Anomaly Mediation from Unbroken Supergravity

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Jan 8, 2014

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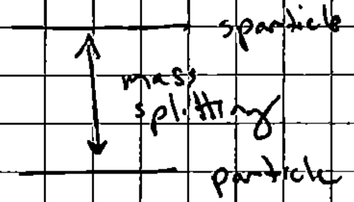
LHC is putting ~~SUSY~~ to the test!

Weak scale SUSY? If so, how is ~~SUSY~~ communicated to SSM?

= Today: More Basic Question

How do we know SUSY is broken?

Standart answer:



or $\langle V \rangle > 0$

= Today: Standard answer is incomplete.

Focus on goldstino couplings to emphasize subtleties of AMSB and SUGRA.

Start with simpler question:

How do we know that top mass breaks electroweak?

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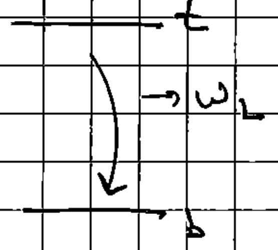
Standard Lore for Global Symmetries.

Symmetry Breaking Terms $\Longleftrightarrow$ Goldstone Couplings



$m_t t t^c \longrightarrow \frac{m_t}{v_{EW}} \pi^+ b t^c$

breaks $SU(2)_L$

(irreducible) goldstone coupling

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Two Ways to Understand

1) Linear Sigma Model $\lambda_{top}\, q h t^c$ $h \sim v_{EW}\, e^{i\pi^a T^a / v_{EW}}$

2) Current Conservation $\mathcal{L} = |\partial_\mu \pi|^2 + \frac{1}{f_\pi} \partial_\mu \pi J^\mu$

integrate by parts, use EOM to see coupling proportional to mass.

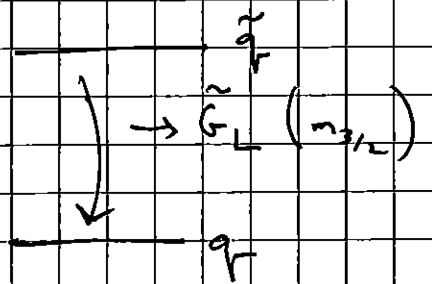
Repeat this exercise for SUSY

Standard Lore for SUSY

$\cancel{\text{SUSY}}$ soft masses $\Longleftrightarrow$ Goldstino Couplings

$$\tilde m^2 \tilde q^\dagger \tilde q \longrightarrow \frac{\tilde m^2}{F}\, \eta\, \tilde q^\dagger q$$

$\uparrow$ goldstino (longitudinal gravitino in $E \gg m_{3/2}$ limit)



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Two Ways to Understand

1) SUSY Breaking Multiplet X

$$\int d^4\theta \ \frac{Q^\dagger Q X^\dagger X}{\Lambda^2}$$

$$X = \sqrt{2}\,\theta\eta + \theta^2 F_X$$

2) Supercurrent Conservation

$$\mathcal{L} \supset \frac{1}{F}\partial_\mu \eta J^\mu$$

Use EoM:

$$\frac{\tilde m^2_{ij} - (M^2)_{ij}}{F}\, \eta\, \chi^i \phi^{\dagger j}$$

scalar mass, fermion mass, fermion, scalar

Goldstino couplings proportional to mass splittings within SUSY multiplets.

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Seems like a good idea to check this lore explicitly in SUGRA.

At tree-level all the information is in Wess & Bagger (after fixing a few typos)

$$\mathcal{L} = -m^2{}_i{}^j \phi^{\dagger i}\phi^j - \frac{1}{2}B_{ij}\phi^i\phi^j - \frac{1}{2}M_{ij}\chi^i\chi^j$$

$$+ \frac{a_i{}^j}{F}\phi^{\dagger i}\chi^j\eta + \frac{b_{ij}}{F}\phi^i\chi^j\eta + h.c.$$

Explicit computation:

$$a_i{}^j = m^2{}_i{}^j - M_i{}^k M_{kj} + \underline{2m_{3/2}^2\,\delta_{ij}}$$

$$b_{ij} = B_{ij} + \underline{m_{3/2}M_{ij}}$$

What?!

