

Generating a Little Hierarchy from Accidental SUSY

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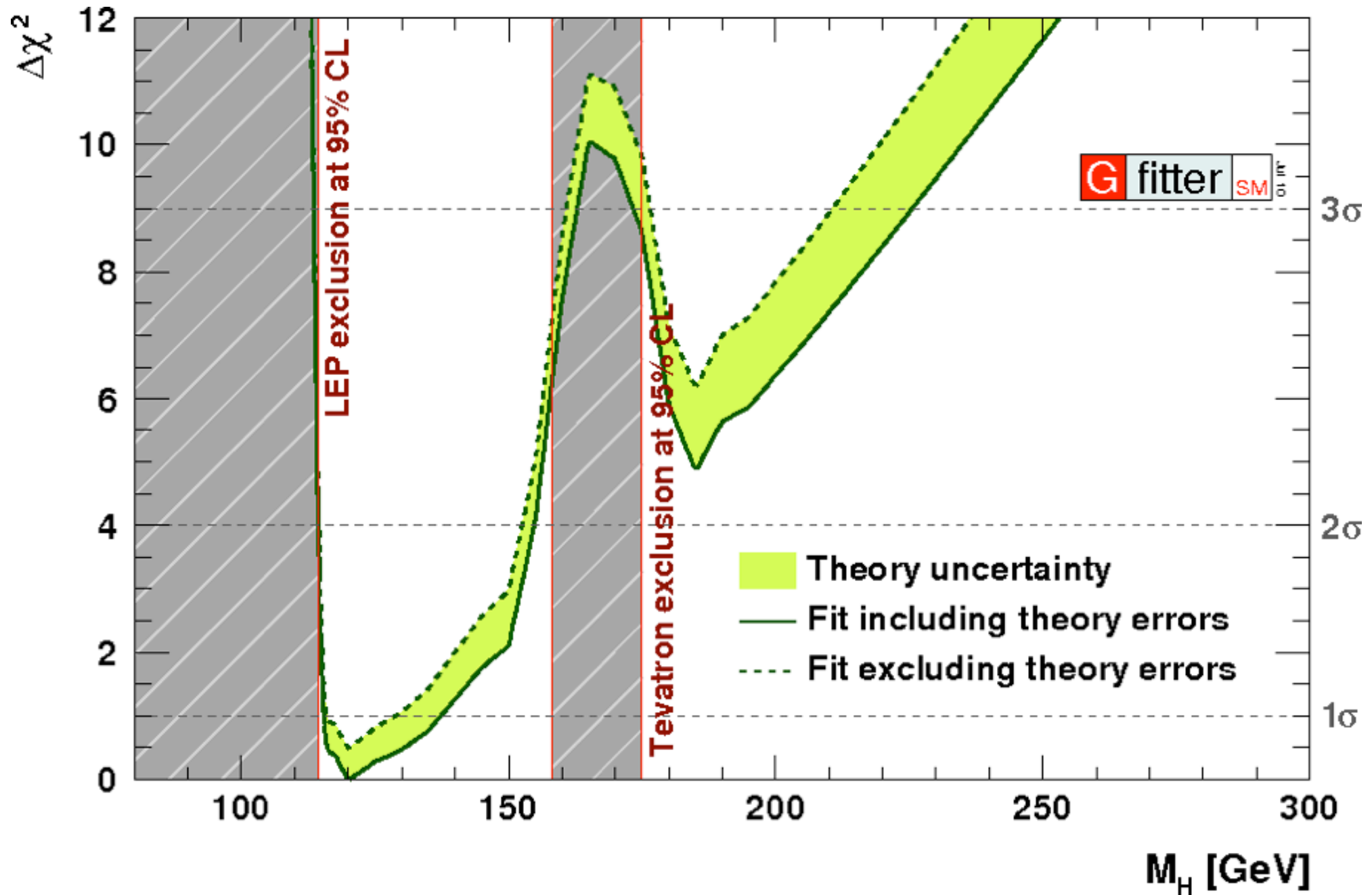
University of California, Davis Seminar, May 23, 2011

with Benedict von Harling and Nick Setzer
[arXiv:1104.3171]

Outline

- Introduction and Motivation
- Partial and Accidental SUSY
- 5D Gravity Model and Particle Spectrum
- Conclusion

What is the Higgs boson mass?



Hierarchy Problem

HIGGS MASS

$$114 \text{ GeV} \lesssim m_H \lesssim 200 \text{ GeV}$$

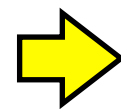
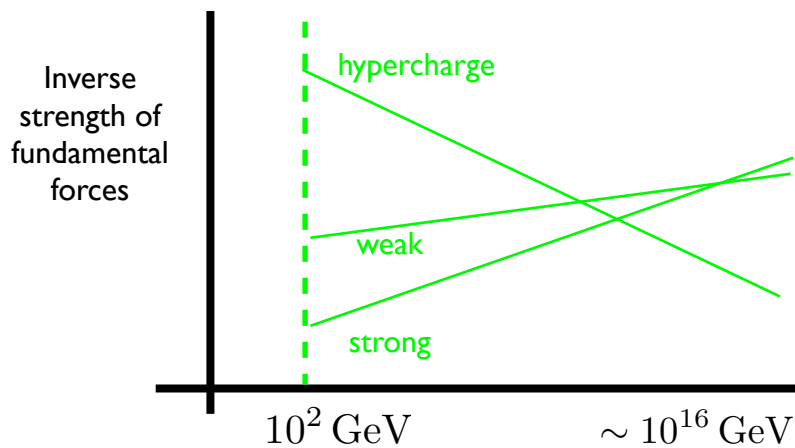
Standard Model prediction:



$$m_H^2 = -m_0^2 + \frac{3h_t^2}{16\pi^2} \Lambda^2$$

Quadratic dependence on cutoff scale, Λ

What is the value of the cutoff scale Λ ?



