Dynamical SUSY breaking without scales

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DESY

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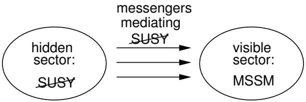
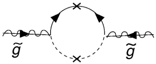
Gauge-mediated supersymmetry breaking

Build a model of SUSY breaking which is as UV-independent as possible

- no higher-dimensional operators
- SUSY broken in hidden sector
- massive messenger fields with SM charges couple to hidden sector
- ~~SUSY~~ communicated to SM through messenger loops



- e.g. gluino masses:



- Solves SUSY flavour problem

This talk will mainly concern the hidden sector.

The hidden sector: Dynamical SUSY breaking

Q: Why is $M_{\text{EWSB}} \ll M_{\text{Planck}}$?

A: SUSY protects Higgs potential from quadratic divergences
EWSB scale set by soft SUSY breaking terms, $M_{\text{EWSB}} \sim M_{\text{soft}}$
In gauge-mediated $\not{\text{SUSY}}$:

$$M_{\text{soft}} \sim \frac{1}{16\pi^2} \frac{M_{\not{\text{SUSY}}}^2}{M_{\text{mess}}}$$

Q: Why is $M_{\not{\text{SUSY}}} \ll M_{\text{Planck}}$?

A: Dynamical SUSY breaking.
$M_{\not{\text{SUSY}}}$ generated by strong gauge dynamics / dimensional transmutation
(just like Λ_{QCD} in Standard Model) → Witten '81, Affleck/Dine/Seiberg '80s

Q: How could this look like?

→ this talk (and other models. . .)

Review: *F*-term SUSY breaking

General Wess-Zumino model:

$$W = f_i\,\Phi_i + \mu_{ij}\,\Phi_i\Phi_j + \lambda_{ijk}\,\Phi_i\Phi_j\Phi_k$$

- W =superpotential, Φ_i =chiral superfields
- $\not{\text{SUSY}}$ iff $\langle \frac{\partial W}{\partial \Phi_i} \rangle \neq 0$ for some i
- $\not{\text{SUSY}}$ scale set by $M^2_{\not{\text{SUSY}}} \sim \left| \langle \frac{\partial W}{\partial \Phi_i} \rangle \right|$

Example 1: Polonyi model

$$W = f\,\Phi$$

- $\langle \frac{\partial W}{\partial \Phi} \rangle = f =$ const. $\neq 0$
  $M^2_{\not{\text{SUSY}}} \sim$ coefficient of linear term in W
- scalar potential exactly flat $\Rightarrow$ not so interesting

Review: *F*-term SUSY breaking

Example 2: O'Raifeartaigh model

$$W = \lambda\,\Phi_1(\mu^2 - \Sigma^2) + m\,\Phi_2\Sigma$$

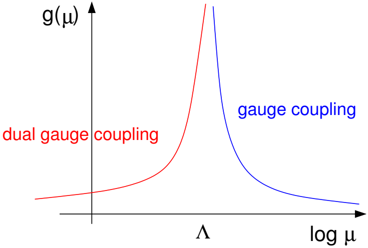
- For $|m|^2 > |\lambda\mu^2|$ vacuum is at $\Phi_1 = \Phi_2 = \Sigma = 0$
- $M^2_{\not{\text{SUSY}}} = \left|\langle \frac{\partial W}{\partial \Phi_1}\rangle\right| = |\lambda\mu^2| =$ coefficient of linear term in W
- No flat directions in (loop-corrected) scalar potential $\Rightarrow$ more interesting
- Origin of small scale $\sqrt{|\lambda|}|\mu|$ unclear. Not a dynamical model.

Review: F-term SUSY breaking

Example 3: ISS model

SQCD = SU(N) SUSY gauge theory, "quark" and "antiquark" superfields Q, $\tilde{Q}$
For suitable numbers of flavours and colours:

- asymptotically free
- strongly coupled at IR scale Λ
- at energies below Λ, described by IR-free Seiberg dual "magnetic" theory
- magnetic theory contains composite meson superfield $\Phi \sim Q\tilde{Q}/\Lambda$ and "dual quarks" and antiquarks χ, $\tilde{\chi}$



Add quark mass term $W = m\, Q\tilde{Q} \quad \Rightarrow \quad W_{\text{IR}} = \chi\Phi\tilde{\chi} + m\Lambda\ \text{tr}\,\Phi$

Linear term leads to ~~SUSY~~ with $M^2_{\cancel{\text{SUSY}}} \sim m\Lambda$ → Intriligator/Seiberg/Shih '06
(only metastable, but with long-lived vacuum if $m \ll \Lambda$)

Looks better: $M_{\cancel{\text{SUSY}}}$ depends on dynamical scale Λ
but $m \ll \Lambda$ still put in by hand...

