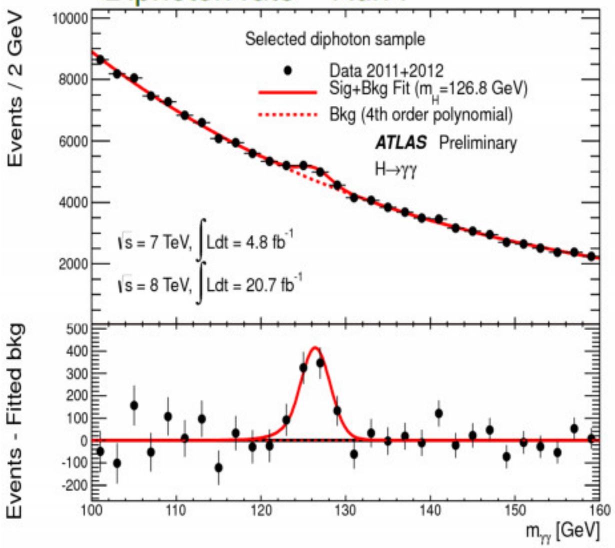
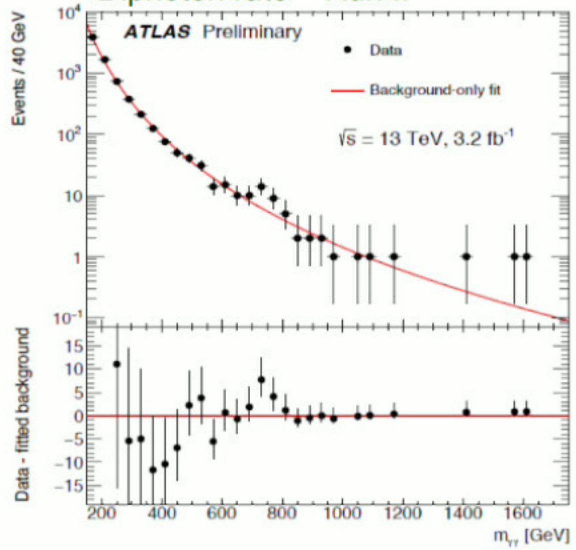
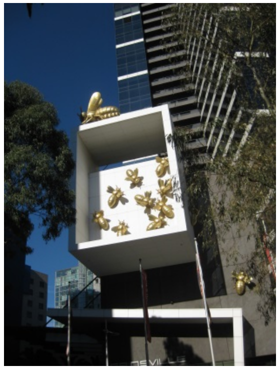
Warped Graviton Interpretation of the 750GeV Di-photon Excess

Diphoton rate – Run I



Diphoton rate – Run II





J. Hewett & T. Rizzo, 1603.08250 + work in progress w/ D. Rueter & G. Wojcik 7/5/16

- Needless to say, a new particle at ~750 GeV would be an extremely exciting discovery independent of what its spin might be… ~450+ theory papers can’t be wrong !

- The spin-0 possibility is more ‘familiar’ & more easily modeled as, e.g., a singlet Higgs produced by VLF loops or a radion or…

- The spin-2 case is arguably even more exciting as the ‘natural’ explanation is a ‘warped’ graviton KK excitation signaling the existence of extra dimensions. But model building is more complicated.