$$\Lambda \simeq 10^{16} \text{ GeV}$$

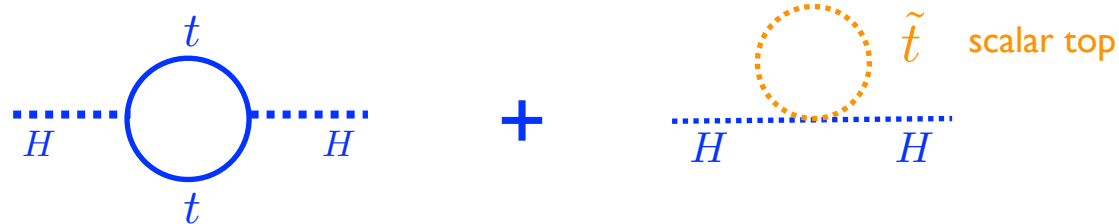
$$\longrightarrow m_H^2 \gg (100 \text{ GeV})^2 \quad !!$$

Why is $m_H \ll \Lambda \sim 10^{16} \text{ GeV}$?

HIERARCHY PROBLEM

Natural Solutions of Hierarchy Problem

Idea #1: Supersymmetry



→
$$m_H^2 = -m_0^2 + \cancel{\frac{3h_t^2}{16\pi^2}\Lambda^2} - \cancel{\frac{3h_{\tilde{t}}^2}{16\pi^2}\Lambda^2} + \frac{6h_t^2}{16\pi^2}(m_t^2 - m_{\tilde{t}}^2) \log \frac{\Lambda}{m_{\tilde{t}}}$$

Thus, $m_H \ll \Lambda$ provided $m_{\tilde{t}} \lesssim \mathcal{O}(\text{TeV})$

BUT

- Supersymmetric flavor problem

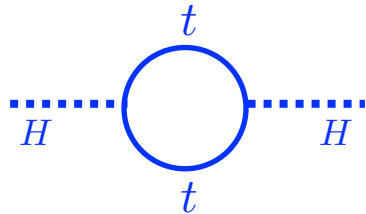
e.g. K-K mixing: $\frac{\delta \tilde{m}_{ds}^2}{(10 \text{ TeV})^2} \lesssim 10^{-2} \frac{(F/M)^3}{(10 \text{ TeV})^3}$ or $\tilde{m}_{1,2} \gtrsim 1000 \text{ TeV}$

- Higgs mass $m_H \lesssim 130 \text{ GeV}$

LITTLE HIERARCHY PROBLEM



Idea #2: Strong dynamics



$$m_H^2 = -m_0^2 + \frac{3h_t^2}{16\pi^2}\Lambda^2$$

If $\Lambda \simeq \text{TeV}$  mass correction $\simeq 100 \text{ GeV}$ ✓ O.K.

BUT

- Flavor and CP problem

$$\frac{1}{\Lambda_F^2} \Psi_i \Psi_j \Psi_k \Psi_l$$

$$\Lambda_F \gtrsim 2 - 30 \text{ TeV}$$

- Higgs mass Why is $m_H \ll \Lambda$?

LITTLE HIERARCHY PROBLEM

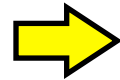


Either supersymmetry or strong dynamics have
little hierarchy problems...

 **Combine both ideas to solve big and
little hierarchy problems!**

(Big) Hierarchy Problem:

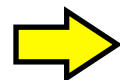
Strong dynamics



$$m_H \propto \Lambda_{strong} \ll M_P$$

Little Hierarchy Problem:

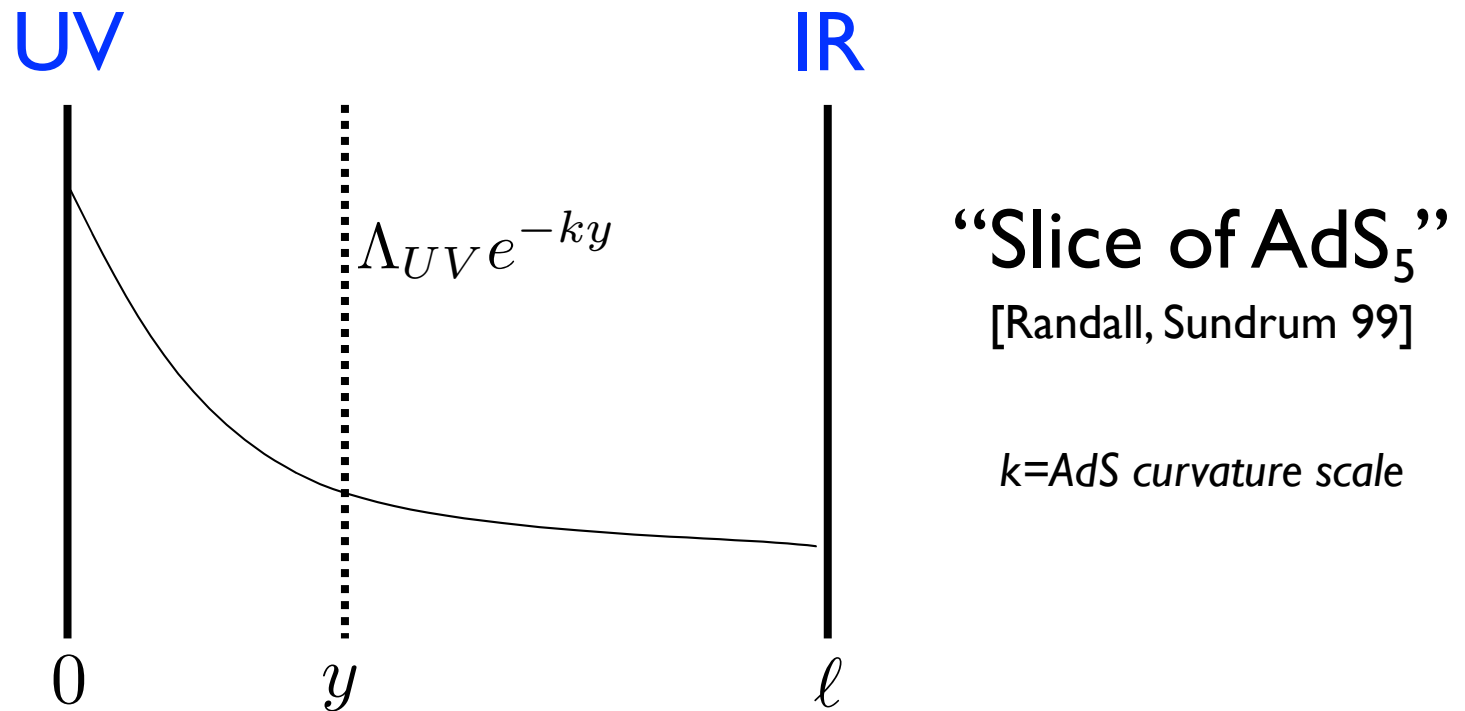
Supersymmetry



$$m_H \ll \Lambda_{strong}$$

Natural framework:

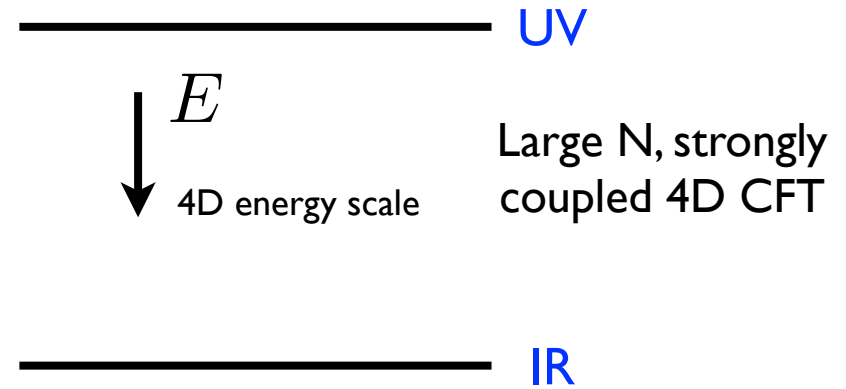
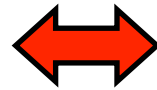
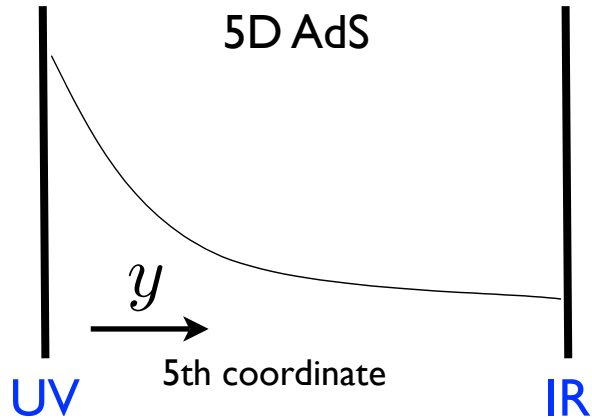
Warped Extra Dimension \rightarrow Explain hierarchies



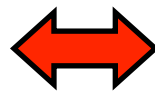
5D metric : $ds^2 = e^{-2ky} dx^2 + dy^2$

AdS/CFT dictionary

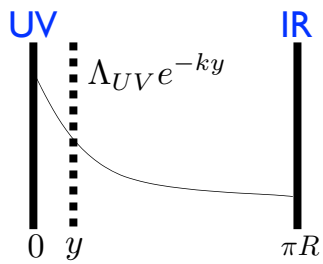
[Arkani-Hamed, Randall, Porrati 00; Rattazzi, Zaffaroni 00]



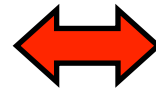
“Slice of AdS”



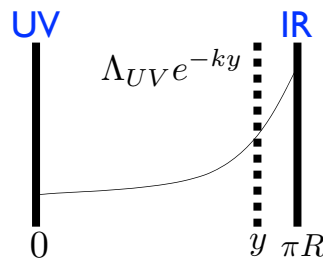
CFT + Dynamical elementary “source”



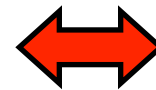
UV localized field



elementary “source” state

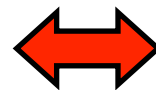
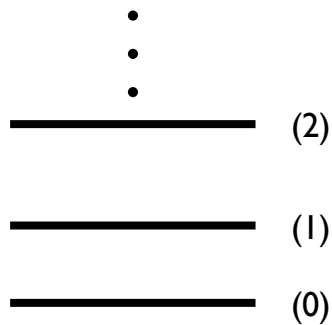


IR localized field



CFT bound state

Kaluza-Klein tower



Tower of resonances

[e.g. large N QCD: Witten 79]

$$\sum_{n=0}^{\infty} \frac{d_n^2}{p^2 + m_n^2}$$

Plan

Build strongly-coupled 4D model using 5D warped model

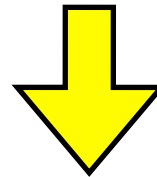
SUSY broken
at UV scale

weakly-coupled
e.g. “Split SUSY”

SUSY-breaking
irrelevant operators

SUSY emerges
at IR scale

strongly-coupled
“accidental SUSY”



