Higgs Physics in Warped Extra Dimensions

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Rencontres de Moriond
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Casagrande, FG, Haisch, Neubert, Pfoh, JHEP 1009(2010)014 [arXiv:1005.4315]

Outline

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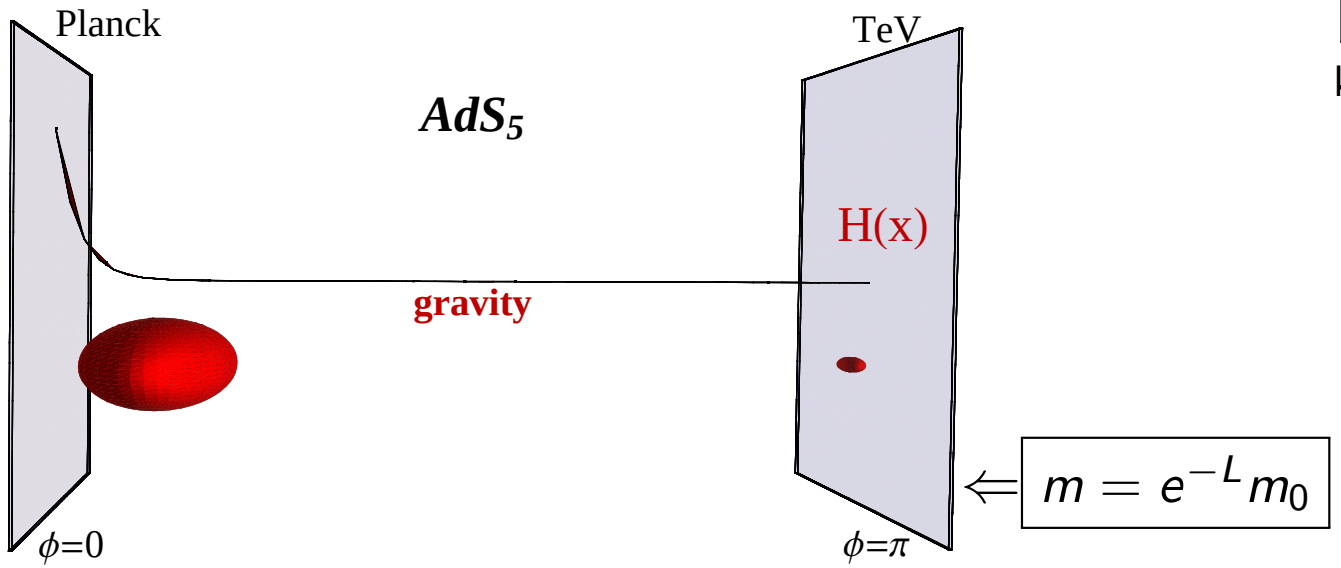
The Randall-Sundrum (RS) Model hep-ph/9905221

- Solution to the gauge hierarchy problem in 5D spacetime
- Hierarchy between the electroweak- and Planck scale generated through non-factorizable metric

$$ds^2 = e^{-2L|\phi|/\pi}\eta_{\mu\nu}dx^\mu dx^\nu - r^2 d\phi^2$$



$$L = kr\pi \approx 37 \gg 1$$

k: curvature of AdS_5

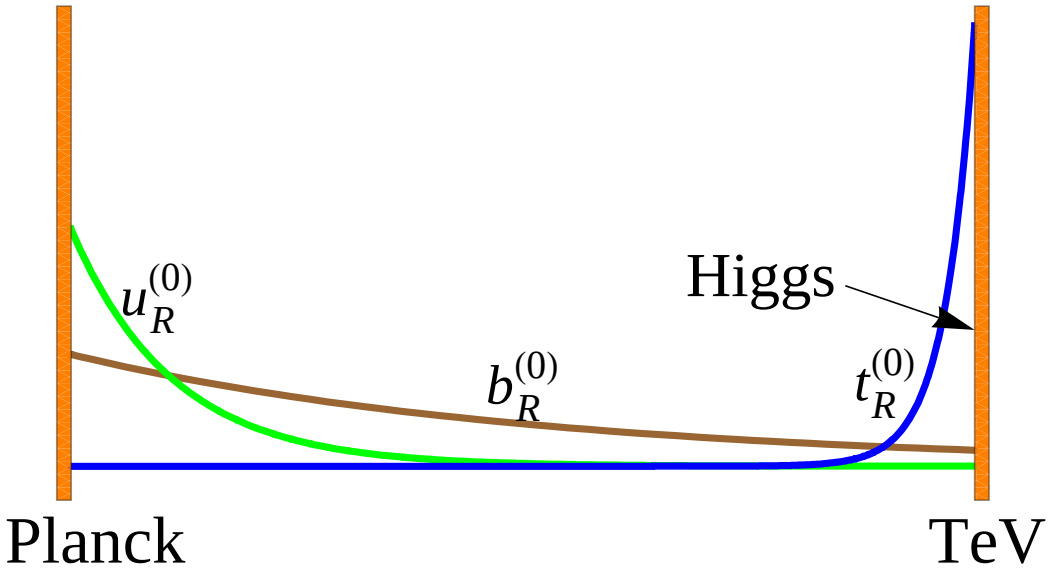
many observables enhanced by L

$$\Leftarrow m = e^{-L} m_0$$

- All fundamental mass parameters of $\mathcal{O}(M_{PL})$

The Standard Model in the Bulk

Just the Higgs boson has to be localized at (close to) the TeV brane in order to solve the hierarchy problem $\Rightarrow$ *Bulk-SM*



Davoudiasl, Hewett, Rizzo, hep-ph/9911262,
Pomarol, hep-ph/9911294
Grossman, Neubert, hep-ph/9912408,
Gherghetta, Pomarol, hep-ph/0003129

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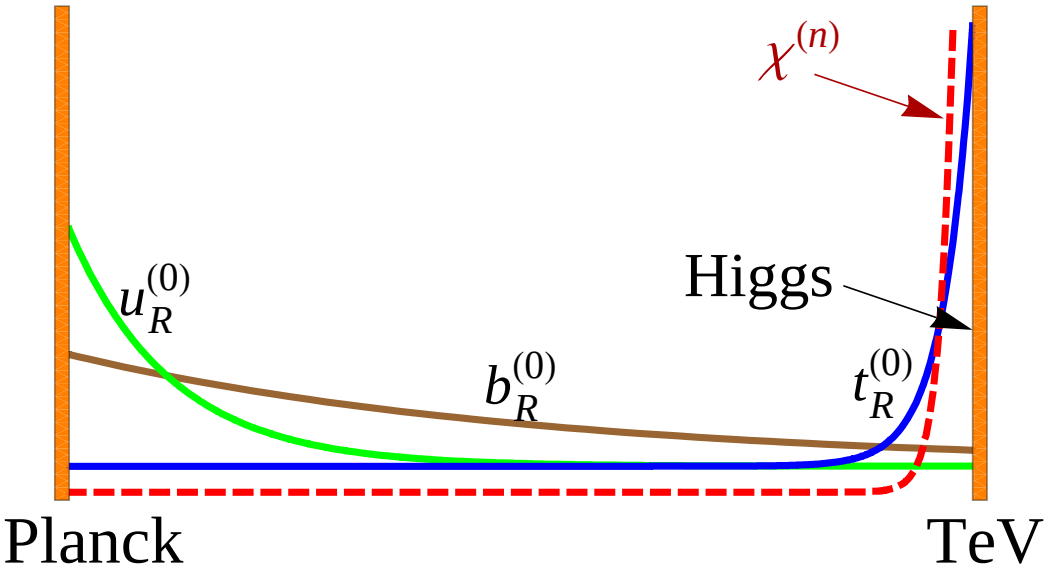

