Exploring General Gauge Mediation

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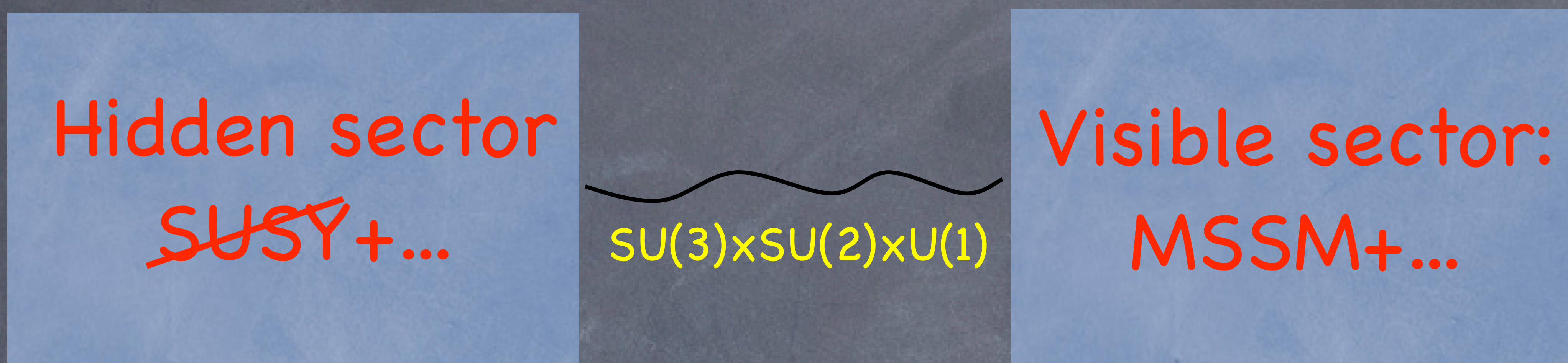
Meade, Seiberg, DS (0801.3278)
Buican, Meade, Seiberg, DS (to appear)

Motivation

- What are the most general predictions/ parameters of gauge mediation?
- Especially important question in the LHC era.
- To date many models of gauge mediation have been constructed.
- However, it has not been clear up to now which features of these models are general and which are specific.

General Gauge Mediation



- Theory decouples into separate hidden and visible sectors in g->0 limit.
- (Messengers, if present, are part of the hidden sector.)
- Hidden sector:
  - spontaneously breaks SUSY at a scale M
  - has a weakly-gauged global symmetry

$$G \supset G_{SM}$$

General Gauge Mediation

All the information we need about the hidden sector is encoded in the currents of G and their correlation functions.

Current Supermultiplet

- Current sits in a real linear supermultiplet defined by:

$$\mathcal{J} = \mathcal{J}(x, \theta, \bar{\theta}), \qquad D^2 \mathcal{J} = \bar{D}^2 \mathcal{J} = 0$$

SUSY generalization of current conservation

- In components:

$$\mathcal{J} = J + i\theta j - i\bar{\theta}\bar{j} - \theta\sigma^\mu\bar{\theta} j_\mu + \frac{1}{2}\theta\theta\bar{\theta}\bar{\sigma}^\mu\partial_\mu j - \frac{1}{2}\bar{\theta}\bar{\theta}\theta\sigma^\mu\partial_\mu\bar{j} - \frac{1}{4}\theta\theta\bar{\theta}\bar{\theta}\Box J$$

ordinary U(1) current, satisfies

$$\partial_\mu j^\mu = 0$$

Current correlators

$$\mathcal{J} = J + i\theta j - i\bar{\theta}\bar{j} - \theta\sigma^\mu\bar{\theta}j_\mu + \ldots$$

- Nonzero two-point functions constrained by Lorentz invariance, current conservation:

