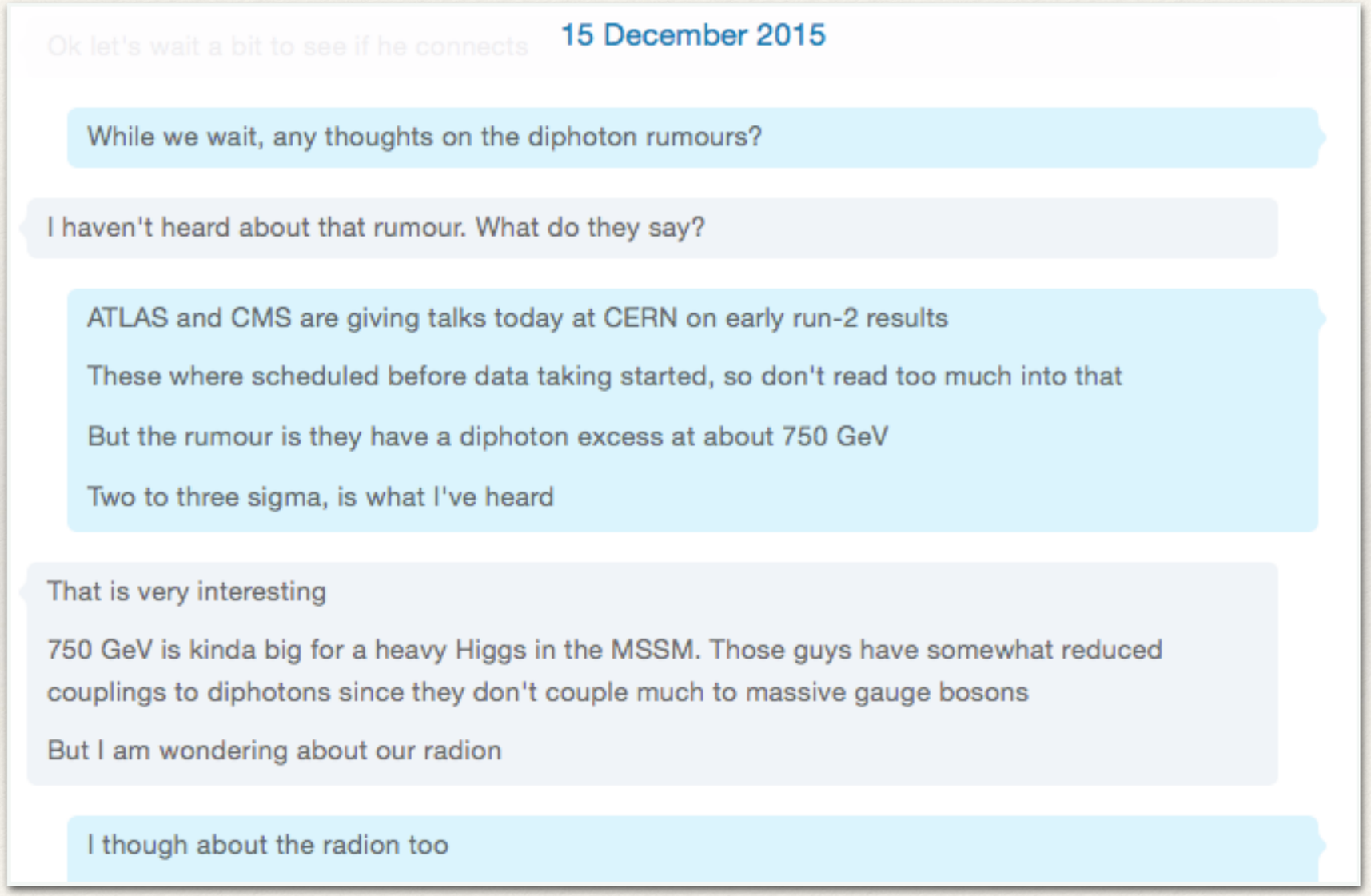
8th January 2016, CTPU Diphoton Workshop

