Partially composite supersymmetry

Andrew S. Miller

School of Physics and Astronomy
University of Minnesota

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Motivation

▶ Supersymmetry has numerous attractive theoretical features
  ▶ solution to hierarchy problem
  ▶ dark matter candidate
  ▶ gauge unification
  ▶ incorporation of gravity

▶ Current constraints on SUSY suggest split sparticle spectrum
  ▶ LHC bounds suggest heavier superpartners (\(\sim\) TeV scale)
  ▶ 125 GeV Higgs requires \(\gtrsim\) 10 TeV stops in the MSSM
  ▶ Flavor-changing neutral currents (FCNCs) can be suppressed if masses of first- and second-generation sfermions are above \(\sim\)100 TeV

▶ Yukawa couplings (fermion masses) in the standard model are parameters of the theory and span six orders of magnitude
For each SM fermion introduce an elementary chiral superfield $\Phi$ and supersymmetric composite operator $\mathcal{O}$ with linear mixing:

$$\mathcal{L}_\Phi = [\Phi^\dagger \Phi]_D + \frac{1}{\Lambda_{UV}^{\delta-1}} ([\Phi \mathcal{O}^c]_F + \text{H.c.}),$$

where $\delta$ is the anomalous dimension of $\mathcal{O}$

Massless eigenstate is partially composite:

$$|\Phi_0\rangle \simeq \mathcal{N}_\Phi \left\{ |\Phi\rangle - \frac{1}{g_{\Phi}^{(1)} \sqrt{\zeta \Phi}} \sqrt{\frac{\delta - 1}{\left( \frac{\Lambda_{IR}}{\Lambda_{UV}} \right)^{(1-\delta)}} - 1} |\Phi^{(1)}\rangle \right\}.$$
Fermion and sfermion spectra

- Elementary Higgs couples to elementary chiral fermions:

\[ y_\psi \sim \begin{cases} 
\frac{\lambda}{\zeta_\Phi} (\delta - 1) \frac{16\pi^2}{N} & \delta \geq 1 \text{ (mostly elementary)} \\
\frac{\lambda}{\zeta_\Phi} (1 - \delta) \frac{16\pi^2}{N} \left( \frac{\Lambda_{\text{IR}}}{\Lambda_{\text{UV}}} \right)^2 (1 - \delta) & 0 \leq \delta < 1 \text{ (admixture)}
\end{cases} \]

- Anamalous dimension of the chiral superfields chosen to explain fermion mass hierarchy

- Composite sector breaks supersymmetry (spurion \( \mathcal{X} \)):

\[ \tilde{m}^2 \sim \begin{cases} 
\frac{(\delta - 1)}{\zeta_\Phi} \frac{16\pi^2}{N} \frac{|F_{\mathcal{X}}|^2}{\Lambda_{\text{IR}}^2} \left( \frac{\Lambda_{\text{IR}}}{\Lambda_{\text{UV}}} \right)^2 (\delta - 1) & \delta \geq 1 \text{ (mostly elementary)} \\
\frac{(1 - \delta)}{\zeta_\Phi} \frac{16\pi^2}{N} \frac{|F_{\mathcal{X}}|^2}{\Lambda_{\text{IR}}^2} & 0 \leq \delta < 1 \text{ (admixture)}
\end{cases} \]

- Inverted sfermion spectrum
**Gravitational dual theory**

**Slice of AdS$_5$**
We take a five-dimensional (5D) spacetime $(x^\mu, y)$ with AdS$_5$ (warped) metric

$$ds^2 = e^{-2k|y|} \eta_{\mu\nu} \, dx^\mu \, dx^\nu + dy^2$$

compactified $(-\pi R \leq y \leq \pi R)$ on a $S^1/Z_2$ orbifold of radius $R$

- The 5D spacetime is a slice of AdS$_5$ geometry, bounded by two 3-branes located at the orbifold fixed points $y = 0$ (UV brane) and $y = \pi R$ (IR brane)

**AdS/CFT duality**

- Anomalous dimension of operators in 4D CFT is dual to localization of fields in AdS$_5$:

$$\delta = |c + \frac{1}{2}|$$

- Warping extra dimension provides a natural way to explain hierarchies:

$$\frac{\Lambda_{\text{IR}}}{\Lambda_{\text{UV}}} = e^{-\pi k R}$$
Extradimensional setup

- The Higgs are confined to the UV brane
- SUSY in broken on the IR brane
- Gauge, gravity, and matter fields propagate in the bulk