Dim'less

Real

$$C_0(p^2/M^2) = \langle J(p)J(-p)\rangle$$

$$C_{1/2}(p^2/M^2) = \frac{1}{p^2}p^\mu\sigma_\mu^{\alpha\dot{\alpha}}\langle j_\alpha(p)\bar{j}_{\dot{\alpha}}(-p)\rangle$$

$$C_1(p^2/M^2) = \frac{1}{p^2}\langle j^\mu(p)j_\mu(-p)\rangle$$

Complex

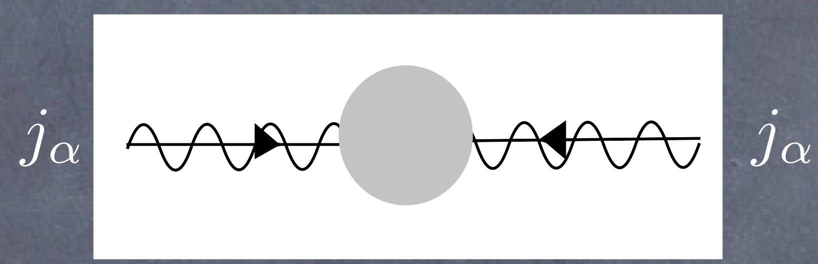
$$B(p^2/M^2) = M^{-1}\langle j_\alpha(p)j_\beta(-p)\rangle$$

- (M = scale of ~~SUSY~~ in hidden sector)

Soft Masses

$$\mathcal{L}_{int} = 2g\int d^4\theta \mathcal{J}\mathcal{V} + \dots = g(JD - \lambda j - \bar{\lambda}\bar{j} - j^\mu V_\mu) + \dots$$

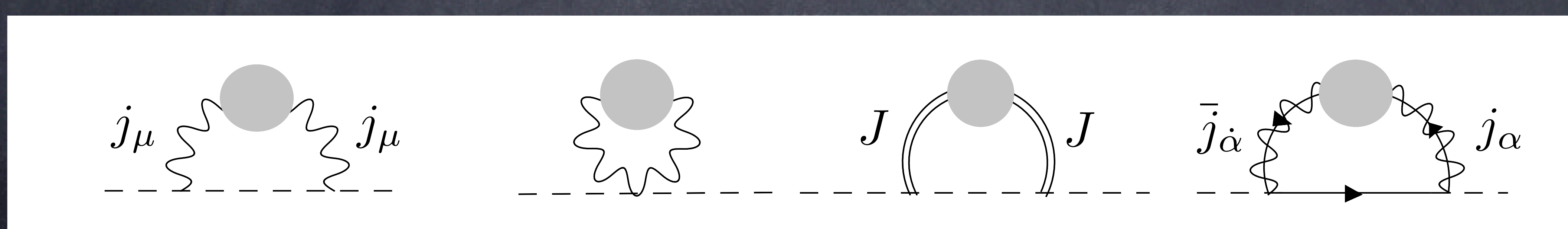
- Gaugino: $M_\lambda = g^2 M B(p=0)$



Why does this integral converge?
Not obvious...

- Scalars: $m^2_{\tilde{f}} = g^4 A$

$$A \equiv -\int \frac{dp^2}{(2\pi)^4}\Big(3C_1(p^2/M^2) - 4C_{1/2}(p^2/M^2) + C_0(p^2/M^2)\Big)$$



Current Supermultiplet

- An equivalent formulation of the current s'multiplet is to start with the defining relation:

$$Q^2 J = \bar{Q}^2 J = 0$$

- It follows that

$$\begin{aligned} j_\alpha &\equiv Q_\alpha J \\ \bar{j}_{\dot{\alpha}} &\equiv \bar{Q}_{\dot{\alpha}} J \\ \sigma^\mu_{\alpha\dot{\alpha}} j_\mu &\equiv [Q_\alpha, \bar{Q}_{\dot{\alpha}}] J \end{aligned}$$

- Analogous to chiral superfield:

$$\bar{D}\Phi = 0 \quad \Leftrightarrow \quad Q\phi = 0$$

Rewriting the soft masses

Using action of supercharges, can show:

$$\begin{aligned} \langle\ !^2\ (\#)\ (-\#)\rangle &= \langle\ !^\alpha\ (\#)\ !_\alpha\ (-\#)\rangle \\ &= \langle\ "^\alpha(\#)\ "_\alpha(-\#)\rangle \\ &= (\#) \end{aligned}$$

Similar manipulations lead to

$$\langle Q^2\bar{Q}^2 J(p)J(-p)\rangle = \\ p^2\Big(3C_1(p^2/M^2) - 4C_{1/2}(p^2/M^2) + C_0(p^2/M^2)\Big)$$

Rewriting the soft masses

- Thus:

$$M_\lambda = g^2 \langle Q^2 J(0) J(0) \rangle$$

$$m_{\tilde{f}}^2 = g^4 \int \frac{dp^2}{p^2} \langle Q^2 \bar{Q}^2 J(p) J(-p) \rangle$$

