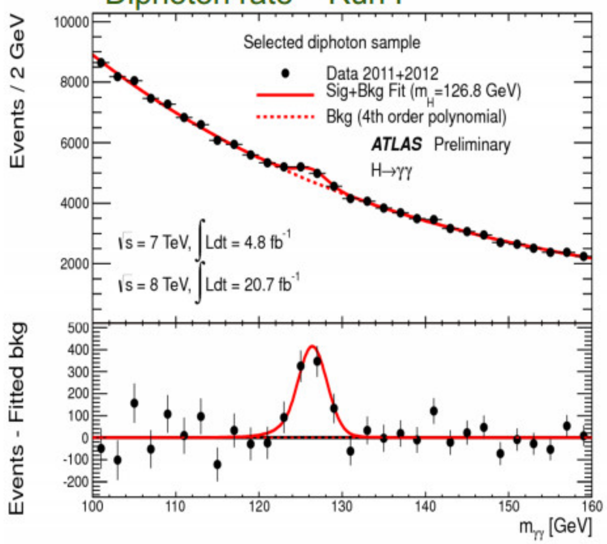
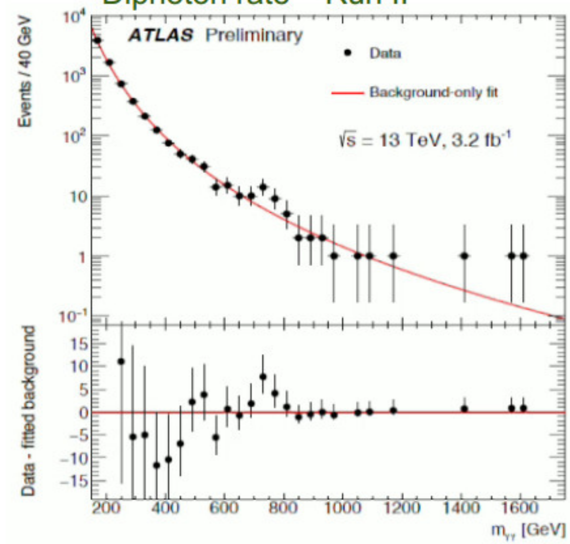
# The 750 GeV Di-photon Excess as a Spin-2 Graviton

Diphoton rate – Run I




Diphoton rate – Run II




**How the $\gamma\gamma$ Resonance Stole Christmas**

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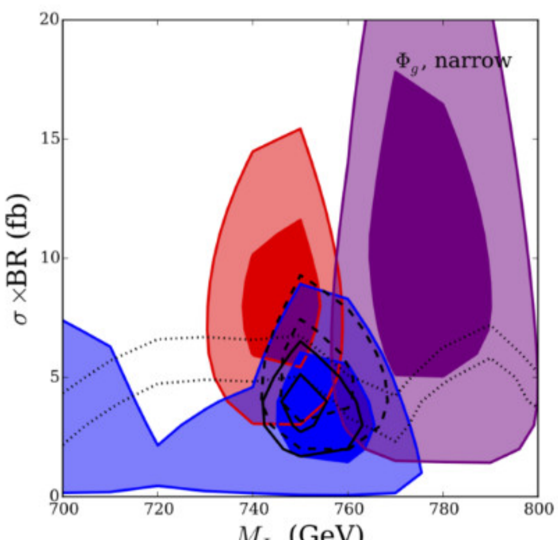
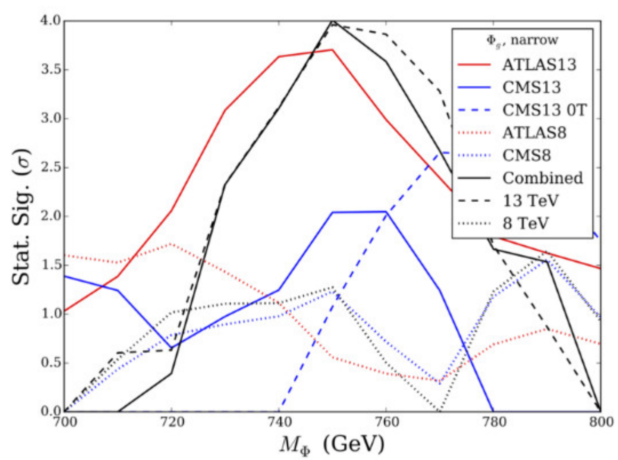



J. Hewett & T. Rizzo, 1603.08250 + lots more work in progress w/ D. Rueter & G. Wojcik

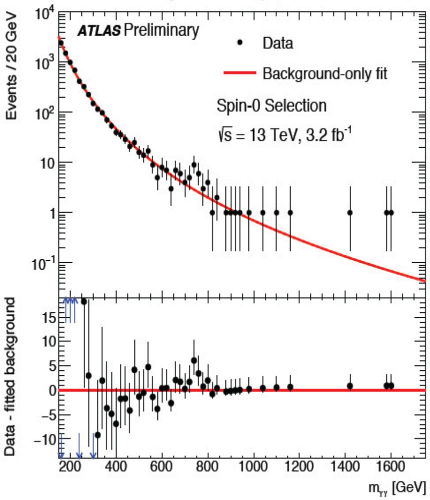
M. Buckley

6/13/16

# Results

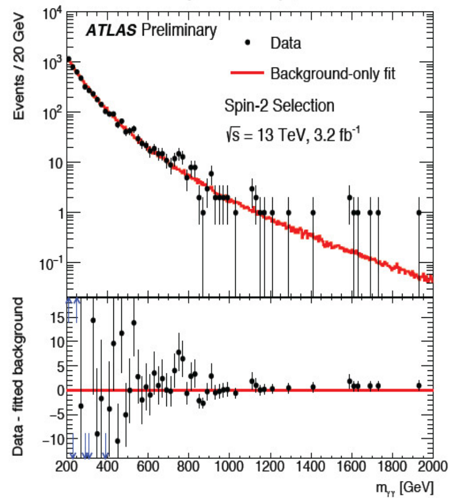
SPIN-0 ANALYSIS

*background-only fit*




SPIN-2 ANALYSIS

*background-only fit*



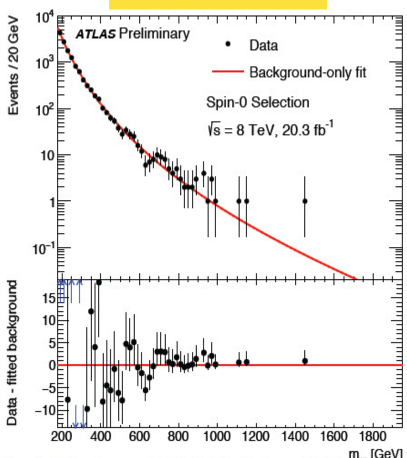

**I will not summarize the data in this talk.. most of you know it as well if not better than I do!**

**I will only present a possible interpretation -- assuming the excess is real -- which we may learn more about in ~7 weeks (& counting!)**

