Split-Supersymmetry in AdS_5

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Motivation

- Supersymmetry has numerous attractive theoretical features
  - solution to hierarchy problem
  - dark matter candidate
  - gauge unification
- 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

Motivation

- Warped compact extra dimension provides a natural way to explain hierarchies
  - Localization in AdS_5 can explain the SM Yukawa coupling hierarchy
  - In a supersymmetric model, this localization pattern gives rise to an inverted split sfermion spectrum

Slice of AdS_5

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

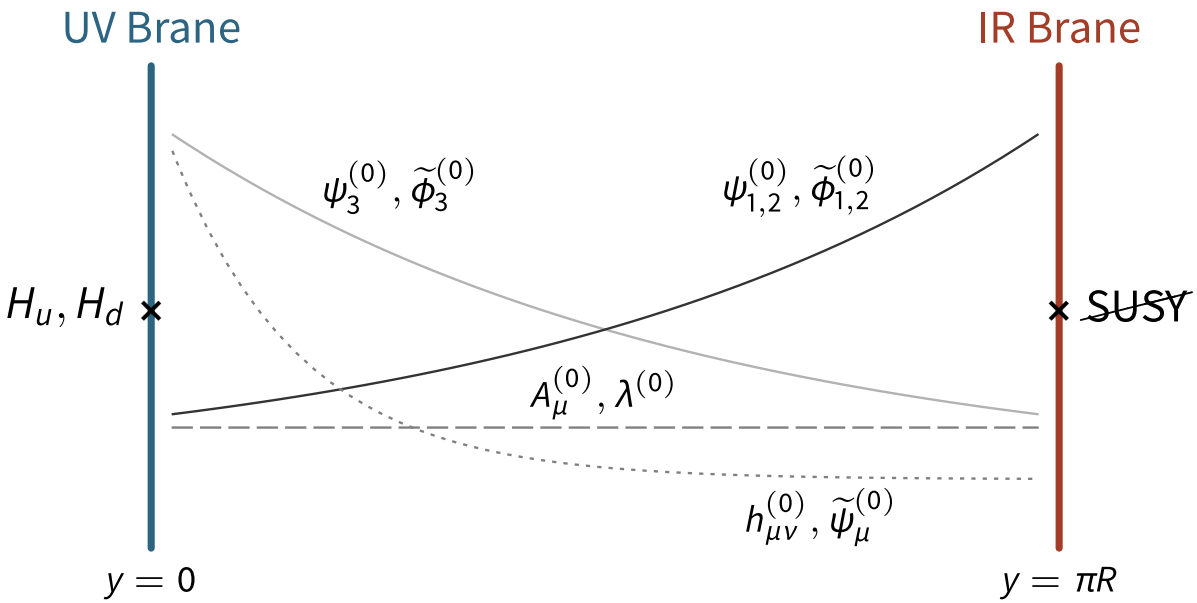
$$ds^2 = e^{-2k|y|}\eta_{\mu\nu}\, dx^\mu\, dx^\nu + dy^2$$

compactified $(-\pi R \leq y \leq \pi R)$ 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)

Extra-dimensional 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



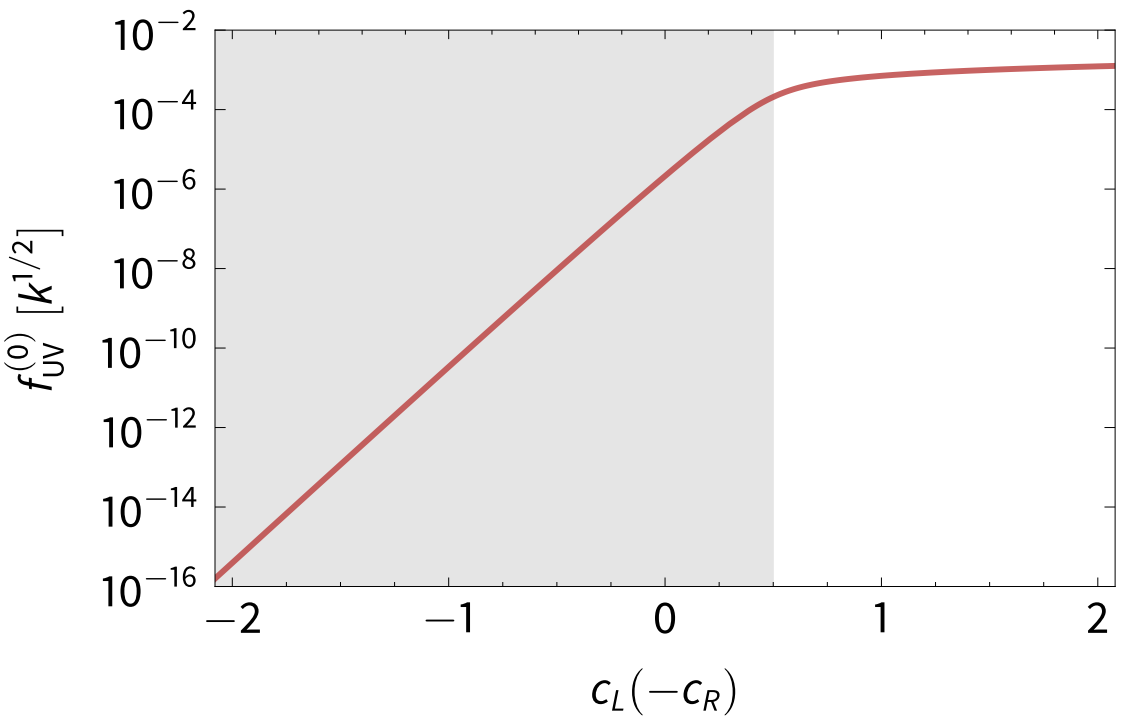
- Higgs plus zero modes of the KK towers provide an effective MSSM

