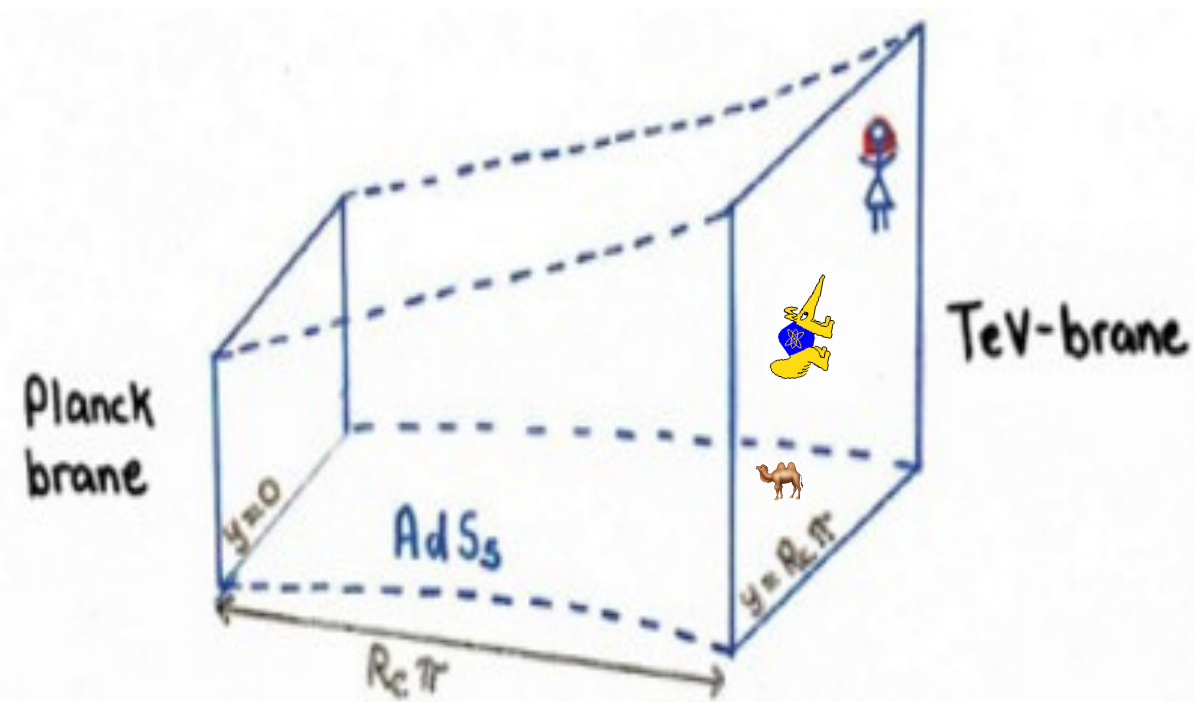
Light KK States in Randall-Sundrum Models



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The warped ED scenario provides an attractive model-building framework to address many SM problems, e.g.,

- The gauge hierarchy
- The fermion mass hierarchy
- The nature of Dark Matter…etc.

But constraints from LHC resonance searches, FCNCs & EWK precision data can naively push KK excitation masses to large values ~10-30 TeV even w/ custodial symmetries(CS).

Question: Is it possible solve these hierarchy problems w/ 'light' KKs at the ~1 TeV scale (or below) even w/o CS?

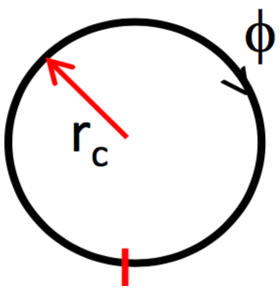
(… work inspired by the much maligned 750 GeV γγ excess)

R&S hep-ph/9905521

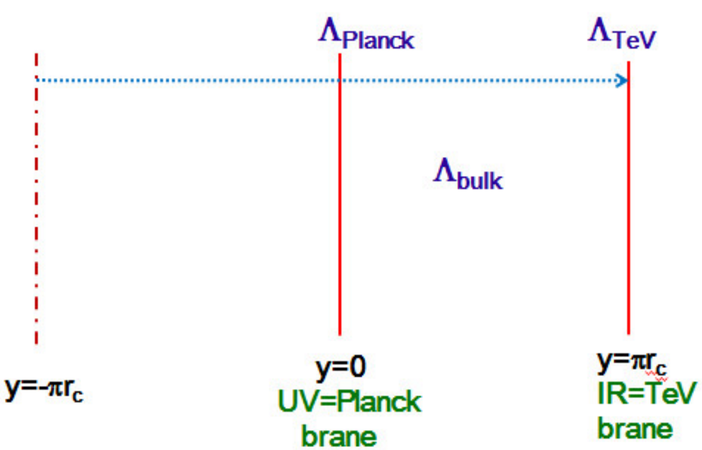
Review:

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

$\rightarrow kr_c \sim 10\text{-}12$



One ED w/ a warped metric w/ periodic BC + a Z_2 symmetry. $\Lambda_\pi = \bar{M}_{pl}\, e^{-\pi kr} \sim$TeV $\rightarrow$ Higgs on TeV brane + warping solves HP.



RS setup

SM fermions & gauge fields are in the bulk. Goldstones on TeV brane w/ Higgs

NB: Gravity + SM actions contain (too) many free parameters !

Action contains Brane Localized Kinetic Terms for gravity, 3 SM gauge fields & fermion reps + bulk mass terms for each fermion :

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

($\gamma_{0,\pi} \sim kr_c \sim 10$)

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

$$S_F = \int d^4x \int r_c d\phi \sqrt{-G} \left\{ \frac{-i}{2} \bar{\Psi}\Gamma^A \partial_A \Psi + [2\tau_0/kr_c \ \delta(\phi) + 2\tau_\pi/kr_c \ \delta(\phi - \pi)] \, \frac{-i}{2} \bar{\Psi}\gamma^\mu \partial_\mu \Psi + h.c. - sgn(\phi) \ m_\Psi \bar{\Psi}\Psi \right\} . \qquad (3)$$

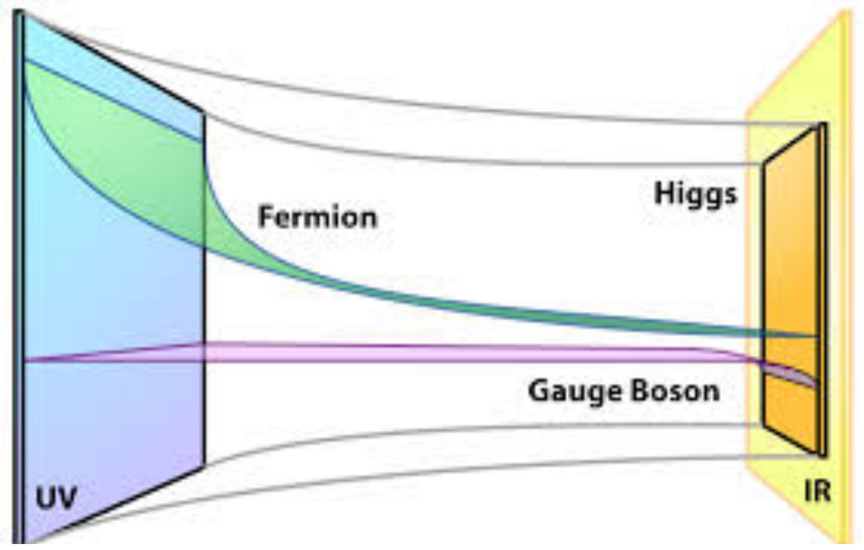
~ 50+ parameters!

Yikes !

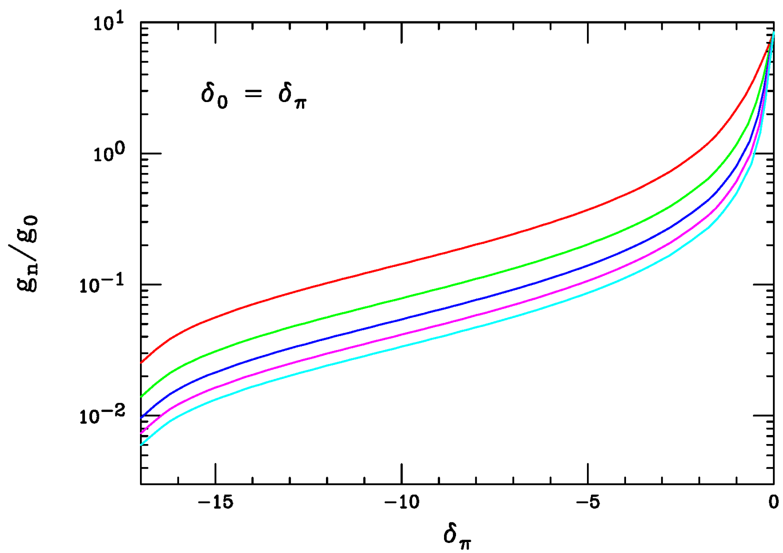
These parameters are useful…

Fermion mass terms used to 'localize' fermions & control their 'overlap' w/ Higgs on TeV brane to generate exponential mass hierarchy:

$m_f = - c_f \, k \, (v_f \, k)$



BLKTs help control potentially large fermion couplings to KK gauge fields



A suitable balance could beneficial..