- Comments on the result:
  - Check: vanish when SUSY is unbroken.
  - Generalization of small F-term SUSY-breaking relations (cf. Distler & Robbins; Intriligator & Sudano)

$$M_\lambda \sim F, \qquad m_{\tilde{f}}^2 \sim |F|^2$$

Rewriting the soft masses

- Thus:

$$M_\lambda = g^2 \langle Q^2 J(0) J(0) \rangle$$

$$m^2_{\tilde{f}} = g^4 \int \frac{dp^2}{p^2} \langle Q^2 \bar{Q}^2 J(p) J(-p) \rangle$$

- Comments on the result:
  - At high momentum, only the OPE of J with itself matters! Can use this to prove convergence of the scalar mass integral.

An aside on the sign of A

$$m_{\tilde{f}}^2 = g^4 A$$

$$A \equiv -\int \frac{dp^2}{(2\pi)^4}\Big(3C_1(p^2/M^2) - 4C_{1/2}(p^2/M^2) + C_0(p^2/M^2)\Big)$$

- Notice that A is a linear combination of two-point functions with different signs -- it is not obviously positive
- Indeed, simple models with A<0 already exist in the literature...

Messengers with D-terms

Poppitz & Trivedi; Nakayama, Taki, Watari, Yanagida

- Consider a model with messengers ϕ, $\tilde{\phi}$ with charge +1, -1 under a U(1)′.

- If the U(1)′ breaks SUSY via an FI term,

$$V \supset V_D = (D/2 + |\phi|^2 - |\tilde{\phi}|^2)^2$$

the messengers receive "D-type" SUSY-splittings

$$M_F = m, \qquad M_B^2 = \begin{pmatrix} m^2 + D & 0 \\ 0 & m^2 - D \end{pmatrix}$$

- Then explicit calculation shows that in this model, $A = -D^4/M^6 + \cdots < 0$

An aside on the sign of A

- One important consequence of the indefiniteness of the sign of A
- One cannot be sure that a given gauge mediation model is consistent unless the sfermion masses are calculable.
- In particular, the viability of many strongly-coupled direct mediation models is now suspect.

(Phenomenological) Constraints on GGM

Messenger Parity

- We have related the soft masses to the current two-point functions. However, we ignored the possible contribution of the one-point function (FI parameter):

$$\langle J \rangle = \zeta \neq 0$$

- This can be nonzero for $U(1)_Y$ without breaking gauge symmetry.

Messenger Parity

- It is dangerous because it contributes to the scalar masses:

$$\delta m^2_{\tilde{f}} = g_1^2 Y_f \zeta$$

- Not positive definite and $\mathcal{O}(g^2)$ (vs. $\mathcal{O}(g^4)$ for usual GM contributions).
- So if zeta is too large this can cause some scalars (esp. sleptons) to become tachyonic!

Messenger Parity

- Thus we would like the hidden sector to be invariant under a symmetry that forbids J one-point functions.
- The simplest such symmetry is a Z2 parity:

$$\mathcal{J} \to -\mathcal{J}$$

- Examples of this symmetry in the context of minimal gauge mediation have been discussed in the literature. (Dine & Fischler; Dimopoulos & Giudice)

Messenger Parity

- E.g. in models with weakly-coupled messengers,

$$J = \phi_i^\dagger \phi_i - \tilde{\phi}_i^\dagger \tilde{\phi}_i$$

- So can always choose a basis in which messenger parity is explicitly realized as:

$$\phi_i \leftrightarrow \tilde{\phi}_i$$

- Couplings of the hidden sector must be invariant under this transformation. (In particular, this places restrictions on possible U(1)' extensions.)

CP phases

- The B's are complex and independent in GGM. However, B's with arbitrary phases would typically lead to an unacceptable level of CP violation.
- So either the hidden sector is CP invariant, or its CP violation is somehow shielded from the visible sector.

Unification

- We would like the hidden sector to be compatible with 3-2-1 gauge coupling unification.

- Note that in GGM the beta functions are related to the high momentum behavior of the C's -- in general they have nothing to do with gaugino masses.

R-symmetry breaking

- DSB sector must have an R-symmetry (Nelson & Seiberg)
- Meta-stable DSB must have an approximate R-symmetry (ISS).
- R-symmetry must be broken for Majorana gaugino masses.