Localization and the Yukawa hierarchy

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

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

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

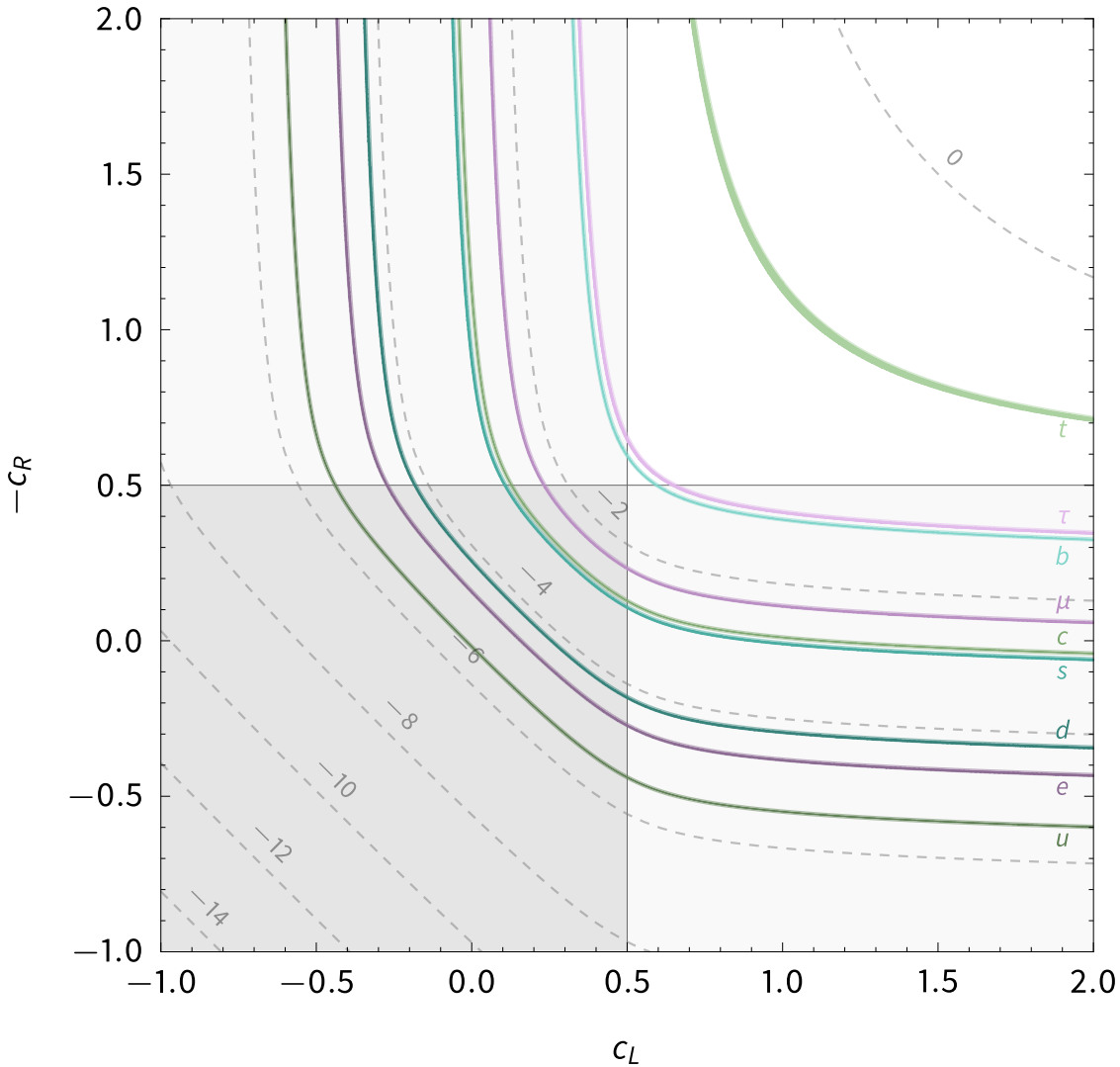


4D Yukawa couplings

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

where c parameterizes the 5D fermion bulk mass $m_\Psi = ck$

Localization and the Yukawa hierarchy



$$(y_e)_{ij} = Y^{(5)}_{ij} f^{(0)}_{\mathrm{UV}}(c_{L_i}) f^{(0)}_{\mathrm{UV}}(c_{e_j})$$