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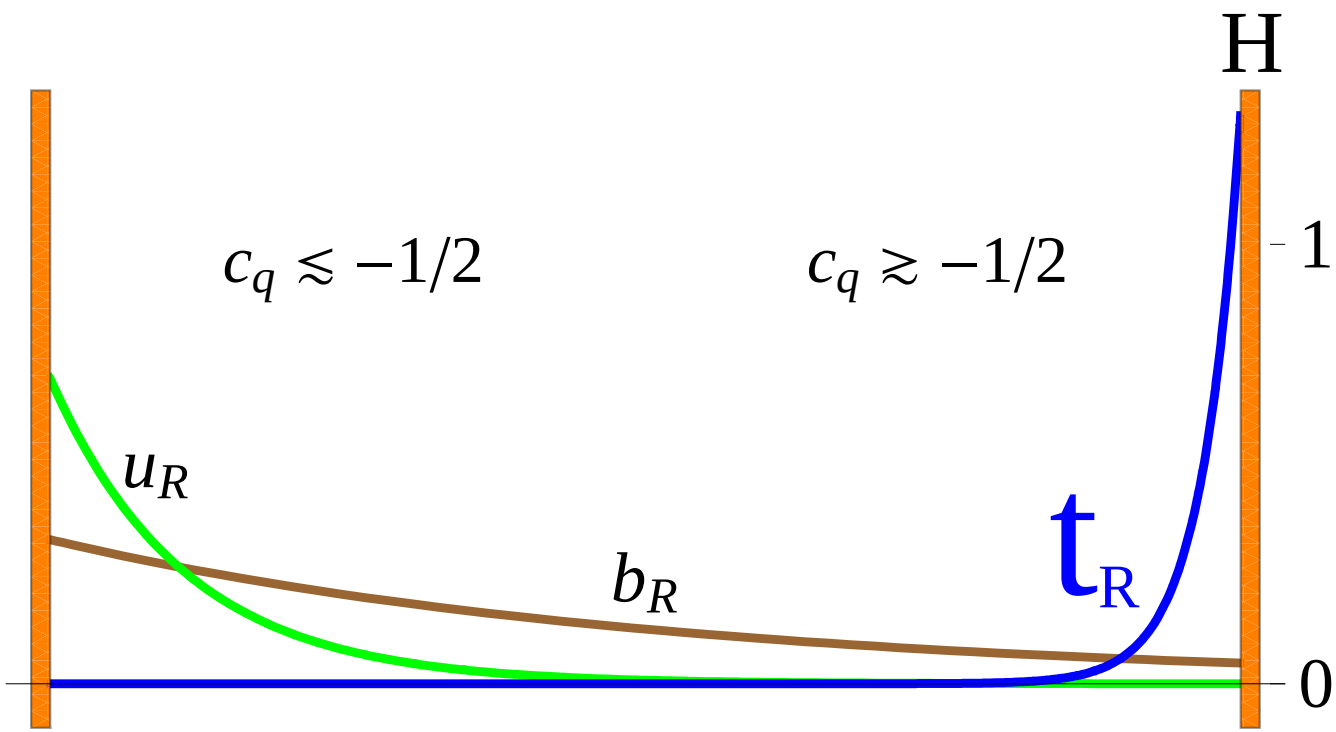
$m^{(0)} \sim v$

Kaluza-Klein excitations with

$M_{\rm KK} = ke^{-L} \sim TeV$
$m^{(1)} \approx 2.5\, M_{\rm KK}$
$\vdots$

RS as a Solution to the Flavor Puzzle

- RS offers explanation for fermion mass hierarchies and small CKM mixing angles, $(Y_q)_{ij} \sim \mathcal{O}(1)$ Huber, hep-ph/0303183; Agashe, Perez, Soni, hep-ph/0408134



$c_{Q,q} = \pm M_{Q,q}/k$: $\mathcal{O}(1)$ dimensionless 5D-mass parameters

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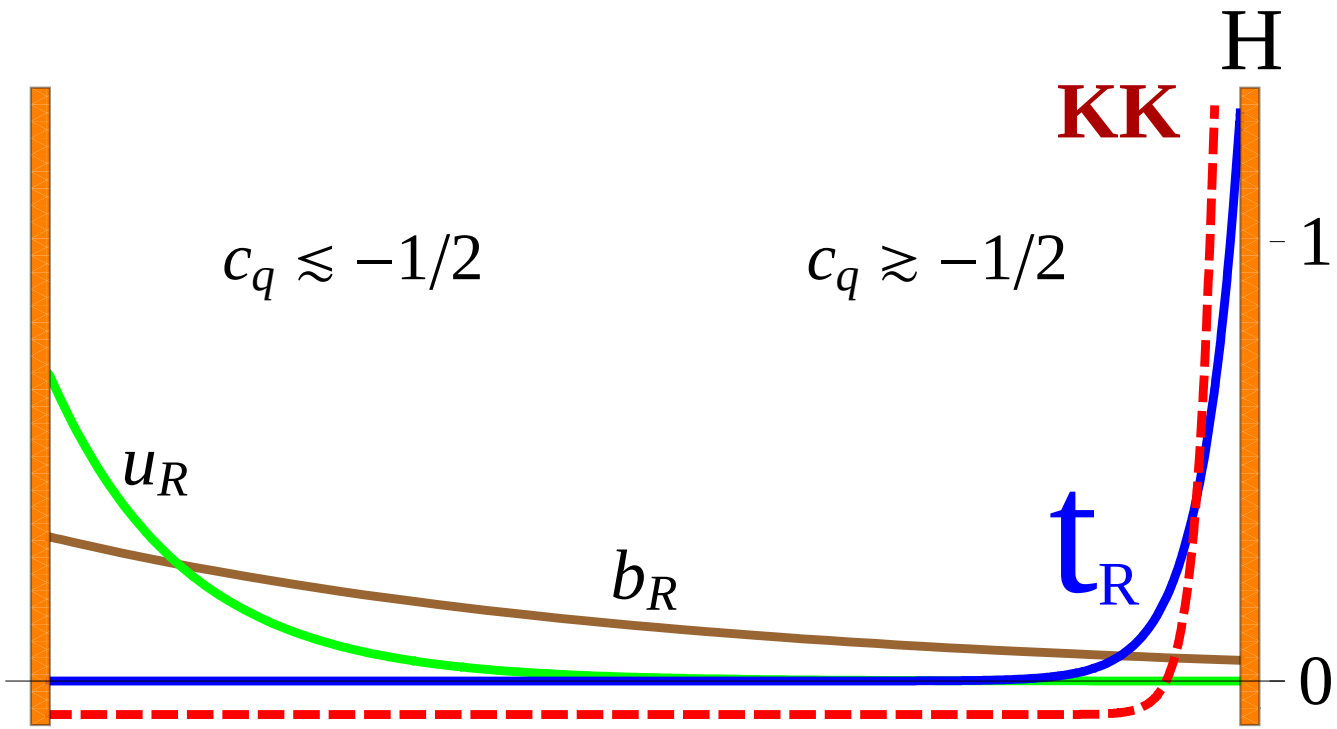

