Hypercharged Anomaly Mediation

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Introduction: In supersymmetric models, the superpartner spectrum is dictated by the mechanism by which supersymmetry (SUSY) breaking is transmitted to the Standard Model. Available scenarios fall into two main categories. In Planck scale mediation, SUSY is broken at a high scale and transmitted to the visible sector via Planck scale modes. Alternatively, in gauge-mediation, SUSY breaking takes place at a lower scale and is communicated via gauge theory degrees of freedom.

An attractive geometric set-up for messenger mediated SUSY breaking is via string models in which the visible and hidden sectors are both localized on branes [1]. To realize gauge mediation, the hidden and visible branes must be placed at a small relative distance \(d \ll \ell_s\), so that the messengers arise as light open strings that stretch between the two. In Planck scale mediation, on the other hand, the hidden and visible sector are typically taken to be separated by a distance \(d > \ell_s\), and SUSY breaking is transmitted via closed string modes. Since the properties of the closed string messengers depend sensitively on details of the Planck scale geometry, the SUSY flavor and CP problems – the strict bounds on flavor and CP violations from new physics – impose severe constraints on high scale mediation scenarios.

The most elegant Planck scale mediation mechanism is anomaly mediation (AMSB) [2]. This scenario, in which the soft mass parameters are generated via the rescaling anomaly, has several attractive features: it has just one free parameter (the gravitino mass \(m_{3/2}\)), avoids the flavor problem, and the predicted spectrum is UV insensitive. The anomaly induced contributions are always present whenever SUSY is broken; anomaly mediation refers to the case when these terms dominate the observable SUSY breaking effects. For this to happen, the SUSY breaking scale needs to be high, while all effects due to tree-level gravity mediation are suppressed.

It is non-trivial to find string scenarios where these conditions are satisfied [3]. The most promising set-up is to localize the SUSY breaking at the bottom of a strongly warped hidden region, geometrically separated from the visible region where the MSSM resides. The warping effectively filters out all unwanted observable contributions due to tree-level gravity mediation [3]. In the dual perspective, the warped throat describes a strongly coupled hidden CFT and the sequestering takes place due to RG suppression of the dangerous cross couplings [3].

Recent studies have shown that this warped sequestering mechanism plausibly creates the pre-conditions for realizing anomaly mediation in string theory [4]. This insight opens up interesting new avenues for string model building. However, minimal AMSB predicts a negative mass squared for the sleptons [3]. Therefore, one needs to include at least one other type of SUSY breaking effect. In this note, we will identify an attractively simple, string motivated mediation mechanism, that naturally teams up with anomaly mediation, and cures the tachyonic slepton problem.

Hypercharged Anomaly Mediation: Suppose that the MSSM is realized on a local stack of D-branes [1]. The closed string moduli that govern the MSSM couplings are then typically localized near the MSSM branes. The sequestering mechanism relies on this fact. However, there is one geometrically well-motivated exception: the hypercharge gauge coupling may depend on moduli that are localized far from the visible region.

Hypercharge \(U(1)_Y\) is carried by a particular Dp-brane inside the MSSM stack. (One usually considers D6-branes in IIA, and D5-branes in IIB.) To ensure that \(U(1)_Y\) survives as a low energy gauge symmetry, the hypercharge brane needs to wrap a homologically trivial cycle [6]. To arrange for this, one typically introduces a partner brane in the same homology class [1], which could be part of a hidden sector. In this setup, depicted in Fig. 1, the two branes each produce their own \(U(1)\) vector multiplet, \(A_v\) and \(A_{\mu}\), and the open string action splits up as (here \(Q\) encodes all other MSSM fields)

\[
\mathcal{L}_{\text{mssm}}(Q, A_v) + \mathcal{L}_{\text{hidden}}(A_{\mu}).
\]  

As explained in [7], the interaction with the closed string sector enforces a low energy field identification between \(A_v\) and \(A_{\mu}\). This phenomenon is specific to \(U(1)\) gauge fields. The mechanism relies on the CS coupling \(\int C_{p-1} \wedge \text{tr} F\). Here \(C_{p-1}\) is the RR \((p-1)\)-form, that lives in the bulk region between the branes. Upon KK reduction, it
leads to a massless 2-form $C$ with 4-d action
\[ \mathcal{L}_{RR} = C \wedge d(A_V + A_H) + \frac{1}{2\mu^2} |dC|^2. \] (2)

This is equivalent to a St"uckelberg mass term for $A_V + A_H$. The mass scale $\mu$ is typically of order the string scale. The combination $A_V + A_H$ thus gets lifted from the low energy spectrum. The remaining light vector boson
\[ A_1 = A_V - A_H \] (3)
is the hypercharge vector boson. This works independently of the distance between the two branes.

