Partially composite supersymmetry

Andrew S. Miller

School of Physics and Astronomy
University of Minnesota

Work in collaboration with Yusuf Buyukdag and Tony Gherghetta
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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

Partial compositeness

- For each SM fermion introduce an elementary chiral superfield Φ and supersymmetric composite operator $\mathcal{O}$ with linear mixing:

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

  where δ is the anamalous dimension of $\mathcal{O}$

- Massless eigenstate is partially composite:

$$|\Phi_0\rangle \simeq \mathcal{N}_\Phi \left\{ |\Phi\rangle - \frac{1}{g_\Phi^{(1)} \sqrt{\zeta_\Phi}} \sqrt{\frac{\delta - 1}{\left(\frac{\Lambda_{\rm IR}}{\Lambda_{\rm UV}}\right)^{2(1-\delta)} - 1}} \, |\Phi^{(1)}\rangle \right\} .$$

  - $\delta \geq 1$: mostly elementary
  - $0 \leq \delta < 1$: elementary-composite admixture

Fermion and sfermion spectra

- Elementary Higgs couples to elementary chiral fermions:

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

- Anamalous dimension of the chiral superfields chosen to explain fermion mass hierarchy
- Composite sector breaks supersymmetry (spurion $\mathcal{X}$):

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

- Inverted sfermion spectrum

Gravitational dual theory

Slice of AdS_5

We take a five-dimensional (5D) spacetime (x^μ, y) with AdS_5 (warped) metric

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

compactified $(-\pi R \le y \le \pi R)$ on a $S^1/\mathbb{Z}_2$ 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

- Anamolous dimension of operators in 4D CFT is dual to localization of fields in AdS_5:

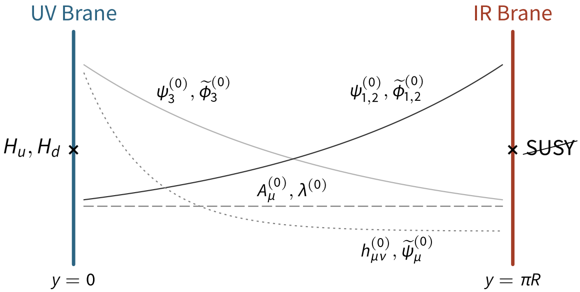
$$\delta = |c + \tfrac{1}{2}|$$

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

$$\frac{\Lambda_{\mathrm{IR}}}{\Lambda_{\mathrm{UV}}} = e^{-\pi k R}$$

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



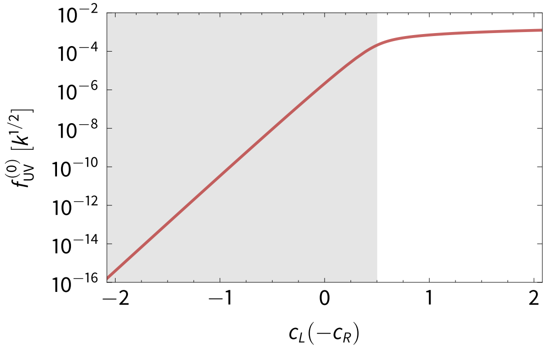
- Higgs plus zero modes of the KK towers provide an effective MSSM

Localization and the Yukawa hierarchy

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

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

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



4D Yukawa couplings

$$y_{ij} = Y^{(5)}_{ij} f^{(0)}_{\mathrm{UV}}(c_L)\, f^{(0)}_{\mathrm{UV}}(c_R)$$

