R-symmetric Gauge Mediation and the MRSSM

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Based on work with
S. De Lope Amigo, P. Fox and E. Poppitz
arXiv:0809.1112, ...

Motivation

- Supersymmetry pairs each Standard Model (Weyl) fermion with a spin-0 boson, and each boson with a (Weyl) fermion.
- Solves the gauge hierarchy problem by canceling quantum corrections in the Higgs sector.
- Also improves Grand Unification, provides Dark Matter candidates, has many nice theoretical properties, ...

Motivation

- Problem: we do not see scalar electrons or fermionic gluons! This can be resolved by Spontaneous Symmetry Breaking.
- Solution to hierarchy problem is assured as long as SUSY-breaking operators are "soft" ($d<4$).
- Naively doubling the SM content, adding a second Higgs doublet, and writing down all soft SUSY breaking operators allowed by symmetries is called the Minimal Supersymmetric Standard Model.

The MSSM Soft Operators

- Hermitian scalar masses:

$$m_{ij}^2 \tilde{q}_i^* \tilde{q}_j$$

- Holomorphic scalar mass (“B-terms”):

$$B_\mu H_u H_d$$

- Holomorphic trilinear couplings (“A-terms”):

$$A_{ij} H_{u,d} \tilde{q}_L^i \tilde{q}_R^j$$

- Majorana gaugino masses:

$$M_{1/2} \lambda\lambda$$

A New Puzzle

- With all these new operators, the MSSM has 124 parameters - and that's the MINIMAL model!
- Many of those parameters are flavor mixing angles and phases, implying large FCNC's and CP violation. This is called the **SUSY Flavor/CP Puzzle**.
- We need some principle to eliminate this flavor violation to avoid conflicts with observation and reduce the parameter space to something manageable for experiments.

A New Solution

- An R-symmetry rotates fields within a supermultiplet differently.
- Kribs, Poppitz, Weiner (arXiv:0712.2039) found that by imposing an additional R-symmetry to the MSSM you can have sizable flavor-violating operators while not generating large FCNC's or CP violation, as long as gluinos are heavy.
- We impose a $U(1)_R$ symmetry, although a discrete symmetry would work as well.

The MRSSM

- Features of the MRSSM:
  - No Majorana masses for the gauginos, but there are Dirac masses.
  - No A-terms for the scalars; hence no left-right squark/slepton mixing.
  - No mu-term, but there is a B-term (complicated Higgs sector).

K-Kbar Mixing

Strongest constraint in SUSY flavor physics.

Parametrize mixing: $\delta_L \equiv \frac{m^2_{\tilde{Q}12}}{M^2_{\tilde{q}}}$ $\delta_R \equiv \frac{m^2_{\tilde{d}12}}{M^2_{\tilde{q}}}$