We assume that $A_H$ is massless and that any coupling to hidden matter meshes with the identification of $A_1$ with the hypercharge boson. This does not preclude that SUSY is broken on the hidden $U(1)$ brane. As a concrete mechanism, consider the hidden $U(1)$ gauge kinetic term
\[ \mathcal{L}_{\text{hidden}} = \int d^3 \theta \frac{1}{4} f_\mu(\varphi) W^\alpha W_{\alpha \mu} + \text{c.c.} \] (4)
The coupling $f_\mu(\varphi)$ depends on closed string moduli $\varphi_m$, some of which may be in direct contact with the region where SUSY is broken. Their F-term vevs $F_m$ induce a mass term for the superpartner of $A_H$, which via the identification, manifests itself in the visible sector as the bino mass
\[ \tilde{M}_1 = F^m \partial_m \log(f_V + f_\mu). \] (5)
We conclude that: The bino mass plays a special role in phenomenological D-brane models with sequestered SUSY breaking.

**UV Initial Conditions:** The SUSY breaking F-term vevs $F^m$ of the closed string moduli are expressed in terms of supergravity data as $F^m = e^{K/2} K^{mn} D_n W$, where $K$ is the Kähler potential and $W$ the superpotential evaluated at the local minimum that specifies the compactification geometry. $K^{mn}$ is the inverse of the Kähler metric and $D_n = \partial_n - \partial_n K$. With sequestering, The resulting flavor blind scenario is hypercharged anomaly mediation: only the bino mass receives a hidden sector contribution while all other MSSM soft parameters are generated via the rescaling anomaly. The size of the anomaly contributions is set by the gravitino mass
\[ m_{3/2} = e^{K/2} W. \] (6)

At the high scale $M_*$, which for simplicity we assume to be the GUT scale, we adopt the following initial conditions for the soft masses and trilinear couplings
\[ M_1 = \tilde{M}_1 + \frac{b_1 g_1^2}{8\pi^2} m_{3/2}; \] (7)
\[ M_a = \frac{b_a g_3^2}{8\pi^2} m_{3/2}, \quad a = 2, 3; \] (8)
\[ m_i^2 = \frac{1}{32\pi^2} \frac{d\gamma_i}{d \log \mu} m_{3/2}^2; \] (9)
\[ A_{ijk} = -\frac{\gamma_i + \gamma_j + \gamma_k}{16\pi^2} m_{3/2}. \] (10)
Here $b_a$ are the beta function coefficients, and $\gamma_i$ the anomalous dimensions of $Q_i$, evaluated at $M_{GUT}$. Upon RG evolution, all hypercharged particles receive mass contributions at one loop via their interaction with the $A_1$ vector multiplet.

The relative size of the hypercharge and anomaly contributions is determined by the ratio
\[ \alpha \equiv \tilde{M}_1/m_{3/2}. \] (11)

Hypercharge mediation dominates when $\alpha$ is larger compared to $1/\pi$, AMSB when $\alpha$ is very small. Both limits can be realized, but neither produces an acceptable spectrum. We will therefore assume that neither mechanism is negligible relative to the other. This is not an unreasonable assumption. Eqns. (6) and (7) show that the value of $\alpha$ is sensitive to the form of the superpotential $W$, moduli stabilization mechanism, and SUSY breaking mechanism. In the dilaton dominated limit $\alpha \lesssim \sqrt{3}$, in KKLT-type scenarios, a typical value is $\alpha \sim 1/4\pi^2$. As we will see shortly, hypercharged anomaly mediation works optimally in the intermediate range $0.05 \lesssim |\alpha| \lesssim 0.25$.

**RG Flow and Spectrum:** The free parameters are
\[ m_{3/2}, \quad \alpha, \quad \tan \beta, \quad \text{sign} (\mu). \] (12)

Here $\tan \beta$ replaces the $B_0$ parameter and the magnitude of the $\mu$ is fixed by requiring electroweak symmetry breaking (EWSB) and the measured value of the mass of the Z boson. Thus hypercharged anomaly mediation is a highly predictive scenario.
The mass of the light Higgs boson does not change dramatically with $\alpha$. For parameter choices in Fig. 3 and $|\alpha| \lesssim 0.2$ it varies between 116 – 114 GeV as calculated by FeynHiggs2.6.2 [10] (with $m_t = 171$ GeV). It drops to 111 GeV for $\alpha \sim 0.25$ where $Q_3$ becomes very light. Considering estimated ±3 GeV theoretical uncertainty it is consistent with the LEP limit, 114 GeV, for $m_{3/2}$ as low as $\sim 35$ TeV and $|\alpha| \lesssim 0.2$. Electroweak precision tests, flavor physics observables and $g_\mu - 2$ could impose some additional constraints for $|\alpha| > 0.2$ and $|\alpha| < 0.05$.

