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, ...

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

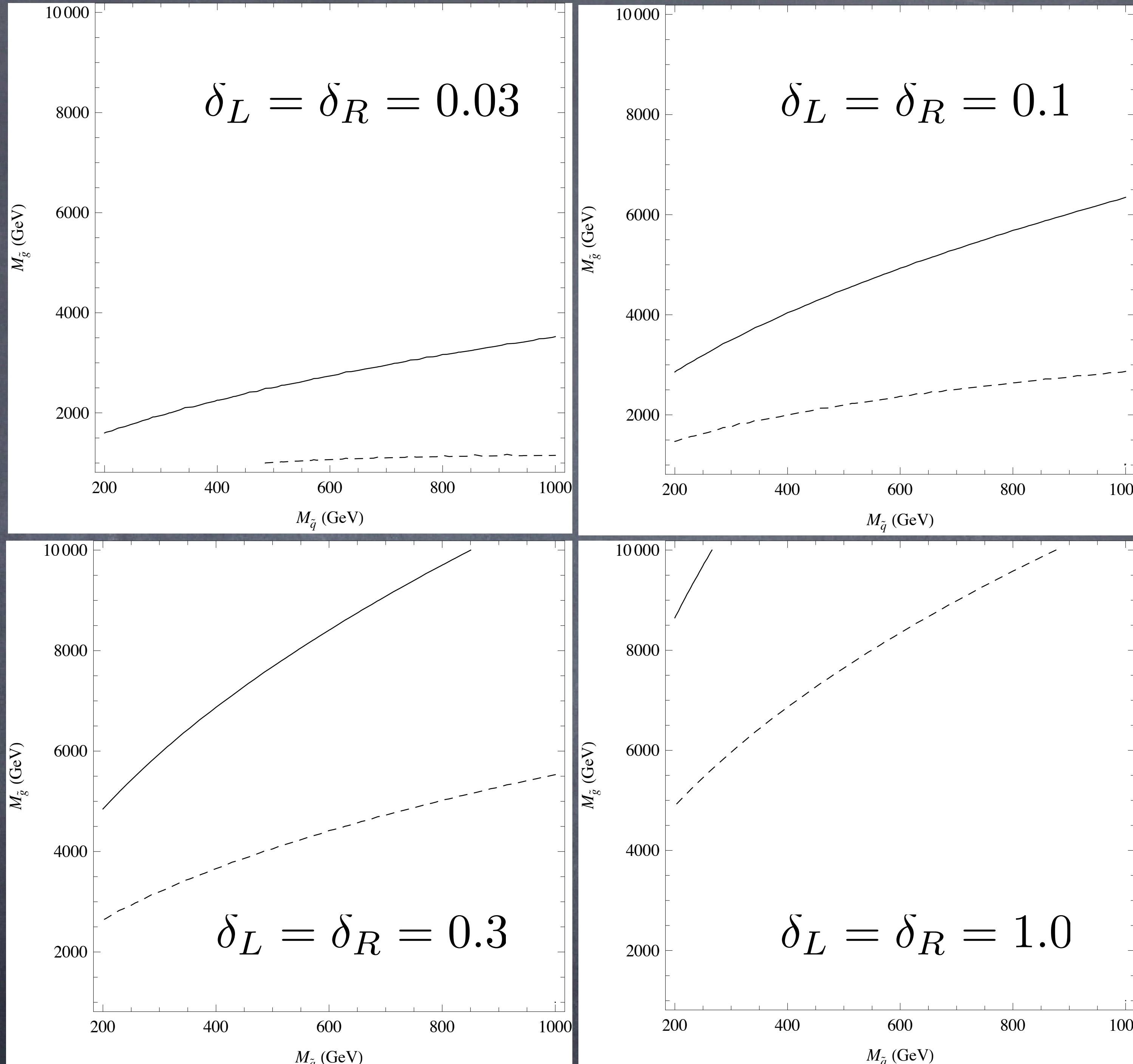
- Features of the MRSSM:
  - No Majorana masses for the gauginos, but there are Dirac masses.
  - No A-terms for the scalars; hence no left-right squark/slepton mixing.
  - No mu-term, but there is a B-term (complicated Higgs sector).

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 was published in KPW, with QCD corrections included in A.B., S.-P. Ng, arXiv:0803.3811



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

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

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.
- 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).

- We will write the SU(6) fields in terms of SU(5) fields (with the SM as a gauged subgroup):

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

- We also include two additional adjoints: Φ, M'

- We can write down a superpotential:

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

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

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

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 $M_{\rm mess}^2$

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

R-preserving!!

Fermions:

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

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

Soft terms in the Visible Sector

There are two contributions:

- Contributions from unknown UV physics.
- 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.
- $\Lambda \sim \dfrac{\Lambda_3}{4\pi}$: 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:

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

Small!

