Bonn
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# A Solution to the Flavor Problem & LHC Bounds for Warped Extra Dimensions


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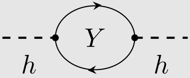
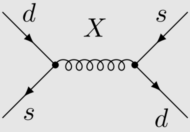
# A Motivation for more than the SM

$$\mathcal{L}_{\rm eff} = \Lambda_{\rm UV}^2 \Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2 + \mathcal{L}^{(4)}_{\rm Gauge} + \mathcal{L}^{(4)}_{\rm Yukawa} + \frac{\mathcal{L}^{(5)}}{\Lambda_{\rm UV}} + \frac{\mathcal{L}^{(6)}}{\Lambda_{\rm UV}^2} + \dots$$




$$\sim \frac{g_Y^2}{16\pi^2}\Lambda_{\rm UV}^2$$

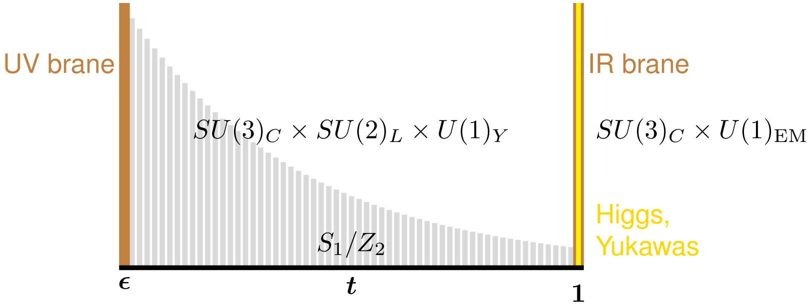
$\Lambda_{\rm UV} \lesssim 1$ TeV




$$\sim \frac{g_X^2}{\Lambda_{\rm UV}^2}$$

$\Lambda_{\rm UV} \gtrsim 10^3$ TeV

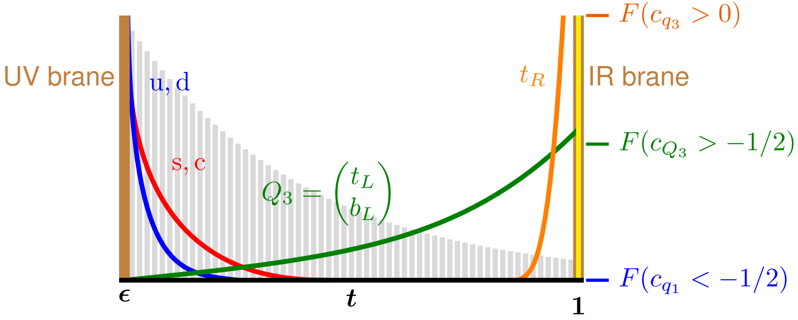
# Flavor in Warped Extra Dimensions




$$ds^2 = \frac{\epsilon^2}{t^2}\,\eta_{\mu\nu}\,dx^\mu dx^\nu - \frac{1}{k^2 t^2} dt^2$$

$$\epsilon = \frac{\Lambda_{\text{Weak}}}{\Lambda_{\text{PL}}} \qquad\qquad L = -\log\epsilon \approx 37$$

# Flavor in Warped Extra Dimensions



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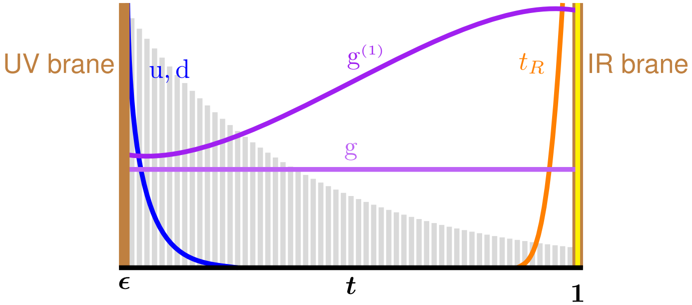
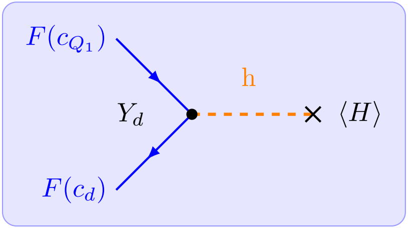