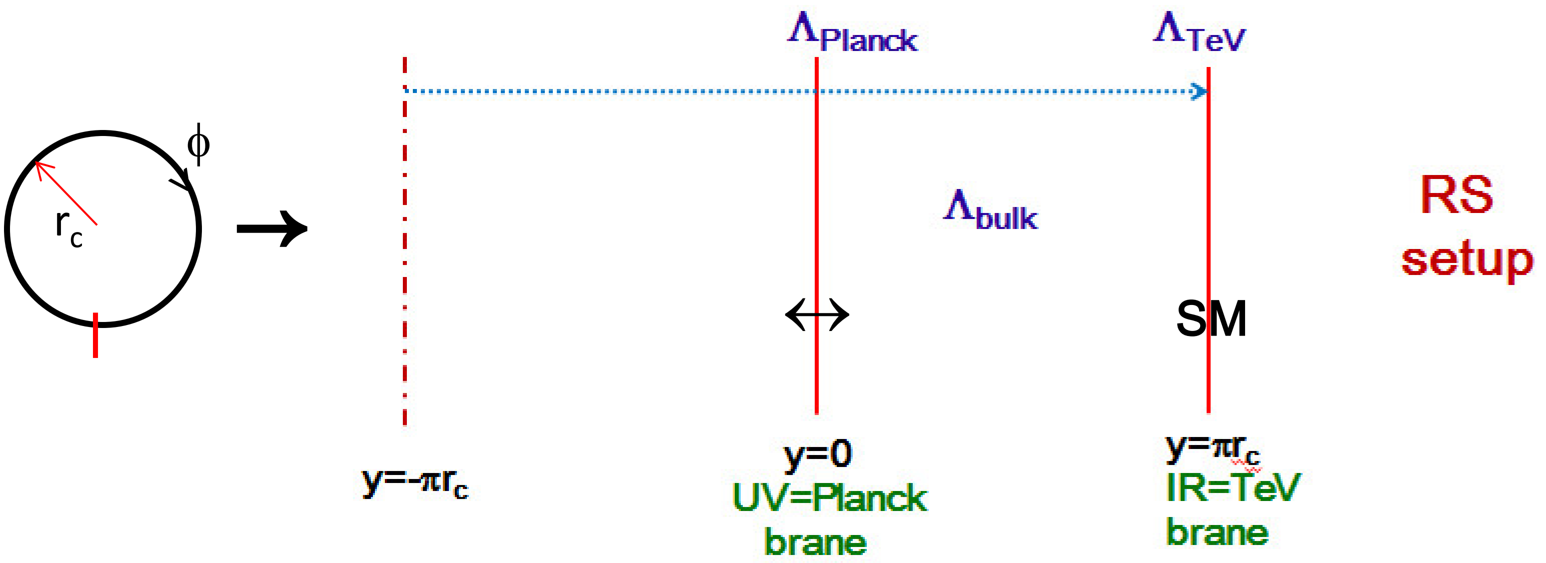
- Clearly IF this state is real, a spin determination will be a mandatory next step

- Simplest case: the original RS model with only gravity in the bulk & all the SM fields localized on the TeV brane.

R&S hep-ph/9905521

→ One compactified extra dimension with a non-trivial metric + periodic BC, including a parity (Z_2) symmetry around y=0.

$$ds^2 = \underline{e^{-2ky}}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$



What does this setup buy you? A ‘solution’ to the gauge hierarchy problem!

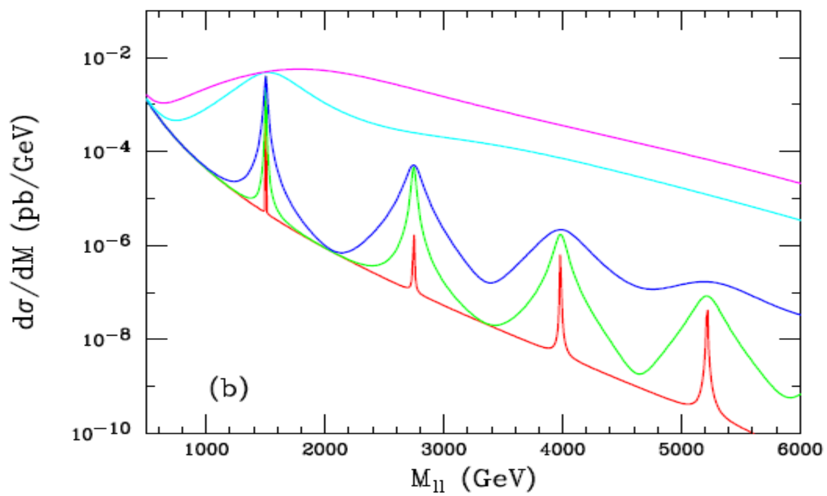
Why? All Lagrangian parameters are ~M_{pl} - BUT due to the 'warp factor'

$$\epsilon \equiv e^{-kr_c\pi} \qquad kr_c \simeq 11 - 12.$$

masses on the IR brane, such as the SM Higgs vev, are scaled down by ε & are ~TeV ! No 'large mass ratios' occur.

