Beyond the Standard Model in a **Warped Extra Dimension**

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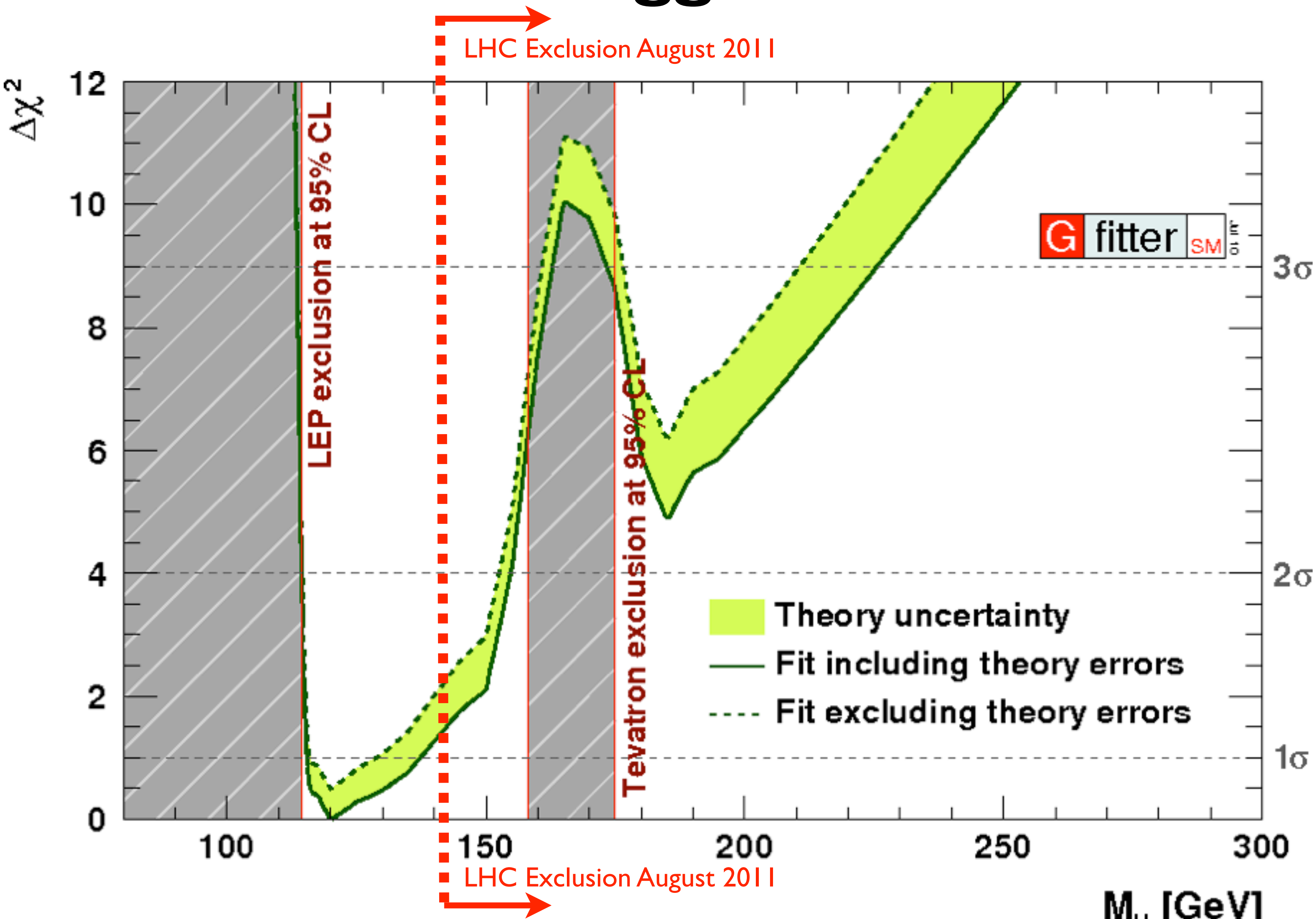
What is the Higgs boson mass?

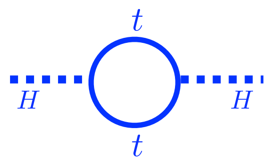


$$m_H = \text{“}130 \pm 15\text{”}\ \text{GeV}$$

Gauge Hierarchy Problem:

Standard Model prediction:

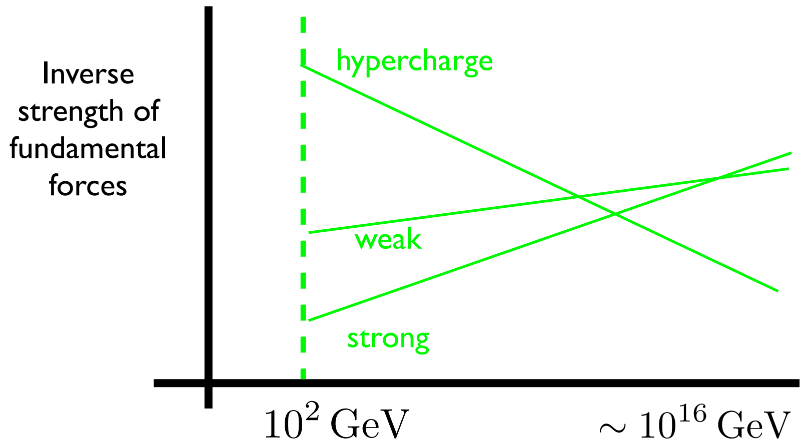
e.g. top quark



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

Quadratic dependence on cutoff scale, Λ

What is the value of the cutoff scale Λ?



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

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

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

Possible explanations:

Cancellation or No Cancellation

$$\delta m_H^2 \sim \Lambda^2 - \Lambda^2 + \ldots$$

e.g. supersymmetry, global symmetry

$$\Lambda \sim \mathrm{TeV}$$

e.g. strong dynamics, low-scale string theory

or just fine-tuned!

$$(\Lambda \sim M_P)$$

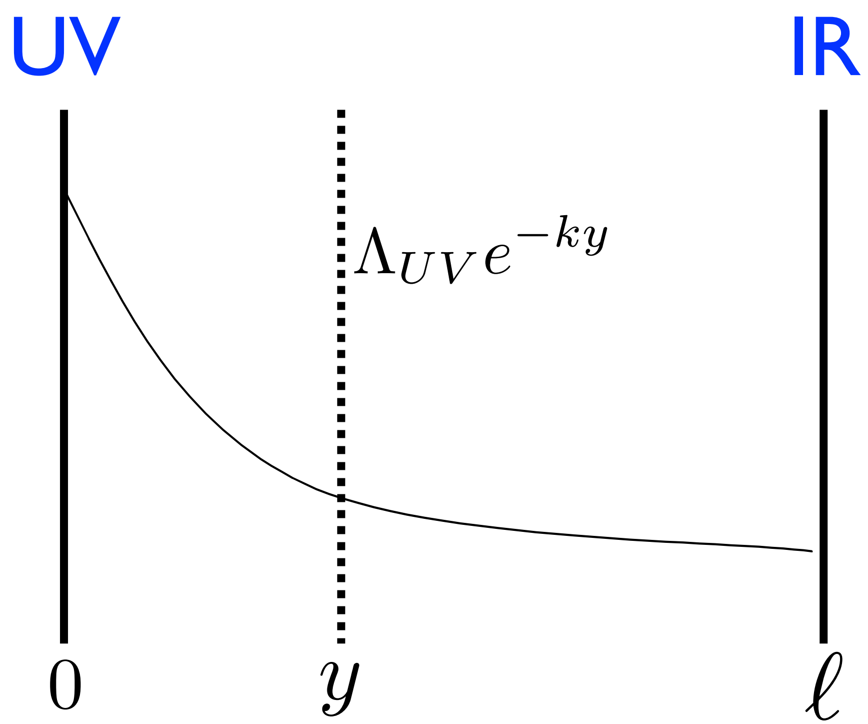
e.g. string theory Landscape!

