Gauge/Anomaly Syzygy and Generalized Brane World Models of Supersymmetry Breaking

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In theories in which SUSY is broken on a brane separated from the MSSM matter fields, supersymmetry breaking is naturally mediated in a variety of ways. Absent other light fields in the theory, gravity will mediate supersymmetry breaking through the conformal anomaly. If gauge fields propagate in the extra dimension they, too, can mediate supersymmetry breaking effects. The presence of gauge fields in the bulk motivates us to consider the effects of new messenger fields with holomorphic and non-holomorphic couplings to the supersymmetry breaking sector. These can lead to contributions to the soft masses of MSSM fields which dramatically alter the features of brane world scenarios of supersymmetry breaking. In particular, they can solve the negative slepton mass squared problem of anomaly mediation and change the predictions of gaugino mediation.

I. INTRODUCTION

The standard model has been an exceptionally successful theory, explaining all observed phenomena except gravity, dark matter, and neutrino masses. Nonetheless, it is improbable that this is a complete effective theory of weak scale physics. It seems contrary to all reasonable expectations that the Higgs boson, whose renormalized mass squared receives contributions proportional to the cutoff squared, should be so light compared to the the Planck scale, the likely cutoff of field theory.

Because supersymmetry has not been observed, if it exists, it must be a broken symmetry of nature. Supersymmetry breaking can be parameterized by a spurion field $X$, with non-vanishing F-component. We generically expect the operators

$$\int d^{4}\theta \frac{X F_{i}^{\dagger} F_{j}}{M_{Pl}}$$

(1)

where $F_{i}$ is a Minimal Supersymmetric Standard Model (MSSM) matter field, and $i,j$ index flavor. In supergravity mediated theories, the contribution of these local operators to squark and slepton masses dominates over the contribution of long range gravitational interactions. Since there is no reason to expect that these operators will be flavor diagonal (or CP conserving), they generate potentially excessive additional contributions to FCNC and CP violating processes, such as the $K_{L} - K_{S}$ mass difference, $\mu \rightarrow e\gamma$ and the electron and neutron EDMs. However, precision tests have shown no deviation from the standard model. Thus, supersymmetry breaking and mediation must be largely CP conserving and flavor blind.

A. Brane World Supersymmetry Breaking

Beginning with [1] and more recently with [2], models have been constructed in which the dangerous supergravity operators are absent at tree level due to locality in a fifth dimension. In these models, the MSSM matter fields are confined to a three-brane in a fifth dimension. Supersymmetry breaking occurs on a different three brane, and, consequently, no higher dimension operators can exist at tree-level. Absence of contact terms in the low energy theory ("sequestering") requires there be no fields in the bulk lighter than the compactification scale, which is not a generic feature of string theory [2]. However, as we live in a vacuum with broken supersymmetry and (possibly) non-zero cosmological constant, it seems that we already live in a non-generic vacuum, at least in the currently accepted conventional sense, so these issues may not be significant. Moreover, motivated by the AdS/CFT correspondence, Luty and Sundrum have recently demonstrated sequestering in certain four dimensional theories [3,4]. Brane world and other scenarios of sequestered supersymmetry breaking have so many desirable features that we feel they should be taken seriously even without an explicit string realization.

The mediation of supersymmetry breaking occurs by fields which exist in the bulk. Gravity alone will mediate supersymmetry breaking via the conformal anomaly (anomaly mediated supersymmetry breaking or AMSB) [3]. If gauge fields propagate in the fifth dimension, and if supersymmetry breaking gives a large F-term to a gauge singlet chiral superfield, then gaugino masses can arise at tree level which are larger than the AMSB contribution. Then gaugino mediation (gMSB) can generate the soft masses of the scalar matter fields through renormalization group effects.

Each of these models has problematic issues of varying severity. Anomaly mediation generically predicts negative slepton masses squared, although there are solutions to this problem [5]. Gaugino mediation has the stau as the lightest superpartner (LSP) over much of its parameter space [4]. In all of these models,
II. GAUGE/ANOMALY MEDIATED SYZYGY

We will begin by studying the simplest case, in which there are no singlets with F terms. The anomaly mediated contribution to the slepton mass squared is negative. However, we now have messenger fields which can alter the slepton mass prediction.