This should worry any series student of SUSY.

Punchlines:

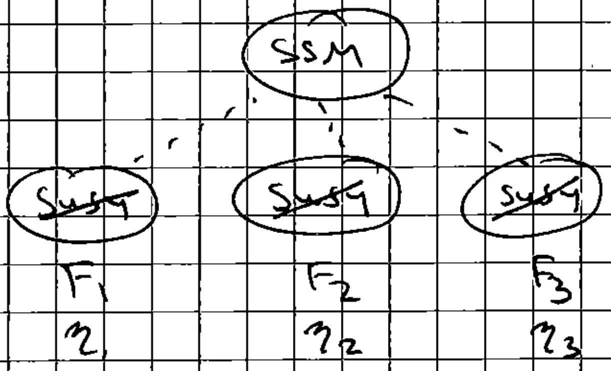
- This effect is the essense of Anomaly Mediation.
- Underlying Physics:
  Our universe is SUSY in AdS_4.

  (extra terms needed for conservation of <u>AdS</u> supercurrent.)

Aside: How did I get into this?

"Goldstini"

Cheung, Nomura, JDT
1002.1967 + ...



True goldstino : $\eta = \frac{1}{F} \sum_i \eta_i F_i$ eaten by gravitino ($m_{3/2}$)

Pseudo-goldstini : $m_{\eta} = \underline{\underline{2}}\, m_{3/2}$

↳ Bizarre fact

↳ Same underlying physics as AMSB

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Known since 1977 (Zumino)

If you break ~~[illegible]~~ SUSY in rigid AdS space

then goldstino "mass" is $\frac{2}{\lambda_{AdS}}$

In SUGRA $\frac{1}{\lambda_{AdS}} = m_{3/2}$.

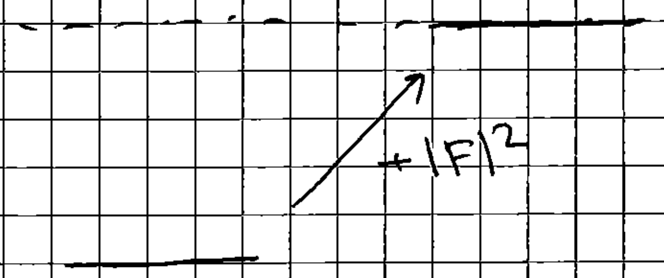
Key: $m_{3/2}$ is <u>not</u> an order parameter for ~~SUSY~~.

$m_{3/2}$ <u>defines</u> (AdS) SUSY

SUSY in AdS_4

$$V_{SUGRA} \simeq |F|^2 - 3\frac{|W|^2}{M_{Pl}^2}$$

If we have ~~SUSY~~ in flat space now..
... need AdS_4 SUSY to begin with



$V=0$ (now four polarizations)

Have to fine-tune to get CC $=0$

$$V = -3\frac{|W|^2}{M_{Pl}^2}$$

Gravitino "mass" $m_{3/2} = \frac{W}{M_{Pl}^2}$.
(but only two physical polarizations.)

$$\underset{\substack{\uparrow \\ \text{SUSY preserving} \\ \text{(actually, SUSY defining)}}}{m_{3/2}} \Longrightarrow \underset{\substack{\uparrow \\ \text{SUSY breaking.}}}{\frac{F}{\sqrt{3}M_{Pl}}}$$

After tuning, unclear whether "$m_{3/2}$" is SUSY-breaking or not. Have to be very careful.. or just track goldstino couplings

AdS$_4$ SUSY: A Different Algebra.

$$\{Q_\alpha, Q^\dagger_{\dot\alpha}\} = 2\sigma^\mu_{\alpha\dot\alpha} P_\mu .$$

$$\{Q_\alpha, Q^\beta\} = 2i\, \underset{\substack{\uparrow \\ \text{defines algebra, breaks } U(1)_R .}}{m_{3/2}} (\sigma^{\mu\nu})_{\alpha\beta} \overset{\substack{\text{Lorentz generators.} \\ \downarrow}}{M_{\mu\nu}}$$

!

