General Gauge Mediation

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Strings '08

Based on:
Meade, Seiberg & DS, 0801.3278
Buican, Meade, Seiberg & DS, 0808.zzzz

SUSY and its breaking

- Suppose we find SUSY at the LHC.
- SUSY must be broken spontaneously (dynamically) in a separate hidden sector.

Hidden sector:
~~SUSY~~+...

Visible sector:
MSSM+...

- Explaining how SUSY is broken and communicated to the SSM will be one of the great challenges of our time.

Gauge Mediation

Hidden sector:
~~SUSY~~+...

SU(3)xSU(2)xU(1)

Visible sector:
MSSM+...

- Gauge mediation is a promising framework for communicating SUSY-breaking to the SSM.
- Its advantages include:
  - Automatic flavor universality (no FCNCs)
  - Viable spectrum
  - Calculability
  - Distinctive phenomenology

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.

Ordinary gauge mediation

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

- Spurion for hidden sector ~~SUSY~~:

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

- Messengers ϕ in real representation of G_{SM} receive tree-level ~~SUSY~~ mass splittings.

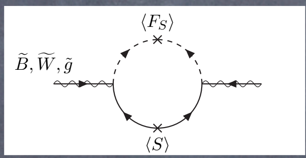
$$W = \lambda X \phi^2$$

- Loops of the messengers and SM gauge fields communicate ~~SUSY~~ to the MSSM.

Ordinary gauge mediation

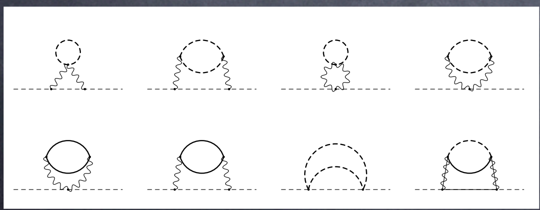
(Dine, Nelson, Nir, Shirman, ...)

- 1-loop gaugino masses:



$$M_{r=1,2,3} \sim \frac{\alpha_r}{4\pi} \frac{F}{M}$$

- 2-loop sfermion mass-squareds:



$$m_{\tilde{f}}^2 \sim \sum_{r=1}^{3} c_2(f;r) \left(\frac{\alpha_r}{4\pi}\right)^2 \left(\frac{F}{M}\right)^2$$

Predictions of (O)GM

- Gravitino LSP
- No FCNCs
- Small A terms
- ...

Always true. Follows from general considerations.

- Gaugino unification
- Sfermion mass hierarchy
- Bino or slepton NLSP
- Positive sfermion masses
- ....

True only in certain models

Beyond OGM

$$W = \lambda_{ij} X \phi_i \tilde{\phi}_j + m_{ij} \phi_i \tilde{\phi}_j + fX$$
$$\phi_i \in \mathbf{5}, \quad \tilde{\phi}_i \in \overline{\mathbf{5}}$$

- Large class of simple, renormalizable extensions of OGM.
  "(Extra)Ordinary Gauge Mediation"
  (Cheung, Fitzpatrick, DS)
- By including doublet/triplet splitting in the messenger couplings, can already violate some of the standard predictions.

Beyond OGM

- Gravitino LSP
- No FCNCs
- Small A terms
- Sum rules

True in general

- ~~Gaugino unification~~
- ~~Sfermion mass hierarchy~~
- ~~Bino or slepton NLSP~~
- Positive sfermion masses
- ....

True only in certain models

General Gauge Mediation

Hidden sector
~~SUSY~~+...

SU(3)xSU(2)xU(1)

Visible sector:
MSSM+...

- 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

$$G \supset G_{SM}$$

Hidden sector at g=0

- Start by analyzing the hidden sector at g=0. Assume for simplicity G=U(1).
- Global currents and their correlators are natural objects to study.
- Try to understand general properties of the theory before we know the underlying Lagrangian.