- Higgs plus zero modes of the KK towers provide an effective MSSM
Localization and the Yukawa hierarchy

4D effective Yukawa couplings arise from 5D couplings upon compactification

\[
S_5 = \int d^5x \sqrt{-g} \ Y^{(5)}_{ij} \left[ \bar{\Psi}_{iL}(x^\mu, y) \Psi_{jR}(x^\mu, y) + h.c. \right] H(x^\mu) \delta(y)
\]

\[
\equiv \int d^4x \left[ y_{ij} \bar{\psi}_{iL}^{(0)}(x^\mu) \psi_{jR}^{(0)}(x^\mu) H(x^\mu) + h.c + \cdots \right]
\]

4D Yukawa couplings

\[
y_{ij} = Y^{(5)}_{ij} f_{UV}^{(0)}(c_L) f_{UV}^{(0)}(c_R)
\]

where \( c \) parameterizes the 5D fermion bulk mass

\[
m_\psi = c k
\]
SUSY breaking

We assume SUSY is broken on the IR brane, which we parametrize using the spurion field \( X = \theta \theta F_X \)

- Typical soft mass scale is \( F/\Lambda_{\text{IR}} \), where \( F = F_X e^{-2\pi kR} \)
- Gravitino LSP: \( m_{3/2} \sim F/M_P \)
- Spurion coupling to sfermions depends on localization:

\[
S_5 \supset \int d^5x \sqrt{-g} \int d^4\theta \frac{X^\dagger X}{\Lambda_{\text{UV}}^2 k} \phi^\dagger \phi \delta(y - \pi R)
\]

such that the sfermions acquire **flavor-dependent** masses

\[
m_{\phi L,R}^{\text{tree}} \simeq \begin{cases} 
(\pm c - \frac{1}{2})^{1/2} \frac{F}{\Lambda_{\text{IR}}} e^{(\frac{1}{2} \mp c)\pi kR} & \pm c > \frac{1}{2} \text{ (UV-localized)} \\
(\frac{1}{2} \mp c)^{1/2} \frac{F}{\Lambda_{\text{IR}}} & \pm c < \frac{1}{2} \text{ (IR-localized)}
\end{cases}
\]

- Tree-level mass for UV-localized sfermions (\( \pm c > 1/2 \)) is exponentially suppressed, so radiative corrections become dominant
UV-localized sfermion masses can be hierarchically suppressed below IR-localized sfermion masses
SUSY breaking: gauginos

- If $X$ is a **singlet**, it couples to the gauginos as:

$$S_5 = \int d^5x \sqrt{-g} \int d^2\theta \left[ \frac{1}{2} \frac{X}{\Lambda_{UV} k} W^{\alpha a} W_{\alpha}^a + h.c. \right] \delta (y - \pi R)$$

such that the gauginos acquire mass $M_\lambda \simeq g^2 \frac{F}{\Lambda_{IR}}$

- If the SUSY-breaking sector contains **no singlets** with large $F$-terms, it couples to the gauginos as:

$$S_5 = \int d^5x \sqrt{-g} \int d^2\theta \left[ \frac{1}{2} \frac{X^\dagger X}{\Lambda_{UV}^3 k} W^{\alpha a} W_{\alpha}^a + h.c. \right] \delta (y - \pi R)$$

such that the gauginos acquire mass $M_\lambda \simeq g^2 \frac{F^2}{\Lambda_{IR}^3}$
Spectrum cartoon

KK states

- $\tilde{e}, \tilde{u}, \tilde{d}$
- $\tilde{b}, \tilde{t}, H, \tilde{\tau}$
- $h, W, Z$

$m$ [GeV]
Parameter space A: singlet spurion

- BBN: $\tau_{\text{NLSP}} \lesssim 0.1 \text{ s}$
- collider limits: $m_{\tilde{g}}, m_{\tilde{t}_1} \gtrsim 1 \text{ TeV}$
- FCNCs: $m_{\tilde{\phi}_{1,2}} \gtrsim 100 \text{ TeV}$
- gauge unification: $|\mu| \lesssim 100 \text{ TeV}$
- Higgs mass: $m_{\tilde{Q}_3}, m_{\tilde{u}_3} \lesssim 100 \text{ TeV}$
- structure formation: $m_{3/2} \gtrsim 1 \text{ keV}$
Parameter space B: nonsinglet spurion