where c parameterizes the 5D fermion bulk mass

$$m_\Psi = ck$$

SUSY breaking

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

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

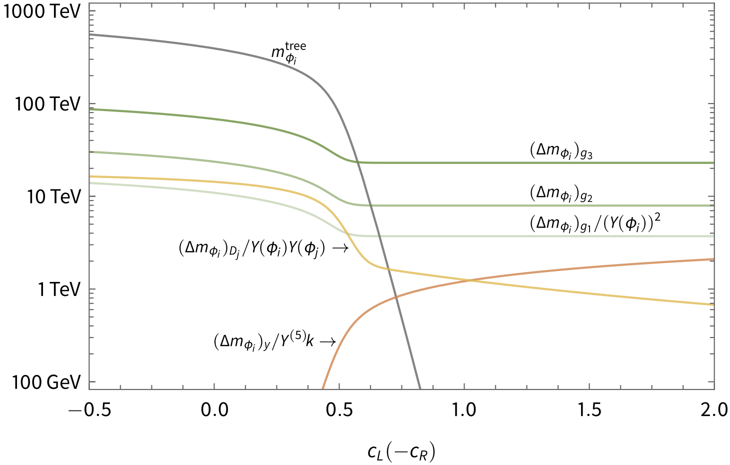
$$S_5 \supset \int d^5x \sqrt{-g} \int d^4\theta \, \frac{X^\dagger X}{\Lambda_{\rm UV}^2 k} \Phi^\dagger \Phi \, \delta(y - \pi R)$$

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

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

- Tree-level mass for UV-localized sfermions ($\pm c > 1/2$) is exponentially suppressed, so radiative corrections become dominant

SUSY breaking: sfermions



- 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:

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

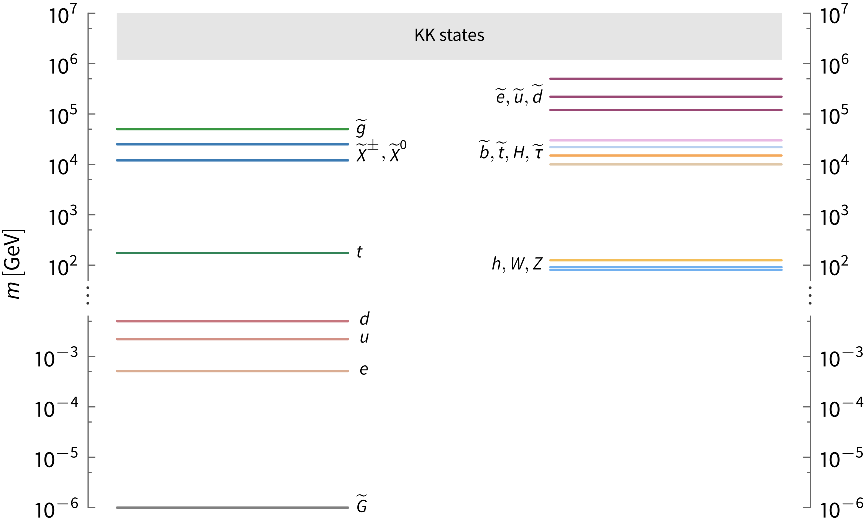
such that the gauginos acquire mass $M_\lambda \simeq g^2\dfrac{F}{\Lambda_{\rm IR}}$

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

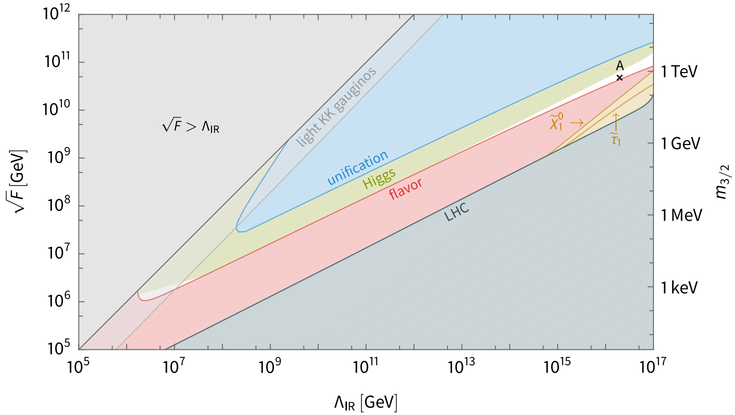
$$S_5 = \int d^5x\,\sqrt{-g}\int d^2\theta\,\left[\frac{1}{2}\frac{X^\dagger X}{\Lambda^3_{\rm UV}k}W^{\alpha a}W^a_\alpha + h.c.\right]\delta(y-\pi R)$$

such that the gauginos acquire mass $M_\lambda \simeq g^2\dfrac{F^2}{\Lambda^3_{\rm IR}}$

