Fermilab,
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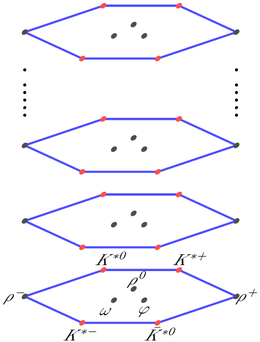


On the Flavor Problem of Strongly Coupled Theories

Martin Bauer

1. Shortcomings of the Standard Modell (SM)

2. The Randall-Sundrum Model

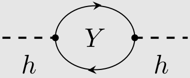
3. AdS/CFT

4. Flavor Physics in the RS Model

5. The RS Flavour Problem

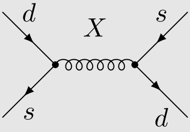
The SM as an effective field theory

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



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

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



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

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

The Hierarchy Problem

It is interesting, that mass terms for (chiral) fermions and gauge bosons are forbidden by gauge symmetries.

$$\cancel{m\,\bar{Q}_L\,q_R^c} \qquad \cancel{m^2\,A_\mu\,A^\mu} \qquad m^2\,H^\dagger H$$

A mass term for a fundamental scalar however can only be eliminated by an extension of the spacetime symmetry. Such extensions can be divided into two classes ,

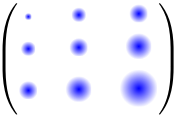
- Supersymmetry
- Conformal Symmetry

The Flavor Problem

The term “Flavor Problem” refers to two different issues.

The first is, that the SM does not explain the orgin of the structure of the Yukawa matrices and therefore of the CKM matrix.

$$Y \sim$$



$$\Rightarrow \qquad V_{\mathrm{CKM}} \sim$$

The other aspect is, that new resonances in possible extensions of the SM can lead to flavor-changing neutral currents (FCNCs), which are loop and GIM suppressed in the SM.

The Flavor Problem

Theories, which try to explain the flavor structure of the SM are often based on abelian flavor symmetries, so called Froggatt-Nielsen models.

$$\mathcal{L}_{\rm Yuk} \ni \left(\frac{\phi}{\Lambda_{\rm Fl}}\right)^{a-b} \overline{Q}_L\, H\, q_R^c\,. \quad \Rightarrow \quad Y \sim \begin{pmatrix} \lambda^4 & \lambda^3 & \lambda^3 \\ \lambda^3 & \lambda^2 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}\,, \text{ with } \quad \frac{\langle\phi\rangle}{\Lambda_{\rm Fl}} \equiv \lambda\,.$$

However, such a symmetry still allows for large contributions to FCNCs.

$$\sum_{i,j=1}^{3} \frac{C_{ij}^d}{\Lambda_{\rm Fl}^2}(\bar{Q}_i\, d_i^c)(\bar{Q}_j\, d_j^c)\,, \qquad \longrightarrow \qquad \frac{(C_{11}^d + C_{22}^d)\lambda^2}{\Lambda_{\rm Fl}^2}(\bar{Q}_2\, d_1^c)(\bar{Q}_2\, d_1^c)\,.$$

The Flavor Problem

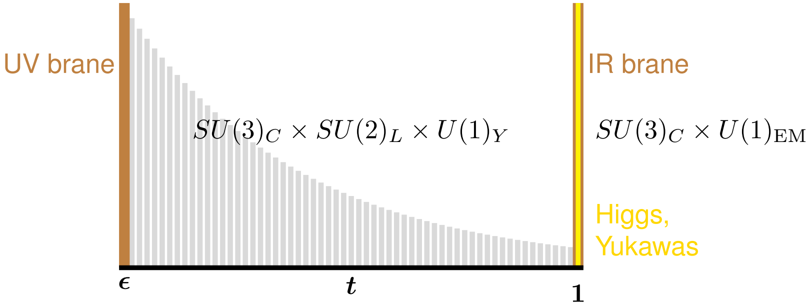
A larger non-abelian symmetry group can solve that problem. In so called minimal flavor violating (MFV) scenarios, the Wilson coefficients are proportional to spurions, whose vev corresponds to the Yukawa couplings, $\frac{\langle \chi_q \rangle}{\Lambda_{\rm Fl}} \equiv Y_q$, so that

$$C^d = \frac{1}{\Lambda_{\rm Fl}^2} \chi_d \chi_d \; \rightarrow \; Y_d \, Y_d$$

Clearly, this ansatz will not shed any light on the origin of the structure of the Yukawa matrices.

