A Solution to the Flavor Problem in Warped Extra Dimensions

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An Effective Field Theory Assault on the Zeptometer Scale: Exploring the Origins of Flavor and Electroweak Symmetry Breaking

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based on: M. Bauer, R. Malm, MN: arXiv:1110.0471 (Phys. Rev. Lett.)

Flavor as a portal beyond the SM

Besides the **hierarchy problem** (mechanism of EWSB) and the **dark-matter puzzle**, the **origin of flavor** is one of the unsolved mysteries of fundamental physics

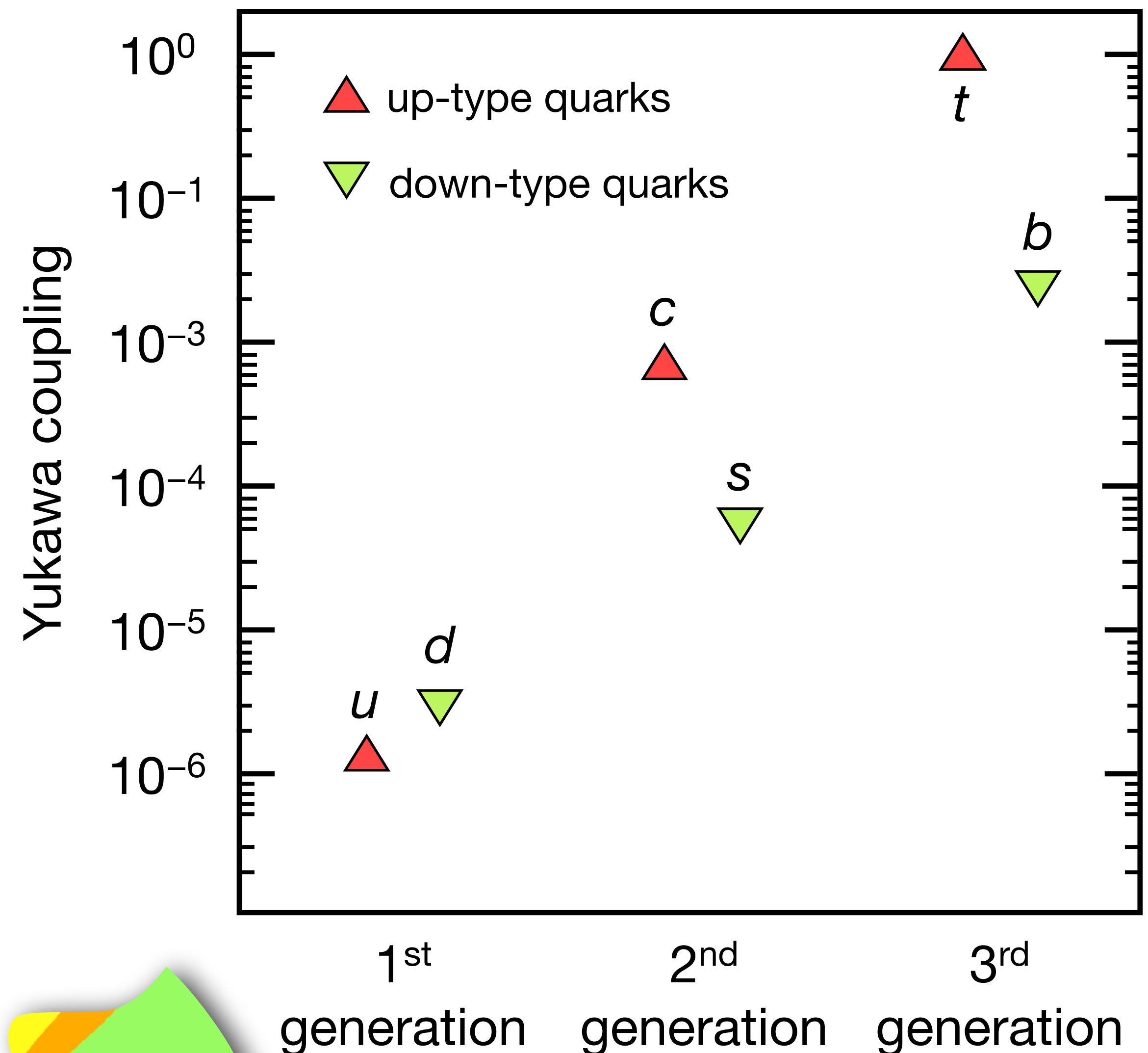
- connected to deep questions such as the **matter-antimatter asymmetry** in the Universe, the origin of **fermion generations**, and the reason for the strong **hierarchies** seen in the spectrum of fermion masses and mixing angles
- in SM, **flavor physics is connected to EWSB** via the Higgs Yukawa interactions

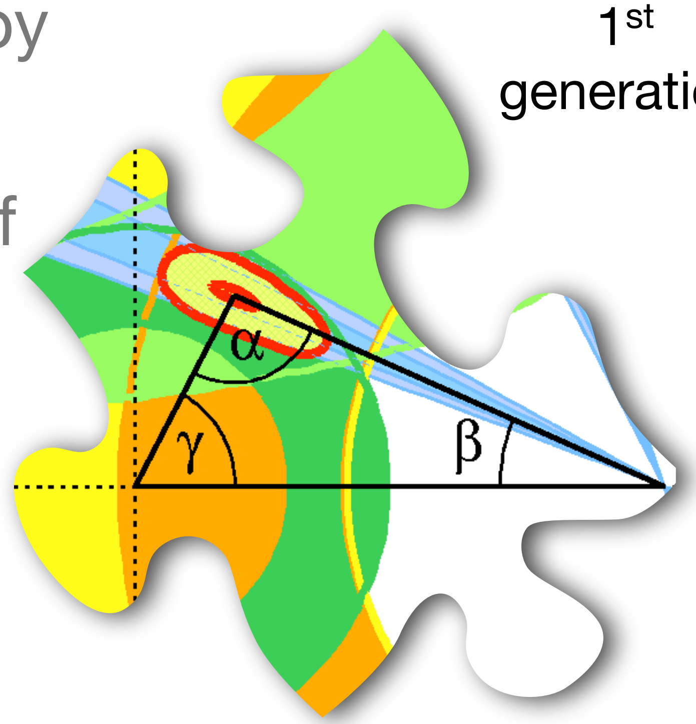
Flavor physics is an issue for any extension of the SM ("flavor problem"), and it provides opportunities to probe the **structure of electroweak interactions** at the quantum level, thereby offering a sensitive probe of physics beyond the SM

What is the dynamics of flavor?

While SM **describes** flavor physics very accurately, it does not **explain** its mysteries:

- Why are there three generations in nature?
- Why does the spectrum of fermion masses cover so many orders of magnitude?
- Why is the mixing between different generations governed by small mixing angles?
- Why is the CP-violating phase of the CKM matrix unsuppressed?

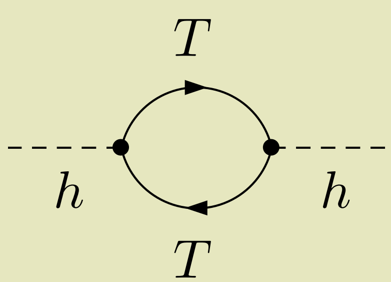




Flavor physics as an indirect BSM probe

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

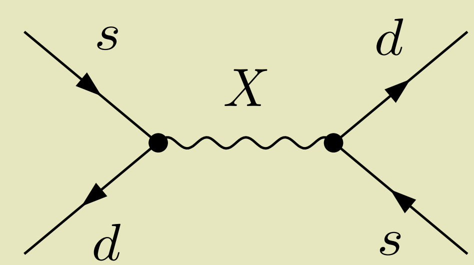
electroweak symmetry breaking $\Downarrow$ Higgs mass



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

no fine-tuning $\Downarrow$

$\Downarrow$



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

bounds on flavor mixing $\Downarrow$ assuming *generic* flavor structure

$\Lambda_{\rm Higgs} \lesssim 1$ TeV $\qquad$ $\Lambda_{\rm flavor} \gtrsim 10^3$ TeV

