Yukawa Deflected Gauge Mediation in Four Dimensions

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Abstract

We construct a four dimensional realization of a higher dimensional model, Yukawa deflected gauge mediation, in which supersymmetry breaking is communicated to the visible sector through both gauge and Yukawa interactions. The reduction to four dimensions is achieved by ‘deconstructing’ or ‘latticizing’ the extra dimension. Three sites (gauge groups) are sufficient to reproduce the spectrum of the higher dimensional model. The characteristic features of Yukawa deflected gauge mediation, in particular, alignment of squarks and quarks, and a natural solution to the mu problem, carry over to the deconstructed version of the model. We comment on the implications of our results for a solution of the mu problem in the context of deconstructed gaugino mediation.
1 Introduction

Supersymmetry is perhaps the most attractive solution to the hierarchy problem. However, the supertrace theorem implies that SUSY breaking cannot be communicated at tree level through renormalizable interactions. Indeed, tree level breaking would predict superpartners lighter than observed Standard Model particles. Consequently, a viable supersymmetric solution to the hierarchy problem typically includes a “hidden” sector where supersymmetry is spontaneously broken and from where it is radiatively communicated to the MSSM. The spectrum of superparticle masses depends crucially on the mechanism through which supersymmetry breaking is mediated to the MSSM fields. It thus becomes important to investigate various forms of mediation of SUSY breaking between the MSSM and the hidden sector. If the hidden sector and the visible sector are localized on different branes in a higher dimensional space \[1\] then direct contact operators between the hidden and visible sectors are forbidden by locality. If the extra dimension is an order of magnitude or so larger in size than the cutoff of the higher dimensional theory, then the form of the four dimensional effective theory depends on the light fields in the bulk and on their couplings to physics on the brane. The various possibilities for the light fields in the bulk give rise to different patterns of supersymmetry breaking (for example \[1\], \[2\], \[3\], \[4\]).

An interesting model, called Yukawa deflected gauge mediation, was proposed in \[5\]. Here SUSY breaking was communicated to the MSSM (or visible sector) through gauge mediation \[6\], as well as through mixing between the Higgs and messenger fields. As a result, besides the universal gauge mediation soft scalar masses, there are additional contributions because of direct couplings between messengers and MSSM fields. These new contributions, which are parametrically of the same order as gauge mediation, are linked to the Yukawa couplings, and thus lead to a mass spectrum with squark-quark alignment. Hence, the Higgs-messenger mixing of \[5\] still preserves one of the crucial features of gauge mediation – namely, lack of dangerous flavor changing neutral currents (FCNC’s). On the other hand, the model does not suffer from the \(\mu\) problem which plagues gauge mediation. In the context of the NMSSM, one finds that due to Higgs-messenger mixing, the singlet field couples more strongly to SUSY breaking and it is straightforward to obtain the right pattern of electroweak breaking.

The setup of \[5\] crucially relied on an extra-dimensional mechanism to restrict interactions between the MSSM and the messengers. There it was
assumed that the MSSM and the messengers live on separate branes, while gauge and Higgs fields propagate in the bulk. In this paper, inspired by recent ideas of deconstruction (or latticization) [7], [8] of higher dimensional dynamics, we propose a entirely four dimensional setup which realizes the same physics as the higher dimensional setup of [5].

As opposed to genuine extra-dimensional theories, theories with deconstructed extra dimensions do not have any dimensional coupling, and therefore do not require an UV cutoff. Deconstructed extra-dimensions have been used earlier to obtain four dimensional realizations of gaugino mediation [9], [10]. They have also appeared in connection with, among other things, new attempts to address the hierarchy problem ( [11], [12], [13]), models of GUT symmetry breaking ( [14], [15]), low scale unification ( [16], [17], [18]) and fermion localization ( [19]). Other interesting, more formal results involving deconstruction may be found in, for example [20], [21], [22], [23], [24], [25], [26], [27].

In the next section we present a three link model which is a four dimensional realization of [5]. Here, the link vevs will be much larger than the messenger scale, and one obtains gauge mediation with the appropriate Higgs-messenger mixing. Section 3 will address the $\mu$ problem within the context of this model. We conclude in section 4 and speculate on two possible $\mu$ problem solutions in the context of deconstructed gaugino mediation.
2 A gauge-mediation model with Higgs-messenger mixing

The model consists of three sites. Each site indicates a gauge group, with \( G_1 = \text{SM}, \ G_2 = SU(5) \times U(1), \) and \( G_3 = SU(5) \times U(1). \) The field content associated with each site is shown in the figure 1, and corresponds to a straightforward theory space embedding of the model of [5]. The product of \( SM \times SU(5) \times SU(5) \) is broken down to the diagonal standard model by the VEVs of the link fields \( L \) and \( \bar{L}. \) The additional U(1) factors (which are also broken by the link fields) and the adjoints \( A_2 \) and \( A_3 \) serve only to lift fields which would otherwise remain massless after symmetry breaking. As we will see, having three sites is the minimum required to obtain a light Higgs field below the link vev scale without fine tuning.

