Accidental SUSY at the LHC

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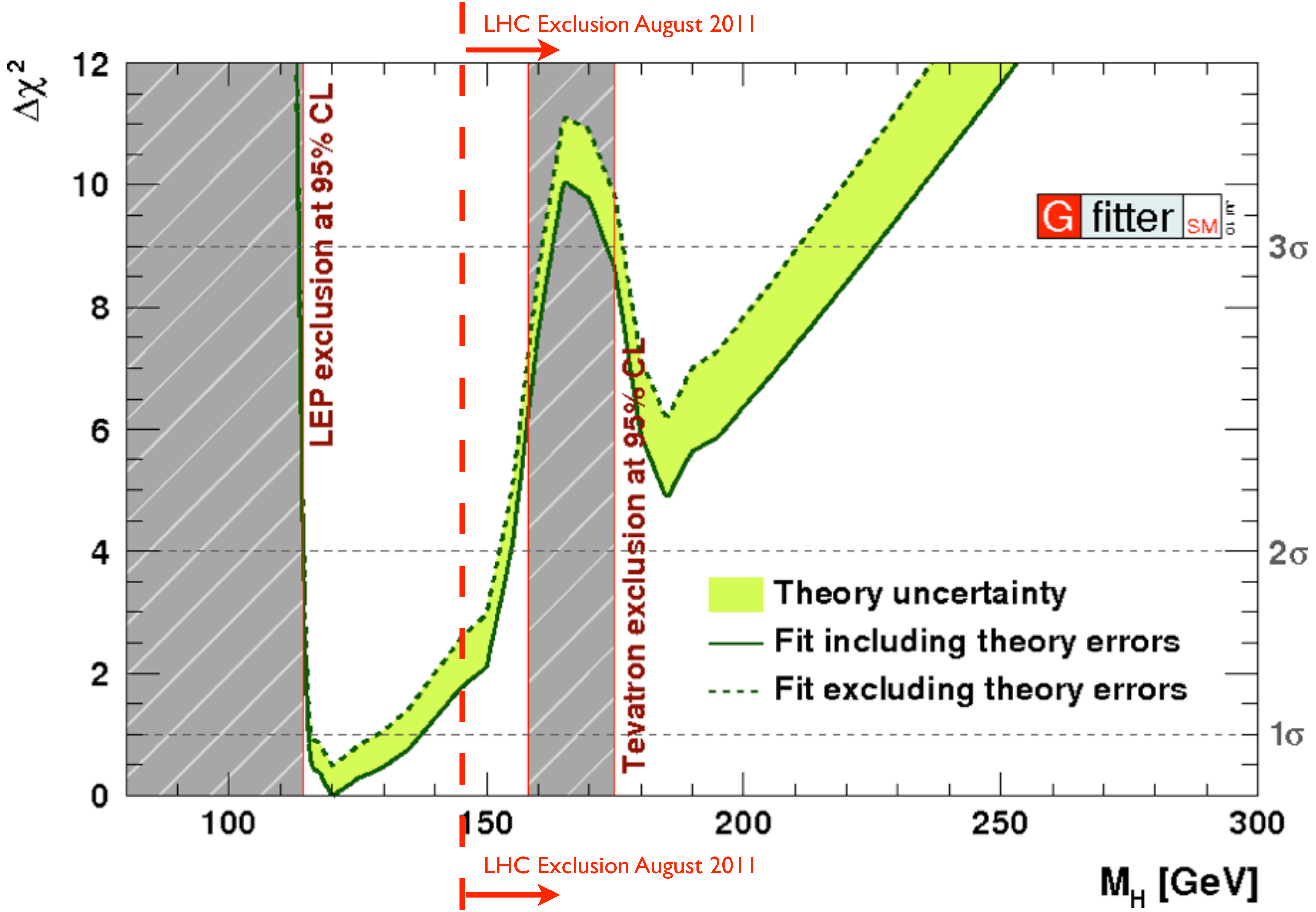
with Benedict von Harling and Nick Setzer

[arXiv:1104.3171]

What is the Higgs boson mass?

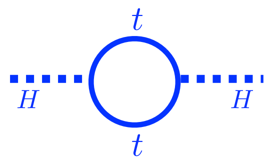


Hierarchy Problem

HIGGS MASS $\boxed{114\,\mathrm{GeV} \lesssim m_H \lesssim 145\,\mathrm{GeV}}$ Direct experimental limits

Standard Model prediction:

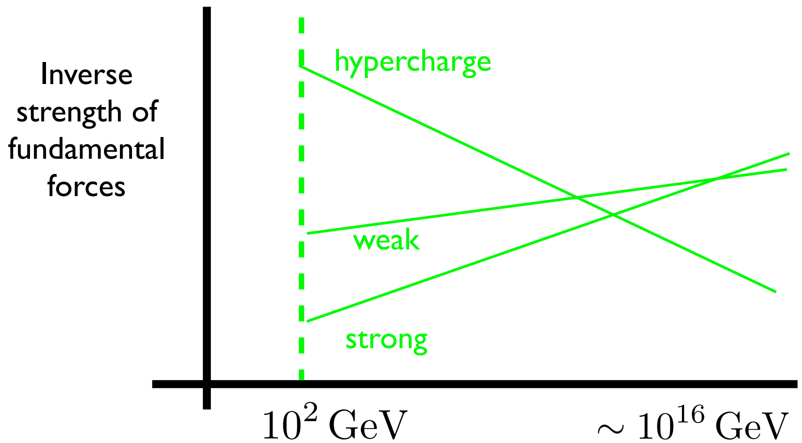
e.g. top quark



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

Quadratic dependence on cutoff scale, Λ

What is the value of the cutoff scale Λ?



