

String Phenomenology and SUSY Breaking

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1. Part I: constructing visible and hidden sectors

Before plunging into specific scenarios, I would like to make two general remarks about string phenomenology.

The first point I would like to emphasize is that there is no ‘royal road’ to particle physics. What I mean by that is that according to our present understanding, consistency of the UV completion of the Standard Model seems to put only mild constraints on the low energy physics. If correct, this implies a shift in perspective with respect to how string phenomenology has been pursued over the last 20 years. It means that the Standard Model must not be ‘found’ (by guessing the UV completion and running it down to the TeV scale), but it must be ‘engineered’. In particular, string phenomenologists will encounter and have to address the same model building issues that traditional phenomenologists have had to deal with for building possible extensions of the SM.

One might then ask what is the added value of doing string phenomenology as opposed to traditional phenomenology. We believe one important advantage is that string theory provides a dual geometric picture which makes many issues more intuitive than they would have been from a purely 4D point of view. Nevertheless it is true for TeV scale phenomena that at the end of the day one may write down an effective Lagrangian and treat the model in terms of conventional field theory. It seems unlikely that one would be able to make a definite prediction with a stringy signature.

The second point we would like to emphasize is that string phenomenology is really supersymmetric phenomenology. This is really because non-supersymmetric string theory is still very poorly

understood. Thus if the LHC does not show some signs of supersymmetry, string phenomenology in its current form will not have much to say about particle physics.

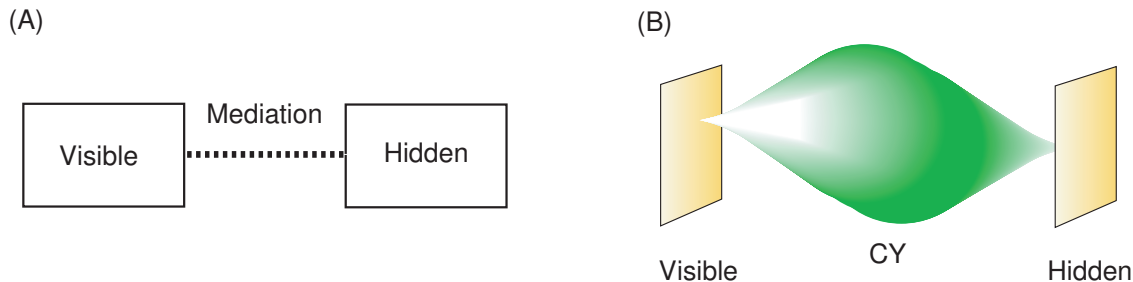


Figure 1: (A) *SUSY must be broken in a separate hidden sector, then mediated to the MSSM.* (B) *Schematic picture of the brane world model.*

With these two points out of the way, we now turn to stringy model building. We are going to discuss D-brane models, although there are many parallels with heterotic string models. A popular scenario is the ‘brane world’ model, where the visible sector and the hidden sector are localized in different regions in the extra dimensions (see picture). This is a geometric realization for the usual SUSY scenario, visible-mediation-hidden. The brane world scenario allows us to separate difficult issues of quantum gravity, such as moduli stabilization, from more prosaic issues of model-building. That is, it allows us to say something interesting without knowing the full UV completion. This is also known as the bottom-up approach to string phenomenology.

With this picture in mind, we can now describe the plan for the remainder. In part I, we will describe some recent progress on constructing local models of the MSSM and DSB. In part II, we will describe some recent progress on the mediation mechanism.

A perturbative open string has two ends, and at each end we may have a Chan-Paton factor. This implies that all the gauge groups must be $U(n)$, $O(n)$ or $USp(n)$, and all the matter must live in a tensor product of two fundamental representations of these gauge groups. Such matter is called ‘bifundamental.’ In particular this scenario implies problems for GUT model building, because it disallows an E_6 gauge field or an $SO(10)$ gauge group with a $\mathbf{16}$, which is a spinor representation (although such states can be constructed if we allow ‘multi-pronged’ open strings with multiple ends).