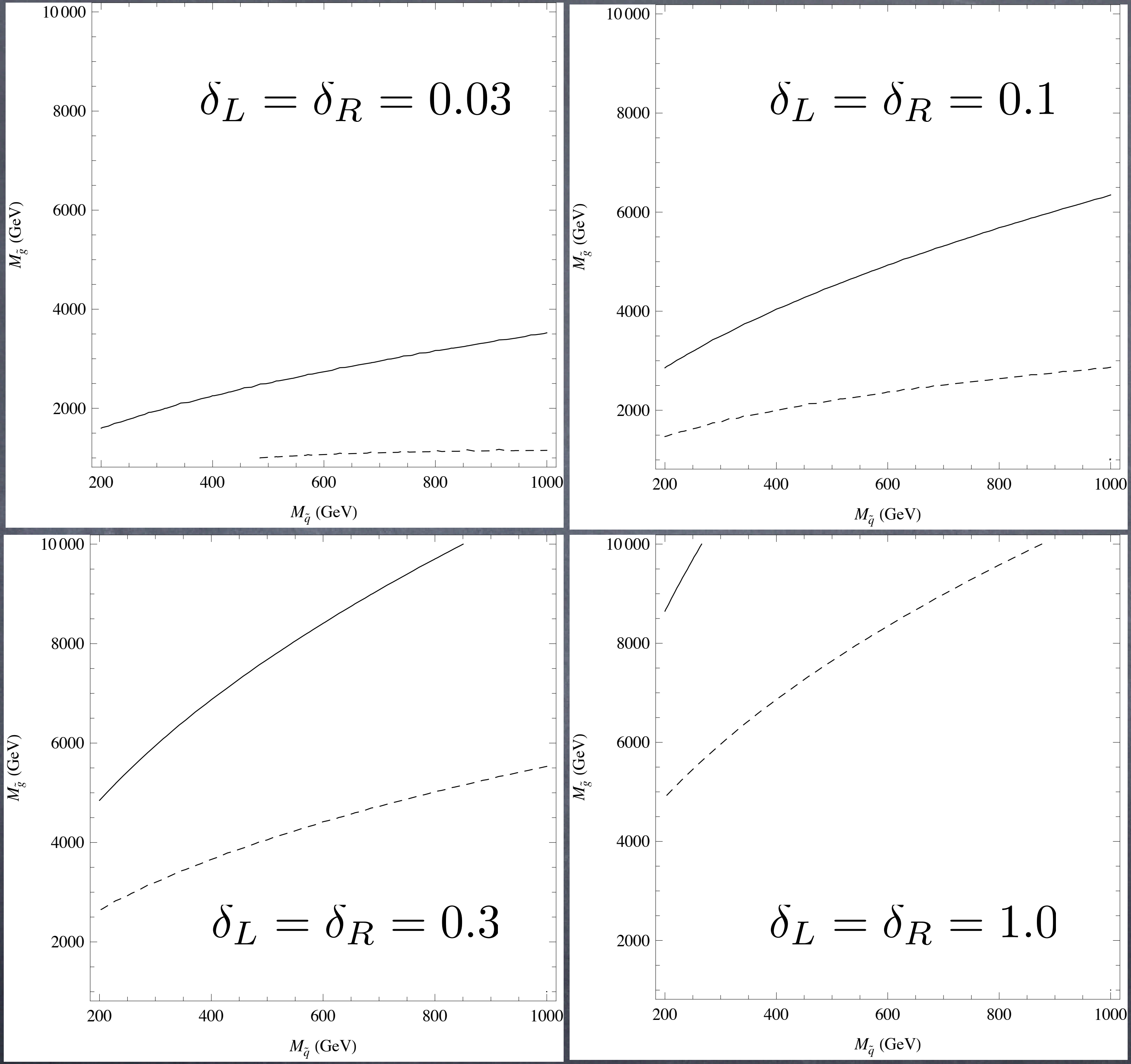
The Low-Energy Effective Lagrangian is:

$$\mathcal{L}_{\text{eff}} = \frac{\alpha_s^2(M_{\tilde{g}})}{216}\left(\frac{M^2_{\tilde{q}}}{M^4_{\tilde{g}}}\right)\sum_n C_n(\mu)\mathcal{O}_n(\mu)$$

$$\begin{aligned}
\mathcal{O}_1 &= (\bar{d}^i_L \gamma^\mu s^i_L)(\bar{d}^j_L \gamma_\mu s^j_L) \\
\mathcal{O}_4 &= (\bar{d}^i_R s^i_L)(\bar{d}^j_L s^j_R) \\
\mathcal{O}_5 &= (\bar{d}^i_R s^j_L)(\bar{d}^j_L s^i_R)
\end{aligned}$$

QCD Corrections computed in
A.B., S.-P. Ng, arXiv:0803.3811

$M_{\tilde{g}}(\mathrm{GeV})$



$M_{\tilde{q}}(\mathrm{GeV})$

Results: CP Violation

Assuming this contribution saturates the measured bound of ϵ_K:

$M_{\tilde{g}}$	$M_{\tilde{q}}$	$\delta_L \equiv \delta_R$	KPW phase	BN phase
3.5 TeV	400 GeV	0.06	0.15	9.8×10^{-3}
3.5 TeV	400 GeV	0.25	0.01	5.7×10^{-4}

A Problem…

- Anytime you spontaneously break SUSY, you have a goldstino and a cosmological constant.
- When turning on supergravity, this goldstino is “eaten” by the gravitino (gauge field of SUSY) and it gains a mass which is R-violating (at least in N=1 SUSY).
- This mass term feeds into the MSSM through anomaly mediation, so it looks like this model can never be realized…

… A Solution!