$\Lambda \simeq 10^{16}\,\mathrm{GeV}$

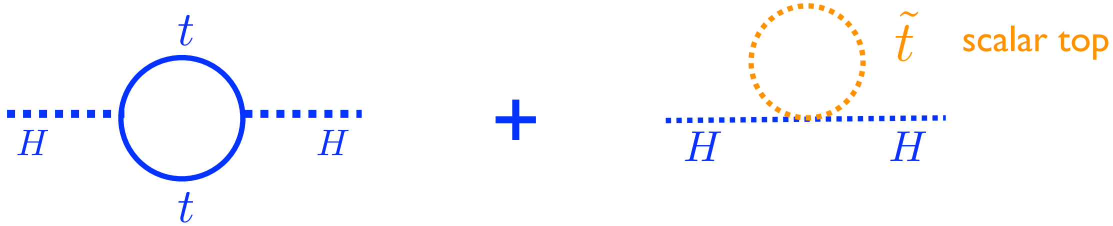
$\longrightarrow m_H^2 \gg (100\,\mathrm{GeV})^2$!!

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

HIERARCHY PROBLEM

Natural Solutions of Hierarchy Problem

Idea #1: Supersymmetry



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

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

BUT

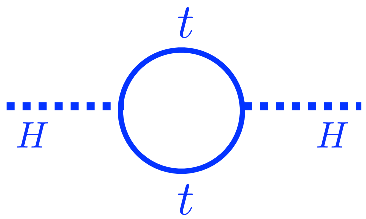
- Supersymmetric flavor problem

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

- Higgs mass $\quad m_H \lesssim 130\,\mathrm{GeV}$ with $m_{\tilde{t}} \gtrsim 1\,\mathrm{TeV}$

LITTLE HIERARCHY PROBLEM

Idea #2: Strong dynamics



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

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

BUT

- Flavor and CP problem

$$\frac{1}{\Lambda_F^2}\Psi_i\Psi_j\Psi_k\Psi_l \qquad\qquad \Lambda_F \gtrsim 2 - 30\,\mathrm{TeV}$$

- 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:

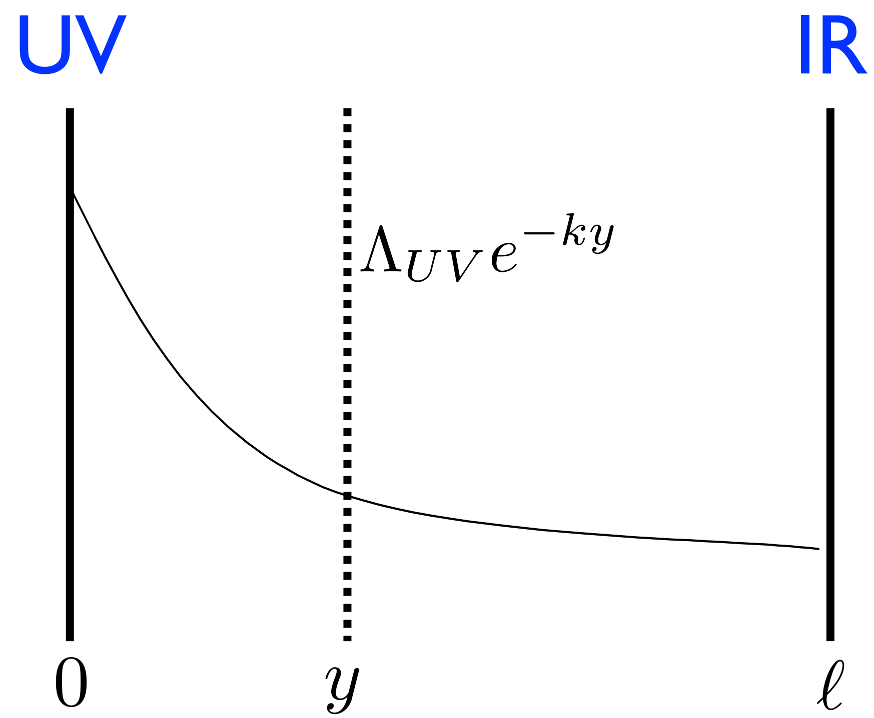
Strong dynamics $\Rightarrow$ $m_H \propto \Lambda_{strong} \ll M_P$

Little Hierarchy Problem:

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

Natural framework:

Warped Extra Dimension ➡ Explain hierarchies



"Slice of AdS_5"