This reasoning seems to allow for an $SU(5)$ GUT, because $SU(5) \subset U(5)$. However problems arise at the level of interactions. The field content is of the form

$$10 = \begin{pmatrix} Q & u^c \\ & e^c \end{pmatrix}, \quad \bar{5} = \begin{pmatrix} L \\ d^c \end{pmatrix}, \quad 5_h = \begin{pmatrix} T_u \\ H_u \end{pmatrix}, \quad \bar{5}_h = \begin{pmatrix} T_d \\ H_d \end{pmatrix} \quad (1.1)$$

Thus we see that the quark Yukawa coupling come from the following:

$$10 \times 10 \times 5_h \rightarrow Qu^c H_u$$

$$10 \times \bar{5} \times \bar{5}_h \rightarrow Qd^c H_d \tag{1.2}$$

Now the second of these is neutral under the extra $U(1) \subset U(5)$, whereas the second is proportional to the epsilon tensor and thus has charge 5 under the extra $U(1)$. In other words, the down quark Yukawa coupling is allowed classically but the top quark Yukawa coupling must be generated non-perturbatively through D-instantons. Since in real life the top quark Yukawa coupling is order 1 and the other Yukawa couplings are hierarchically smaller, such models are ruled out¹.

Although we may still look for rationales for gauge coupling unification, this situation leads us to try to construct the MSSM directly. Actually the best we can do with D-branes is construct the MSSM with an extra Z' , and usually we add a second Z' as well. The reason is that the colour group must now be embedded as $SU(3) \subset U(3)$, and the extra $U(1)$ corresponds to gauged baryon number B (models in which the right-handed quarks live in an anti-symmetric representation and the extra $U(1)$ has some other interpretation again yield problematic interactions). Moreover we would like to have R-parity in the MSSM, and the only way we know how to get an exact symmetry from string theory is to gauge it. R-parity arises as the Z_2 subgroup of $B - L$, where L is gauged lepton number, so in addition to B we also gauge L . The $B - L$ can be Higgsed to a Z_2 subgroup. The gauged $B+L$ is anomalous, and in string theory always couples to a closed string axion through a Stückelberg coupling:

$$\mathcal{L}_4 \supset g_s \ell_s^{-2} f(m) (A_\mu^{B+L} + \partial_\mu a)^2 \tag{1.3}$$

where $f(m)$ is a function of the closed string moduli m . Thus generically this Z' gets a mass close to the string scale and can be ignored in low energy phenomenology. If however, for some reason or other, this Z' turns out to be relatively light, it would have some interesting signatures due to its anomalous nature.

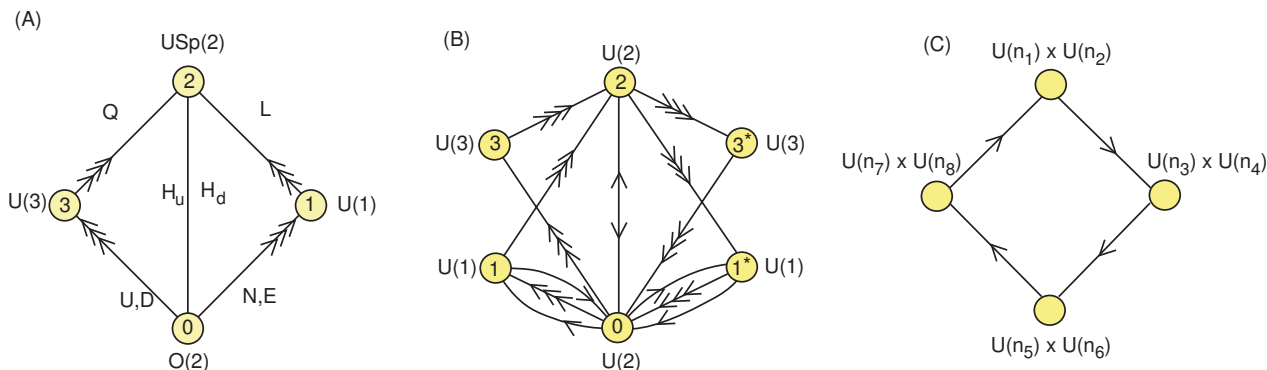


Figure 2: (A) Quiver for the MSSM extended by two Z' -primes. (B) Covering quiver. (C) Quiver for branes on a Del Pezzo 5 singularity.

¹The situation can be ameliorated in flipped $SU(5)$ models, but these do not necessarily predict gauge coupling unification and so undermine the rationale for looking for such models in the first place.

With these preliminaries, we can now draw a quiver for the MSSM extended by two Z-primes. It is given in figure 2A. Actually there are a few closely related versions which are slightly different. We won't discuss that here and just drew the simplest one.

Let us make some comments on the right handed neutrinos. Integrating out the heavy sterile neutrinos, assumed to have a large mass

$$M\nu^c\nu^c \tag{1.4}$$

we generate the dimension five operator

$$\frac{\lambda_\nu^2}{M}LLH_uH_u \tag{1.5}$$

which is the leading correction to the renormalizable MSSM. Upon electroweak symmetry breaking this yields naturally small masses for the neutrinos (this is called the seesaw mechanism). However note that integrating out heavy closed string modulinos or $U(1)$ adjoints could also lead to small neutrino masses, and in a typical stringy set-up all such contributions will be there (of course each mode that contributes should come with a large mass M). Thus there does not seem to be a general way to declare some particular open or closed string mode to be the right-handed neutrino.