Warped Extra Dimension ➡ New framework....

Warped Extra Dimension

➡ Can explain hierarchies!

5D spacetime : (x^μ, y) [anti-de Sitter = AdS]



"Slice of AdS_5"

[Randall, Sundrum '99]

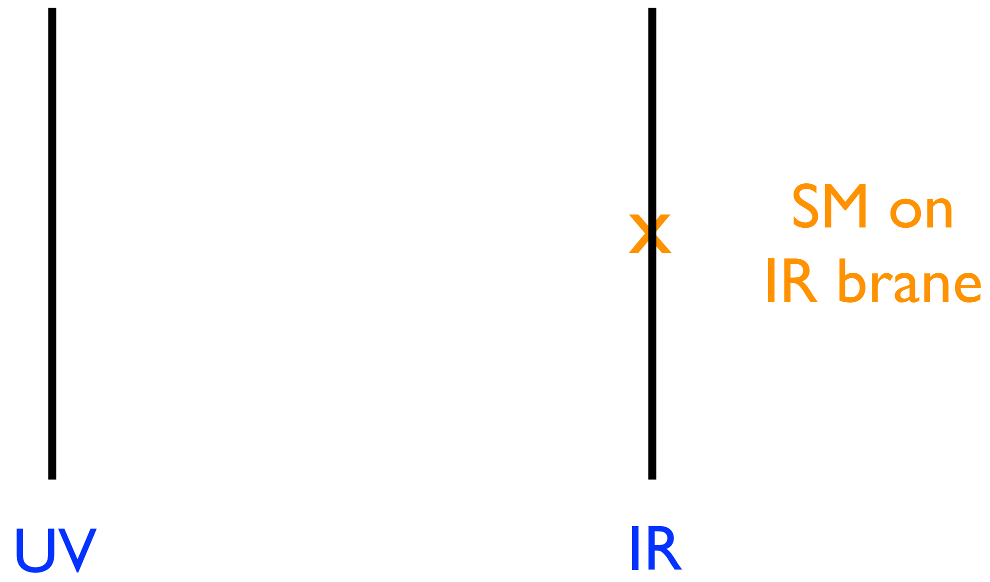
$k =$ *AdS curvature scale*

$\ell =$ size of 5th dimension

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

- Gauge hierarchy problem: Higgs mass

[Randall, Sundrum ‘99]



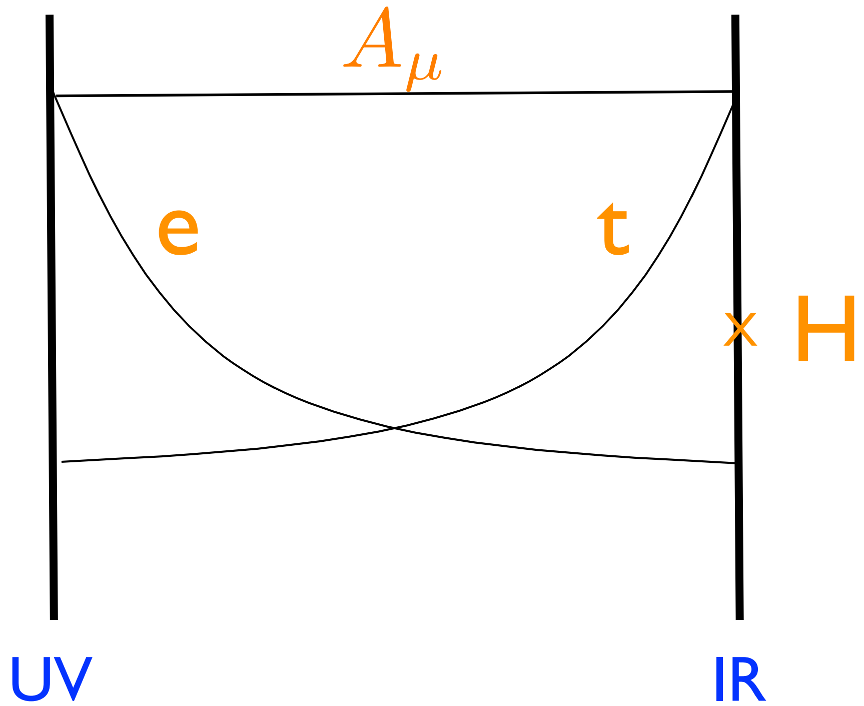
$$\Lambda_{SM} = \Lambda_{UV} e^{-k\ell}$$

$$\Rightarrow \quad m_H \sim \Lambda_{SM} = \mathcal{O}(\text{TeV})$$

$$(\Lambda_{UV} \sim M_P, k\ell \simeq 35)$$

Assuming a stabilization mechanism [Goldberger, Wise ’99]

- Fermion masses: e.g. electron, top [TG, Pomarol '00]



$$\psi^{(0)} \sim e^{(\frac{1}{2}-c)ky}$$

$c =$ bulk mass parameter

$$S_\Psi = \int d^5x \sqrt{-g}\,(\bar{\Psi}\Gamma^M D_M \Psi + \underbrace{M_\Psi}_{\equiv\, c\,k} \bar{\Psi}\Psi)$$

$-0.5 \lesssim c_i \lesssim 0.64$ explains fermion mass hierarchy $m_e \longrightarrow m_t$

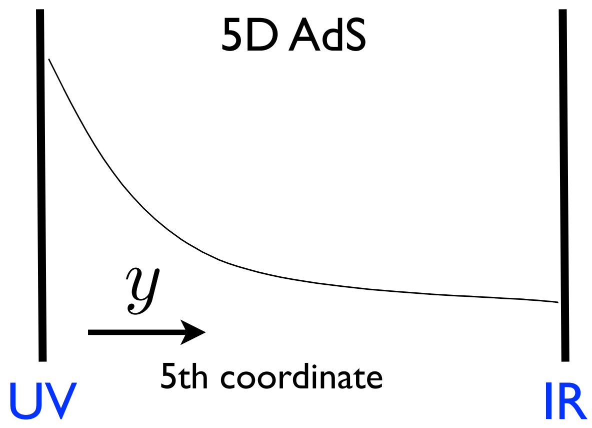
Neutrino masses [Grossman, Neubert '99]

Remarkably, warped 5th dimension encodes 4D strong dynamics!

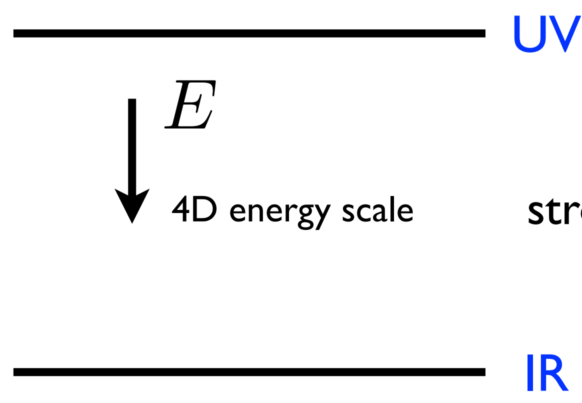
AdS/CFT [Maldacena ’97]