Let us consider matter fields $M$ and $\overline{M}$, transforming nontrivially under the MSSM gauge group, localized on the supersymmetry breaking brane. Below the compactification scale, we have the ordinary supergravity operators

$$\int d^4\theta \frac{\lambda X^i X M^i M}{M^2} + \frac{\lambda X^i X M^i M}{M^2},$$

(2)

which generate soft masses for the messenger fields $\delta m^2 = \lambda M^2 V_n m_{3/2}^2$. These terms do not violate the R-symmetry of the theory and will not contribute to the gaugino masses. However, they will contribute to the soft masses of the MSSM matter fields by an amount \[6\] \[7\].

$$m_i^2 = -\sum_a \frac{g_a^2}{128\pi^4} S_Q C_{ai} \text{Str} M^2_{\text{mess}} \log \left( \frac{A^2}{m^2_{1R}} \right),$$

(3)

where $m^2_{1R}$ is the mass of the messenger fields, $S_Q$ is the Dynkin index of the messenger representation, and $C_{ai}$ is the quadratic Casimir for the representation of the MSSM matter field in question. When the log terms are large, these terms should be resummed to yield

$$\sum_a S_Q C_{ai} \text{Str} M^2_{\text{mess}} \left( g_a^2 (m^2_{1R}) - g_a^2 (A^2_{UV}) \right) / 8\pi^2 b_a,$$

(4)

where $b_a$ is the coefficient of the one-loop $\beta$ function for $g_a$ above the messenger scale.

When the messengers are localized on the SUSY breaking brane the contribution to the supertrace is naturally $\sim \lambda F^2 / M^2 = \lambda F^2 M^2 V_n / M^2_{3/2} = \lambda m^2_{3/2} M^2 V_n$. Since the anomaly mediated contribution also occurs at two loops, it will be smaller by the volume factor, which can be $O(10 \sim 100)$. Moreover, the messenger contribution can receive a logarithmic enhancement relative to the anomaly mediated contributions. The sign of the messenger contribution depends on the sign of the nonrenormalizlable operator, but can be positive.

To address the negative slepton mass squared problem, while retaining the phenomenologically desirable feature that gaugino and scalar masses are about the same size, these effects should be comparable. One can simply assume that the coefficients of the messenger/SUSY breaking contact operators are small to compensate for the volume factor, but a more natural solution would be to assume that the messenger fields themselves propagate in the extra dimension, in which case the coefficients $\lambda, \tilde{\lambda}$ are suppressed by precisely this same volume factor. The alignment or “syzygy” of these contributions appears fortuitous, because they have distinct origins. Yet within this model, it occurs completely naturally. However, as pointed out in ref. \[13\], in this case contact terms between messengers and MSSM fields could lead to flavor violation and FCNC at one loop, unless suppressed by a mechanism for repelling the messengers from our brane. Several such mechanisms were suggested in ref. \[18\].

III. MESSENGERS IN GAUGINO MEDIATION

If singlets with F terms exist on the SUSY breaking brane, then gauge particles naturally have contact terms with the singlet which give rise to supersymmetry breaking gaugino masses which dominate the anomaly mediated contributions \[2\] \[3\]. We are now also allowing messenger fields. What effects can we expect?

The first important point is that the gaugino mass, being localized on a brane, is volume suppressed \[14\]. If the messengers are localized on the brane (as opposed to propagating in the bulk, as discussed in the previous section), then their contributions to scalar masses are naturally larger than the gaugino mediated terms.