Radion (Dilaton) Explanations

A. Spray, based on work with
P. Cox, T. S. Ray & A. Medina,
arXiv:1311.3663 & 1512.05618

A Chance Skype Conversation



Outline

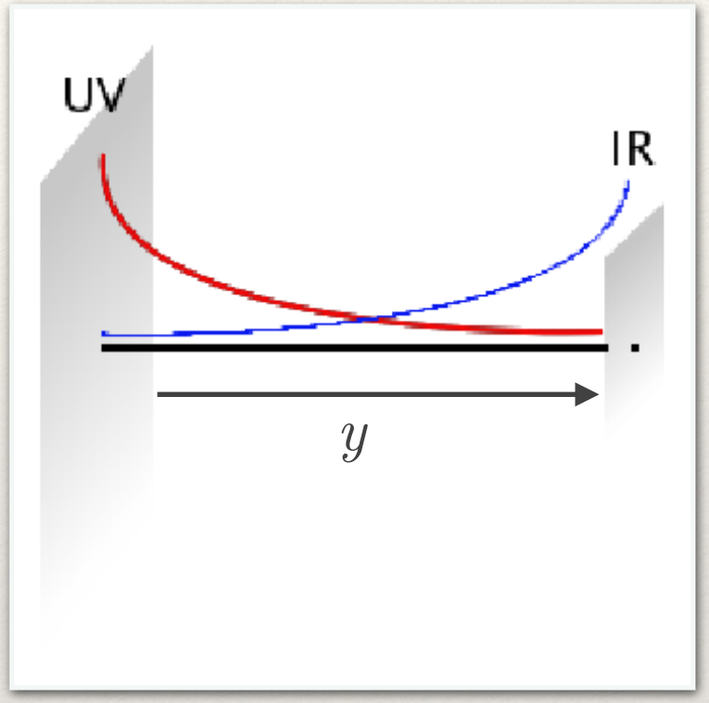
1. Radions
   (a) Randall-Sundrum Models
   (b) Brane and Bulk Higgses
2. Fitting the Diphoton Excess
   (a) The problem of WW and $\mathrm{t\bar{t}}$
   (b) Allowed regions
3. Implications
   (a) Future resonance measurements
   (b) RS Models
4. Conclusions

Radions

Randall-Sundrum Models

- 5D extension of SM:
  - Non-trivial warped geometry (AdS_5,)
  - $\mathbb{Z}_2$ orbifold with two fixed points (branes)

$$ds^2 = e^{-2ky}\, dx^\mu dx_\mu - dy^2$$



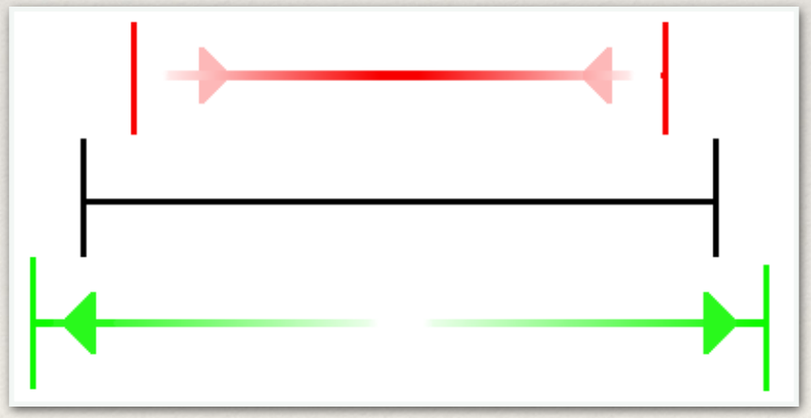
- Curvature useful:
  - Solution to hierarchy problem
  - Model of flavour physics
- SM fields (except possibly Higgs) live in full 5D space

The Radion

- Metric fluctuations = Graviton field
  - 5 degrees of freedom in 5D
  - 3 have zero modes: normal graviton plus scalar radion

$$ds^2 = e^{-2ky-2r}\left(\eta_{\mu\nu} + h_{\mu\nu}\right) dx^\mu dx^\nu - (1+2r)^2 dy^2$$

- Radion:
  - Corresponds to fluctuations in 5D size
  - Couples to stress-energy tensor
  - Is massless in pure RS

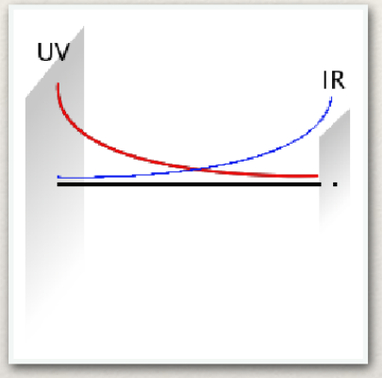


- Must add scalar(s) to give radion mass (Goldberger & Wise, PRL **83**)

Radion as Dilaton

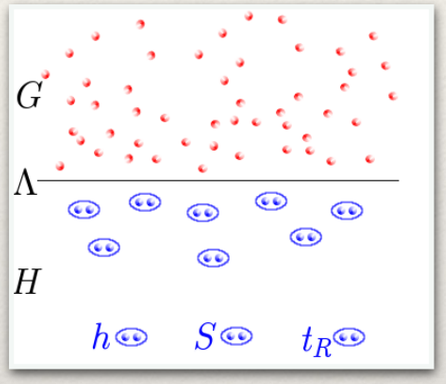
- AdS/CFT duality:

- 5D RS models



  - UV (IR) localised fields
  - Gauge Symmetries
  - Radion
    (size of extra dimension)