The bifundamental link fields transform as \( L_{12}(\bar{5}, 5, 1), \ L_{23}(1, \bar{5}, 5), \) under the three non-abelian gauge factors, with \( \bar{L}_{12}, \bar{L}_{23} \) in the conjugate representations, respectively. Here, for notational simplicity, we have labeled the transformation of \( L_{12} \) under the SM in terms of the transformation of the \( \bar{5} \) representation under the SM subgroup of \( SU(5). \) The first lattice point hosts the quark and lepton superfields of the MSSM with the usual standard model charge assignments, along with the Higgs fields \( H^u_2 \) and \( H^d_2. \) The second site hosts Higgs type field \( H_2 \) in fundamental representation of \( SU(5) \) together with an antifundamental \( \bar{H}_2, \) and an adjoint \( A_2. \) The third site hosts an Higgs type fundamental \( H_3 \) and antifundamental \( \bar{H}_3, \) an adjoint \( A_3, \) plus the messengers, namely two other fundamentals of \( SU(5), \ Q_m (m = 1, 2), \) with their conjugates \( \bar{Q}_m. \)

The charge assignments of the above fields under the additional \( U(1) \) factors are summarized below.
The SU(2) doublets in the $H_i$'s together with $H'_u$ correspond to the bulk up type Higgs of [5] while the doublets in the $\bar{H}_i$ together with $H'_d$ correspond to the bulk down type Higgs. The quark and lepton superfields localized on the first link correspond to having the chiral matter of the MSSM on the brane in [5]. The $Q_i$'s and $\bar{Q}_i$'s correspond to the messengers localized on the hidden brane in the higher dimensional model.

The messengers couple to $H_3$ and $\bar{H}_3$ through the superpotential interaction

$$W_{\text{mix}} = X(\lambda_m Q_m \bar{Q}_m + \lambda_d Q_1 \bar{H}_3 + \lambda_u H_3 \bar{Q}_2).$$

Here $X$ is the spurion with the SUSY violating vev. This is the most general renormalizable coupling between these fields subject to a discrete $Z_2$ symmetry under which $X, Q_1$ and $\bar{Q}_2$ are odd while everything else is even, and a discrete $R$ symmetry under which all fields are odd. When $X$ picks up a VEV, this interaction will lead to messenger-Higgs mixing as in the higher dimensional model.

The five dimensional physics of a bulk Higgs field is captured via a site hopping interaction and link Higgsing potentials:

$$W_{\text{link}} = \bar{\gamma}_1 H'_d \bar{L}_{12} H_2 + \gamma_2 \bar{H}_2 \bar{L}_{23} H_3 + \gamma_1 H'_u \bar{L}_{12} \bar{H}_2 + \bar{\gamma}_2 H_2 L_{23} \bar{H}_3 + \sum_{i=2,3} S_i (L_{i-1,i} \bar{L}_{i-1,i} - \alpha_i^2 \Lambda^2) + \text{tr}(L_{i-1,i} A_i L_{i-1,i}).$$

Here, we assume that both singlets $S_i$ couple to a sector which experiences strong dynamics and generates a term $S_i \alpha_i^2 \Lambda^2$. For example, this could be
SQCD with an equal number, \( N = 2 \), of flavors and colors and the couplings

\[
\frac{S_i}{M_P^2} \epsilon_{mjk} \epsilon_{\alpha\beta} \epsilon_{\alpha'\beta'} Q_{i,m} Q_{j,k} Q_{i',l} \epsilon_{\alpha'\beta'}. \tag{4}
\]

Here \( Q \) represents the quarks of the SU(2) theory, \( m, j, k, l \) are flavor indices and \( \alpha, \beta, \alpha' \) and \( \beta' \) are color indices.

It is straightforward to verify that the fields \( A_i \) in the adjoint representation of \( G_i \) ensure that there will not be unwanted massless fields, corresponding to additional flat directions upon Higgsing.

We impose an additional global \( U(1)_R \) symmetry and a discrete global \( Z_{2R} \) symmetry in order to restrict the possible couplings in the superpotential.