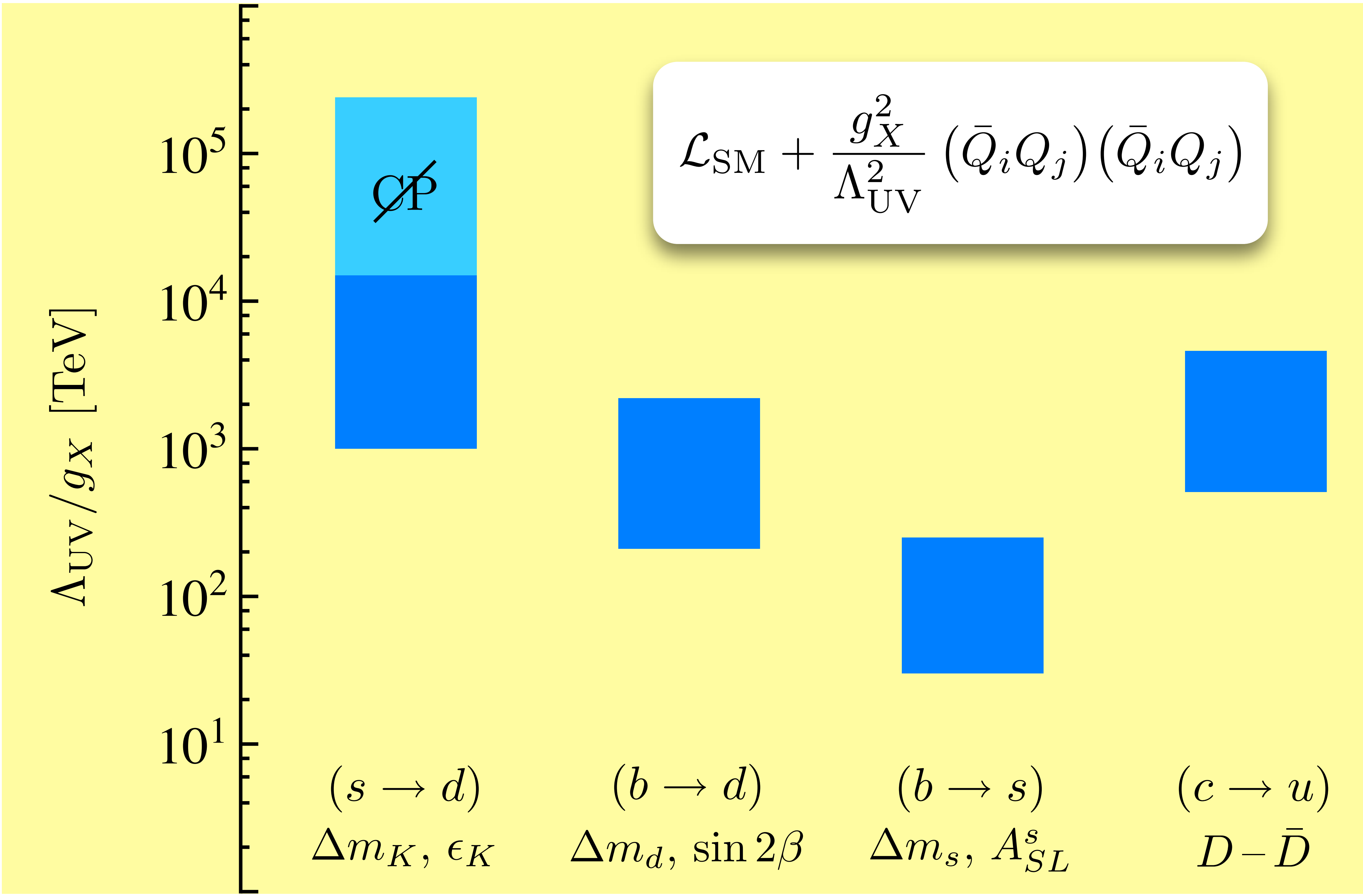
Possible solutions to flavor problem explaining $\Lambda_{\rm Higgs} << \Lambda_{\rm flavor}$:

(i) $\Lambda_{\rm UV} >> 1$ TeV: **Higgs fine tuned**, new particles too heavy for LHC

(ii) $\Lambda_{\rm UV} \approx 1$ TeV: quark flavor-mixing protected by a **flavor symmetry**

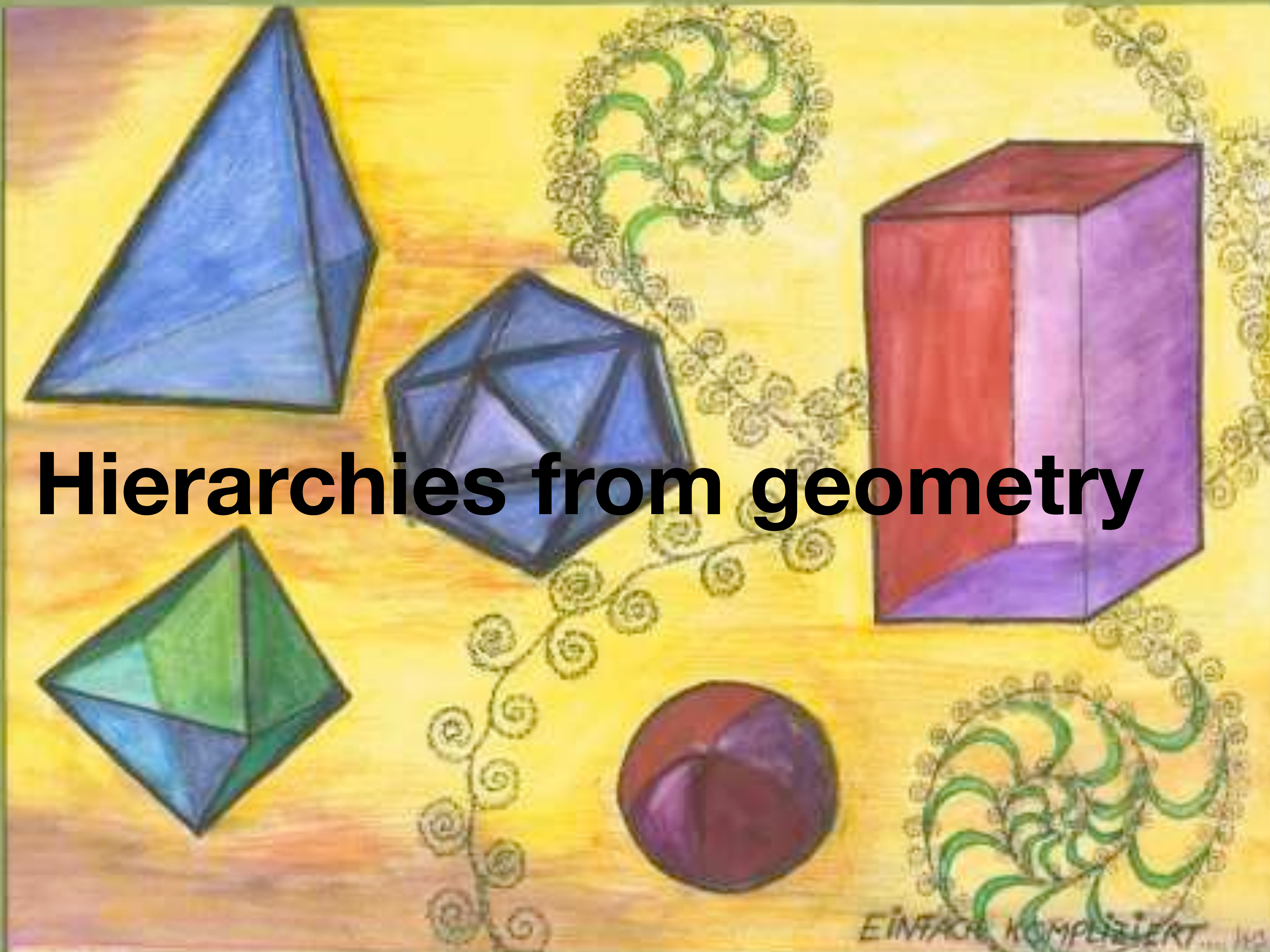
Flavor physics as an indirect BSM probe

Isidori, Nir, Perez (2010)

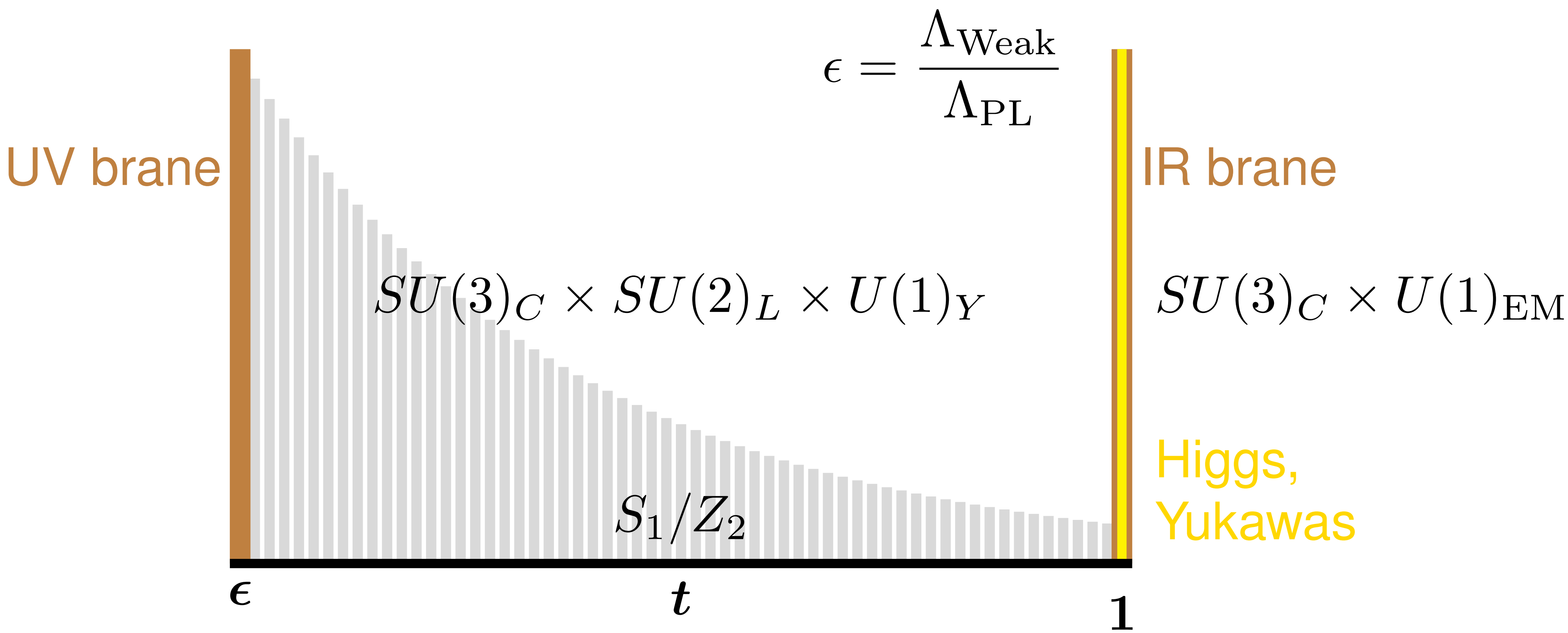


Generic bounds on New Physics scale (for $g_X \sim 1$)