It is remarkable, that there are theories, which combine the advantages of MFV models and the Frogatt Nielsen idea.

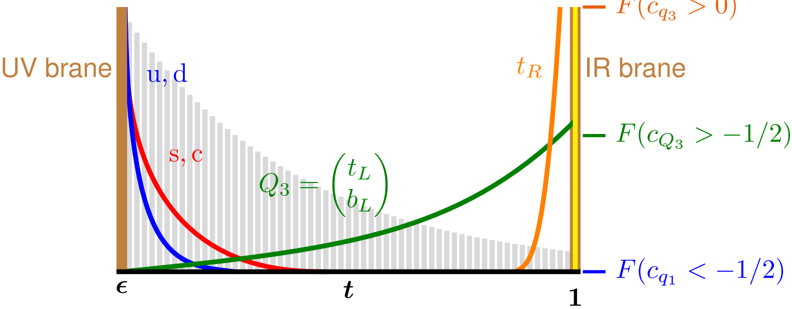
The Randall-Sundrum Model



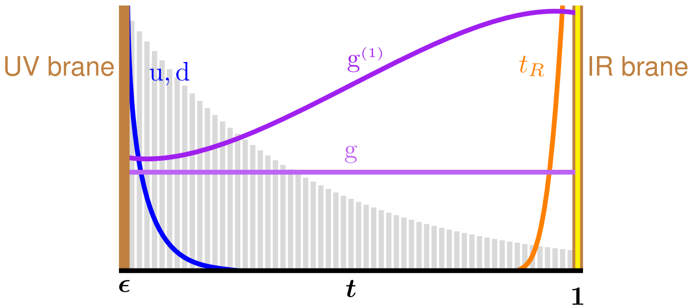
$$ds^2 = \frac{\epsilon^2}{t^2}\left(\eta_{\mu\nu}\, dx^\mu dx^\nu - \frac{1}{M_{\mathrm{KK}}^2} dt^2\right)$$

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

The Randall-Sundrum Model



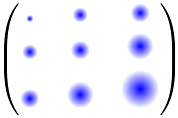
The Randall-Sundrum Model



The Randall-Sundrum Model

- The entries of the fundamental Yukawa matrices $(Y_d)_{ij}$ are anarchical and $\propto 1$:

$$(Y_d^{\text{eff}})_{ij} \equiv F(c_{Q_i})(Y_d)_{ij}^{(5D)} F(c_{d_j}) \sim$$



$$_{ij}$$

- Hierarchies in the masses and mixing angles depend solely on natural parameters,

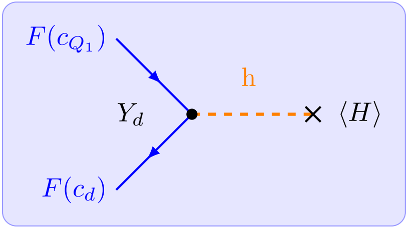
$$m_{q_i} = \mathcal{O}(1) \frac{v}{\sqrt{2}} F(c_{Q_i}) F(c_{q_i})$$

$$\bar{\rho}, \bar{\eta} = \mathcal{O}(1)\,, \qquad \lambda = \mathcal{O}(1) \frac{F(c_{Q_1})}{F(c_{Q_2})}\,, \qquad A = \mathcal{O}(1) \frac{F^3(c_{Q_2})}{F^2(c_{Q_1}) F(c_{Q_3})}$$

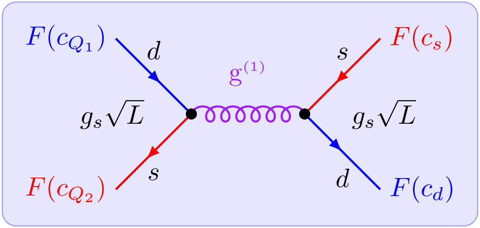
The Randall-Sundrum Model

The same parameters, which generate the masses of the light quarks suppress contributions to FCNCs: RS-GIM.