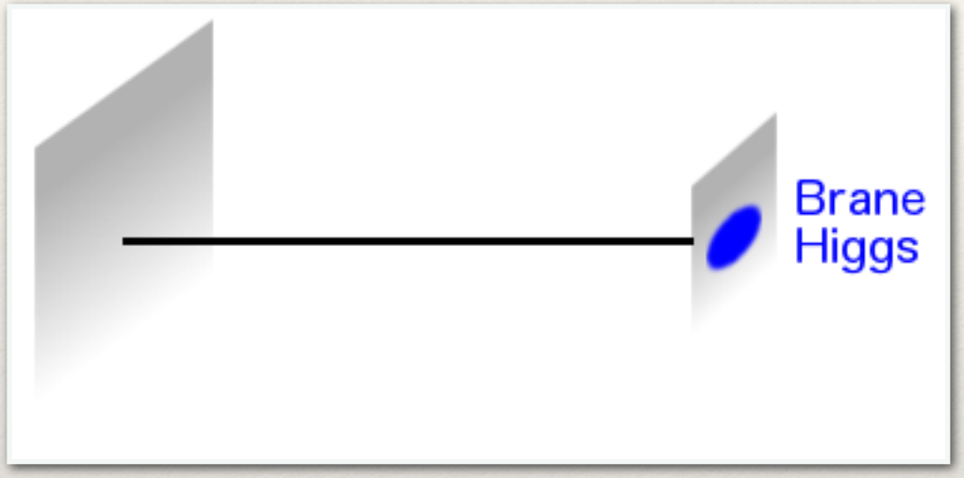
- 4D composite models

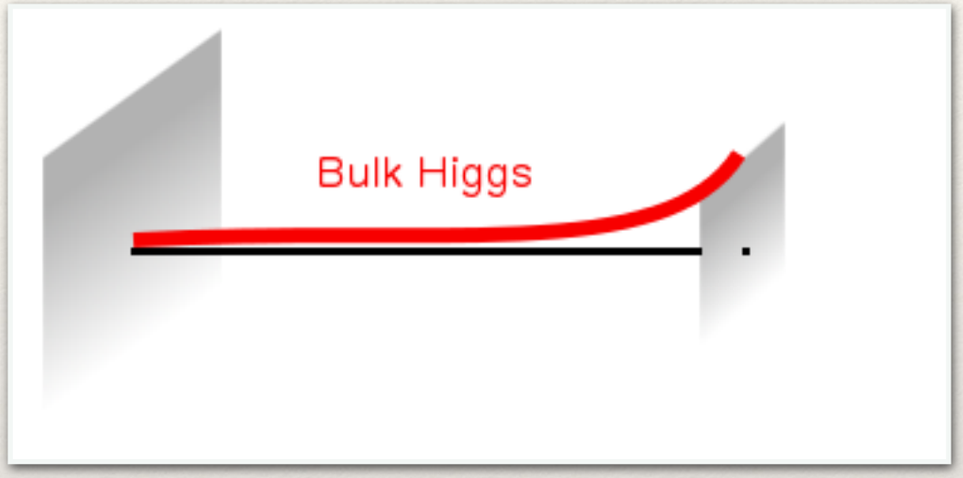


  - Elementary (Composite)
  - Global symmetries
  - Dilaton
    (conformal symmetry)

Bulk and Brane Higgses

- Choice for location of Higgs:





- More popular choice
- Radion-Higgs kinetic mixing
- Radion couples to SM mass terms

$$\mathcal{L} \supset \frac{m_W^2}{\Lambda_r}\, r\, W_\mu^+ W^{-\mu} + \frac{m_Z^2}{2\Lambda_r}\, r\, Z_\mu Z^\mu$$

- Valid 5D choice
- Mass & kinetic mixing
- Radion DOES NOT couple to W/Z mass terms

$$\mathcal{L} \supset \frac{1}{kL}\,\frac{1}{\Lambda_r}\, r\, W^a_{\mu\nu} W^{a\mu\nu}$$

Dilaton Coupling to Gauge Bosons

- In dual 4D theory, dilaton couples through conformal covariant derivative

$$\left(D_\mu - \Delta \frac{\partial_\mu r(x)}{r(x)}\right) H(x) + (1-6\xi)\left(H^\dagger D_\mu H\right) \frac{\partial_\mu r(x)}{r(x)}$$

- Vanishing coupling to W/Z mass terms: $\xi = 1/6$

- Also exists a 5D brane Higgs interpretation

$$S \supset \int_{IR} d^4x\, \xi\, R_4 H^\dagger H$$

- See Ahmed *et al*, `1512.05771`

A 4D Effective Model

- Previous work studied Radion-bulk Higgs system
  1311.3663
  - Back-reaction of Higgs VEV on metric
  - Varying Higgs 5D profile
  - Bulk & brane mixing terms
- Low energy theory: mixings as free parameters

$$\mathcal{L}_{eff} = \frac{1}{2}(\partial h)^2 - \frac{1}{2}m_h^2 h^2 + \frac{1}{2}(\partial r)^2 - \frac{1}{2}m_r^2 r^2 - c_1 \frac{v}{\Lambda_r}(\partial h)(\partial r) - c_3 \frac{v}{\Lambda_r} m_r^2 h\, r$$