..just too many parameters !

Simplify your (our) life…

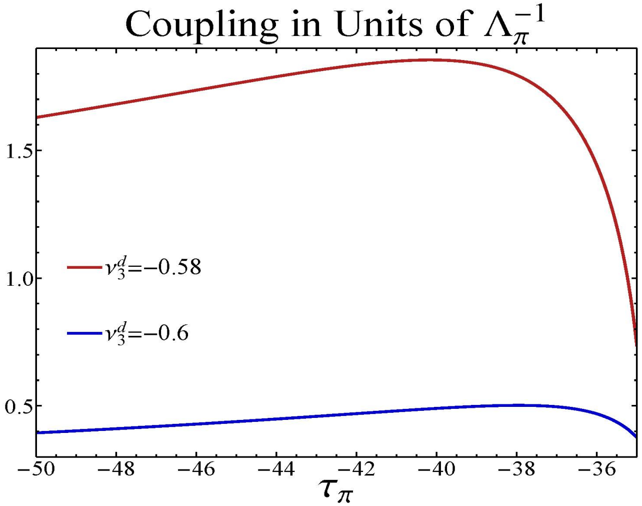
We will assume that the BLKTs on either brane are the same for all species, i.e., 38 → 2 parameters, e.g., $\delta_{0,\pi}$
Not all values are allowed (see next slide)

We will ignore charged leptons for now → 9 fermion masses

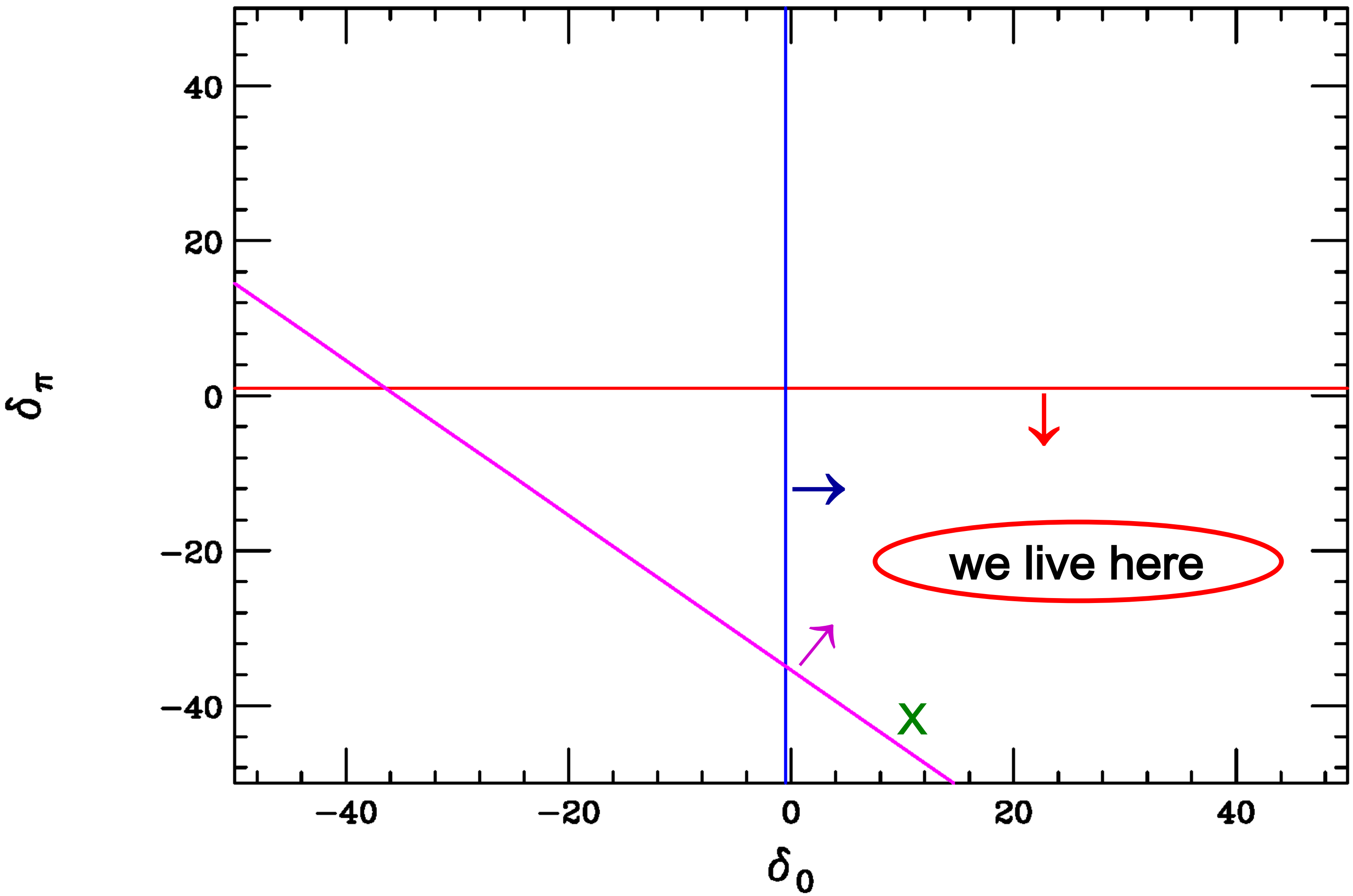
We will choose t_R to have $-\nu=c=1/2$ → orthogonality forbids its coupling to gauge KK states(important!) → 8 fermion masses

Further we will choose b_R to have $\nu \sim -0.6$ to fix the graviton-SM couplings to be $\sim \Lambda_\pi^{-1}$

→ 9 free parameters (to scan)



Graviton +Radion +Gauge Boson Ghost-Free Conditions



The Plan

(i) Place other F's 'close' to t_R to reduce FCNCs but allow them to 'float'

(ii) Use the BLKTs to increase the size of F wavefunctions at the TeV brane. Easier as both $t_{L,R}$ have similar profiles

(iii) Decrease KK gauge field couplings to H on TeV brane → reduces inter-KK gauge mixing & STU constraints
Large $\delta_\pi < 0$ will be required.

(iv) Generate 0^{th} order model where KK couplings to Higgs are ignored to get CKM & F masses… then 'correct' for these (small effect) & generate a more realistic model

Fermion Masses a la Anarchy

We follow hep-ph/0807.4937

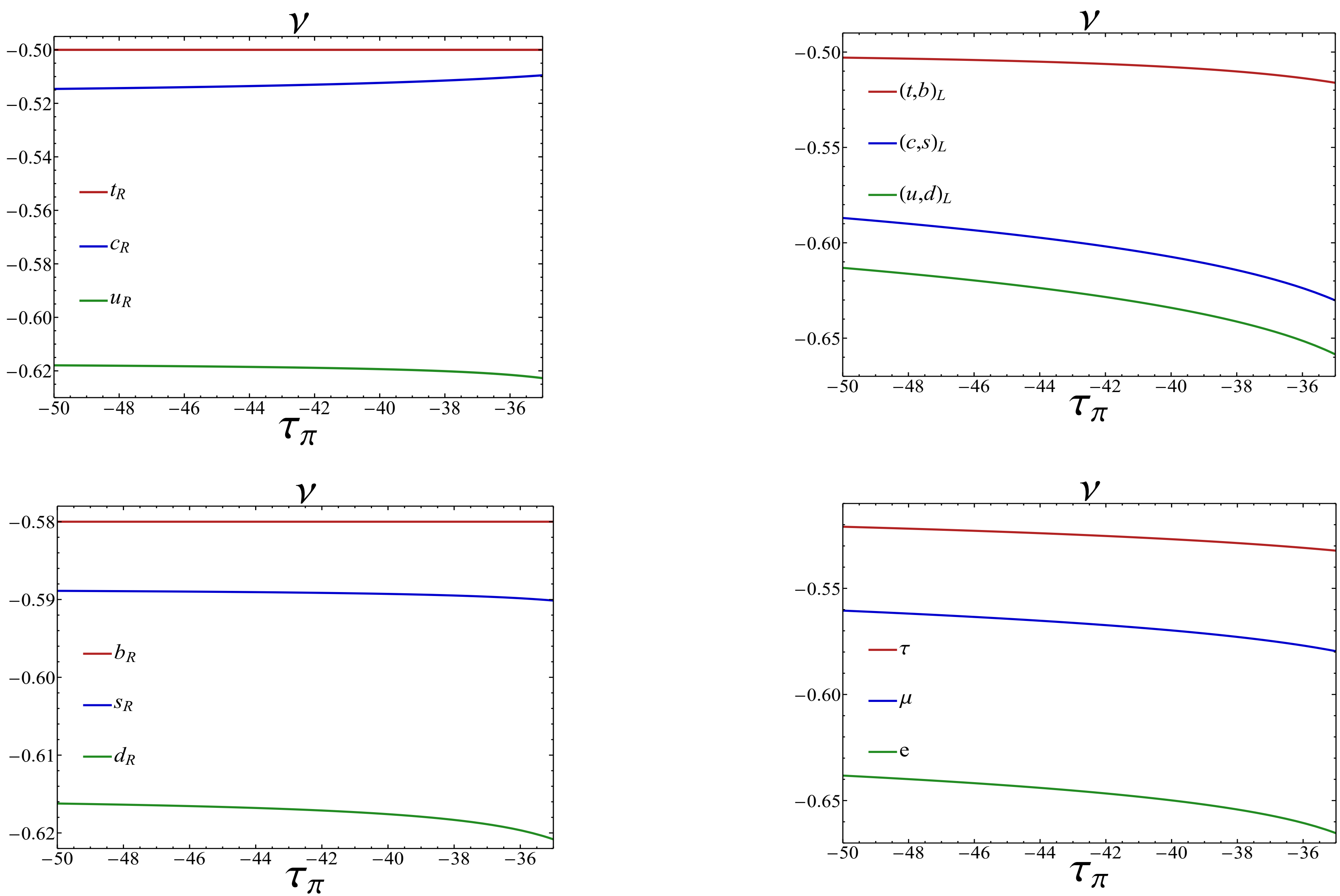
Chose random 0(1) complex Yukawa's + F localizations → quark mass matrices yielding the observed F masses + the CKM elements (within ~1σ) :