$$(y_u)_{ij} = Y^{(5)}_{ij} f^{(0)}_{\mathrm{UV}}(c_{Q_i}) f^{(0)}_{\mathrm{UV}}(c_{u_j})$$

$$(y_d)_{ij} = Y^{(5)}_{ij} f^{(0)}_{\mathrm{UV}}(c_{Q_i}) f^{(0)}_{\mathrm{UV}}(c_{d_j})$$

SUSY breaking

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

- The typical resulting soft mass scale is $F/\Lambda_{\rm IR}$, where $F = F_X e^{-2\pi kR}$

Super-Higgs effect

- Through the super-Higgs effect, the gravitino acquires mass

$$m_{3/2} = \frac{1}{\sqrt{3}} \frac{F}{M_P}$$

  that is highly suppressed compared to the typical soft mass scale.
- Gravitino is the LSP: natural dark matter candidate

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 $M_\lambda \simeq g^2 \dfrac{F^2}{\Lambda^3_{\rm IR}}$

SUSY breaking: sfermions

- The spurion coupling to sfermions depends on localization:

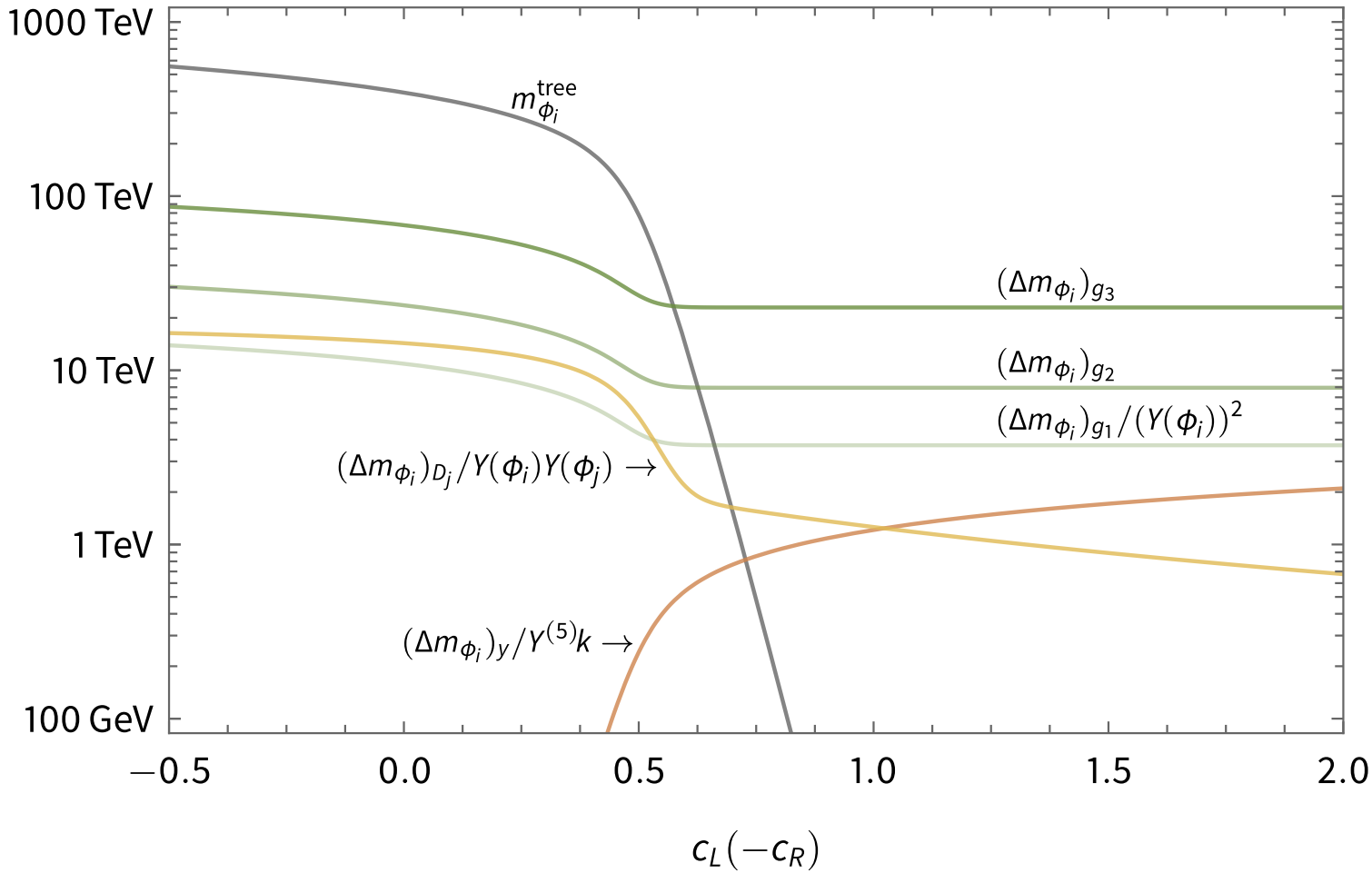
$$S_5 \supset \int d^5x \sqrt{-g} \int d^4\theta \, \frac{X^\dagger X}{\Lambda_{\rm UV}^2 k} \Phi^\dagger \Phi \, \delta(y - \pi R)$$