We summarize in Table 2 the global symmetry transformations of the various fields.

| Field | \( Z_2 \) | \( Z_{2R} \) | \( U(1)_R \) |
|-------|----------|----------|-----------|
| \( X \) | -        | -        | 2         |
| \( S_1 \) | +        | -        | 2         |
| \( S_2 \) | +        | -        | 2         |
| \( A_2 \) | +        | -        | 2         |
| \( A_3 \) | +        | -        | 2         |
| \( L_{12} \) | +        | -        | 2/3       |
| \( \bar{L}_{12} \) | +        | -        | -2/3      |
| \( L_{23} \) | +        | -        | 2/3       |
| \( \bar{L}_{23} \) | +        | -        | -2/3      |
| \( H_u' \) | +        | -        | 2/3       |
| \( H_d' \) | +        | -        | 2/3       |
| \( H_2 \) | +        | -        | 2         |
| \( \bar{H}_2 \) | +        | -        | 2/3       |
| \( H_3 \) | +        | -        | 2         |
| \( \bar{H}_3 \) | +        | -        | -2/3      |
| \( Q_1 \) | -        | -        | 2/3       |
| \( \bar{Q}_1 \) | +        | -        | -2/3      |
| \( Q_2 \) | +        | -        | 2         |
| \( \bar{Q}_2 \) | -        | -        | -2        |
| MSSM | +        | -        | 2/3       |

In the above Table “MSSM” refers to all the usual MSSM fields other than the Higgses.
The MSSM part of the superpotential consists of the Yukawa couplings of $H'_u$ and $H'_d$ to the the MSSM quarks and leptons.

$$W_{\text{MSSM}} = \tilde{y}_{U,ij} H'_u q_i u^c_j + \tilde{y}_{D,ij} H'_d q_i d^c_j + \tilde{y}_{L,ij} H'_d l_i e^c_j$$  \hspace{1cm} (6)

The complete superpotential is $W = W_{\text{mix}} + W_{\text{link}} + W_{\text{MSSM}}$. \footnote{The symmetries we have imposed also allow the terms $S_2 L_{23} \bar{L}_{23}$ and $tr(L_{23} A_2 \bar{L}_{23})$. Addition of these terms does not affect our conclusions in any way. With the addition of these terms the superpotential $W$ is the most general allowed by the symmetries we have imposed at the renormalizable level.}

The dynamics of this model is as follows. We will first assume that the link vevs are much larger than the messenger scale. Thus, at scale $\sim \Lambda$, the gauge group $G_1 \times G_2 \times G_3$ is broken to the diagonal SM gauge group. The interaction of the link variables with the adjoint fields, and the D-terms (which follow from the extra $U(1)$ factors) are enough to insures that there are no massless moduli fields left. The low energy theory contains only one linear combination of the doublets in $H'_u$ and $H_3$, which we denote by $H_u$ and one linear combination of the doublets in $H'_d$ and $\bar{H}_3$, which we denote by $H_d$. All the triplets decouple. The relevant part of the superpotential is

$$W = \Lambda (\gamma_1 \alpha_1 H_2 H'_d + \gamma_2 \alpha_2 H_3 \bar{H}_2 + \gamma_1 \alpha_1 \bar{H}_2 H'_u + \bar{\gamma}_2 \alpha_2 \bar{H}_3 H_2)$$  \hspace{1cm} (7)

This leads to the following expressions for massless doublets:

$$H_u = \frac{\gamma_2 \alpha_2 H'_u - \gamma_1 \alpha_1 H_3}{\sqrt{\gamma_1^2 \alpha_1^2 + \gamma_2^2 \alpha_2^2}}$$  \hspace{1cm} (8)

$$H_d = \frac{\bar{\gamma}_2 \alpha_2 H'_d - \bar{\gamma}_1 \alpha_1 \bar{H}_3}{\sqrt{\gamma_1^2 \alpha_1^2 + \gamma_2^2 \alpha_2^2}}.$$
of the fields $H_u'$ and $H_d'$ to quarks and leptons. Upon integrating out the messengers, the soft parameters generated have the Yukawa deflected gauge mediated form of \[5\]. In particular the new contributions to the soft squark masses respect the flavor structure of the quarks, and do not lead to large FCNCs.

### 3 An NMSSM solution to the $\mu$ problem

Generating comparable $\mu$ and $\mu B$ terms of weak scale size is an important challenge for a SUSY breaking model. In the context of gauge mediation, a possible solution is to add an additional singlet to the MSSM with couplings

\[
W = \lambda S H_u H_d - \frac{\kappa}{3} S^3. \tag{9}
\]

The singlet $S$ is even and odd, respectively, under the $Z_2$ and $Z_{2R}$ symmetries discussed in the previous section, and has charge $2/3$ under the $U(1)_R$ global symmetry.