Expect sizable effects in 3rd generation and Higgs physics
$\longrightarrow$ predictivity

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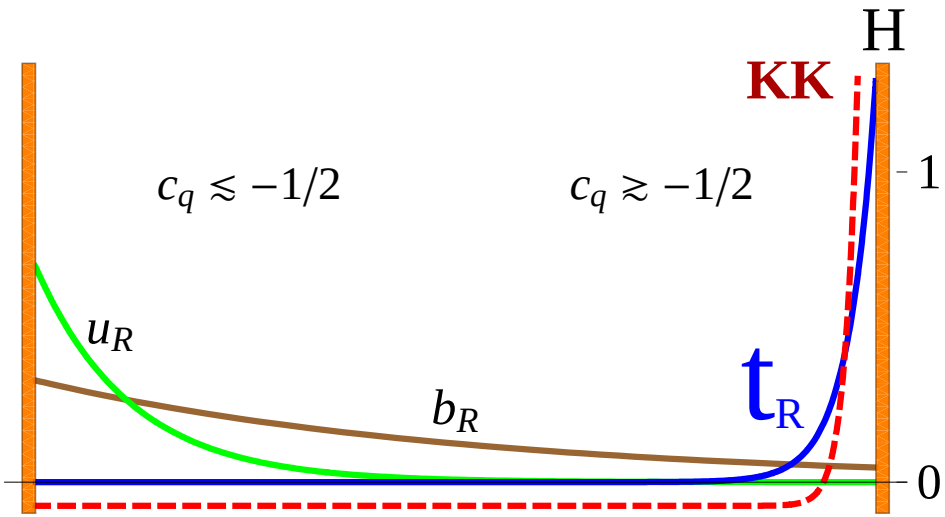

Fermion couplings to massive gauge bosons $\sim$ flavor dependent overlaps

$\overset{\Longrightarrow}{\text{mass basis}}$ Tree-level flavor-changing neutral currents $\Rightarrow$ constraints

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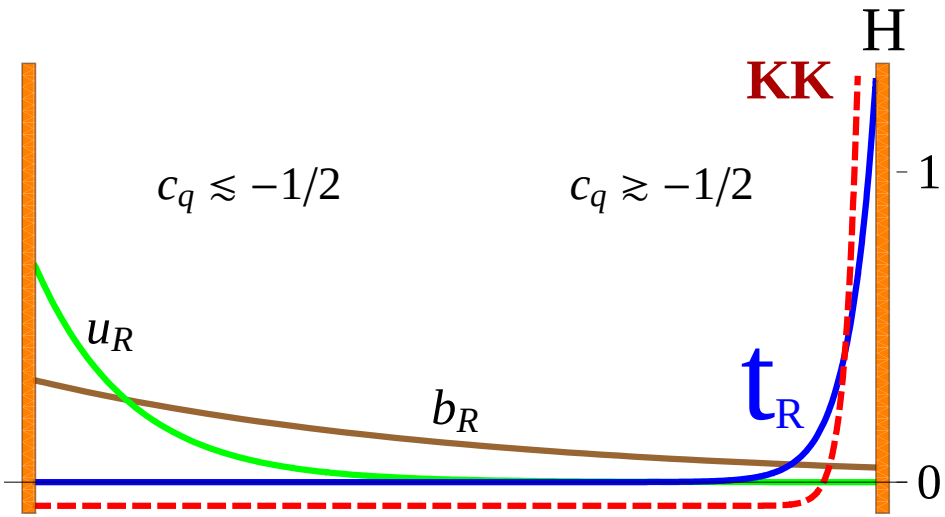

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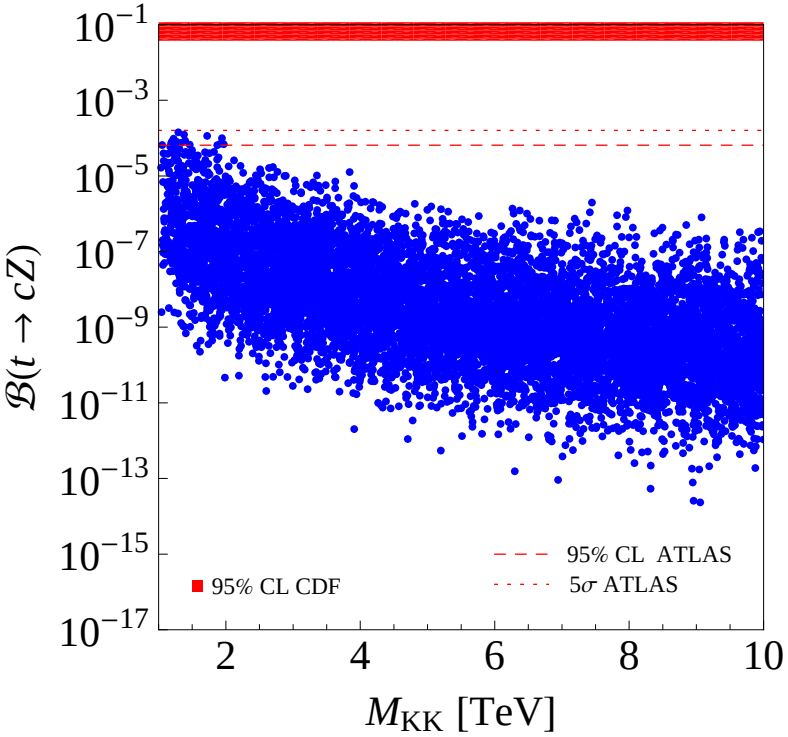
Electroweak Precision Tests