$$\mathcal{M}_{ij}^{u,d} = \frac{v}{\sqrt{2}} Y_{ij}^{u,d} \sqrt{\frac{1+2\nu_i^Q}{1+(1+2\nu_i^Q)\tau_\pi - (1-(1+2\nu_i^Q)\tau_0)\epsilon^{1+2\nu_i^Q}}} \times \sqrt{\frac{1+2\nu_j^{u,d}}{1+(1+2\nu_j^{u,d})\tau_\pi - (1-(1+2\nu_j^{u,d})\tau_0)\epsilon^{1+2\nu_j^{u,d}}}}$$

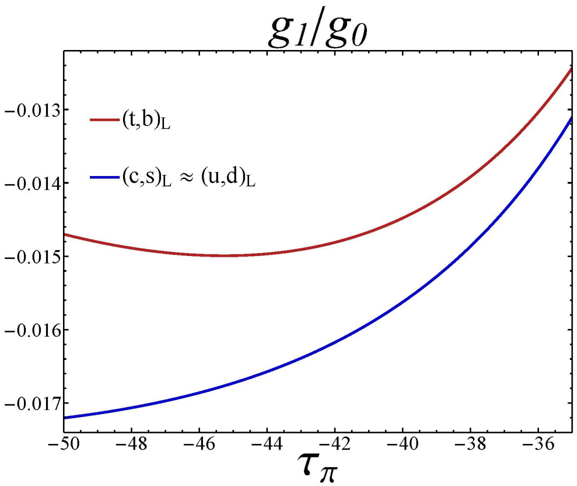
$$\mathcal{M}_D^{u,d} = U_L^{u,d\dagger} \mathcal{M}^{u,d} U_R^{u,d}$$

We generate ~10^7 pts to find benchmark(s) as a proof of principle & subject them to the constraints

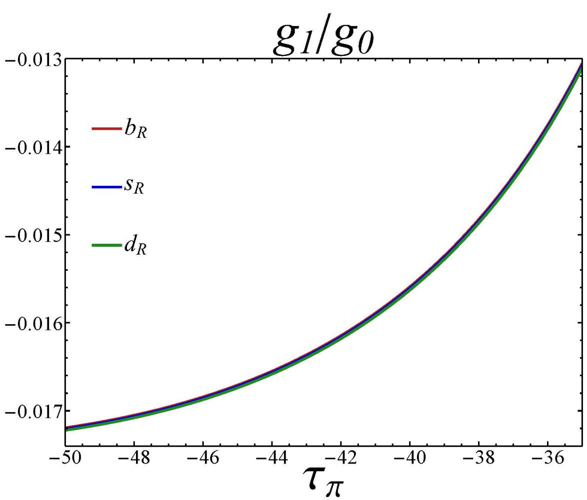
Quark localizations are ~ stable… we can also do this for leptons, ignoring ν masses, with LH- & RH- leptons at the same location

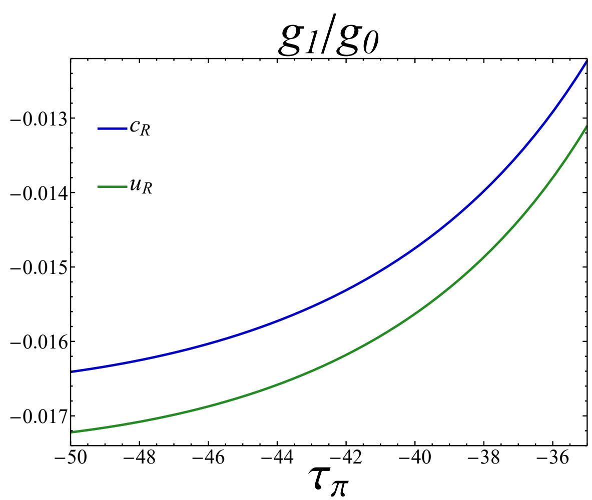


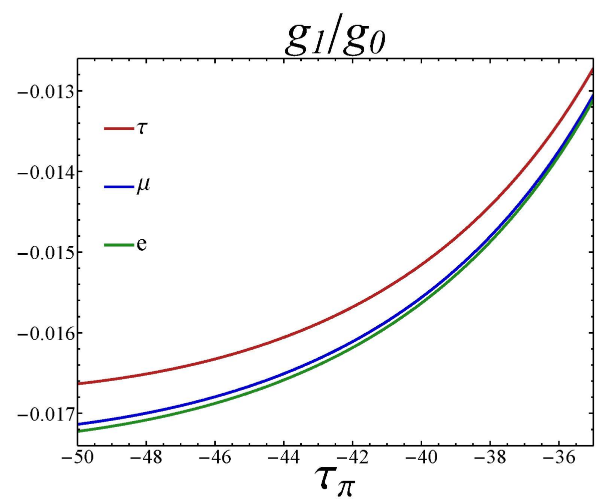
→ F couplings to gauge KKs are dramatically reduced so di-j, di-γ, di-top & di-l, etc., LHC σ's are suppressed by factors of ~5000 (!) wrt SM couplings evading these constraints



→ FCNC's are proportional to the differences in these tiny couplings (times mixing angles) so we expect them to be very small (below)







Turn on Higgs vev-induced KK Mixing: Gauge Bosons & (mostly) Top → EWK data

$$S = S_W + S_Z + S_{\text{EWSB Mass}}$$

$$S_Z = \sum_{n=0,m=0}^{\infty} \int d^4x \left(-\frac{1}{4} Z^{(m)}_{\mu\nu} Z^{(n)\mu\nu} + \frac{m_n^{Z\,2}}{2} Z^{(m)}_{\mu} Z^{(n)\mu}\right)\delta_{mn}$$

$$S_W = \sum_{n=0,m=0}^{\infty} \int d^4x \left(-\frac{1}{2} W^{+\,(m)}_{\mu\nu} W^{-\,(n)\mu\nu} + m_n^{W\,2} W^{+\,(m)}_{\mu} W^{-\,(n)\mu}\right)\delta_{mn}$$

KK masses only !

Higgs-induced masses

$$S_{\text{EWSB Mass}} = \sum_{n,m=0}^{\infty} \int d^5x \, \frac{M_Z^2}{2r_c} Z^{(m)}_{\mu} Z^{(n)\mu} \chi^Z_m(\pi)\chi^Z_n(\pi) + \frac{M_W^2}{r_c} W^{+(m)}_{\mu} W^{-\mu(n)} \chi^W_m(\pi)\chi^W_n(\pi).$$

$$\rightarrow \quad (\mathcal{M}_{W(Z)})_{i,j} = \frac{\chi^{W(Z)}_{i-1}(\pi)\chi^{W(Z)}_{j-1}(\pi)}{\chi^{W(Z)}_{0}(\pi)\chi^{W(Z)}_{0}(\pi)} m^2_{W(Z),0} + (m^{W(Z)}_{i-1})^2\delta_{ij}$$

A mass matrix !

