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Workshop on Strongly Coupled Physics Beyond the Standard Model

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A split sparticle spectrum from accidental SUSY

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A Split Sparticle Spectrum from Accidental SUSY

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(University of Melbourne)

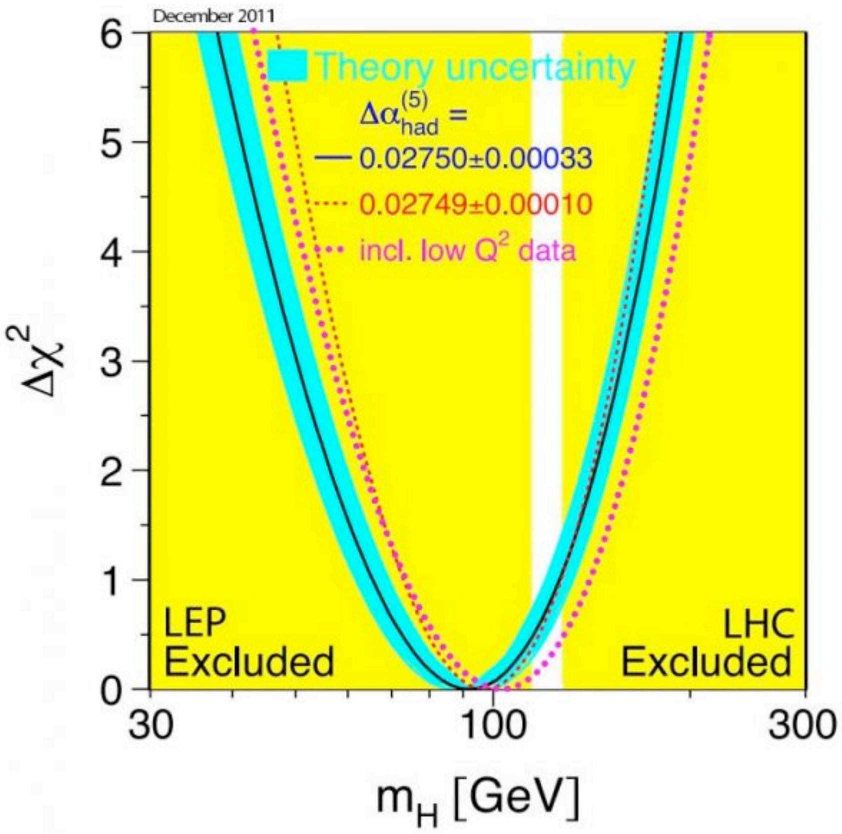
Workshop on Strongly Coupled Physics
Beyond the Standard Model
ICTP Trieste, January 26, 2012

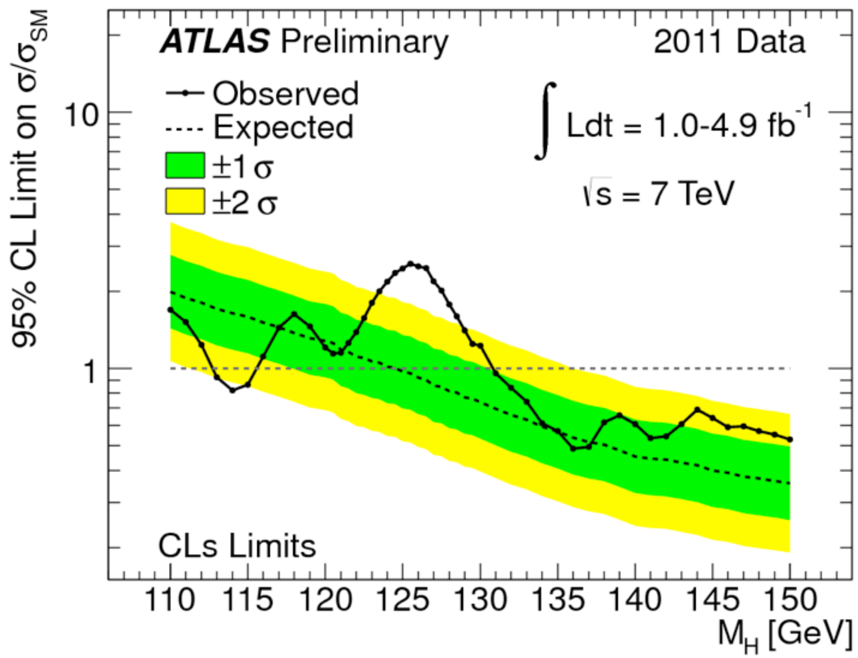
with Benedict von Harling and Nick Setzer

[arXiv:1104.3171]

Hints from the LHC:

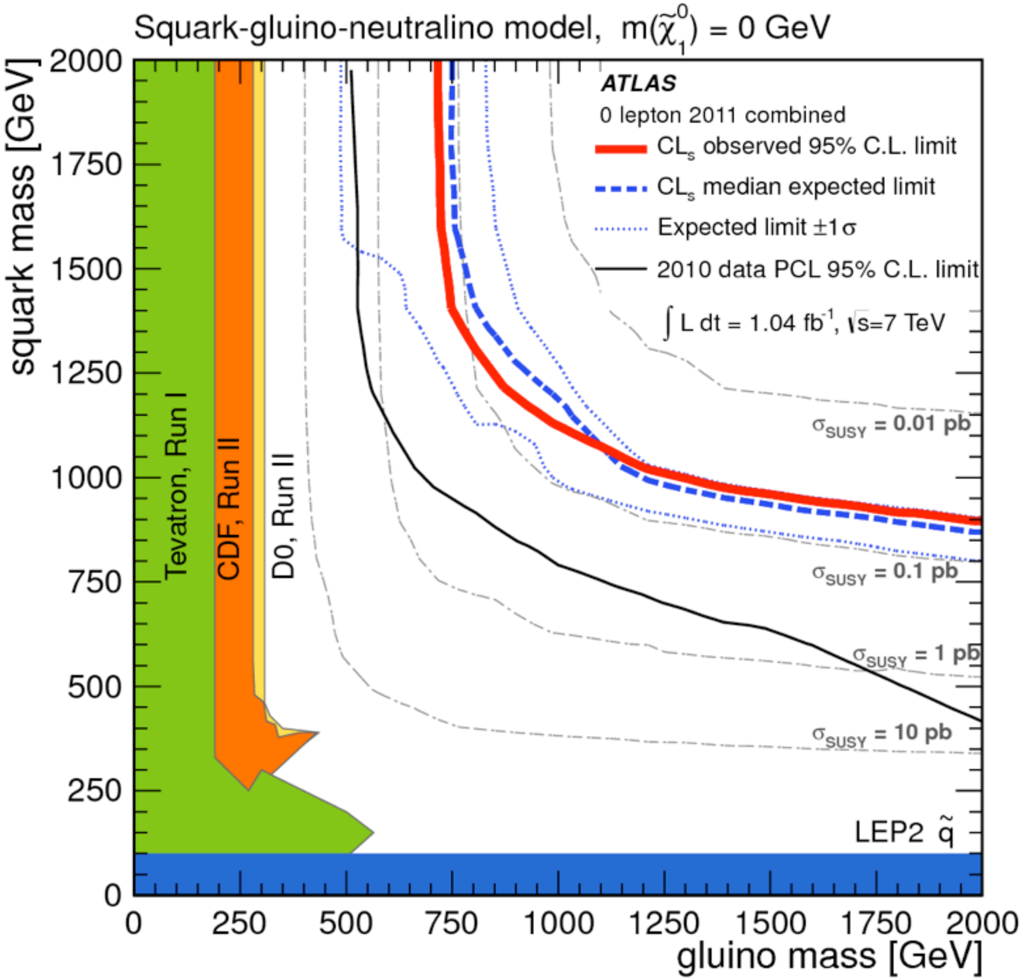
(1) Higgs mass





$$m_H = \text{“}121 \pm 6\text{”}\ \text{GeV}$$

(2) Stringent mass limits in CMSSM/mSUGRA



Assumes:

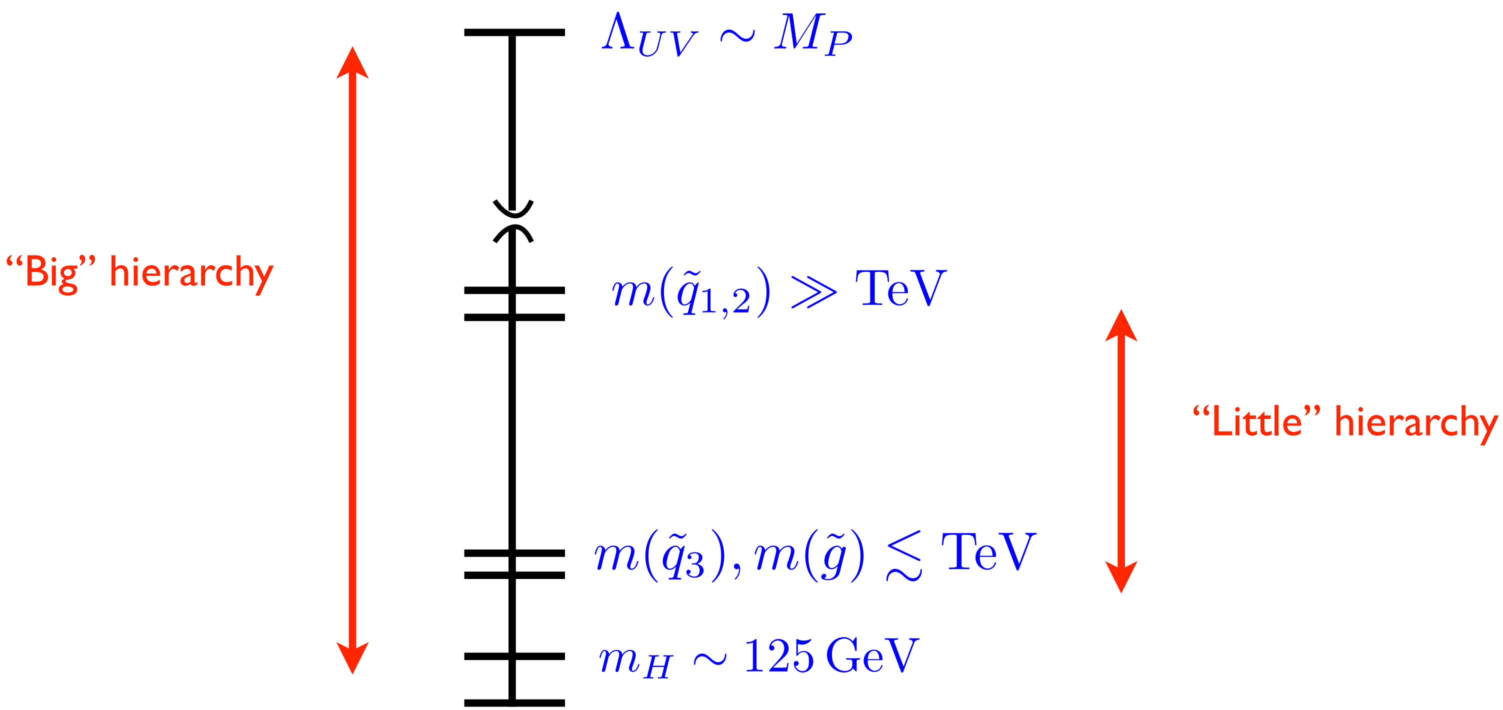
$m(\tilde{q}_3) \gg m(\tilde{g}), m(\tilde{q}_{1,2})$