- This scenario predicts ~TeV scale graviton KK excitations with masses determined by roots of Bessel functions. Only one free parameter if G(KK#1) = 750 GeV… all BF are fixed.

There have been many searches for such states at the Tevatron & LHC with null results



For example: BF($\gamma\gamma$) = 2 BF($l^+ l^-$)

- This prediction is in 'some tension' with the direct LHC searches for Z'-like states: **Giddings & Zhang, 1602.02793**

$\rightarrow$ If the 750 GeV state is real & is spin-2 this needs to be clarified once all the numbers settle down.

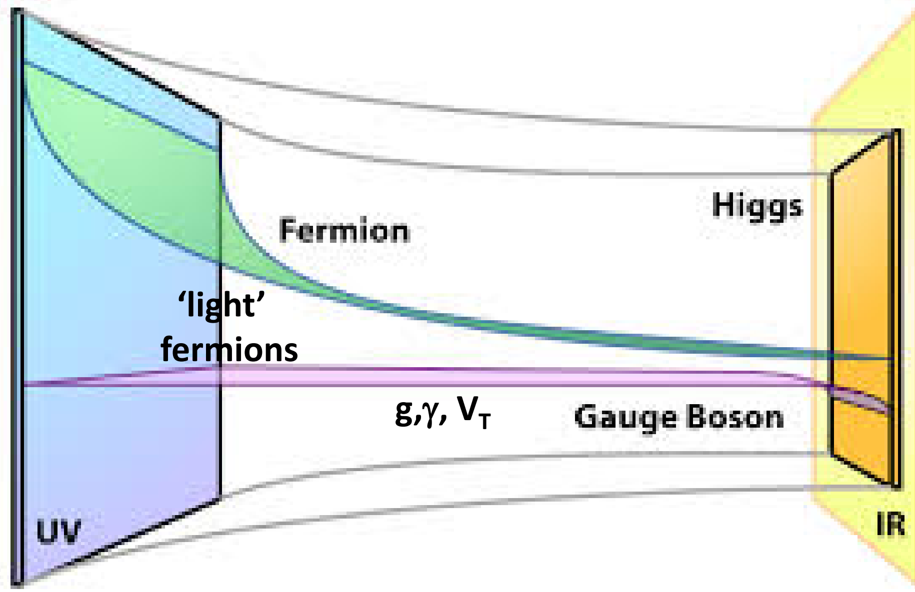
- Assuming this tension is real we need to generalize the RS model by distributing the SM fields out into the bulk. This has the advantage that the fermion mass hierarchy can be (at least partially) addressed-- adds many additional parameters.

- Fortunately(?) there are also many additional constraints

$\rightarrow$ Here we discuss a first-pass toy model that has most of the desired pieces…

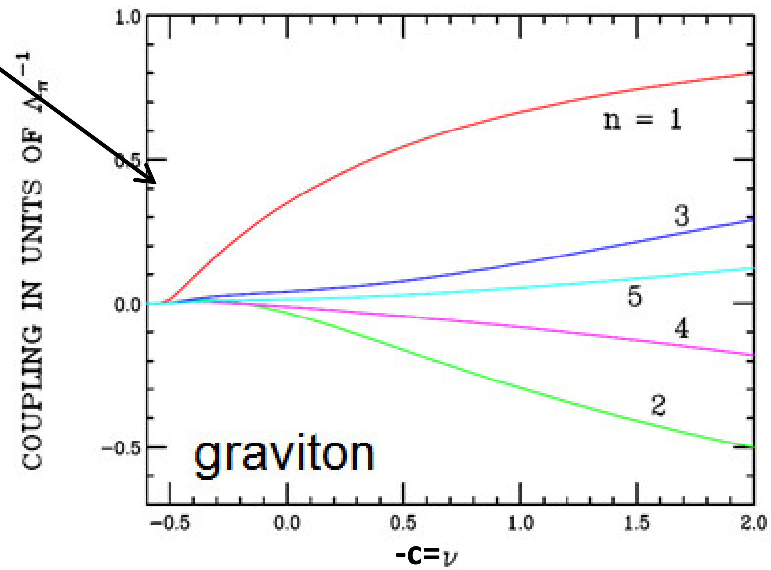
Essentials:

$$\mathcal{L} = \mathcal{L}_{bulk} + \mathcal{L}_{branes}$$



- Matter closer(further) from TeV brane couples more strongly(weakly) to the gravitons ~ e^{ky}/M_{Pl}
- Higgs & V_L(= Goldstones) remain on the TeV brane where SSB occurs as do the heavy 3rd generation quarks. Others out in bulk near ν=-1/2
- Bulk V_T couplings to gravitons are diluted, by a factor δ, compared to being on the IR brane because they are 'spread out' over the extra dimension .

UV



IR

A naïve calculation gives: $\delta = (4\pi k r_c)^{-1} = 0.007$ (this is a problem!)

- Every kinetic term of a 5d Lagrangian can/must have a 4d 'projection' on either brane = BLKTs, e.g.,

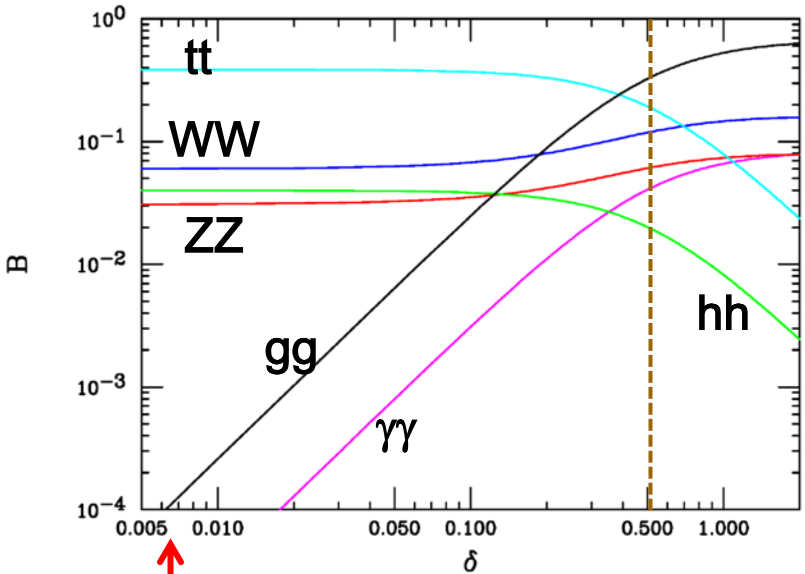
$$S_G = \frac{M_5^3}{4} \int d^4x \int r_c d\phi \sqrt{-G} \left\{ R^{(5)} + [2\gamma_0/kr_c \; \delta(\phi) + 2\gamma_\pi/kr_c \; \delta(\phi - \pi)] \, R^{(4)} + \ldots \right\} ,$$

$$S_V = \frac{-1}{4} \int d^4x \int r_c d\phi \sqrt{-G} \, \{ F_{AB}F^{AB} + [2\delta_0/kr_c \; \delta(\phi) + 2\delta_\pi/kr_c \; \delta(\phi - \pi)] \, F_{\mu\nu}F^{\mu\nu} + \ldots \} , \qquad (2)$$

The values are restricted: $\delta_0 + \delta_\pi > -\pi k r_c$, $\gamma_0 > -1/2$, $\gamma_\pi < 1$ to avoid ghosts, etc. Here we set all gauge BLKTs equal for simplicity

- **Problem**: if we want G(750) to have a reasonable B($\gamma\gamma$) , so we can **see it**, we need to increase δ **substantially***, **e.g.,**

Graviton Branching Fractions



A range of possibilities exist: δ~0.5 (& above) seems to be reasonable giving B($\gamma\gamma$)> ~4%

Note as $\delta\to\infty$, B($\gamma\gamma$) $\to$1/12 so we don't gain too much going to larger δ values

Without BLKTs we live at δ = 0.007 $\rightarrow$

This would be a license to kill this model !