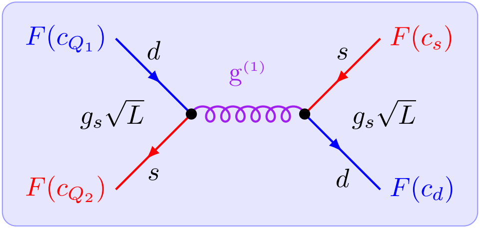
# Flavor in Warped Extra Dimensions

The parameters which control the masses of the light quarks suppress potentially dangerous FCNC's : RS-GIM.

$$m_d \sim \frac{v}{\sqrt{2}} F(c_{Q_1}) Y_d^{(5D)} F(c_d)$$
$$\sim \frac{v}{\sqrt{2}} Y_d^{\text{eff}}$$



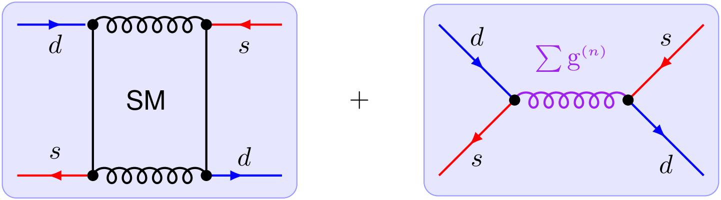

$$\frac{g_s^2 \, L}{M_{\text{KK}}^2} F(c_{Q_1}) F(c_d) F(c_{Q_2}) F(c_s)$$
$$\sim \frac{g_s^2}{M_{\text{KK}}^2} L \frac{2 m_d m_s}{\left(v Y_d^{(5D)}\right)^2}$$



# The RS Flavor Problem

The RS-GIM mechanism is extremely effective, apart from one observable,

$$\epsilon_K = \frac{\kappa_\epsilon e^{i\phi_\epsilon}}{\sqrt{2}(\Delta m_K)_{\rm exp}} \, {\rm Im} \, \langle K^0 | \mathcal{H}_{\rm eff}^{\Delta S=2} | \bar{K}^0 \rangle \, ,$$



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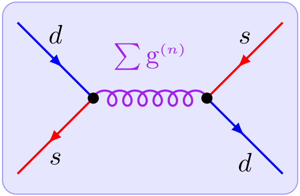
$$Q_1^{sd} = (\bar{d}_L\gamma^\mu s_L)\,(\bar{d}_L\gamma_\mu s_L)$$

$$\widetilde{Q}_1^{sd} = (\bar{d}_R\gamma^\mu s_R)\,(\bar{d}_R\gamma_\mu s_R)$$

$$Q_4^{sd} = -\tfrac{1}{2}(\bar{d}_R^\alpha\gamma^\mu s_R^\beta)\,(\bar{d}_L^\beta\gamma_\mu s_L^\alpha)$$

$$Q_5^{sd} = -\tfrac{1}{2}(\bar{d}_R\gamma^\mu s_R)\,(\bar{d}_L\gamma_\mu s_L)$$



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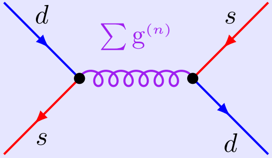


$$\langle K^0 | \mathcal{H}_{\text{RS}}^{\Delta S=2} | \bar{K}^0 \rangle \propto C_1^{\text{SM+RS}} + \widetilde{C}_1^{\text{RS}} + 100 \left( C_4^{\text{RS}} + \tfrac{1}{N_C} C_5^{\text{RS}} \right)$$