We have ignored one important issue here. In the above model, the Majorana neutrino masses are not invariant under $U(1)_L$, and so as it stands they are forbidden. (Recall the $U(1)_L$ was introduced to guarantee R-parity.) One possibility is that they are generated by D-instantons. Recall however that M needs to be large. D-instanton effects will generically be too small (even when we compare M with the string scale) and so this seems unappealing. A second possibility is that we include some new Higgs fields which are charged under $U(1)_L$, so that we can make a gauge invariant expression. In D-brane models however all the fundamental fields are of charge ± 1 , and since we need a charge 2 field this means it should be composite. This means that the Majorana mass comes from a dimension five term and we will have to explain why the VEV of the new Higgs field is so large. Another possibility is of course that the seesaw mechanism is not at work, but the Yukawa couplings happen to be small. Or one could consider a D-brane model without $U(1)_L$ and look for some other explanation to forbid the undesirable superpotential terms.

Now how does one find a model like this? Let us first undo the orientifolding. This yields the oriented quiver in 2B. Apart from the number of generations and the vector-like matter, this is of the same form as the quiver for D-branes on a Del Pezzo 5 singularity. In fact, one can take the DP5 quiver with certain ranks of the gauge groups and turn on some VEVs to get additional quivers of this type. For suitable VEVs and superpotential, one can get exactly the quiver in figure 2A. The extra matter that picked up a mass during Higgsing can be made arbitrarily heavy.

Similarly one can make models of dynamical SUSY breaking. You pick the model you like, draw it as a quiver, and then construct the quiver from branes at singularities. One simple example is the $SU(5)$ gauge theory with one generation of $10 + \bar{5}$. One can draw it as a quiver as indicated in

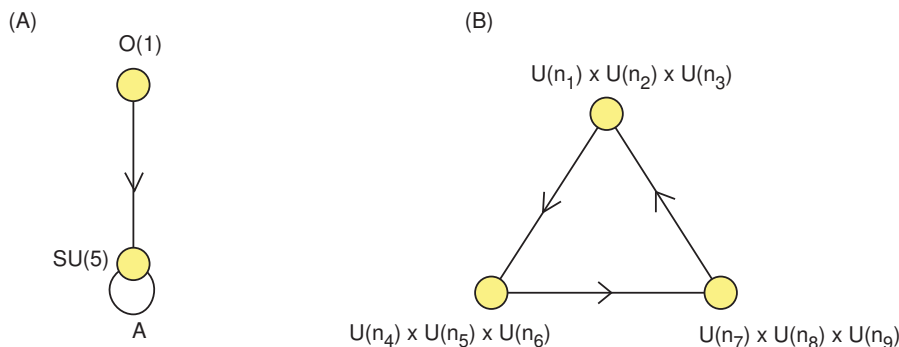


Figure 3: (A) Quiver for a DSB model. (B) Quiver for $\mathbf{C}^3/Z_3 \times Z_3$ orbifold.

figure 3A. Unfolding the quiver, we recognize that it may be obtained as a fractional brane on the orientifold of the orbifold singularity $\mathbf{C}^3/Z_3 \times Z_3$.

As another example, suppose we want to construct an ISS meta-stable vacuum. The ISS examples arise in the IR of SUSY QCD in the range $N_c < N_f < 3N_c/2$ with massive quarks. This can be obtained for instance from the standard conifold quiver in an appropriate range of parameters, with the two ranks of the gauge groups given as $N_1 = N_c$ and $N_2 = N_f/2$.

As a warning however, one typical problem that arises when embedding such models in string theory is that the parameters of the model become dynamical and start running away. Thus part of the assumption here is that the moduli can be stabilized in a regime where the gauge theory arguments for DSB apply.

2. Part II: mediation

We have seen that it is possible to build the MSSM and models of dynamical SUSY breaking from branes at singularities. Now we have to decide how to couple them. This is in some sense the most interesting question, because choosing a mediation scenario will finally lead us to some predictions for observed low energy physics.