Spectrum cartoon

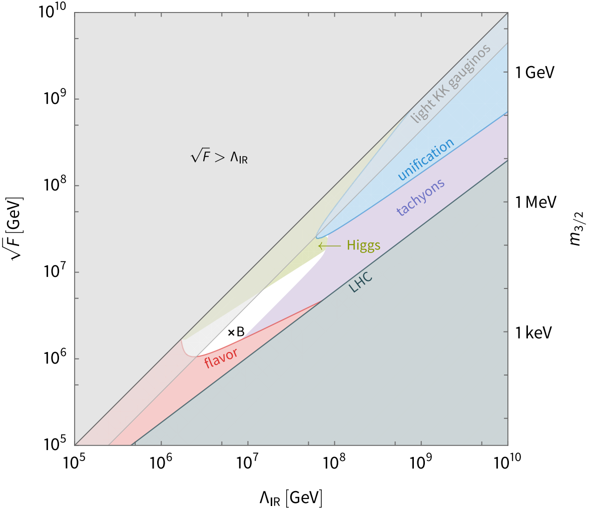


Parameter space A: singlet spurion



- BBN: $\tau_{NLSP} \lesssim 0.1$ s
- 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

Parameter space B: nonsinglet spurion



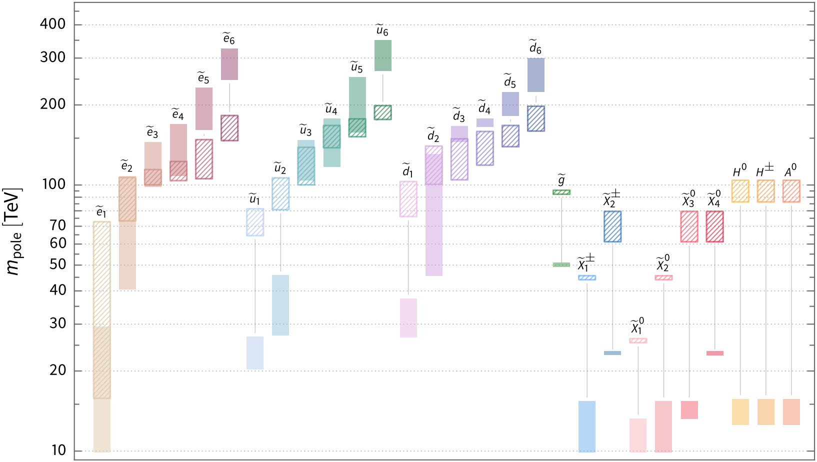
- collider limits: $m_{\tilde{g}}, m_{\tilde{t}_1} \gtrsim 1$ TeV
- FCNCs: $m_{\tilde{\phi}_{1,2}} \gtrsim 100$ TeV
- gauge unification: $|\mu| \lesssim 100$ TeV
- Higgs mass: $m_{\tilde{Q}_3}, m_{\tilde{u}_3} \lesssim 100$ TeV
- structure formation: $m_{3/2} \gtrsim 1$ keV

Benchmark points

	A	B
Λ_{IR}	2×10^{16} GeV	6.5×10^{6} GeV
$\sqrt{F}$	4.75×10^{10} GeV	2×10^{6} GeV
$\tan\beta$	~ 3	~ 5
sign μ	-1	-1
$Y^{(5)}k$	1	1
spurion	singlet	nonsinglet
$M_1(\Lambda_{\text{IR}})$	52.9 TeV	14.60 TeV
$M_2(\Lambda_{\text{IR}})$	50.7 TeV	22.9 TeV
$M_3(\Lambda_{\text{IR}})$	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



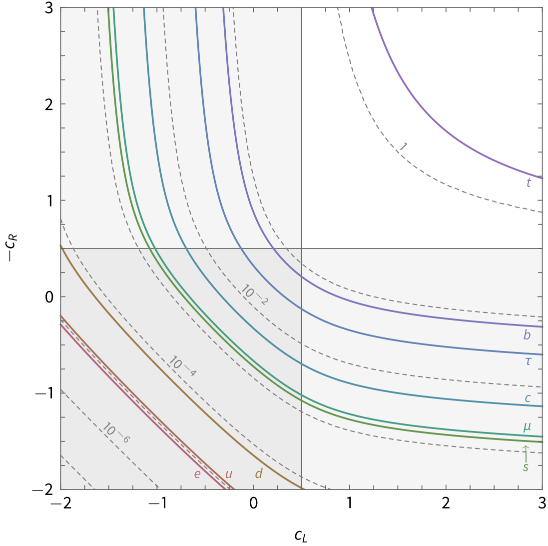
hatched: singlet suprion **solid:** nonsinglet spurion