Hierarchies from geometry



Flavor structure in RS models

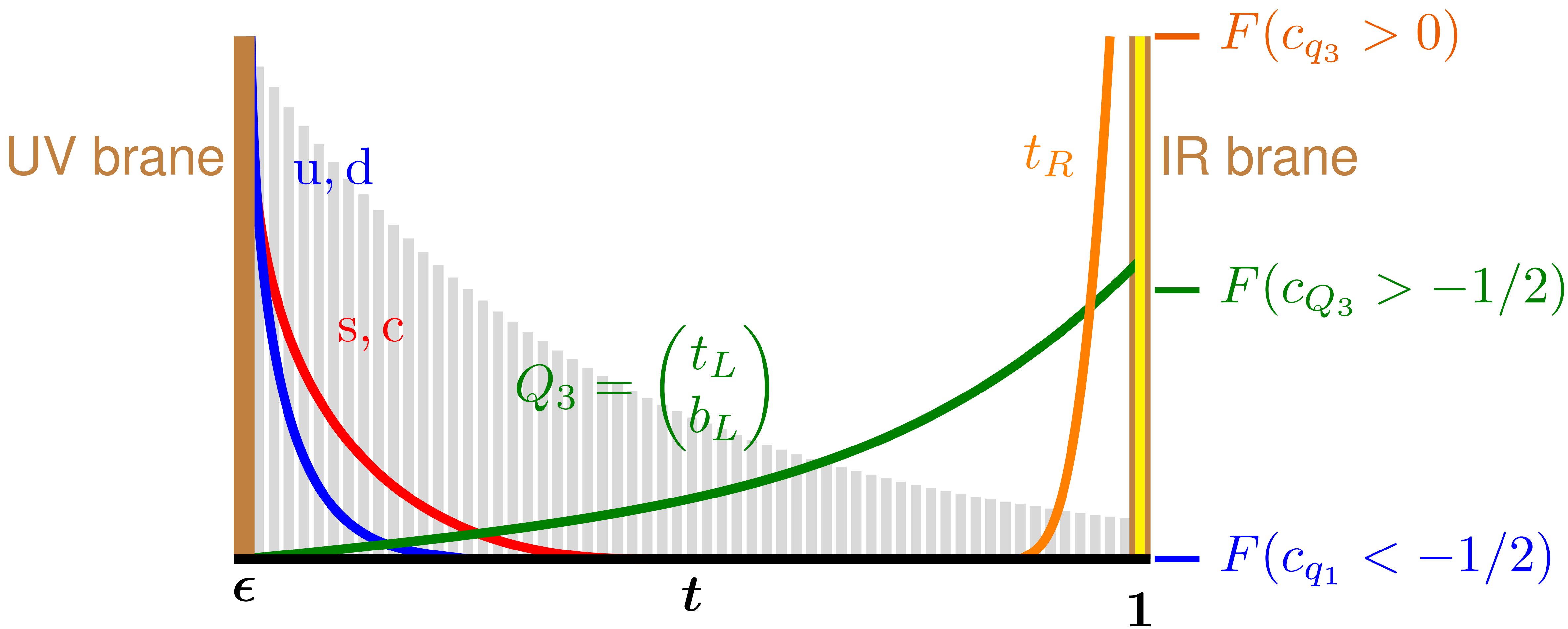


$$ds^2 = \frac{\epsilon^2}{t^2}\,\eta_{\mu\nu}\,dx^\mu dx^\nu - \frac{1}{k^2 t^2} dt^2$$

Randall-Sundrum (RS) models with a warped extra dimension address, at the same time, the **gauge hierarchy problem** and the **flavor problem** (hierarchies in the spectrum of quark masses and mixing angles)

Randall, Sundrum (1999)

Flavor structure in RS models



Localization of fermions in extra dimension depends exponentially on O(1) parameters related to the 5D **bulk masses.** Overlap integrals $F(Q_L)$, $F(q_R)$ with Higgs profile are **exponentially small** for light quarks, while O(1) for top quark: effective Yukawa couplings exhibit **realistic hierarchies**

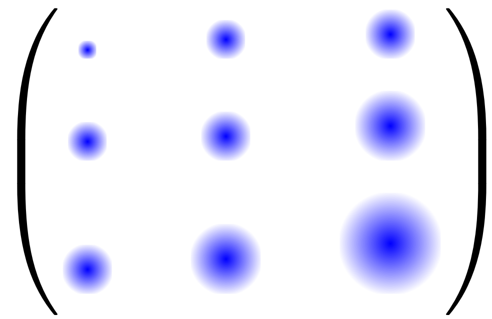
Grossman, Neubert (1999); Ghergetta, Pomarol (2000)

Flavor structure on RS models

Yukawa matrices $(Y_d)_{ij}$ can be chosen to be anarchic and of order one:

Huber (2003)

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



$_{ij}$

Hierarchical masses and mixings can be generated by relying on order one parameters only:

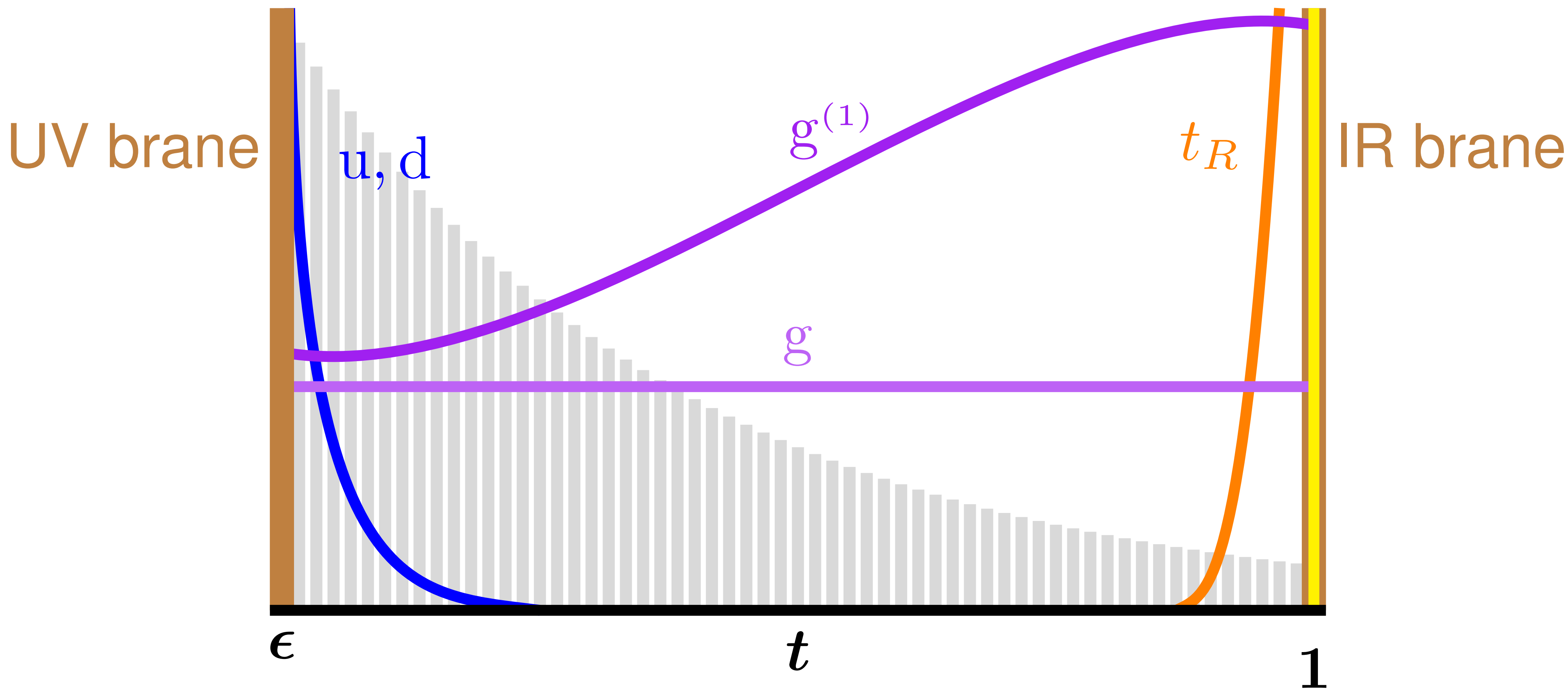
$$m_{q_i} = \mathcal{O}(1) \frac{v}{\sqrt{2}} F(c_{Q_i}) F(c_{q_i})$$

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

Warped-space Froggatt-Nielsen mechanism!