The hope is then that upon SUSY breaking, the singlet will acquire a soft negative mass squared, and thus a vev on the order of the weak scale. The $B\mu$ term then arises from a SUSY breaking A-term

\[
V = A_\lambda S H_u H_d. \tag{10}
\]

However, in gauge mediation this scenario is difficult to arrange, because $S$ does not couple directly to fields with tree-level SUSY breaking splittings, and so obtains only a very small soft mass at three loops. The gauge mediated A-term is also not large enough to produce a $B\mu$ of the right size. This makes it difficult to achieve the right pattern of electroweak symmetry breaking \[28\], \[29\], \[30\]. In the limit in which the A-terms are zero, the NMSSM part of the superpotential has an R symmetry under which all fields have charge $2/3$. Since in gauge mediation the A terms are small, one typically finds that the pseudo-goldstone boson associated with the spontaneous breaking of the approximate R symmetry is too light.

In the higher dimensional theory a way out is offered by Higgs-messenger mixing. Here, the singlet has direct Yukawa couplings to the messenger fields and so naturally gets a soft mass squared at two loops, and A-terms are generated at the one loop level. This then leads to a viable electroweak
breaking scenario, without very light goldstone fields \[3\]. It is interesting to see if the same ideas go through in the four dimensional case.

In our model, including an NMSSM singlet will generically lead to couplings of the form

\[
W = S(\lambda H_u' H_d' + \lambda_3 H_3 H_3 + +\lambda_1 H_3 Q_1 + \lambda_2 Q_2 H_3 + \lambda_0 Q_1 Q_2) - \frac{\kappa}{3} S^3. \quad (11)
\]

These couplings mean that below the link vev scale, the singlet will couple to \( H_u \) and \( H_d \). Further, since \( H_u \) and \( H_d \) are linear combinations of the physical higgs and physical messengers, and also because of the direct couplings to the \( Q \)'s and \( \bar{Q} \)'s the singlet gets a soft mass at two loops which is comparable to the gauge mediated soft masses. A-terms are also generated at one loop from these direct messenger matter couplings. It is then possible to generate the right pattern of symmetry breaking exactly as in the higher dimensional model.

### 4 Conclusions

In conclusion, we have demonstrated that it is possible to realize Yukawa deflected gauge mediation as a four dimensional theory, using the methods of deconstruction. Three sites are sufficient to reproduce the physics of the higher dimensional model. All the consequences of Yukawa deflection in higher dimensions - alignment of squarks and quarks without squark degeneracy, a natural \( \mu \) term mechanism in the context of the NMSSM, and new decay channels for the messengers of gauge mediation - carry over to the four dimensional case.

We end the discussion with a few comments. In our model we have been considering the case where the link VEVs are larger than the messenger scale. It is worth asking the question of what happens if the two scales are interchanged so that the messenger scale \(< X >\) is larger than the link scale \( \Lambda \). In this limit the model becomes a variant of the deconstructed gaugino mediation model of \[9\], \[10\] with the Higgs fields in the bulk. This limit is particularly interesting in the context of the NMSSM model of section 3. Even in the absence of mixing between messengers and Higgs, the coupling of the singlet to the Higgs triplets on the third link can generate a negative mass squared for the singlet radiatively from running between the messenger scale and the link scale (where the Higgs triplets are integrated out).
is possible to use this to generate a VEV for the singlet which can then serve as a $\mu$ term. It may then be possible to achieve a viable pattern of electroweak symmetry breaking for the deconstructed gaugino mediation model without sizable fine tuning. The light pseudo-Goldstone associated with the approximate R symmetry is however a potential problem.

If the messenger number symmetry is relaxed to allow messenger-Higgs mixing interactions the singlet gets a soft mass at two loops at the scale $\Lambda$. Trilinear soft $A$-terms between the singlet and the Higgs are also generated at one loop. The renormalization group evolution to the scale of the link VEVs where the Higgs triplets are integrated out will result in an additional negative contribution to the soft mass of the singlet. The theory below the link scale is just the NMSSM with a gaugino mediated spectrum for the MSSM squarks, sleptons and gauginos but not for the Higgs fields or the singlet. It is plausible that in large regions of parameter space the singlet has a negative mass squared, resulting in a sizable VEV for the singlet. Because the R symmetry is broken at one loop by the singlet-Higgs trilinear $A$ term, there is no pseudo-Goldstone. This seems a promising approach for a solution to the $\mu$ problem of deconstructed gaugino mediation.

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This approach is similar in spirit to that of [3] in the context of the NMSSM with gauge mediation. They obtain a negative mass for the singlet by coupling it to additional vector like matter.
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