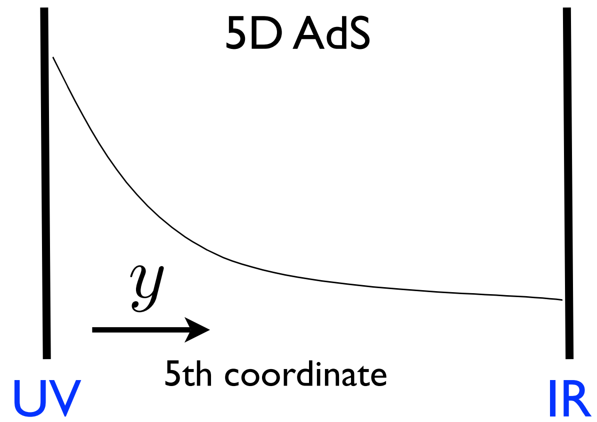
[Randall, Sundrum 99]

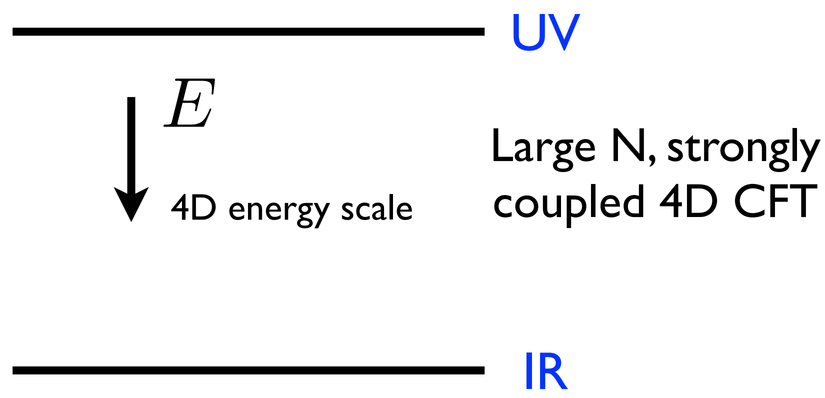
k=AdS curvature scale

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

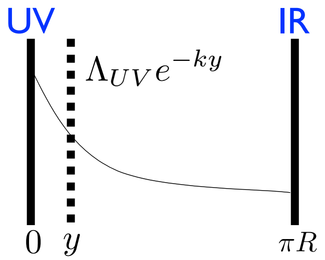
AdS/CFT dictionary

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

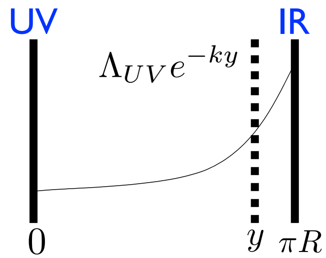




"Slice of AdS" ⟺ CFT + Dynamical elementary "source"



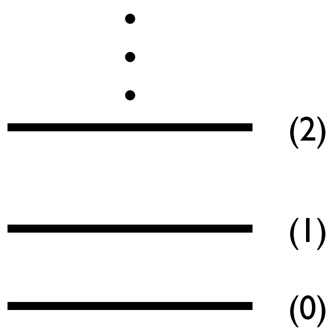
UV localized field ⟺ elementary "source" state



IR localized field ⟺ CFT bound state

Kaluza-Klein tower ⟺ Tower of resonances

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



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

Plan

Use AdS/CFT to build strongly-coupled 4D model using 5D warped model:

SUSY broken at UV scale

$$\mathcal{L}(\mathcal{M}) = -\frac{1}{4}F_{\mu\nu}^2 + i\bar{\lambda}D.\sigma\lambda + |D\phi_0|^2 + M^2|\phi_0|^2$$

weakly-coupled

e.g. "Split SUSY"

strongly-coupled $\{ +|D\phi|^2 + \cancel{M^2|\phi|^2} + \mathcal{O}(\frac{1}{M^k})$

SUSY breaking by irrelevant ops.

$\xrightarrow{\text{flow to IR}}$

SUSY emerges at IR scale

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 + i\bar{\lambda}D.\sigma\lambda + |D\phi\,|^2$$

"accidental SUSY"