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

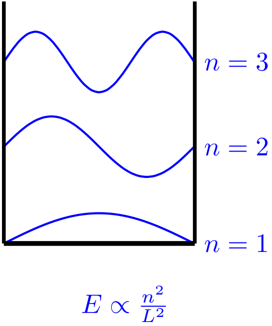


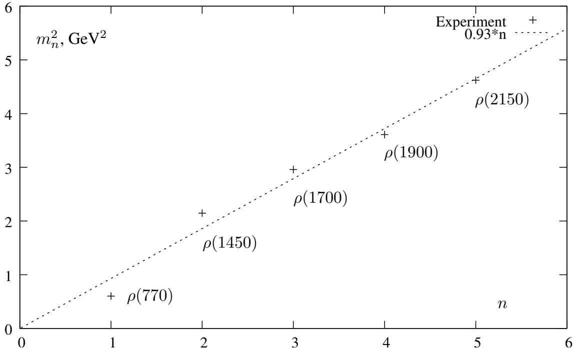
$$\frac{g_s^2 L}{M_{\text{KK}}^2} F(c_{Q_1}) F(c_d) F(c_{Q_2}) F(c_s)$$
$$\sim \frac{g_s^2}{M_{\text{KK}}^2} L \frac{2 m_d m_s}{\left(v Y_d^{(5D)}\right)^2}$$



AdS/CFT

The IR brane corresponds to a confining phase at the scale $\Lambda_{\rm IR}$.





AdS/CFT- Example

Consider a bulk $U(1)$ gauge theory. The dual theory corresponds to a model with an elementary $U(1)$ gauge field and a strongly coupled sector including an operator with the same quantum numbers as the gauge field.

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \omega\, A_\mu J^\mu + \mathcal{L}_{\text{composite}}$$

The boundary conditions on both branes determine the character of this global symmetry:

- Dirichlet BCs on the UV brane remove the gauge field from the dual theory.
- Dirichlet BCs on the IR brane correspond to a spontaneous breaking of the global symmetry through confinement.

AdS/CFT

The dual of a 5D theory with bulk fermions is similar

$$\mathcal{L} \ni \mathcal{L}_{\rm el} + d\,\Lambda_{\rm Pl}\left(\frac{\Lambda_{\rm comp}}{\Lambda_{\rm Pl}}\right)^{\gamma}\,\overline{q}_L B_R\, - m_B \overline{B}B + \overline{B}_L\,(\lambda H B_R^c)\ .$$

Rotating to the mass eigenbasis

$$\begin{pmatrix} q_L \\ B_L \end{pmatrix} = \begin{pmatrix} \cos\varphi_L & -\sin\varphi_L \\ \sin\varphi_L & \cos\varphi_L \end{pmatrix} \begin{pmatrix} \psi_L \\ \chi_L \end{pmatrix}$$

leads to

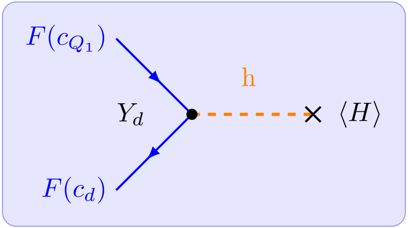
$$\mathcal{L} \ni -m_\chi \overline{\chi}\chi + \left(\overline{\psi}_L \sin\varphi_L + \overline{\chi}_L \cos\varphi_L\right)\lambda H\,(\psi_R \sin\varphi_R + \chi_R^c \cos\varphi_R)\ .$$

Couplings to vector mesons read

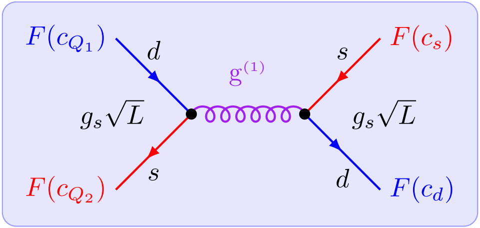
$$\mathcal{L} \ni g_\rho \bar{B} \not{\rho} B \quad\longrightarrow\quad g_\rho \sin\varphi_L^2\ \overline{\psi}_L\,\not{\rho}\,\psi_L + g_\rho\ \sin\varphi_R^2\,\overline{\psi}_R\ \not{\rho}\,\psi_R\,,$$

