# Hypercharged Anomaly Mediation

Radovan Dermíšek,[1] Herman Verlinde,[2] and Lian-Tao Wang[2]
[1]*School of Natural Sciences, Institute for Advanced Study, Princeton, New Jersey 08540, USA*
[2]*Department of Physics, Princeton University, Princeton, New Jersey 08544, USA*
(Received 27 November 2007; published 4 April 2008)

We show that, in string models with the minimal supersymmetric standard model residing on D-branes, the bino mass can be generated in a geometrically separated hidden sector. Hypercharge mediation thus naturally teams up with anomaly mediation. The mixed scenario predicts a distinctive yet viable superpartner spectrum, provided that the ratio $\alpha$ between the bino and gravitino mass lies in the range $0.05 \lesssim |\alpha| \lesssim 0.25$ and $m_{3/2} \gtrsim 35$ TeV. We summarize some of the experimental signatures of this scenario.

DOI: 10.1103/PhysRevLett.100.131804 PACS numbers: 12.60.Jv, 11.25.Wx

*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 setup 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 sectors 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 $m_{3/2}$), it 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 nontrivial to find string scenarios where these conditions are satisfied [3]. The most promising setup is to localize the SUSY breaking at the bottom of a strongly warped hidden region, geometrically separated from the visible region where the minimal supersymmetric standard model (MSSM) resides. The warping effectively filters out all unwanted observable contributions due to tree-level gravity mediation [4]. In the dual perspective, the warped throat describes a strongly coupled hidden conformal field theory and the sequestering takes place due to renormalization group (RG) suppression of the dangerous cross couplings [5].

Recent studies have shown that this warped sequestering mechanism plausibly creates the preconditions 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 [2]. Therefore, one needs to include at least one other type of SUSY breaking effect. In this Letter, 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 D$p$-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 $A_H$, and the open string action splits up as (here $Q$ encodes all other MSSM fields)

$$\mathcal{L}_{\text{mssm}}(Q, A_V) + \mathcal{L}_{\text{hidden}}(A_H). \tag{1}$$

As explained in [7], the interaction with the closed string sector enforces a low energy field identification between $A_V$ and $A_H$. This phenomenon is specific to $U(1)$ gauge fields. The mechanism relies on the Chern-Simons coupling $\int C_{p-1} \wedge \mathrm{tr}F$. Here $C_{p-1}$ is the Ramond-Ramond (RR) $(p-1)$ form that lives in the bulk region between the branes. Upon Kaluza-Klein reduction, it leads to a massless 2-form $C$ with 4D action

$$\mathcal{L}_{RR} = C \wedge d(A_V + A_H) + \frac{1}{2\mu^2}|dC|^2. \tag{2}$$

This is equivalent to a Stückelberg 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

$$A_1 = A_V - A_H \tag{3}$$

is the hypercharge vector boson. This works independently of the distance between the two branes [7].

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

$$\mathcal{L}_{\text{hidden}} = \int d^2\theta \frac{1}{4} f_H(\varphi) W_H^\alpha W_{H,\alpha} + \text{c.c.} \tag{4}$$

The coupling $f_H(\varphi)$ depends on closed string moduli $\varphi_m$, some of which may be in direct contact with the region where SUSY is broken. Their nonzero $F$ terms induce a mass term for the superpartner of $A_H$, which via the identification (3), manifests itself in the visible sector as the bino mass

$$\tilde{M}_1 = F^m \partial_m \log(f_V + f_H). \tag{5}$$

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 (5) 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

$$m_{3/2} = e^{K/2} W. \tag{6}$$

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

$$M_1 = \tilde{M}_1 + \frac{b_1 g_1^2}{8\pi^2} m_{3/2}; \tag{7}$$

$$M_a = \frac{b_a g_a^2}{8\pi^2} m_{3/2}, \qquad a = 2, 3; \tag{8}$$

$$m_i^2 = -\frac{1}{32\pi^2} \frac{d\gamma_i}{d\log\mu} m_{3/2}^2; \tag{9}$$

$$A_{ijk} = -\frac{\gamma_i + \gamma_j + \gamma_k}{16\pi^2} m_{3/2}. \tag{10}$$

Here $b_a$ are the beta function coefficients, and $\gamma_i$ the anomalous dimensions of $Q_i$, evaluated at $M_{\text{GUT}}$. 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

$$\alpha \equiv \tilde{M}_1 / m_{3/2}. \tag{11}$$

Hypercharge mediation dominates when $\alpha$ is larger compared to $1/4\pi$, and 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. Equations (5) and (6) 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 $\alpha \lesssim \sqrt{3}$ [8]; in the scenario of Ref. [9], a typical value is $\alpha \sim 1/4\pi^2$ [9]. 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