- Collider limits: $m_{\tilde{g}}, m_{\tilde{t}_1} \gtrsim 1$ TeV
- FCNCs: $m_{\tilde{\phi}_{1,2}} \gtrsim 100$ TeV
- Gauge unification: $|\mu| \lesssim 100$ TeV
- Higgs mass: $m_{\tilde{Q}_3}, m_{\tilde{u}_3} \lesssim 100$ TeV
- Structure formation: $m_{3/2} \gtrsim 1$ keV
Benchmark points

|                | A                  | B                  |
|----------------|--------------------|--------------------|
| $\Lambda_{IR}$ | $2 \times 10^{16}$ GeV | $6.5 \times 10^{6}$ GeV |
| $\sqrt{F}$    | $4.75 \times 10^{10}$ GeV | $2 \times 10^{6}$ GeV |
| $\tan \beta$  | $\sim 3$           | $\sim 5$           |
| sign $\mu$    | $-1$               | $-1$               |
| $Y^{(5)}k$    | 1                  | 1                  |
| spurion       | singlet            | nonsinglet         |
| $M_1(\Lambda_{IR})$ | 52.9 TeV           | 14.60 TeV          |
| $M_2(\Lambda_{IR})$ | 50.7 TeV           | 22.9 TeV           |
| $M_3(\Lambda_{IR})$ | 49.85 TeV          | 38.94 TeV          |
| $m_{3/2}$     | 535 GeV            | 1 keV              |

- For each point randomly sample over allowed sfermion localizations
- Pole mass spectrum: MSSM renormalization
- Higgs mass: EFT calculation
- Select points consistent with observed value $m_h = 125.18 \pm 0.16$ GeV and with all first- and second-generation sfermion masses above 100 TeV
Pole mass spectrum

**hatched:** singlet spurion  
**solid:** nonsinglet spurion
Conclusions

**Partially composite supersymmetry**

- Partial compositeness (localization) can explain SM fermion mass hierarchy

- In a supersymmetric model, this predicts split sfermion spectrum with inverted Yukawa ordering
  - 125 GeV Higgs mass
  - suppression of FCNCs

- Light gravitino dark matter
  - additional cosmological constraints (work in progress)

- Heavy first- and second-generation sfermions can be indirectly probed by flavor-violation experiments such as Mu2e (work in progress)

- Distinctive stau or neutralino NLSP decays may be within reach of a future collider

- Dual 4D and 5D descriptions
Localization and the Yukawa hierarchy

\[(y_e)_{ij} = Y_{ij}^{(5)} f_{UV}^{(0)}(c_{L_i}) f_{UV}^{(0)}(c_{e_j})\]

\[(y_u)_{ij} = Y_{ij}^{(5)} f_{UV}^{(0)}(c_{Q_i}) f_{UV}^{(0)}(c_{u_j})\]

\[(y_d)_{ij} = Y_{ij}^{(5)} f_{UV}^{(0)}(c_{Q_i}) f_{UV}^{(0)}(c_{d_j})\]
The Higgs sector is protected from SUSY breaking at tree-level, but finite radiative corrections involving the bulk gauginos and sfermions induce soft terms at the 1-loop level.
In the MSSM, the tree-level scalar potential has a minimum breaking electroweak symmetry if the following two equations are satisfied:

\begin{align*}
    m^2_{H_u} + |\mu|^2 &- b \cot \beta - \frac{1}{8}(g_1^2 + g_2^2)v^2 \cos 2\beta = 0 \\
    m^2_{H_d} + |\mu|^2 &- b \tan \beta + \frac{1}{8}(g_1^2 + g_2^2)v^2 \cos 2\beta = 0
\end{align*}

In our model, $m^2_{H_u}$, $m^2_{H_d}$, and $b$ are radiatively generated at the IR-brane scale.

EWSB determines two parameters:

\begin{align*}
    \tan \beta &\approx \frac{(m^2_{H_d} - m^2_{H_u}) + \sqrt{(m^2_{H_d} - m^2_{H_u})^2 + 4b^2}}{2b} + \mathcal{O}\left(\frac{v^2}{b}\right) \\
    |\mu|^2 &\approx \frac{m^2_{H_d} - m^2_{H_u} \tan^2 \beta}{\tan^2 \beta - 1} + \mathcal{O}(v^2)
\end{align*}

Solution only for sign $\mu = -1$; also prefers $m^2_{H_u} < 0$.
Gauge-eigenstate mass spectrum

- Hatched: singlet spurion
- Solid: nonsinglet spurion

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