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:

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

ordinary U(1) current, satisfies

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

Current superfield

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

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

$$\begin{aligned} \langle J(x) J(0) \rangle &= x^{-4} C_0(x^2 M^2) \\ \langle j_\alpha(x) \bar{j}_{\dot{\alpha}}(0) \rangle &= -i\sigma^\mu_{\alpha\dot{\alpha}}\partial_\mu \left(x^{-4} C_{1/2}(x^2 M^2) \right) \\ \langle j_\mu(x) j_\nu(0) \rangle &= (\eta_{\mu\nu}\partial^2 - \partial_\mu\partial_\nu) \left(x^{-4} C_1(x^2 M^2) \right) \\ \langle j_\alpha(x) j_\beta(0) \rangle &= \epsilon_{\alpha\beta} x^{-5} B(x^2 M^2) \end{aligned}$$

Real

Complex

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

SUSY limit

- If SUSY is unbroken, can show:

$$C_0(x) = C_{1/2}(x) = C_1(x), \qquad B(x) = 0$$

- More generally, SUSY broken spontaneously, so at short distance must be restored:

$$\lim_{x \to 0} C_0(x),\ C_{1/2}(x),\ C_1(x) = c\ ; \quad \lim_{x \to 0} B(x) = 0$$

- FT to momentum space is log divergent:

$$\tilde{C}_0(p),\ \tilde{C}_{1/2}(p),\ \tilde{C}_1(p) \sim c \log \frac{\Lambda}{p} + finite\ ; \quad \tilde{B}(p) \sim finite$$

Coupling to visible sector

- Weakly gauge G=U(1)

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

- Integrate out hidden sector exactly.
- Effective Lagrangian at $\mathcal{O}(g^2)$:

$$\begin{aligned} \delta\mathcal{L}_{eff} \quad = \quad & \frac{1}{2}g^2\tilde{C}_0(p^2)D^2 - g^2\tilde{C}_{1/2}(p^2)i\lambda\sigma^\mu\partial_\mu\bar{\lambda} - \frac{1}{4}g^2\tilde{C}_1(p^2)F_{\mu\nu}F^{\mu\nu} \\ & -\frac{1}{2}g^2(M\tilde{B}_{1/2}(p^2)\lambda\lambda + c.c.) \end{aligned}$$

Beta function

$$\delta\mathcal{L}_{eff} = \boxed{\frac{1}{2}g^2\tilde{C}_0(p^2)D^2 - g^2\tilde{C}_{1/2}(p^2)i\lambda\sigma^\mu\partial_\mu\bar{\lambda} - \frac{1}{4}g^2\tilde{C}_1(p^2)F_{\mu\nu}F^{\mu\nu}}$$
$$-\frac{1}{2}g^2(M\tilde{B}_{1/2}(p^2)\lambda\lambda + c.c.)$$

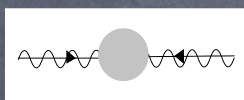
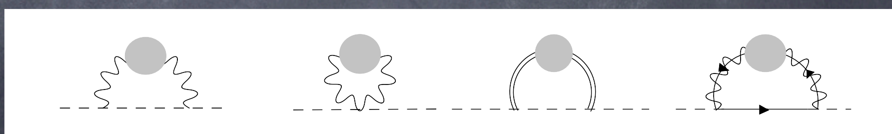
- Integrating out the hidden sector changes the U(1) beta function.

$$\tilde{C}_a \sim c\log\frac{\Lambda}{M} \Rightarrow \Delta b = -(2\pi)^4 c$$

c = hidden sector contrib. to beta function

Soft Masses

$$\delta\mathcal{L}_{eff} = \boxed{\frac{1}{2}g^2\tilde{C}_0(p^2)D^2 - g^2\tilde{C}_{1/2}(p^2)i\lambda\sigma^\mu\partial_\mu\bar{\lambda} - \frac{1}{4}g^2\tilde{C}_1(p^2)F_{\mu\nu}F^{\mu\nu}}$$
$$\boxed{-\frac{1}{2}g^2(M\tilde{B}_{1/2}(p^2)\lambda\lambda + c.c.)}$$

- Soft masses follow from the effective action:
- U(1) gaugino:  $M_\lambda = g^2 M\tilde{B}(0)$
- sfermion: 

$$m^2_{\tilde{f}} = g^4 A$$
$$A \equiv -\int \frac{d^4p}{(2\pi)^4}\frac{1}{p^2}\left(3\tilde{C}_1(p^2/M^2) - 4\tilde{C}_{1/2}(p^2/M^2) + \tilde{C}_0(p^2/M^2)\right)$$

MSSM Soft Masses

- Straightforward to generalize to SU(3)xSU(2)xU(1).

$$M_r = g_r^2 M \tilde{B}^{(r)}(0), \quad r = 1,2,3$$

  - Three independent complex gaugino masses. So gaugino unification not guaranteed. GGM has SUSY CP problem?