AdS/CFT dictionary

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



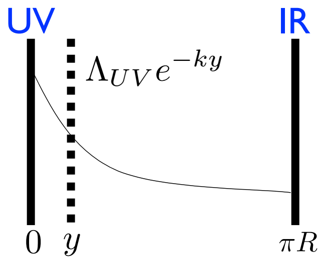
⇔



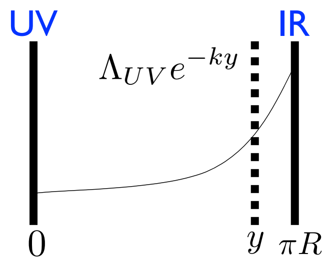
Large N, strongly-coupled 4D CFT

“Slice of AdS” ⇔ strongly-coupled CFT + elementary sector

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

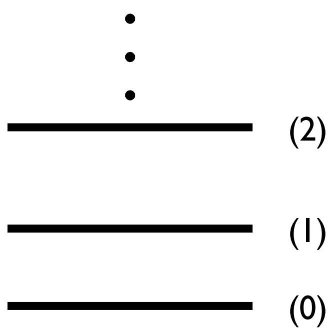


UV localized field ⟺ elementary state



IR localized field ⟺ CFT bound state

Kaluza-Klein tower



⟺

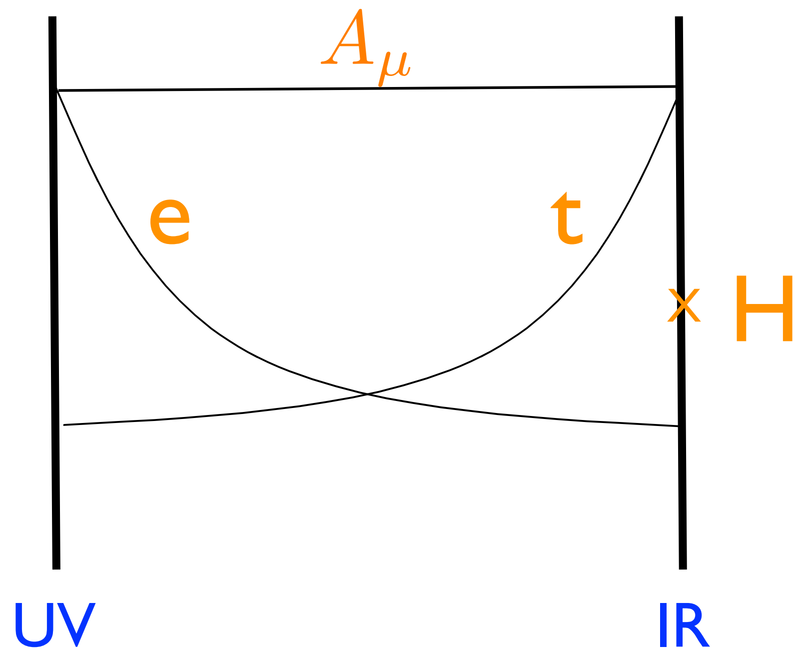
Tower of resonances

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

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

5D warped bulk SM

[Davoudiasl, Hewett, Rizzo '99; Pomarol '00; Chang et al '00; Grossman, Neubert '99; TG, Pomarol '00; Huber, Shafi '00; Agashe, Delgado, May, Sundrum '03]



AdS/CFT

4D Partially Composite SM

[D. B. Kaplan '91]

Composite: Higgs, top quark

$(\Lambda_H \simeq \Lambda_t \sim \Lambda_{IR})$

Elementary: light fermions, gauge bosons

$(\Lambda_A \lesssim \Lambda_f \sim \Lambda_{UV})$

Analogy: QED + hadrons

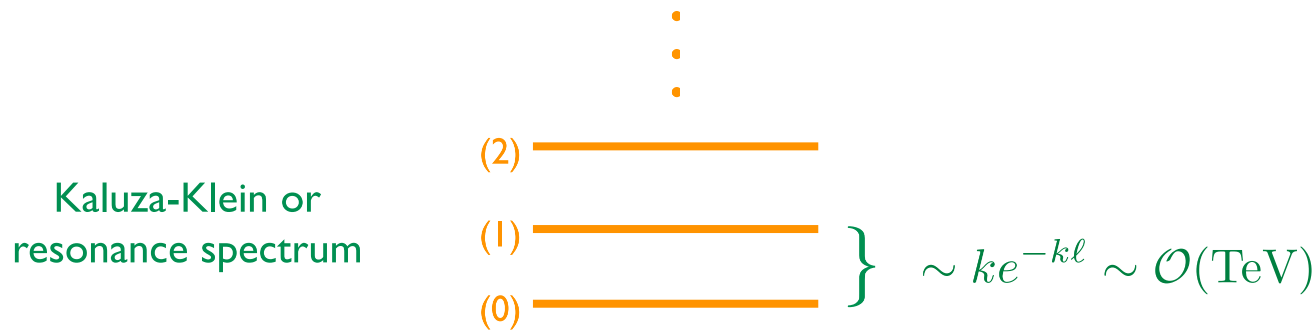
electron = elementary (QED)

$(\Lambda_e \sim M_P)$

p, n = composite (QCD)

$(\Lambda_{p,n} \sim \Lambda_{QCD})$

Signature of a warped extra dimension:



- KK graviton (spin-2 resonances) [Davoudiasl, Hewett, Rizzo '99]

  Most analyses assume original RS1--fermions on IR brane $(e.g. \mathrm{D0} : m_{G^{(1)}} \gtrsim 560 - 1050\,\mathrm{GeV})$

  BUT, with bulk fermions:

  $$e.g. \quad gg \to G^{(1)} \to t_R t_R$$

  ➡ Reach up to 1.5-2 TeV at LHC with 100 fb^-1

  [Fitzpatrick, Kaplan, Randall, Wang '07; Agashe, Davoudiasl, Perez, Soni '07]

- KK gluon (spin-1 resonance)

  $$m_g^{(1)} \simeq 0.64\, m_G^{(1)}$$

  ➡ Reach up to 4 TeV at LHC with 100 fb^-1

  [Agashe, Belyaev, Krupovnickas, Perez, Virzi '06; Lillie, Randall, Wang '07]

What about the Higgs boson?

(Big) hierarchy problem solved!

$$m_H \propto \underbrace{\Lambda_{IR}}_{\sim \text{TeV}} \ll \underbrace{\Lambda_{UV}}_{\sim \text{M}_\text{P}}$$

BUT want $\quad m_H \ll \underbrace{\Lambda_{IR}}_{\sim \text{TeV}}$

Little hierarchy problem!

Solution: Use symmetry!

Spontaneous symmetry breaking $(\phi \to \phi + c)$

OR

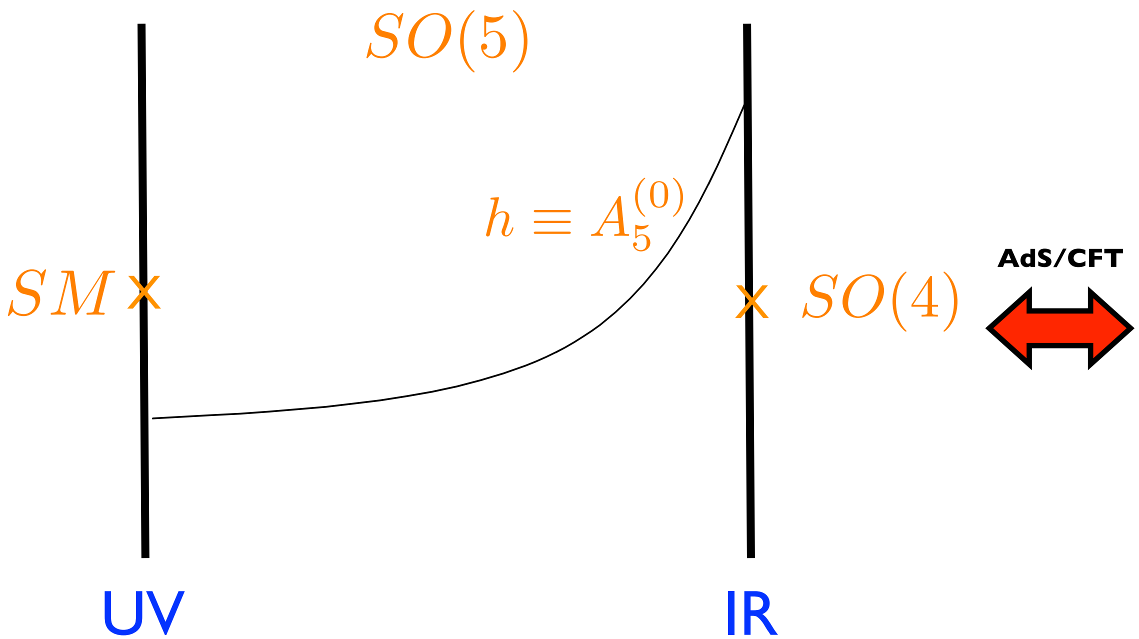
Supersymmetry!