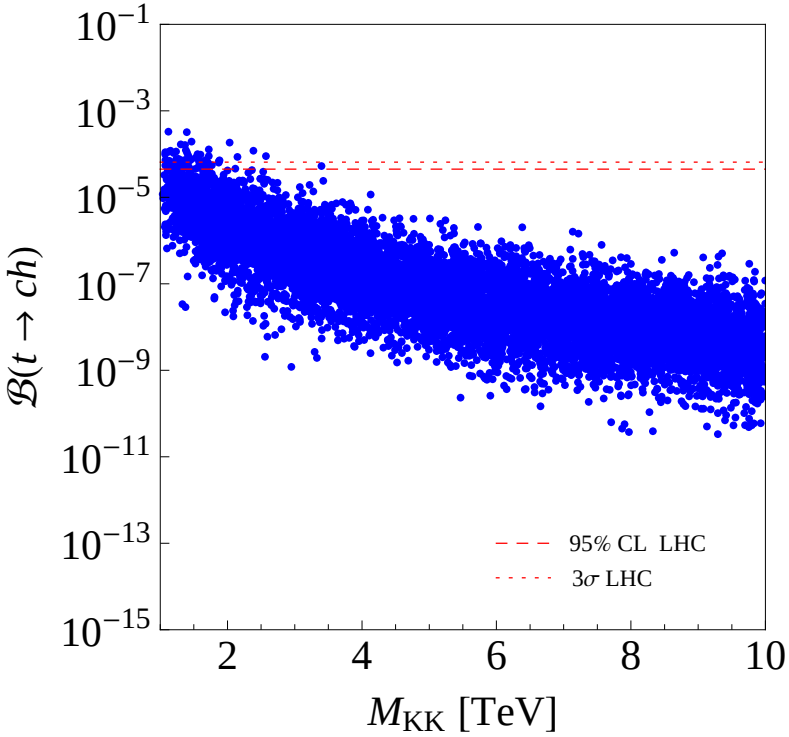
$\Rightarrow m^{(1)} > 5$ TeV (custodial model or heavy higgs)

Outline

Rare Decays $t \to cZ^0$ and $t \to ch$

- Fermion masses generated through Higgs mechanism *and* compactification $\Rightarrow$ misalignment between mass- and Yukawa matrix $\Rightarrow$ tree-level Higgs FCNCs