- Radion/Higgs couplings unchanged (in this basis)

Fitting the Diphoton Excess

Signal Strength and Constraints

- Signal strength estimates (1512.04929):

$$\mu^{\rm ATLAS}_{13\ \rm TeV} = \sigma(pp \to S)_{13\ \rm TeV} \times \mathcal{B}(S \to \gamma\gamma) = 6.2^{+2.4}_{-2.0}\ \rm fb,$$

$$\mu^{\rm CMS}_{13\ \rm TeV} = \sigma(pp \to S)_{13\ \rm TeV} \times \mathcal{B}(S \to \gamma\gamma) = 5.6 \pm 2.4\ \rm fb.$$

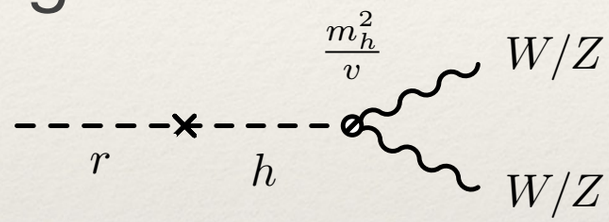
- 8 TeV Limits:

Final State	Observed Bound
$t\bar{t}$	< 300 fb
WW	< 38 fb
ZZ	< 17 fb
$Z\gamma$	< 4.0 fb
$\gamma\gamma$	< 1.4 fb
hh	< 36 fb
jj	< 2.5 pb

Stringent constraints for electroweak final states

Mixing Paramaters

- Deleterious effects of Radion-Higgs mixing:
  - Enhanced WW/ZZ signal at 750 GeV from Higgs coupling