1. Higgs as a pseudo Nambu-Goldstone boson

[Contino, Nomura, Pomarol ‘03; Agashe Contino, Pomarol ‘04]

5D gauge field: $A_M = (A_\mu, \underbrace{A_5})$

Scalar component--Identify as Higgs!



Elementary SM gauge bosons

$SO(5)/SO(4) = \mathbf{2}$ of $SU(2)_L$

→ Composite Higgs!

Fermions

e.g. top quark:

$$\mathbf{5} = \underbrace{2_{7/6}} + \overbrace{2_{1/6}}^{t_L} + \overbrace{1_{2/3}}^{t_R}$$

Exotic states of charge 5/3!

LHC: $q\bar{q}, gg \to q^*_{5/3}\bar{q}^*_{5/3} \to W^+ t W^- \bar{t}$

up to TeV with 20 fb^-1
same-sign dilepton

SO(5) broken by top-quark $(m_{2_{7/6}} \gg m_t)$

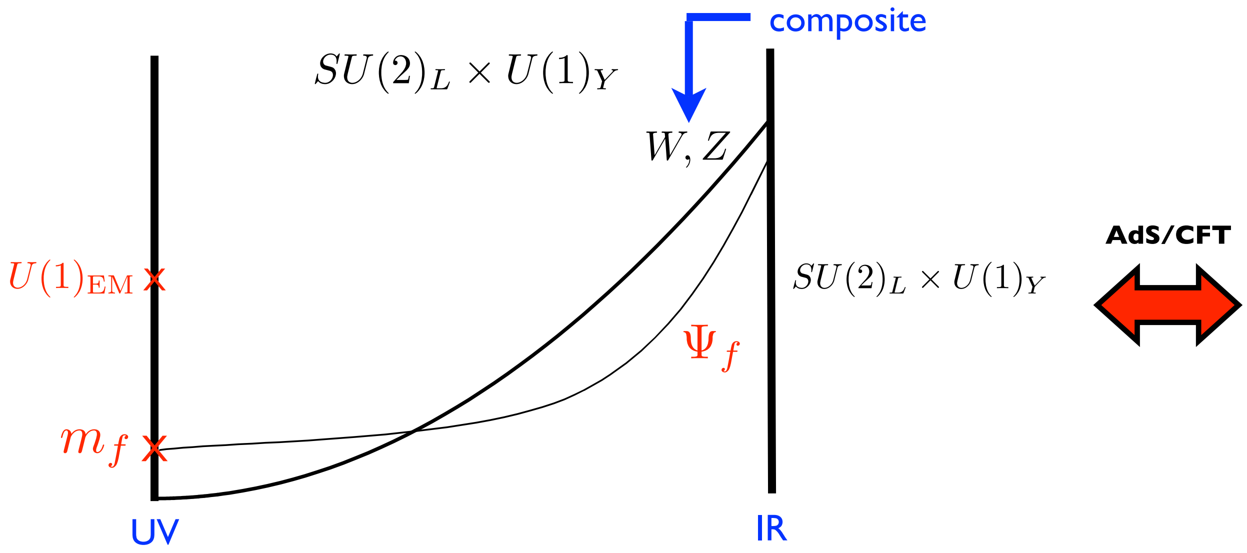
$$\Rightarrow \quad m_H^2 = 0 + \frac{g^2}{16\pi^2}(ke^{-k\ell})^2$$

shift symmetry (5D gauge symmetry)

Obtain:

$m_H \lesssim 160\,\mathrm{GeV}$ $\quad S \lesssim 0.3$ $\quad T \simeq 0$

Can even have no Higgs! *Emergent EWSB* [Cui, TG, Wells '09]



Composite W, Z bosons

→ Electroweak symmetry is NOT fundamental!

Obtain: $\zeta_L k \simeq 1000, \zeta_Q k \simeq 1700, \zeta_Y k \simeq 0.2$
$m_{IR} \simeq 1.8\,\text{TeV}$
⇒ $S \simeq 0.1, \quad T \simeq 0.02$

W,Z boson-fermion couplings: [Cui, TG, Stokes: arXiv:1006.3322]

⇒ {
- Light fermions: nonuniversality at the per-mille level!
- 3rd generation: nonuniversality at 15%-25% level ← Anomalous top couplings lead to tension with EWPT

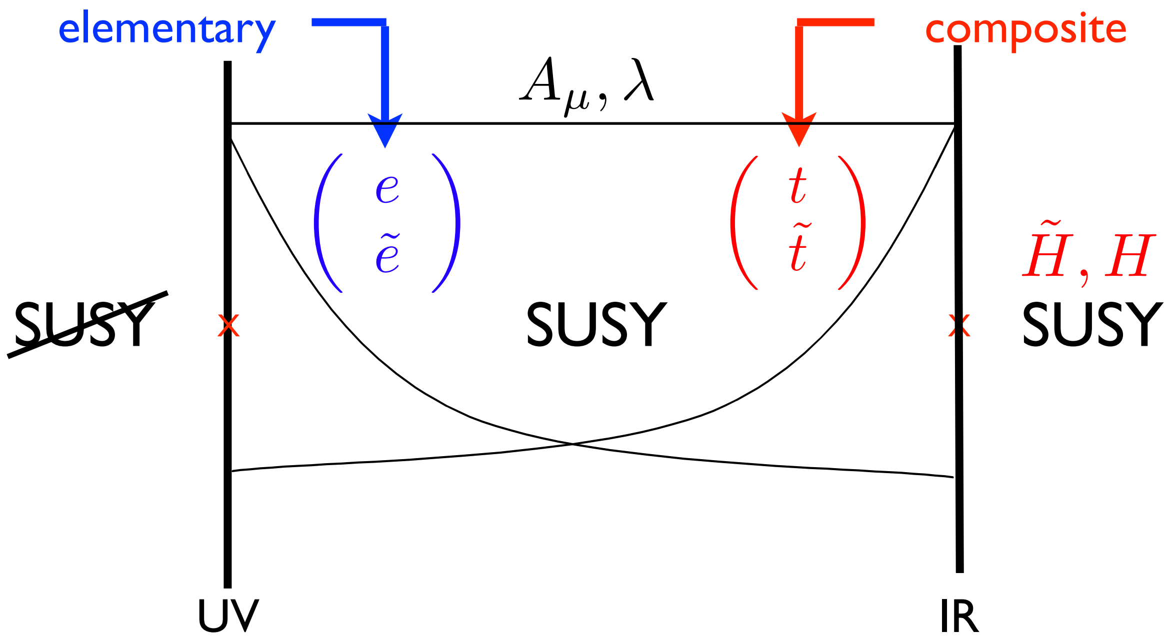
→ Wtb: 20% level @ Tevatron arXiv:0903.0850
Single top production

Ztt: 40% level @ LHC with 300 fb^-1

2. Partial/Accidental SUSY

Use supersymmetry to keep Higgs boson light!