Can we do better?

Goal: Build a model of (metastable) SUSY breaking which

- is renormalizable (minimize dependence on UV physics)
- generates all scales dynamically
- can serve as a realistic hidden sector for gauge-mediated $\not{S}\!USY$
- is as simple as possible

Idea 1: Renormalizable + scale-free means cubic W
ISS: Seiberg duality turns mass term $mQ\tilde{Q}$
into linear term $m\Lambda \operatorname{tr}\Phi$ for composite $\Phi \sim Q\widetilde{Q}/\Lambda$
Now: Use two dualities to turn cubic term (for elementary fields)
into linear term (for composites)

Idea 2: Take SQCD + SQCD′ + singlet S
$W = SQ'\tilde{Q}' + S^3$ gives $\langle S \rangle = \Lambda'$ in SUSY vacuum
Use $\langle S \rangle$ as dynamically generated quark mass parameter for SQCD

1. SUSY breaking from a sequence of dualities

Roughly:

SU(N)$\times$ SU(n); chiral superfields $\widetilde{Q}$, Σ, $\widetilde{\Sigma}$; UV superpotential $W = \lambda\, \Sigma\widetilde{\Sigma}\widetilde{Q}$

	SU(N)	SU(n)
Σ	$\square$	1
$\widetilde{\Sigma}$	$\overline{\square}$	$\square$
$\widetilde{Q}$	1	$\overline{\square}$

SU(N) strongly coupled at scale Λ_N: meson $Q \sim \Sigma\widetilde{\Sigma}/\Lambda_N$

$W_{\text{eff}} = \underbrace{\lambda\Lambda_N}_{\equiv m} Q\widetilde{Q}$: effective ISS model for SU(n) if λ is small

SU(n) strongly coupled at $\Lambda_n \Rightarrow$ linear term for meson $Q\widetilde{Q}$ with coeff. $\lambda\Lambda_N\Lambda_n$

1. SUSY breaking from a sequence of dualities

And in detail:

Gauge group SU(N)$\times$ SU(n), flavour group SU(N)$_F\times$SU($N-n$)
Choose $n < N < \frac{3}{2}N$ (free magnetic range)

	SU(n)	SU(N)	SU(N)$_F$	SU($N-n$)
$\widetilde{\Sigma}$	$\square$	$\overline{\square}$	1	1
$\widetilde{Q}$	$\overline{\square}$	1	$\square$	1
Σ	1	$\square$	$\overline{\square}$	1
$\widetilde{P}$	1	$\overline{\square}$	1	$\square$
S	1	1	$\square$	$\overline{\square}$

Superpotential $W = \lambda\,\Sigma\widetilde{\Sigma}\widetilde{Q} + \Sigma\widetilde{P}S$

SU(N) strongly coupled at scale Λ_N: SU(N) SQCD with $F = N$ flavours
Baryons B, $\widetilde{B}$ and mesons $Q \sim \Sigma\widetilde{\Sigma}/\Lambda_N$, $\widetilde{S} \sim \Sigma\widetilde{P}/\Lambda_N$

$$W_{\rm eff} = \lambda\Lambda_N\, Q\widetilde{Q} + \Lambda_N\, S\widetilde{S} + \underbrace{T\Lambda_N^2\left(\frac{\det(\Sigma\oplus\widetilde{S})}{(\Lambda_N)^N} - \frac{B\widetilde{B}}{\Lambda_N^2} - 1\right)}_{\text{deformed moduli space constraint}}$$

1. SUSY breaking from a sequence of dualities

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S and $\widetilde{S}$ decouple: constraint satisfied on baryonic branch $B\widetilde{B} = -\Lambda_N^2$

$$W_{\text{eff}} = \lambda\Lambda_N\, Q\widetilde{Q}$$

For λ small, Q and $\widetilde{Q}$ can stay light to below SU(n) strong-coupling scale