Casagrande et al. (2008); Blanke et al. (2008)

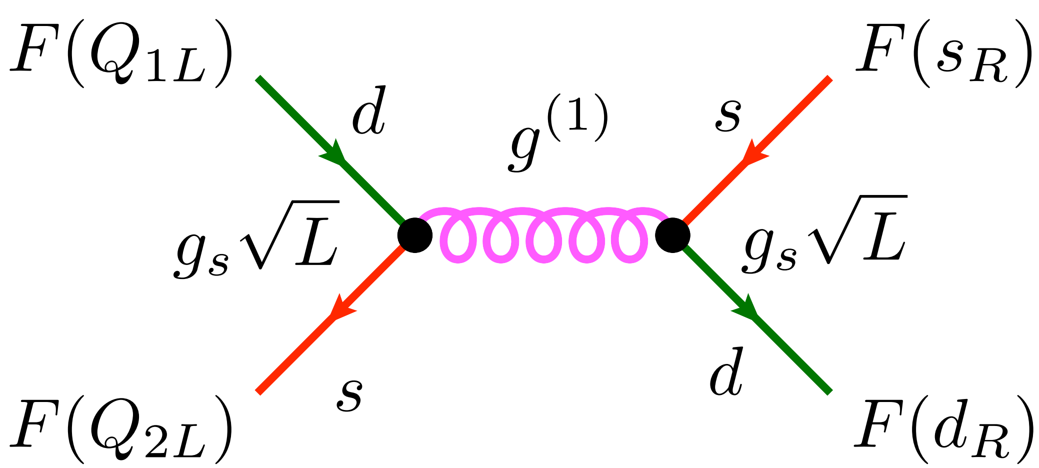
Flavor structure in RS models



Kaluza-Klein (KK) excitations of SM particles live close to the IR brane

Davoudiasl, Hewett, Rizzo (1999); Pomarol (1999)

RS-GIM protection of FCNCs

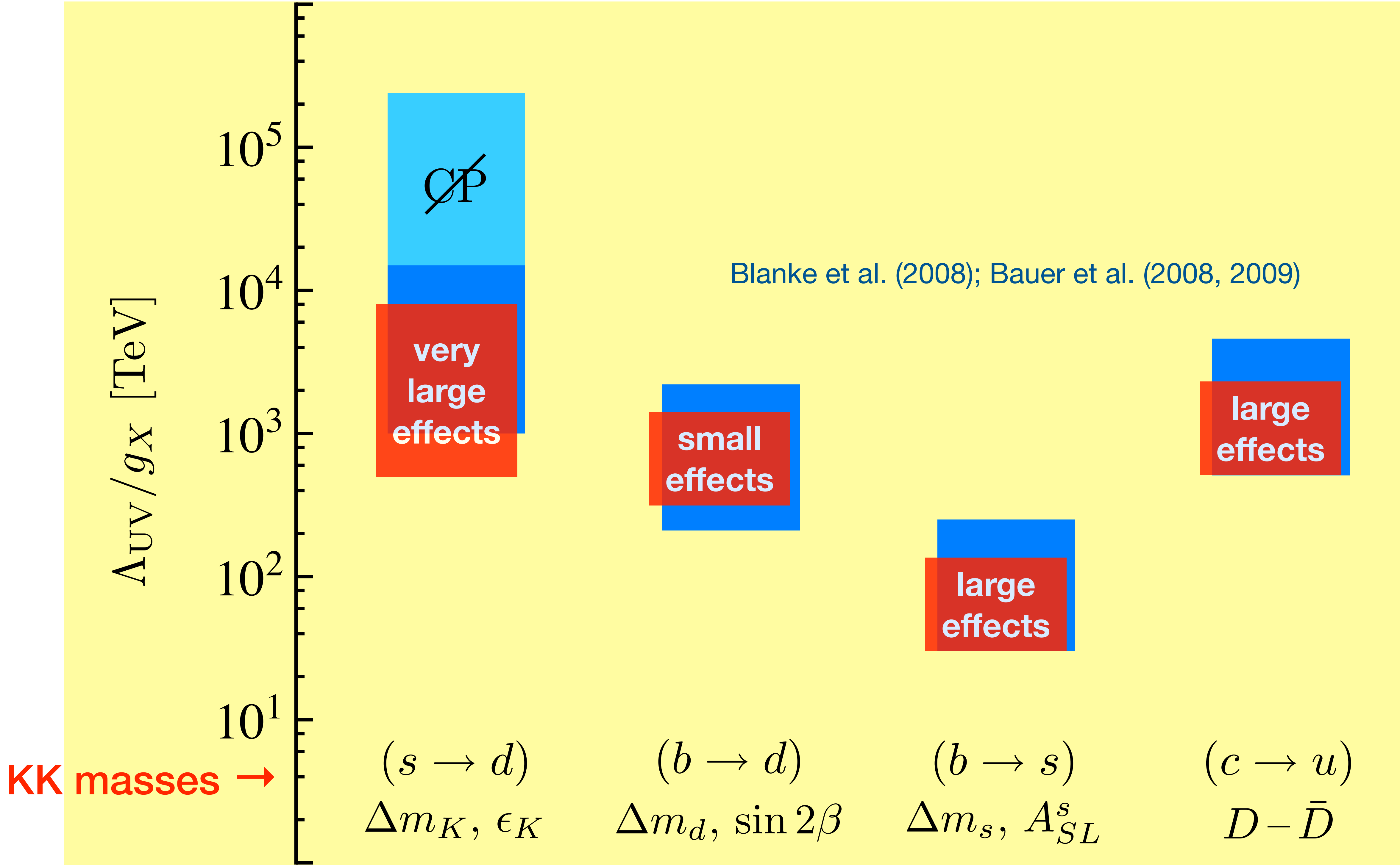


$$\sim \frac{g_s^2}{M_{\rm KK}^2}\, L\, F(Q_{1L})F(d_R)\, F(Q_{2L})F(s_R)$$

- Tree-level quark FCNCs induced by **virtual exchange of Kaluza-Klein (KK) gauge bosons** (including gluons!)
  Huber (2003); Burdman (2003); Agashe et al. (2004); Casagrande et al. (2008)
- Resulting FCNC couplings depend on same **exponentially small** overlap integrals $F(Q_L)$, $F(q_R)$ that generate fermion masses
- FCNCs involving light quarks are strongly suppressed: **RS-GIM mechanism**
  Agashe et al. (2004)

This mechanism suffices to suppress all (but one) of the dangerous FCNC couplings!

