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

The LHC is across the corner
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

- 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 \(\phi\) 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, Nic, Shifman, ...)

1-loop gaugino masses:

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

2-loop sfermion mass-squareds:

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

**Predictions of (O)GM**

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

Gaugino unification

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

Always true: Follows from general considerations.

True only in certain models.
Beyond OGM

\[ W = \lambda_{ij} X \phi_i \tilde{\phi}_j + m_{ij} \phi_i \tilde{\phi}_j + f X \]
\[ \phi_i \in 5, \quad \tilde{\phi}_i \in \bar{5} \]

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

True in general

True only in certain models
General Gauge Mediation

Theory decouples into separate hidden and visible sectors in $g \to 0$ 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:

\[ \mathcal{J} = \mathcal{J}(x, \theta, \bar{\theta}), \quad D^2 \mathcal{J} = \bar{D}^2 \mathcal{J} = 0 \]

In components:

\[
\mathcal{J} = \begin{pmatrix}
J + i\theta j - i\bar{\theta} \bar{j} - \theta \sigma^\mu \bar{\theta} j_\mu \\
\frac{1}{2} \theta \theta \bar{\theta} \sigma^\mu \partial_\mu j - \frac{1}{2} \bar{\theta} \bar{\theta} \theta \sigma^\mu \partial_\mu \bar{j} - \frac{1}{4} \theta \theta \bar{\theta} \bar{\theta} \Box J
\end{pmatrix}
\]

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:

\[ \langle J(x)J(0) \rangle = x^{-2} C_0(x^2 M^2) \]
\[ \langle j_{\alpha}(x)\bar{j}_{\dot{\alpha}}(0) \rangle = -i \gamma^\alpha_{\alpha} \partial_\mu (x^{-4} C_{1/2}(x^2 M^2)) \]
\[ \langle j_{\mu}(x)j_{\nu}(0) \rangle = (\eta_{\mu \nu} \partial^2 - \partial_\mu \partial_\nu) (x^{-4} C_1(x^2 M^2)) \]
\[ \langle j_{\alpha}(x)j_{\beta}(0) \rangle = \epsilon_{\alpha \beta} x^{\frac{5}{2}} B(x^2 M^2) \]

(Remember: \( M \) = scale of SUSY in hidden sector)
**SUSY limit**

- If SUSY is unbroken, can show:
  \[ C_0(x) = C_{1/2}(x) = C_1(x), \quad B(x) = 0 \]

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

**Coupling to visible sector**

- Weakly gauge \( G = U(1) \)
  \[ \mathcal{L}_{\text{int}} = 2g \int d^4 \theta J \mathcal{V} + \cdots = g(JD - \lambda j - \bar{X}j - j^\mu V_\mu) + \cdots \]

- Integrate out hidden sector exactly.

- Effective Lagrangian at \( \mathcal{O}(g^2) \):
  \[ \delta \mathcal{L}_{\text{eff}} = \frac{1}{2} g^2 \tilde{C}_0(p^2) D^2 - g^2 \tilde{C}_{1/2}(p^2) i\lambda \sigma^\mu \partial_\mu \lambda - \frac{1}{4} g^2 \tilde{C}_1(p^2) F_{\mu\nu} F^{\mu\nu} - \frac{1}{2} g^2 (M \tilde{B}_{1/2}(p^2) \lambda \lambda + \text{c.c.}) \]
Beta function

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

$$- \frac{1}{2} g^2 (M \tilde{B}_{1/2}(p^2) \lambda \lambda + \text{c.c.})$$

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

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

$c = \text{hidden sector contrib. to beta function}$

Soft Masses

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

$$- \frac{1}{2} g^2 (M \tilde{B}_{1/2}(p^2) \lambda \lambda + \text{c.c.})$$

Soft masses follow from the effective action:

- U(1) gaugino: $M_\lambda = g^2 M \tilde{B}(0)$

- Sfermion:

$$m_f^2 = g^4 A$$

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

- Straightforward to generalize to SU(3) x SU(2) x U(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?

\[ m^2_{\tilde{f}} = \sum_{r=1}^{3} g_r^4 c_2(f; r) A_r \]

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

- 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

Strataghed to generalize to SU(3)xSU(2)xU(1).

\[ m^2_f = \sum_{r=1}^{3} g_r^4 c_2(f;r) A_r \]

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

Sfermion masses must be finite -- constraints on two-point functions at \( O(1/p^2) \).

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)

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

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

Check: vanish when SUSY is unbroken.

GGM analogue of OGM relations (more precise connection; cf. Distler & Robbins; Intriligator & Sudano)

\[ M_\lambda \sim F, \quad m^2_f \sim |F|^2 \]

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

\[ m_f^2 = \sum_{r=1}^{3} g_r^4 c_2(f; r) A_r \]

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)

\[ \text{Tr} Y m^2 = \text{Tr} (B - L) m^2 = 0 \]

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?
Can lead to tachyonic sleptons. Forbid with messenger parity:

\[ \langle J \rangle = \zeta \]

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

\[ \delta m_f^2 = g_1^2 Y_f \zeta \]

Tree-level in effective theory. Corresponds to FI parameter.

Can lead to tachyonic sleptons. Forbid with "messenger parity": \[ J \rightarrow -J \]