SU(n) strongly coupled at Λ_n

- N flavours ($Q =$ composite, $\widetilde{Q} =$ elementary)
- in free magnetic range since $n < N < \frac{3}{2}n$ by assumption
- if $\lambda\Lambda_N < \Lambda_n \Rightarrow$ effective ISS model with $M^2_{\text{SUSY}} \sim |\lambda\Lambda_n\Lambda_N|$

Small marginal coupling λ required to satisfy $\lambda\Lambda_N < \Lambda_n$
(since $\Lambda_n < \Lambda_N$ by construction)

2. SUSY breaking with a singlet

Idea:
SU(n) SQCD with $f < n$ flavours $\Sigma, \widetilde{\Sigma}$: dynamical W admits no stable vacuum

But adding a singlet S and a tree-level superpotential

$$W_{\text{tree}} = S^3 + S\,\Sigma\widetilde{\Sigma}$$

gives

$$W_{\text{exact}} = S^3 + S\Sigma\widetilde{\Sigma} + \left(\frac{\Lambda^{3n-f}}{\det \Sigma\widetilde{\Sigma}}\right)^{\frac{1}{n-f}}$$

Stable SUSY vacuum with $\langle S \rangle \sim \Lambda$.

Use $\langle S \rangle$ as dynamically generated ISS mass parameter

Simplest version: $n = 2$ and $f = 1$,
SU(2) gauge group with one flavour $\Sigma, \widetilde{\Sigma}$ and scale Λ_2

2. SUSY breaking with a singlet

Take SU(N) with F flavours Q, $\widetilde{Q}$ in free magnetic range, $N < F < \frac{3}{2}N$

Add auxiliary gauge group: SU(2) with Σ, $\widetilde{\Sigma}$, and singlet S

$$W_{\rm tree} = S\Sigma\widetilde{\Sigma} + \lambda S Q\widetilde{Q} - \frac{1}{3}S^3$$

Strong-coupling scales: Assume $\Lambda_2 > \Lambda_N$.
Near Λ_2, SU(2) generates dynamical superpotential:

$$\Delta W_{\rm ADS} = \frac{(\Lambda_2)^5}{\Sigma\widetilde{\Sigma}}$$

Use this to integrate out S and $\Sigma\widetilde{\Sigma}$: $\langle S\rangle \sim \Lambda_2$

$$W_{\rm eff} = \lambda\Lambda_2\, Q\widetilde{Q}$$

If $\lambda\Lambda_2 < \Lambda_N$ (requiring $\lambda \ll 1$), again recover ISS superpotential:
Effective ISS model with $M^2_{\not{\rm SUSY}} \sim |\lambda\Lambda_n\Lambda_N|$

Messenger couplings

Straightforward to couple this model to gauge mediation messengers

$$W_{\text{tree}} = S\Sigma\widetilde{\Sigma} + \lambda\, SQ\widetilde{Q} - \frac{1}{3}S^3 + \kappa\, Sf\tilde{f}$$

Gauge symmetries now

	SU(2)	SU(N)	SU(5)
Σ	$\square$	1	1
$\widetilde{\Sigma}$	$\overline{\square}$	1	1
Q	1	$\square$	1
$\widetilde{Q}$	1	$\overline{\square}$	1
f	1	1	$\mathbf{R}$
$\tilde{f}$	1	1	$\overline{\mathbf{R}}$

$\supset$ SU(3)$\times$ SU(2)$\times$ U(1)

Supersymmetric messenger mass Λ_2 after setting $\langle S\rangle \approx \Lambda_2$

~~SUSY~~ mass splittings induced from effective $Q\widetilde{Q}f\tilde{f}$ couplings

(similar to $\to$ Murayama/Nomura '06)

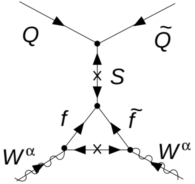
Messenger couplings

$$W_{\text{tree}} = S\Sigma\widetilde{\Sigma} + \lambda\, SQ\widetilde{Q} - \frac{1}{3}S^3 + \kappa\, Sf\tilde{f}$$

induces coupling

$$\mathcal{L} \supset \frac{g^2}{16\pi^2}\frac{\kappa\lambda C_{\mathbf{R}}}{(\Lambda_2)^2}\int d^2\theta\, Q\widetilde{Q}\ \text{tr}\, W^\alpha W_\alpha$$

to MSSM gauge fields W^α by



With $\Phi \sim Q\widetilde{Q}/\Lambda_N$ and $F_\Phi = N\,\lambda\Lambda_2\Lambda_N$: MSSM gaugino masses

$$M_a \sim \frac{g_a^2}{16\pi^2}\frac{\kappa\lambda^2\, C_{\mathbf{R}}\, N\,\Lambda_N^2}{\Lambda_2}$$