If δ=0.5

Channel	Scaled partial width	Branching Fraction
$\Gamma_{\gamma\gamma}$	$0.25\ \Gamma_0$	4.05%
Γ_{gg}	$2.0\ \Gamma_0$	32.39%
Γ_{ZZ}	$0.37\ \Gamma_0$	6.06%
Γ_{WW}	$0.73\ \Gamma_0$	11.84%
Γ_{hh}	$0.12\ \Gamma_0$	2.01%
$\Gamma_{b\bar{b}}$	$1.5\ \Gamma_0$	24.29%
$\Gamma_{t\bar{t}}$	$1.2\ \Gamma_0$	19.35%

*We require δ >0 here.

To get larger δ, we need to use the γ_π BLKT for the graviton

$$\delta = \frac{2(1-J_0(x_1^G)) + (\delta_\pi - \gamma_\pi)(x_1^G)^2 J_2(x_1^G)}{(\pi k r_c + \delta_\pi + \delta_0)(x_1^G)^2 |J_2(x_1^G))|}$$

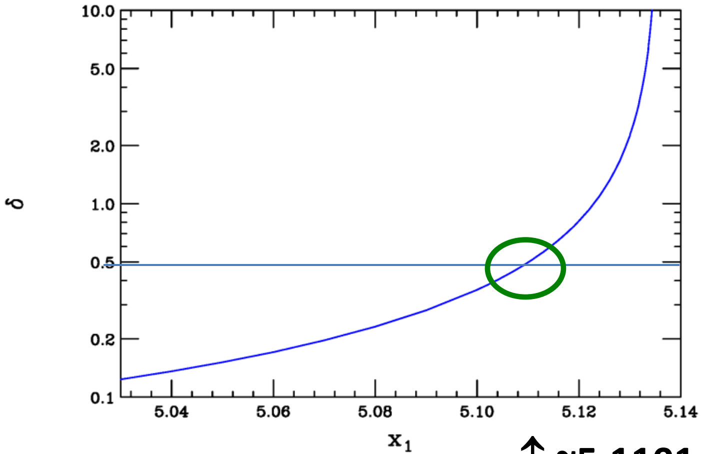
Forget $\delta_{0,\pi}$ for the moment… The $x^G{}_1$ is a Bessel function root that gives the graviton its mass value

$$m_n^G = x_n^G k\epsilon = x_n^G \Lambda_\pi k/\overline{M}_{Pl}.$$

As we'll see below this tells us that $k\varepsilon$~147 GeV ~ v_{SM}~174 GeV

Now float $x_1{}^G$ (which then fixes all the other KK masses) until we get the required value of δ & then determine the necessary value of γ_π.

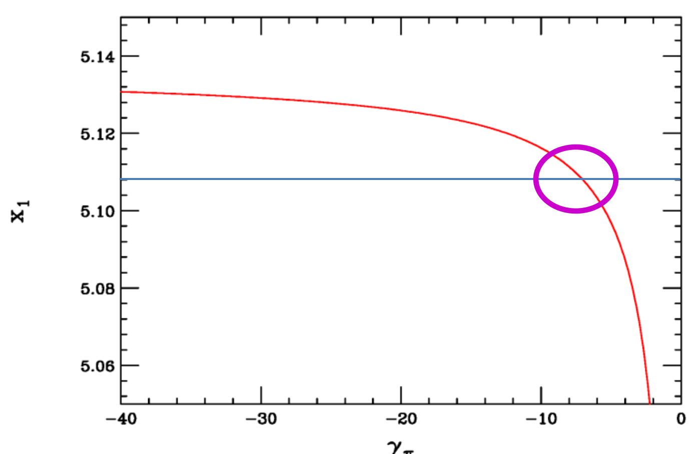
Fixes mass spectrum



↑ ~5.1101

KK mass root eq.

$$\boxed{J_1(x_n^G) - \gamma_\pi x_n^G J_2(x_n^G) = 0}$$



↑ ~ -7.652

There are now no free parameters remaining in the graviton sector except for an overall scale & all KK masses, BFs and couplings are completely fixed ! At 13 TeV :

$$\sigma_{\gamma\gamma} = 4.86 \text{ fb } (1 + 2\gamma_0)/25 \ (5 \text{ TeV}/\Lambda_\pi)^2$$

(..but what σ value do we aim for ??)