$$\Rightarrow \quad m(\tilde{g}), m(\tilde{q}_{1,2}) \gtrsim \text{TeV}$$

How do we deal with the LHC hints?

Assume (i) weakly-coupled Higgs (~125 GeV)

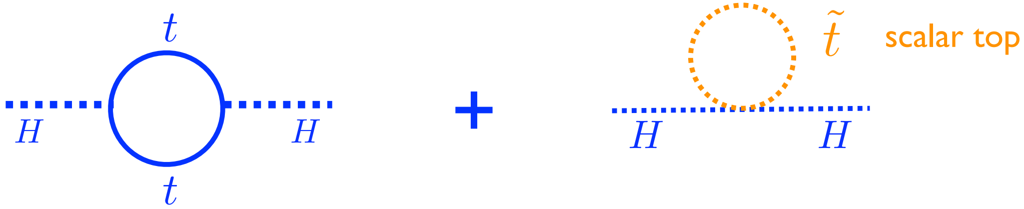
(ii) $m(\tilde{q}_{1,2}) \gg m(\tilde{g}), m(\tilde{q}_3)$ (stringent mass limits do **NOT** apply)



Look for natural solution with split mass spectrum...

Natural Solutions of Hierarchy Problem

Idea #1: Supersymmetry



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

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

BUT

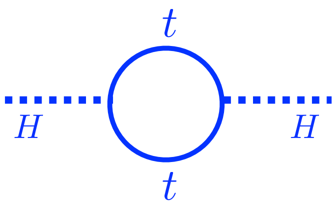
- Supersymmetric flavor problem

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

- Higgs mass $m_H \sim 125\,\mathrm{GeV}$ with $m_{\tilde{t}} \gg 1\mathrm{TeV}$

LITTLE HIERARCHY PROBLEM

Idea #2: Strong dynamics



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

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

BUT

- Flavor and CP problem

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

- 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:

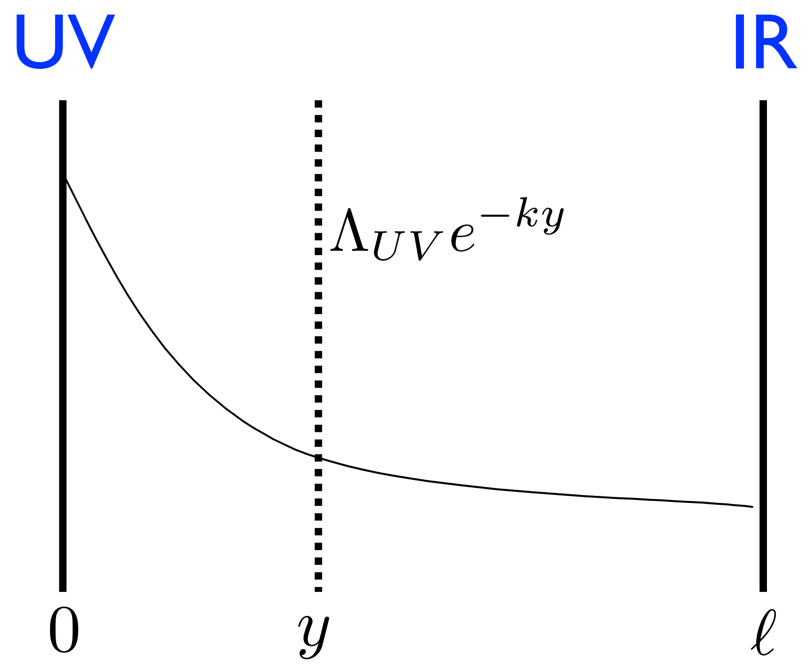
Strong dynamics ➡ $m_H \propto \Lambda_{strong} \ll M_P$