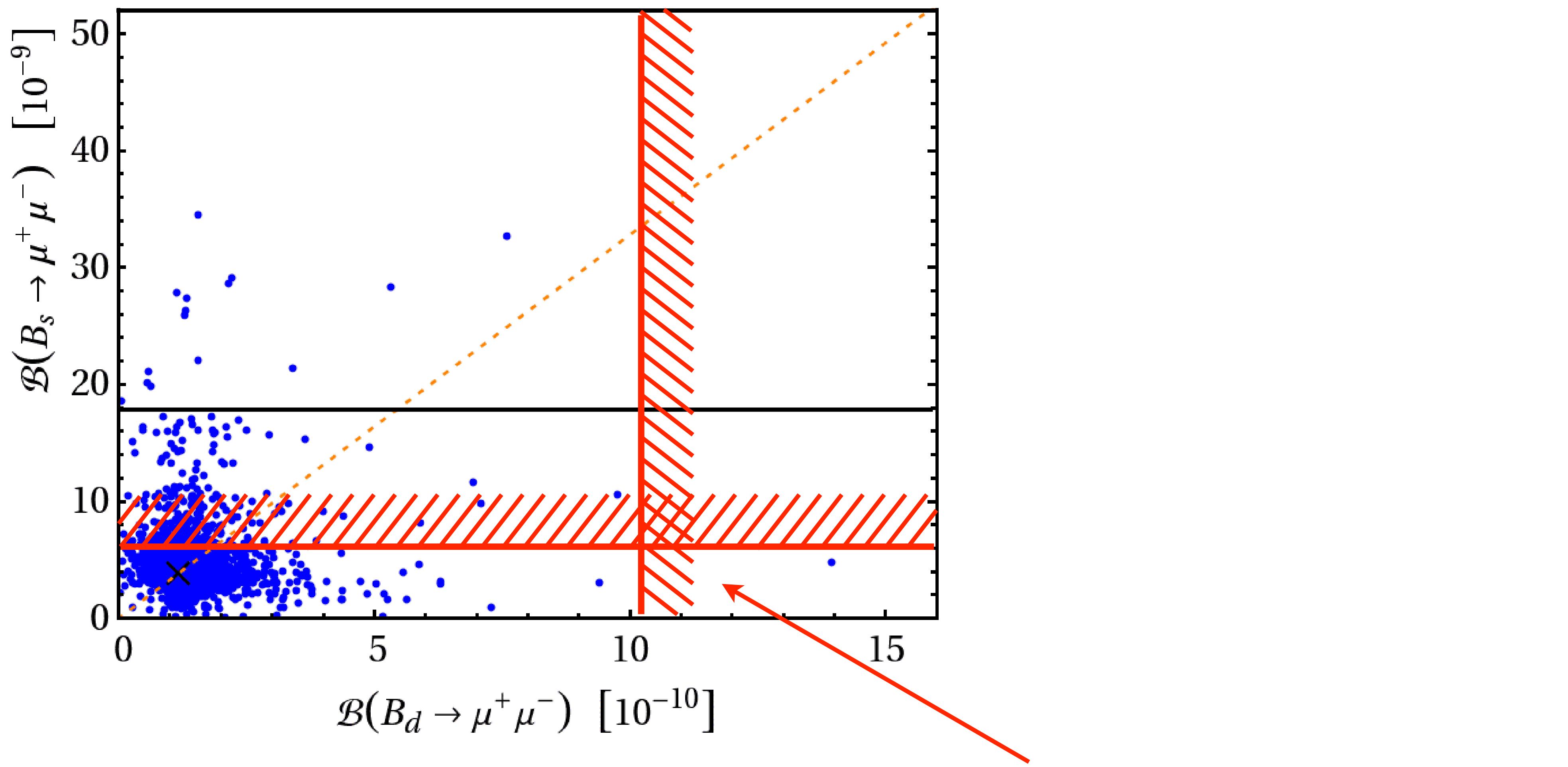
RS-GIM protection of FCNCs



RS-GIM protection with KK masses of order few TeV

Example: Rare leptonic $B_{s/d} \to \mu^+\mu^-$ decays

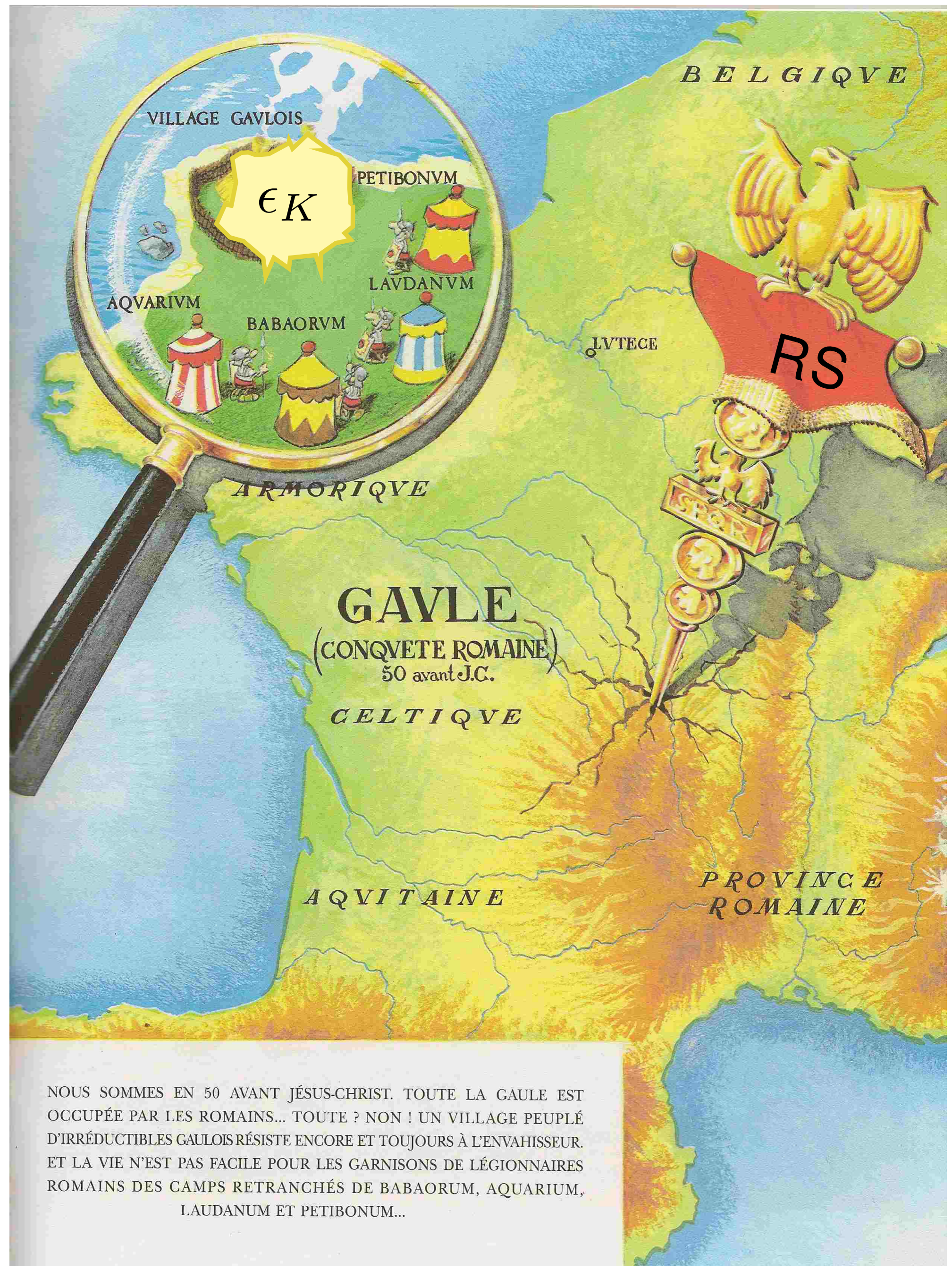
Rare decays $B_{d,s} \to \mu^+\mu^-$ could be significantly affected, but RS-GIM protection is sufficient to prevent too large deviations from SM are not generic:



Bauer, Casagrande, Haisch, MN (2009);
see also: Blanke et al. (2008)

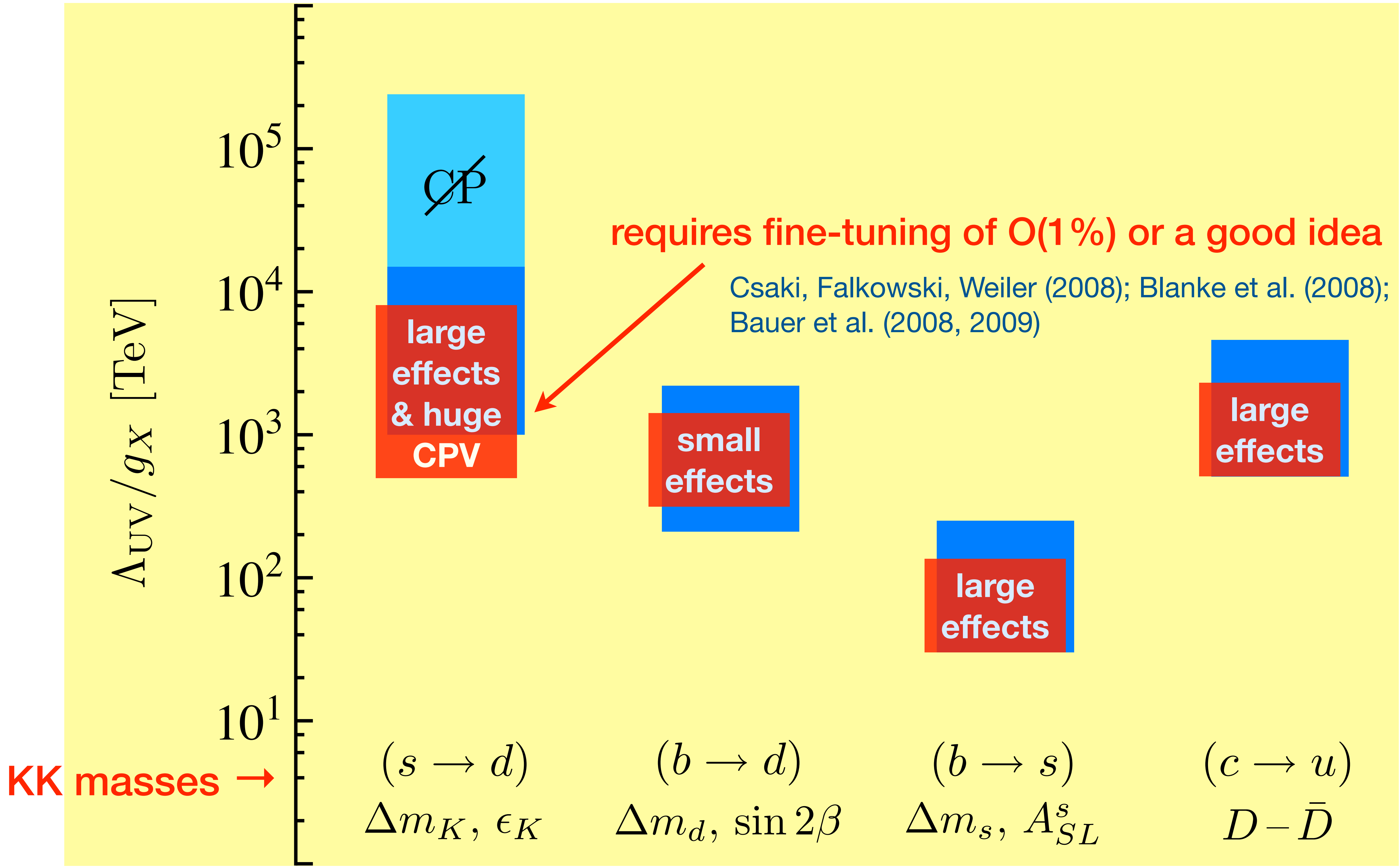
- Recent LHC(b) results on $B_s \to \mu^+\mu^-$ begin cutting into the interesting parameter space

RS-GIM protection of FCNCs



The RG-GIM mechanism suffices to suppress all **but one** of the dangerous FCNC couplings!