5D gravity
dual

SUSY broken
on UV brane

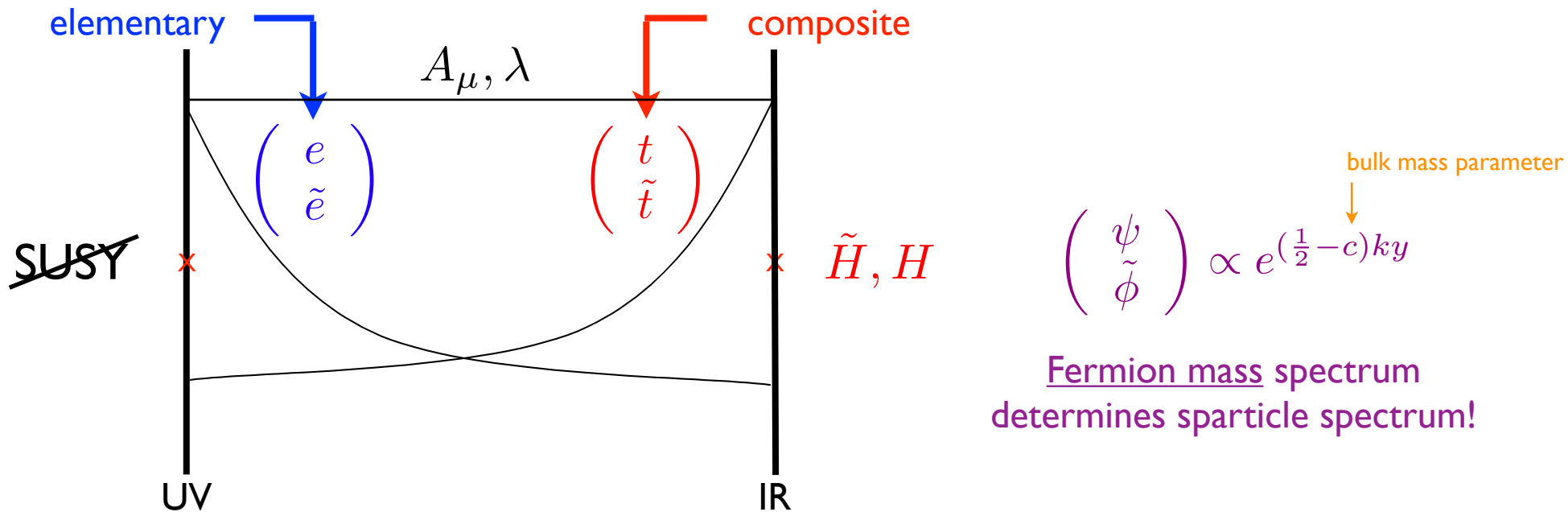
transmit SUSY-
breaking via bulk

SUSY IR brane

Partial SUSY

[TG, Pomarol, hep-ph/0302001]

SUSY broken at UV scale



Low-energy SUSY spectrum

\tilde{t}, \tilde{H}

$(\tilde{f}_{1,2}, \lambda \text{ decouple})$

KK spectrum

$m_f^{(n)} \simeq m_{\tilde{f}}^{(n)}$

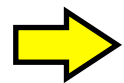
$n = 1, 2, \dots$

BUT:

- Potentially large D-term contributions to soft masses $\mathcal{L} \supset m_0^2 D$
- No light gaugino $\Rightarrow \Delta m_H^2 \sim \frac{g^2}{16\pi^2} \Lambda_{IR}^2 \rightarrow$ Limit to increasing Λ_{IR}

Sundrum: arXiv:0909.5430 [hep-th]

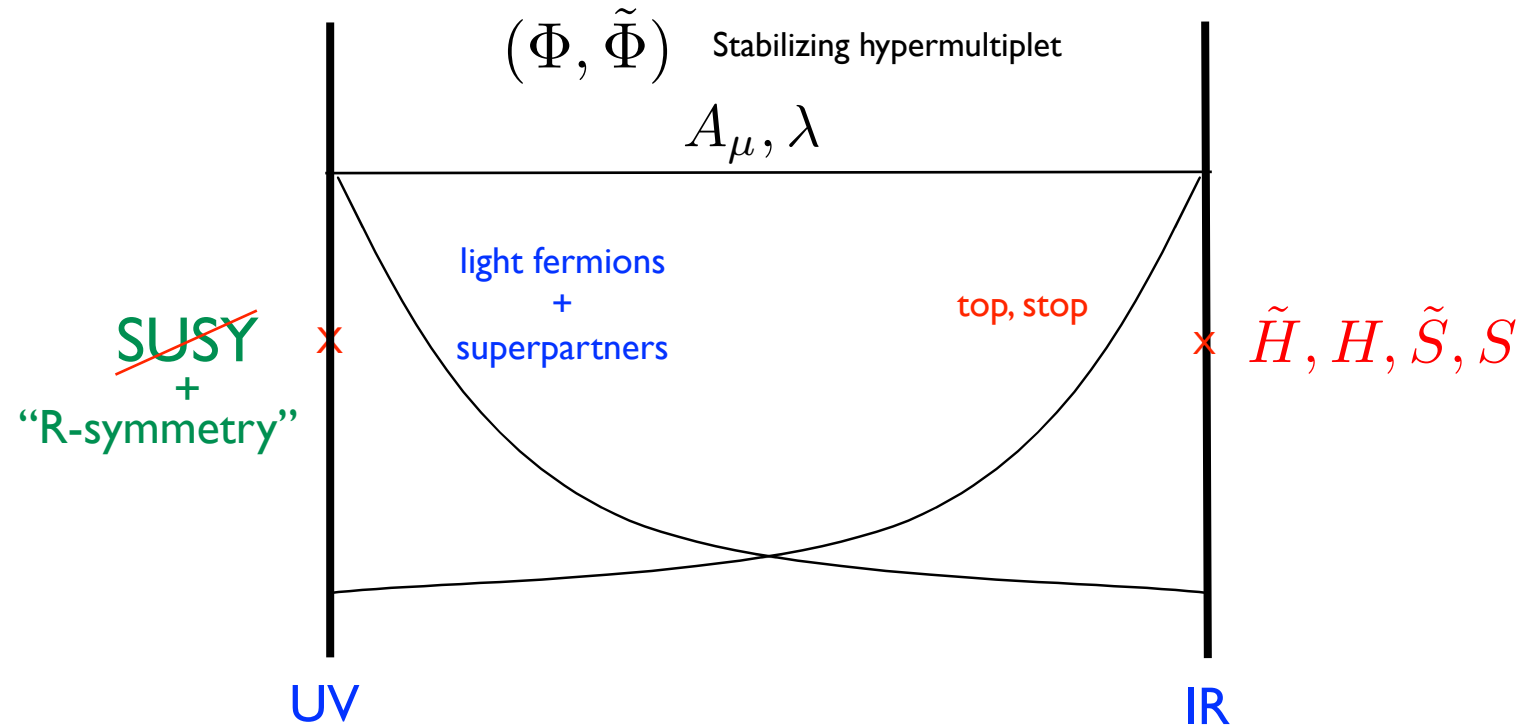
- Embed SM gauge group in Pati-Salam to avoid linear D-term
- Keep gaugino light with R-symmetry $\Delta m_H^2 \sim \frac{\Delta g^2}{16\pi^2} \Lambda_{IR}^2$