## Compatibility with 8 TeV data

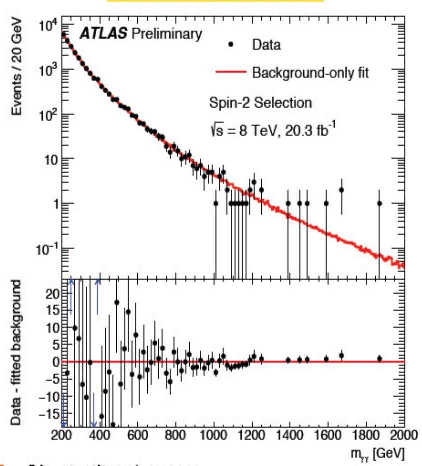
- 8 TeV data re-analyzed: latest Run I γ calibration + same Run I selections + 13 TeV analysis methods

SPIN-0 ANALYSIS

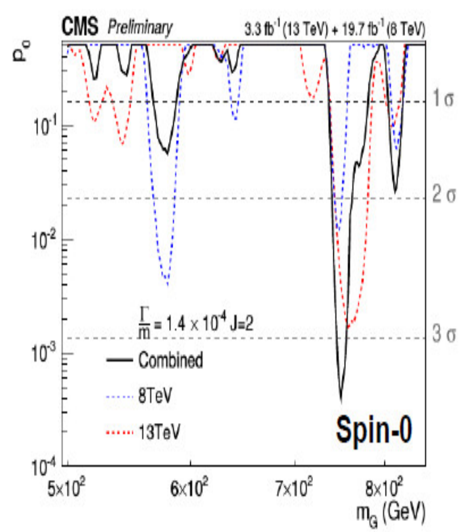


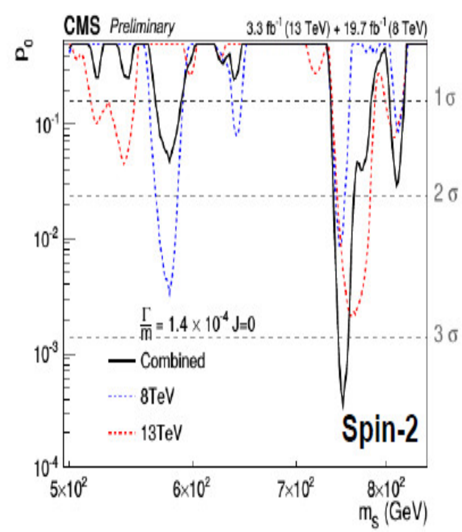

- 1.9 σ at $m_X$ = 750 GeV , $\Gamma_X/m_X$ = 6%
- Compatibility with 13 TeV scalar
  - ✓ gg (scaling: 4.7) → compatibility: 1.2 σ
  - ✓ qq (scaling: 2.7) → compatibility: 2.1 σ

SPIN-2 ANALYSIS




- No significant excess
- Compatibility with 13 TeV graviton
  - ✓ gg → compatibility: 2.7 σ
  - ✓ qq → compatibility: 3.3 σ



- "Much" theoretical excitement about the 750 GeV excess.. >430 papers on the arXiv since mid-December!

- If real, this is a new spin-0 or spin-2 particle. The "natural" interpretation for spin-0 is a new Higgs-like state produced via loops of yet to be discovered VLF (work in progress – see backups for representative discussion). In the spin-2 case (~2-3% of papers), this is the lightest KK graviton excitation which occurs in warped extra dimensions.

Both possibilities would be exciting…

→ but *spin-2* ?!?!!

However this possibility is a 'bit' more complicated requiring more 'effort', than a new Higgs-like state..

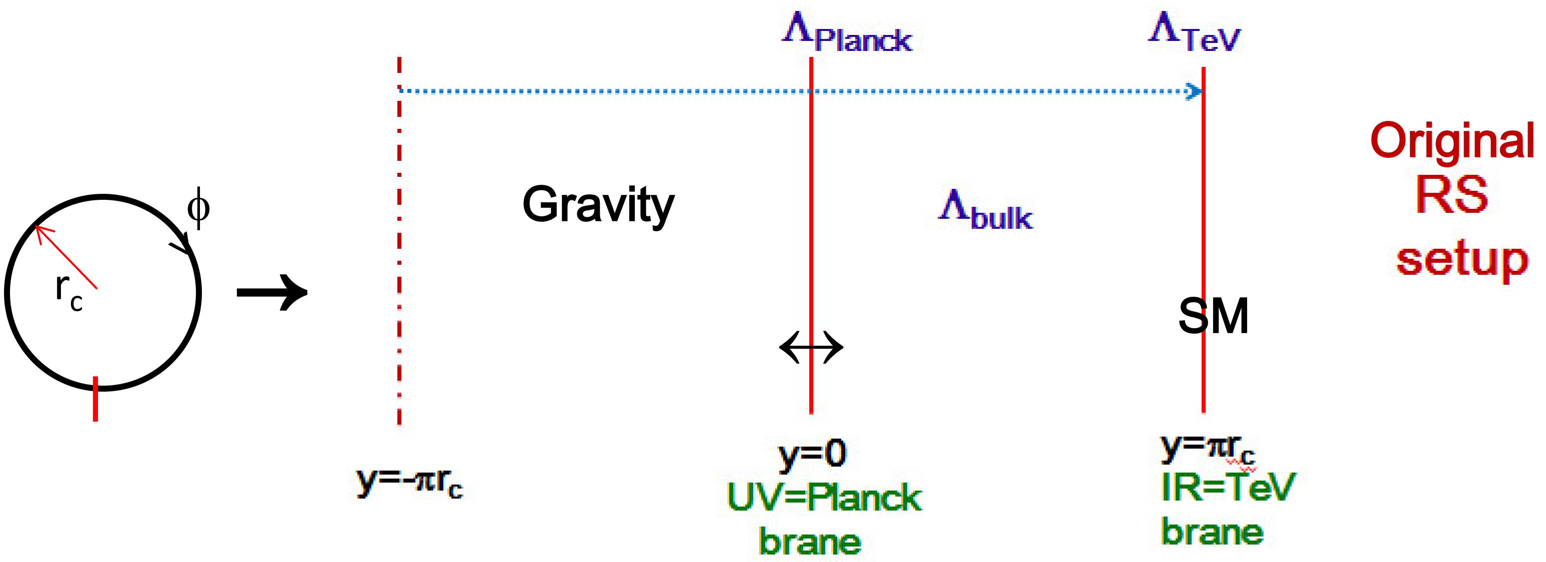
Turn back your clocks to the turn of the century..