RS-GIM protection of FCNCs



RS-GIM protection with KK masses of order few TeV

The RS flavor problem

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

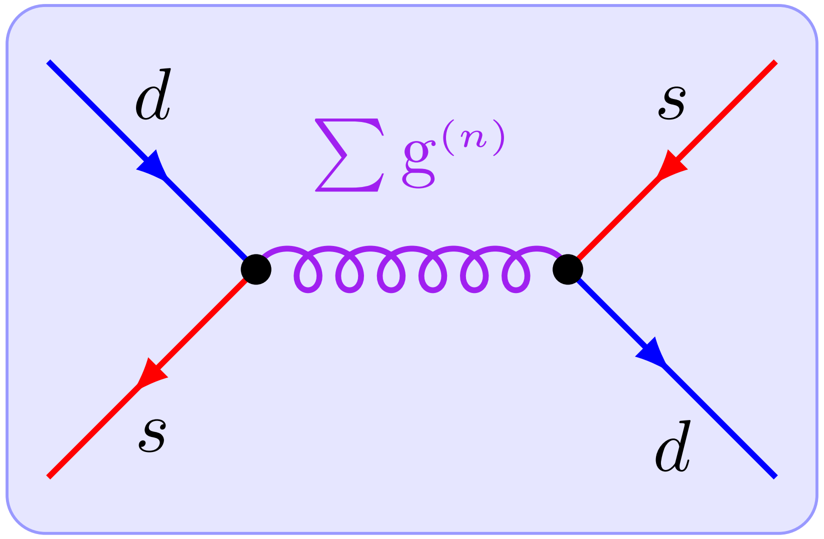
$$\epsilon_K = \frac{\kappa_\epsilon e^{i\phi_\epsilon}}{\sqrt{2}(\Delta m_K)_{\rm exp}} \, {\rm Im}\, \langle K^0 | \mathcal{H}_{\rm eff}^{\Delta S=2} | \bar{K}^0 \rangle$$

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

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

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

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



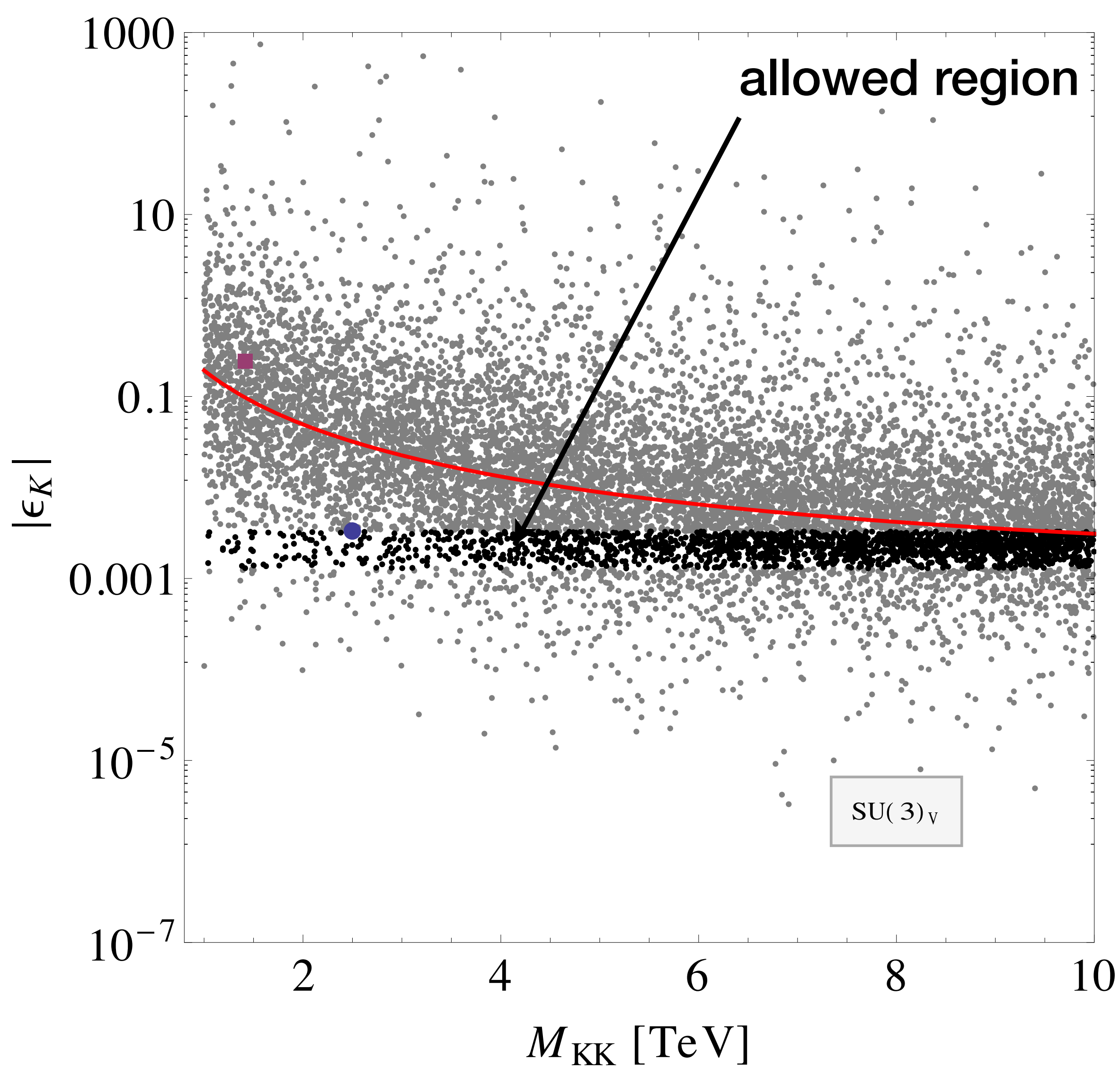
$$\langle K^0 | \mathcal{H}_{\rm RS}^{\Delta S=2} | \bar{K}^0 \rangle \propto C_1^{\rm SM+RS} + \widetilde{C}_1^{\rm RS} + 100 \left(C_4^{\rm RS} + \tfrac{1}{N_C} C_5^{\rm RS} \right)$$

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

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

The RS flavor problem

Generically, this leads to **very large** New Physics contributions to ε_K:

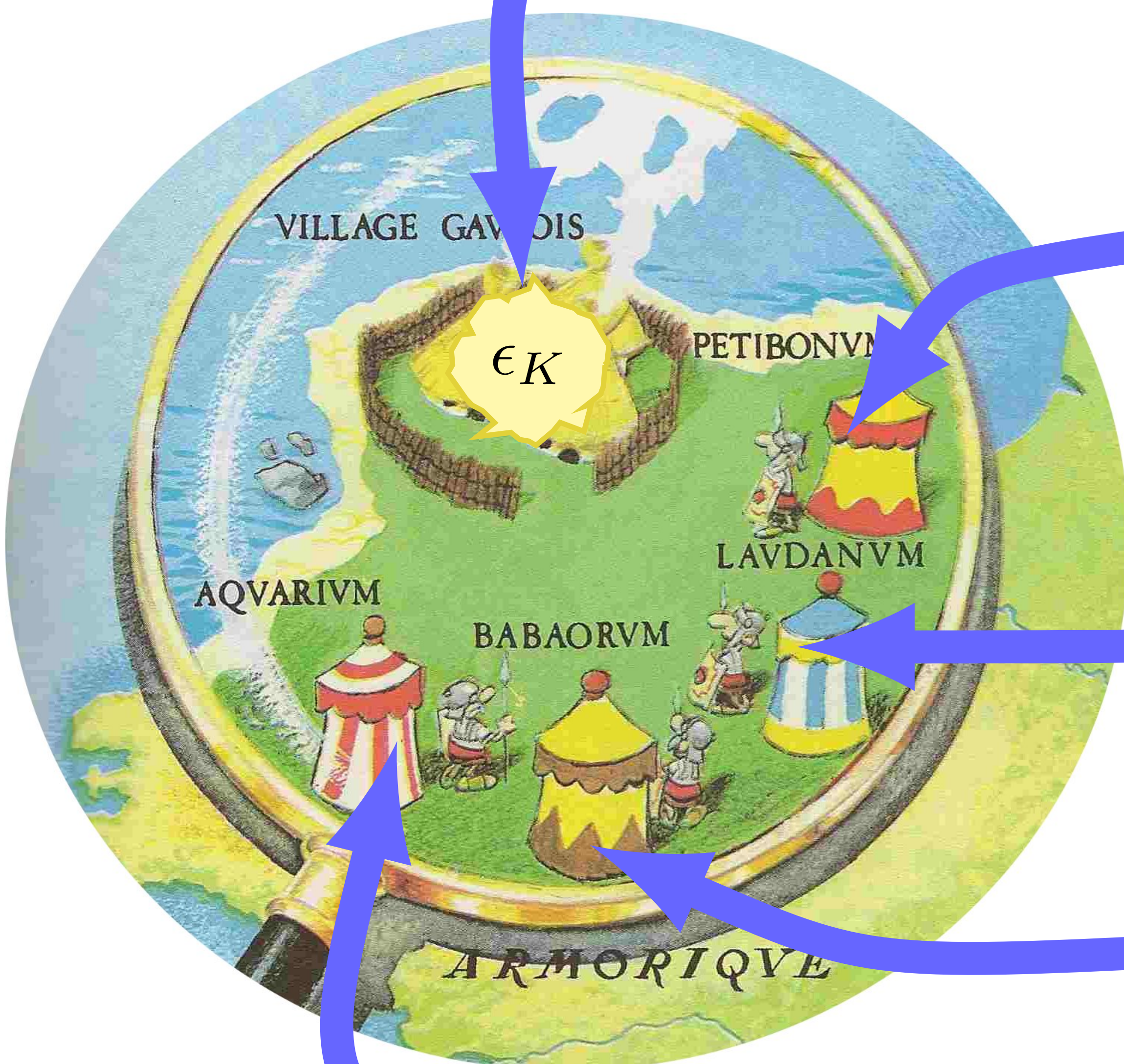


(first KK gluon has mass 2.45 M_{KK})

Csaki, Falkowski, Weiler (2008); Blanke et al. (2008);
Bauer et al. (2008, 2009)