EWSB induced mixing KK

EWK

$$m^2_{W(Z)} = m^2_{W(Z),0}[1 - \sum_{n=1}^{\infty} \frac{2(\pi k r_c + \tau_0 + \tau_\pi) m^2_{W(Z),0}}{(1+\tau_\pi^2 (x_n^{W(Z)})^2)((m_n^{W(Z)})^2 - m^2_{W(Z),0})}]$$

→ ~565 GeV for n=1

Next $$\frac{G_F}{\sqrt{2}} = \sum_{n=0}^{\infty} \frac{(g_n^{W\mu\bar{\nu}})(g_n^{We\bar{\nu}})}{8m_n^2}$$ **but** $$\frac{G_F^{SM}}{\sqrt{2}} = \frac{g_0^2}{8m^2_{W,0}}$$

So $G_F = G_F^{SM}(1+V)$ **& calculate $M_W^{indirect}$ (M_Z, G_F, α)**

$$\frac{G_F}{\sqrt{2}} \frac{1}{1+V} = \frac{\pi\alpha(1+\delta_W)}{2m_W^2\left(1 - \frac{1}{\rho}\frac{m_W^2}{m_Z^2}\right)}$$

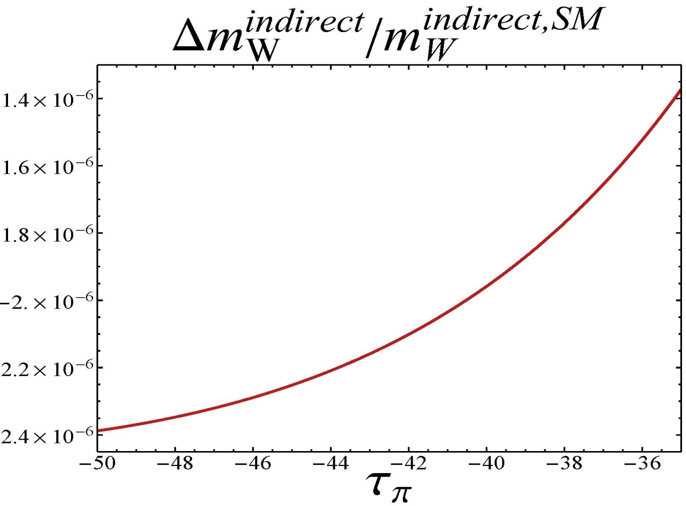
$$m^2_{W(Z)} = (1+\delta_{W(Z)}) m^2_{W(Z),0}$$

$\delta_{W,Z}$ and ρ as above..

We obtain $$m_W^2 = \frac{\rho m_Z^2}{2}\left[1 + \left[1 - \frac{2\sqrt{2}\pi\alpha(1+V)(1+\delta_Z)}{m_Z^2 G_F}\right]^{\frac{1}{2}}\right]$$

but in the SM $$\tilde{m}_W^2 = \frac{m_Z^2}{2}\left[1 + \left[1 - \frac{2\sqrt{2}\pi\alpha}{m_Z^2 G_F}\right]^{\frac{1}{2}}\right]$$ **implying a shift in**

$M_W^{indirect}$ →



We can go further & use the W mass + Z leptonic asymmetries + the Z invisible width to define tree-level STU parameters:

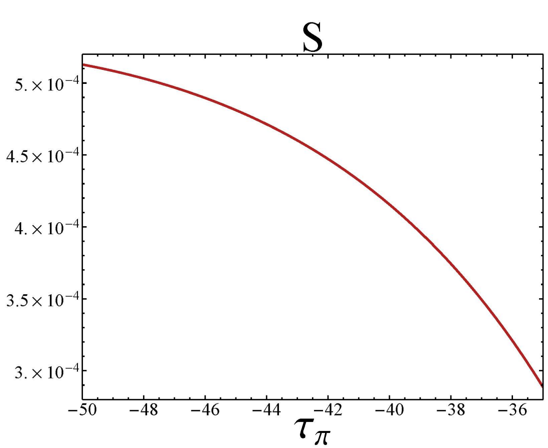
calculate these

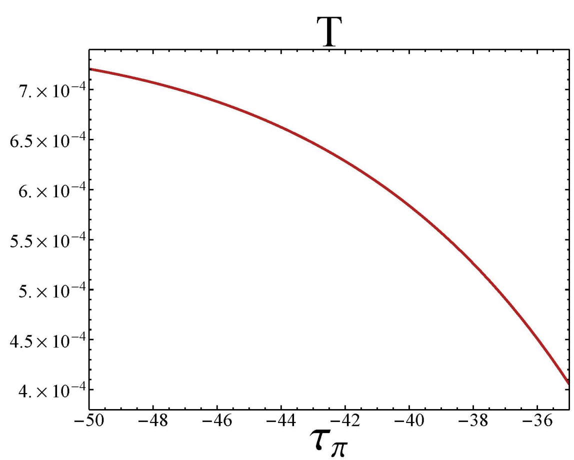
$$\left.\frac{m_W^2}{m_Z^2}\right|_{RS} - \left.\frac{m_W^2}{m_Z^2}\right|_{SM} \equiv \frac{\alpha c^2}{c^2 - s^2}\left[-\frac{1}{2}S + c^2 T + \frac{c^2 - s^2}{4s^2}U\right]$$

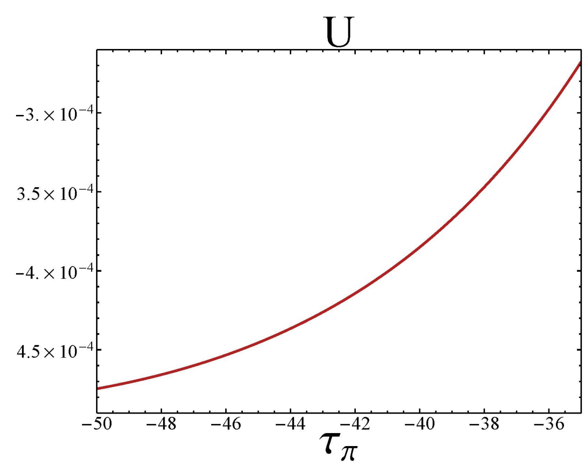
$$\left.\sin^2\theta_{eff}\right|_{RS} - \left.\sin^2\theta_{eff}\right|_{SM} \equiv \frac{\alpha}{c^2 - s^2}\left(\frac{1}{4}S - s^2 c^2 T\right)$$