Let us quickly review the different scenarios. We assume that SUSY is broken in the hidden sector through an F-term VEV which we denote $\langle F \rangle$. The scenarios basically come in two types:

- high scale mediation: in this case the superpartner masses of order $m_{soft} \sim \langle F \rangle / M_{pl}$. Quantum gravity is not believed to have any global symmetries, so high scale mediation is typically not flavour universal and this leads to large FCNCs. The problem of suppressing flavour non-universal couplings between the visible and the hidden sector is called sequestering. It is

difficult to achieve in string theory, but one important class of models which may achieve sequestering is D-branes at the end of a long conifold-like warped throat (these are dual to field theory models which are approximately conformal over a long energy range).

- Low scale mediation: The main mechanism here is gauge mediation, i.e. mediation by messenger fields which are charged under Standard Model gauge groups. The soft masses are of order $m_{soft} \sim \alpha \langle F \rangle / M_{mess}$, where α is the 1-loop factor from Feynman diagrams with gauge interactions, and M_{mess} is the mass of the messenger fields. Gauge interactions are flavour universal. Possible ‘gravity induced’ flavour non-universal masses of order $\langle F \rangle / M_{pl}$ are small for low $\langle F \rangle$.

Analogously, in string theory mediation would again seem to come in two types. Let d denote the spatial separation in the extra dimensions between the visible and the hidden branes. Then roughly we may expect

- $d > l_s$: closed string mediation. (high scale)
- $d < l_s$: open string mediation. (low scale)

Actually this is not quite true in general, due to open/closed mixing. In particular, a mechanism we will discuss later has $d > l_s$ but could be low scale (and flavour universal).

Gauge mediation can be realized in string theory and, as noted above, one nice feature of gauge mediation is that it is flavour universal. However there is no single compelling model, and moreover it would require us to add a lot of extra mediation fields to our set-up. It would be more elegant and economical to use the ingredients we already have. We have seen that string theory often forces us to add an extra Z' to our model. Moreover the Z' explores the full Calabi-Yau and can be made to couple to both hidden and visible sectors, as we will explain. Also, its interactions are restricted to be flavour universal due to gauge invariance. So we are going to explore the use of a Z' (or more precisely, the prime-ino) to be the mediator.

In fact, we might consider doing away with a Z' altogether and construct a direct model, by using the bino. We comment on this as well.

Let us first discuss the Stückelberg couplings in a bit more detail. We may dualize the axion a to a RR two-form field C . This two-form field descends from a RR field in ten dimensions with additional indices, let’s say it comes from a four-form field C_4 integrated over a 2-cycle S . Now if we have several D5-branes wrapping the two-cycles in the same homology class S , then from the Chern-Simons part of the D-brane actions $\int C_4 \wedge \text{Tr exp}(F)$ we get a four-dimensional coupling of

the form

$$\int d^4x C_{\kappa\lambda} \wedge \sum_i \text{Tr}(F_{\mu\nu}^i) \tag{2.1}$$

where i runs over the different D5-branes wrapping the same cycle S . Therefore, the diagonal gauge field $\sum_i A_\mu^i$ eats the axion and becomes very massive, but all the orthogonal linear combinations remain massless. This is independent of how far the D5-branes are separated in the extra dimensions. Morally one could say there is a vacuum with an enhanced gauge symmetry where all the D5-branes sit on top of each other and the vacuum where they sit apart is obtained by Higgsing an adjoint, even though there may not be any unified gauge theory in the traditional sense.

In particular we see that if we have a visible D5-brane and a hidden D5-brane wrapping cycles which are homologous, then $A_\mu^1 + A_\mu^2$ receives a mass close to the string scale, and a few orders of magnitude below the string scale we are just left over with $A_\mu^1 - A_\mu^2$, which is our Z' . So we can make our Z' couple to both the hidden and visible sectors. A similar mechanism can also be implemented in the $E_8 \times E_8$ heterotic string.

One immediate tension of this model is that the squarks obtain masses at one loop, and gauginos (which do not directly couple to the Z') get masses at two loops. Thus the gauginos end up being quite a bit lighter than the squarks, and in order to evade observational bounds on the gauginos the squarks will then end up being a few orders of magnitude above the TeV scale. This implies a mild fine-tuning for the Higgs mass. Thus the Z' mediation is an example of (mild) split SUSY. The fine-tuning can perhaps be ameliorated by combining with other mediation mechanisms.

As emphasized in part I, the natural Z' to take is $B - L$. One can do the RG analysis, things seem to work fine modulo the fine-tuning, and one gets a predictive spectrum. One could also consider taking the mediator to be the bino. In this case however, because the hypercharge for the left-handed quarks is the smallest, the squarks become tachyonic before the Higgs becomes tachyonic, i.e we break colour at low energies, so on its own this does not seem like a viable scenario.

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