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

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

- Tree-level mass for UV-localized sfermions ($\pm c > 1/2$) is exponentially suppressed, so radiative corrections become dominant
- We calculate 1-loop threshold corrections to sfermion soft masses-squared at the IR-brane scale from gaugino and sfermion fields in the AdS_5 bulk

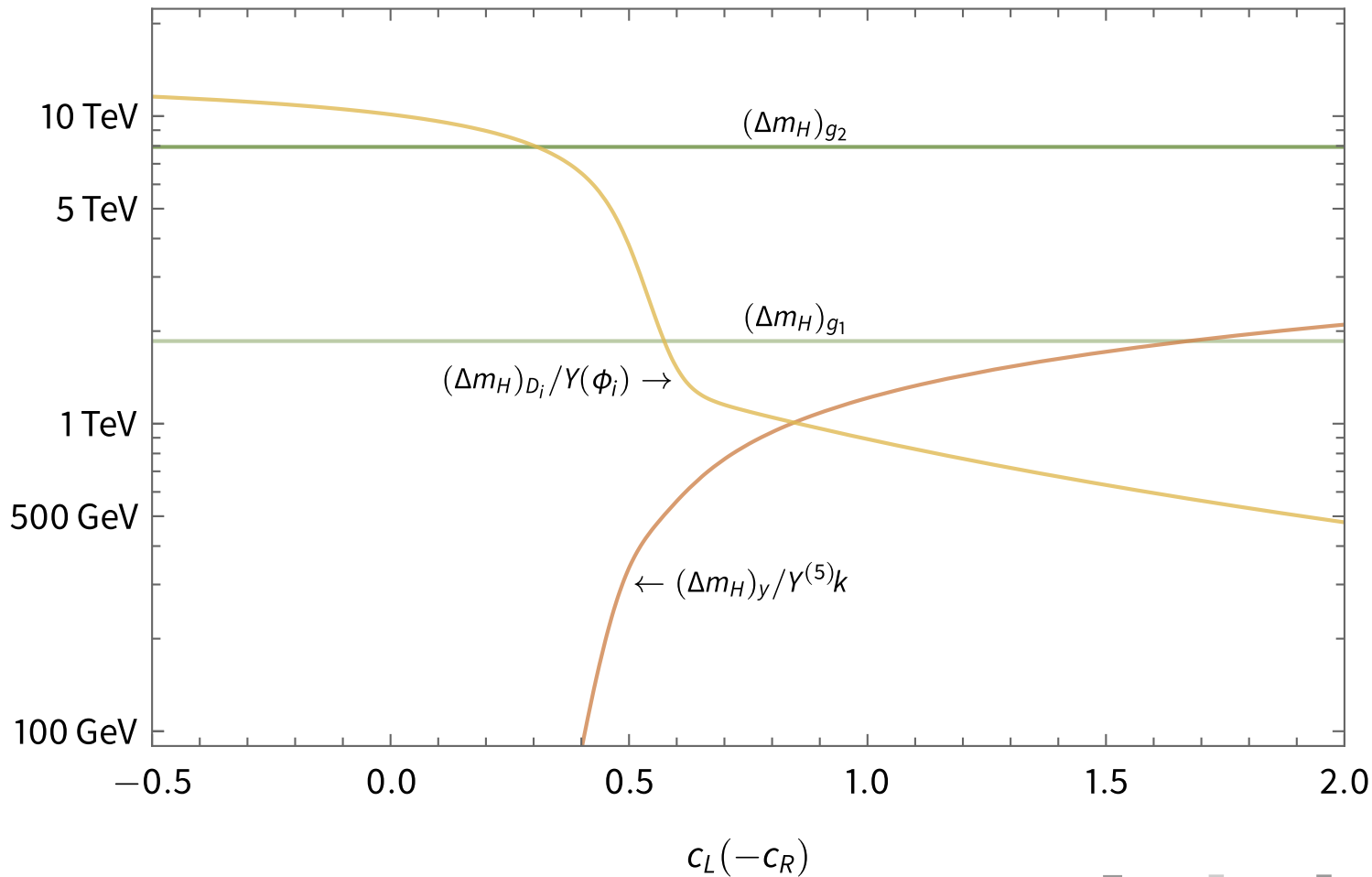
SUSY breaking: sfermions



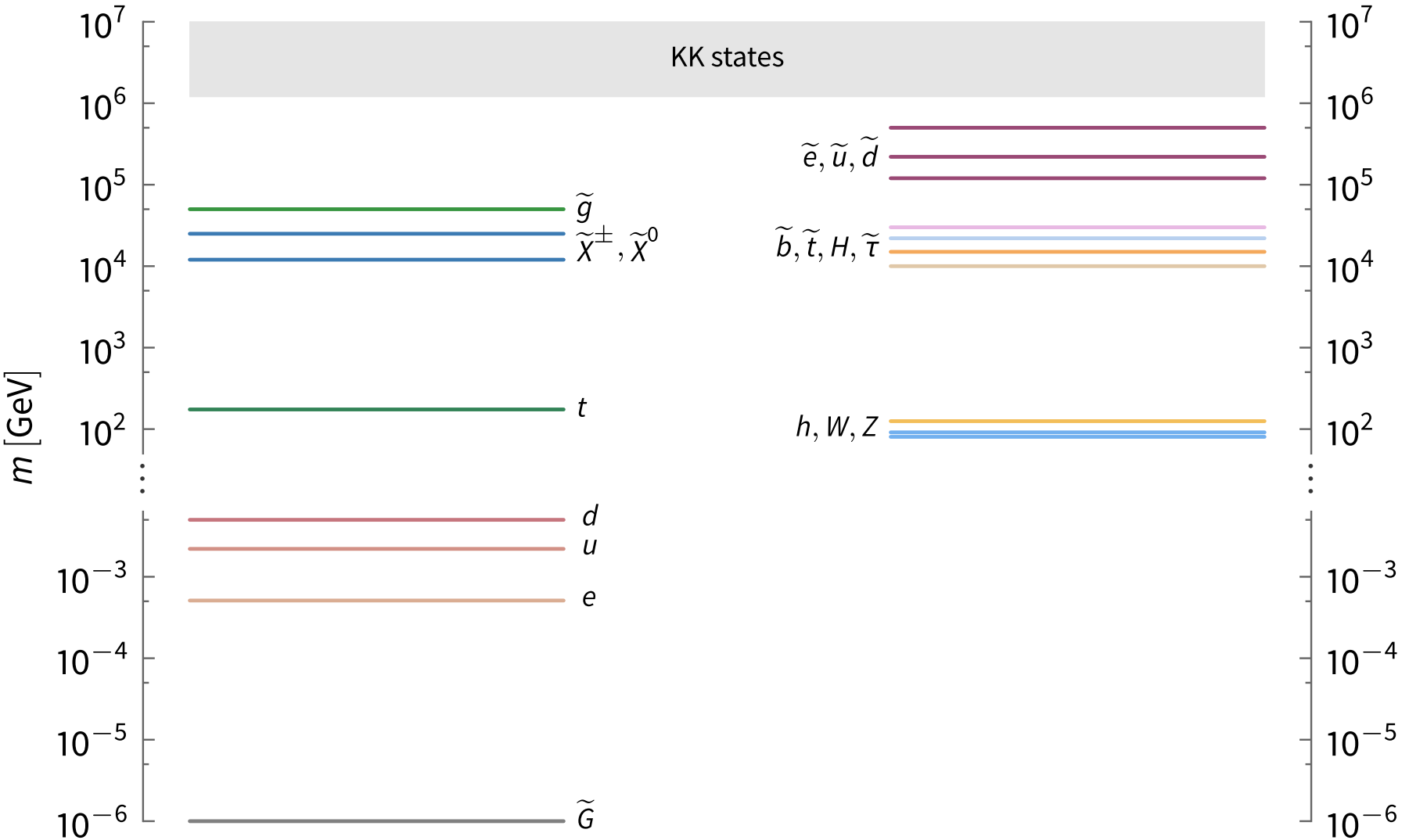
- UV-localized sfermion masses can be hierarchically suppressed below IR-localized sfermion masses