- Gauge mediation has a very light gravitino, typically around 1 keV or so, rendering these troublesome effects irrelevant.
- Ordinary gauge mediation breaks the R-symmetry, but if we can find a framework where we can maintain the symmetry through a gauge-mediation-like mechanism, then we might realize the MRSSM naturally…

ISS Models

- Intriligator, Seiberg and Shih (hep-th/0609529) show that certain SUSY-QCD theories have a "metastable" vacuum that spontaneously breaks SUSY but preserves an R-symmetry.

- The electric theory has N_f quark superfields, an $SU(N_c)$ gauge group, and a superpotential:

$$W_{el.} = \mathrm{Tr}\, m\, Q\bar{Q}$$

- The magnetic theory has a "meson" superfield, N_f "dual quark" superfields, an $SU(N_F - N_c)$ gauge group and a superpotential:

$$W_{magn.} = \bar{q}\,\mathcal{M}\,q + \ m\,\Lambda\,\mathcal{M} + \ldots$$

A Minimal Model

- Previously, much effort has gone into finding ways to break the R-symmetry so as to give the gauginos Majorana masses (see our paper for a list of references).
- We will consider $N_F = 6$, $N_C = 5$ as the simplest model - no gauge fields in the magnetic theory (Csaki, Shirman, Terning, hep-ph/0612241).
- The dual squarks will get vevs, breaking

$$SU(6) \to SU(5)$$

- We will write the SU(6) fields in terms of SU(5) fields:

$$\mathcal{M} = \begin{pmatrix} M & N \\ \bar{N} & X \end{pmatrix} \, , \; q = \begin{pmatrix} \varphi \\ \psi \end{pmatrix} \, , \; \bar{q} = \begin{pmatrix} \bar{\varphi} \\ \bar{\psi} \end{pmatrix}$$

We embed the Standard Model group as a gauged subgroup of SU(5).

We also add two additional adjoint superfields.

	$SU(5)_V$	$U(1)$	$U(1)_R$
M	**Adj+1**	0	+2
X	**1**	0	+2
N	**5**	+6	+2
$\bar{N}$	$\bar{\mathbf{5}}$	–6	+2
φ	**5**	+1	0
$\bar{\varphi}$	$\bar{\mathbf{5}}$	–1	0
ψ	**1**	–5	0
$\bar{\psi}$	**1**	+5	0
Φ	$\mathbf{Adj}'$	0	0
M'	**Adj**	0	0

- Because of the symmetry breaking, there will be 11 massless Nambu-Goldstone modes - we would like to get rid of these since they will have charge under the SM gauge group.
- We therefore “tilt” the ISS superpotential to explicitly break the SU(6) symmetry and give masses to these NG modes:

$$W = W'_{\rm magn} + W_1$$

$$W_{\rm magn} = \lambda\left(\bar\varphi M \varphi + \kappa'\,\bar\psi X \psi + \kappa\,\bar\varphi N \psi + \kappa\,\bar\psi \bar N \varphi\right) - f^2(X + \omega\,{\rm Tr}M)$$

and $$W_1 = y\left(\bar\varphi \Phi N - \bar N \Phi \varphi\right)$$

Messenger Spectrum

At the SUSY-breaking metastable vacuum:

$$\begin{aligned} \langle \bar{\psi}\psi \rangle &\equiv v^2 = \frac{f^2}{\lambda\kappa'}, \\ \langle F_{\mathrm{Tr}M} \rangle &= \omega f^2 \end{aligned}$$

We can parametrize all the masses in terms of two scaleless variables and a mass:

$$x \equiv \lambda\omega \qquad\qquad z \equiv \frac{\omega\kappa'}{\kappa^2}$$

$$M_{\mathrm{mess}}^2 \equiv \frac{x}{z} f^2$$

Messenger Spectrum

Scalars:

$N, \bar{N}$: SUSY-preserving mass² M_{mess}^2

$\varphi, \bar{\varphi}$: SUSY-breaking mass² $(1 \pm z) M_{\text{mess}}^2$

R-preserving!!