Let us assume that the messenger fields have masses at some lower scale, $m$. Then the nonrenormalizable operators already described give rise to contributions modifying the sfermion masses. In terms of the gravitino mass and the size of the extra dimensional volume

$$m_i^2 \sim -\sum_a \frac{g_a^2}{128\pi^4} S_Q C_{ai} m_{3/2} V_n M^2 \log \left( \frac{A^2}{m^2_{1R}} \right).$$

(5)
In contrast, the gaugino mass is given by
\[ m_{\tilde{g}} \sim \frac{m_{3/2}}{\sqrt{V_n M_*}} \] (6)

The usual one-loop RG contribution to soft masses is
\[ \delta m^2 \sim \frac{g^2}{16\pi^2} \frac{m_{3/2}^2}{V_n M_*^2} \log\left( \frac{\Lambda^2}{m_{1/2}^2} \right) \] (7)

The relative strength of these effects is then (taking the logarithms to be of comparable size)
\[ \frac{\text{messenger contributions}}{gM_{\text{SB}}} \sim \frac{g^2}{16\pi^2} S_Q(V_n M_*^2)^2. \] (8)

For \( V_n M_*^2 \sim 10 \), these can be of comparable size, dramatically changing the spectrum of gaugino mediation. In particular, if these effects are positive, the scalar masses can be naturally heavier than the gaugino masses, leading to, e.g., a bino LSP over broader ranges of parameter space. The bino is preferable to the stau as LSP since stable charged relics are extremely constrained \[21\], while a stable bino is an acceptable dark matter candidate.

Up to this point, we have only considered the effects of non-holomorphic masses for the messengers. With messengers coupled to a singlet, we have the expectation of additional holomorphic masses as well.

In particular, we must assume that the messengers are sufficiently light compared with the fundamental scale of the theory so that we can treat them within effective field theory. We will not explain the origin of their mass here, but simply introduce a superpotential operator,
\[ W \supset m M \tilde{M} \] (9)

Given the presence of the singlet field \( X \), we expect the presence of the additional operator
\[ W \supset \frac{X}{M_*} m M \tilde{M} \] (10)

If the gaugino mass arose from an order one coupling to \( X \), this would lead to insignificant contributions to soft masses. However the gaugino mass is volume suppressed, and \( F/M \sim m_{3/2} \sqrt{V_n M_*^2} \). These terms will generate contributions to the scalar and gaugino masses which are of the conventional gauge mediated sort \[21\ [22\ [23\).

The additional gaugino masses scale as
\[ \delta m_{\tilde{g}} = \frac{\alpha_i S_Q}{4\pi} \frac{F}{M} \sim \frac{\alpha_i}{4\pi} S_Q m_{3/2} \sqrt{V_n M_*^2} \] (11)

which compares with the tree level piece
\[ \frac{\text{messenger contribution}}{\text{tree level}} \sim \frac{\alpha_i}{4\pi} S_Q V_n M_*^2, \] (12)

so that these effects can be competitive. Of course, if all the new pieces are simply proportional to gauge couplings, these effects are consistent with a unified tree level piece at some higher scale. The distinctions between this case and traditional gaugino mediation come from the additional contributions to the scalar masses from the holomorphic terms and from eq. (7), both of which are volume enhanced.

A. \( \mu \) and \( B \mu \)

Brane world models such as gaugino mediation in which the gravitino mass is comparable to the weak scale have a natural solution to the \( \mu \) problem. If Higgs fields propagate in the bulk, one can simply employ the Giudice-Masiero mechanism \[24\] by coupling the Higgs fields directly to the supersymmetry breaking fields \[9\]. However, even when the Higgs field is localized to a brane isolated from the supersymmetry breaking, it is trivial \[13\]. One simply includes a term in the Kähler potential
\[ \int d^4\theta \phi \bar{\phi} H_u H_d, \] (13)

where \( \phi \) is the conformal compensator. Because \( \langle \phi \rangle = 1 + \theta^2 m_{3/2} \) this generates both a \( \mu \) and \( B \mu \) term. However, in the limit of gauge-anomaly syzygy, in which case the soft masses are down by a loop factor from the gravitino mass, this is unworkable \[1\].