Large chiral enhancement $\sim \left( \frac{m_K}{m_s + m_d} \right)^2$

RGE running $3\,\text{TeV} \to 2\,\text{GeV}$

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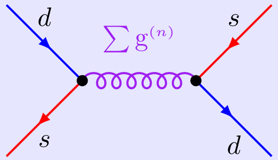


$$\langle K^0 | \mathcal{H}_{\rm RS}^{\Delta S=2} | \bar{K}^0 \rangle \propto C_1^{\rm SM+RS} + \widetilde{C}_1^{\rm RS} + 100 \left( C_4^{\rm RS} + \tfrac{1}{N_C} C_5^{\rm RS} \right)$$

$$\langle B | \mathcal{H}_{\rm RS}^{\Delta B=2} | \bar{B} \rangle \propto C_1^{\rm SM+RS} + \widetilde{C}_1^{\rm RS} + 7 \left( C_4^{\rm RS} + \tfrac{1}{N_C} C_5^{\rm RS} \right)$$

$$\langle D | \mathcal{H}_{\rm RS}^{\Delta C=2} | \bar{D} \rangle \propto C_1^{\rm SM+RS} + \widetilde{C}_1^{\rm RS} + 13 \left( C_4^{\rm RS} + \tfrac{1}{N_C} C_5^{\rm RS} \right)$$

# Solving the RS Flavor Problem

If we had a gauge boson which couples with opposite sign to left- and right-handed quarks, but with the same coupling strength as the KK gluons, we could evade the $\epsilon_K$- constraint. Something like a 5D axigluon.

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Extend the strong bulk gauge group to $SU(3)_{\mathrm{Doublet}} \otimes SU(3)_{\mathrm{Singlet}}$

$$\mathcal{L}_{\mathrm{int}} \ni g_D \, \bar{Q} \, G^D_\mu \gamma^\mu Q + g_S \, \bar{q} \, G^S_\mu \, \gamma^\mu q$$

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and break it via boundary conditions into the gluon

$$g_\mu = G^D_\mu \cos\theta + G^S_\mu \sin\theta \qquad \text{with} \qquad \tan\theta = g_D/g_s$$

and the *axigluon* (only for $\tan\theta = 1$ it is a *clean* axigluon)

$$A_\mu = G^D_\mu \sin\theta - G^S_\mu \cos\theta$$

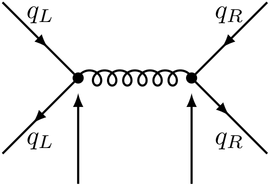
so that

$$\begin{aligned}\mathcal{L}_{\text{int}} \ni\; & g_s\, (\bar{Q}\, g_\mu \gamma^\mu Q + \bar{q}\, g_\mu\, \gamma^\mu q\,) \\ & +g_s\, (\,\tan\theta\;\; \bar{Q}\, A_\mu \gamma^\mu Q - \cot\theta\;\; \bar{q}\, A_\mu\, \gamma^\mu q\,)\end{aligned}$$

# Solving the RS Flavor Problem

Since the SM quarks are (up to small admixtures suppressed by the KK scale), the zero modes of the 5D doublets/singlets respectively, we achieve the opposite sign coupling, independent of the mixing angle $\theta$

$C_4 \sim$




| | | |
|---|---|---|
| KK gluon: | $g_s$ | $g_s$ |
| KK *axigluon*: | $g_s \tan\theta$ | $-g_s \cot\theta$ |

Note that for $C_1/\widetilde{C}_1$ the contributions add up!

The contributions cancel, if the flavorchanging non-diagonal couplings are the same. These are specified by overlap integrals of the whole tower of KK bosons with the profile functions of the SM quarks.

$\Rightarrow$ Set by the boundary conditions.