Implement in 5D model

5D Model

[TG, von Harling, Setzer arXiv:1104.3171]



FEATURES

- Stabilizing bulk hypermultiplet $(\Phi, \tilde{\Phi})$
- Approximate R-symmetry
- Extended Higgs sector (S, \tilde{S})

Stabilization mechanism

[Goh, Luty, Ng: arXiv:hep-th/0309103]

SUSY-breaking potential ($V = -\theta^4 U$)

$$\mathcal{L}_5 \supset \int d^4\theta \left[e^{-2k|y|} \left(\Phi^\dagger \Phi + \tilde{\Phi}^\dagger \tilde{\Phi} \right) + \delta(y) \overbrace{V(\Phi, F)} \right] \\ + \left[\int d^2\theta e^{-3k|y|} \tilde{\Phi} \left(\partial_y + \left(c' - \frac{3}{2} \right) k\epsilon(y) \right) \Phi + \text{h.c.} \right]$$

UV brane SUSY-breaking potential:

$$U(\Phi, F) = \left(e^{i\varphi_U} \frac{M_{\text{SUSY}}^2}{\sqrt{k}} F + \text{h.c.} \right) + \frac{M_{\text{SUSY}}^2}{k} |\Phi|^2$$



$$V_4 \supset \frac{1}{2} \frac{\Delta - 3}{1 - \omega^{2\Delta - 6}} M_{\text{SUSY}}^4 + \text{h.c.}$$

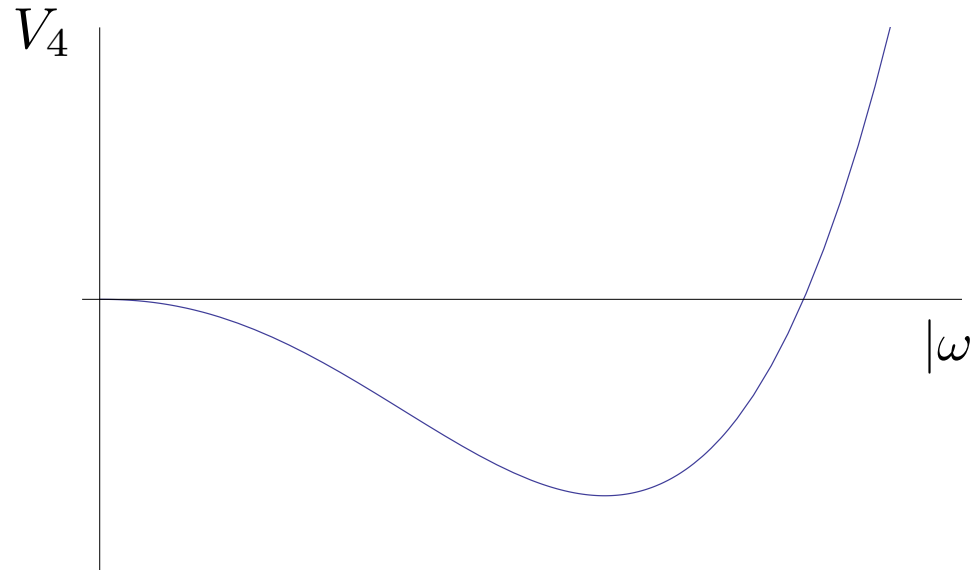
$\Delta =$ Dimension of operator dual to Φ
 $\omega =$ radion

Add UV and IR constant superpotential:

$$V_4 \supset 3 \frac{C_{\text{IR}}^6}{M_4^2} |\omega|^4 - 3 \frac{C_{\text{UV}}^6}{M_4^2}$$

$C_{UV}(C_{IR}) =$ constant UV(IR) superpotential

4D potential:
$$V_4 \supset 3 \frac{C_{IR}^6}{M_4^2} |\omega|^4 - (\Delta - 3) M_{SUSY}^4 |\omega|^{2\Delta - 6} + \dots$$



Minimum at:

$$e^{-k\ell} = |\omega| \simeq \left[\frac{\Delta - 3}{\sqrt{6}} \frac{M_{SUSY}^2 M_4}{C_{IR}^3} \right]^{\frac{1}{5-\Delta}} \quad \Rightarrow \quad \text{Determines IR scale} \\ (m_{IR} \equiv k e^{-k\ell})$$

e.g. $\Delta = 4.1 \quad M_{SUSY} \approx 10^{11} \text{ GeV} \rightarrow m_{IR} \approx 10 \text{ TeV}$

