\lambda| < 1$ the potential is unbounded from below along the direction where the $3 \times 3$ matrices $\Sigma = (\Sigma_1 \Sigma_2) \propto (\Sigma_1 \Sigma_2) = \Sigma$ are rank one. However, for $\lambda < -1$ and $g, \bar{g}$ of the same sign, the global minimum can break $SU(3)_W \times SU(2) \times U(1)$ to $SU(2)_W \times U(1)_Y$ at
a scale of order 10 TeV, with both $\Sigma$ and $\bar{\Sigma}$ proportional to the identity. If we relax the requirement that $\lambda_1 = \lambda_2$, we will still break to $SU(2) \times U(1)$, in stages. Either we have $SU(3) \times SU(2) \times U(1) \rightarrow SU(2)^2 \times U(1) \rightarrow SU(2) \times U(1)$ or $SU(3) \times SU(2) \times U(1) \rightarrow SU(2) \times U(1)^2 \rightarrow SU(2) \times U(1)$. Quantitatively, this will contribute only a threshold loop effect to the low energy value of $\sin^2 \theta_W$.

To compute the scalar masses, we follow Giudice and Rattazzi. We treat each vev as a superfield with both $F$- and $A$- components, and extract the scalar masses from wave function renormalization. If the vev $X$ is driving the breaking $SU(3) \rightarrow SU(2) \times U(1)$, we parametrize $F_X/X = \gamma m_{3/2}$, we can write the mass of the sleptons as (considering only gauge interactions)

$$m_{\tilde{f}}^2 = m_{3/2}^2 \times \left( -\frac{\alpha_Y c_f b_w a_{3/2}}{8\pi^2} (1 - \gamma)^2 \right)$$

where $\alpha_Y$ are the couplings of the low energy groups, and $b_i$ and $b_i'$ are the beta functions of the $i$th gauge group above and below the $SU(3)$ breaking scale, respectively. $\gamma = 0$ corresponds to retaining the SUSY breaking masses of the theory above $m_{3/2}$ while $\gamma = 1$ maintains the anomaly mediated trajectory, with negative slepton masses squared. For sufficiently small (but still order one) $\gamma$, the scalar masses squared will be positive. Radiative effects from the top-stop loops will drive electroweak symmetry breaking via the vev of $H$. Masses for quarks, leptons and spectators arise from the superpotential couplings

$$\phi^3 \left( \frac{1}{m_{3/2}^2} h_{ij}^l \ell_i \ell_j \Sigma_2 \Sigma_1 H + h_{ij}^u q_i u_j + h_{ij}^d q_i d_j H ight) + h_1 \chi_2 \Sigma_1 + h_2 \chi_1 \chi_2 \Sigma_2 + \xi_i \chi_2 \ell_i H \right).$$

The nonrenormalizable operators giving rise to lepton masses can arise, for instance, from integrating out vector-like leptons charged under $SU(2) \times U(1)$ at the scale $m_{3/2}$. The fields responsible for the lepton Yukawas will affect the gaugino masses but not the scalar masses at leading order in supersymmetry breaking, as described in the previous section. The light lepton fields will mix weakly with the vectorlike leptons carrying $SU(2) \times U(1)$, but this need not lead to large corrections to the masses.

Note that the neutral $\chi_2$ fields can mix with the neutrino components of the lepton fields via the $\xi_i$ couplings—this could lead to lepton number and flavor violation in the neutrino sector. For $\xi_i = 0$, a linear combination of a global symmetry and an $SU(3)_W$ generator remains unbroken in the ground state, and can be identified as total lepton number. It would be interesting to study whether the observed neutrino oscillations can be accounted for in this model.

### III. THE HIGGS $\mu$ PARAMETER

So far we have avoided dwelling on a potential embarrassment for EAM, the fact that in the MSSM the Higgs fields are in a real representation of the MSSM gauge group and so, according to our philosophy, should either remain massless or obtain masses of order 10 TeV. The most popular solution in the MSSM is to simply allow a bilinear Higgs term to appear in the Kähler potential $\mu \phi^2$, which will give a Higgs $\mu$ parameter of order $m_{3/2}$. With $m_{3/2} \sim 10$ TeV this won’t work. Even if one were to simply put in a small parameter so that the $\mu$ parameter for the Higgs fields were in the phenomenologically desirable range of several hundred GeV, the $B$ parameter would be 10 TeV and there would be no stable minimum of the potential. To get an acceptable spectrum, we therefore extend the MSSM at the TeV scale. The minimal such extension is to add a singlet $S$ to the MSSM, with superpotential couplings $\lambda S H_d H_u + k S^3$. $S$ must get an $O(100)$ GeV vev at the minimal of its potential. In minimal AMSB the $S$ mass squared term can be computed to be positive. One way for getting $S$ a large negative mass squared, suggested in ref. [6], in the context of gauge mediation, is to add new colored fields $Q, \bar{Q}$ to the MSSM in a vector-like representation and with superpotential coupling $hSQ\bar{Q}$. This mechanism will also work in anomaly mediation. Unless it is quite large, the coupling constant $h$ is asymptotically free, and will give $S$ a negative mass squared.

### IV. SUMMARY

In anomaly mediated theories of supersymmetry breaking, 10 TeV is a natural mass scale for new physics beyond the MSSM. Such new physics makes a strong imprint on the superpartner spectrum, but can naturally preserve flavor universality. We have presented two simple models for new physics, and shown that the resulting superpartner mass spectrum is acceptable, and resembles none of the standard supersymmetry breaking scenarios. In particular, the gaugino masses are neither of the anomaly mediated nor unified type. In conclusion, anomaly mediation is a much richer framework than has been previously realized.

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