A Model of Dirac Gauginos: Dynamics and Operator Analysis

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work in progress with C. Csaki, J. Goodman, and R. Pavesi

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Motivation

- SUSY extensions of the SM are severely tested by non-observation of SUSY at the LHC
- Several scenarios for keeping idea of naturallness
  - R-parity violating SUSY
  - Light stops with heavy first generations
  - Dirac gauginos
- The goal of this talk: construct a fully dynamical model of SUSY breaking leading to Dirac gaugino masses and more natural superpartner spectra.

Supersoft SUSY Breaking

(Nelson, Fox, Weiner)

- SUSY breaking dominated by a D-term of an extra $U(1)$

$$W_\alpha \supset D\theta_\alpha, \quad D \neq 0$$

  - No-go theorem for pure D-term breaking in a field theory
  - A combined D/F-term SUSY breaking is realistic
  - Mediation mechanism may be dominated by D-terms
- Additional chiral adjoint superfield charged under SM:

$$\mathcal{M}_j = \mathcal{M}_j + \theta\psi_{M_j} + \theta^2 F_{M_j}, \quad j = SU(3), SU(2), U(1)_Y$$

- Operators in the effective Lagrangian

$$\frac{WW_j}{\Lambda}\mathcal{M}_j \quad \Longrightarrow \quad \mathcal{L} \supset -m_D\lambda_j\psi_{M_j} - m_D^2\left(\mathcal{M} + \mathcal{M}^\dagger\right)^2$$

$$\frac{W_\alpha W^\alpha}{\Lambda^2}\mathcal{M}^2 \quad \Longrightarrow \quad \mathcal{L} \supset -m_h^2(\mathcal{M}^2 + \mathcal{M}^{*2})$$

$$m_D \sim \frac{D}{\Lambda}, \quad m_h^2 \sim \frac{D^2}{\Lambda^2}$$

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Operator Analysis and Toy Models

- The problem of negative mass^2 for the $\mathrm{Im}\,\mathcal{M}$ could be solved by

$$m_{\mathcal{M}}^2 \mathcal{M}^\dagger \mathcal{M}$$

- $\mathcal{M}$ is essentially a light messenger multiplet with soft terms

$$m_D, \quad m_h^2, \quad m_{\mathcal{M}}^2$$

- The supertrace within the multiplet is proportional to $m_{\mathcal{M}}^2$
- It was argued in the literature that in supersoft models with interacting $U(1)$ a non-holomorphic mass $m_{\mathcal{M}}^2$ is generated and arises from

$$\int d^4\theta \frac{W_\alpha D_\alpha V}{\Lambda^2} \mathcal{M}^\dagger \mathcal{M}$$

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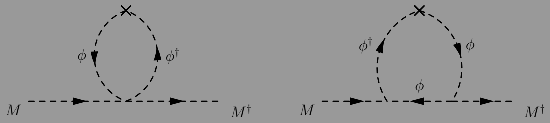
Operator Analysis and Toy Models: Model 1

- $U(1)$ with a D-term and heavy charged messengers

$$W = \bar{\phi}\mathcal{M}\phi + \Lambda\bar{\phi}\phi$$

- Explicit calculation demonstrates the cancellation of the diagrams contributing to $m^2_{\mathcal{M}}$



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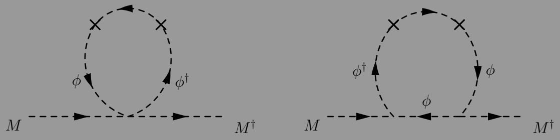

$$y^2 \int dp^2 \left[\frac{1}{(p^2 - m_\phi^2)^3} - \frac{3m_\phi^2}{(p^2 - m_\phi^2)^4} \right] = 0$$

- Only second diagram exists for $\mathcal{M}^2$ term
- No cancellation between ϕ and $\bar{\phi}$ contributions

Operator Analysis and Toy Models

- No need for Feynman diagrams
- Integrating out heavy messengers renormalizes $U(1)$ coupling

$$\left(\frac{1}{g^2(\Lambda)} + \frac{b_L}{4\pi}\log\frac{\mu}{\mathcal{M}} + \frac{b_H}{4\pi}\log\frac{\mathcal{M}}{\Lambda_{UV}}\right) W_\alpha W^\alpha$$

- Expand $\mathcal{M} \to \Lambda + \mathcal{M}$

$$\int d^2\theta \frac{y^2}{8\pi^2}\frac{1}{\Lambda^2} W_\alpha W^\alpha M^2 + h.c.$$

Operator Analysis and Toy Models: Model 2

- Generate D-term through vevs of charged fields ψ and $\bar{\psi}$

$$W = \bar{\phi}\mathcal{M}\phi + \Lambda\bar{\phi}\phi \,, \qquad D \sim \mathcal{O}\left(|\psi|^2 - |\bar{\psi}|^2\right)$$

- New allowed operator

$$\int d^4\theta \sum_i \frac{\psi_i^\dagger e^{q_i V}\psi_i}{\Lambda^2}\mathcal{M}^\dagger\mathcal{M}$$

- Not generated at one loop. Is it generated at higher order?
- Treat $\mathcal{M}$ as a spurion: renormalizes ψ kinetic terms.
- ψ anomalous dimension
  - At one loop: proportional to g^2 and independent of $\mathcal{M}$
  - At higher orders: depends on $\mathcal{M}$ through running of g^2
- Wave-function renormalization Z
  - At one loop: depends on $\mathcal{M}$ but is a sum of holomorphic and anti-holomorphic terms
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- At higher loop orders supersoft is never supersoft.