# Randall-Sundrum Model of Warped Extra Dimensions*

hep-ph/9905221

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

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




*It is a fair to say that much (most?) of the phenomenology of this model & its generalizations originated with the members of the SLAC Theory Group in the following months & years.

What does this setup buy you? A 'solution' to the gauge hierarchy problem! All Lagrangian parameters are $\sim M_{pl}$ - BUT due to the 'warp factor'

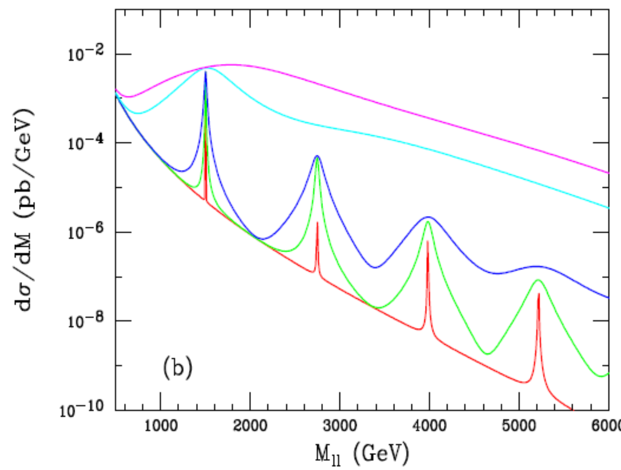
$$\epsilon \equiv e^{-kr_c\pi} \qquad kr_c \simeq 11-12.$$

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

Prediction: there is a tower of spin-2 KK gravitons whose masses and BF (via roots of Bessel functions) are fixed, except for an overall strength factor, $\Lambda_\pi$ ~few TeV, once $m_1$ is known. E.g.,

$BF(\gamma\gamma) = 2\, BF(l^+ l^-)$

This leads to these famous dilepton bump plots that you've seen for many years & for which searches have been done from the beginning of the LHC as well as at the Tevatron…with null results



- Problem: if we know $\sigma(\gamma\gamma)$ for the 750 GeV state then we also know $\sigma(l^+ l^-)$. This value is 'in tension' with the dilepton peak searches @ LHC
  Giddings & Zhang 1602.02793

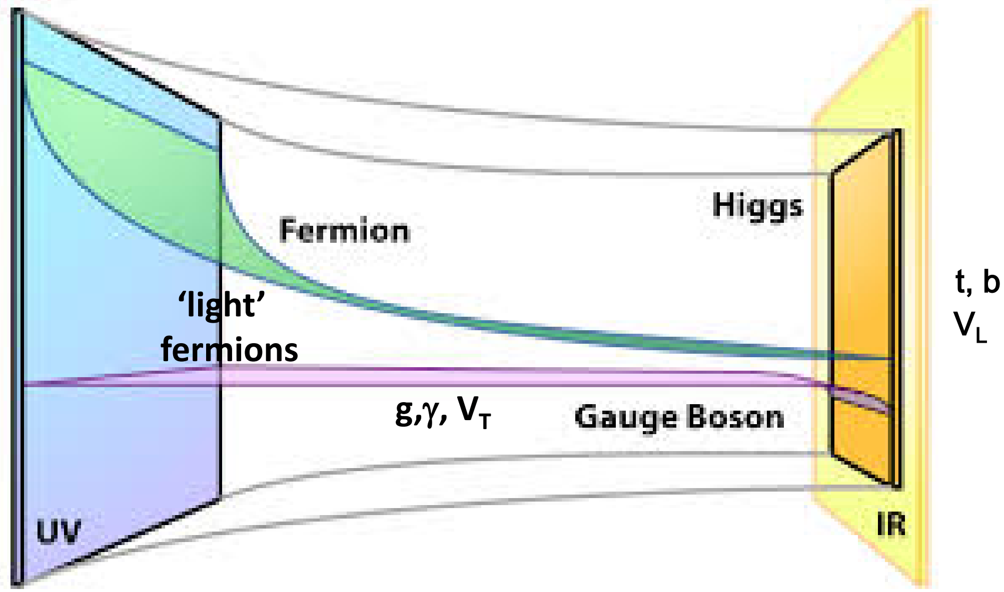
- Furthermore, we can get MORE out of this model by peeling SM fields out into the 'bulk' with some appropriate placement E.g., we can partially 'explain' the fermion mass hierarchy (!) by placing fermions 'appropriately' in the bulk ! SSB (the Higgs) still occurs on the IR brane to explain the gauge hierarchy.

The penalty is more parameters.. but there are many theoretical & experimental restrictions to abide by.. e.g., heavier SM fermions live near the IR brane to couple more strongly to the Higgs (& so the Goldstones live there too) etc.