Addressing the RS flavor problem

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



Discrete symmetries for right-handed [Santiago '08] or down-sector [Csaki *et al.* '08]

Soft wall or Bulk Higgs [Batell, Gherghetta, Sword '08]

Little RS models [Davoudiasl, Perez, Soni '08]

Modified metric [Cabrer, von Gersdorff, Quiros '11]

A solution to the RS flavor problem

An elegant solution is to extend the strong gauge group to

$$SU(3)_{\text{doublet}} \otimes SU(3)_{\text{singlet}}$$

Bauer, Malm, MN (2011)

and break it to $SU(3)_V$ using boundary conditions on the UV and IR branes:

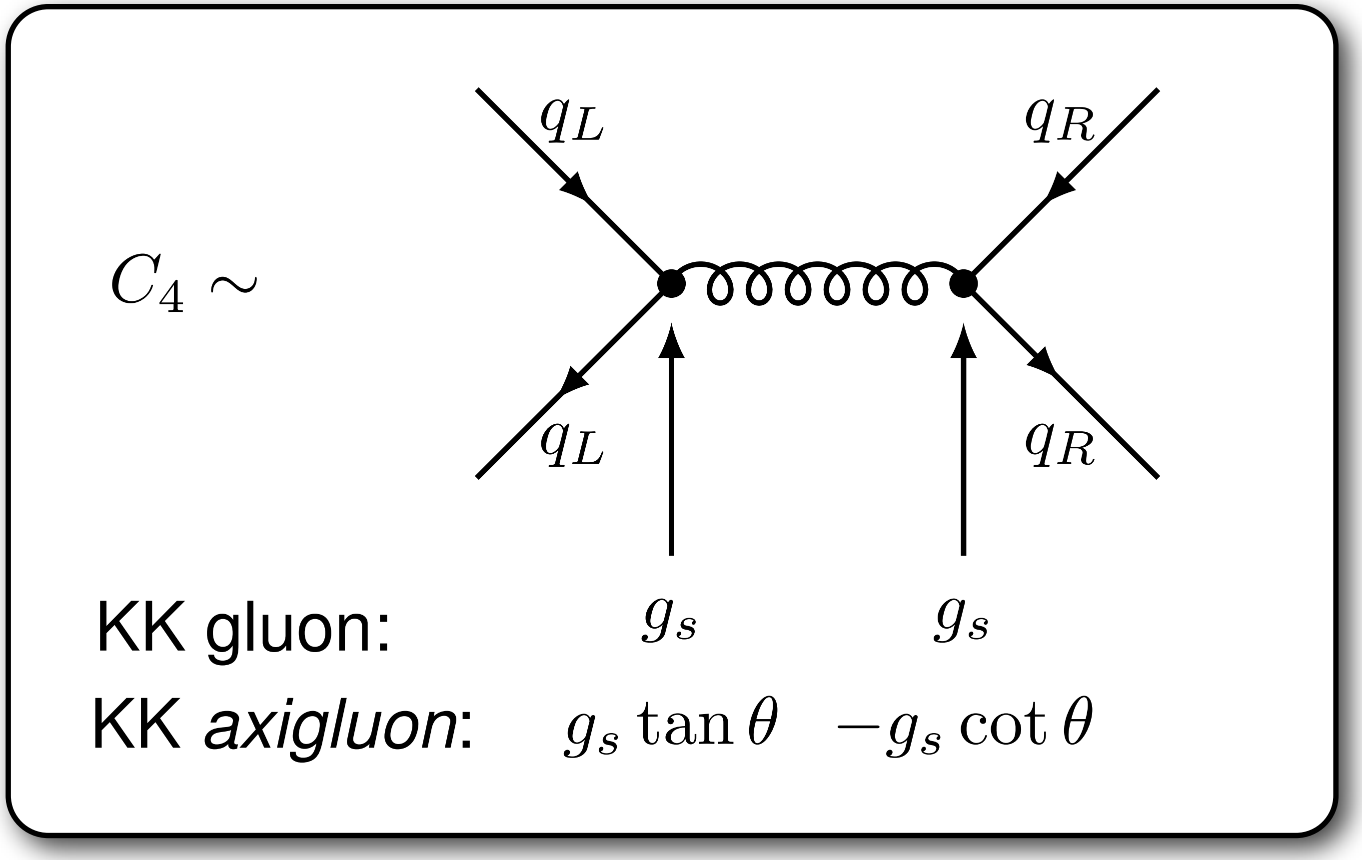
$$\mathcal{L}_{\text{int}} \ni g_D \, \bar{Q} \, G_\mu^D \gamma^\mu Q + g_S \, \bar{q} \, G_\mu^S \, \gamma^\mu q$$

$$= g_s \, (\bar{Q} \, g_\mu \gamma^\mu Q + \bar{q} \, g_\mu \, \gamma^\mu q \,) \\ + g_s \, (\tan\theta \; \bar{Q} \, A_\mu \gamma^\mu Q - \cot\theta \; \bar{q} \, A_\mu \, \gamma^\mu q \,)$$

The gluon field $g_\mu = G_\mu^D \cos\theta + G_\mu^S \sin\theta$ with $\tan\theta = g_D/g_S$ has a massless zero mode (the SM gluon), while the **pseudo-axial gluon** $A_\mu = G_\mu^D \sin\theta - G_\mu^S \cos\theta$ only gives rise to massive KK modes

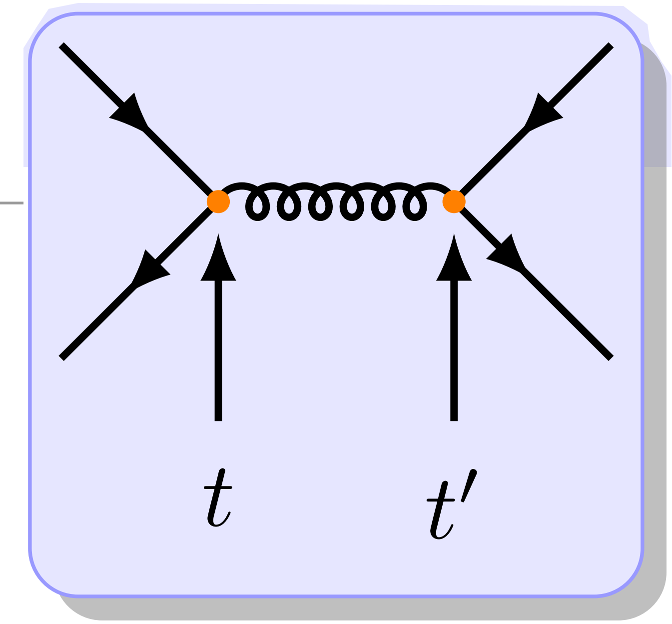
A solution to the RS flavor problem

Since the left/right-handed SM quarks are the zero modes of SU(2) doublet/singlet fields, we achieve opposite-sign couplings for mixed-chirality 4-quark operators for any value of θ:



These contributions from the two KK towers cancel exactly for a large set of boundary conditions!

A solution to the RS flavor problem



We have to sum over the KK modes:

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

$$\partial_t\chi_n(t)\big|_{\rm UV}=r_{\rm UV}\,\chi_n(t)\big|_{\rm UV}\qquad \partial_t\chi_n(t)\big|_{\rm IR}=-r_{\rm IR}\,\chi_n(t)\big|_{\rm IR}$$

Pick Neuman BCs for gluon tower, **arbitrary BCs** for axi-gluon tower:

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

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

with:

$$A=1\qquad\qquad B=\frac{2\epsilon r_{\rm IR}}{2r_{\rm UV}-2\epsilon r_{\rm IR}-r_{\rm UV}r_{\rm IR}}$$

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

A solution to the RS flavor 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.

A solution to the RS flavor problem

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

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:

$$\mathcal{L} \ni Y_u\, \overline{Q}\, \epsilon\, \mathbf{H}^*\, u + Y_d\, \overline{Q}\, \mathbf{H}\, d$$

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 $\mathbf{H} \sim (\mathbf{3}, \bar{\mathbf{3}}, \mathbf{2})$.
This gives

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

For $r_\epsilon \gg \epsilon$ and $r_1 = \mathcal{O}\Big(\frac{v^2}{M_{\rm KK}^2}\Big)$.