AdS/CFT

$$m_d \sim \frac{v}{\sqrt{2}} \sin\varphi_{L_1}\, \lambda \sin\varphi_{R_1}$$
$$\sim \frac{v}{\sqrt{2}}\, Y_d^{\mathrm{eff}}$$

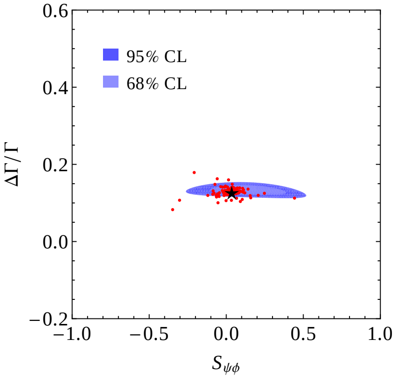


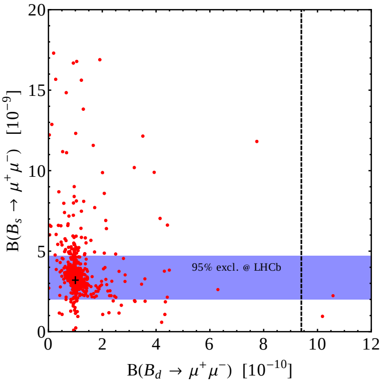
$$\frac{g_s^2\, L}{M_{\mathrm{KK}}^2} \sin\varphi_{L_1} \sin\varphi_{R_1} \sin\varphi_{L_2} \sin\varphi_{R_2}$$
$$\sim \frac{g_s^2}{M_{\mathrm{KK}}^2} L \frac{2 m_d m_s}{(v\lambda)^2}$$



Flavor Physics in the RS Model

Large mixing angles suggest large effects in observables which are sensitive to couplings of third generation quarks.

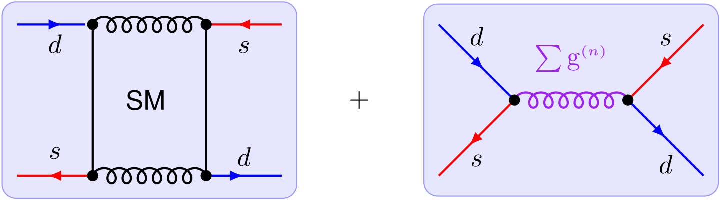




The RS Flavour Problem

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

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



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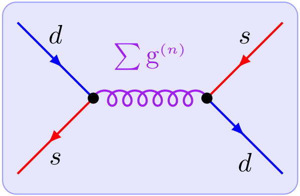
$$Q_1^{sd} = (\bar{d}_L\gamma^\mu s_L)\,(\bar{d}_L\gamma_\mu s_L)$$

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

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

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



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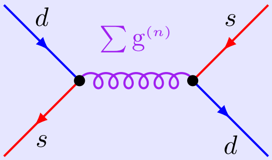
$$Q_5^{sd} = -\tfrac{1}{2}(\bar{d}_R \gamma^\mu s_R)\,(\bar{d}_L \gamma_\mu s_L)$$



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

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

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

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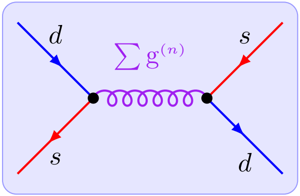

$$\langle K^0 | \mathcal{H}_{\rm RS}^{\Delta S=2} | \bar{K}^0 \rangle \propto C_1^{\rm SM+RS} + \widetilde{C}_1^{\rm RS} + 100 \left(\boxed{C_4^{\rm RS}} + \tfrac{1}{N_C} C_5^{\rm RS} \right)$$

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

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

The RS Flavour 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 ϵ_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)

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

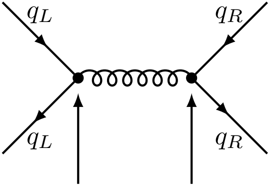
so that

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

The RS Flavour 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 θ

$C_4 \sim$



KK gluon: g_s g_s

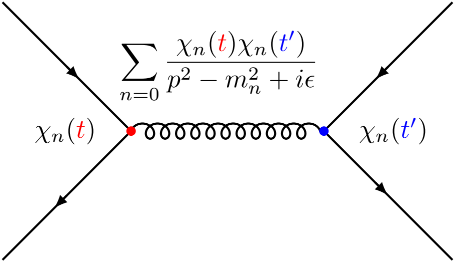
KK *axigluon*: $g_s \tan\theta$ $-g_s \cot\theta$

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

The contributions cancel, if the flavourchanging 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.