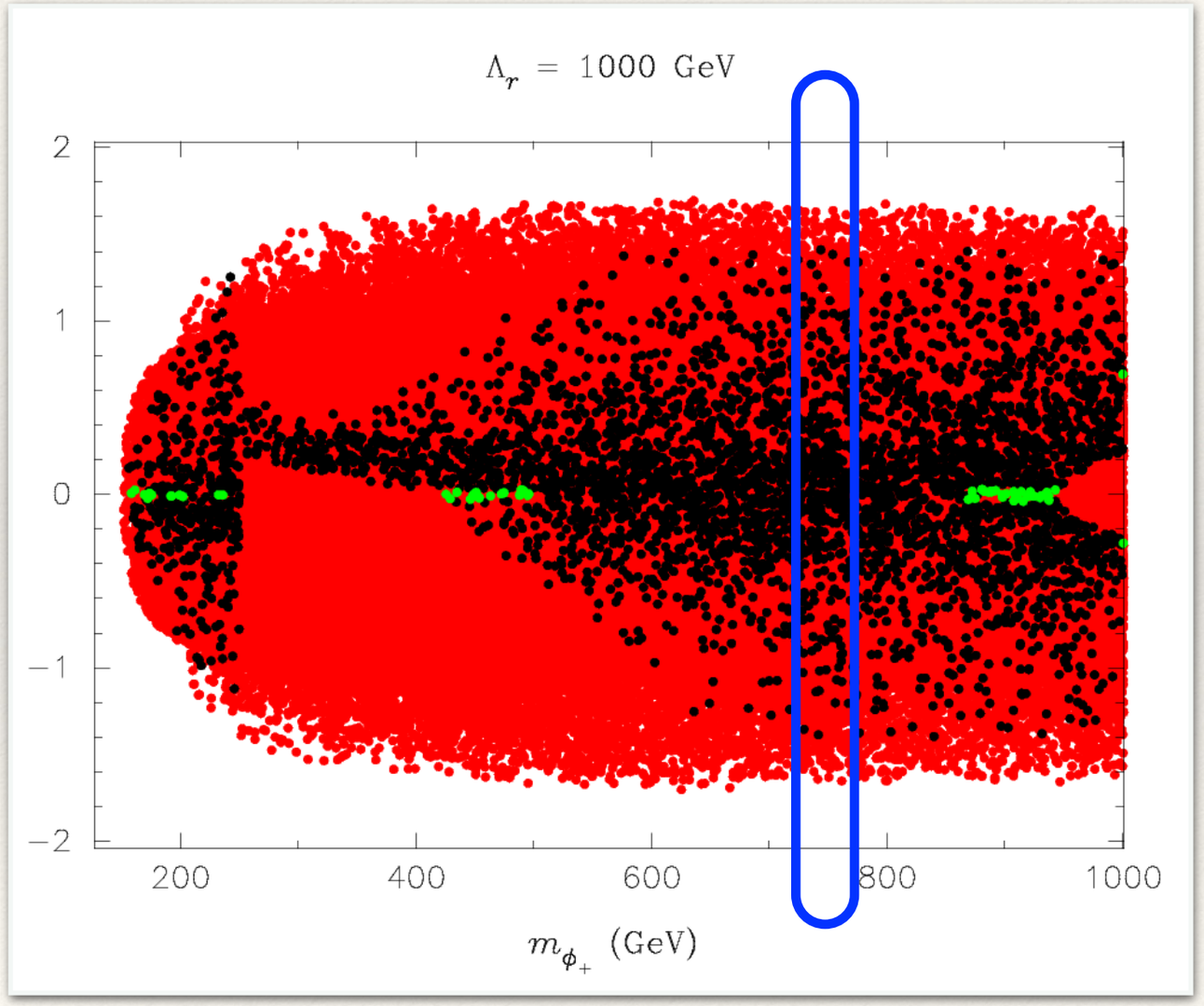


  - Enhanced hh signal at 750 GeV directly from mixing

$$\mathcal{L} \supset \frac{1}{2} \frac{2m_h^2 - c_1 m_r^2}{\Lambda_r} r\, h^2$$

- Consider zero-mixing over than fine-tuned couplings (*cf* conformal limit)
- See also Ahmed *et al* (`1512.05771`), similar conclusion

A Parameter Scan



- Parameter scan from 1311.3663
  - Excluded by Higgs decays
  - Excluded by direct searches
  - Allowed
- No points found at 750 GeV

Problems with ditops

- $t\bar{t}$ searches at 8 TeV bound branching ratios

$$\frac{\mathcal{B}(r \to t\bar{t})}{\mathcal{B}(r \to \gamma\gamma)} < \frac{300}{6} \times \frac{\sigma(pp \to r)_{13\ \mathrm{TeV}}}{\sigma(pp \to r)_{8\ \mathrm{TeV}}} \approx 235$$

- Inconsistent with RS warping from $\mathrm{M_{Pl}}$ to TeV scale
- Radion coupling to γ & g enhanced with less warping

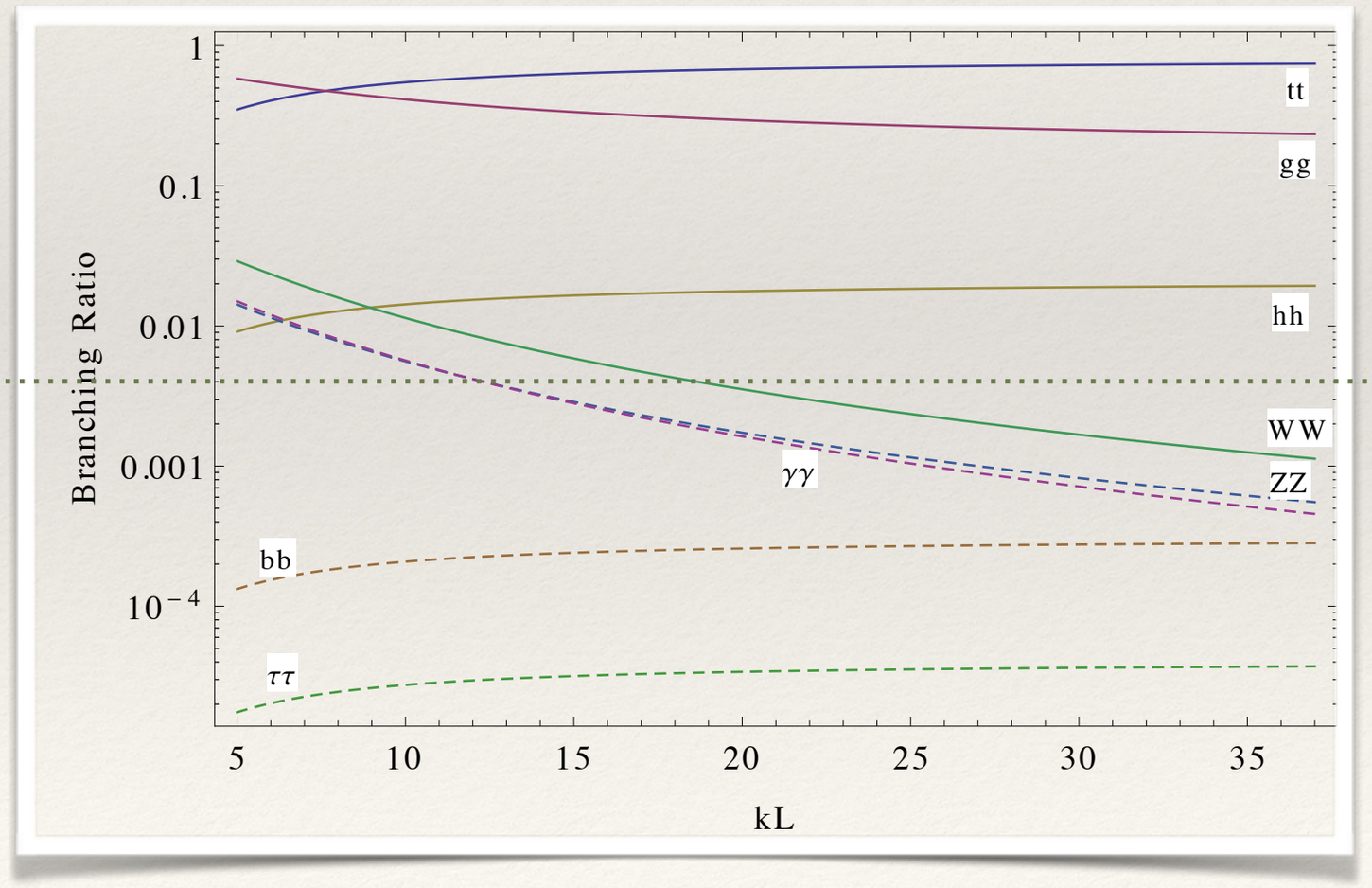
SM final state	Radion coupling
$\gamma\gamma$	$-\frac{1}{\Lambda_r}\left(\frac{1}{kL} + \left[b_{QED} - F_1(\tau_{W,r}) - \frac{4}{3}F_{1/2}(\tau_{t,r})\right]\frac{\alpha_{EM}}{2\pi}\right)$
gg	$-\frac{1}{\Lambda_r}\left(\frac{1}{kL} + \left[b_{QCD} - \frac{1}{2}F_{1/2}(\tau_{t,r})\right]\frac{\alpha_3}{2\pi}\right)$