SUSY breaking: Higgs sector

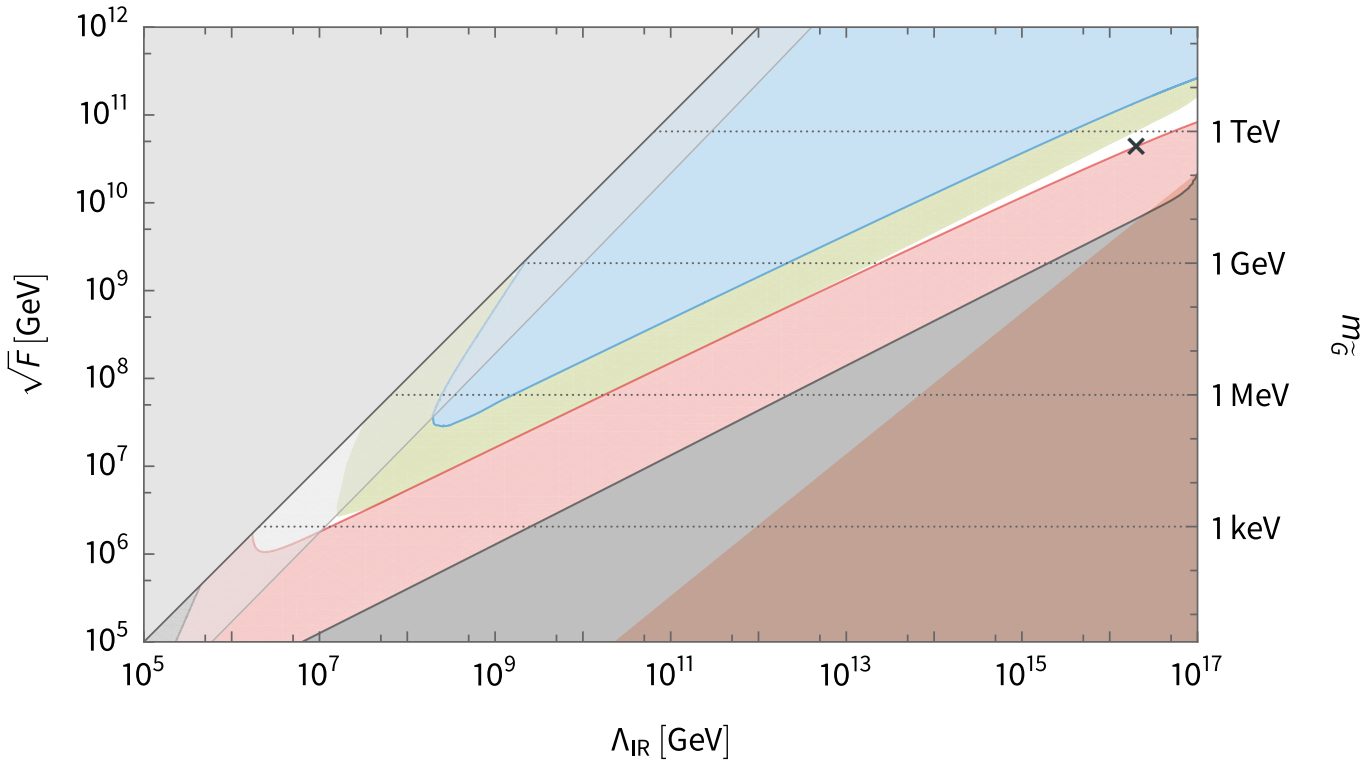
- The Higgs sector is protected from SUSY breaking at tree-level, but finite radiative corrections involving the bulk gauginos and sfermions induce soft terms at the 1-loop level