This is where the serious model building has gone on

# Essentials:

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

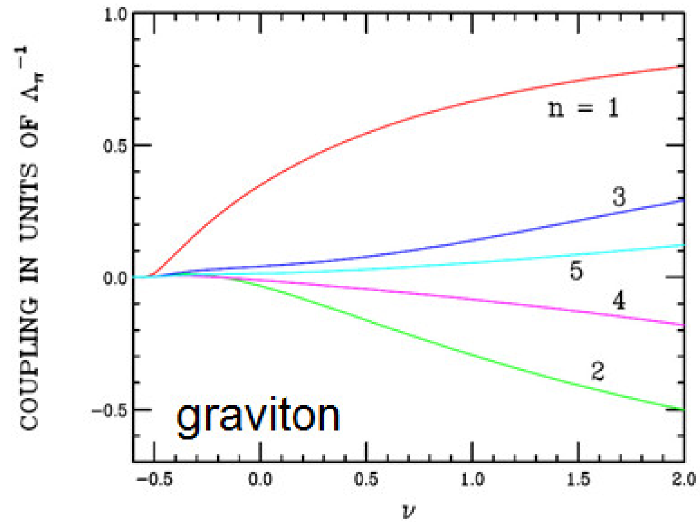



- Matter closer(further) from TeV brane couples more strongly(weakly) to the gravitons ~ $e^{ky}/M_{Pl}$

- 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 :

$$\delta = (4\pi k r_c)^{-1} = 0.007 \text{ (problem!)}$$

UV

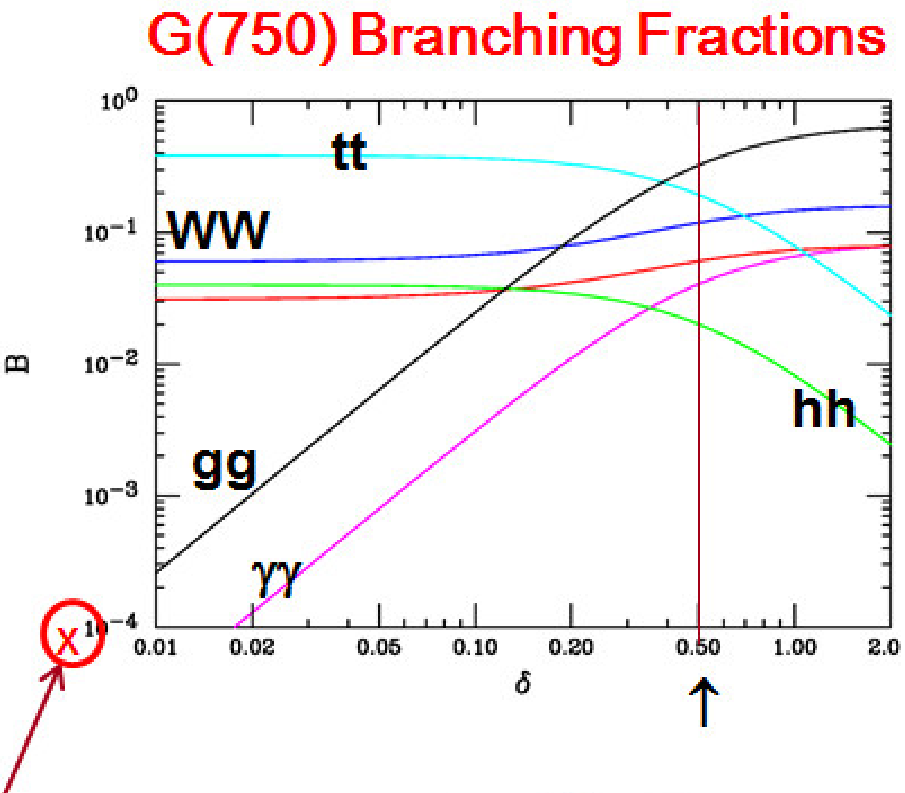



IR

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

Every bulk field can/must have part of its Lagrangian localized on either brane (= Brane Localized Kinetic Terms) with some 'restricted' values

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




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

**Note as δ→∞, B(γγ) →1/12 so we don't gain too much going to larger δ values**

**Without BLKTs we live at δ = 0.007**

**δ=0.5**

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

To get larger $\delta$, we need to use the $\gamma_\pi$ 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

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

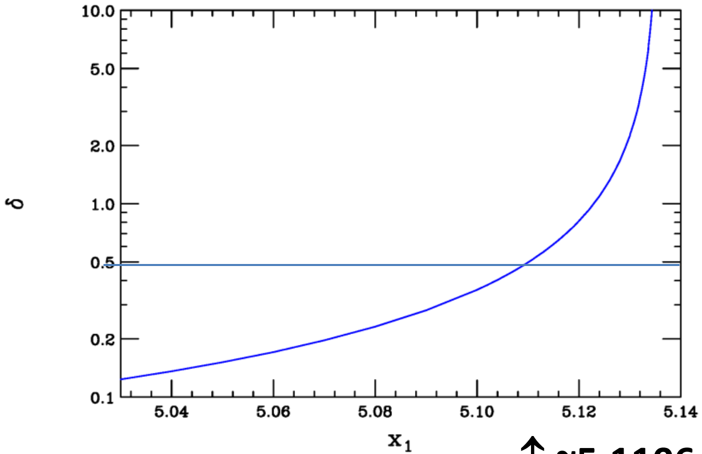
As we'll see below this tells us that $k\varepsilon$~147 GeV ~ $v_{SM}$ ~174 GeV

Now move $x_1^G$ (which fixes all the KK masses) until we get the required value of $\delta$. Then determine the necessary $\gamma_\pi$



*** first calculated by G. Wojcik, SLAC TH rotator !

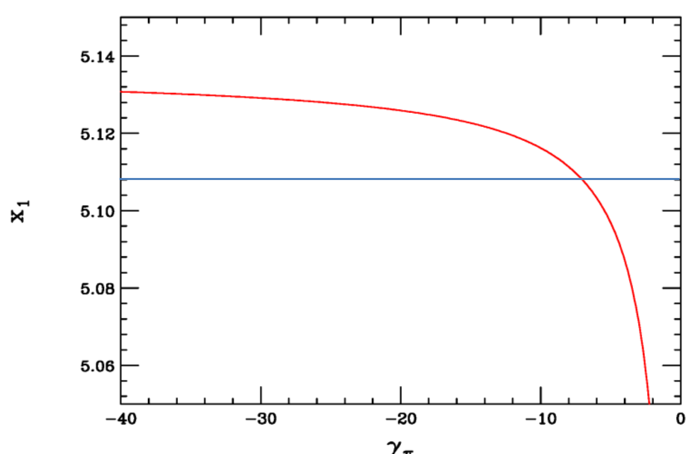
Fixes mass spectrum




↑ ~5.1106

KK mass root eq.