Clearly correlated choices of γ_0 & Λ_π will provide the correct rate

BF's & KK spectrum are functions of a single parameter, γ_π , which is fixed by δ requirement. γ_0 then fixed by the production rate at 13 TeV.

We learn that G(750) must be <u>very</u> narrow :

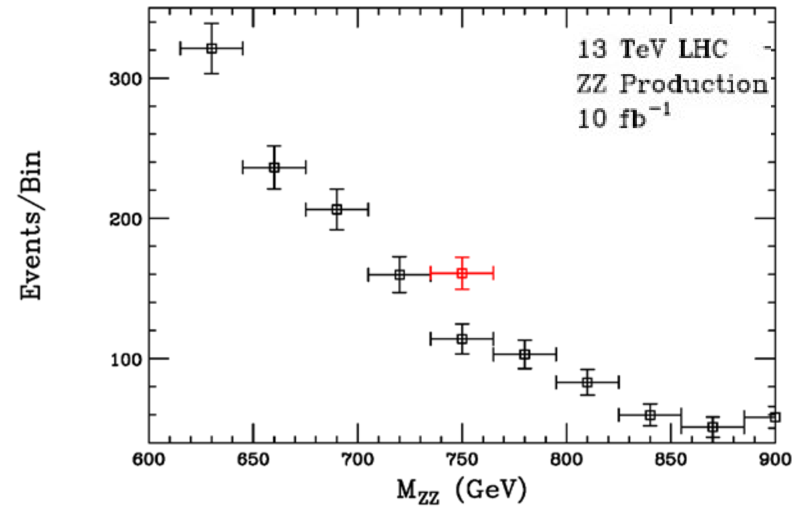
$$\Gamma_0 = \lambda_1^2 \frac{(m_1^G)^3}{80\pi\Lambda_\pi^2} = 1.09 \times 10^{-3} \left[\frac{1+2\gamma_0}{25}\right] \left[\frac{5 \text{ TeV}}{\Lambda_\pi}\right]^2 \text{GeV} . \qquad (7)$$

$$\lambda_n \equiv \left[\frac{1+2\gamma_0}{1+(x_n^G\gamma_\pi)^2-2\gamma_\pi}\right]^{1/2}. \qquad \Gamma = 6.17\Gamma_0$$

If $\Lambda_\pi = 5$ TeV then $k/\overline{M}_{Pl} = 0.029$, a typical value used in standard searches

BTW: the 2nd G KK is at ~1233 GeV but is predicted to be very weakly coupled since both δ_2 & λ_2 are much smaller than for G_1 & it couples mostly to TeV brane fields. Lots of lumi will be needed!

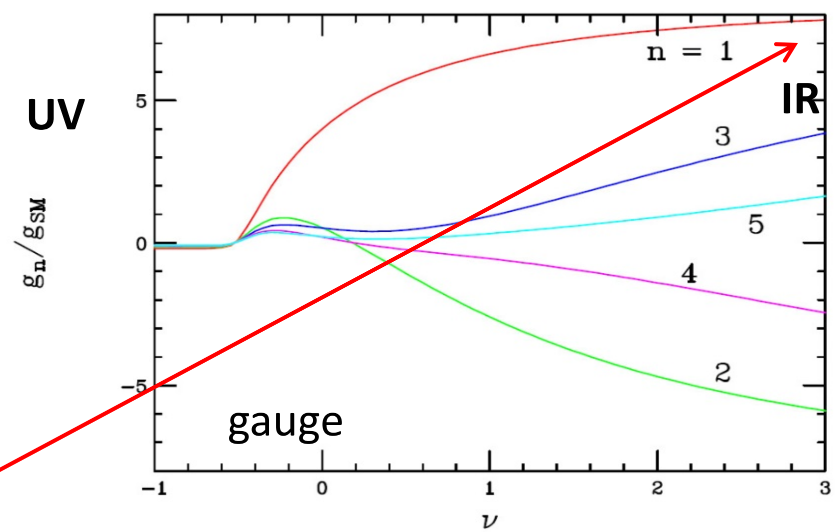
	13 TeV	8 TeV
Channel	σ^{13} (fb)	σ^{8} (fb)
$\sigma_{\gamma\gamma}$	5.0	1.18
σ_{gg}	40.0	9.44
σ_{ZZ}	7.48	1.77
σ_{WW}	14.6	3.45
σ_{hh}	2.48	0.59
$\sigma_{b\bar{b}}$	29.9	7.06
$\sigma_{t\bar{t}}$	23.9	5.64



1st KK should eventually be visible in other channels.. but is consistent with all present limits. Note no dileptons.