Fermions:

$\varphi \bar{N} + N \bar{\varphi}$: SUSY-preserving (Dirac) mass M_{mess}

Note: with all this matter, QCD will develop a Landau Pole Λ_3

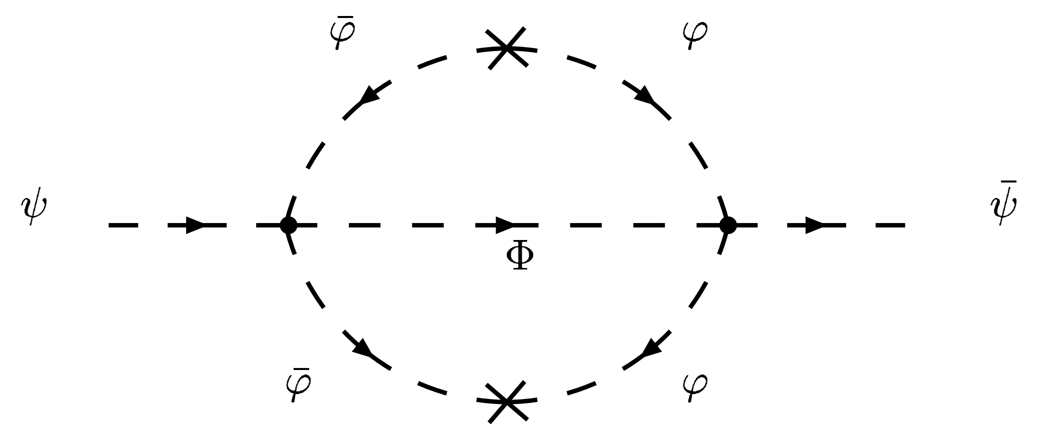
Messenger Spectrum

$$\left.\begin{aligned}\psi &= ve^{(\eta+i\xi)/v}\\ \bar{\psi} &= ve^{-(\eta+i\xi)/v}\end{aligned}\right\}$$

Coleman-Weinberg calculation gives

$$\langle\eta\rangle = 0$$

ξ is the NG boson of the U(1) symmetry.
W$_1$ explicitly breaks this symmetry and so will generate a potential for the NG boson at two loops:



$$V_{\text{eff}}(\xi) = -\mu^2 v^2 \cos\left(\frac{2\xi}{v}\right)$$

$$m_\xi^2 = \left(\frac{\lambda\kappa y}{16\pi^2}\right)^2 M_{\text{mess}}^2 H(z)$$

where $H(1) = \dfrac{2\pi^2}{3}$

Charge Conjugation

- Charge conjugation symmetry exchanges barred and unbarred fields.
- Gauge fields (including gaugino) change sign, so to make a Dirac mass:

$$\Phi \longrightarrow -\Phi$$

- This explains the relative sign in W_1.
- This also forbids a tadpole for the hypercharge adjoint, up to SM contributions that we assume are small.
- This also forbids dangerous kinetic mixing of the SUSY breaking spurion with the hypercharge D term which could generate tachyonic sleptons.

Soft terms in the Visible Sector

There are two contributions:

- Contributions from unknown UV physics.

Flavor violation can occur here!

- IR (“Gauge Mediation”) contributions.

UV Contributions

All terms can be generated by a SUSY-breaking spurion:

$$\Xi \equiv \langle \mathrm{Tr} M \rangle = \theta^2 \omega f^2$$

and all UV contributions are proportional to a single scale:

$$M_{UV} = \frac{\omega f^2}{\Lambda} = \left(\frac{z}{\lambda}\right)\left(\frac{M_{\mathrm{mess}}}{\Lambda}\right) M_{\mathrm{mess}}$$

where Λ is the scale at which these operators are generated.

UV Contributions: The Size of Λ

There are two extremes for estimating the UV scale:

- $\Lambda \sim M_P$: UV operators are irrelevant; does not realize the large flavor-violating operators of the MRSSM, so we will not consider it here.
- $\Lambda \sim \frac{\Lambda_3}{4\pi}$: UV operators are important - this is the maximal size of the operators (using NDA). We will consider this case, but it could overestimate the size of these contributions.