5D gravity dual

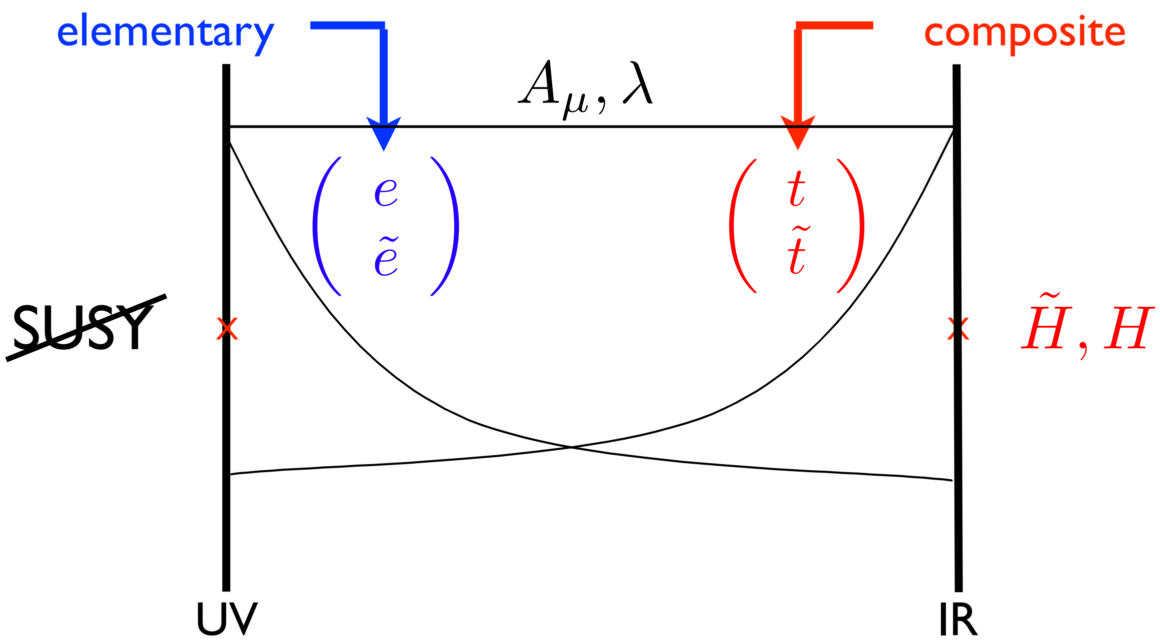
SUSY broken on UV brane

$\xrightarrow{\text{transmit SUSY-breaking via bulk}}$

SUSY IR brane

Partial SUSY [TG, Pomarol, hep-ph/0302001]

SUSY broken at UV scale



bulk mass parameter

$$\begin{pmatrix} \psi \\ \tilde{\phi} \end{pmatrix} \propto e^{(\frac{1}{2}-c)ky}$$

Fermion mass spectrum determines sparticle spectrum!

Low-energy SUSY spectrum $\tilde{t}, \tilde{H}$ $(\tilde{f}_{1,2}, \lambda \quad \text{decouple})$

KK spectrum $m_f^{(n)} \simeq m_{\tilde{f}}^{(n)}$ $n = 1, 2, \ldots$

BUT:

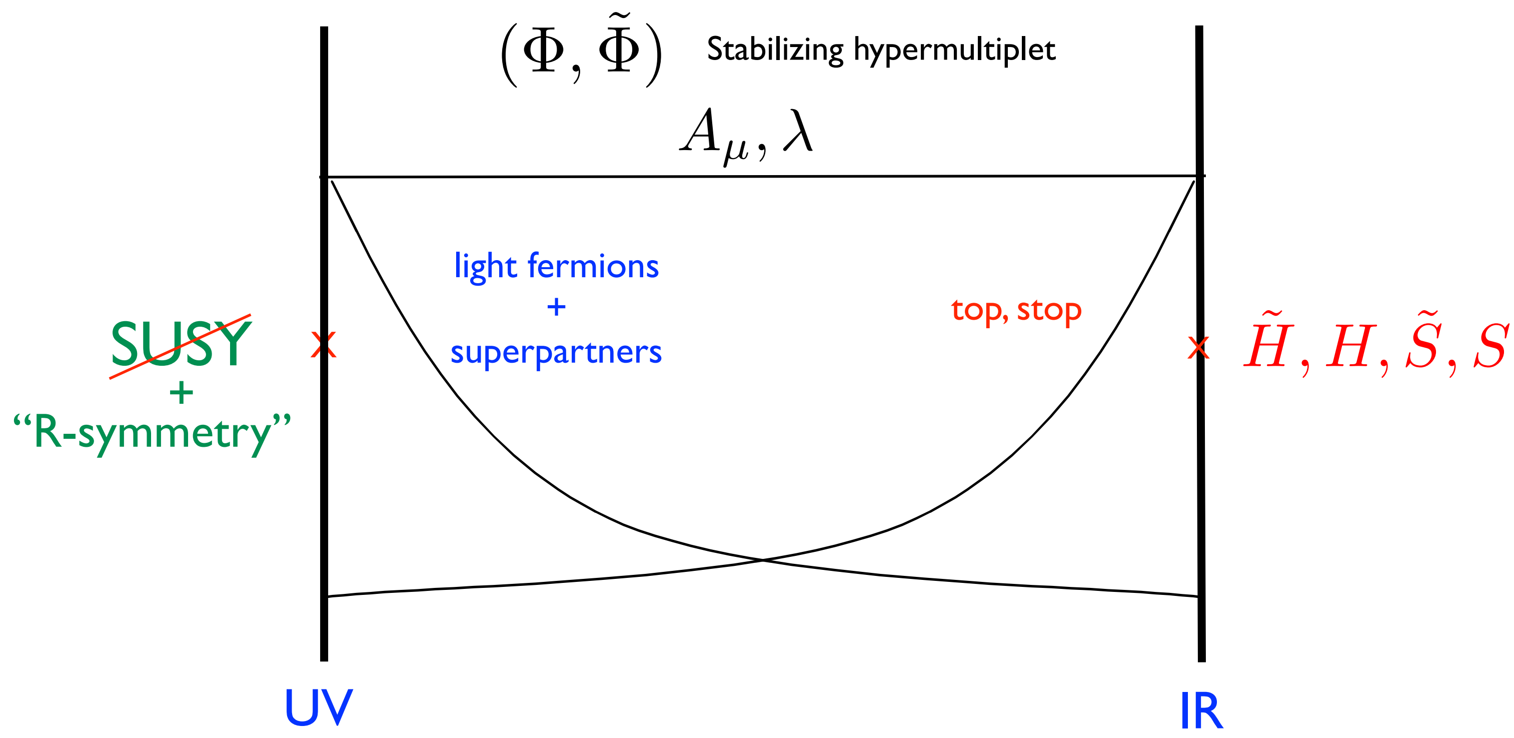
- Potentially large D-term contributions to soft masses $\mathcal{L} \supset m_0^2 D$
- No light gaugino ➡ $\Delta m_H^2 \sim \frac{g^2}{16\pi^2}\Lambda_{IR}^2 \longrightarrow$ Limit to increasing Λ_{IR}