The mass of the Z boson as a result of EWSB crucially depends on the boundary condition of $m_{H_u}^2$ at $M_\star$ and the contribution it receives from the RG evolution. For tan $\beta = 10$, we have:

$$m_Z^2 \simeq -1.9\mu^2 - 0.0053(\alpha - 0.32)(\alpha + 0.55)m_\tau^2/2.$$  \hfill (15)

The second term is the sum of $-2m_{H_u}^2(M_\star)$ and $-2\delta m_{H_u}^2$. As is clear from Fig. 2 the RG contribution tends to cancel itself. (A similar behavior was found in models with negative stop mass squared at $M_\star$.) This is an attractive feature, not present in most other SUSY breaking scenarios, since the EWSB requires smaller amount of conspiracies among dimensionless couplings, soft SUSY breaking parameters and/or the $\mu$ term.

We briefly comment on a few distinctive phenomenological features of hypercharged anomaly mediation, focusing on the regime where the hypercharge contribution dominates. As expected, the bino is at the top of the spectrum. Its absence from the dominant decay chains provides an obvious distinction with many other scenarios. A second characteristic feature is the large left-right splitting of the sfermions resulting from the difference in their hypercharge assignments, and the related fact that, among all squarks, only the left-handed third generation doublet is lighter than the gluino. Left-handed stops and sbottoms thus form important links in the gluino decay chain. Top rich final state can be important discovery channels, as it typically give multiple leptons and jets. Disentangling these top/bottom rich final states, however, could be quite challenging experimentally, since due to large multiplicity and combinatorics, the typical top reconstruction method is expected to suffer from very low efficiency. Improved reconstruction techniques are currently under development. Distinguishing the left-handed stops from the right-handed stops, and thereby uncovering the left-right asymmetry of the spectrum, is
another non-trivial challenge. One possible route is to measure their decay branching ratios into higgsino and wino final states.

The lightest supersymmetric particle (LSP) is the neutral wino (except for tiny regions of $\alpha$ where stau or stop is the LSP) which is almost degenerate with the lightest charged wino. Since the wino mass is highly insensitive to $\alpha$, the resulting cosmological features of our model, including the possibility of generating the correct dark matter density, are very similar to other AMSB scenarios [12].

The absence of bino and sleptons, the presence of light left-handed third generation squarks, a wino LSP, and the mass of the CP odd Higgs boson, $A$, is the LSP) which is almost degenerate with the lightest charged wino. Since the wino mass is highly insensitive to $\alpha$, the resulting cosmological features of our model, including the possibility of generating the correct dark matter density, are very similar to other AMSB scenarios [12].

Hypercharged anomaly mediation is a flavor blind mechanism for communicating SUSY breaking to the MSSM sector, c.f. [13]. Among possible $U(1)'$, a combination of $U(1)_Y$ and $U(1)_{B-L}$ is a natural generalization. Furthermore, in models with a PQ-like $U(1)'$, the $\mu$ term can be generated dynamically. This removes the problem with large size of the corresponding $B_\mu$ term generated by AMSB.

Alternatively, if the hidden sector is not completely sequestered, one can use the Giudice – Masiero mechanism to generate the $\mu$ and $B_\mu$ terms by gravity mediation. Additional contribution to scalar masses can be generated to remove the tachyonic $Q_3$ problem of pure hypercharge mediation, and also small gaugino masses can be generated. Thus a combination of hypercharge mediation with some contribution from gravity mediation can easily produce a viable SUSY spectrum.

Discussion: Hypercharged anomaly mediation is a flavor blind mechanism for communicating SUSY breaking between a geometrically sequestered hidden and visible sector. It is a highly predictive scenario and relies on two known long distance forces in Nature. In string models with the MSSM and hidden sector localized on D-branes, the special role of the bino is geometrically well-motivated, given that – via the RR-form mechanism [7] – only the superpartners of abelian gauge bosons can receive a mass contribution from the sequestered sector.

Hypercharged anomaly mediation predicts a low energy spectrum, that is quite insensitive to details of the high scale physics. It would clearly be of interest to find concrete string models in which the ratio $\alpha$ between the bino and gravitino mass naturally ends up in the phenomenologically optimal range [14]. We expect that such models can be constructed, though doing so will require a much more detailed set-up than considered here.

Besides hypercharged anomaly mediation it is possible to extend the model by an additional $U(1)'$ which can communicate SUSY breaking to the MSSM sector, c.f. [13]. Among possible $U(1)'$, a combination of $U(1)_Y$ and $U(1)_{B-L}$ is a natural generalization. Furthermore, in models with a PQ-like $U(1)'$, the $\mu$ term can be generated dynamically. This removes the problem with large size of the corresponding $B_\mu$ term generated by AMSB.

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