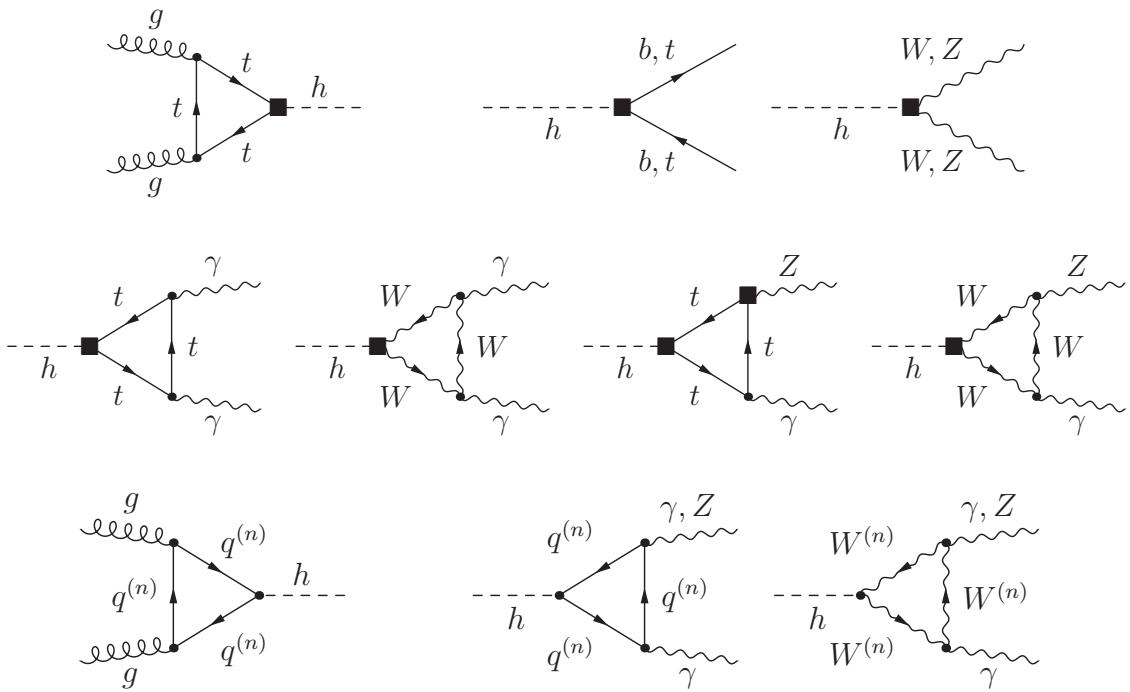




Higgs Production and Decay

First complete one-loop calculation in RS

see also: Azatov, Toharia, Zhu, 1006.5939



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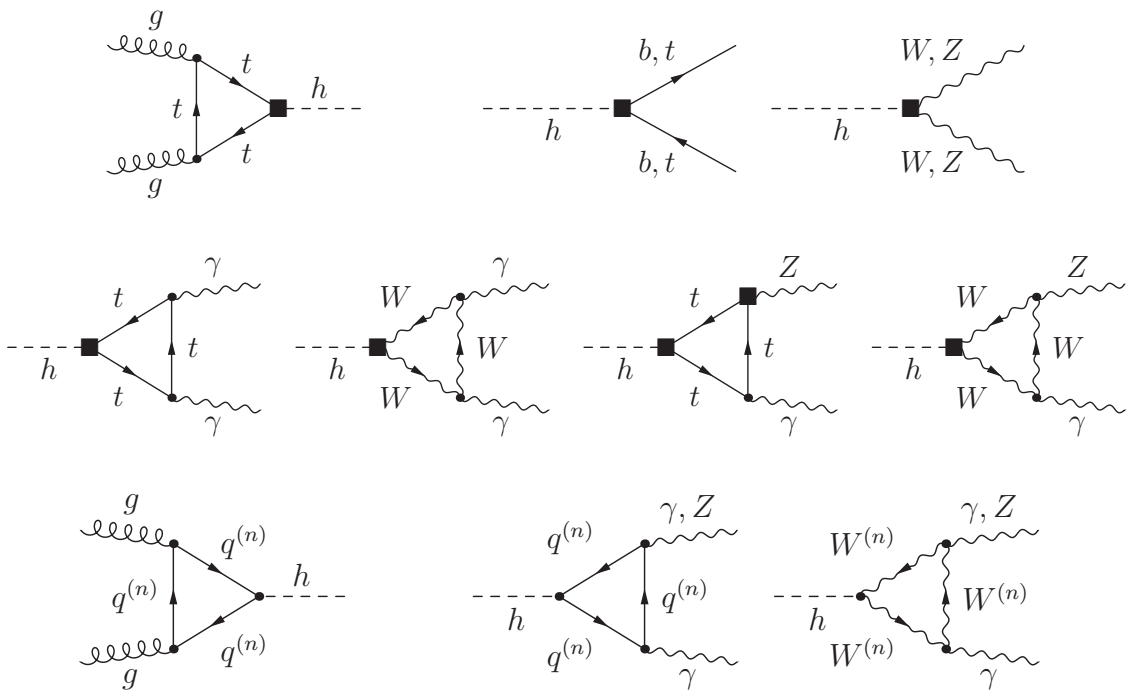
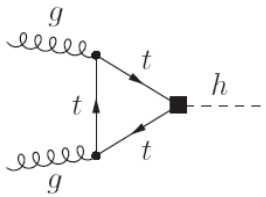
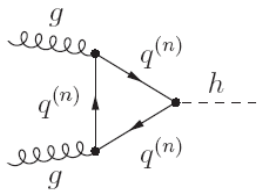
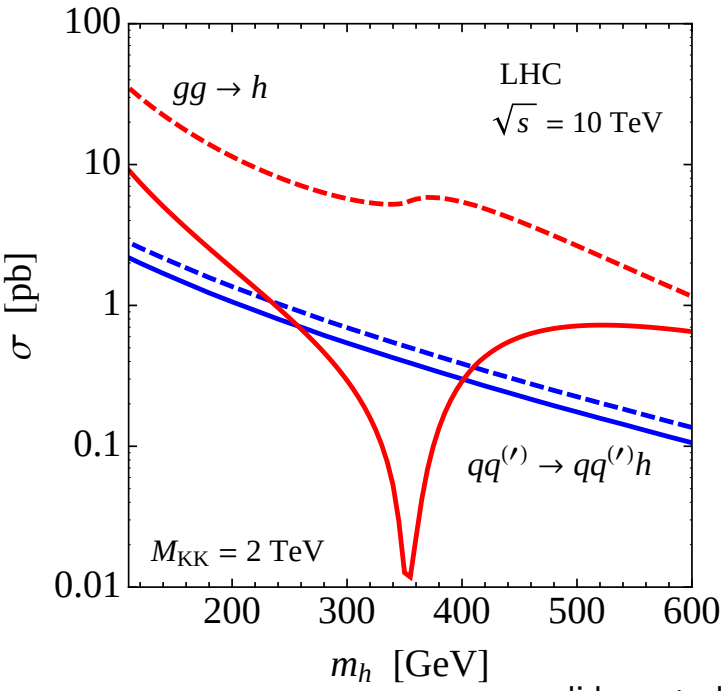


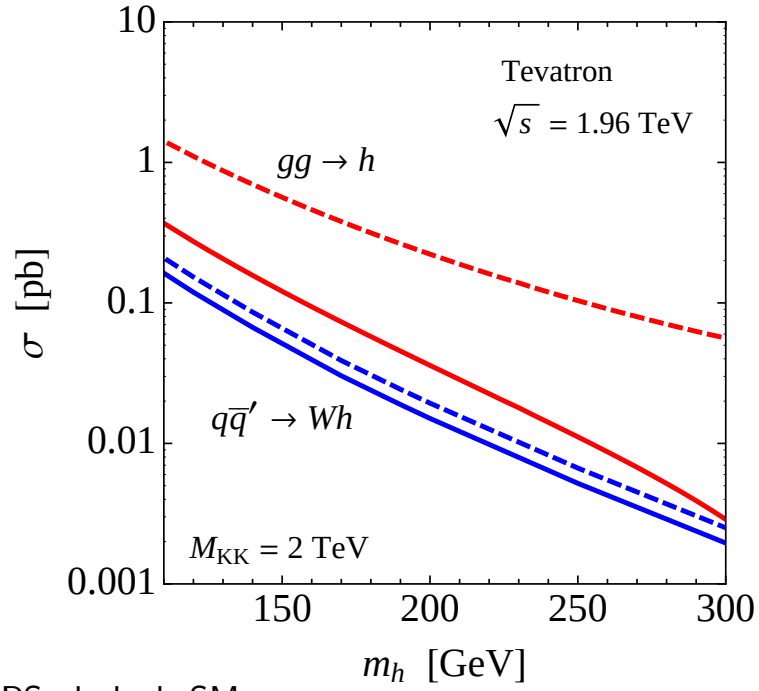
- Higgs couplings to heavy quarks receive sizable negative corrections up to -50% ($M_{\rm KK} = 2$TeV), negative sign = generic prediction
- Additional contributions from Kaluza-Klein towers