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]

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

UV brane SUSY-breaking potential:

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

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

$\Delta =$ Dimension of operator dual to Φ

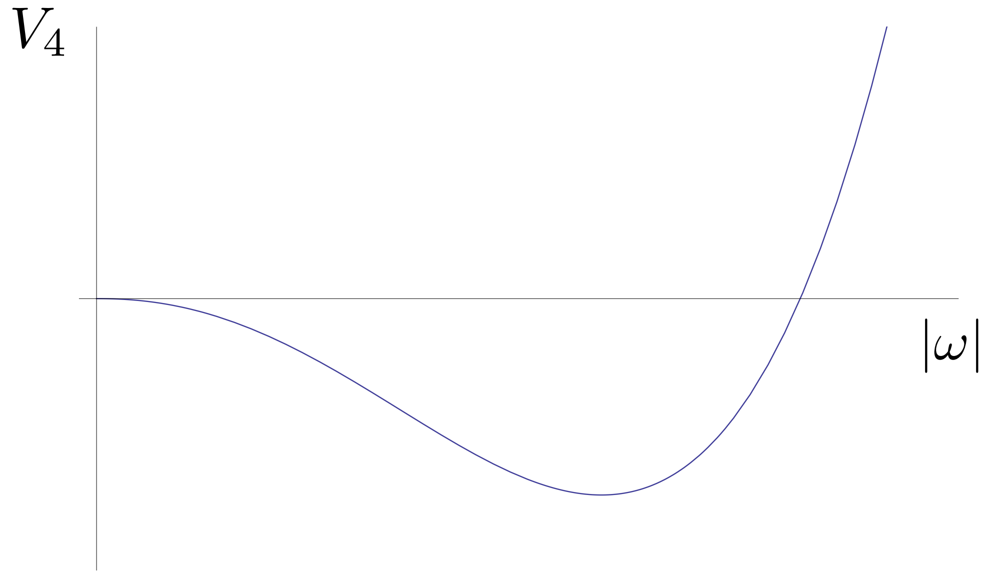
$\omega =$ radion

Add UV and IR constant superpotential:

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

$C_{UV}(C_{IR}) =$ 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:

$$e^{-k\ell} = |\omega| \simeq \left[\frac{\Delta-3}{\sqrt{6}}\frac{M_{\rm SUSY}^2 M_4}{C_{\rm IR}^3}\right]^{\frac{1}{5-\Delta}}$$

Determines IR scale
$(m_{IR} \equiv ke^{-k\ell})$

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

Sparticle mass spectrum

UV-localized matter:

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

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

IR-localized matter:

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

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

Gaugino mass:

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

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

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

Also radion mediation:

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

Higgs sector:

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

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

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

Ameliorates SUSY little hierarchy problem

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

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

Solves mu-problem

Hard SUSY breaking effects

Heavy first and second family sfermions generate hard breaking:

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

[Sundrum arXiv:0909.5430]

$$\Delta m^2_{\tilde t} \approx (1.5\ {\rm TeV})^2 \qquad \Delta m^2_{\rm H} \approx (350\ {\rm GeV})^2$$