$$m_{3/2}, \qquad \alpha, \qquad \tan\beta, \qquad \sin(\mu). \tag{12}$$

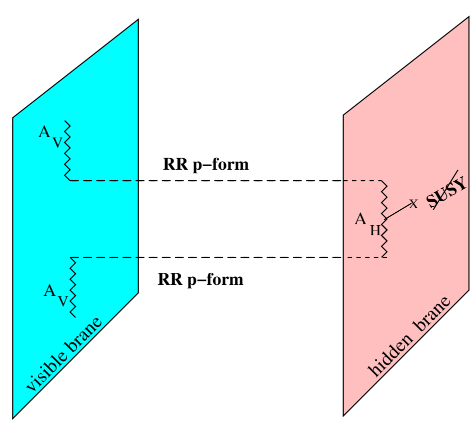


FIG. 1 (color online). SUSY breaking on the hidden brane is mediated to the visible sector via an RR $p$ form. It produces a mass splitting between the $U(1)$ boson $A_V$ and its superpartner. A more detailed account of the mechanism is given in [7].

Here $\tan\beta$ replaces the $B_\mu$ 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.

Figure 2 depicts the separate and combined contributions of hypercharge and anomaly mediation to the RG running of some characteristic soft parameters—the mass squared of the left-handed top squark, left-handed stau and Higgs-up—for $m_{3/2} = 50$ TeV, $\alpha = 0.2$, and $\tan\beta = 10$. In the RG evolution to the weak scale, all scalar masses receive a contribution from the bino mass (here $Y_i$ denotes the hypercharge)

$$\delta m_i^2(\mu) = -\frac{3}{10\pi^2} g_1^2 Y_i^2 M_1^2 \log\left(\frac{\mu}{M_*}\right). \tag{13}$$

This positive contribution dominates at the beginning of the RG evolution. Once sizable scalar masses are developed, the negative contribution from Yukawa couplings becomes important and can overcome the contribution from the bino mass. In pure hypercharge mediation, the left-handed top squark mass squared would be driven to negative values, because out of all scalars its hypercharge is the smallest and its Yukawa coupling is the largest. All other squarks and sleptons remain positive. The wino and gluino masses receive a contribution from the bino mass at the two loop level.

The anomaly induced contribution to the scalar masses is given by anomalous dimensions, which is negative for the mass squared of the sleptons, and positive for the mass squared of the squarks. Therefore, the left-handed top squark mass is pushed above the experimental limit (~100 GeV). This in turn is sufficient to drive $m_{H_u}^2$ to negative values and thus trigger EWSB. Unless the bino contribution is negligible compared to the anomaly contribution, sleptons will remain sufficiently heavy in the combined scenario. The chargino mass is above the experimental limit provided that $m_{3/2} \gtrsim 35$ TeV.

For $3 < \tan\beta < 50$, a viable spectrum is obtained inside the window

$$0.05 \lesssim |\alpha| \lesssim 0.25. \tag{14}$$

A region of $\alpha$ leading to a viable spectrum for $\tan\beta = 10$ can be read out from Fig. 3 showing the spectrum as a function of $\alpha$ for $m_{3/2} = 50$ TeV. The lower bound is given by the slepton limit, and the upper bound is given by the limit on the top squark mass. Hypercharge mediation dominates when $|\alpha| \gtrsim 0.15$.

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 and 114 GeV as calculated by FEYN-HIGGS 2.6.2 [10] (with $m_t = 171$ GeV). It drops to 111 GeV for $\alpha \sim 0.25$ where $Q_3$ becomes very light. Considering estimated $\pm 3$ GeV theoretical uncertainty, it is consistent with the LEP limit, 114 GeV, for $m_{3/2}$ as low as ~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 $M_*$ and the contribution it receives from the RG evolution. For $\tan\beta = 10$, we have

$$m_Z^2 \simeq -1.9\mu^2 - 0.0053(\alpha - 0.32)(\alpha + 0.55)m_{3/2}^2. \tag{15}$$

The second term is the sum of $-2m_{H_u}^2(M_*)$ 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 top squark mass squared at $M_*$ [11].) This is an attractive feature, not present in most other SUSY breaking

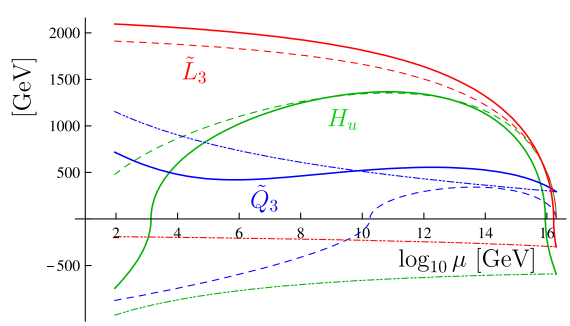


FIG. 2 (color online). Renormalization group running of $m_{H_u}$ (green), $m_{Q_3}$ (blue), and $m_{L_3}$ (red) for $\tan\beta = 10$, $m_{3/2} = 50$ TeV and $\alpha = 0.2$ for $M_\star = M_{\rm GUT}$. We define $m_{H_u} \equiv m_{H_u}^2/\sqrt{|m_{H_u}^2|}$ and similarly for $m_{Q_3}$ and $m_{L_3}$. The contribution of pure hypercharge mediation is given by dashed lines, and the separate contribution from anomaly mediation is represented by the corresponding dotted lines.