R-symmetry breaking

- Different ways of breaking R-symmetry:
  - Explicitly (fine tuning for metastability? problem with CP phases?)
  - Spontaneously:
    - one-loop in renormalizable models (DS)
    - gauge interactions (small window? Dine & Mason; ISS2)
    - higher-loops
    - ...

Covering the parameter space of GGM

Parameter space

- The GGM parameter space consists of 9 real parameters:

$$A_{1,2,3}, \qquad |B_{1,2,3}|, \qquad \arg(B_{1,2,3})$$

- CP limits us to 3+3 real parameters (we ignore the overall phase of B)
- Question: are there simple models of weakly coupled messengers that cover the entire parameter space?
- We are looking for an ``existence proof"

Parameter space

- Carpenter, Dine, Festuccia & Mason studied this question recently in the context of messenger models with small F-type SUSY breaking.
- They found models with the right number of parameters (6) but which did not cover the entire parameter space.

Setup

- We will also consider models with messengers with tree-level SUSY splittings, but allow for the possibility of D-type splittings from a U(1)′
- To satisfy the phenomenological constraints, we will also require our models to have
  - CP invariance
  - Messenger parity
  - Broken R-symmetry
  - Unification -- complete GUT multiplets

Warmup: OGM

(Dine, Nelson, Nir, Shirman, ...)

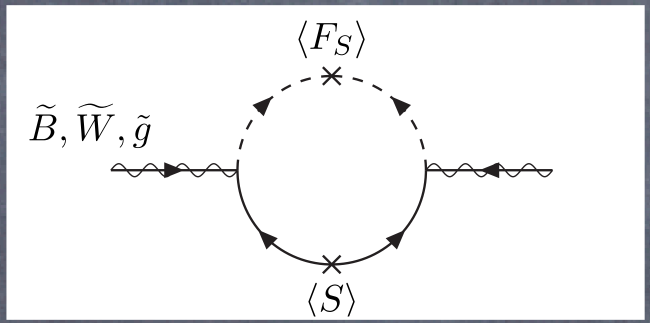
$$W = \lambda_i X \phi_i \tilde{\phi}_i$$

$$\langle X \rangle = M + \theta^2 F$$

- $\phi_i, \ \tilde{\phi}_i$: messengers in irreps of G_{SM}. They receive tree-level SUSY breaking mass splittings through their coupling to X.
- X: spurion for hidden sector SUSY breaking and R-symmetry breaking.
- Loops of the messengers and SM gauge fields communicate SUSY- and R-breaking to the MSSM

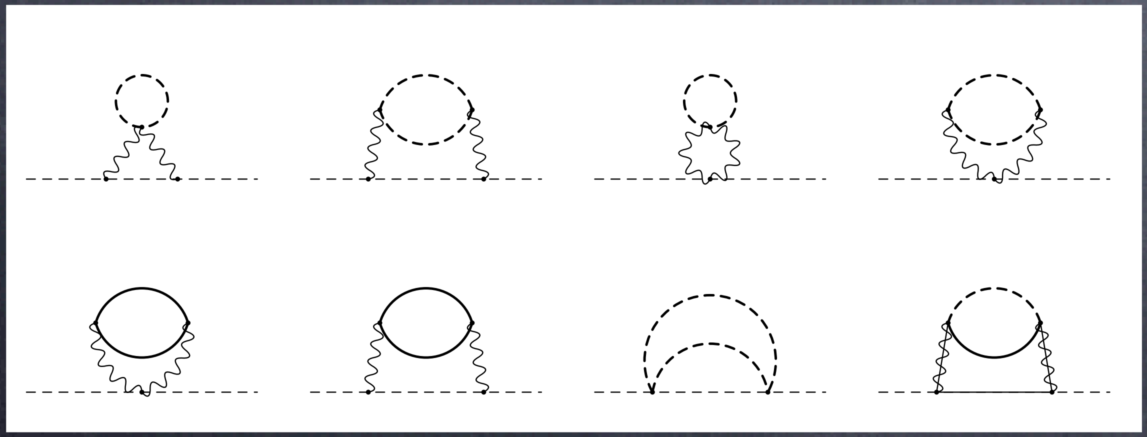
Warmup: OGM

- 1-loop gaugino masses:



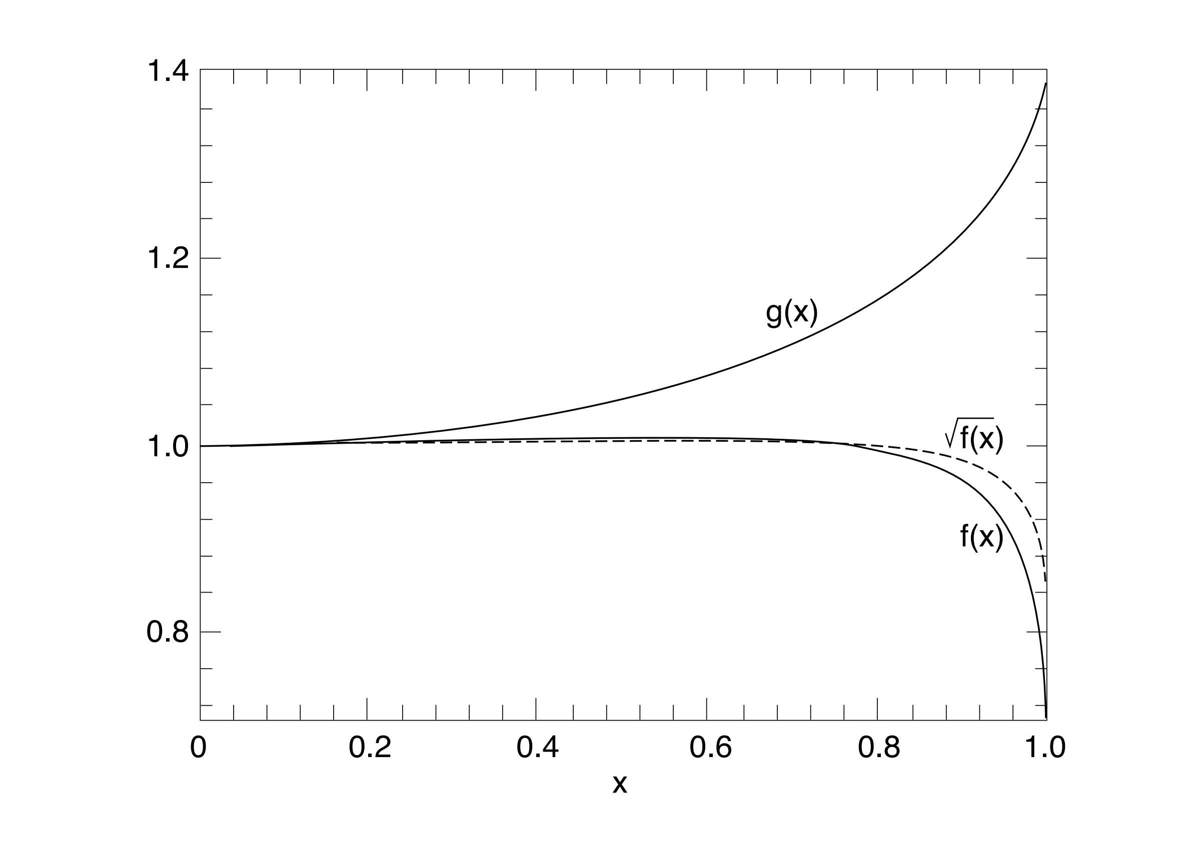
$$B_r = \frac{1}{16\pi^2} \frac{F}{M} \sum_i N_{ri} g(F/\lambda_i M^2)$$

- 2-loop sfermion mass-squareds:



$$A_r = \frac{1}{16\pi^2} \frac{F^2}{M^2} \sum_i N_{ri} f(F/\lambda_i M^2)$$

Warmup: OGM



- $f(x),\ g(x)$ bounded in a small window -- can never cover parameter space in OGM
- Most commonly considered case of small SUSY breaking => $f,\ g \rightarrow 1$

Warmup: OGM

- In this limit, OGM only covers a 1-d subspace of GGM parameter space.
- Leads to many specific and well-known predictions of “gauge mediation”:
    - Gaugino unification
    - Sfermion mass hierarchy
    - Bino or slepton NLSP
    - Positive sfermion masses
    - ....