$$\frac{g^2(\nu)|_{RS}}{g^2(\nu)|_{SM}} \equiv 1 + \alpha T$$

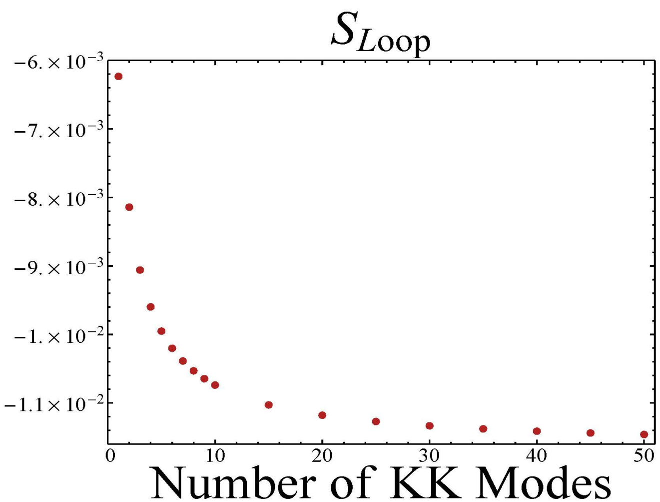
solve for these

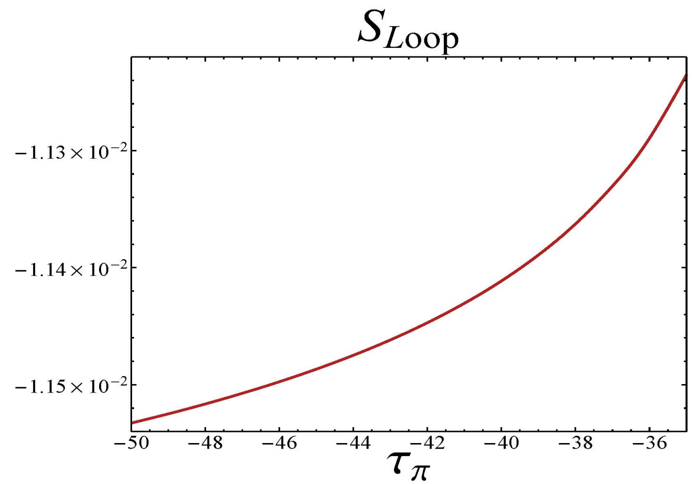


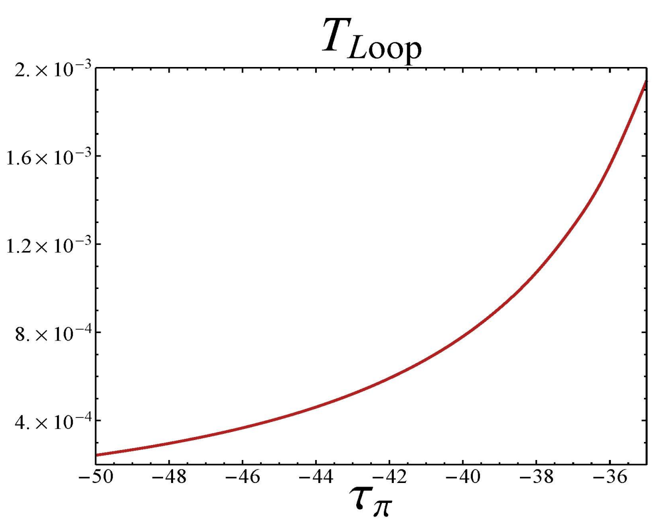


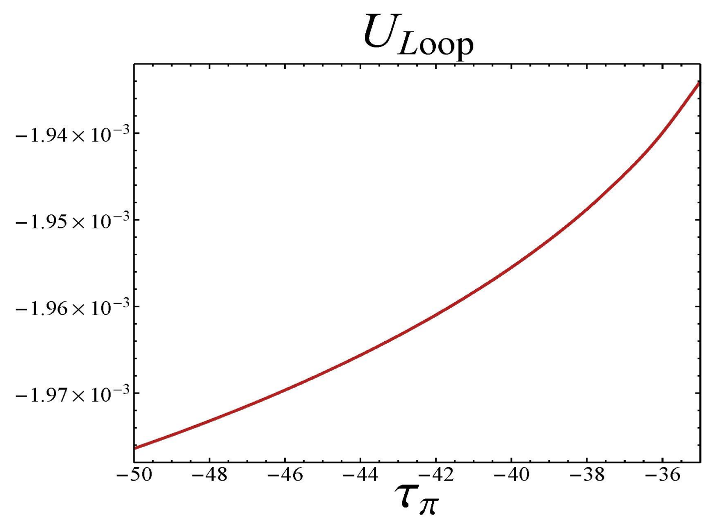


Next: Loop contributions to STU from KK mixings → also tiny !



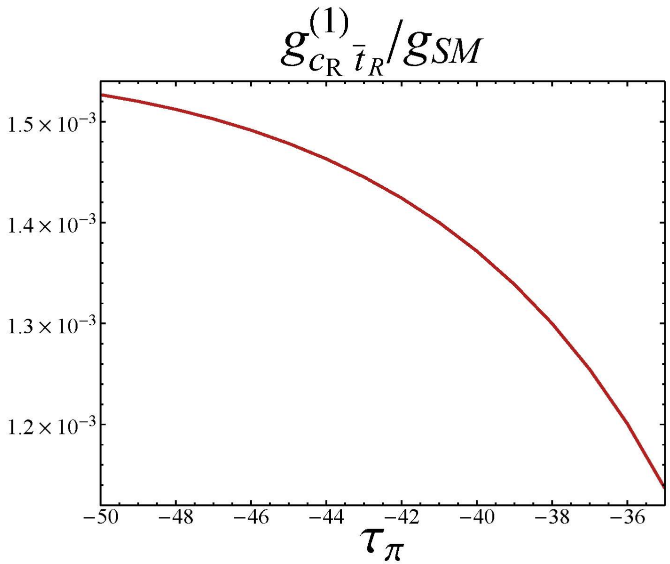




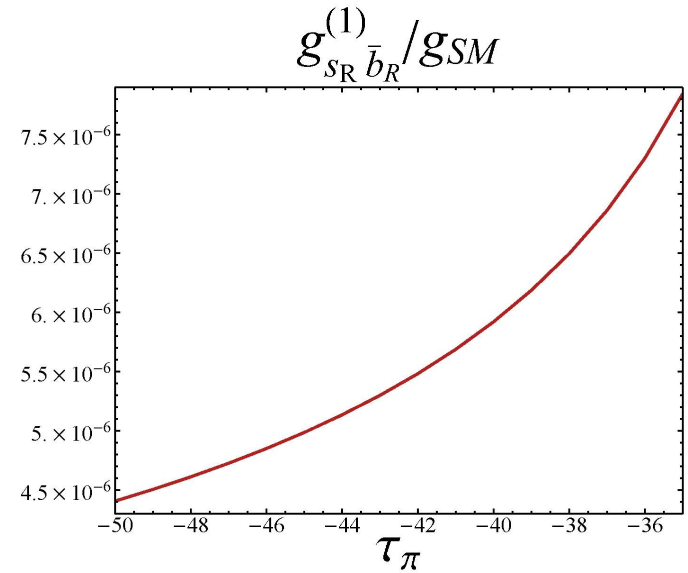


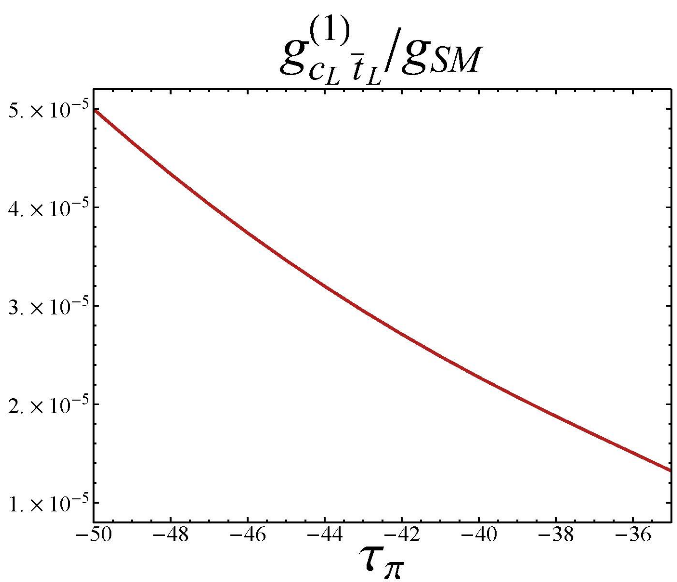
What about FCNC? Multiple sources..

FCNC couplings of the lightest KK gluon…all others much smaller

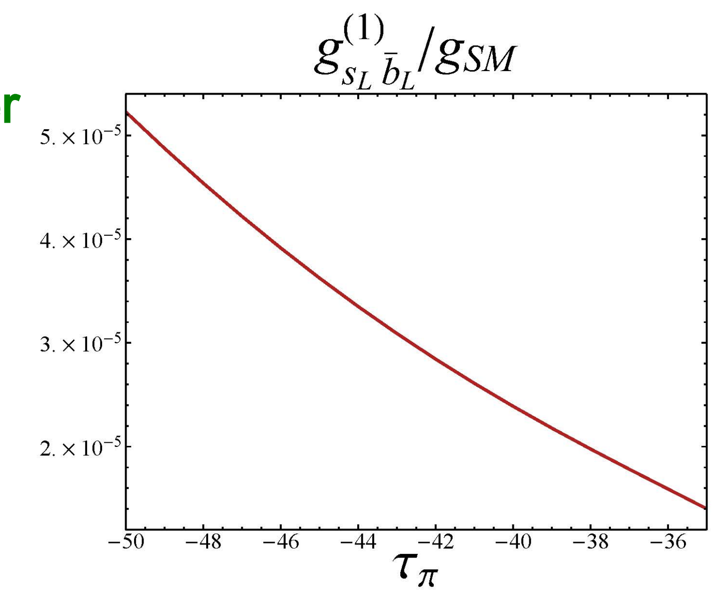


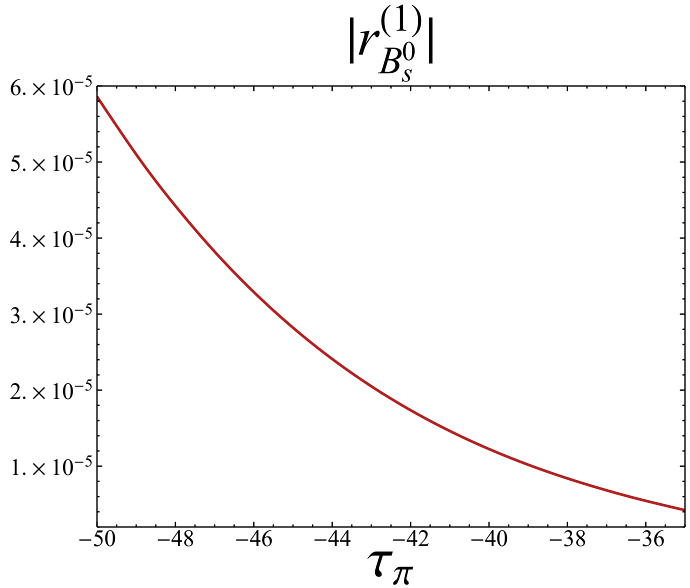
Even the largest is only ~10^{-3} !





B_s - $\bar{B}_s$ mixing provides another constraint..