SUSY broken at UV scale ⇨ **Partial SUSY** [TG, Pomarol '03]



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

Fermion mass spectrum determines sparticle spectrum!

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

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

BUT:

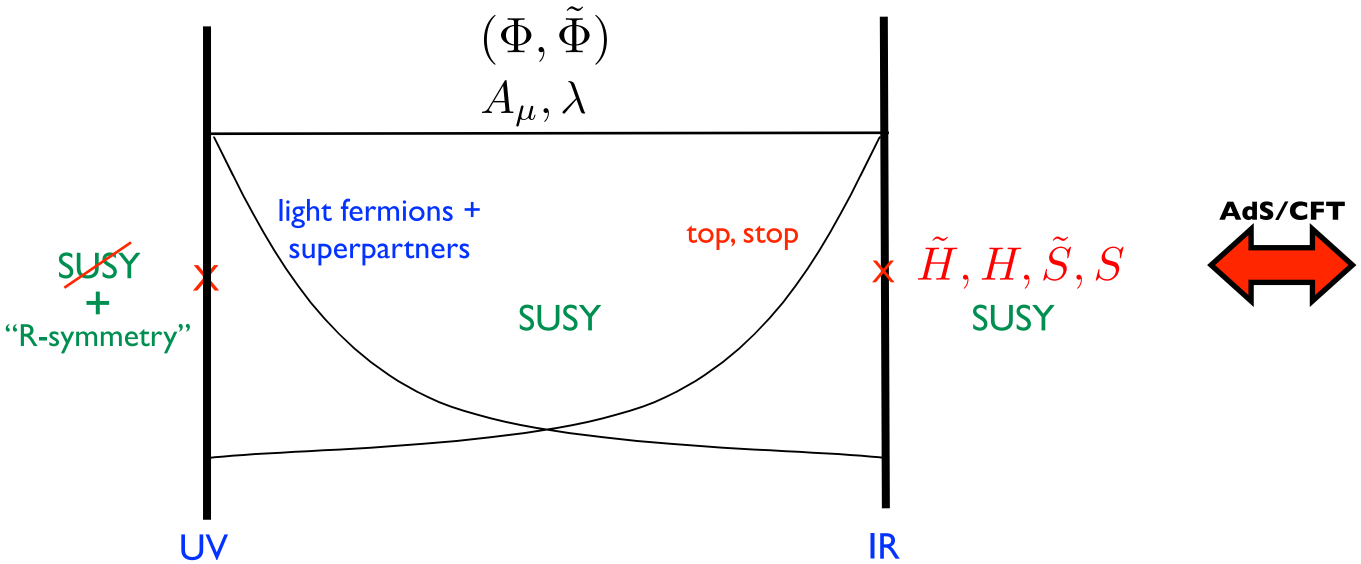
- Potentially large D-term contributions to soft masses $\mathcal{L} \supset m_0^2 D$
- No light gaugino ➡ $\Delta m_H^2 \sim \frac{g^2}{16\pi^2}\Lambda_{IR}^2 \longrightarrow$ Limit to increasing Λ_{IR}

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]



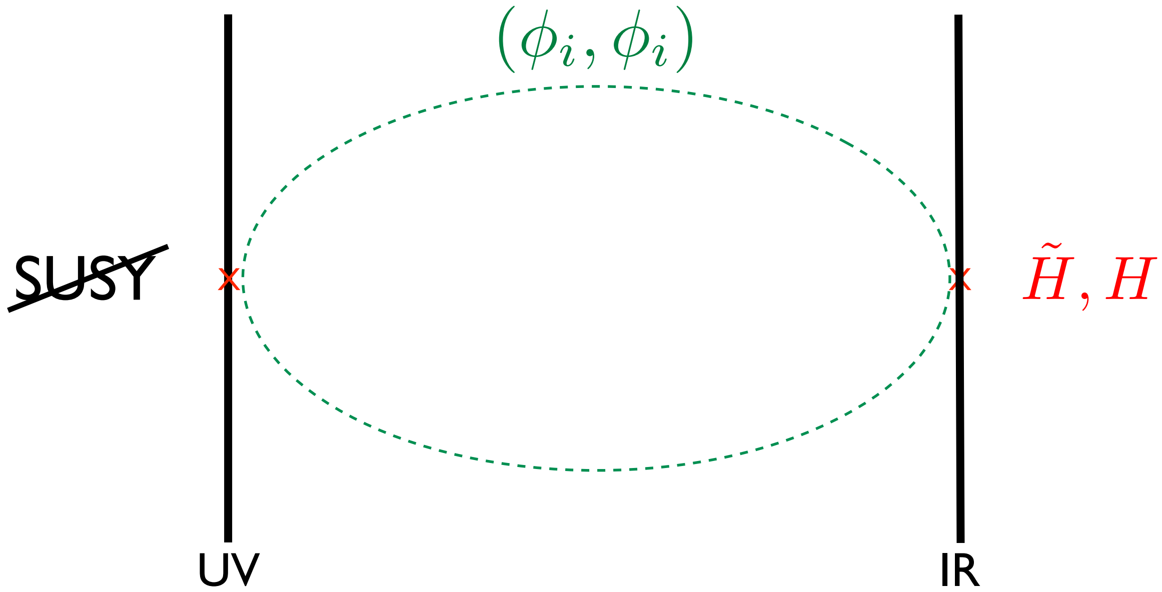
SM + composite H, Higgsino, t, stop

FEATURES

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

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:

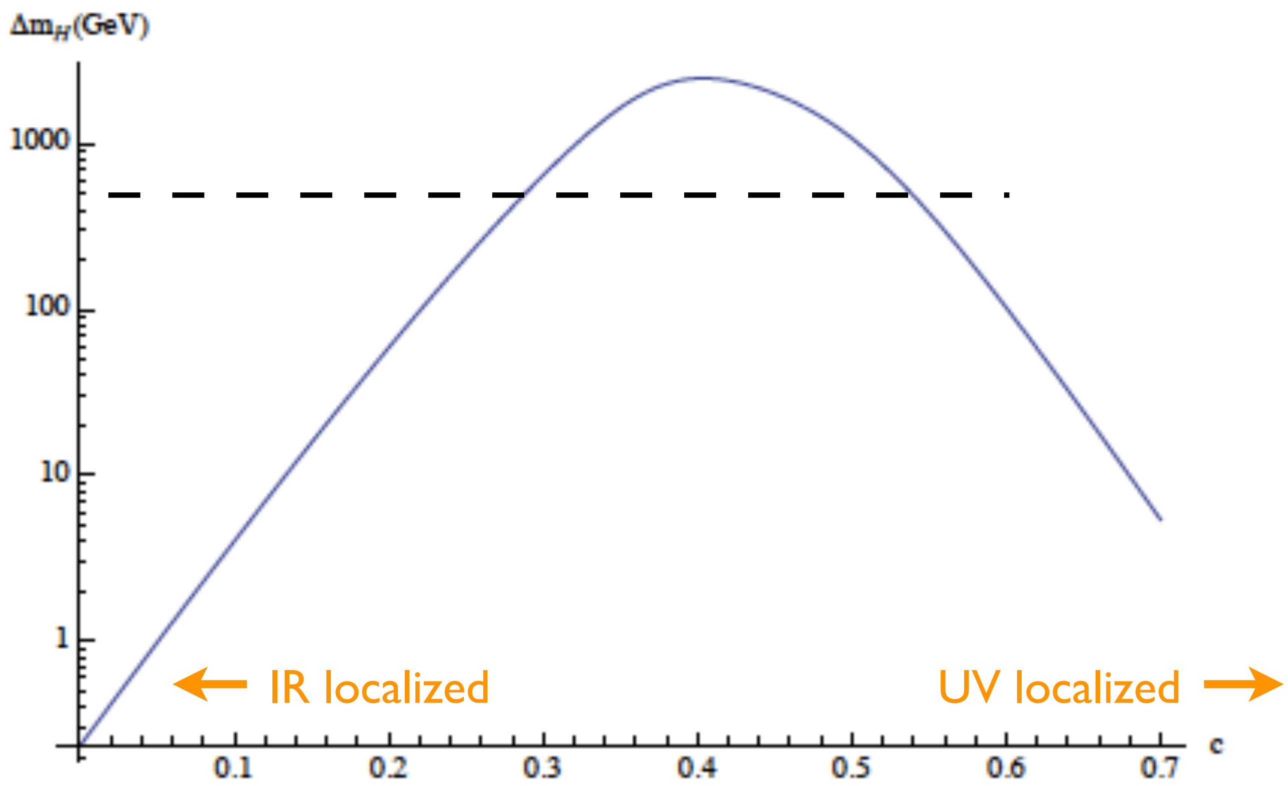
$$G_{F,B}(p) = -\frac{e^{2k\ell}}{k}\frac{\tilde{I}^{\rm UV}_{c+1/2}(\frac{p}{k})\; K_{c+1/2}(\frac{p}{m_{\rm IR}}) - \tilde{K}^{\rm UV}_{c+1/2}(\frac{p}{k})\; I_{c+1/2}(\frac{p}{m_{\rm IR}})}{\tilde{I}^{\rm IR}_{c+1/2}(\frac{p}{m_{\rm IR}})\;\tilde{K}^{\rm UV}_{c+1/2}(\frac{p}{k}) - \tilde{I}^{\rm UV}_{c+1/2}(\frac{p}{k})\;\tilde{K}^{\rm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