UV Contributions

UV Dirac Gaugino Mass:

$$\int d^2\theta \, \frac{1}{\Lambda^3} \, (W^\alpha \Phi) \, \bar{D}^2 D_\alpha \, (\Xi^\dagger \Xi) \qquad m_{1/2} \sim M_{UV} \left(\frac{M_{UV}}{\Lambda} \right)$$

Small!

UV Scalar Mass:

$$\int d^4\theta \, \frac{c_{ij}}{\Lambda^2} \, (\Xi^\dagger \Xi) \, Q_i^\dagger Q_j \qquad m_{0\,ij} \sim M_{UV}$$

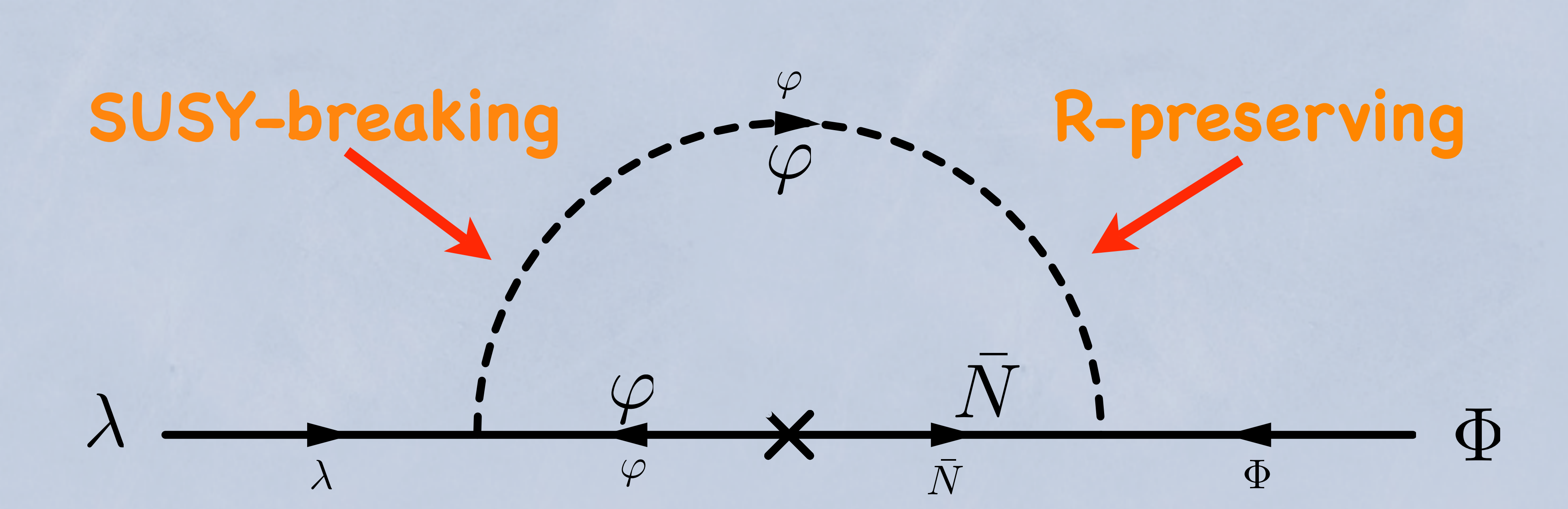
Adjoint Masses:

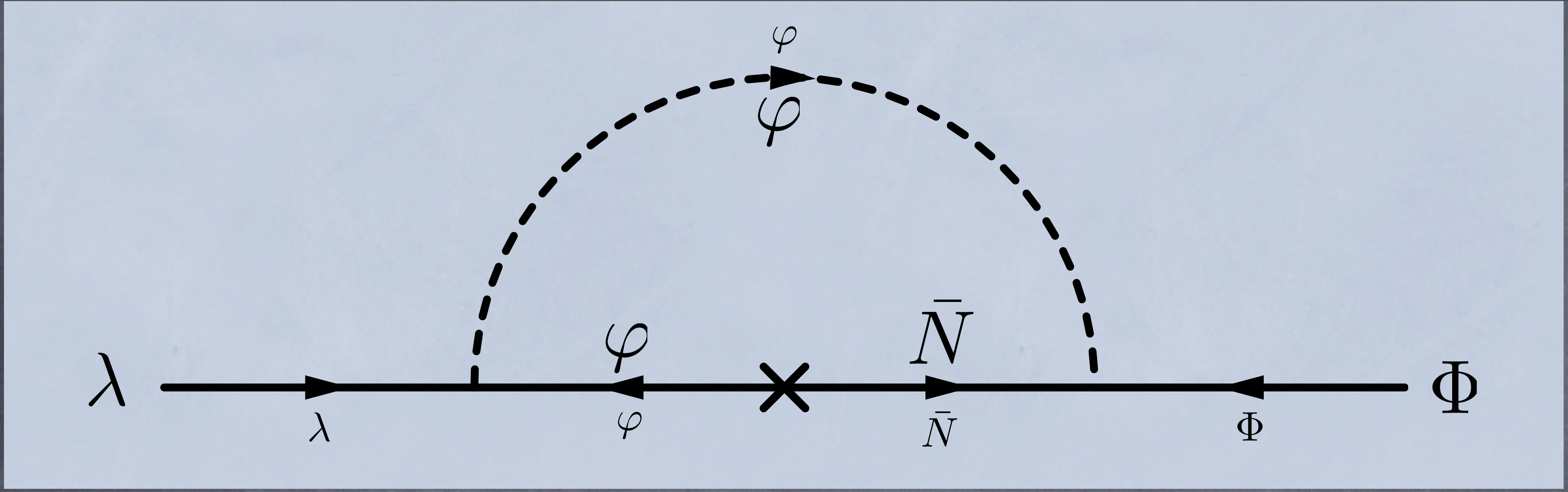
scalars **scalars & fermions**

$$\int d^4\theta \, \frac{\Xi^\dagger \Xi}{\Lambda^2} \, (\mathrm{Tr}\Phi^\dagger \Phi + \mathrm{Tr}\Phi^2) \, + \int d^4\theta \, \frac{1}{\Lambda} \, \Xi^\dagger M M'$$

IR Contributions: Dirac Gaugino Mass

There is a new diagram:





This diagram gives:

Yukawa dependent!

$$m_{1/2} = \frac{gy}{16\pi^2} M_{\text{mess}} R(z) \cos\left(\frac{\langle\xi\rangle}{v}\right)$$

where we have the new function:

$$R(z) = \frac{1}{z}\left[(1+z)\log(1+z) - (1-z)\log(1-z) - 2z\right]$$

IR Contributions: Scalar Masses

Identical to Gauge Mediation with **one** messenger:

$$m_0^{(IR)2} = 2C_F^{(a)} \left(\frac{\alpha_a}{4\pi}\right)^2 M_{\rm mess}^2 F(z)$$

where F(z) is the usual GM function:

$$F(z) = (1+z)\left[\log(1+z) - 2\mathrm{Li}_2\left(\frac{z}{1+z}\right) + \frac{1}{2}\mathrm{Li}_2\left(\frac{2z}{1+z}\right)\right] + (z \to -z)$$

IR Contributions: Adjoint Scalar Masses

- Messenger loops will also generate masses for the adjoint scalars (at **ONE** loop!):

$$\begin{aligned} m_\phi^2 &= \frac{y^2}{16\pi^2} M_{\rm mess}^2 R_s(z) \\ B_\phi &= \frac{y^2}{16\pi^2} M_{\rm mess}^2 R(z) \end{aligned}$$

- This leads to the prediction:

$$\boxed{\frac{m_\phi}{m_{1/2}} \sim \frac{\sqrt{|B_\phi|}}{m_{1/2}} \sim \sqrt{\frac{4\pi}{\alpha}}}$$

IR Contributions: Adjoint Scalar Masses

- Notice that $m_\phi^2 \sim |B_\phi|$ and $B_\phi < 0$ so the scalar will be lighter than the pseudoscalar.
- So the adjoint scalars are typically quite heavy - this can have consequences for the low energy spectrum, since these scalars contribute at two loops.
- Interesting phenomenology in its own right: single production of scalars through gluon fusion; double production at the LHC if light enough (Plehn,Tait, arXiv:0810.3919 [hep-ph]).