The RS Flavour Problem



$$,\sum_{n\geq 0} \frac{\chi_n(t)\chi_n(t')}{m_n^2} = \frac{L}{4\pi M_{\mathrm{KK}}^2}\left[A\, t_<^2 + B\,(t^2 \times \mathbf{1}' + \mathbf{1} \times t'^2) + C\, t^2 t'^2 + D\, \mathbf{1} \times \mathbf{1}'\right]$$

$$\Rightarrow B \underbrace{\int dt\ t^2\ \textit{Fermion Profiles}(t)}_{\text{Flavour changing!}} \times \int dt' \mathbf{1}\ \textit{Fermion Profiles}(t')$$

The RS Flavour 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 $(r_1, r_\epsilon \to 0)$

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

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

The RS Flavour 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

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

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

The RS Flavour Problem

Choosing Neumann BCs on one brane results in

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

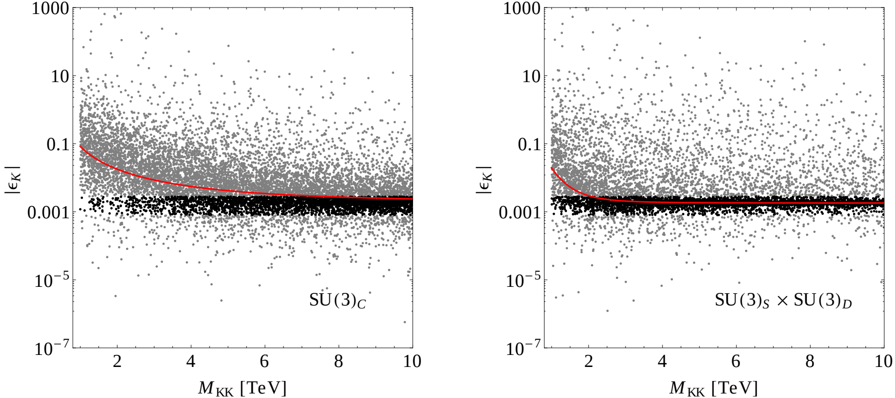
$$\sum_{n\geq 0} \frac{\chi_n(t)\,\chi_n(t')}{m_n^2}\bigg|_{r_1\to 0} = \frac{L}{4\pi M_{\rm KK}^2}\left(t_<^2 + \frac{2\epsilon}{r_\epsilon}\right).$$

Both cases lead to identical $\Delta F = 2$ overlap integrals, i.e. couplings as in the NN case.

There is a cancellation of the contributions to the dangerous mixed chirality operators, while the equal chirality operators get a factor 2.

Therefore, effects in B and D mixing are still possible.

The RS Flavour Problem



The RS Flavour Problem

The first option ($r_\epsilon \to 0$) is ruled out, because it predicts a first KK axigluon with $m_{A^{(1)}} \lesssim 0.235\, M_{\mathrm{KK}}$.

However, there must be a source of $SU(3)_D \times SU(3)_S$ breaking on the IR brane, in order to generate Yukawa couplings for the quarks:

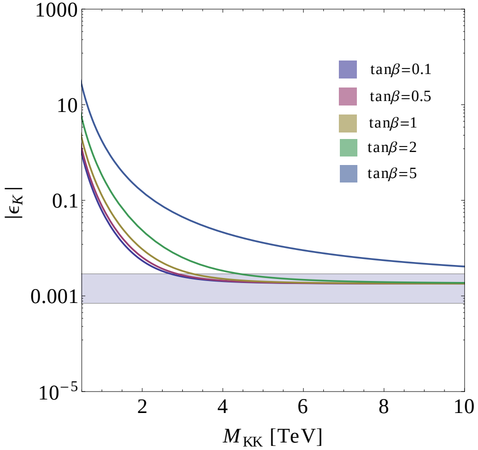
$$\mathcal{L} \ni Y_u\, \overline{Q}\, \mathbf{H_u}\, u + Y_d\, \overline{Q}\, \mathbf{H_d}\, d$$

since $Q \sim (\mathbf{3}, \mathbf{1}, \mathbf{2})$ and $u, d \sim (\mathbf{1}, \mathbf{3}, \mathbf{1})$ under $SU(3)_D \times SU(3)_S \times SU(2)_L$, the Higgs must transform as $\mathbf{H_{u,d}} \sim (\mathbf{3}, \overline{\mathbf{3}}, \mathbf{2})$.
This gives