(no BF's or ε's here !)

Next issue: There are GAUGE KK excitations that we need to worry about & their masses are correlated with the gravitons (they're also roots of some Bessel functions)

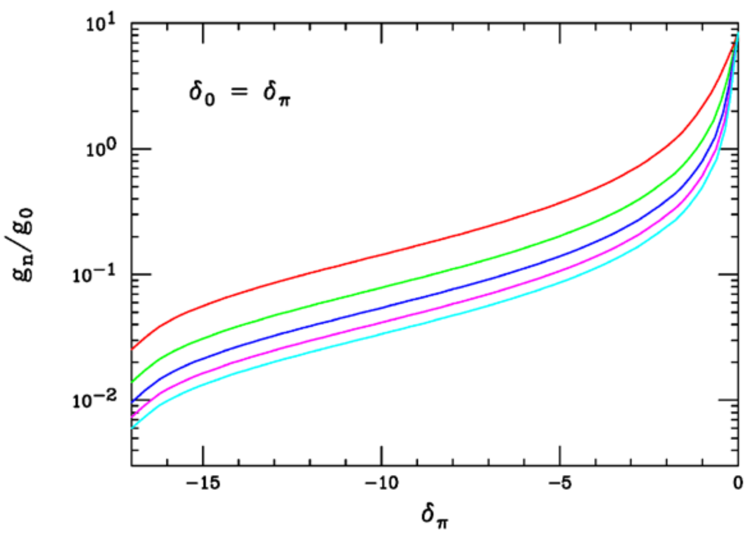


If we do nothing extra we have a serious problem due to large couplings!

- Even worse.. generally the lowest gauge KK is lighter than the lightest graviton KK (!) so we have to ‘hide’ it.

- Fortunately gauge fields also have BLKTs on both branes & these now come to the rescue!

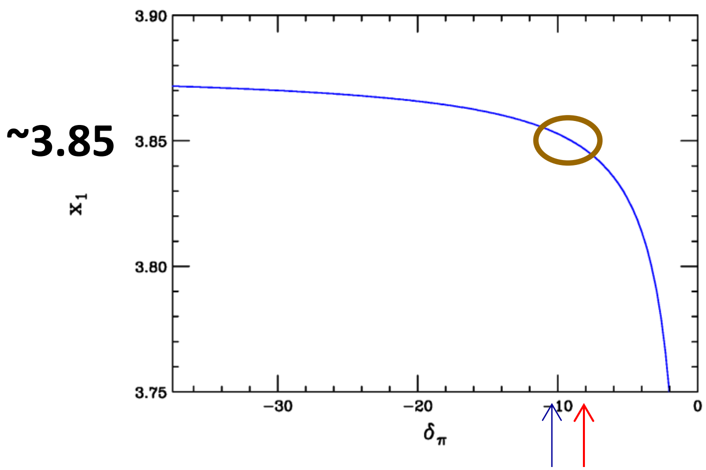
These BLKTs (i) reduce the KK couplings to matter on the TeV brane, (ii) resulting in reduction of SSB/Higgs-induced mixing of the various KK states on the TeV brane – both softening constraints. (Further (t, b) are purely 4d here & don’t have KK excitations.)