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

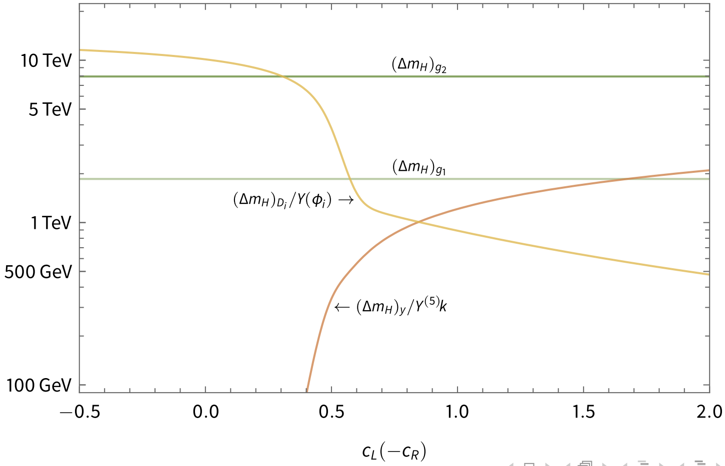
Localization and the Yukawa hierarchy



$$(y_e)_{ij} = Y^{(5)}_{ij}\, f^{(0)}_{\rm UV}(c_{L_i})\, f^{(0)}_{\rm UV}(c_{e_j})$$
$$(y_u)_{ij} = Y^{(5)}_{ij}\, f^{(0)}_{\rm UV}(c_{Q_i})\, f^{(0)}_{\rm UV}(c_{u_j})$$
$$(y_d)_{ij} = Y^{(5)}_{ij}\, f^{(0)}_{\rm UV}(c_{Q_i})\, f^{(0)}_{\rm UV}(c_{d_j})$$

SUSY breaking: Higgs sector

- 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



EWSB

- In the MSSM, the tree-level scalar potential has a minimum breaking electroweak symmetry if the following two equations are satisfied:

$$m_{H_u}^2 + |\mu|^2 - b\cot\beta - \frac{1}{8}(g_1^2 + g_2^2)v^2\cos 2\beta = 0$$

$$m_{H_d}^2 + |\mu|^2 - b\tan\beta + \frac{1}{8}(g_1^2 + g_2^2)v^2\cos 2\beta = 0$$

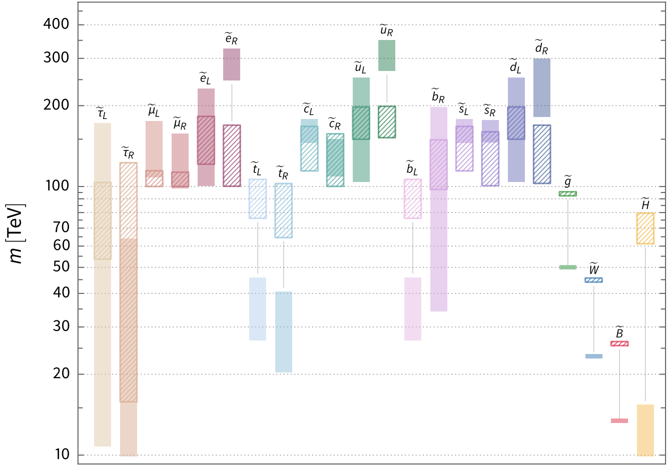
- In our model, $m_{H_u}^2$, $m_{H_d}^2$, and b are radiatively generated at the IR-brane scale
- EWSB determines two parameters:

$$\tan\beta \simeq \frac{(m_{H_d}^2 - m_{H_u}^2) + \sqrt{(m_{H_d}^2 - m_{H_u}^2)^2 + 4b^2}}{2b} + \mathcal{O}\left(\frac{v^2}{b}\right)$$

$$|\mu|^2 \simeq \frac{m_{H_d}^2 - m_{H_u}^2\tan^2\beta}{\tan^2\beta - 1} + \mathcal{O}(v^2)$$

- Solution only for $\operatorname{sign}\mu = -1$; also prefers $m_{H_u}^2 < 0$

Gauge-eigenstate mass spectrum



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