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

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

Bulk hypermultiplet correction to Higgs mass

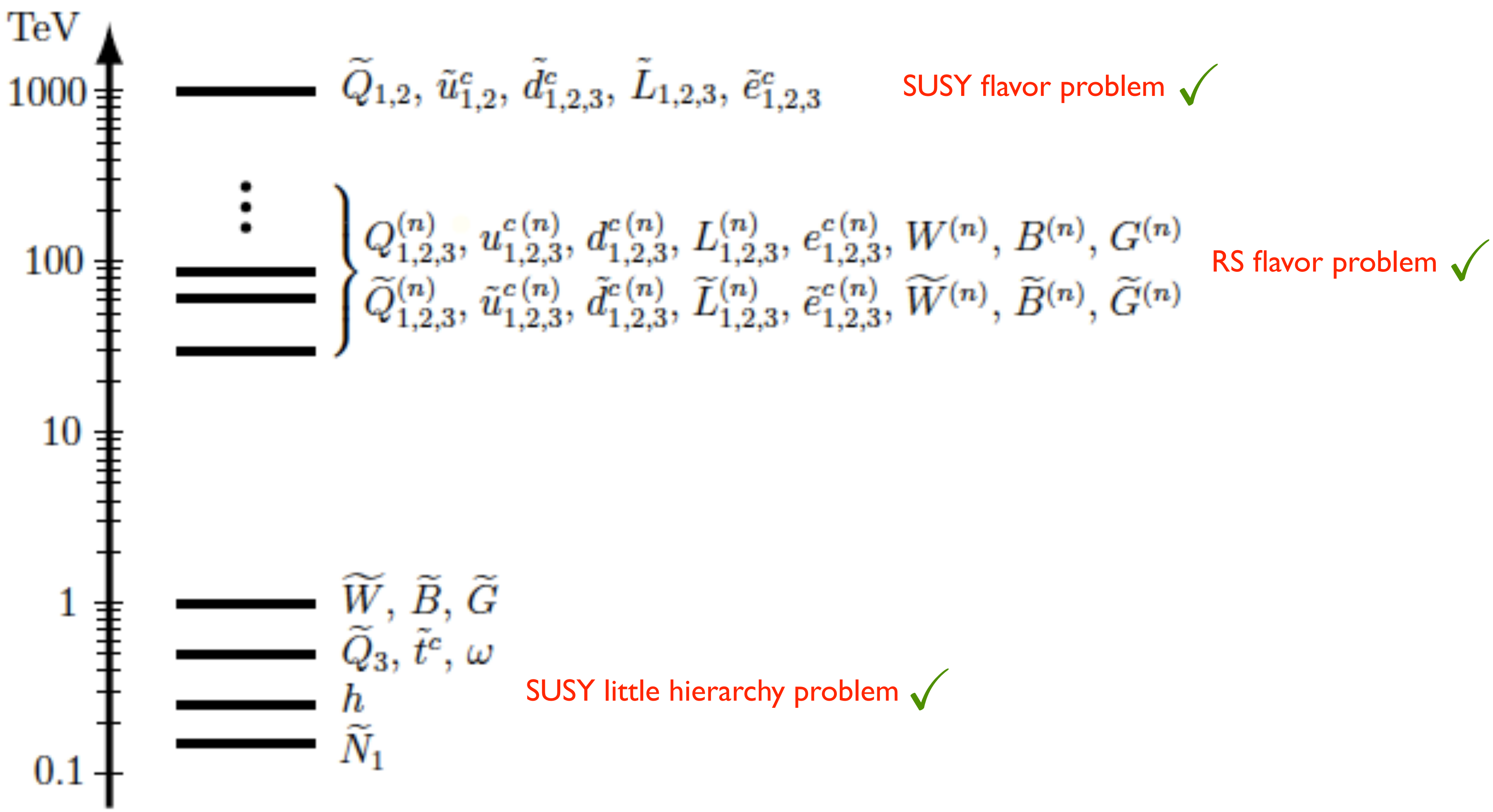
$(m_{IR} = 10\,\mathrm{TeV},\ m^{UV}_{soft} = 1000\,\mathrm{TeV})$ [TG, von Harling,Setzer arXiv:1104.3171]