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




↑ ~ -7.652

There are now no free parameters remaining in the graviton sector except for an overall scale & all KK masses 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 value are we to aim at ?? )

Clearly correlated choices of $\gamma_0$ & $\Lambda_\pi$ will provide the correct rate

BF's & KK spectrum are functions of a single parameter, $\gamma_\pi$ , which is fixed by δ requirement. $\gamma_0$ then fixed by the production rate at 13 TeV.

## We learn that G(750) must be very narrow :

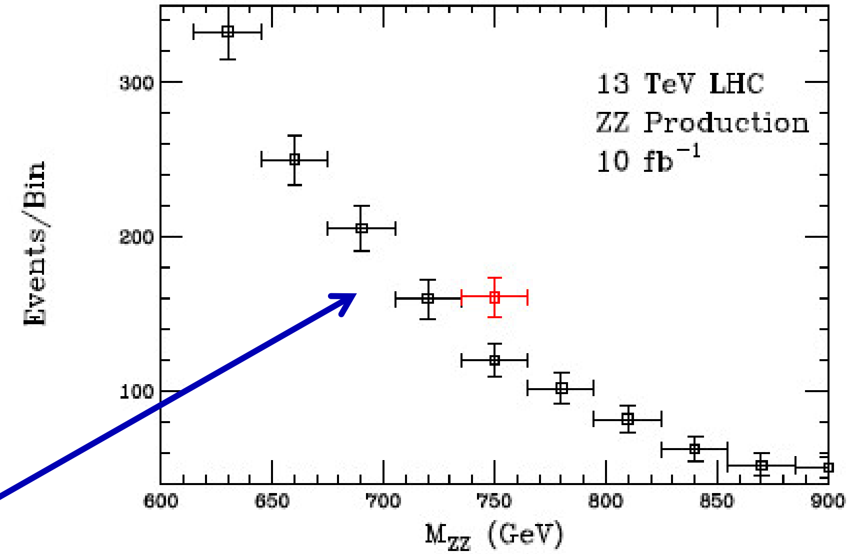
$$\Gamma_0 = \lambda_1^2 \frac{(m_1^G)^3}{80\pi\Lambda_\pi^2} = 1.09 \times 10^{-3} \left[\frac{1+2\gamma_0}{25}\right] \left[\frac{5 \text{ TeV}}{\Lambda_\pi}\right]^2 \text{GeV} . \qquad (7)$$

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

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

BTW: the 2nd G KK is at ~1233 GeV but is predicted to be very weakly coupled since both $\delta_2$ & $\lambda_2$ are much smaller than in the lightest KK case & mostly to TeV brane fields. Lots of lumi needed here!

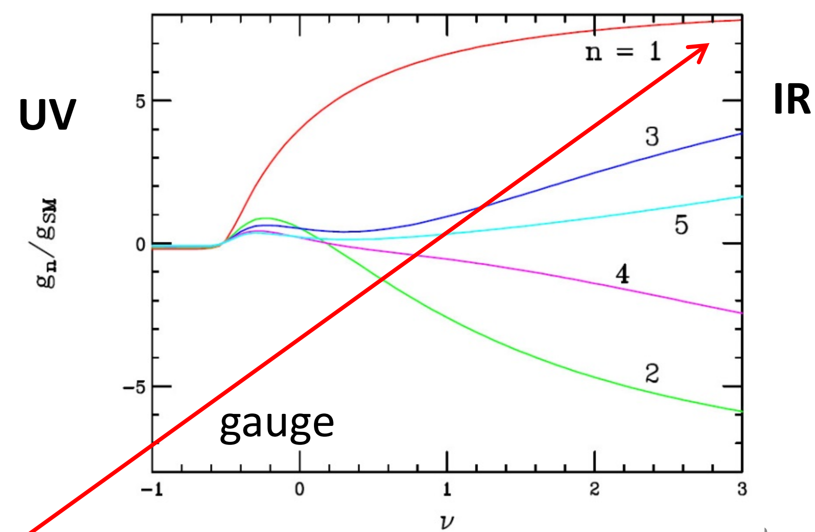
| Channel | 13 TeV<br>$\sigma^{13}$ (fb) | 8 TeV<br>$\sigma^{8}$ (fb) |
|---|---|---|
| $\sigma_{\gamma\gamma}$ | 5.0 | 1.18 |
| $\sigma_{gg}$ | 40.0 | 9.44 |
| $\sigma_{ZZ}$ | 7.48 | 1.77 |
| $\sigma_{WW}$ | 14.6 | 3.45 |
| $\sigma_{hh}$ | 2.48 | 0.59 |
| $\sigma_{b\bar{b}}$ | 29.9 | 7.06 |
| $\sigma_{t\bar{t}}$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




1[st] 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 !)

Issue: There are GAUGE KK excitations 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!

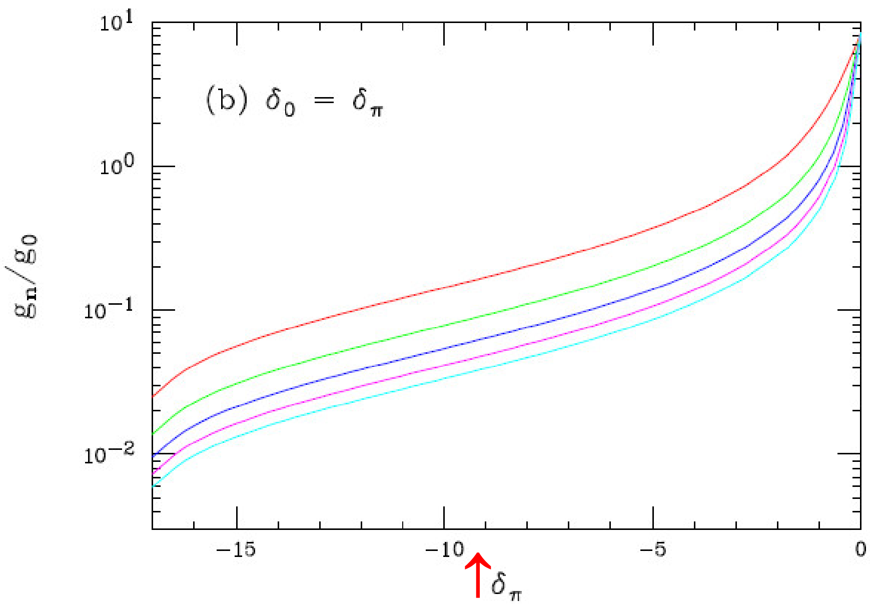
- Even worse.. generally the lightest gauge KK is lighter than the lightest graviton KK (!) so we have to ‘hide’ it.