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

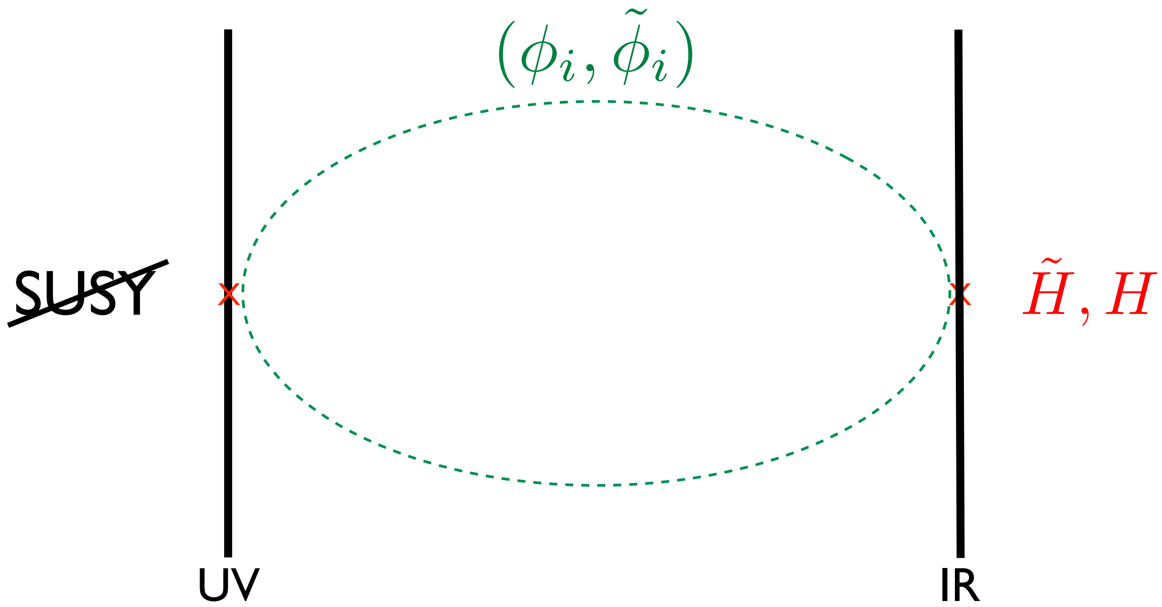
Total contribution:

$$m^2_{\tilde t} = \Delta m^2_{hard} + \Delta m^2_{soft} \approx (600\,{\rm GeV})^2$$

Tuning of Higgs mass is of order 20%

AdS calculation

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



5D propagator:

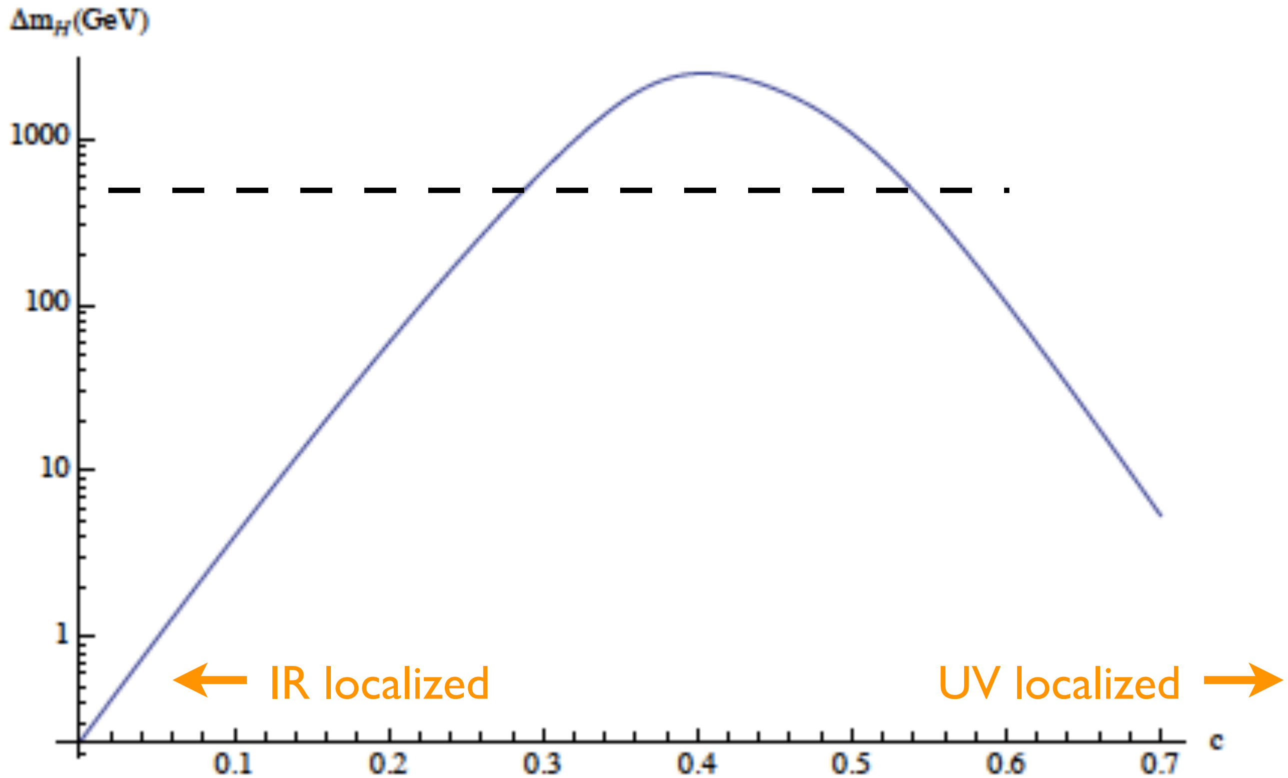
$$G_{F,B}(p) = -\frac{e^{2k\ell}}{k} \frac{\widetilde{I}^{\mathrm{UV}}_{c+1/2}(\frac{p}{k})\ K_{c+1/2}(\frac{p}{m_{\mathrm{IR}}}) - \widetilde{K}^{\mathrm{UV}}_{c+1/2}(\frac{p}{k})\ I_{c+1/2}(\frac{p}{m_{\mathrm{IR}}})}{\widetilde{I}^{\mathrm{IR}}_{c+1/2}(\frac{p}{m_{\mathrm{IR}}})\ \widetilde{K}^{\mathrm{UV}}_{c+1/2}(\frac{p}{k}) - \widetilde{I}^{\mathrm{UV}}_{c+1/2}(\frac{p}{k})\ \widetilde{K}^{\mathrm{IR}}_{c+1/2}(\frac{p}{m_{\mathrm{IR}}})}$$