Among other things, in AdS scalars are "tachyonic"

$$\text{Massless fermions} \Longrightarrow m_\phi^2 = \underset{\substack{\uparrow \\ \text{Still satisfies} \\ \text{Breitenlohner-Freedman} \\ \text{bound.}}}{-} 2m_{3/2}^2$$

To have viable theory in flat space after $\cancel{\text{SUSY}}$, have to lift this tachyonic mass.

$$\hat{m}^2 = -2m_{3/2}^2 + 2m_{3/2}^2$$

$$a = +2m_{3/2}^2$$

required by AdS$_4$ Supercurrent Conservation.

☆ Add to Master Table

For pheno purposes, we often approximate effect of AdS space through conformal compensator.

$$\mathcal{L} = \int d^4\Theta\, \Phi^\dagger \Phi \left(-3e^{K/3}\right) + \int d^2\Theta\, \Phi^3 W$$

+ graviton / gravitino terms

$$\Phi = 1 + \left(\sqrt{2}\Theta \frac{K_i X^i}{3}\right) + \Theta^2 F_\phi$$

$$\hookrightarrow = m_{3/2} + \frac{1}{3} K_i F^i$$

Conformal compensator couples to all mass scales (including regulators)

$$\mathcal{L} = \frac{1}{4} \int d^2\Theta \frac{1}{g^2(\mu/\Lambda\Phi)} W_\alpha W^\alpha$$

AMSB : $$m_\lambda = \frac{-g^2}{16\pi^2}\left(3\underset{\substack{\uparrow \\ \text{beta function}}}{T_G} - T_R\right) F_\phi$$

Randall / Sundrum

Guidice / Luty /
Murayama / Rattazzi

~~But~~ Two very different Effects! :

$$F_\phi = \underset{\substack{\uparrow \\ \text{defines} \\ \text{SUSY}}}{m_{3/2}} + \frac{1}{3} \underset{\substack{\uparrow \\ \text{breaks} \\ \text{SUSY}}}{K_i F^i}$$

In minimal AMSB (our first paper)

$$\mathcal{L} = -\frac{1}{2} m_\lambda \lambda^a \lambda^a + \frac{c_\lambda}{\sqrt{2} F} \lambda^a \sigma^{\mu\nu} \eta F^a_{\mu\nu}$$

$$m_\lambda = -\frac{g^2}{16\pi^2} m_{3/2} \left(3T_G - T_R\right) \equiv m_{AdS}$$

$$c_\lambda = \underline{\underline{0}}$$

For any $\cancel{\text{SUSY}}$ at one-loop $\quad m_\lambda - c_\lambda = m_{AdS}$.

e.g. No-scale: $\quad m_\lambda = 0$

$$c_\lambda = -m_{AdS}.$$

So in this context

"Sequestering" = Sequestering from Goldstino

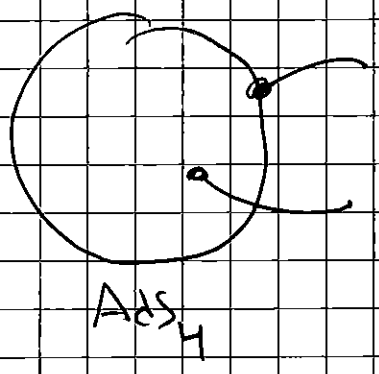
(condition for minimal AMSB) $\quad (c_\lambda = 0)$

Physical Picture.

(Minimal) AMSB = Splittings of multiplets from AdS algebra.

Wait! By AdS algebra $m_\chi^{phys} = 0$?

Beautiful paper by Gripaios / Kim / Redi / Rattazzi / Scrucca



One-loop bdry mass = $-m_{AdS}$.

must be cancelled by bulk mass = m_{AdS}.

When SUSY is broken, bdry $\to \infty$, leaving just bulk mass.

$\Rightarrow$ Bulk mass preserves SUSY (in fact, necessary to include to preserve SUSY), hence no goldstino couplings.

Famously, AMSB gives rise to two-loop scalar masses.