E.g., if $\delta_0 = \delta_\pi = -12$, the 1st gauge KK coupling to TeV brane matter is ~1/10 of the SM value & even smaller for higher KK states

- Properly localizing the 1st/2nd fermion generations near $\nu = -c = -1/2$ in the bulk substantially reduces these couplings & also softens FCNC constraints

Gauge root → mass

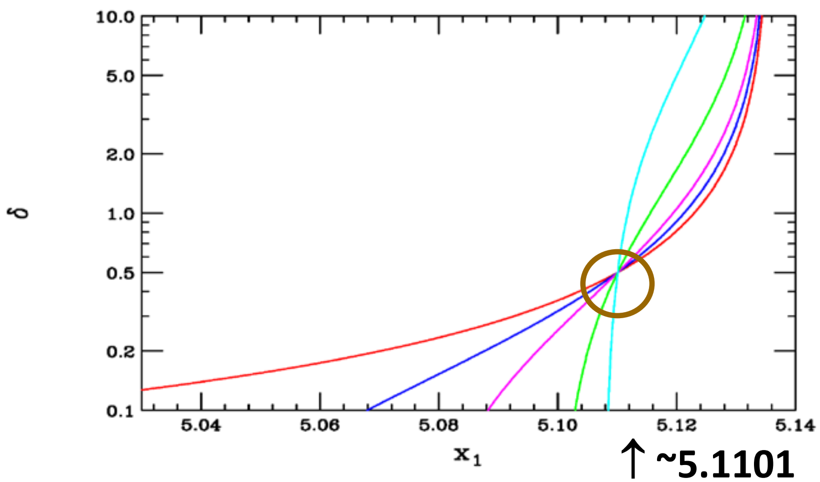


$m^A_{1(2)} \approx 565(1033)$ GeV

Now that the gauge fields have BLKTs we have to recalculate the value of δ to make sure our result above is maintained.

Simple cases for demo: set all brane terms equal: $\delta_\pi = \gamma_\pi$ (= -7.652) = δ_0 (red) or set $\delta_0 = \delta_\pi$ =-10 (blue), -5(mag), -15(gr), -17 (cy)

The numerics differ at the ~<0.01% level. Graviton results are quite stable. Many solutions possible!



- To do list :

→ Construct a more detailed/realistic model

→ Bring dark matter into the game.. What, if any, is the role of G(750)?

→ Examine other phenomenological implications, e.g., study the production of the other KK states

Most importantly: Find out if it's real !

Summary & Conclusions

- The 750 GeV excess is *very* interesting & if real will have a very significant impact whether it is spin-0 or spin-2. If real, spin measurement (by angular distribution and line shape) & info on other modes critical

- However, spin-2 indicates extra dimensions exist! *Wow*!

- Model building in this case is more challenging but leads to many testable consequences for the LHC & most likely elsewhere keeping all of us busy for a very long time.

- Hopefully we will know more soon!

Backup

How does 'warping' work ?

- imagine the Higgs field on the TeV brane....

$$S = \int d^4x \, dy \, \sqrt{-g} \, \left\{ g^{\mu\nu} \partial_\mu \hat{H}^\dagger \partial_\nu \hat{H} - \lambda \left(\hat{H}^2 - v_0^2 \right)^2 \right\} \delta(y - \pi r_c)$$

$\sqrt{-g} \to \left\{ \left[e^{-2ky} \right]^4 \right\}^{1/2}$ $\qquad g^{\mu\nu} \to e^{2ky} \delta^{\mu\nu}$ $\qquad v_0$: Higgs vev $\sim M_{Pl}$

$0 \le y \le \pi r_c$

$$S = \int d^4x \left\{ e^{-2kr_c\pi} \partial_\mu \hat{H}^\dagger \partial^\mu \hat{H} - e^{-4kr_c\pi} \lambda \left(\hat{H}^2 - v_0^2 \right)^2 \right\}$$

now rescale $\hat{H} \to e^{kr_c\pi} H$

$$S = \int d^4x \, \{ \partial_\mu H^\dagger \partial^\mu H - \lambda (H^2 - \underbrace{v_0^2 e^{-2kr_c\pi}}_{v})^2 \}$$

"Canonically" normalized!

V is TeV scale now

The Higgs on the TeV brane gets a TeV scale vev ... even though we started at $\sim M_{Pl}$!

- Warping modifies all energy scales.

- A figure of merit for most EWK precision measurements

$$V = \Sigma_n \ (g_n^2/g^2) \ (M_W^2 / M_n^2) \ \sim < 3.10^{-4}$$