- Also enhances W/Z coupling, but under control

Branching Ratios

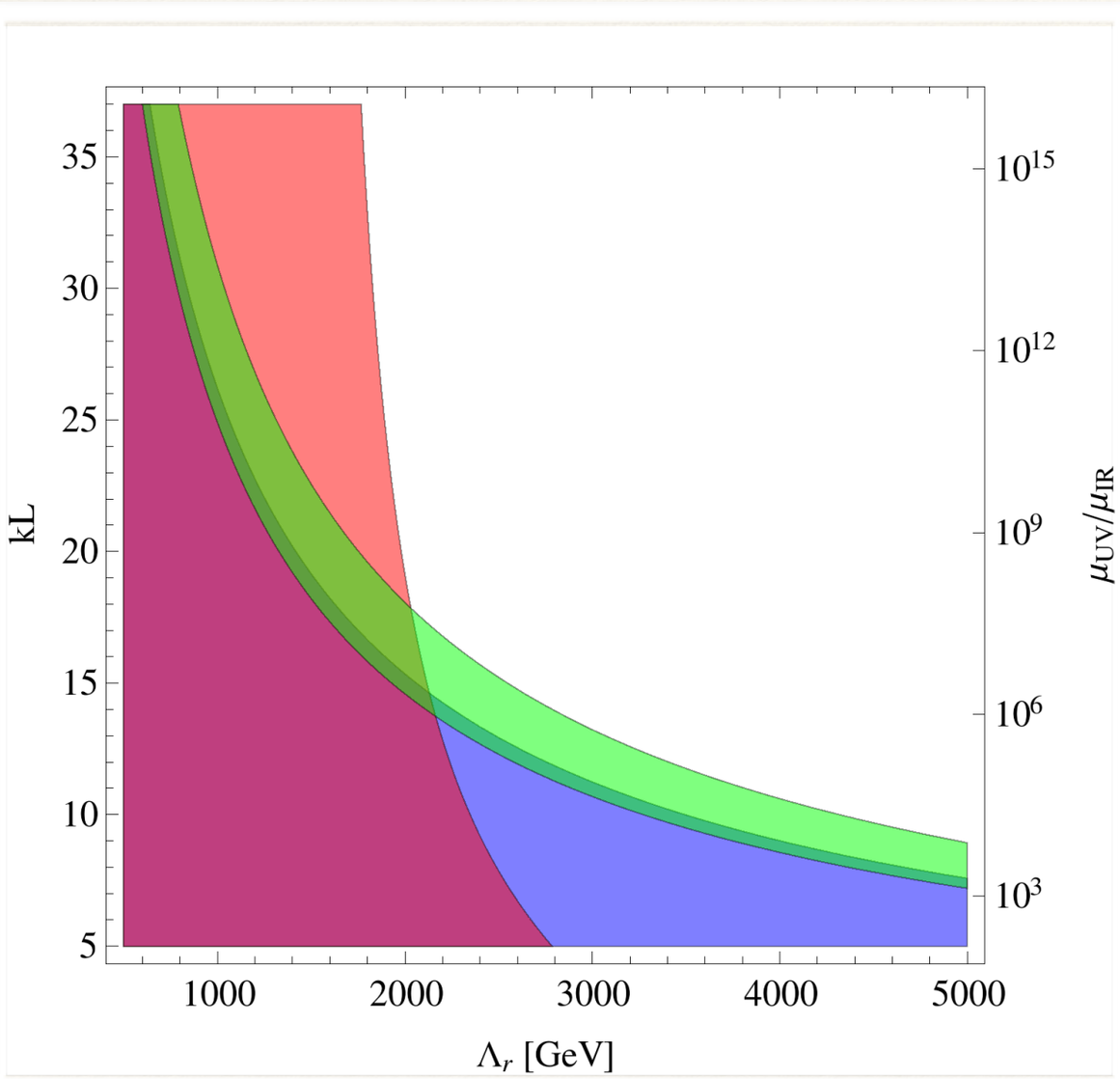
- $t\bar{t}$ searches at 8 TeV bound branching ratios