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Operator Analysis and Toy Models: Model 3

- Introduce superpotential couplings to neutral fields

$$W = \bar{\phi}\mathcal{M}\phi + \Lambda\bar{\phi}\phi + \psi\bar{\phi}N + \bar{\psi}\phi\bar{N}$$

- Soft mass operator generated at one loop

$$\int d^4\theta \frac{1}{16\pi^2}\frac{s\psi^\dagger e^V\psi + \bar{s}\bar{\psi}^\dagger e^{-V}\bar{\psi}}{\Lambda^2}\mathcal{M}^\dagger\mathcal{M}$$

- Mixing: no cancellation between cubic/quartic diagrams
- $\psi \neq \bar{\psi}$: no cancellation between ϕ and $\bar{\phi}$ contributions
- Soft mass is technically linear in D

$$\frac{s|\psi|^2 - \bar{s}|\bar{\psi}|^2}{\Lambda^2}D$$

  but naturally $\mathcal{O}(D^2)$ and can be made smaller/larger
- Possible to flip signs of m_h^2 and $m_{\mathcal{M}}^2$

Dynamical supersoft model

- s-confining SQCD

	$SU(5)$	$SU(6)$	$SU(6)$	$U(1)_B$	$U(1)_R$
Q	$\square$	$\square$	$\mathbf{1}$	1	$\frac{1}{6}$
$\overline{Q}$	$\overline{\square}$	$\mathbf{1}$	$\overline{\square}$	-1	$\frac{1}{6}$

- Low energy dofs

	$SU(6)$	$SU(6)$	$U(1)_B$	$U(1)_R$
$\tilde{M}$	$\overline{\square}$	$\square$	0	$\frac{1}{3}$
B	$\square$	$\mathbf{1}$	5	$\frac{5}{6}$
$\overline{B}$	$\mathbf{1}$	$\overline{\square}$	-5	$\frac{5}{6}$

- $SU(5)_D$ subgroup of global symmetry identified with SM

$$\tilde{M} = \begin{pmatrix} M & N \\ \overline{N} & X \end{pmatrix}, \; B = \begin{pmatrix} \phi \\ \psi \end{pmatrix}, \; \bar{B} = \begin{pmatrix} \overline{\phi} \\ \overline{\psi} \end{pmatrix}$$

- $U(1)_B$ gauged, acquires D-term

Dynamical model of supersoft SUSY breaking

- Superpotential

$$W_1 = \lambda(\overline{\phi} M \phi + \psi N \overline{\phi} + \overline{\psi}\overline{N} \phi + \psi \overline{\psi} X) - \mu^2 X$$

- To generate a D-term

$$W_2 = hS(\psi + T) + h' \overline{S}(\overline{\psi} + \overline{T}) + \alpha Z T \overline{T}$$

- S, $\bar{S}$, T, $\bar{T}$ are charged under $U(1)$. Z is neutral.
- hST is a tree level mass
- $hS\psi \sim \left(\frac{1}{\Lambda_{UV}}\right)^3 SQ^5$ arises after confinement
- Need SUSY mass for messengers

$$W_3 = m' \chi (TrM - v_M)$$

Dynamical model of supersoft SUSY breaking

- O'Rafeartaigh model of SUSY breaking

$$F_X = \bar{\psi}\psi - \mu^2, \quad F_S = h(\psi + T), \quad F_{\bar{S}} = h'(\bar{\psi} + \bar{T}), \quad F_Z = \alpha \bar{T} T$$

- Non-vanishing F-terms are: F_X, F_S, $F_{\bar{S}}$, F_Z. These fields do not couple to SM charged messengers
- D-term is generated after $U(1)_B$ gauging. Leading SUSY breaking effect for SM fields

Dynamical model of supersoft SUSY breaking

- For small g the minimum is at $T \approx \psi \neq 0$, $\bar{T} = \bar{\psi} = 0$
- For sufficiently large g and $h \neq h'$ the minimum is at

$$\psi \neq 0, \quad \bar{\psi} \neq 0$$

- Can choose parameters so that
  - Both scalar mass^2 eigenvalues are positive
  - Holomorphic m_h^2 soft mass squared

$$\frac{s|\psi|^2 - \bar{s}|\bar{\psi}|^2}{v_M^2} D > 0$$

    and can have either sign
  - Mass ratio $m_{\mathcal{M}}^2/m_D^2$ can take a wide range of values
  - Examples of adjoint mass spectra

$$m_D = 1.6\,TeV, \qquad m_r = 2.1\,TeV, \qquad m_i = 2.2\,TeV$$

$$m_D = 1.6\,TeV, \qquad m_r = 5\,TeV, \qquad m_i = 1\,TeV$$

Conclusions

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- Reanalized effective operators in UV completions of supersoft
  - Supersoft is never truly supersoft
  - Positive adjoint masses can be generated in Yukawa extended supersoft models
- Constructed a complete dynamical model of SUSY breaking with supersoft mediation mechanism
  - Sufficient freedom in adjusting parameters to obtain realistic spectra
  - While expect a need for some finu-tuning, there will be multiple acceptable islands in the parameter space