"Little" Hierarchy Problem:

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

Natural framework:

Warped Extra Dimension ➡ Explain hierarchies



"Slice of AdS_5"

[Randall, Sundrum 99]

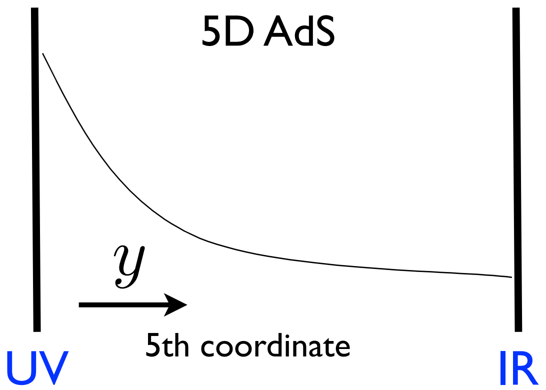
k=AdS curvature scale

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

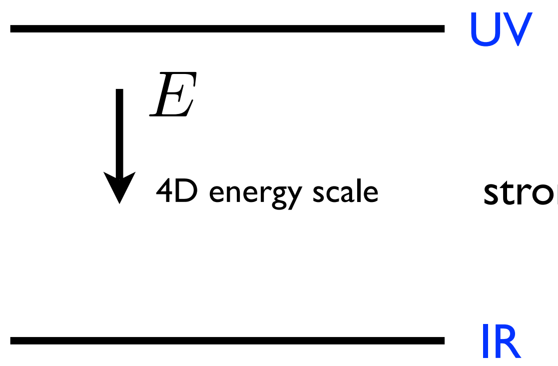
Remarkably, warped
5th dimension encodes
4D strong dynamics! ⟺ **AdS/CFT** [Maldacena '97]

AdS/CFT dictionary

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



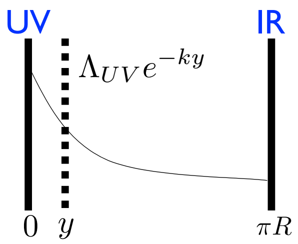
⟺



Large N,
strongly-coupled
4D CFT

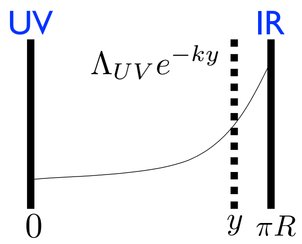
"Slice of AdS" ⟺ strongly-coupled CFT
+ elementary sector

$$\mathcal{L}_4 = \mathcal{L}_{UV}[\Phi_i] + \mathcal{L}_{CFT}[\mathcal{O}_i] + \lambda \Phi_i \mathcal{O}_i$$



UV localized field

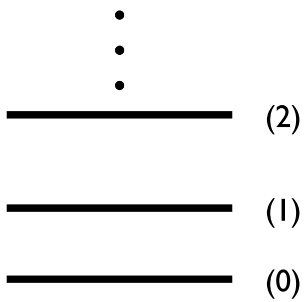
elementary state



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.

flow to IR →

SUSY emerges at IR scale

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

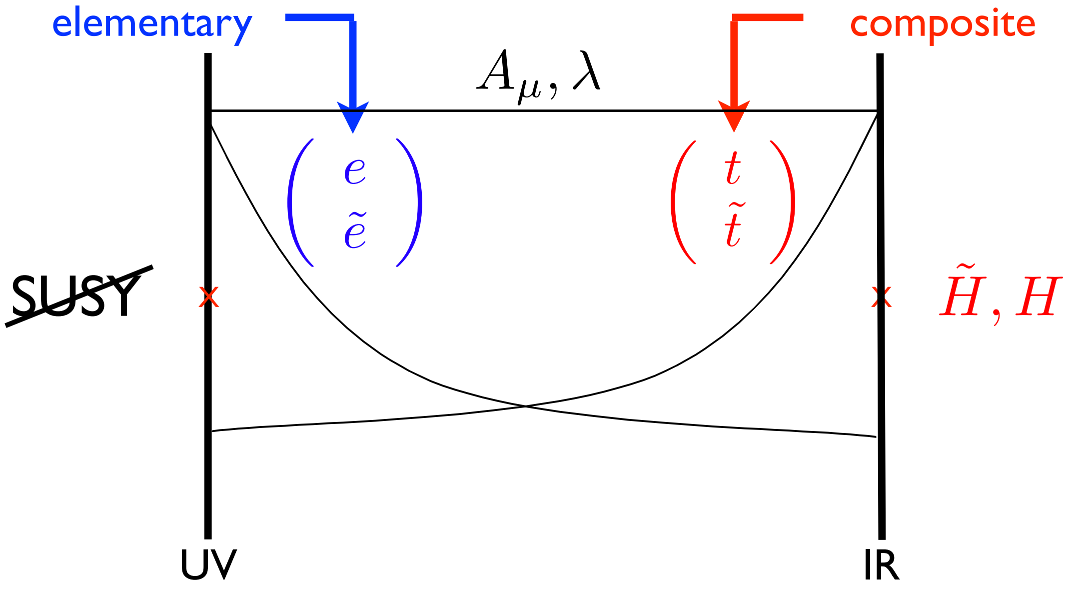
"accidental SUSY"

⇓ 5D gravity dual

SUSY broken on UV brane — transmit SUSY-breaking via bulk → **SUSY IR brane**

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

SUSY broken at UV scale



bulk mass parameter

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

<u>Fermion mass</u> spectrum
determines sparticle spectrum!