# Solving the RS Flavor Problem

We have to sum over the KK modes

$$D(t,t';p) = \sum_{n=0} \frac{\chi_n(t)\chi_n(t')}{p^2 - m_n^2 + i\epsilon} \approx \sum_{n=0} \frac{\chi_n(t)\,\chi_n(t')}{m_n^2},$$

with general BCs:

$$\partial_t \chi_n(t)\Big|_{t=\epsilon} = r_\epsilon\,\chi_n(t)\Big|_{t=\epsilon} \qquad \partial_t \chi_n(t)\Big|_{t=1} = -r_1\,\chi_n(t)\Big|_{t=1}$$

The gluon needs Neumann BCs on both branes in order to have a massless zero mode $(r_1, r_\epsilon \to 0)$

$$\textstyle\sum_{n\geq 1} \frac{\chi_n(t)\,\chi_n(t')}{m_n^2} = \frac{1}{4\pi M_{\rm KK}^2}\Big[\; L\,t_<^2 - t^2\left(\frac{1}{2} - \ln t\right) - t'^2\left(\frac{1}{2} - \ln t'\right) + \frac{1}{2L}\Big],$$

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$$\sum_{n\geq 1}\frac{\chi_n(t)\,\chi_n(t')}{m_n^2}=\frac{1}{4\pi M_{\rm KK}^2}\left[\;L\,t_<^2\;-t^2\left(\tfrac{1}{2}-\ln t\right)-t'^2\left(\tfrac{1}{2}-\ln t'\right)+\tfrac{1}{2L}\right],$$

where these terms are responsible for $\Delta F=2$ effects

# Solving the RS Flavor Problem

General boundary conditions lead to

$$\sum_{n\geq 0} \frac{\chi_n(t)\,\chi_n(t')}{m_n^2} = \frac{L}{4\pi M_{\rm KK}^2}\,\frac{(2+r_1(t_>^2-1))(2\epsilon+r_\epsilon t_<^2)}{2r_\epsilon-2\epsilon r_1-r_\epsilon r_1}$$

$$= \frac{L}{4\pi M_{\rm KK}^2}\left[A\,t_<^2+B\,(t^2+t'^2)+C\,t^2t'^2+D\right]$$

with

$$A = 1\,, \qquad B = \frac{2\epsilon r_1}{2r_\epsilon-2\epsilon r_1-r_\epsilon r_1}$$

$$C = \frac{r_1\,r_\epsilon}{2r_\epsilon-2\epsilon r_1-r_\epsilon r_1}\,, \qquad D = \frac{2\epsilon(2-r_1)}{2r_\epsilon-2\epsilon r_1-r_\epsilon r_1}$$

# Solving the RS Flavor Problem

However, collider bounds and the Higgs sector on the IR brane specify one combination of possible boundary conditions:

- Implicit $SU(3)_D \times SU(3)_S$ breaking on the IR brane

$$\mathcal{L} \ni Y_u \, \overline{Q} \, \epsilon \, \mathbf{H}^* \, u + Y_d \, \overline{Q} \, \mathbf{H} \, d \qquad \Rightarrow \quad \mathbf{H} \sim (\mathbf{3}, \bar{\mathbf{3}}, \mathbf{2})$$

- Neumann BC in the UV ruled out, because it predicts a first KK axigluon with $m_{A^{(1)}} \lesssim 0.235 \, M_{\rm KK}$

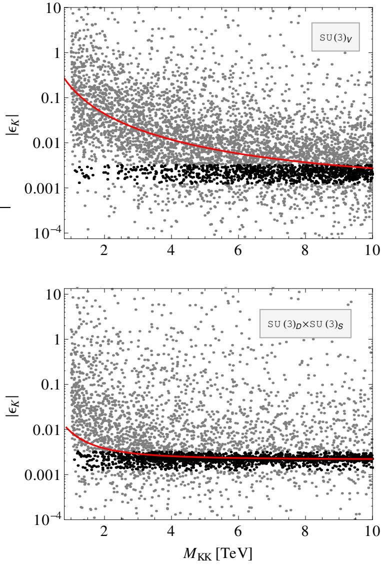
$$\Rightarrow \sum_n \frac{\chi_n^{(A)}(t) \, \chi_n^{(A)}(t')}{m_n^2} = \frac{L}{4\pi M_{\rm KK}^2} \left[ t_<^2 - \frac{r_1}{2 + r_1} \, t^2 t'^2 + \mathcal{O}(\epsilon) \right]$$

with $r_\epsilon \sim \Lambda_{\rm UV}$ and $r_1 = \mathcal{O}\Big( \frac{v^2}{M_{\rm KK}^2} \Big)$ .