MSSM Soft Masses

- Straightforward to generalize to SU(3)xSU(2)xU(1).

$$m_{\tilde{f}}^2 = \sum_{r=1}^{3} g_r^4 \, c_2(f;r) A_r$$

$$A_r \equiv -\int \frac{d^4p}{(2\pi)^4} \frac{1}{p^2} \Big(3\tilde{C}_1^{(r)}(p^2/M^2) - 4\tilde{C}_{1/2}^{(r)}(p^2/M^2) + \tilde{C}_0^{(r)}(p^2/M^2) \Big)$$

  - Sfermion masses not necessarily positive. Indeed, can find simple examples where they are negative. E.g. U(1)′ D-term SUSY. (Nakayama et al,...)
  - Typical momentum in sfermion integral is O(M) -- can't be computed in low-energy theory.

MSSM Soft Masses

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$$A_r \equiv -\int \frac{d^4p}{(2\pi)^4}\frac{1}{p^2}\Big(3\tilde{C}_1^{(r)}(p^2/M^2) - 4\tilde{C}_{1/2}^{(r)}(p^2/M^2) + \tilde{C}_0^{(r)}(p^2/M^2)\Big)$$

  - Sfermion masses must be finite -- constraints on two-point functions at $\mathcal{O}(1/p^2)$.
  - 3 independent real parameters -- sfermion masses not tied to gauge couplings or to gaugino masses.

Rewriting the soft masses

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

$$\langle Q^2 J(x) J(0)\rangle = x^{-5} B(x)$$

$$\langle Q^4 J(x) J(0)\rangle = \partial^2\Big(x^{-4}(3C_1(x) - 4C_{1/2}(x) + C_0(x))\Big)$$

  - Check: vanish when SUSY is unbroken.
  - GGM analogue of OGM relations (more precise connection? cf. Distler & Robbins; Intriligator & Sudano)

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

  - All the information contained within the OPE of J with itself. Can use this to prove convergence of sfermion mass integral.

Sum Rules

$$m_{\tilde{f}}^2 = \sum_{r=1}^{3} g_r^4\, c_2(f;r) A_r$$

Quadratic Casmir

- Five MSSM sfermion masses f=Q,U,D,L,E are given in terms of 3 parameters $A_{r=1,2,3}$
- So there must be 2 relations (per generation)

$$\mathrm{Tr}\, Y m^2 = \mathrm{Tr}\,(B-L) m^2 = 0$$

- Corrections: sum rules true at the scale M. (Small) corrections from RG and EWSB.

Summary

- We have constructed a framework for analyzing general models of gauge mediation: arbitrary hidden sectors coupled to the MSSM via SM gauge interactions.
- We used our framework to understand the general predictions of gauge mediation.
  - Parameter space: 3 complex parameters (gaugino masses) and 3 real parameters (sfermion masses)
- Our framework is suitable for analyzing strongly-coupled hidden sectors.
(cf. Ooguri, Ookouchi, Park & Song)

Outlook: Exploring GGM

- Can one build (simple) models which cover the entire parameter space of GGM? What is the minimal construction?
- Carpenter, Dine, Festuccia & Mason exhibit generalizations of OGM that have the right number of parameters (3+3)...

Outlook

- Connections to string theory?
  - Currents and their correlators appear naturally in the AdS/CFT correspondence. Can we use AdS/CFT to study strongly-coupled hidden sectors?
- Main outstanding challenge for gauge mediation: mu/Bmu problem.
  - Can translate existing approaches into GGM framework, but can the framework teach us something new?

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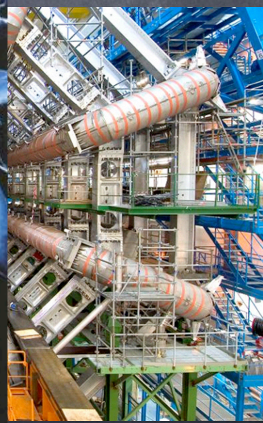
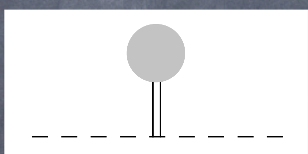


Messenger Parity

$$\langle J \rangle = \zeta$$

- One point function of J can also contribute to the sfermion masses:



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

- Tree-level in effective theory. Corresponds to FI parameter.
- Can lead to tachyonic sleptons. Forbid with "messenger parity": $\mathcal{J} \to -\mathcal{J}$