- Fortunately gauge fields also have BLKTs on both branes !

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

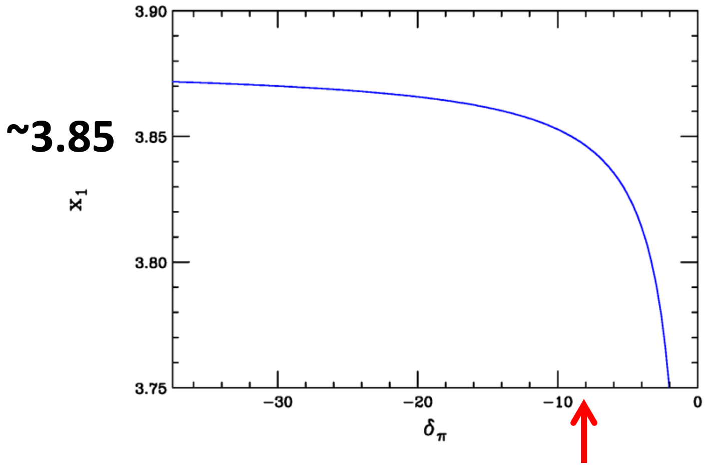
We assume all gauge fields have the same BLKTs for simplicity (no Zγ mode!) + a custodial symmetry

These BLKTs (i) reduce the KK couplings to matter on the TeV brane , (ii) reduce the mixing of KK states due to SSB on TeV brane – both softening constraints



- Properly localizing the 1st/2nd fermion generations near $\nu = -1/2$ in the bulk substantially reduces these couplings

Gauge root → mass

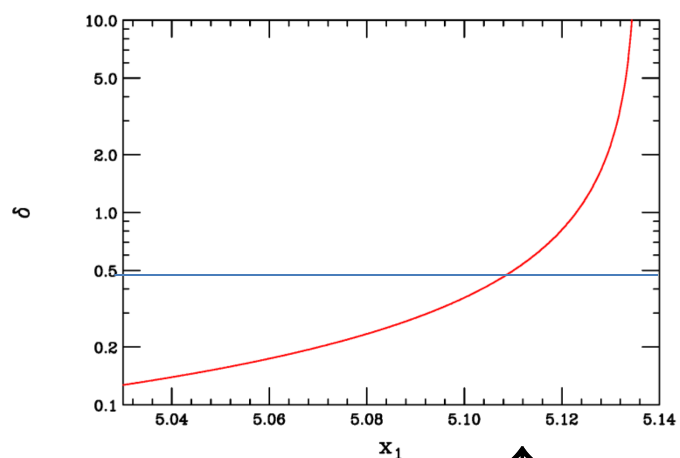



$m^A_{1(2)} \approx 565(1033)$ GeV

Now that the gauge fields have BLKTs we have to recalculate $\delta$ to make sure our solution above is maintained. Call George !

Simple case for demo; set all brane terms equal: $\delta_\pi = \gamma_\pi$ (= -7.652) = $\delta_0$

The result differs from the above only result at the ~0.01% level (!) so the previous graviton results are rather stable



- There's still lots to do here :

1. Construct a more realistic model employing fermion BLKTs
2. Bring dark matter into the game.. what is the role of G(750)?
3. Examine other phenomenological implications
4. Find out if it's real & watch out for weasels!

# Summary & Conclusions

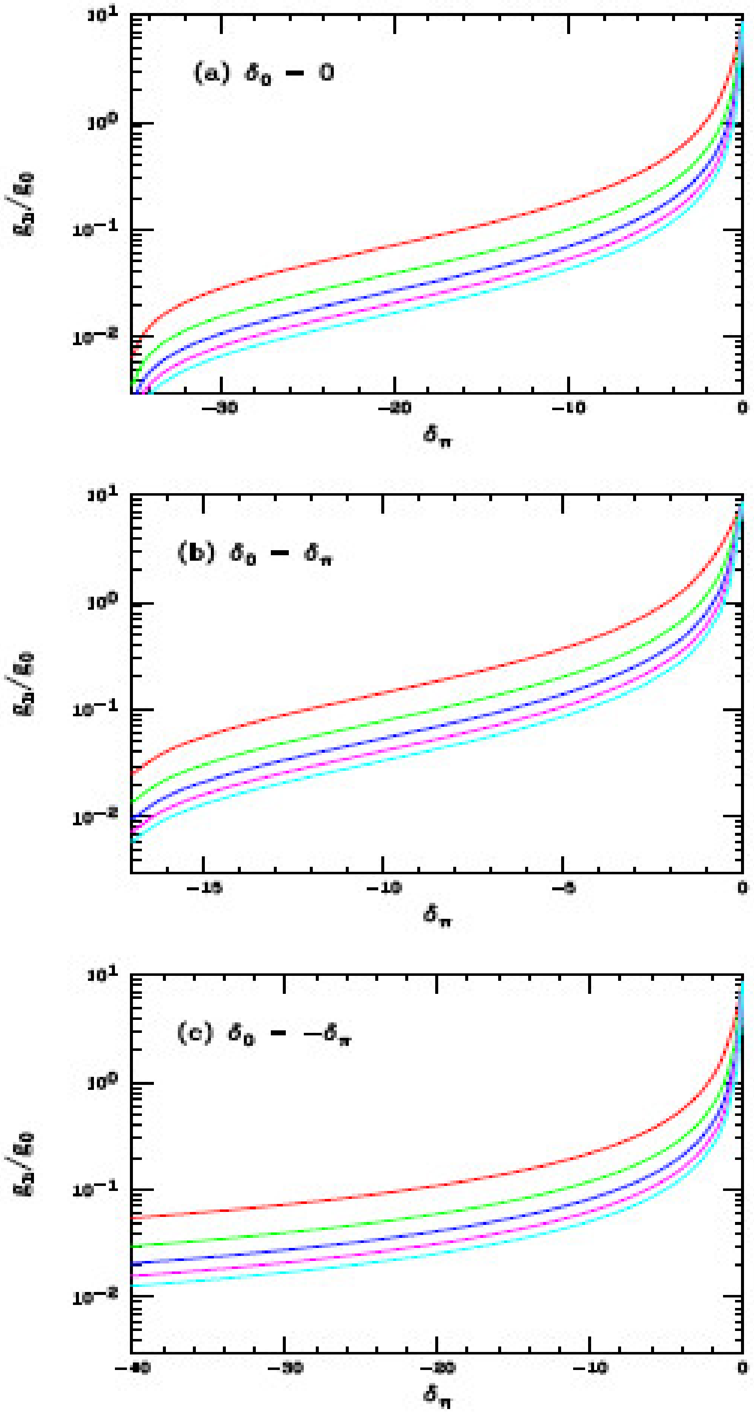
- The 750 GeV excess is *very* interesting & if real will have a very significant impact whether it is spin-0 or spin-2. If real, spin measurement (by angular distribution and line shape) & info on other modes critical