# Solving the RS Flavor Problem

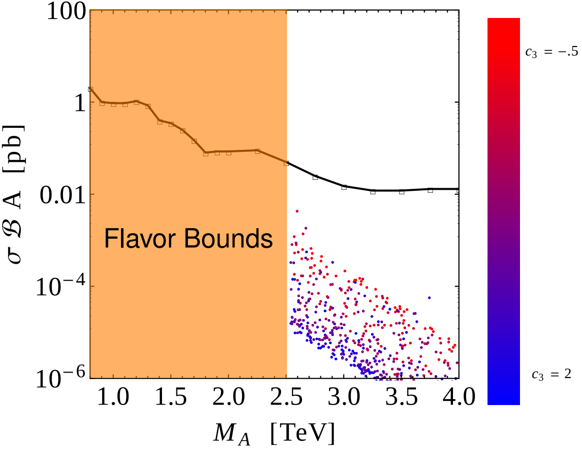
For $r_1 = \xi\, L \frac{v^2}{M_{\mathrm{KK}}^2}, \tan\theta = 1$

| $M_{\mathrm{KK}}$ [TeV] | 1–2 | 2–3 | 3–4 | 4–5 | 5–10 |
|---|---|---|---|---|---|
| min | 3% | 7% | 10% | 15% | 29% |
| $(\xi = 0.5)$ | 11% | 33% | 50% | 59% | 71% |
| $(\xi = 1)$ | 10% | 27% | 47% | 58% | 71% |
| $(\xi = 2)$ | 8% | 24% | 39% | 55% | 71% |

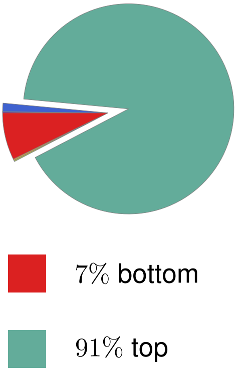



The extended model predicts a first axigluon KK mode at $m_{A^{(1)}} \approx 2.54\, M_{\mathrm{KK}}$ as well as a scalar color octet on the IR brane.

# LHC Bounds: Dijet Bounds

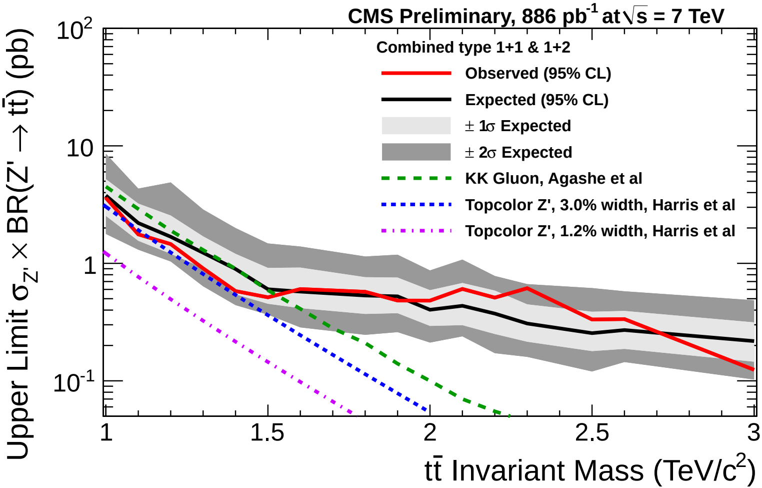



KK (Axi-)Gluon Branching Ratio:




[ATLAS '11]

# LHC Bounds: $t\bar{t}$ Resonances




[CMS '11]

# Conclusions

- Randall-Sundrum Models explain the mass hierarchies in the quark sector and solve the gauge hierarchy problem.
- The $SU(3)^2$ Randall-Sundrum model solves the RS Flavor problem without fine-tuning, while allowing for a New Physics scale of $M_{\rm KK} \sim 1-2$ TeV.
- It is in agreement with current LHC bounds but makes predictions in the $t\bar{t}$ resonance search which will be tested within the next year.