$$\frac{\mathcal{B}(r \to t\bar{t})}{\mathcal{B}(r \to \gamma\gamma)} < \frac{300}{6} \times \frac{\sigma(pp \to r)_{13\ \mathrm{TeV}}}{\sigma(pp \to r)_{8\ \mathrm{TeV}}} \approx 235$$



$$\frac{1}{235}$$

Allowed Parameter Space



- Blue: 8 TeV $\gamma\gamma$ limits
- Red: other 8 TeV exclusions
- Green: 13 TeV signal region

- Allowed region:
  - Warp factor ~ 10^3—10^7
  - Radion scale Λ_r ~ 2—5 TeV

Implications

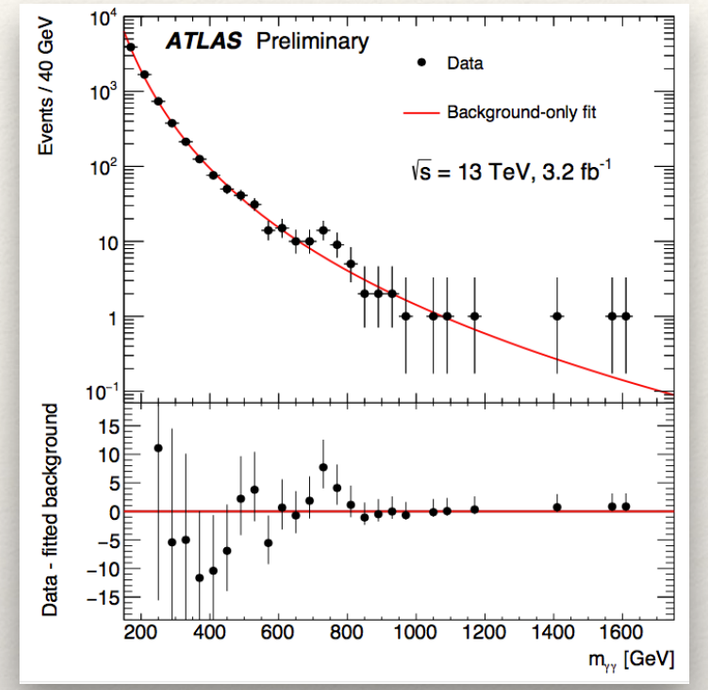
Radion Properties

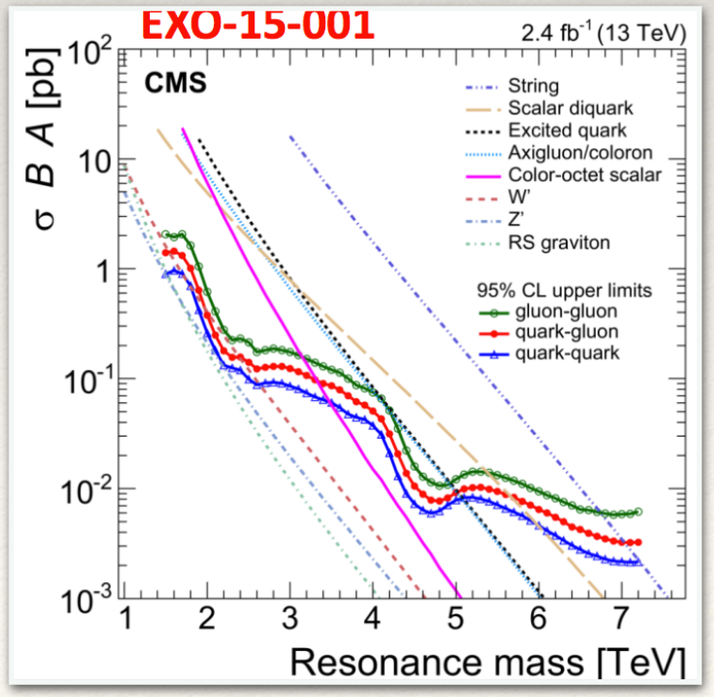
- Radion is narrow
  - If Γ = 45 GeV persists, probably excluded
- Other channels
  - $t\bar{t}$ should be accessible