Higgs Production



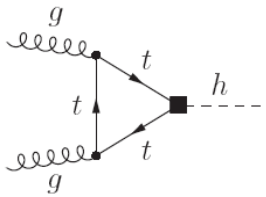


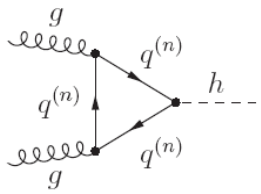


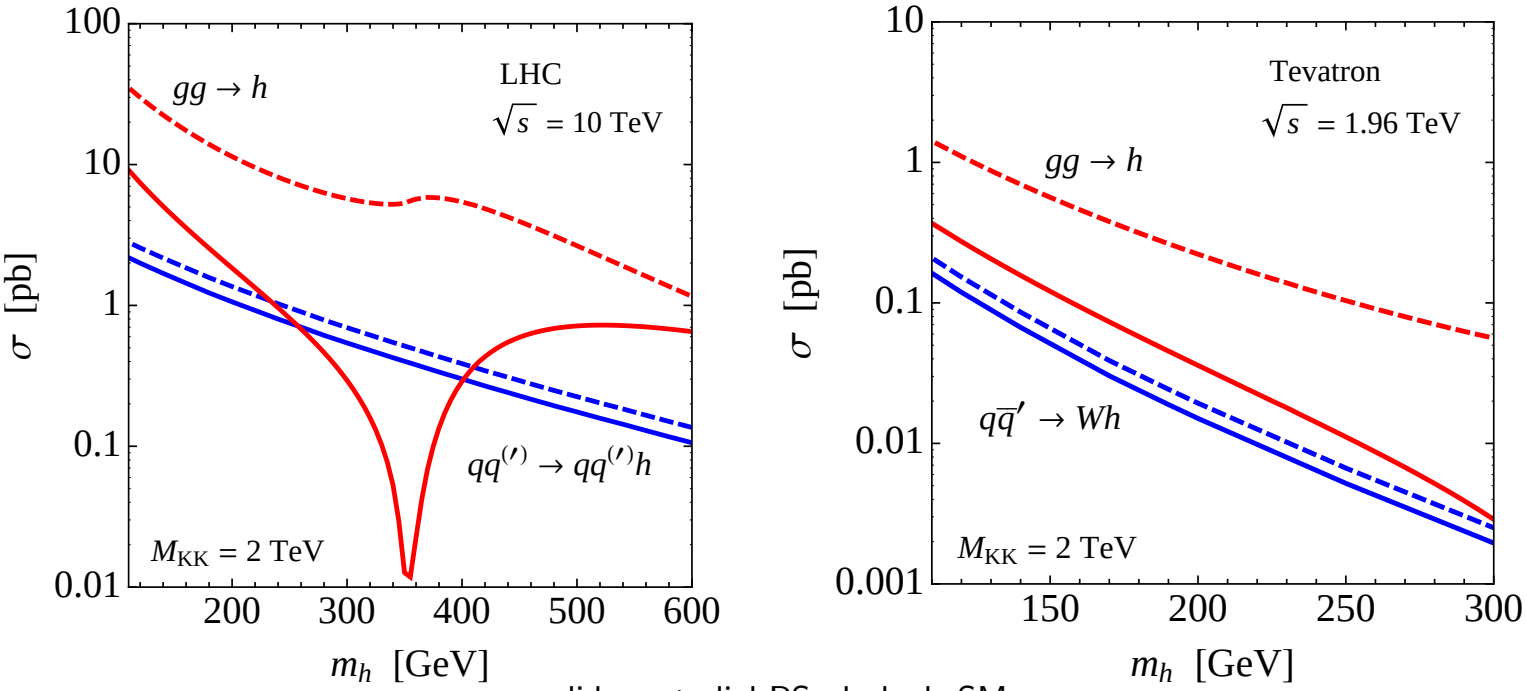


solid: custodial RS, dashed: SM

Higgs Production



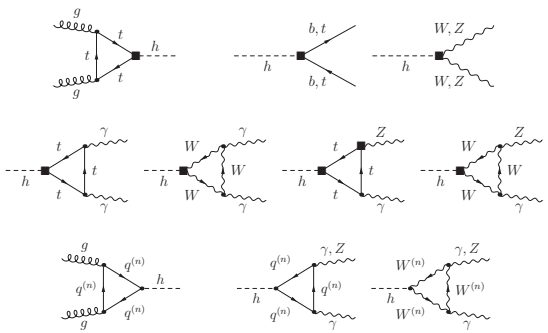




solid: custodial RS, dashed: SM

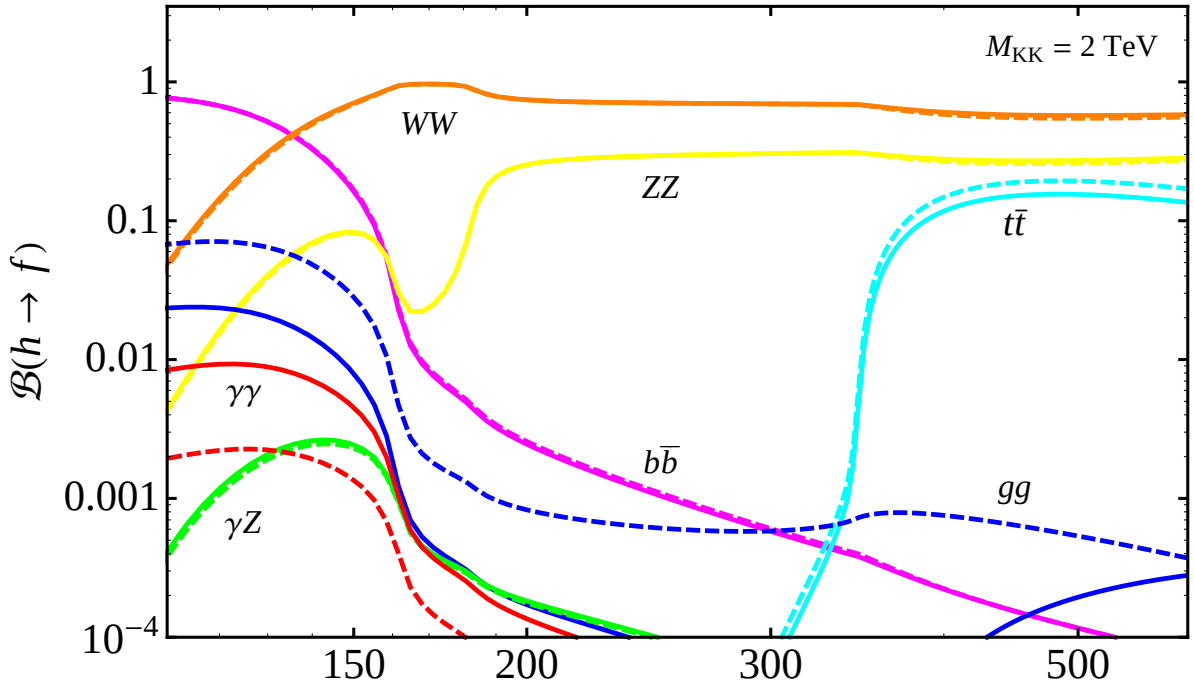
- Higgs mass bounds changed
- Only mild dependence on RS parameters besides $M_{\rm KK}$
- At $M_{\rm KK} = 5$ TeV still suppressions up to -40 % $\longrightarrow$ sensitivity to high scales!

Higgs Decay



Sum up fermions and

W-bosons in loop



solid: custodial RS, dashed: SM

- Above WW threshold: Higgs discovery via golden channel
  $gg \to h \to Z^{(*)}Z^{(*)} \to l^+l^-l^+l^-$ more difficult
- Below WW threshold: slightly better potential to discover the Higgs via
  $gg \to h \to \gamma\gamma$ for $M_{\mathrm{KK}} = 2$ TeV

Summary

- RS models offer interesting possibility to address unexplained hierarchies
- Couplings involving third generation quarks or especially the Higgs boson could provide first hints of warped extra dimension

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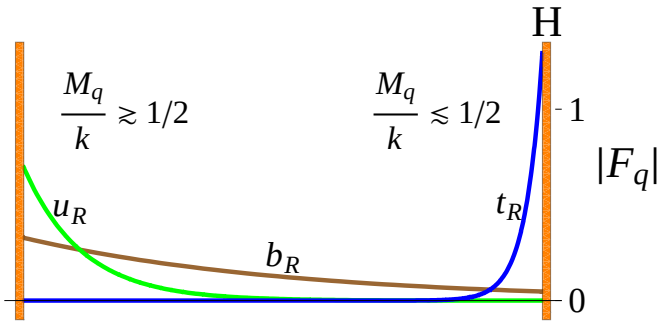
- Couplings involving third generation quarks or especially the Higgs boson could provide first hints of warped extra dimension

Thank you for your attention!