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

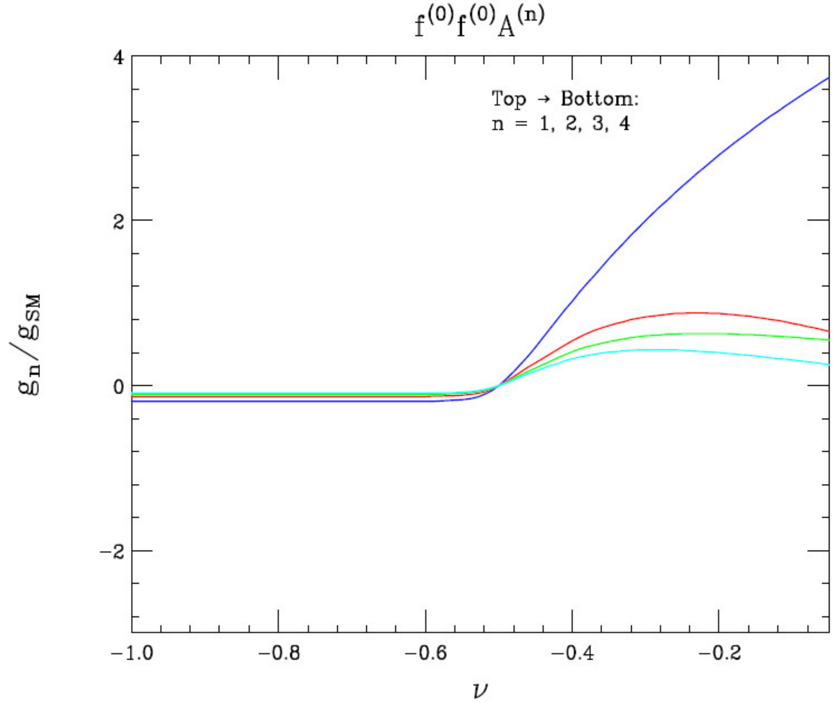
- Model building in this case is more challenging but leads to many testable consequences for the LHC & most likely elsewhere keeping all of us busy for a very long time.

- Hopefully we will know more soon!

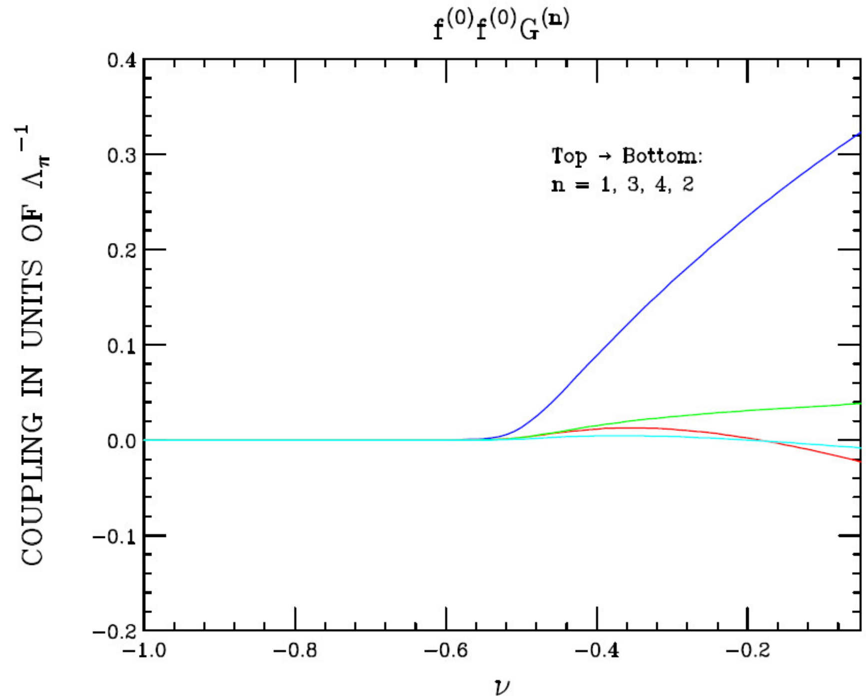
# Backup



(a) δ0 = 0
(b) δ0 = δπ
(c) δ0 = −δπ
gn/g0
δπ

f(0)f(0)A(n)
Top → Bottom:
n = 1, 2, 3, 4
gn/gSM
ν

f(0)f(0)G(n)
Top → Bottom:
n = 1, 3, 4, 2
COUPLING IN UNITS OF Λπ−1
ν

- Figure of merit for EWK precision measurements

$$V = \Sigma_n \ ( g_n^2/g^2 ) \ ( M_W^2 / M_n^2 ) \ \sim (2200)^{-1}$$

# How does 'warping' work ?

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

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

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

$0 \leq y \leq \pi r_c$

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

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

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

↑ "Canonically" normalized!

**v is TeV scale now**

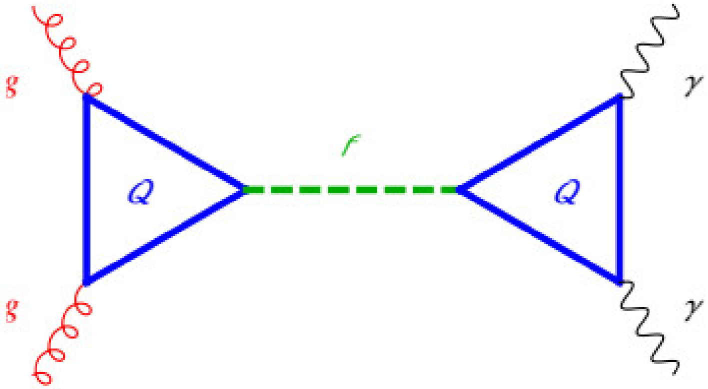
The Higgs on the TeV brane gets a TeV scale vev ... even though we started at $\sim M_{Pl}$ !