Sparticle mass spectrum

UV-localized matter:

$$\mathcal{L}_5 \supset \delta(y) \int d^4\theta \frac{\Phi^\dagger \Phi}{k^2 M_X^2} Q^\dagger Q$$

➔ $m_{\tilde{q}}^{\text{UV}} \sim \frac{|F_{\text{UV}}|}{\sqrt{k} M_X} \sqrt{\frac{\frac{1}{2} - c}{e^{2k\ell(\frac{1}{2}-c)} - 1}} \sim \frac{M_{\text{SUSY}}^2}{M_X} \gtrsim \mathcal{O}(1000 \text{ TeV}) \quad (c > \frac{1}{2})$

IR-localized matter:

$$\mathcal{L}_4 \supset \int d^4\theta \omega^\dagger \omega \frac{[\Phi^\dagger \Phi]_{\text{IR}}}{M_5^3} \left(Q^\dagger Q + H_u^\dagger H_u + H_d^\dagger H_d + \overbrace{S^\dagger S}^{\text{Higgs singlet term}} \right)$$

➔ $m_{\text{soft}}^{\text{IR}} = \frac{|F_{\text{IR}}|}{M_5^{3/2}} \sim \frac{M_{\text{SUSY}}^2}{M_4} |\omega|^{\Delta-4} \sim \underbrace{\left(\frac{C_{\text{IR}}}{M_5} \right)^3}_{\sim 1/3} m_{\text{IR}} \sim \mathcal{O}(\text{TeV})$

Gaugino mass:

An accidental R-symmetry forbids $\Phi W^\alpha W_\alpha$. Instead:

$$\mathcal{L}_5 \supset \delta(y) \int d^4\theta \frac{\Phi^\dagger \Phi}{k^2 M_X^3} W^\alpha W_\alpha + \text{h.c.}$$

$$\Rightarrow m_{\tilde{g}}^{UV} \sim \frac{M_{\text{SUSY}}^4}{k\ell M_X^3} \ll m_{\tilde{q}}^{UV}$$

Also radion mediation:

$$F_T \neq 0 \quad \Rightarrow \quad m_{\tilde{g}}^T \sim \frac{m_{\text{soft}}^{\text{IR}}}{k\ell} \left[1 + \left(\frac{m_{\text{IR}}}{k} \right)^{4-\Delta} \right] \ll m_{\tilde{q}}^{UV}$$

Higgs sector:

Also: Barbieri, Hall, Nomura, Rychkov: arXiv:0607332
Gripaios, Redi: arXiv:1004.5114; Franceschini, Gori: arXiv:1005.1070

$$\mathcal{L}_5 \supset \cdot \delta(y - \ell) \left[\int d^2\theta \omega^3 \left(y_u H_u Q Q + y_d H_d Q Q + \lambda S H_u H_d + \frac{\kappa}{3} S^3 \right) + \text{h.c.} \right]$$

Composite Higgs sector $\Rightarrow m_H \lesssim 300 \text{ GeV}$
 $\lambda^2 \sim 4\pi$

Ameliorates SUSY little hierarchy problem

μ -term $\boxed{\mu = \lambda \langle S \rangle}$ For large λ and $\kappa < \lambda$ obtain

$$\frac{1}{\sqrt{2}} m_{h_1} \lesssim \mu \lesssim \frac{3}{2} m_{h_1} \Rightarrow \mu \ll \Lambda_{IR}$$


Solves μ -problem

Hard SUSY breaking effects

Heavy first and second family sfermions generate hard breaking:

$$\Delta m_{\text{scalar}}^2 \approx \frac{n^2 - 1}{6\pi^2 n \gamma_n} \frac{g_n^4}{16\pi^2} \left[\left(\frac{m_{\text{soft}}^{\text{UV}}}{\Lambda_{\text{IR}}} \right)^{\gamma_n} - 1 \right] \Lambda_{\text{IR}}^2$$

[Sundrum
arXiv:0909.5430]

 $\Delta m_{\tilde{t}}^2 \approx (1.5 \text{ TeV})^2 \quad \Delta m_{\text{H}}^2 \approx (350 \text{ GeV})^2$

$(g_2 = 0.6, \gamma_2 = 1/12; g_3 = 1, \gamma_3 = 1/4)$

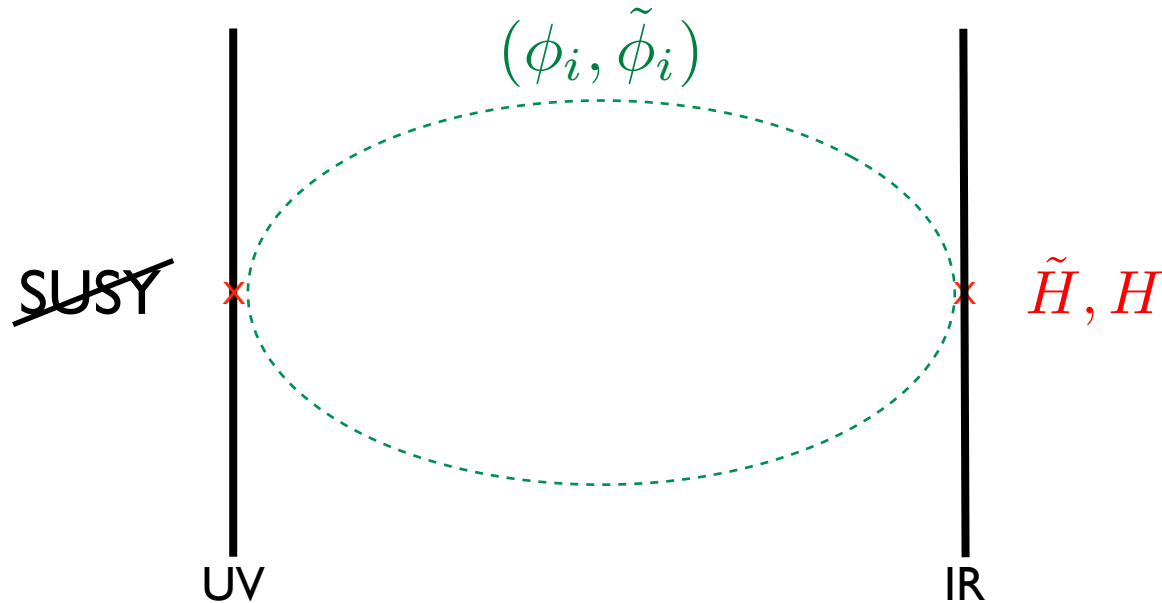
Total contribution:

$$m_{\tilde{t}}^2 = \Delta m_{\text{hard}}^2 + \Delta m_{\text{soft}}^2 \approx (600 \text{ GeV})^2$$

 **Tuning of Higgs mass is of order 20%**

AdS calculation

Consider bulk fermion \longrightarrow 2 bulk hypermultiplets with same c value $\Phi_i \propto e^{(\frac{1}{2}-c)ky}$



5D propagator:

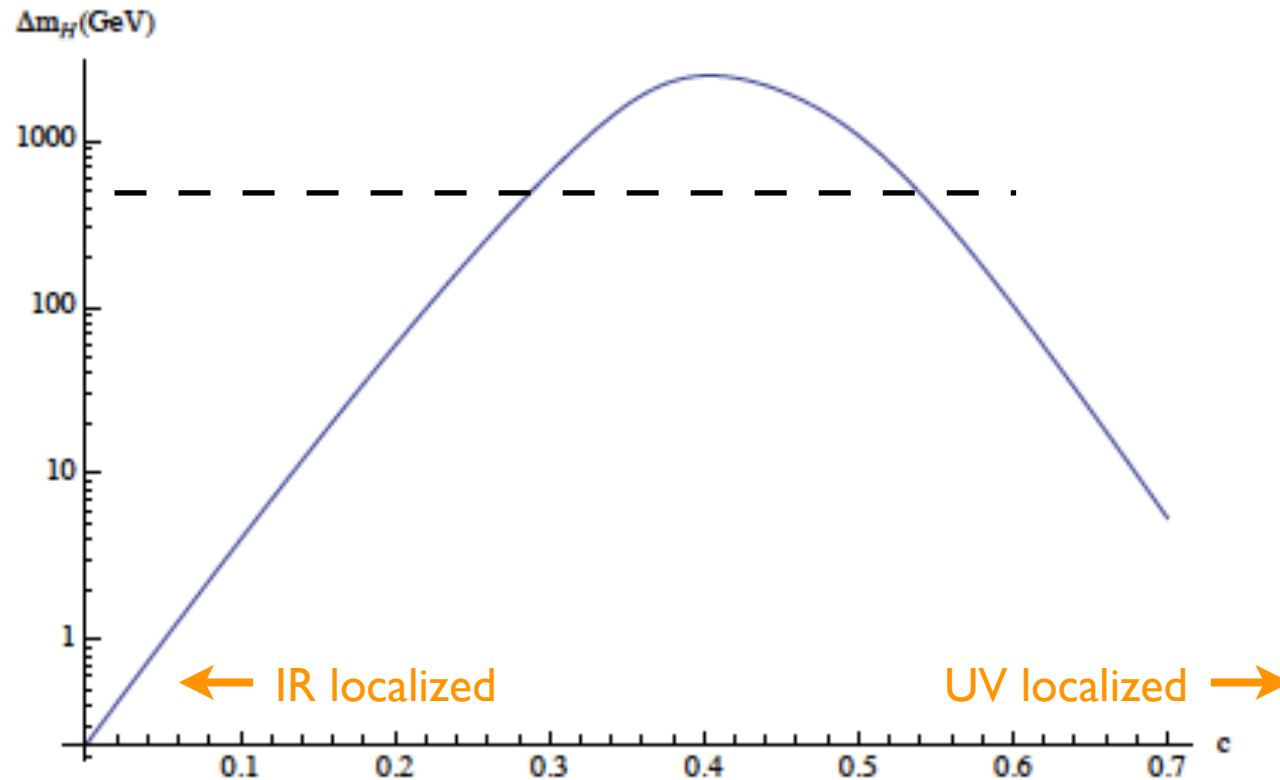
$$G_{F,B}(p) = -\frac{e^{2kl} \tilde{I}_{c+1/2}^{\text{UV}}\left(\frac{p}{k}\right) K_{c+1/2}\left(\frac{p}{m_{\text{IR}}}\right) - \tilde{K}_{c+1/2}^{\text{UV}}\left(\frac{p}{k}\right) I_{c+1/2}\left(\frac{p}{m_{\text{IR}}}\right)}{k \tilde{I}_{c+1/2}^{\text{IR}}\left(\frac{p}{m_{\text{IR}}}\right) \tilde{K}_{c+1/2}^{\text{UV}}\left(\frac{p}{k}\right) - \tilde{I}_{c+1/2}^{\text{UV}}\left(\frac{p}{k}\right) \tilde{K}_{c+1/2}^{\text{IR}}\left(\frac{p}{m_{\text{IR}}}\right)}$$

where $\tilde{I}_\alpha^i(x) \equiv x I_{\alpha-1}(x) - \delta^i I_\alpha(x)$ with $\delta^{\text{UV}} = (m_{\text{soft}}^{\text{UV}})^2 / 2k^2$

$$\Delta m_H^2 = \frac{3y_{5D}^2}{4\pi^2} \int dp p^5 [G_F^2(p) - G_B^2(p)]$$

Bulk hypermultiplet correction to Higgs mass

$$(m_{IR} = 10 \text{ TeV}, m_{soft}^{UV} = 1000 \text{ TeV})$$



At most 20% tuning if exclude $0.3 \lesssim c \lesssim 0.53$
($m_h \simeq 250 \text{ GeV}$)

