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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Introduction

Operator Analysis and Toy Models

Dynamical supersoft model

Conclusions
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

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

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

$$m_D \sim \frac{D}{\Lambda}, \quad m_h^2 \sim \frac{D^2}{\Lambda^2}$$
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The problem of negative mass$^2$ for the $\text{Im} \, \mathcal{M}$ could be solved by

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

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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

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**Operator Analysis and Toy Models: Model 1**

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

\[ W = \bar{\phi} M \phi + \Lambda \bar{\phi} \phi \]

- Explicit calculation demonstrates the cancellation of the diagrams contributing to $m^2_M$

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

- Only second diagram exists for $M^2$ term

- Cancellation between $\phi$ and $\bar{\phi}$ contributions
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Explicit calculation demonstrates the cancellation of the diagrams contributing to \( m^2_{\mathcal{M}} \)

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

Only second diagram exists for \( \mathcal{M}^2 \) term

No cancellation between \( \phi \) and \( \bar{\phi} \) contributions
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 $\psi$ and $\bar{\psi}$

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

- New allowed operator

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

- Not generated at one loop. Is it generated at higher order?

- Treat $M$ as a spurion: renormalizes $\psi$ kinetic terms.

- $\psi$ anomalous dimension
  - At one loop: proportional to $g^2$ and independent of $M$
  - At higher orders: depends on $M$ through running of $g^2$

- Wave-function renormalization $Z$
  - At one loop: depends on $M$ but is a sum of holomorphic and anti-holomorphic terms
  - At higher orders: must depend on $M \dagger M$

- At higher loop orders supersoft is never supersoft.
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Introduce superpotential couplings to neutral fields

\[ W = \bar{\phi} M \phi + \Lambda \bar{\phi} \phi + \psi \bar{\phi} N + \bar{\psi} \phi \bar{N} \]

Soft mass operator generated at one loop

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

Mixing: no cancellation between cubic/quartic diagrams

\( \psi \neq \bar{\psi} \): no cancellation between \( \phi \) 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 \( m_M^2 \)
Dynamical supersoft model

- **s-confining SQCD**

<table>
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<th>$SU(6)$</th>
<th>$SU(6)$</th>
<th>$U(1)_B$</th>
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<td></td>
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<td>$\frac{1}{6}$</td>
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- **Low energy dofs**

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<tr>
<td>$\bar{B}$</td>
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<td></td>
<td>$-5$</td>
<td>$\frac{5}{6}$</td>
</tr>
</tbody>
</table>

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

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

- **$U(1)_B$** gauged, acquires $D$-term
Dynamical model of supersoft SUSY breaking

- **Superpotential**

\[
W_1 = \lambda (\phi^* M \phi + \psi^* N \phi + \psi^* N \bar{\phi} + \psi \bar{\psi} X) - \mu^2 X
\]

- To generate a **$D$-term**

\[
W_2 = h S (\psi + T) + \lambda' \bar{S} (\bar{\psi} + \bar{T}) + \alpha Z T \bar{T}
\]

- $S, \bar{S}, T, \bar{T}$ 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

\[
W_3 = m' \chi (Tr M - v_M)
\]
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 $\psi \neq 0, \bar{\psi} \neq 0$

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

\[
\frac{s|\psi|^2 - \bar{s}|ar{\psi}|^2}{v_M^2} D > 0
\]

and can have either sign
- Mass ratio $m_M^2/m_D^2$ can take a wide range of values
- Examples of adjoint mass spectra

\[
\begin{align*}
  m_D &= 1.6 \text{ TeV}, & m_r &= 2.1 \text{ TeV}, & m_i &= 2.2 \text{ TeV} \\
  m_D &= 1.6 \text{ TeV}, & m_r &= 5 \text{ TeV}, & m_i &= 1 \text{ TeV}
\end{align*}
\]
Conclusions
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- Reanalyzed 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 finetuning, there will be multiple acceptable islands in the parameter space