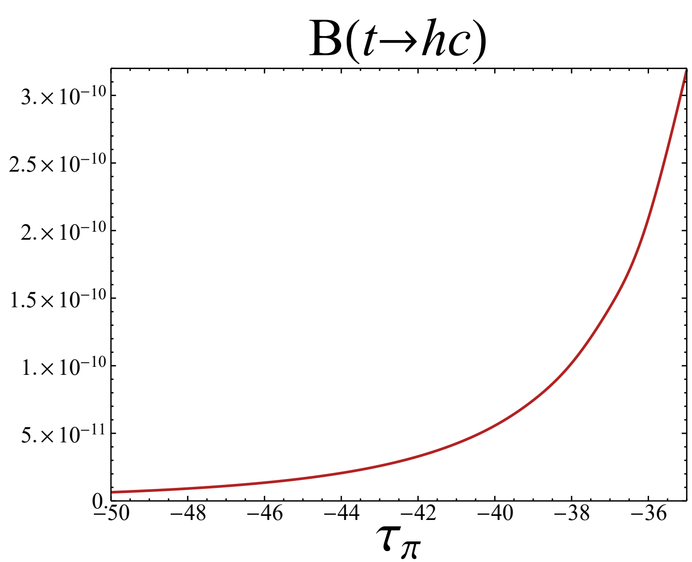




Ratio of FC gluon KK amplitude to the SM:

$$|r^{(1)}_{B^0_s}| \sim \frac{16\pi^2}{3}\frac{\sin^2\theta_W \alpha_s}{\alpha G_F S_0(m_t/m_W)|V^*_{tb}V_{ts}|^2}\left|\frac{(g^{(1)}_{s_L\bar{b}_L}/g_s)^2}{(m^A_1)^2}\right|.$$

Tiny!



FCNC Higgs couplings in t → ch:

$$\mathcal{B}(t \to ch) = \frac{2(1-r_h^2)^2 r_W^2}{(1-r_W^2)^2(1+2r_W^2)g^2}(|g^h_{ct}|^2 + |g^h_{tc}|^2)$$

where $g^h_{ab} = \vec{a}^\dagger_D H \vec{b}_S$ **Again tiny!**

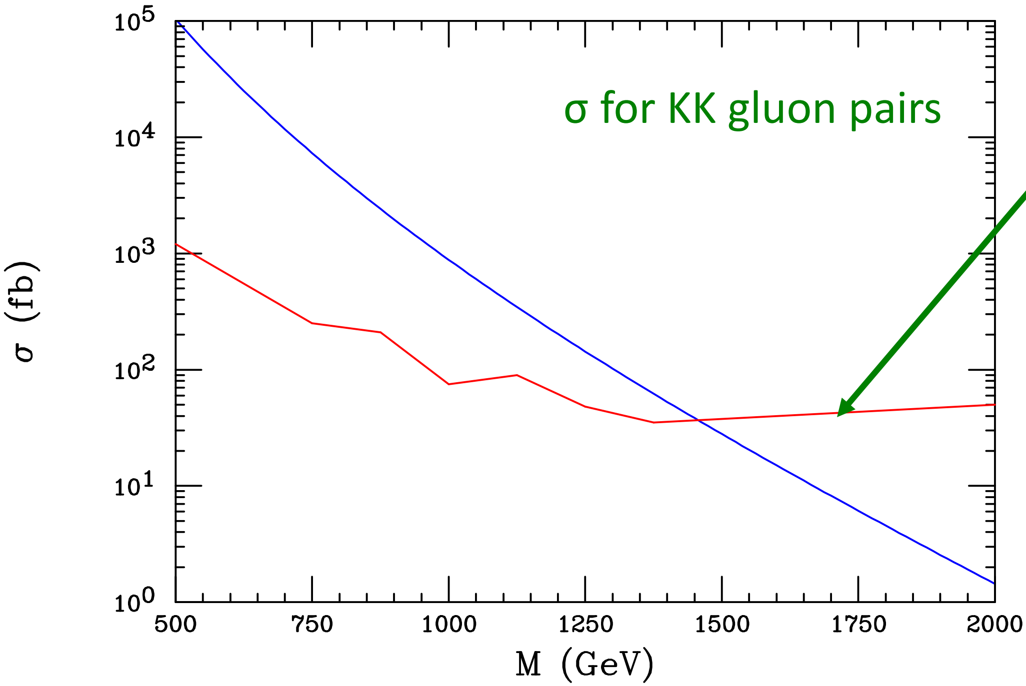
FC Z couplings also tiny !

How do you test this scenario.. everything's decoupled ??

(i) Gauge KK pair production

(ii) Graviton → γγ

Can't turn these off !

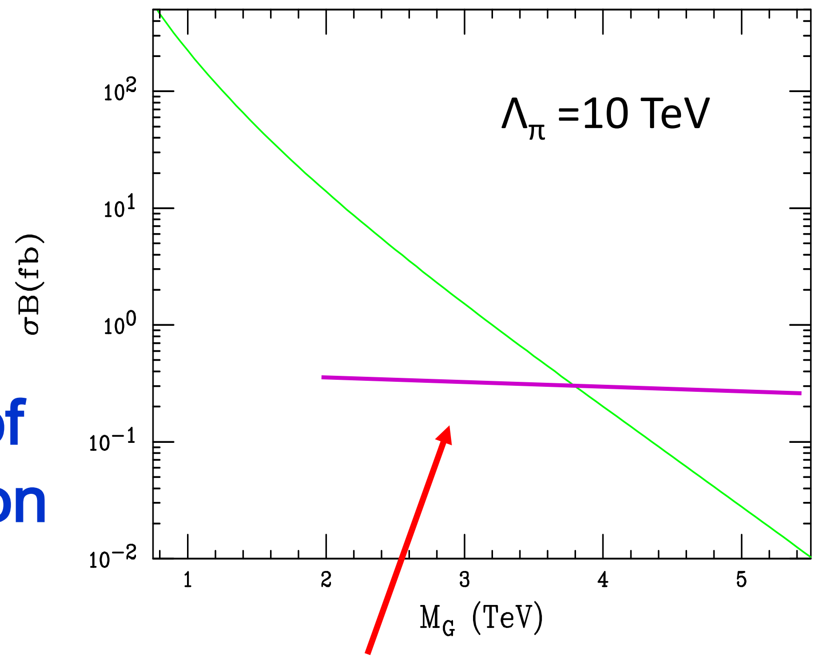


ATLAS-CONF-2016-084 (15.4/fb) places bound on pair production of Colorons – spin-1 objects decaying to di-jets - similar to gauge KK pair production

→ > 1.45 TeV, the strongest constraint on the KK scale: kε > ~ 380 GeV

Graviton →γγ

→ $\sigma \sim \Lambda_\pi^{-2}$



The lower bound on the mass of the KK g implies that the graviton is above ~ 1.9 TeV.

ATLAS & CMS both have searches (ATLAS-CONF-2016-059 & CMS 1609.02507) → place a lower limit on Λ_π for different graviton masses: For M = 2(3, 4) TeV → Λ_π > 68(25, 10) TeV.

A heavy spin-2 object will be an obvious signal for RS models

Summary & Conclusions

→ The generality of the RS model allow for relatively light KK states for a reasonable parameter range, avoiding LHC searches + precision EWK + FCNC constraints, w/o any new custodial symmetry etc.

→ This scenario can 'explain'/accommodate all of the charged fermion masses as well as the CKM matrix.

→ The strongest existing bound (& earliest signature!) arises from KK gluon pair-production @ LHC. KK gravitons in the 2γ mode provides a cross check.

→ This scenario can be extended to include thermal DM

Backup

How does 'warping' work ?

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

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

$\left\{ \left[e^{-2ky} \right]^4 \right\}^{1/2}$ $\qquad e^{2ky} g^{\mu\nu}$

Higgs vev ~ 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 $\hat{H} \to e^{kr_c\pi} H$

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

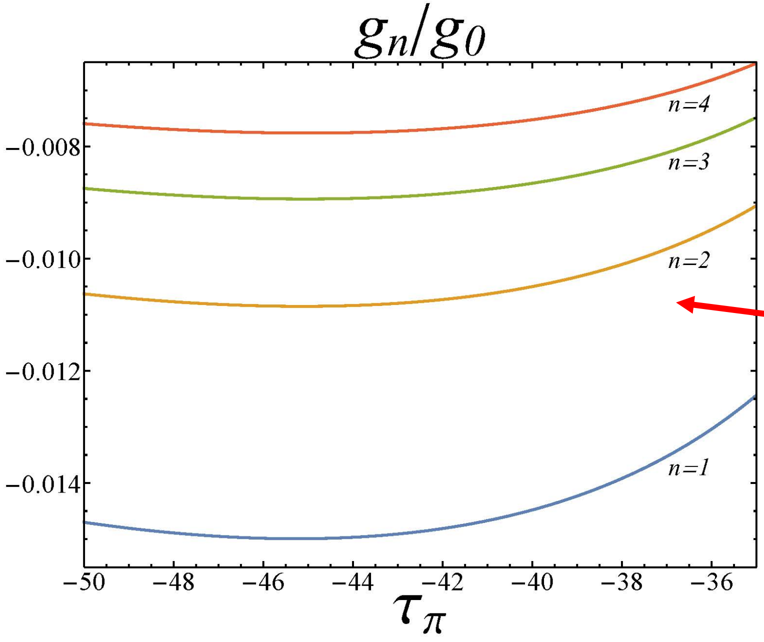
"Canonically" normalized!