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

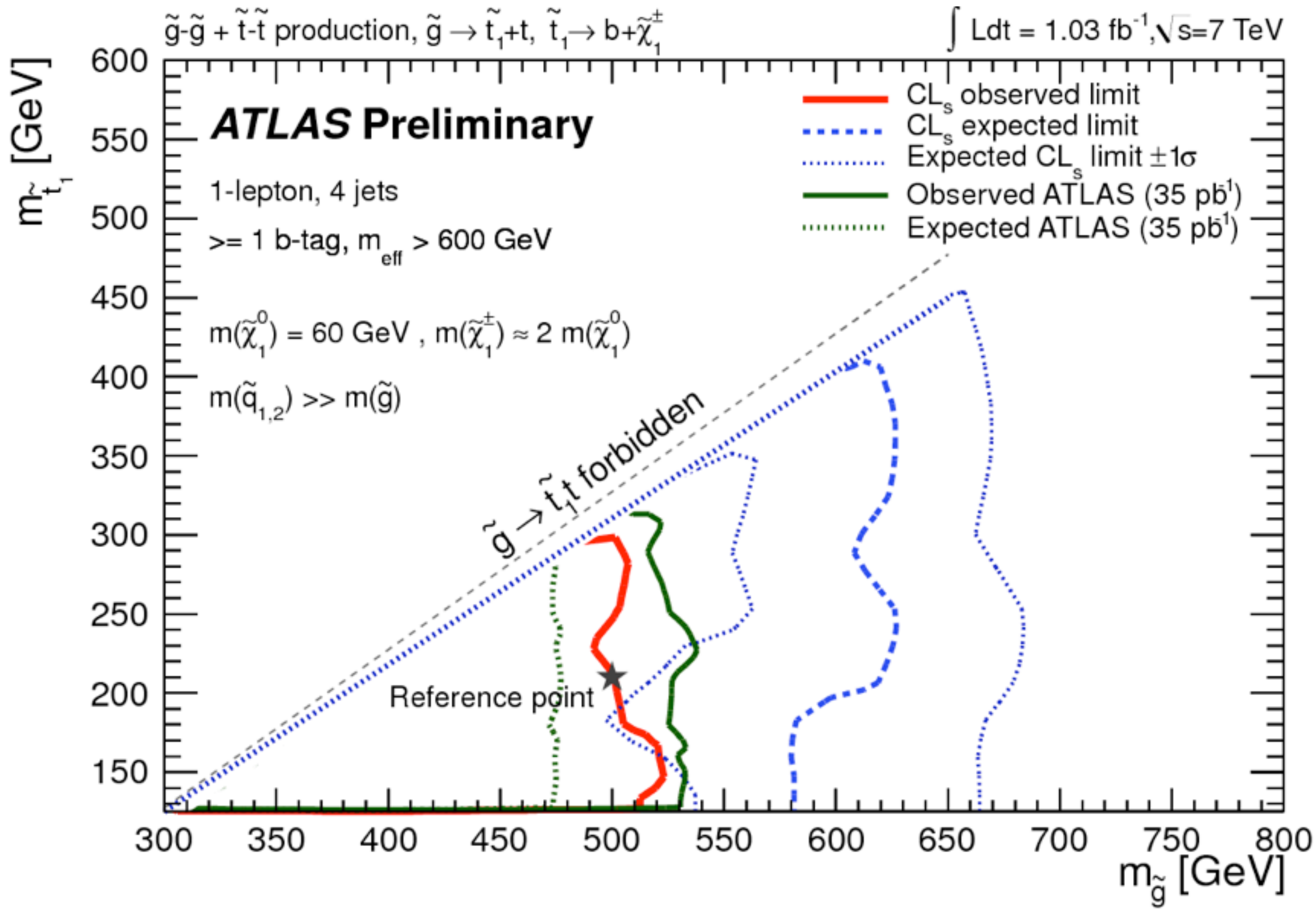
Accidental SUSY spectrum:

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



LHC 3rd generation limits:

ATLAS-CONF-2011-130 17 August 2011

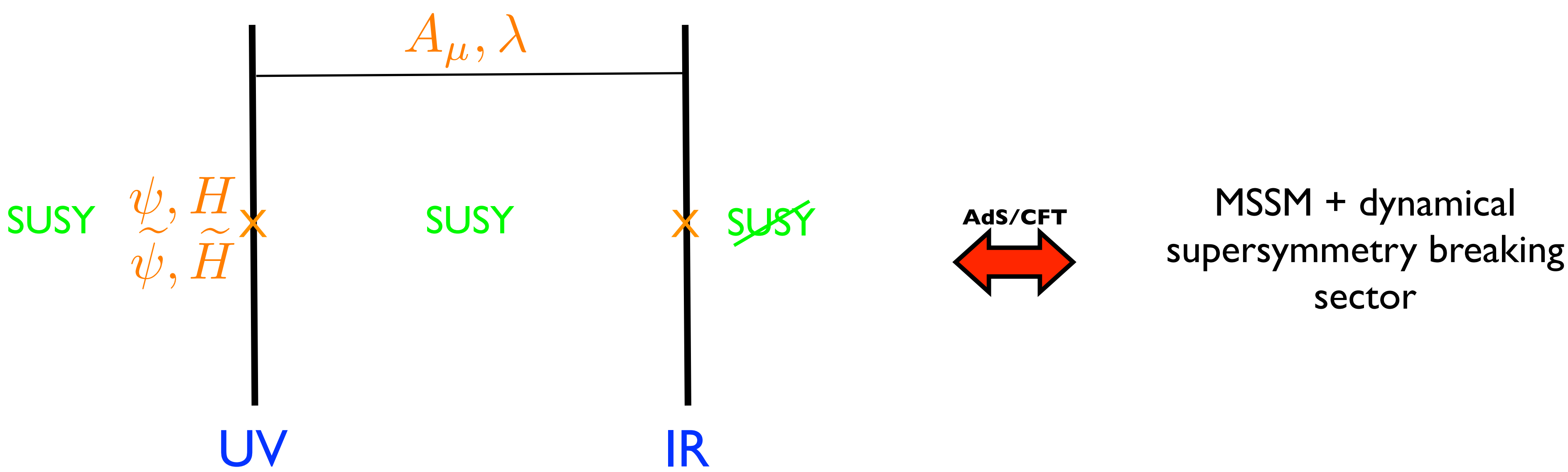


$$m_{\tilde{g}} \gtrsim 500\,\mathrm{GeV} \qquad m_{\tilde{t}} \gtrsim ?$$

Alternate possibilities:

Use strong dynamics to break SUSY!

e.g. warped MSSM [TG, Pomarol 00]



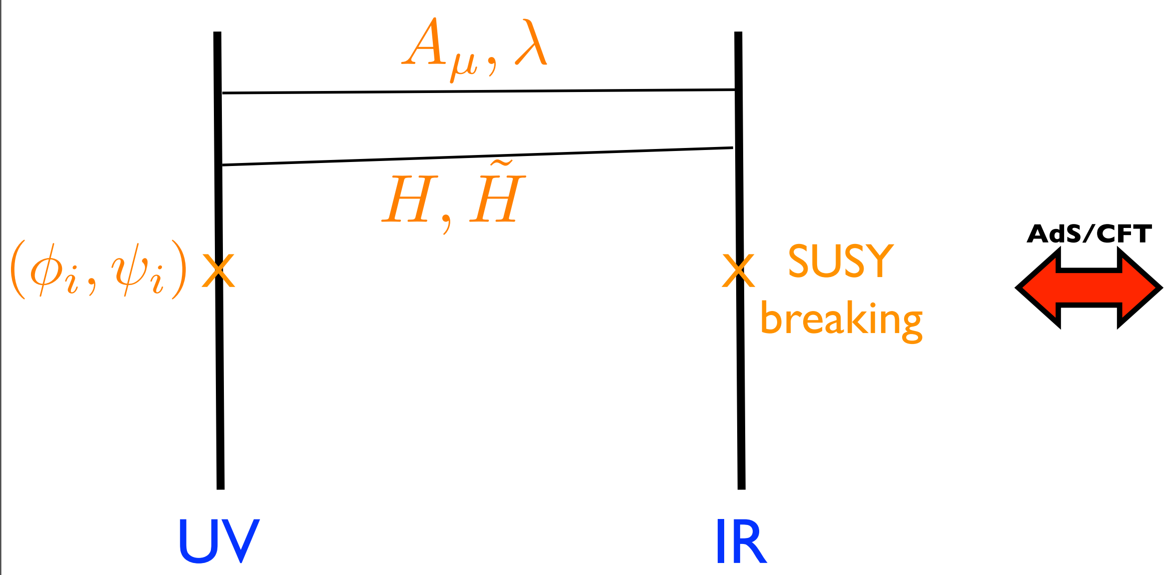
$$\Lambda_{SUSY} = \Lambda_{UV} e^{-k\ell} \sim \mathcal{O}(\text{TeV})$$

Naturally explains SUSY breaking scale!