- Thus we have ordinary scalar GM masses, but a new kind of gaugino mass.
- Recall that the MRSSM needed gauginos heavier than squarks by a factor of 5. However:

$$\frac{m_{1/2}}{m_0^{IR}} = \frac{1}{\sqrt{2C_F}} \left(\frac{y}{g}\right) \left(\frac{R(z)}{\sqrt{F(z)}}\right)$$

- This ratio function of z is strictly less than unity, so to make gauginos heavy requires a large Yukawa.

A Generalized Model

- The key to generating the spectrum was that we had a SUSY-breaking **AND** an R-preserving messenger scalar mass, as well as an R-preserving chirality flip.
- We can seek to capture these effects in a more general model that removes any excess material in the messenger sector:

$$W_{mess} = \sum_{i=1}^{N_{\rm mess}} \left(\Xi \, \bar{\varphi}^i \varphi^i + M_{\rm mess} \, \bar{\varphi}^i N^i + M_{\rm mess} \, \bar{N}^i \varphi^i + y \, \bar{\varphi}^i \Phi N^i - y \, \bar{N}^i \Phi \varphi^i \right)$$

- Less adjoints means the QCD Landau pole is higher, which will help us control the UV operators.

Benefits of The Generalized Model

- The Generalized Model has an additional parameter: N_{mess}
- Both the gaugino mass and the squark mass squared are proportional to N_{mess}. Thus the gaugino:squark mass ratio $\propto \sqrt{N_{\text{mess}}}$.
- This will also lower the Landau pole, but not as much as the adjoints do.

Sample Spectra

Let us consider three sample spectra:

- ISS Model, small Yukawa
- ISS Model, large Yukawa
- Generalized Model

NOTE: All scalar masses are only IR contributions.

We will use $z = 0.99, \ \lambda = 1$

and all other couplings $\mathcal{O}(1)$

Spectrum 1:
ISS, Small Yukawa

$SU(3)$	$m_{\tilde{q}}$	1400 GeV	$m_{\tilde{g}}$	880 GeV
$SU(2)$	$m_{\tilde{l}}$	360 GeV	$m_{\tilde{W}}$	520 GeV
$U(1)$	$m_{\tilde{e}^c}$	160 GeV	$m_{\tilde{B}}$	370 GeV
Messenger	$M, M', \tilde{\Phi}$	15 TeV	m_-	10 TeV
sector		100 TeV	m_ξ	3100 GeV

$$y = 2 \qquad \Lambda_3 = 8 \times 10^3 \text{TeV}$$

Spectrum 2: ISS, Large Yukawa

$SU(3)$	$m_{\tilde{q}}$	1300 GeV	$m_{\tilde{g}}$	3500 GeV
$SU(2)$	$m_{\tilde{l}}$	350 GeV	$m_{\tilde{W}}$	2100 GeV
$U(1)$	$m_{\tilde{e^c}}$	160 GeV	$m_{\tilde{B}}$	1500 GeV
Messenger sector	$M, M', \tilde{\Phi}$	13 TeV 100 TeV	m_{-} m_{ξ}	10 TeV 13 TeV

$$y = 8 \qquad \Lambda_3 = 10^4 \mathrm{TeV}$$

Spectrum 3: Generalized Model

$SU(3)$	$m_{\tilde{q}}$	1900 GeV	$m_{\tilde{g}}$	5300 GeV
$SU(2)$	$m_{\tilde{l}}$	620 GeV	$m_{\tilde{W}}$	3500 GeV
$U(1)$	$m_{\tilde{e^c}}$	290 GeV	$m_{\tilde{B}}$	2600 GeV
Messenger sector		80 TeV		

$$y = 3,\ N_{\text{mess}} = 6 \qquad \Lambda_3 = 5 \times 10^4 \text{TeV}$$

Tuning

Recall that scalar masses have two relevant contributions: UV and IR.