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

For $r_\epsilon \gg 1/\epsilon$ and $r_1 = \mathcal{O}\Big(\dfrac{v^2}{M_{\mathrm{KK}}^2}\Big)$.

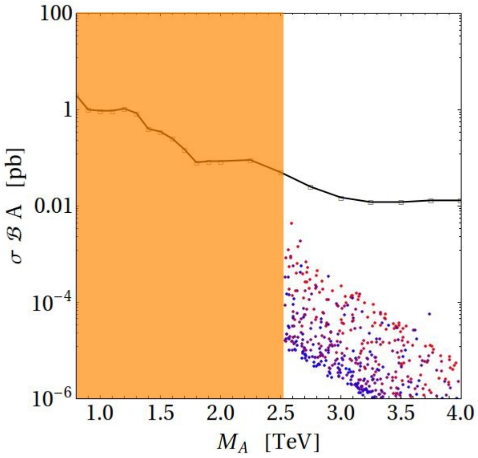
The RS Flavour Problem



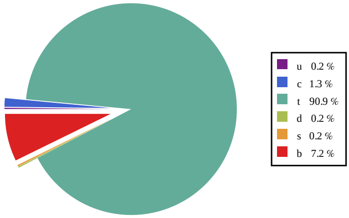
The scalar sector is severely constrained in these models

$$\tan\beta = \frac{v_u}{v_d}$$

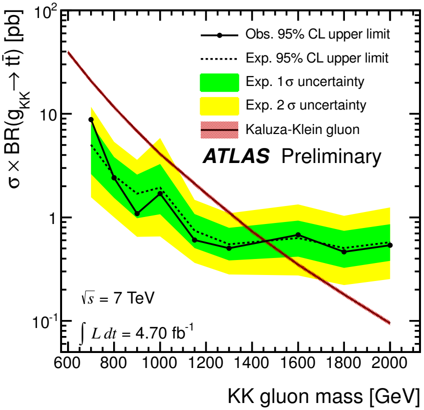
LHC Bounds



Branching Fraction:



LHC Bounds



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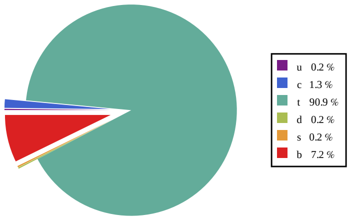
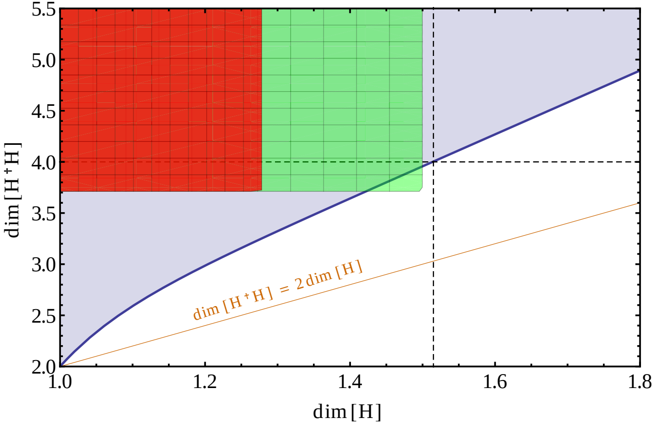


Beyond RS?



[Rattazzi et al. ’08, Poland et al. ’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 flavour problem without fine-tuning, while allowing for a New Physics scale of $M_{\mathrm{KK}} \sim 1-2$ TeV.
- It is in agreement with current LHC bounds but makes predictions for $t\bar{t}$ resonance searches and requires additional scalars.
- The idea of a custodial flavor symmetry can be adopted in a wider class of strongly coupled solutions to the hierarchy problem.