Beyond OGM

$$W = \lambda_{ij} X \phi_i \tilde{\phi}_j + m_{ij} \phi_i \tilde{\phi}_j$$

- "(Extra)Ordinary Gauge Mediation" (Cheung, Fitzpatrick, DS)
- Most general model of weakly-coupled F-term messengers
- At small F, can easily compute soft masses
- Can get interesting deviations from OGM phenomenology, but still can't cover the entire GGM parameter space

General Result

- Consider a collection of vectorlike messengers all transforming in the same rep $(R, \tilde{R})$ of 3-2-1. Then they contribute

$$\delta A_r = a_r A(R), \qquad \delta B_r = b_r B(R)$$

  - $a_r, \ b_r$: trivial group theory factors
  - In general, A(R) and B(R) are independent functions of hidden sector parameters.
- So on general grounds, need at least three different 3-2-1 representations.

Applications

D L

$$5 \to (\bar{3}, 1, 1/3) \oplus (1, 2, -1/2)$$

$$10 \to (3, 2, 1/6) \oplus (\bar{3}, 1, -2/3) \oplus (1, 1, 1)$$

Q U E

- Case 1: any number of $(5, \bar{5})$ (not necessarily OGM) -- only two reps (D,L) => can cover at most a 4d subspace

- Case 2: single $(10, \bar{1}0)$ -- right # of reps, but messenger parity allows only OGM => can't cover entire space (cf. CDFM).

Applications

- Case 3: single $(10,\bar{1}0)+(5,\bar{5})$ -- same as case 2
- Case 4: that leaves

$$(10,\bar{1}0)+2(5,\bar{5}) \quad \text{and} \quad 2(10,\bar{1}0)$$

as the minimal possibilities.

Can show that by including D-type SUSY breaking, one can cover the entire parameter space of GGM with these models.

Example

$$W = \sum_{\substack{R=Q,U,E \\ i=1,2}} \left(\lambda_{Ri} X R_i \tilde{R}_i + m_{Ri} R_i \tilde{R}_i \right)$$

$$V \supset V_D = \left(a + \sum_R q_R (|R_1|^2 - |R_2|^2 - |\tilde{R}_1|^2 + |\tilde{R}_2|^2) \right)^2$$

$$M_F = \begin{pmatrix} m_{R1} & 0 \\ 0 & m_{R2} \end{pmatrix}$$

$$M_B^2 = \begin{pmatrix} m_{R1}^2 + q_R a & 0 & 0 & \lambda_{R1} f \\ 0 & m_{R2}^2 - q_R a & \lambda_{R2} f & 0 \\ 0 & \lambda_{R2} f & m_{R2}^2 + q_R a & 0 \\ \lambda_{R1} f & 0 & 0 & m_{R1}^2 - q_R a \end{pmatrix}$$

Example

$$B = \frac{\lambda_{R1} f}{m_{R1}} + \frac{\lambda_{R2} f}{m_{R2}}$$

$$A = \left(\frac{\lambda_{R1} f}{m_{R1}}\right)^2 + \left(\frac{\lambda_{R2} f}{m_{R2}}\right)^2 + a q_R \log(m_{R1}/m_{R2})$$

- Thanks to the nonzero U(1)′ D-term, can easily cover the parameter space A,B>=0.

Summary

- We have a new and improved presentation of GGM in terms of supercharge commutators which makes manifest certain aspects of the framework.
- We discussed the phenomenological constraints on GGM.
- We presented weakly-coupled messenger models which satisfy these constraints and still cover the entire GGM parameter space.

Outlook

- Can one derive the supercharge relations directly, e.g. using supergraphs?
- Imposing precision unification on messenger models, can we still cover the entire space?
- Is there a theorem for positivity of A for pure F-term breaking?
- Detailed study of GGM at colliders
- mu/Bmu still an important open problem...

Messenger supertrace

- Supertrace indicates sensitivity to UV physics
-

- Integrate out chiral messengers => supertrace positive

- Integrate out vector messengers => supertrace negative

EOGM

$$B_r = \frac{1}{16\pi^2}\Lambda_G = \frac{1}{16\pi^2}\frac{nF}{X}, \qquad A_r = \frac{1}{16\pi^2}\Lambda_G^2 N_{eff,r}^{-1}$$

- n=0,1,...,N => gaugino masses can be zero!
- Example of CP phase shielding: no relative phase between gaugino masses even though messenger sector need not respect CP!
- Can cover 4d subspace -- but still can't make Ar arbitrary small...