There are two types of tuning in these models:

- To make the squarks light enough, there is a UV-IR cancelation.
- To satisfy flavor constraints, there is a tuning of the off-diagonal mass terms in the UV contribution.

UV-IR Cancelation

- Recall that the UV operators contribute

$$c_D \frac{M_{\text{mess}}^2}{\lambda \Lambda}$$

to the diagonal masses.

- If m_0 is the physical mass, then this puts an estimate on c_D :

$$c_D = \frac{m_0^2 - m_{IR}^2}{M_{UV}^2}$$

Thus:

$c_D \sim 10^{-2}$ for ISS Models

$c_D \sim 1$ for Generalized Models

Flavor Tuning

- Ideally we would like $c_D \sim c_{OD}$ to solve the flavor puzzle.
- We can estimate the size of c_{OD}

$$c_{OD} = \delta \left(\frac{m_0}{M_{UV}} \right)^2 \qquad (\delta_L = \delta_R)$$

- From this we can derive a general formula for the flavor tuning:

$$t \equiv \left| \frac{c_{OD}}{c_D} \right| = \frac{\delta}{|1 - (m_{IR}/m_0)^2|}$$

- Note that this is independent of M_{UV}

Flavor Tuning

$$t \equiv \left|\frac{c_{OD}}{c_D}\right| = \frac{\delta}{|1-(m_{IR}/m_0)^2|}$$

- From this formula, it is clear that it is difficult to avoid tuning.

- Using the results from $K-\bar{K}$ mixing:

	m_0	δ	t
ISS with Large y	600 GeV	0.05	1.4%
General Model	1 TeV	0.07	2.7%

Next Step: Higgs Sector

- The Higgs sector is quite complicated compared to the MSSM. It can be thought of as two hypermultiplets (H_u,R_u), (H_d,R_d) in N=2 SUSY:

$$\delta W = \mu_u H_u R_u + \lambda_1^u H_u \Phi_1 R_u + \lambda_2^u H_u \Phi_2 R_u + (u \to d)$$

- The H superfields have R-charge 0 while the R superfields have R-charge +2. Notice the new form of the mu-term.
- Due to the supersoft nature of this model, the Higgs D-term vanishes in the limit that the soft mass terms for the adjoint scalars vanish, thus making EWSB difficult in general...

Next Step: Higgs Sector

- mu and B terms can be generated through UV operators:

$$\int d^4\theta \, \frac{1}{\Lambda^2} \, (\Xi^\dagger \Xi) \, H_u H_d \qquad \sqrt{B_\mu} \sim M_{UV}$$

$$\int d^4\theta \, \frac{1}{\Lambda} \, \Xi^\dagger \, H_{u(d)} R_{u(d)} \qquad \mu_{u(d)} \sim M_{UV}$$

- Except for the B term, the Higgs sector obeys a PQ symmetry. This is different than the MSSM where **both** mu and B violate this symmetry.
- This implies that these operators must be generated by different physics!

Charginos

- In ordinary GM, the gravitino is the LSP, and it is so here as well:

$$m_{3/2} \sim \frac{f^2}{M_P} \sim 1\ \mathrm{keV}$$

- Kribs, Martin and Roy (arXiv:0807.4936) study the EW gauginos/higgsinos.
- In many regions of parameter space, they find the charginos are the NLSP, and that all SUSY particles can decay through a cascade involving the charged wino (lower bound at 101 GeV). This leads to interesting new collider signals.

Discussion

- MRSSM: A new class of SUSY model with some fascinating possibilities!
- Besides a new and untried phenomenological model, it is a great home for ISS-like models.
- RGM: A modified SUSY-breaking mediator that provides a new and unique spectrum, both through what it allows, and the nature of the mass spectrum.

Discussion

- For RGM to realize MRSSM, it is possible but requires a better understanding of the UV theory.
- "mu problem" solved, but "B problem" is still open - where does this operator come from?
- The Higgs sector, even at low energy, provides a rich environment for new physics due to the N=2 couplings and pseudo-SuperSoft nature of the model - work in progress...

The End!