UV Scalar Mass:

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

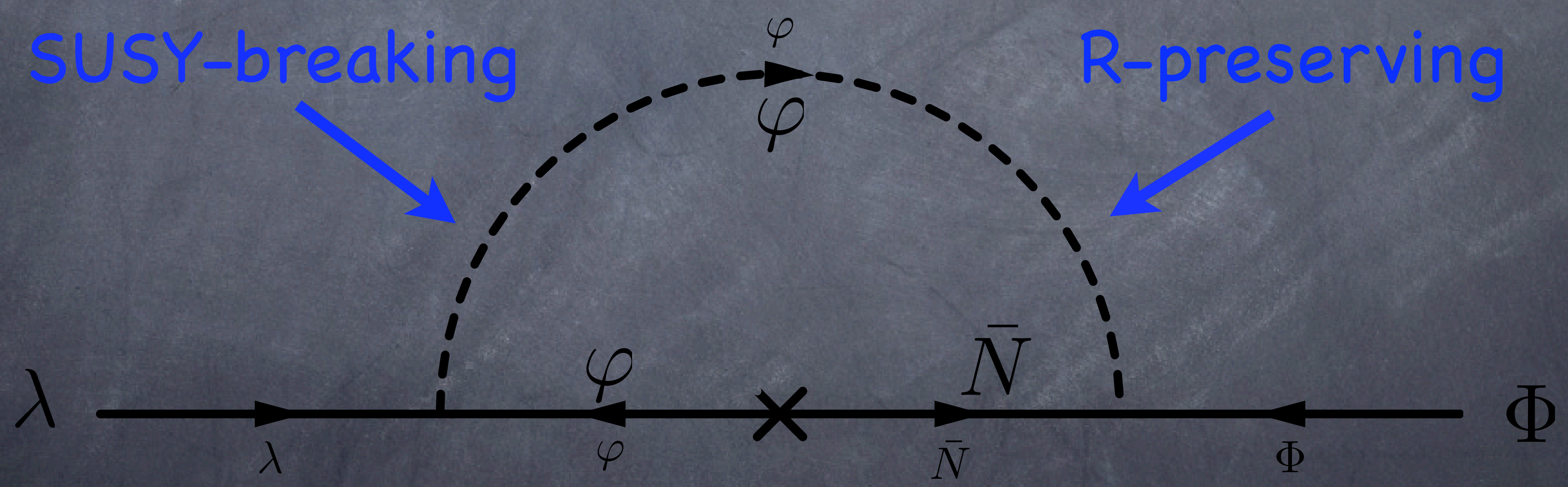
Adjoint Masses:

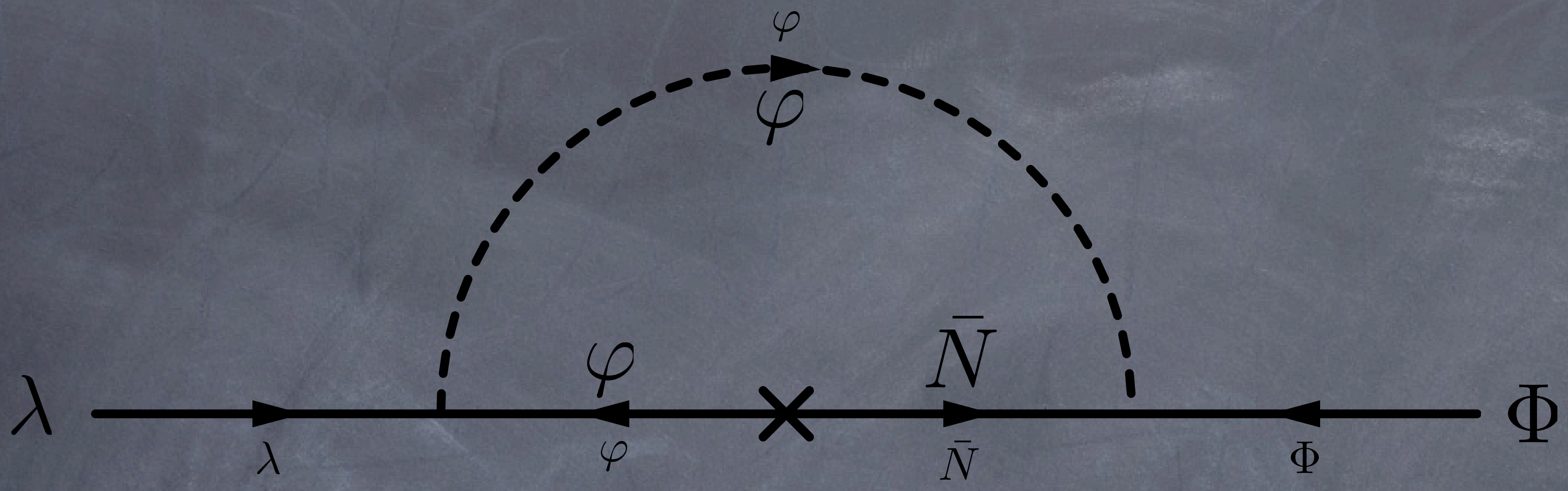
scalars **scalars & fermions**

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

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:

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

- 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 messenger, and an R-preserving chirality flip, requiring fields of R-charge 0 **AND** 2.
- 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 $\propto \sqrt{N_{\mathrm{mess}}}$.
- 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 sector	$M, M', \tilde{\tilde{\Phi}}$	15 TeV 100 TeV	m_- m_ξ	10 TeV 3100 GeV

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

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		

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

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

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

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}

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

- 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%

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 running.
- For RGM to realize MRSSM, it is possible but requires a better understanding of the UV theory.

Work in Progress

- Getting a viable Higgs sector
- Spectrum running: hybrid of SuperSoft and GM - light stops/staus, heavier first two generation squarks.
- Collider signals: see Tim Tait's talk; Kribs, Martin and Roy (arXiv:0807.4936).