Messenger couplings

- Can induce μ term at one-loop e.g. by taking f and $\tilde{f}$ in **10** and $\overline{\mathbf{10}}$ of SU(5), from superpotential

$$W \supset y_u \, f \, f \, H_u + y_d \, \tilde{f} \, \tilde{f} \, H_d$$

  leading to

$$\mu \sim \frac{y_u y_d}{16\pi^2} \frac{\kappa \lambda^2 \, C_{\mathbf{R}} \, N \, \Lambda_N^2}{\Lambda_2}$$

- Can forbid $S H_u H_d$ coupling by symmetries (e.g. suitable R-Symmetry)
- sfermion masses^2, trilinears and $B\mu$: difficult to extract (from operators non-holomorphic in hidden sector fields $\rightarrow$ work in progress)

Conclusions

- Modern models of SUSY breaking often rely on small scale put in by hand
  Not fully dynamical
- Can be cured in SQCD with composite quark superfields
  $\Rightarrow$ generate $\not{\text{SUSY}}$ scale from a sequence of Seiberg dualities...
- ...or by taking two copies of SQCD coupled by a singlet
- Obtain simple, renormalizable, fully dynamical models of $\not{\text{SUSY}}$
- All scenarios require a small ($\lesssim 10^{-3}$) marginal parameter λ
- First scenario might be used for direct gauge mediation
- Second one can be elegantly coupled to gauge mediation messengers:
  - renormalizable
  - natural (except for tuning of λ)
  - potentially realistic (possible $B\mu$ problem)

Backup

SUSY QCD

SQCD = SU(N) SUSY gauge theory, F copies of Q and $\widetilde{Q}$ chiral superfields

	SU(N)	SU(F)$_L$	SU(F)$_R$
Q	$\square$	$\overline{\square}$	1
$\widetilde{Q}$	$\overline{\square}$	1	$\square$

Take $N < F < \frac{3}{2}N$: "Free magnetic range"

- asymptotically free, strongly coupled at IR scale Λ
- IR degrees of freedom constitute Seiberg-dual gauge theory→ Seiberg '93
  - F copies of dual quark superfields χ and dual antiquarks $\tilde{\chi}$...
  - ...and composite meson superfield $\Phi \sim Q\widetilde{Q}/\Lambda$
  - dual gauge group: SU($F - N$). IR free, strongly coupled at UV scale $\approx \Lambda$

	SU($F - N$)	SU(F)$_L$	SU(F)$_R$
Φ	1	$\square$	$\overline{\square}$
χ	$\square$	$\overline{\square}$	1
$\tilde{\chi}$	$\overline{\square}$	1	$\square$

- IR superpotential $W_{\rm IR} = \chi\Phi\tilde{\chi}$

Review: F-term SUSY breaking (continued)

Example 3: ISS model

Deform SQCD in UV by superpotential $W_{\text{UV}} = m\, Q\widetilde{Q}$

Require $m \ll \Lambda$ (otherwise Q and $\widetilde{Q}$ decouple in UV)

Effect on Seiberg dual IR theory:

$$W_{\text{IR}} = \chi\Phi\tilde{\chi} + m\Lambda \,\text{tr}\,\Phi + \dots$$

$$\frac{\partial W_{\text{IR}}}{\partial \Phi^i_j} = \underbrace{\chi^c_i \tilde{\chi}^j_c}_{\text{rank } F-N} + m\Lambda \underbrace{\delta^j_i}_{\text{rank } F}$$

$\partial W / \partial \Phi^i_j$ cannot all vanish $\Rightarrow$ SUSY broken → Intriligator/Seiberg/Shih '06

- Taking into account (IR-irrelevant) nonperturbative terms:
  SUSY breaking only metastable, but vacuum parametrically long-lived
- $M^2_{\not{\text{SUSY}}} \sim \left| \langle \frac{\partial W}{\partial \Phi^i_j} \rangle \right| \sim |m\Lambda| \sim$ coefficient of linear term in W
- Mechanism still not fully dynamical: small scale m put in by hand