$\boxed{\text{V is TeV scale now}}$

The Higgs on the TeV brane gets a TeV scale vev ... even though we started at ~ M_{pl} !

- Warping modifies all energy scales.

Furthermore, these F couplings experience further reduction for higher gauge KK states, e.g.,



Example: $(t,b)_L$ couplings for higher gauge KKs

Basics: consider charged leptons w/ massless ν's → no flavor mixing.. (w/ only the lowest 2 KK states shown): split into D(=L) & S(=l) fields which have L- or R- components:

$$\Psi_L^l = (L_L^{(0)}, L_L^{(1)}, l_L^{(1)}, L_L^{(2)}, l_L^{(2)}, \ldots)$$
$$\Psi_R^l = (l_R^{(0)}, l_R^{(1)}, L_R^{(1)}, l_R^{(2)}, L_R^{(2)}, \ldots)$$

→

$$\mathcal{M}_l = m_{l,0} \begin{pmatrix} 1 & \mu_{l,1}^S & 0 & \mu_{l,2}^S & 0 \\ \mu_{l,1}^D & \mu_{l,1}^D\mu_{l,1}^S & \frac{m_{l,1}^D}{m_{l,0}} & \mu_{l,1}^D\mu_{l,2}^S & 0 \\ 0 & \frac{m_{l,1}^S}{m_{l,0}} & 0 & 0 & 0 \\ \mu_{l,2}^D & \mu_{l,2}^D\mu_{l,1}^S & 0 & \mu_{l,2}^D\mu_{l,2}^S & \frac{m_{l,2}^D}{m_{l,0}} \\ 0 & 0 & 0 & \frac{m_{l,2}^S}{m_{l,0}} & 0 \end{pmatrix}$$

KK mass terms

here

(really this is ∞ x ∞)

$$\mu_{l,n}^{D(S)} \equiv \sqrt{2} sgn(\zeta_{\frac{1}{2}-\nu_l^{D(S)}}(x_{l,n}^{D(S)})) \left(\frac{1+(1+2\nu_l^{D(S)})\tau_\pi + (1-(1+2\nu_l^{D(S)})\tau_0)\epsilon^{1+2\nu_l^{D(S)}}}{1+(1+2\nu)\tau_\pi + \tau_\pi^2 (x_{l,n}^{D(S)})^2} \right)^{\frac{1}{2}} \quad (69)$$

Produces a shift in the SM predicted l mass :

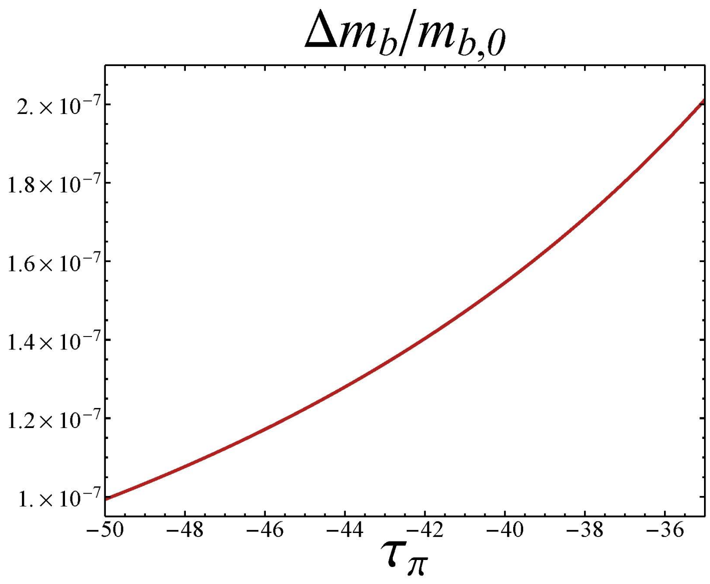
$$m_l = m_{l,0} \left(1 - \sum_{n=1}^{\infty} \frac{\mu_{l,n}^D \mu_{l,n}^S m_l^2}{m_{l,n}^D m_{l,n}^S - m_l^2} \right)$$

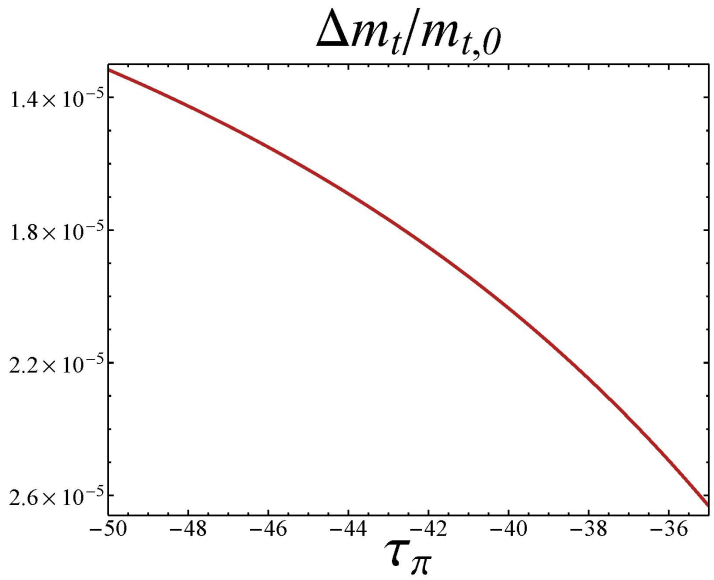
Diagonalization yields masses & also all the FCNC couplings as we will see below. We can truncate our numerics w/ only a few KKs due to rapid all-off of wavefunction ratios.

For the quark case life is tougher as there is extensive flavor mixing. We construct a 3x3 matrix (of ∞ x ∞ submatrices !) using the machinery above & repeat (numerically)

$$\mathcal{M}_{u,d} = \begin{pmatrix} \tilde{\mathbf{Q}}_{11}^{u,d} & \tilde{\mathbf{Q}}_{12}^{u,d} & \tilde{\mathbf{Q}}_{13}^{u,d} \\ \tilde{\mathbf{Q}}_{21}^{u,d} & \tilde{\mathbf{Q}}_{22}^{u,d} & \tilde{\mathbf{Q}}_{23}^{u,d} \\ \tilde{\mathbf{Q}}_{31}^{u,d} & \tilde{\mathbf{Q}}_{32}^{u,d} & \tilde{\mathbf{Q}}_{33}^{u,d} \end{pmatrix}$$

One measure of this KK mixing (other than the FCNCs below) is provided by the t & b masses which feel this effect most strongly (NB: 5-50 KK levels for each flavor is sufficient for convergence)





This is done maintaining the good agreement w/ the CKM predictions & all the lighter quark masses

Now that we have accounted for EVERYTHING we address the EWK & FCNC constraints

The first quantity of interest is G_F which undergoes tree-level modifications due to KK's

W/o mixing among the KK states, the fermion KK tower contributions to vacuum polarization are benign since they are VL. The Higgs induced KK mixing in the t(& b) sectors destroys this + external gauges have KK admixtures. These feed into loop-level STU as do gauge KKs.

$$\delta\Pi_{ab}(q^2) = N_c \frac{1}{2\pi^2} \sum_{ij} \int_0^1 dx\, f_{ab}(q^2, x) \log\left[\frac{m_{ij}^2(x) - q^2 x(1-x)}{\mu^2}\right]$$

$$f_{ab}(q^2, x) = \frac{g_L^a g_L^{b\,*} + g_R^a g_R^{b\,*}}{2}\left[x(1-x)q^2 - \frac{m_{ij}^2(x)}{2}\right] + \frac{g_L^a g_R^{b\,*} + g_R^a g_L^{b\,*}}{2}\left[\frac{m_i m_j}{2}\right]$$