Spectrum cartoon

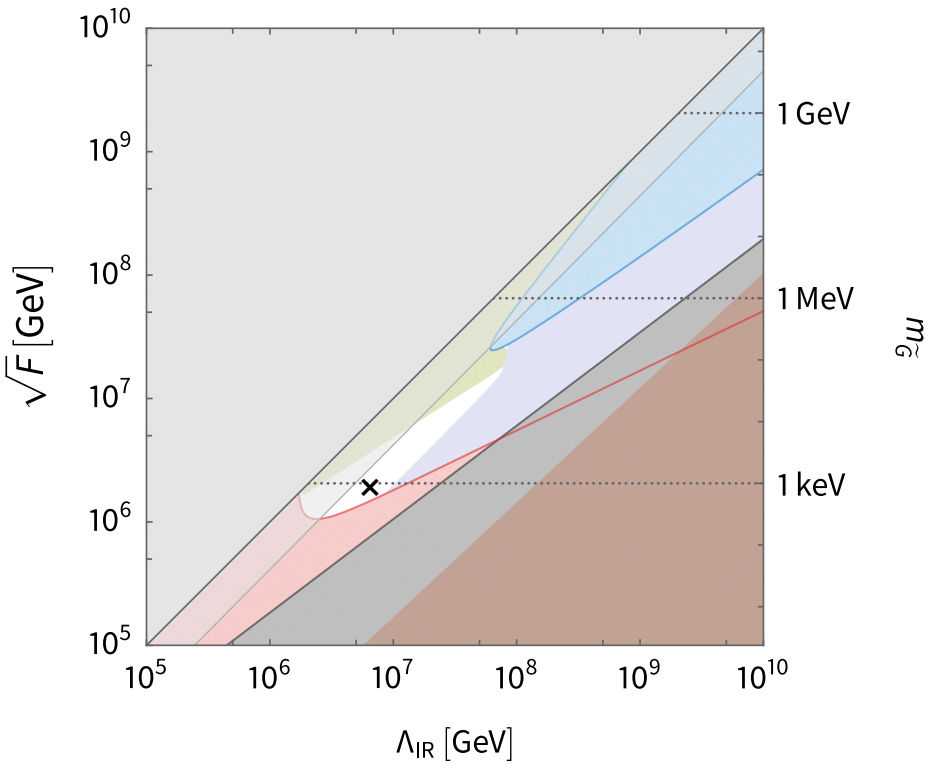


Parameter space (a): heavy gauginos



- DM: $m_{3/2} \gtrsim 1\,\text{keV}$
- BBN: $\tau_{\chi_1^0} \lesssim 0.1\,\text{s}$
- 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: $m_{\tilde{Q}_3}, m_{\tilde{u}_3} \lesssim 100\,\text{TeV}$

Parameter space (a): light gauginos



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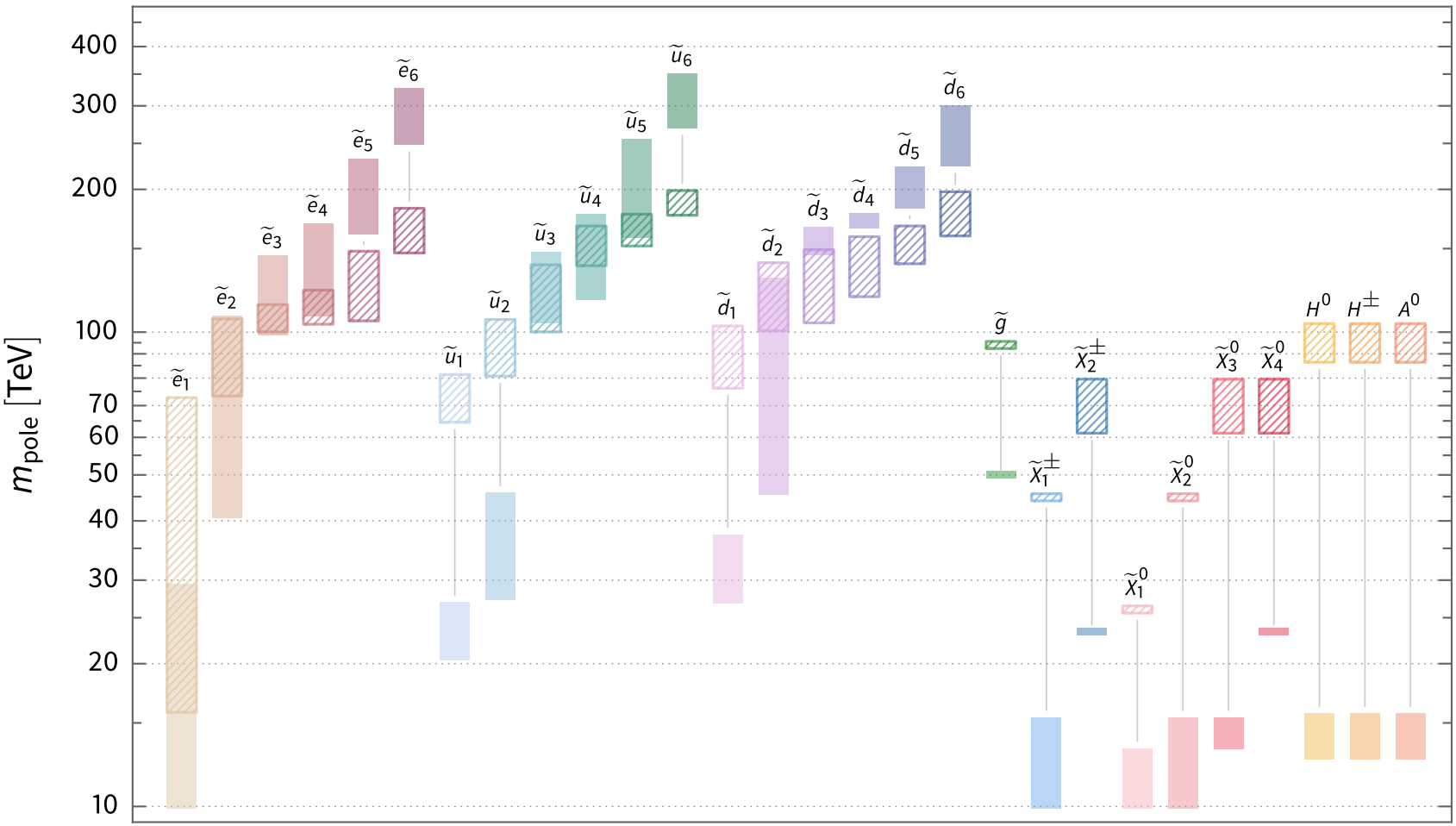
- tachyonic sfermions