- Warping modifies all energy scales.

# Example VLQ model for CP-even S(750)

Assumption : Add only a single VLF rep to SM that couples to S. This coupling generates the VLF mass thru the S vev

The VLF must be a color triplet that has non-zero charge so as to couple to both gg and $\gamma\gamma$. The VLQ must have mixing with SM fermions so that it can decay.. this is induced by their coupling to the SM fermions via the Higgs → restricts possibilities !



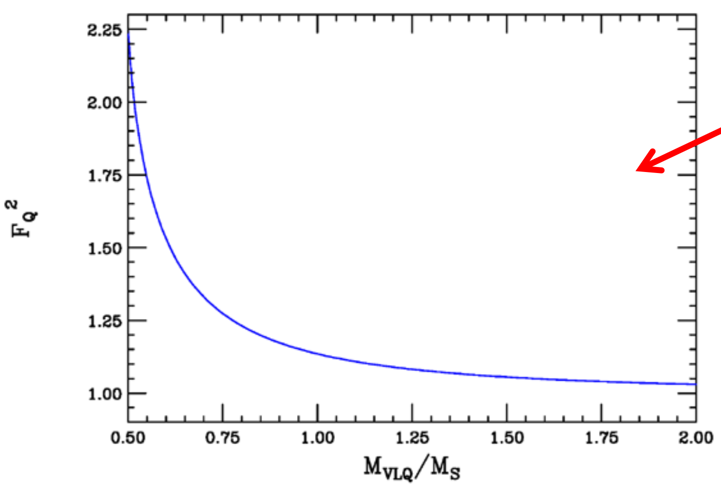

For random choices, cross sections are generally way too small..

An isodoublet VLQ is advantageous as $\Gamma(S \to gg)$ is 4x larger than for a singlet & can also involve larger Q's to enhance $B(\gamma\gamma)$.. $(X(5/3),U)^T$ or $(D,Y(-4/3))^T$ have the largest $\Sigma Q_i^2$

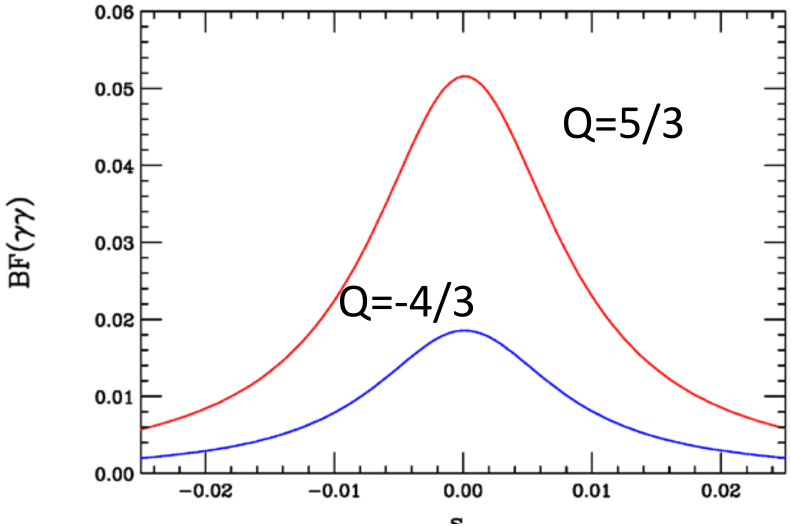
For such an isodoublet the NLO/NLL $\sigma$ @ 13 TeV is …

$$\sigma = 6.17\ \text{fb}\ F_Q^2 \quad (750\ \text{GeV}/v_s)^2 \quad B(\gamma\gamma)/(0.0516)$$

Loop function →1 for very heavy loop fermion VLQ



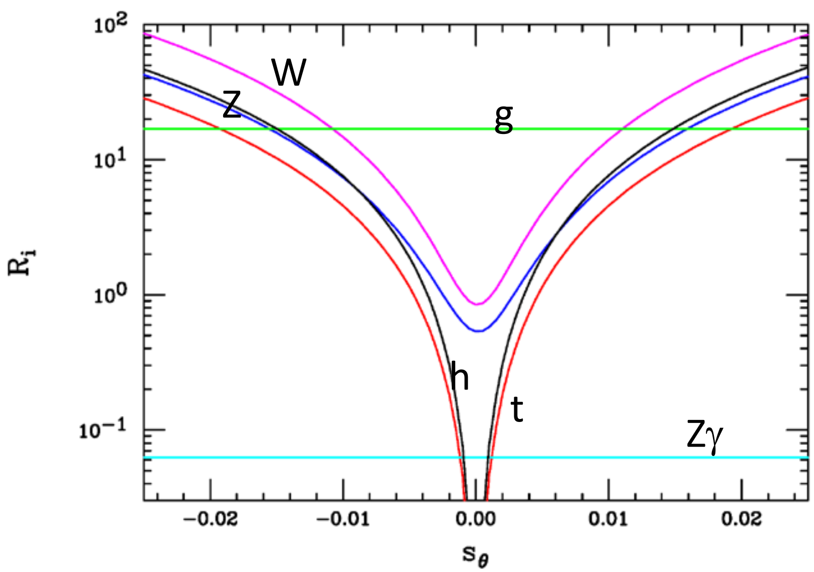

$M_{VLQ} > 0.5M_S$ to avoid being an S decay mode.. We also need to satisfy the direct VLQ searches . Not much room for large $F_Q^2$ effect !




Nothing prevents S-h mixing by $s_{\theta}$. Q=5/3 model is favored but only with $|s_{\theta}|$<~0.01. The Q=-4/3 model is ~disfavored.

$$R_i = \sigma_i / \sigma_{\gamma\gamma}$$

Constraints from the WW resonance searches, i.e., σ <~300fb, also tells us that $|s_{\theta}|$<~0.02




Such small mixings would not be observable as deviations from the SM in Higgs decays