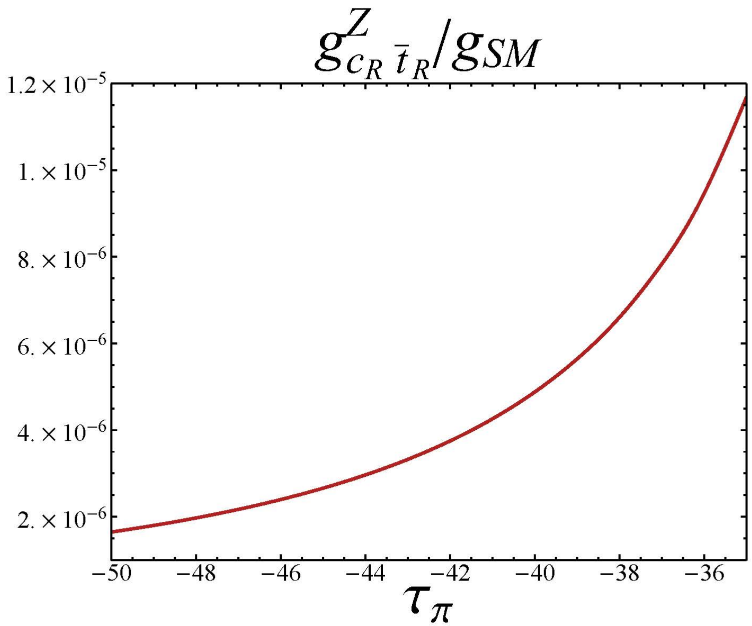
Couplings are calculated from the gauge/fermion tower diagonalization process

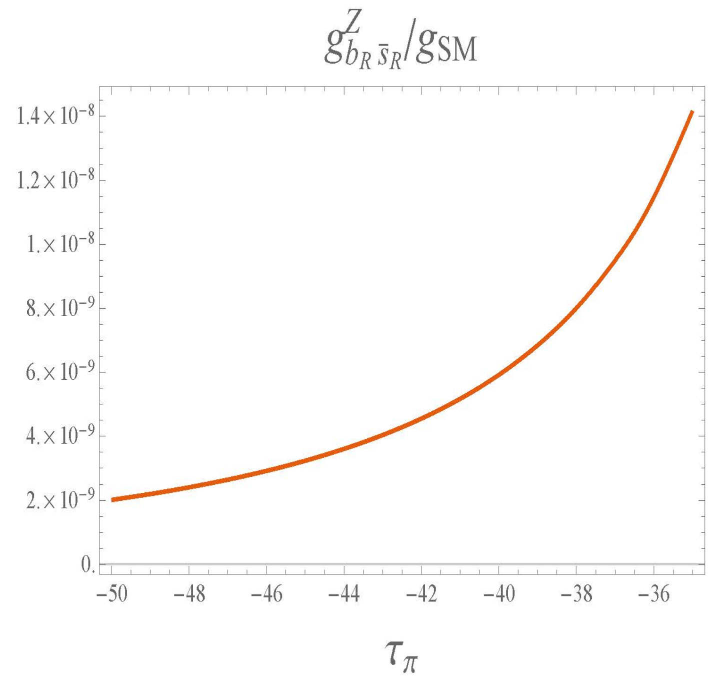
$$\frac{\alpha S}{4s^2c^2} = \left[\frac{\delta\Pi_{ZZ}(m_Z^2) - \delta\Pi_{ZZ}(0)}{m_Z^2}\right] - \frac{c^2 - s^2}{sc}\delta\Pi'_{Z\gamma}(0) - \delta\Pi'_{\gamma\gamma}(0)$$

$$\alpha T = \frac{\delta\Pi_{WW}(0)}{m_W^2} - \frac{\delta\Pi_{ZZ}(0)}{m_Z^2}$$

$$\frac{\alpha U}{4s^2} = \left[\frac{\delta\Pi_{WW}(m_W^2) - \delta\Pi_{WW}(0)}{m_W^2}\right] - c^2\left[\frac{\delta\Pi_{ZZ}(m_Z^2) - \delta\Pi_{ZZ}(0)}{m_Z^2}\right] - s^2\delta\Pi'_{\gamma\gamma}(0) - 2sc\delta\Pi'_{Z\gamma}(0)$$

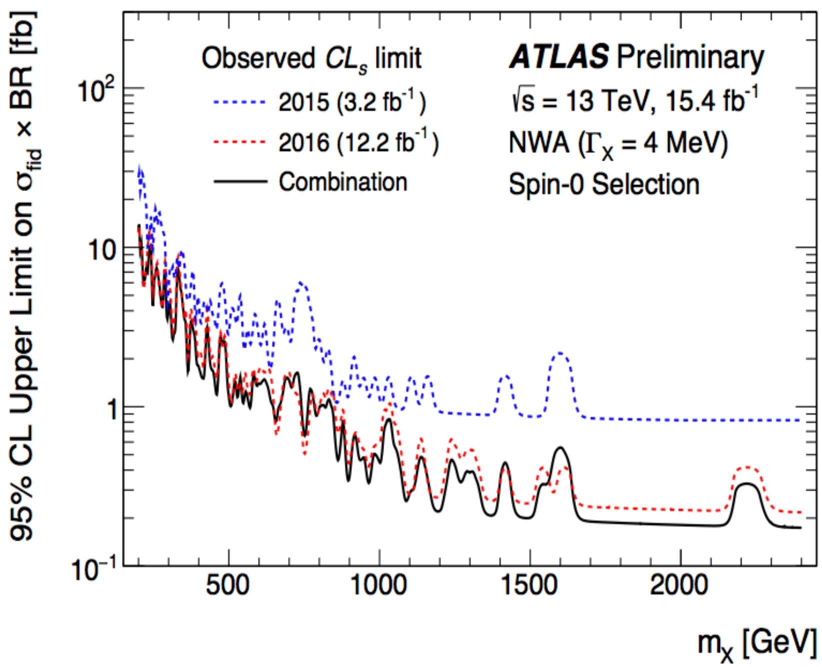
Couplings involving t_R are largest owing to the special localization it possesses. The Ztc coupling is directly probed in FC top decays $t \to cZ$ (currently $B < \sim 10^{-4}$).



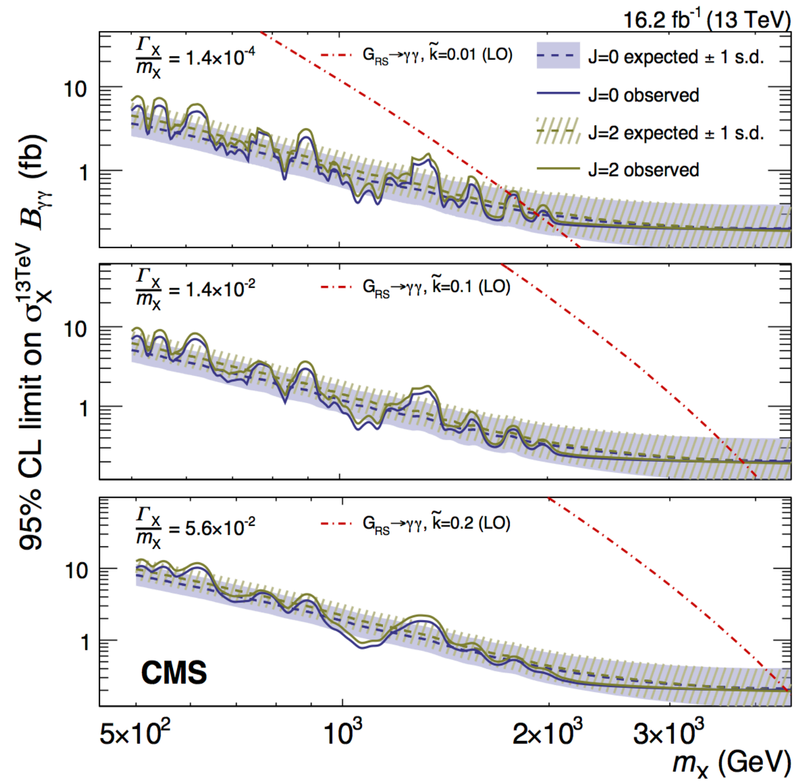


We predict values below $B \sim 10^{-10}$!

In many cases it is the FC gluon KK tower contributions which are the most constrained .. for the lowest KK mode:


Observed CL_s limit
2015 (3.2 fb^{-1})
2016 (12.2 fb^{-1})
Combination
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 15.4 fb^{-1}
NWA (Γ_X = 4 MeV)
Spin-0 Selection
95% CL Upper Limit on σ_{fid} × BR [fb]
10^2
10
1
10^{-1}
500
1000
1500
2000
m_X [GeV]

(a)


16.2 fb^{-1} (13 TeV)
$\frac{\Gamma_X}{m_X}$ = 1.4×10^{-4}
$G_{RS}\to\gamma\gamma$, $\tilde{k}$=0.01 (LO)
J=0 expected ± 1 s.d.
J=0 observed
J=2 expected ± 1 s.d.
J=2 observed
$\frac{\Gamma_X}{m_X}$ = 1.4×10^{-2}
$G_{RS}\to\gamma\gamma$, $\tilde{k}$=0.1 (LO)
$\frac{\Gamma_X}{m_X}$ = 5.6×10^{-2}
$G_{RS}\to\gamma\gamma$, $\tilde{k}$=0.2 (LO)
CMS
95% CL limit on $\sigma_X^{13TeV} B_{\gamma\gamma}$ (fb)
10
1
5×10^2
10^3
2×10^3
3×10^3
m_X (GeV)