IV. PARAMETER SPACE AND PHENOMENOLOGY

A complete treatment of the phenomenology of these models will be left for future work, but we will briefly comment on the most significant qualitative effects. There are two main limiting cases. In the first case, which we refer to as “gaugino-like”, the anomaly mediated contributions are relatively small when compared with contributions arising from singlets. In the second, “anomaly-like” case, the gravitino is heavier than the weak scale by a loop factor, and holomorphic mass terms are small.

A great advantage of the anomaly-like case over minimal anomaly mediation is that sleptons are not tachyonic. Still, the model is highly predictive for the soft masses of the sfermions and gauginos, and retains a solution to the SUSY flavor problem. However, as we have not yet included a solution to the \( \mu \) problem, we cannot speak reliably of the soft mass of the Higgs fields.

The gaugino-like case offers simple solutions to the \( \mu \) problem. Unlike traditional gaugino mediation, the gauge mediated (both holomorphic and non-holomorphic) contributions can compete with the gaugino mediated contributions, changing the size of the sfermion masses relative to the gaugino masses, while maintaining flavor blindness. As in the original gaugino mediated framework, the Higgses can either be on our brane or in the bulk. In the latter case the operators
\[ \int d^4\theta \frac{X}{M_{Pl}} (\xi_u H_u H_u + \xi_d H_d H_d) \] (14)
give A-terms proportional to the Yukawas and a \( B \mu \) parameter. Furthermore, contact terms with the SUSY breaking brane can contribute to the soft Higgs masses.

We can include all cases as limits of the following parameter space, although in most scenarios only a few parameters will be relevant: We have \( \mu, B \mu, m_{3/2}, m_{1/2}, \lambda \) (the strength of non-holomorphic operators), \( S_Q, F/M \)
$M$, $\Lambda$, soft Higgs mass squared parameters $m_{H_d}^2$, $m_{H_u}^2$, $\xi_u$, $\xi_d$. After fixing $m_{Z}$, we have twelve continuous parameters and one discrete parameter (the sign of $\mu$).

The most predictive scenario is the gaugino-like case with Higgs confined to our brane. All soft SUSY breaking parameters can then be computed from $\mu$, $m_{3/2}$ (or equivalently $B$), $m_{1/2}$, $\lambda$, $\Lambda$, $S_Q$, $F/M$ and $M$. One combination can be fixed by $m_{Z}$, leaving seven continuous and one discrete parameter.

Another predictive case is when there are no holomorphic mass terms (anomaly-like). In this case, however we do not have a preferred solution to the $\mu$ problem, so we leave $m_{H_d}^2$, $m_{H_u}^2$, and $B\mu$ free. The other parameters are $\mu$, $m_{3/2}$, $\lambda$, $\Lambda$, and $M$. After fixing $m_{Z}$ we are left with seven continuous and one discrete parameter.

One advantage of including messengers is that there are now significant contributions to slepton masses arising at short distance where their gauge couplings are as large as those of the squarks. Thus, unlike traditional anomaly or gaugino mediation, which both predict relatively light sleptons, slepton and squark masses may now be comparable. Indeed, if these contributions arise above the GUT scale, they might be universal. Such a scenario would require less fine-tuning than either AMSB or $g$MSB.

While the number of parameters is slightly larger than in mSUGRA, generalized brane world models have a much richer phenomenology, a basis in a well defined framework, and no supersymmetric flavor problem. In addition, if CP is only broken on our brane, there are no phases in the soft parameters and the SUSY CP problem is solved.

The inclusion of AMSB and $g$MSB in the same framework — both as realistic models — with a limit that looks like a version of gauge mediation, is a step towards the “generalized model space” previously proposed [25].

V. CONCLUSIONS

In brane world models of supersymmetry breaking where gauge fields propagate in the bulk, it is natural to consider the presence of additional messenger fields transforming under the MSSM gauge group. The effects of these fields can drastically change the features of well known brane world models. In particular, it can solve the negative slepton mass squared problem within anomaly mediated supersymmetry breaking, and change the mass relationships of gaugino mediation.

The phenomenology of these models depends strongly on the inputs: the size of the extra dimensions and the mass scale of the messengers in particular. A study of the phenomenology of these models would be useful.

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