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

⇨ Naturally obtain a split sparticle spectrum!

BUT:

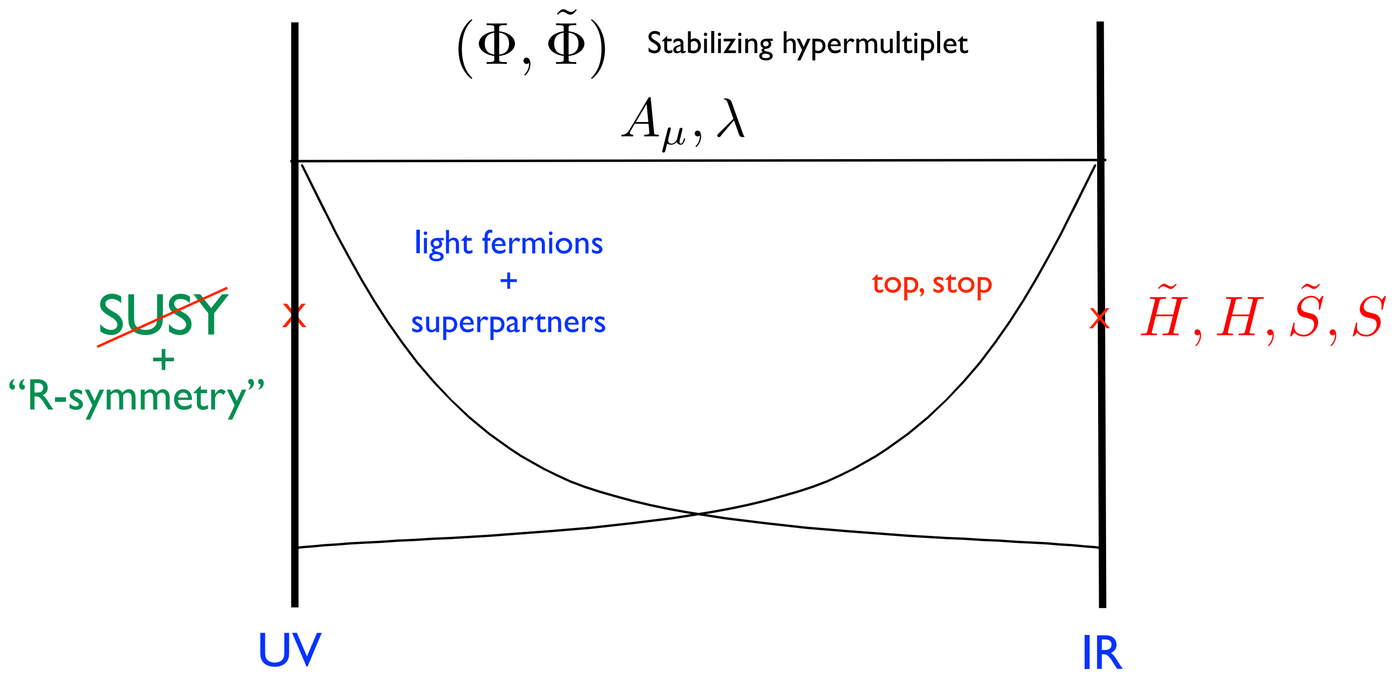
- Potentially large D-term contributions to soft masses $\mathcal{L} \supset m_0^2 D$
- No light gaugino ⇨ $\Delta m_H^2 \sim \frac{g^2}{16\pi^2}\Lambda_{IR}^2$ $\longrightarrow$ Limit to increasing Λ_{IR}

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]

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

$$\mathcal{L}_5 \supset \int d^4\theta \left[e^{-2k|y|}\left(\Phi^\dagger\Phi + \widetilde{\Phi}^\dagger\widetilde{\Phi}\right) + \delta(y)\, \overbrace{V(\Phi, F)}\right]$$

$$+ \left[\int d^2\theta\, e^{-3k|y|}\, \widetilde{\Phi}\left(\partial_y + \left(c' - \frac{3}{2}\right)k\epsilon(y)\right)\Phi + \text{h.c.}\right]$$

UV brane SUSY-breaking potential:

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

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

$\Delta =$ Dimension of operator dual to Φ

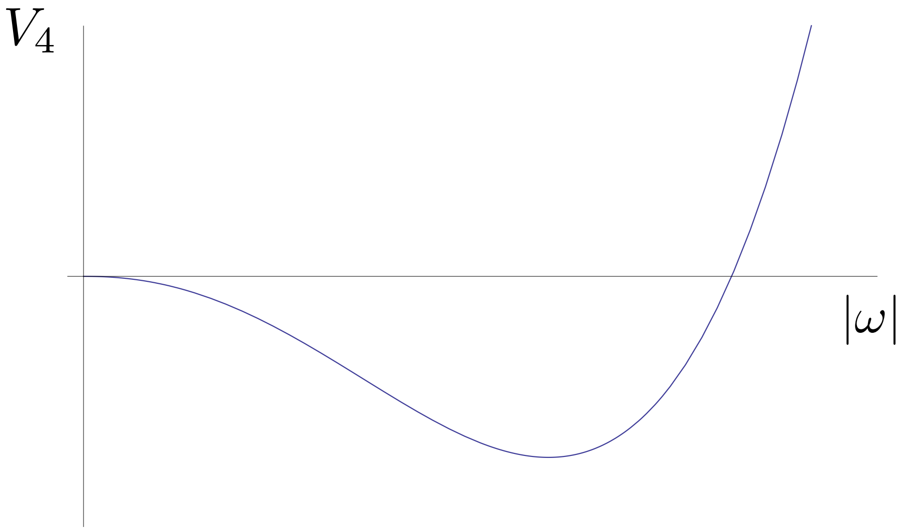
$\omega =$ radion

Add UV and IR constant superpotential:

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

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

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



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

Sparticle mass spectrum

UV-localized matter:

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

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

IR-localized matter:

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

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

Gaugino mass:

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

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

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

Also radion mediation:

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

Higgs sector:

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

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

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

Ameliorates SUSY little hierarchy problem

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

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

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]

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

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

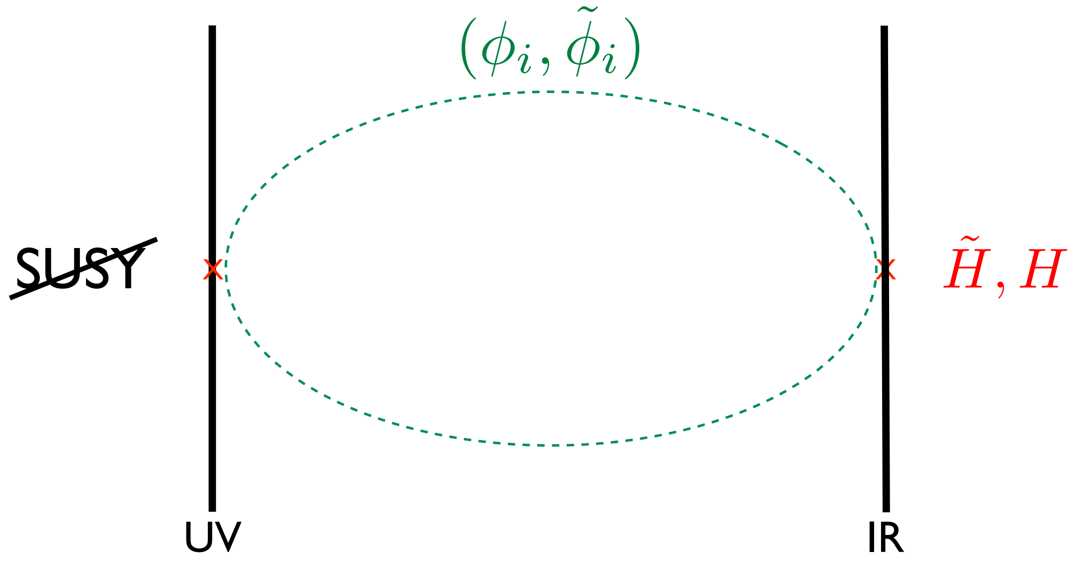
Total contribution:

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

Tuning of Higgs mass is of order 20%

AdS 1-loop Higgs mass contribution:

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



5D propagator:

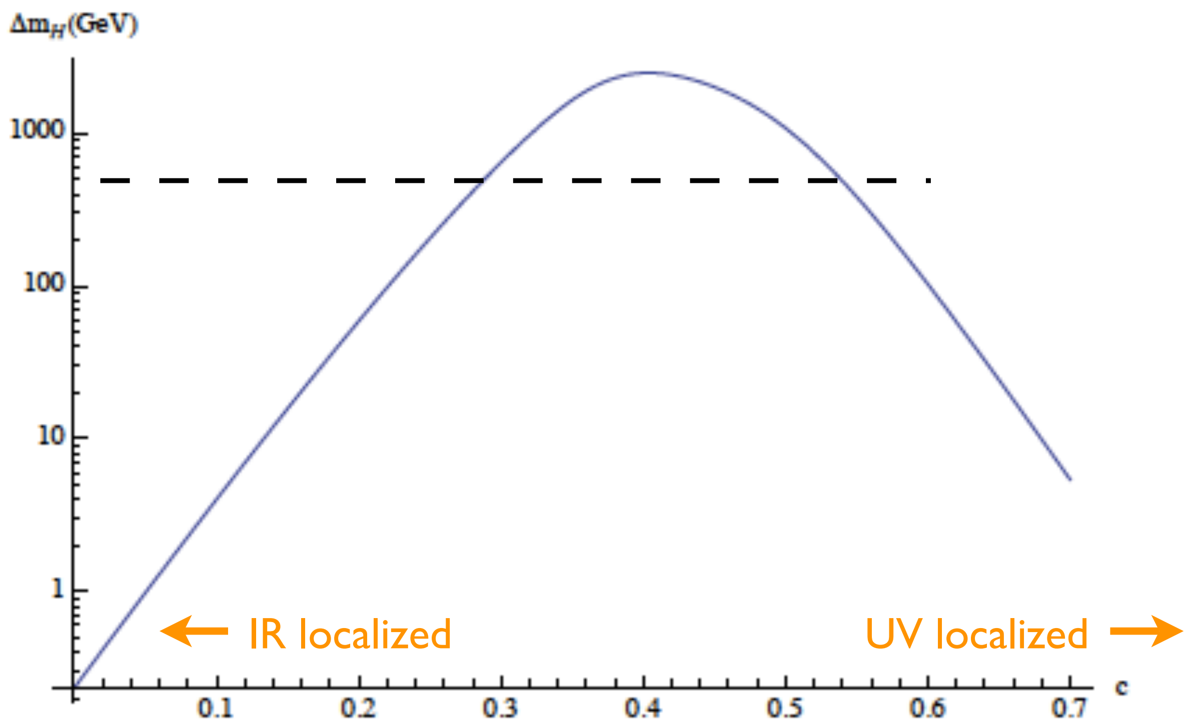
$$G_{F,B}(p) = -\frac{e^{2k\ell}}{k} \frac{\tilde{I}^{\rm UV}_{c+1/2}(\frac{p}{k})\; K_{c+1/2}(\frac{p}{m_{\rm IR}}) \;-\; \tilde{K}^{\rm UV}_{c+1/2}(\frac{p}{k})\; I_{c+1/2}(\frac{p}{m_{\rm IR}})}{\tilde{I}^{\rm IR}_{c+1/2}(\frac{p}{m_{\rm IR}})\; \tilde{K}^{\rm UV}_{c+1/2}(\frac{p}{k}) \;-\; \tilde{I}^{\rm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

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

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

Bulk hypermultiplet correction to Higgs mass

$(m_{IR} = 10\,\mathrm{TeV},\, m_{soft}^{UV} = 1000\,\mathrm{TeV})$ [TG, von Harling,Setzer arXiv:1104.3171]



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:

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

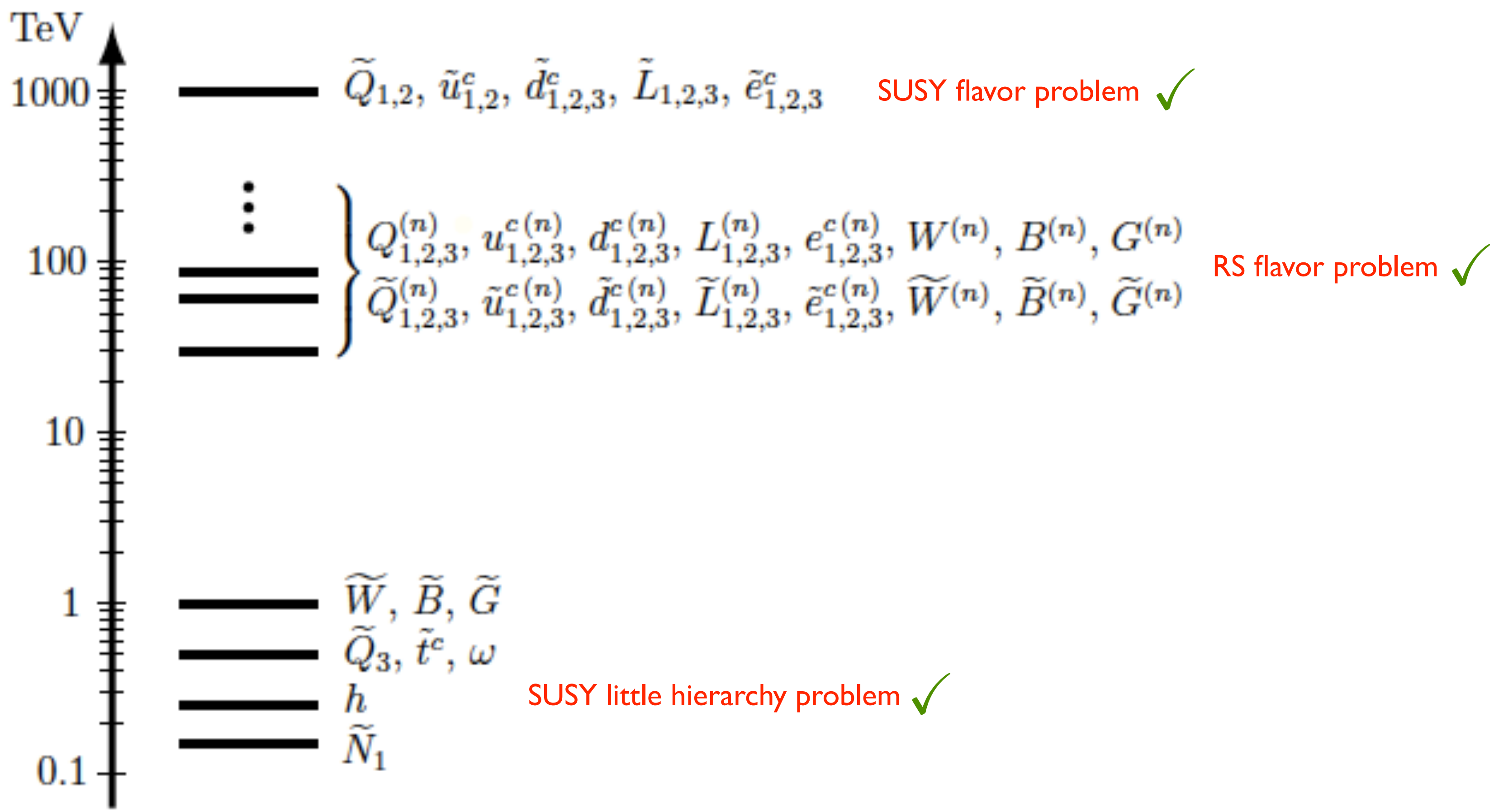
$$\Rightarrow \quad m_{\psi_{3/2}} = \frac{C_{\rm UV}^3}{M_4^2} \sim m_{\rm soft}^{\rm IR} \left(\frac{m_{\rm IR}}{k}\right)^{4-\Delta}$$