Backup: RS as a Solution to the Flavor Puzzle

$$m_{q_i} = \mathcal{O}(1) \times \frac{v}{\sqrt{2}} |F_{Q_i} F_{q_i}| \quad \begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \blacksquare \end{pmatrix} \checkmark \qquad \boxed{(Y_q)_{ij} \sim \mathcal{O}(1)}$$



$$\frac{|F_{Q_1}|}{|F_{Q_2}|} \sim \lambda\,, \qquad \frac{|F_{Q_2}|}{|F_{Q_3}|} \sim \lambda^2\,, \qquad \frac{|F_{Q_1}|}{|F_{Q_3}|} \sim \lambda^3$$

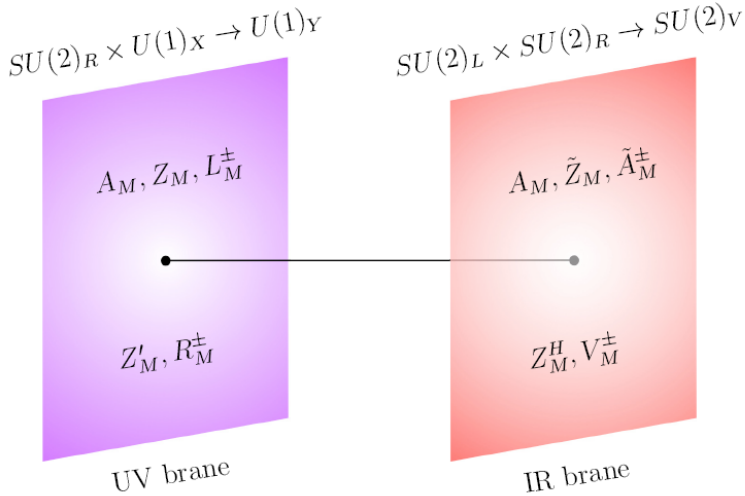
$$\Rightarrow \mathbf{V}_{CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix} \checkmark$$

Backup: Precision Observables Call for Custodial Protection

Implement custodial protection by extending the SM gauge group[a]

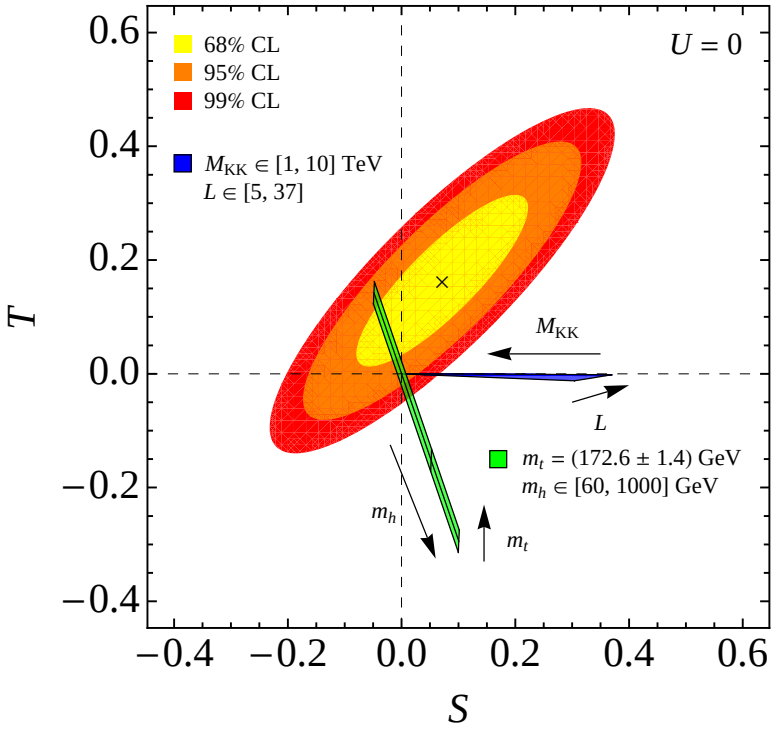
$$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X \times P_{LR}$$

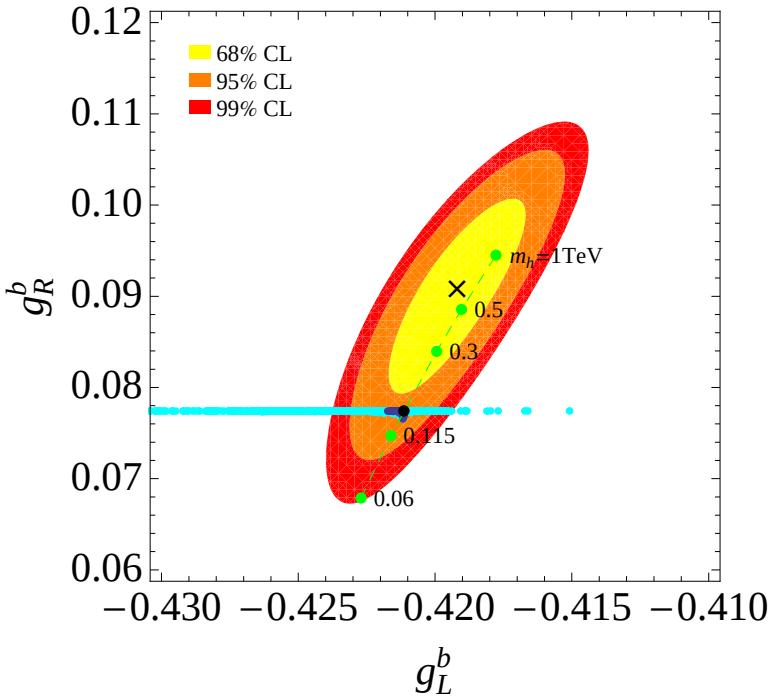
- $SU(2)_R \times U(1)_X \xrightarrow{\text{UV}} U(1)_Y$
- P_{LR} : interchange $SU(2)_L \leftrightarrow SU(2)_R$
- T parameter protected
- $b_L \in (2,2)_{2/3} \rightarrow Zb_L\bar{b}_L$ protected
- S $\Rightarrow M_{\text{KK}} > 2.4$ TeV $\Rightarrow m^{(1)} > 6$ TeV



[a] Agashe, Delgado, May, Sundrum, hep-ph/0308036
Agashe, Contino, Da Rold, Pomarol, hep-ph/0605341

Backup: Electroweak Precision (custodial model)