    σ ~ 1 pb
  - Dijet (gg) signal also large

    σ ~ 1 pb
  - WW/ZZ possibly within reach

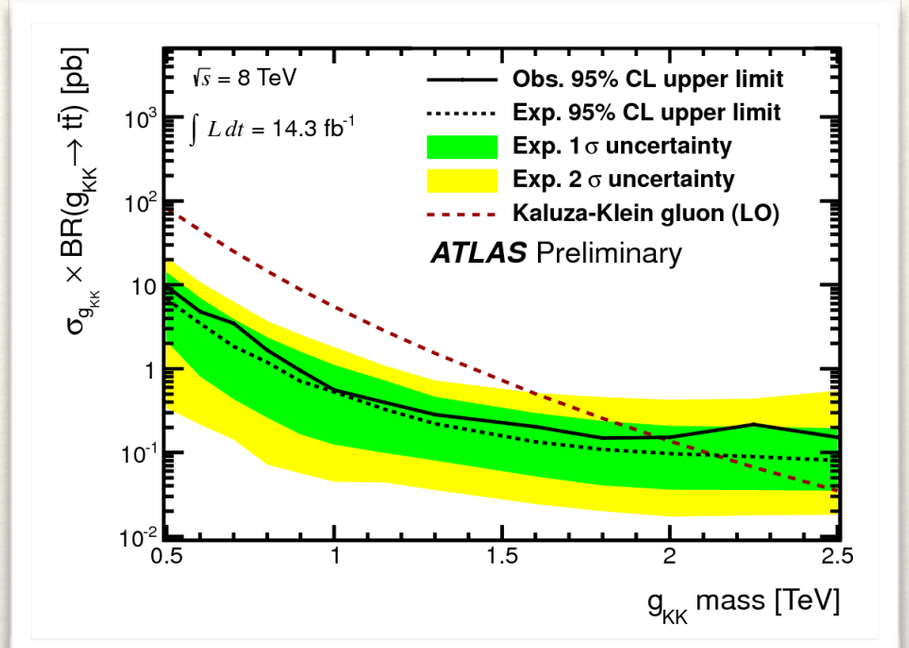
    σ ~ 10—20 fb



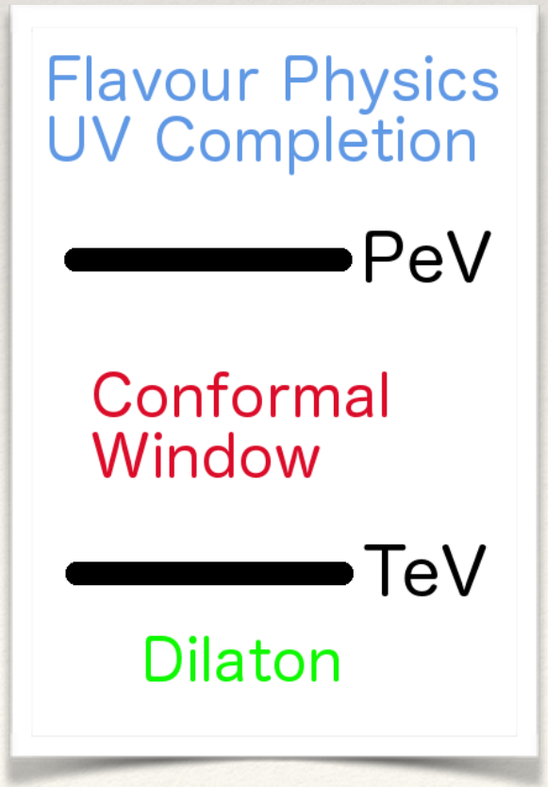


RS Model Implications

- Expect KK states near Λ_r
  - *i.e.* KK gluons at 3—5 TeV



- Small warping: Little RS model
  Davoudiasl *et al*, 0802.0203
  - Composite flavour physics
    UV scale ≳ 10^3 TeV
  - *or* UV-brane Einstein-Hilbert term
    George & McDonald, 1107.0755



Conclusions

Conclusions

- Diphoton excess can be explained with radion (dilaton)
- Strong constraints from electroweak searches prefer conformal limit: no radion—vector mass term coupling
- Expect confirmation or exclusion from $t\bar{t}$ searches (at 750 GeV and few TeV)
- Possible connection to flavour through Little RS model