☆ Add to Master Table

$$\tilde{m}^2 = -\frac{1}{4}\dot{\gamma}\, m_{3/2}^2$$

Easy to show using conformal compensator that this has no goldstino coupling. $a=0$

After two years, and a fight with S. de Alwis, finally figured out one-loop result. I don't know how to derive in any simple way.

Basic idea.

$$\underset{\text{Key}\nearrow}{\mathcal{L}_{1PI}} = \int d^4\theta\; Q^\dagger\, Z\Big(\underset{\uparrow\ \text{fully SUSY/AdS/SUGRA covariant}}{\Box_{AdS}}\Big)\, Q$$

Assumes that regulators preserves AdS_4 algebra. (i.e. non-anomalous SUGRA)

Result:

$$\tilde{m}^2 = 0 \quad \leftarrow \text{in agreement with literature}$$

$$a = -\gamma\, m_{3/2}^2$$

☆ Add to Master Table

Had to be: $(2-\gamma)$ is dimension of $Q^\dagger Q$ operator.

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Summary | Lessons | Questions

(Minimal)

- Anomaly Mediated SUSY Breaking
  - Anomaly ↓ Not Really (prop to anom dim, but already a tree-level result.)
  - Mediated ↓ No messengers here
  - SUSY Breaking ↓ Nope

- $m_{3/2}$ vs. $\frac{F}{\sqrt{3}M_{pl}}$ (only equal because of CC tuning)

  $m_{3/2}$ ↑ defines AdS$_4$ SUSY (breaks $U(1)_R$)

  $\frac{F}{\sqrt{3}M_{pl}}$ ↑ $\cancel{\text{SUSY}}$

- Chiral Curvature Superfield.

$$R = \underbrace{-\frac{1}{6}M}_{\frac{1}{2}m_{3/2}} + F_R\left(\Theta + \frac{\eta}{\sqrt{2}F}\right)^2$$

$\frac{1}{2}m_{3/2}$ Preserves SUSY

$F_R \equiv \frac{1}{12}R_{EH} - m_{3/2}^2$

Detuning from AdS$_4$ breaks SUSY

- Have to revisit AMSB-explaining papers with an eye towards goldstino couplings

Dine / Seiberg   Sanford / Shirman

Bagger / Poppitz / Moroi   Conlon / Goodsell / Palti

All correct, but confusing if you don't know about AdS$_4$ algebra.

- Can never turn AMSB off (since it comes from AdS algebra.)

  e.g. No-scale: $m_\lambda = 0$

  $c_\lambda = -m_{AdS}$.

- Surprises at tree-level for B-terms.

$$b = \underbrace{B_\mu}_{\text{Goldstino coupling}} + m_{3/2}\mu .$$

$$W = \mu H_u H_d \longrightarrow \frac{B_\mu}{\mu} = -m_{3/2} \quad \text{(no goldstino coupling)}$$

Giudice-Masiero

$$K = \xi H_u H_d \longrightarrow \mu = 6 m_{3/2}$$

$$\frac{B_\mu}{\mu} = + m_{3/2} \quad \text{(yes goldstino coupling)}$$

- None of this depended on which SUGRA formalism you used (this is why S. de Alwis is wrong, since his answer is gauge dependent)

- Makes clear that AdS_4 has to be preserved by regulators. But in AdS space, regulators are split, hence radiatively induced (SUSY-preserving) soft masses.

  "gauge mediation by regulators"

- Relied heavily on CC tuning. Perhaps a solution to CC problem won't have AMSB?.

- We have learning something deep about AdS_4. Does this teach us anything about CFT_3.

Pleasure telling you about our work, and look forward to taking further questions.

Thank you.

Master Table: (Put up at beginning of talk)

float

Massless Chiral Multiplet

	tree-level	one-loop	two-loop	← Starting order
soft masses	0 $= -2m_{3/2}^2 + 2m_{3/2}^2$	0	$-\frac{1}{4}\dot{\gamma}m_{3/2}^2$	
goldstino couplings	$+2m_{3/2}^2$	$-\gamma m_{3/2}^2$	0	
difference (AdS$_4$ algebra)	$-2m_{3/2}^2$	$+\gamma m_{3/2}^2$	$-\frac{1}{4}\dot{\gamma}m_{3/2}^2$	← 2 years of my life