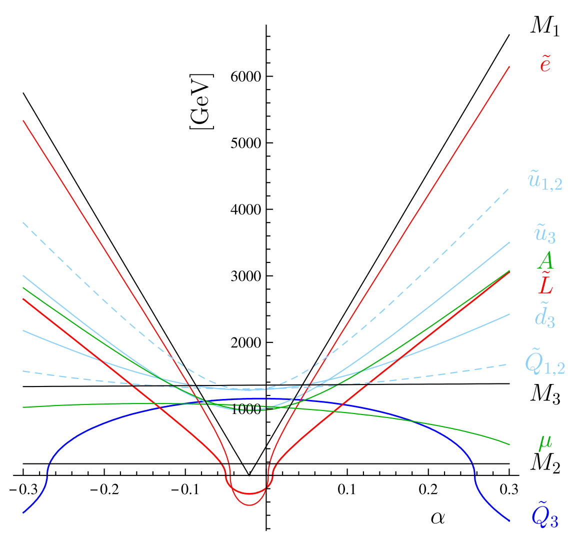


FIG. 3 (color online). Plot of the spectrum of hypercharged anomaly mediation for $\tan\beta = 10$ and $m_{3/2} = 50$ TeV as a function of $\alpha = M_1/m_{3/2}$. Instead of $m_{H_u}$ and $m_{H_d}$ we plot the $\mu$ term and the mass of the $CP$ odd Higgs boson $A$.

scenarios, since the EWSB requires a smaller number 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 top squarks and sbottoms thus form important links in the gluino decay chain. The top rich final state can be important discovery channels, as it typically gives multiple leptons and jets. Disentangling these top or 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 top squarks from the right-handed top squarks, and thereby uncovering the left-right asymmetry of the spectrum, is another nontrivial 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 top squark 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 potentially other observables combined give rise to distinctive signals at the LHC. Finding strategies for distinguishing this scenarios from others could still be a nontrivial challenge, however, and worth further study.

*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 setup 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; cf. [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 Peccei-Quinn-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 $\tilde{Q}_3$ 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.

We acknowledge useful discussions with S. Kachru, P. Langacker, G. Paz, E. Silverstein, T. Volansky, and I. Yavin. This work is supported by the U.S. Department of Energy Grant No. DE-FG02-90ER40542 and by NSF Grant No. PHY-0243680.

[1] For recent reviews of string phenomenology with D-branes, see R. Blumenhagen, B. Kors, D. Lust, and S. Stieberger, Phys. Rep. **445**, 1 (2007); R. Blumenhagen, M. Cvetic, P. Langacker, and G. Shiu, Annu. Rev. Nucl. Part. Sci. **55**, 71 (2005).
[2] L. Randall and R. Sundrum, Nucl. Phys. **B557**, 79 (1999); G. F. Giudice, M. A. Luty, H. Murayama, and R. Rattazzi, J. High Energy Phys. 12 (1998) 027.
[3] A. Anisimov, M. Dine, M. Graesser, and S. D. Thomas, J. High Energy Phys. 03 (2002) 036.
[4] S. Kachru, L. McAllister, and R. Sundrum, J. High Energy Phys. 10 (2007) 013.
[5] M. Schmaltz and R. Sundrum, J. High Energy Phys. 11 (2006) 011.
[6] M. Buican, D. Malyshev, D. R. Morrison, H. Verlinde, and M. Wijnholt, J. High Energy Phys. 01 (2007) 107.
[7] H. Verlinde, L.-T. Wang, M. Wijnholt, and I. Yavin, J. High Energy Phys. 02 (2008) 082.
[8] S. A. Abel, B. C. Allanach, F. Quevedo, L. Ibanez, and M. Klein, J. High Energy Phys. 12 (2000) 026.
[9] K. Choi, A. Falkowski, H. P. Nilles, and M. Olechowski, Nucl. Phys. **B718**, 113 (2005).
[10] S. Heinemeyer, W. Hollik, and G. Weiglein, Comput. Phys. Commun. **124**, 76 (2000).
[11] R. Dermisek and H. D. Kim, Phys. Rev. Lett. **96**, 211803 (2006).
[12] T. Gherghetta, G. F. Giudice, and J. D. Wells, Nucl. Phys. **B559**, 27 (1999).
[13] A recent phenomenological study of pure $U(1)'$ mediation is P. G. Langacker, G. Paz, L. T. Wang, and I. Yavin, Phys. Rev. Lett. **100**, 041802 (2008).