Gravitino is LSP when $\Delta < 4$

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

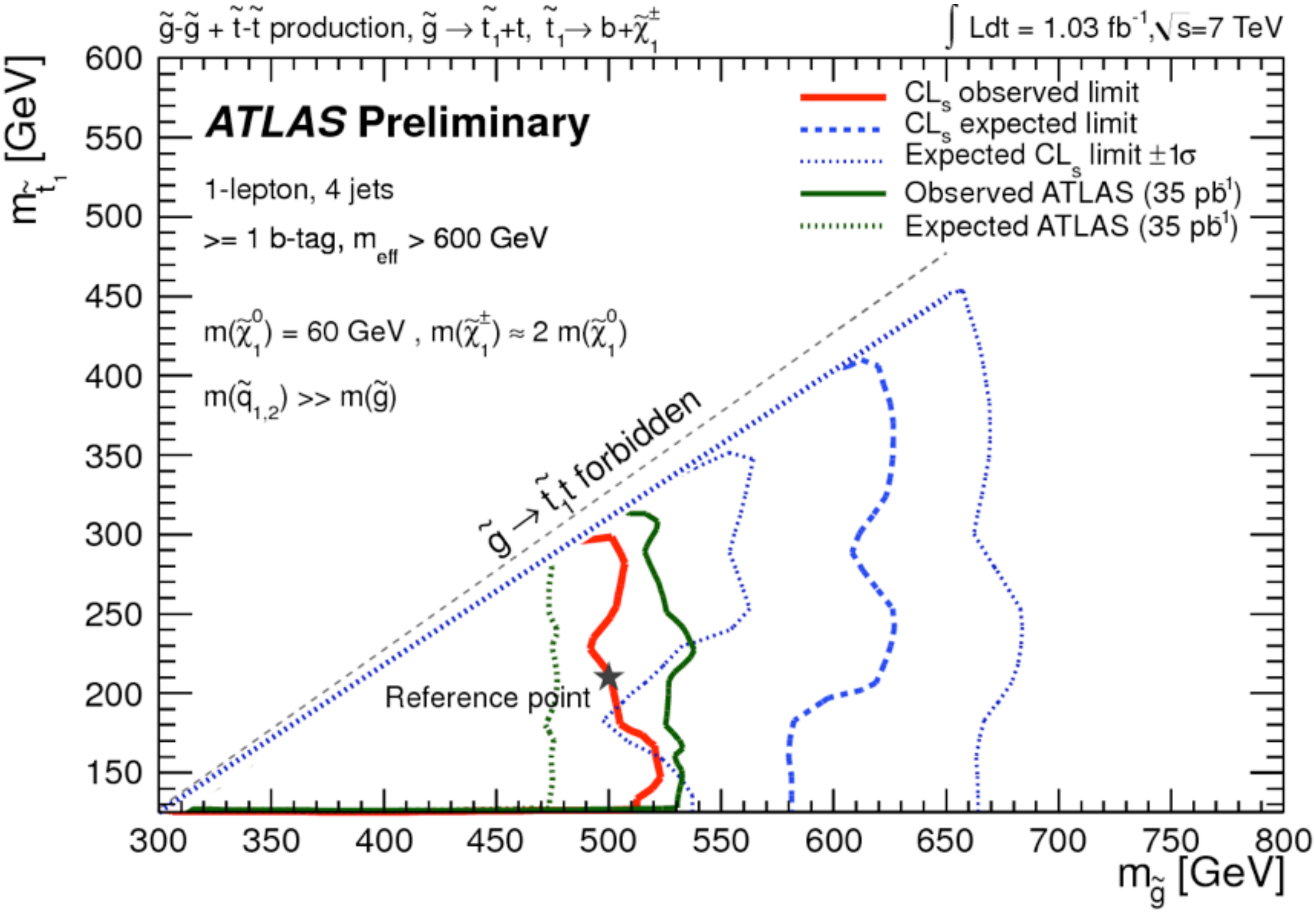
Accidental SUSY spectrum:

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



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