where $\widetilde{I}^i_\alpha(x) \equiv x\, I_{\alpha-1}(x) - \delta^i\, I_\alpha(x)$ with $\delta^{\mathrm{UV}} = (m^{\mathrm{UV}}_{\mathrm{soft}})^2/2k^2$

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

Bulk hypermultiplet correction to Higgs mass

$$(m_{IR} = 10\,\mathrm{TeV},\; m^{UV}_{soft} = 1000\,\mathrm{TeV})$$



At most 20% tuning if exclude $0.3 \lesssim c \lesssim 0.53$

$(m_h \simeq 250\,\mathrm{GeV})$

Gravitational sector:

Cancel energy density to obtain zero 4d cosmological constant:

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

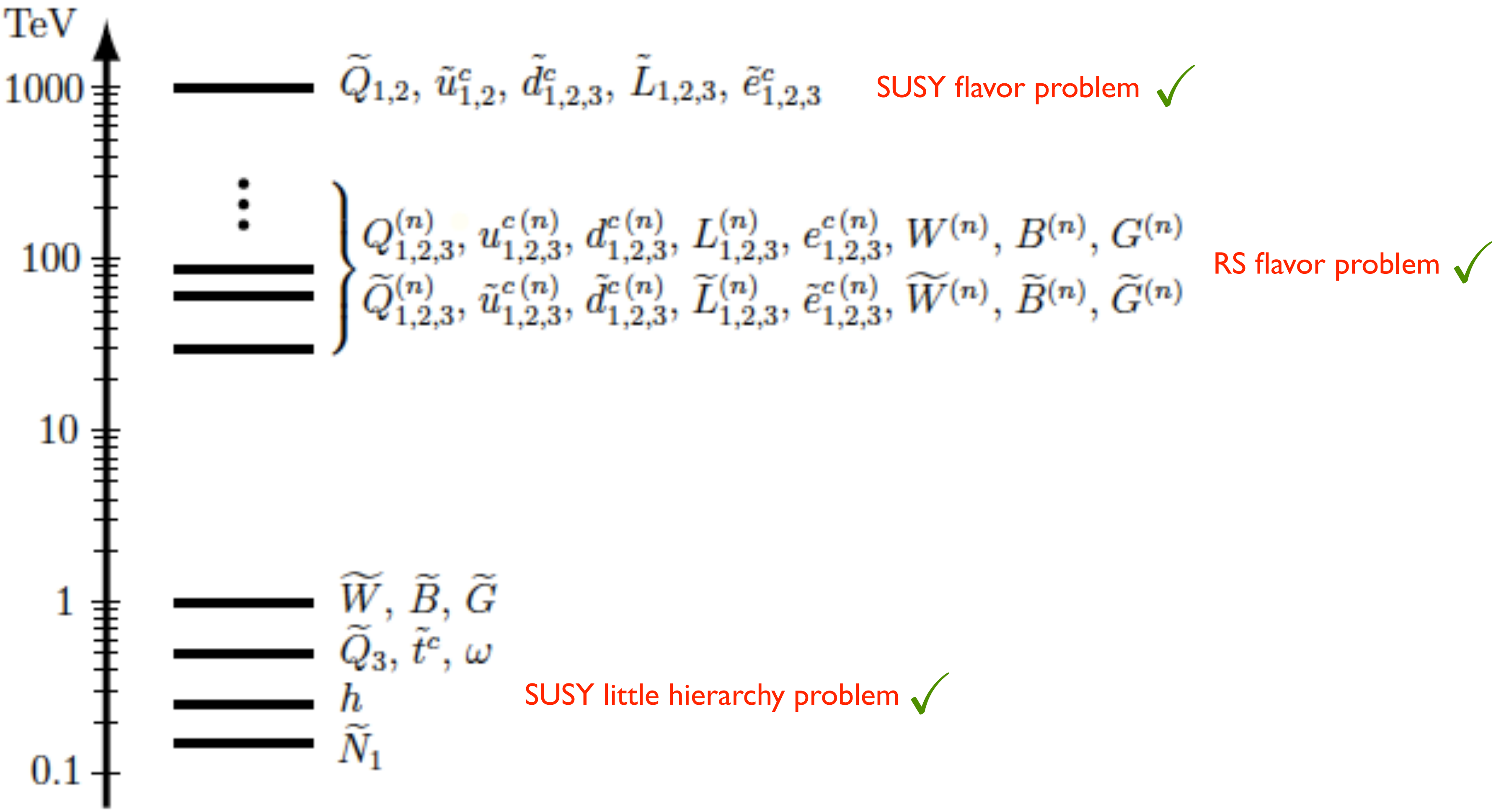
$$\Rightarrow \qquad m_{\psi_{3/2}} = \frac{C_{\rm UV}^3}{M_4^2} \sim m_{\rm soft}^{\rm IR} \left(\frac{m_{\rm IR}}{k}\right)^{4-\Delta}$$