Gravitational sector:

Cancel energy density to obtain zero 4d cosmological constant:

$$C_{\text{UV}}^3 \simeq \sqrt{\frac{\Delta - 3}{3}} M_4 M_{\text{SUSY}}^2$$

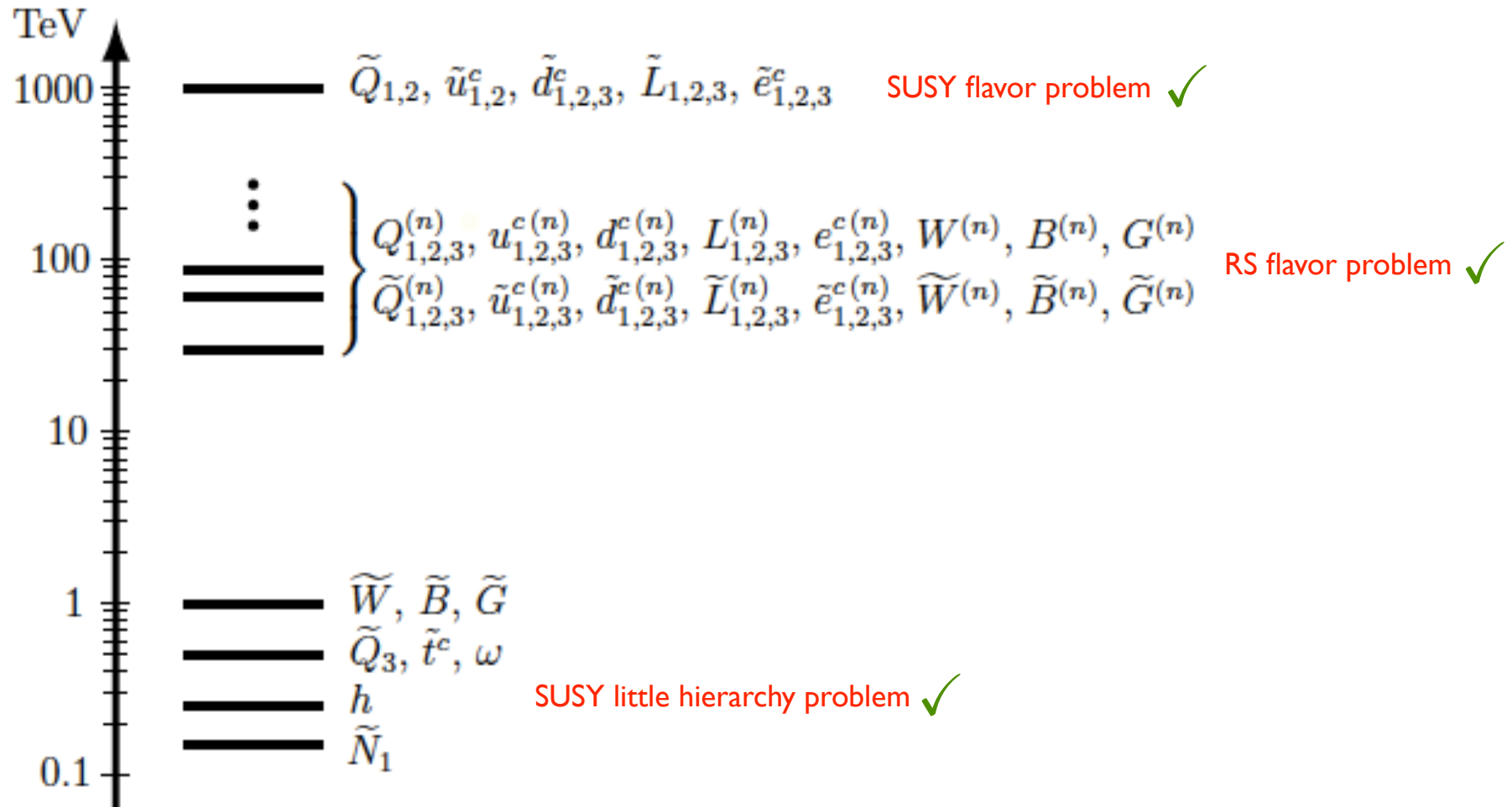
$$\Rightarrow m_{\psi_{3/2}} = \frac{C_{\text{UV}}^3}{M_4^2} \sim m_{\text{soft}}^{\text{IR}} \left(\frac{m_{\text{IR}}}{k} \right)^{4-\Delta}$$

Gravitino is LSP when $\Delta < 4$

$$\text{Radion: } m_{\text{scalar}} \sim m_{\text{pseudoscalar}} \sim \left(\frac{C_{\text{IR}}}{M_5} \right)^3 m_{\text{IR}} \sim m_{\text{soft}}^{\text{IR}}$$

Accidental SUSY spectrum:

$$(\Lambda_{IR} = 40 \text{ TeV}, m_{IR} = 10 \text{ TeV})$$



Questions/Future work

- Embedding into GUT with D-parity?
- Dual 4D explicit model?
- SUSY-Higgs effective Lagrangian?
- Impact of heavy sfermions at LHC?
- Deviations of gauge/gaugino couplings at LHC?
- R-parity violation?
-

Summary

- Supersymmetry may be accidental or “emergent” at IR scale
- Together with a composite Higgs sector can solve big and little hierarchy problems
- Distinctive signals at LHC:
 - only stops, Higgsinos, gauginos
 - deviations in gauge/gaugino couplings
 - composite Higgs sector