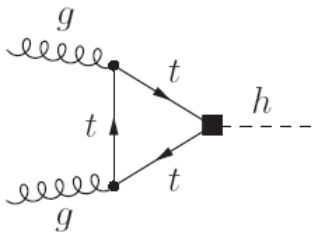


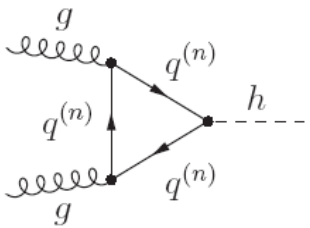
$$T = \frac{\pi v^2}{2\cos^2\theta_W M_{\rm KK}^2}\left(\not{L} - \frac{1}{2L}\right)$$

blue: P_{LR} protection also for fermion mixing

$$\Rightarrow M_{\rm KK} > 2.4\,\text{TeV}\ (99\%\,\text{CL}) \quad (m_h = 150\,\text{GeV})$$

Backup: Higgs Production





$$\sigma(gg \to h)_{\rm RS} = |\kappa_g|^2 \, \sigma(gg \to h)_{\rm SM}$$

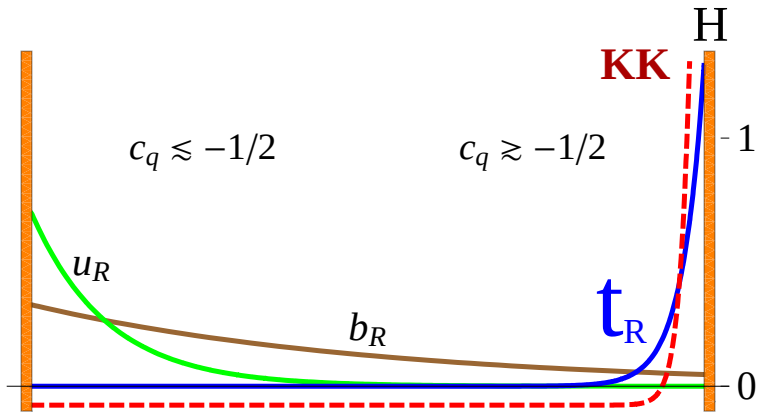
$$\kappa_g = \frac{\sum_{i=t,b} \kappa_i A_q^h(\tau_i) + \sum_{j=u,d,\lambda} \nu_j}{\sum_{i=t,b} A_q^h(\tau_i)}$$

- $\tau_i \equiv 4 m_i^2 / m_h^2$
- Form factor $A_q^h(\tau_i)$ approaches 1 for $\tau_i \to \infty$ and vanishes proportional to τ_i for $\tau_i \to 0$
- $\kappa_t = 1 - \frac{v}{m_t} (\Delta g_h^u)_{33}$, $\kappa_b = 1 - \frac{v}{m_b} (\Delta g_h^d)_{33}$
- ν_j: KK fermions in loop (q = 2/3, -1/3, 5/3)

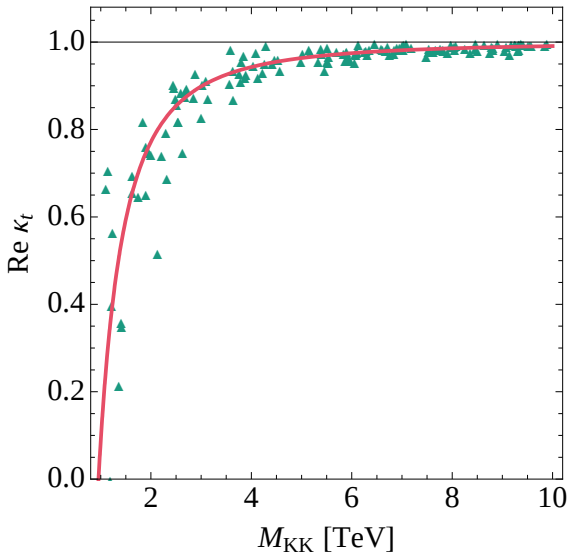
Backup: Higgs Production

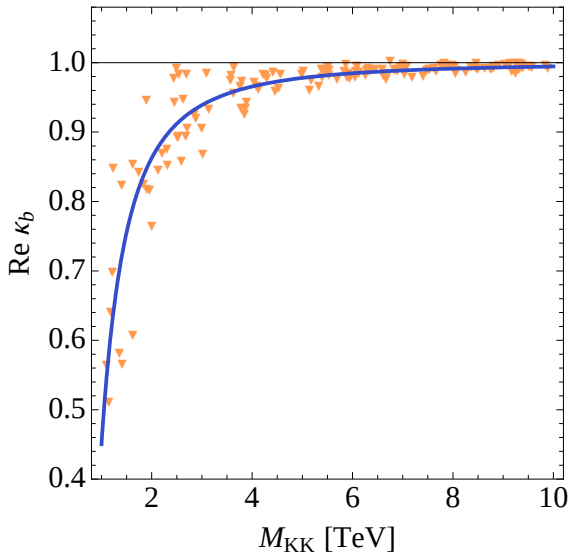
Misalignment between the SM fermion masses and Yukawa couplings

$$(\Delta g_h^q)_{33} = |\cdots|^2 + \mathcal{O}(\frac{m_2}{m_3}) > 0$$



$\Rightarrow$ 3rd generation Higgs couplings suppressed with respect to SM (minimal + custodial model)





Backup: Higgs Couplings

$$\mathcal{L}_{4\mathrm{D}} \ni -\sum_{q,m,n} (g_h^q)_{mn}\, h\, \bar{q}_L^m\, q_R^n + \mathrm{h.c.}\,,$$

$$(g_h^q)_{mn} \equiv \delta_{mn}\,\frac{m_m^q}{v} - (\Delta g_h^q)_{mn}\,,$$

$$(\Delta g_h^q)_{mn} = \frac{m_m^q}{v}\,(\Phi_q)_{mn} + (\Phi_Q)_{mn}\,\frac{m_n^q}{v} + (\Delta \tilde{g}_h^q)_{mn}\,,$$

$$(\Phi_q)_{mn} = \frac{2\pi}{L\epsilon}\int_\epsilon^1 dt\, \vec{a}_m^{Q\dagger}\, \mathbf{S}_m^Q(t)\, \mathbf{S}_n^Q(t)\, \vec{a}_n^Q\,, \qquad (\Phi_Q)_{mn} = \frac{2\pi}{L\epsilon}\int_\epsilon^1 dt\, \vec{a}_m^{q\dagger}\, \mathbf{S}_m^q(t)\, \mathbf{S}_n^q(t)\, \vec{a}_n^q\,,$$

$$(\Delta \tilde{g}_h^q)_{mn} = \frac{1}{\sqrt{2}}\,\frac{2\pi}{L\epsilon}\,\frac{v^2}{3M_{\mathrm{KK}}^2}\,\vec{a}_m^{Q\,\dagger}\,\mathbf{C}_m^Q(1^-)\,\tilde{\mathbf{Y}}_{\vec{q}}\,\bar{\mathbf{Y}}_{\vec{q}}^\dagger\,\tilde{\mathbf{Y}}_{\vec{q}}\,\mathbf{C}_n^q(1^-)\,\vec{a}_n^q$$