MSSM Higgs mixes with strong sector:

[TG, Pomarol arXiv:1107.4697]

[See also: Azatov, Galloway, Luty arXiv:1106.3346; 1106.4815
Heckman, Kumar, Vafa, Wecht arXiv: 1108.3849]



$$\int d^2\theta \, g_i H_i \mathcal{O}_i$$

$\rightarrow$

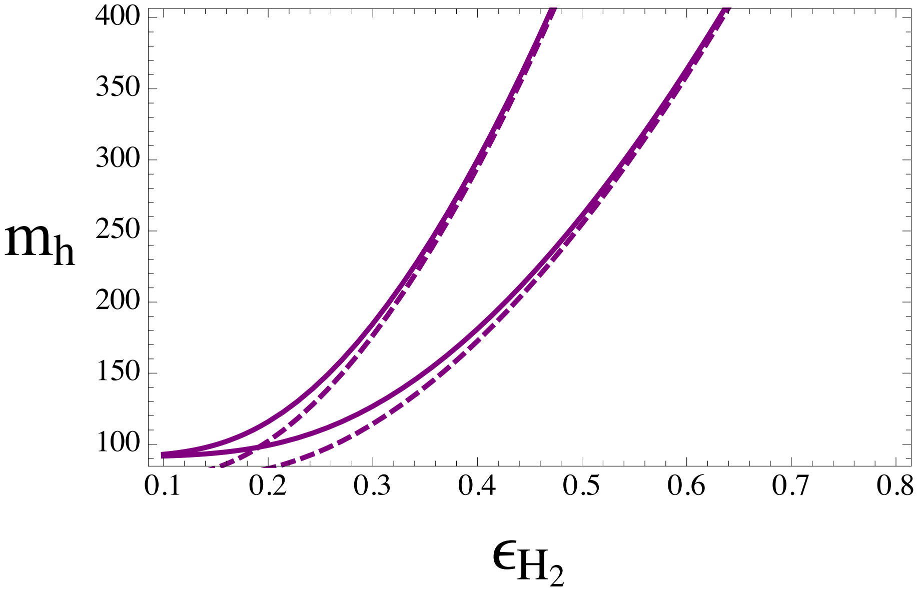
$$\Delta m_i^2 \sim \epsilon_i^2 \Lambda_{IR}^2$$ Higgs mass

$$\Delta \lambda_i \sim \epsilon_i^4 \frac{16\pi^2}{N}$$ Higgs quartic

where $\epsilon_i \sim \dfrac{g_i(\Lambda_{IR})}{4\pi/\sqrt{N}}$

⇨ Can increase lightest MSSM Higgs mass!

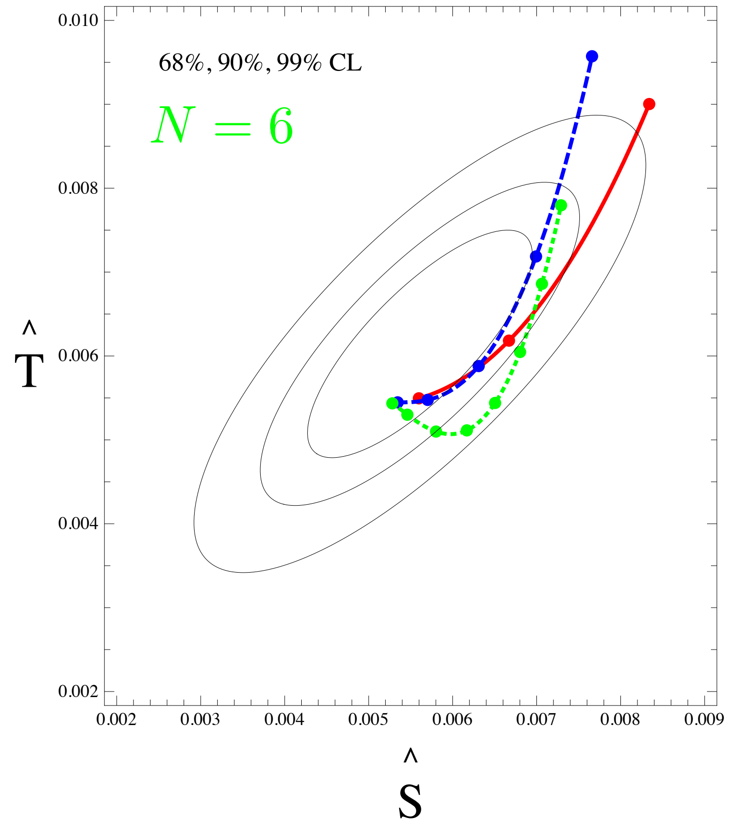
Lightest MSSM Higgs mass



Solid (dashed) = $\tan\beta \gg 1$ $(\tan\beta = 3)$

Upper (lower) = $c_\lambda \simeq 1(0.3)$

Oblique parameters



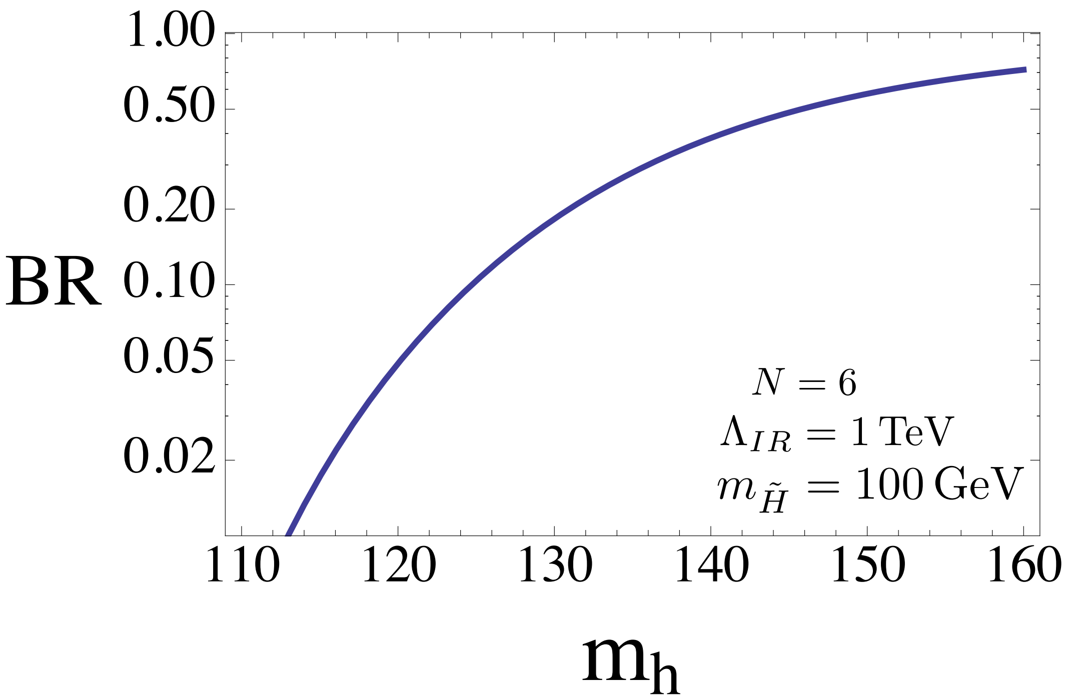
Solid, dashed, dotted = $\Lambda_{IR} = 1, 2, 4\,\text{TeV}$

Dots start at $\epsilon_{H_2} = 0.1$ and increase by 0.1.

LHC signal:

LSP = Gravitino ⇨ Sizeable invisible Higgs decay

$$\Gamma(h \to \tilde{G}\tilde{\chi}) \simeq \frac{1}{16\pi}\frac{m_h^5}{F^2}\left[1-\left(\frac{m_{\tilde{\chi}}}{m_h}\right)^2\right]^4$$



Distinctive signal

⟶ photon + MET

Summary

- Warped dimension provides new ways to explain hierarchies
- AdS/CFT ⇨ equivalent to 4D strong dynamics (EWSB or SUSY breaking)
- Models leads to distinctive collider signals
- Will be tested at LHC