Gravitino is LSP when $\Delta < 4$

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

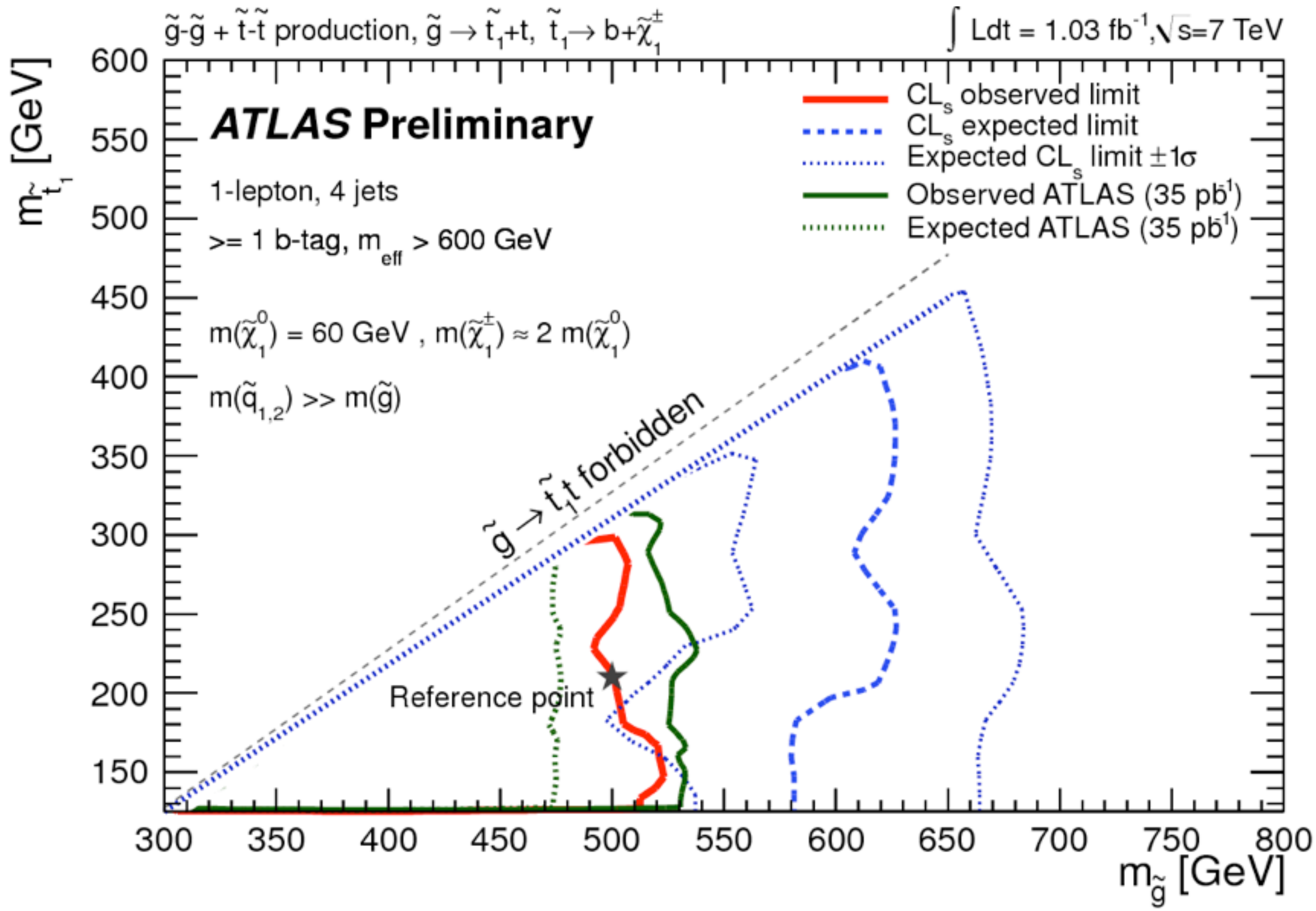
Accidental SUSY spectrum:

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



LHC 3rd generation limits:

ATLAS-CONF-2011-130 17 August 2011



$$m_{\tilde{g}} \gtrsim 500\,\mathrm{GeV} \qquad m_{\tilde{t}} \gtrsim\ ?$$

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
- Current LHC bounds are mild