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
$M_1(\Lambda_{\text{IR}})$	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 we randomly sample over allowed sfermion localizations
- Pole mass spectrum: MSSM renormalization
- Higgs mass: EFT calculation
- Select points and consistent with observed value $m_h = 125.18 \pm 0.16$ GeV and with all first- and second-generation sfermion masses above 100 TeV

Sparticle pole mas spectrum



hatched: heavy gauginos **solid:** light gauginos

Conclusions

Split-supersymmetry in AdS_5

- 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 to a partially composite 4D field theory

EWSB

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

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

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

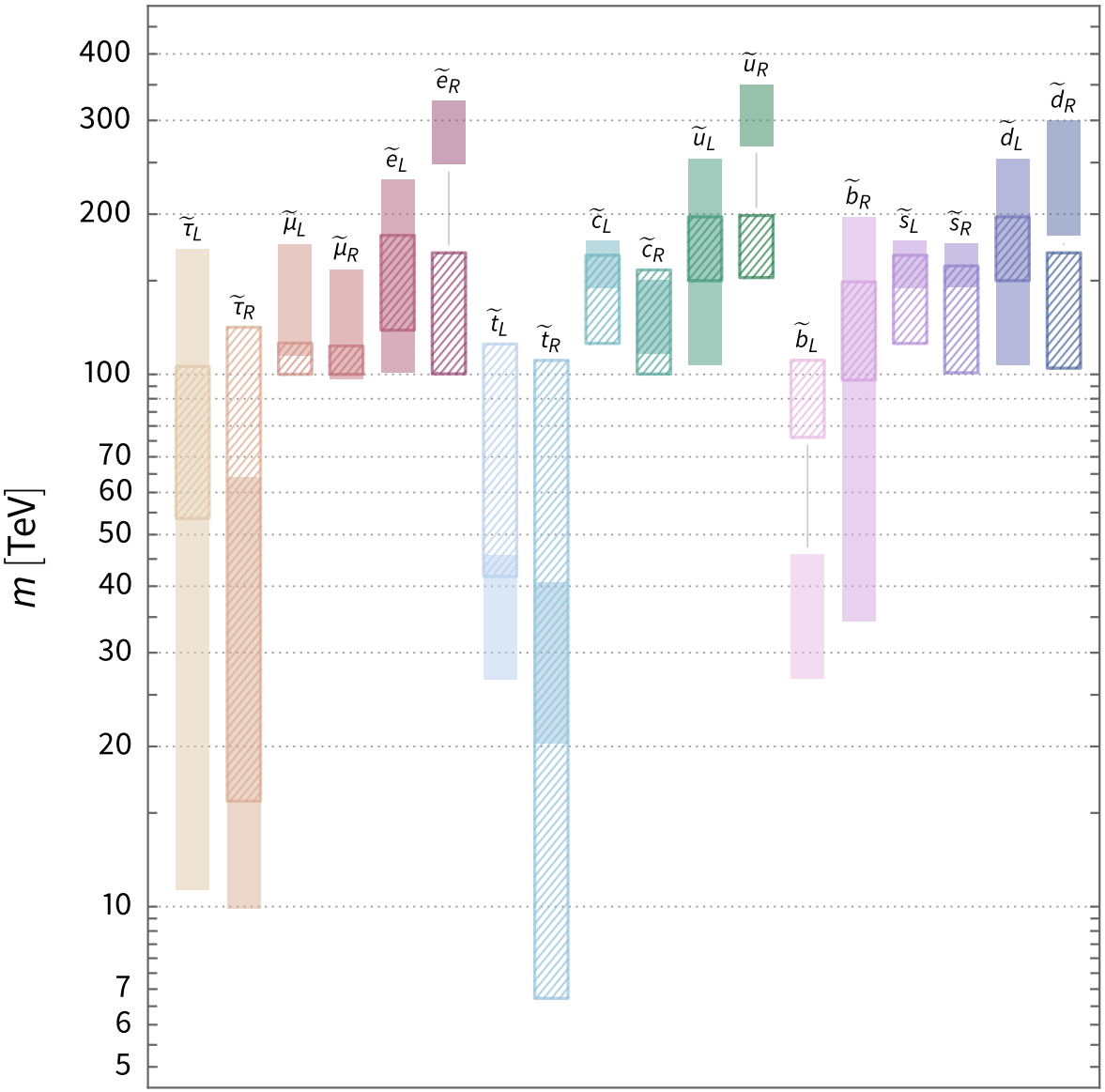
- In our model, $m_{H_u}^2$, $m_{H_d}^2$, and b are radiatively generated at the IR-brane scale
- EWSB determines two parameters:

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

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

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

Sfermion gauge-eigenstate mass spectrum



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