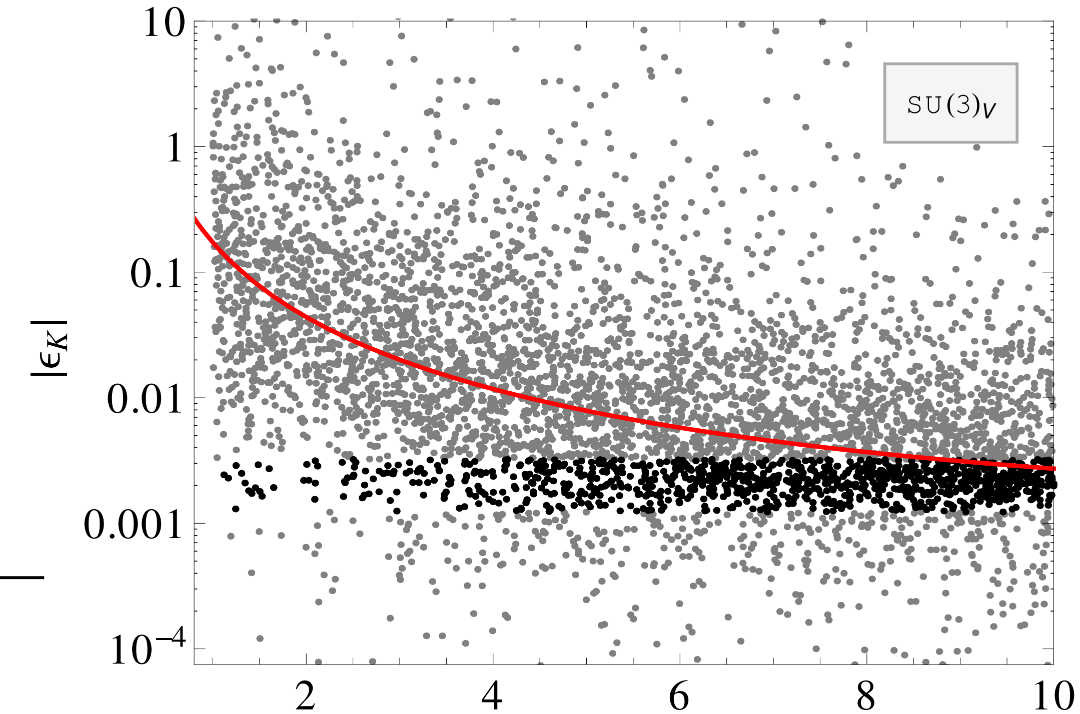
A solution to the RS flavor problem

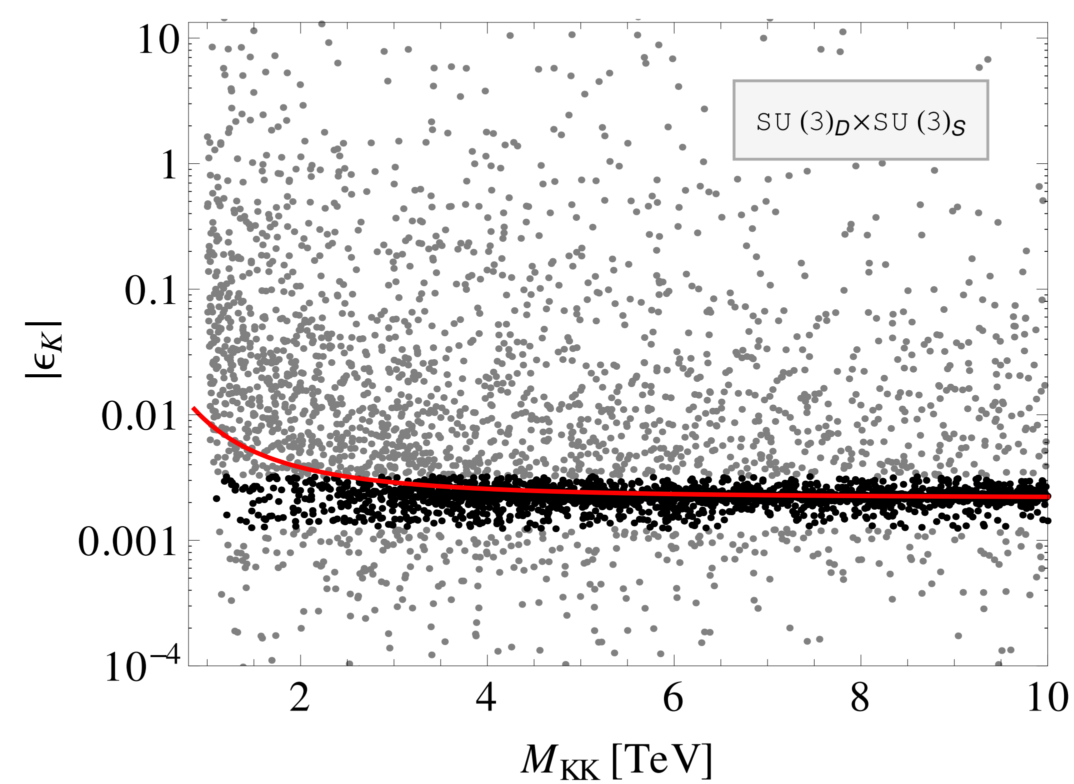
Bauer, Malm, MN (2011)

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

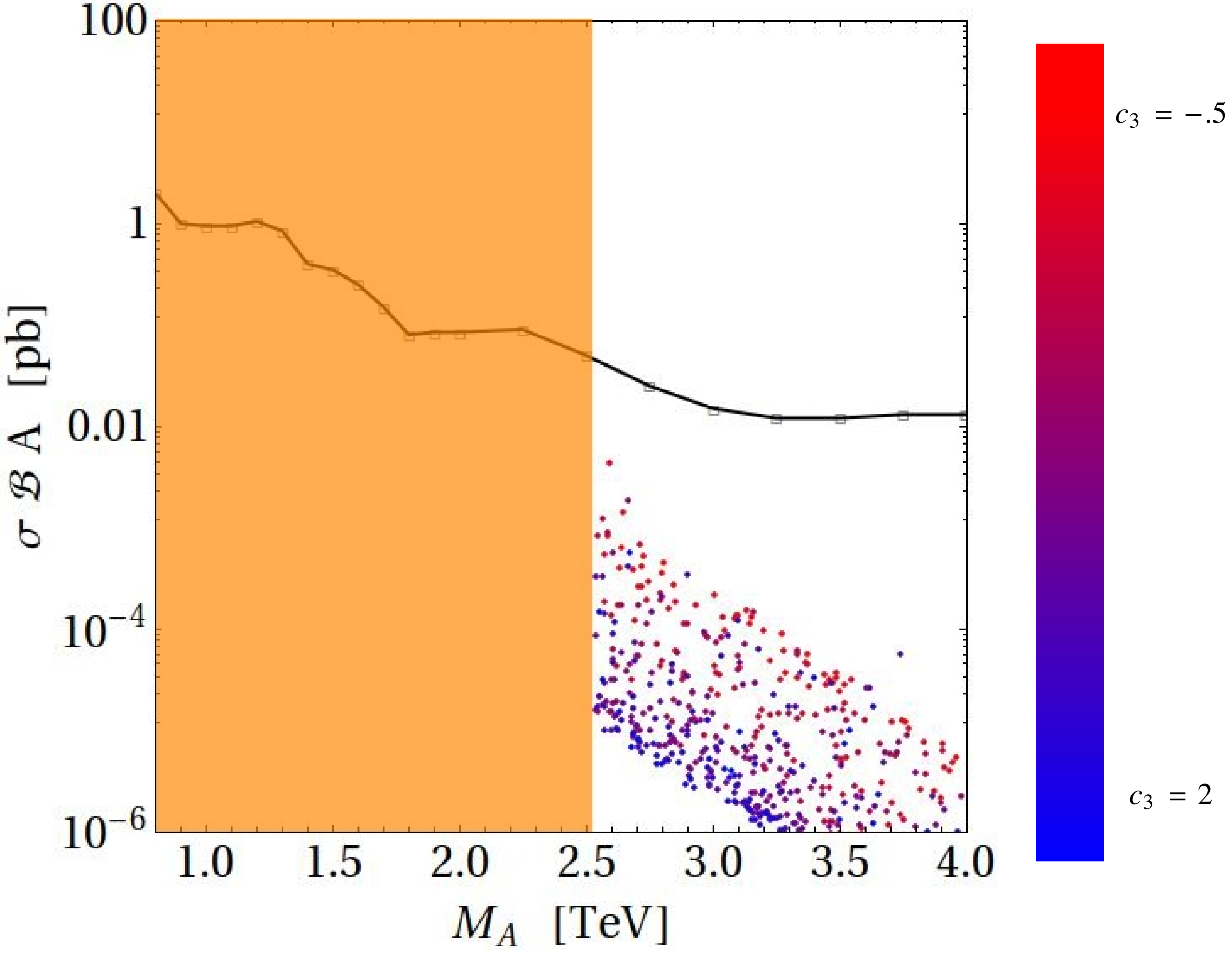
$M_{\rm KK}$ [TeV]	1–2	2–3	3–4	4–5	5–10
min	3%	7%	10%	15%	29%
$(\xi = 0.5)$	11%	33%	50%	59%	71%
$(\xi = 1)$	10%	27%	47%	58%	71%
$(\xi = 2)$	8%	24%	39%	55%	71%

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



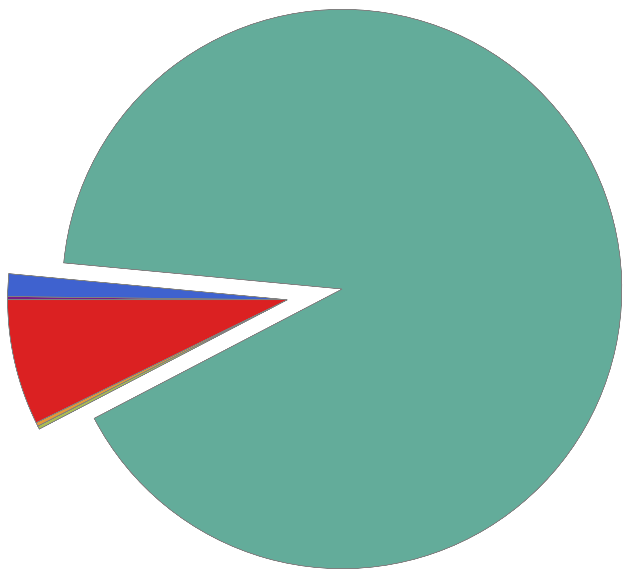


LHC dijet bounds



[ATLAS '11]

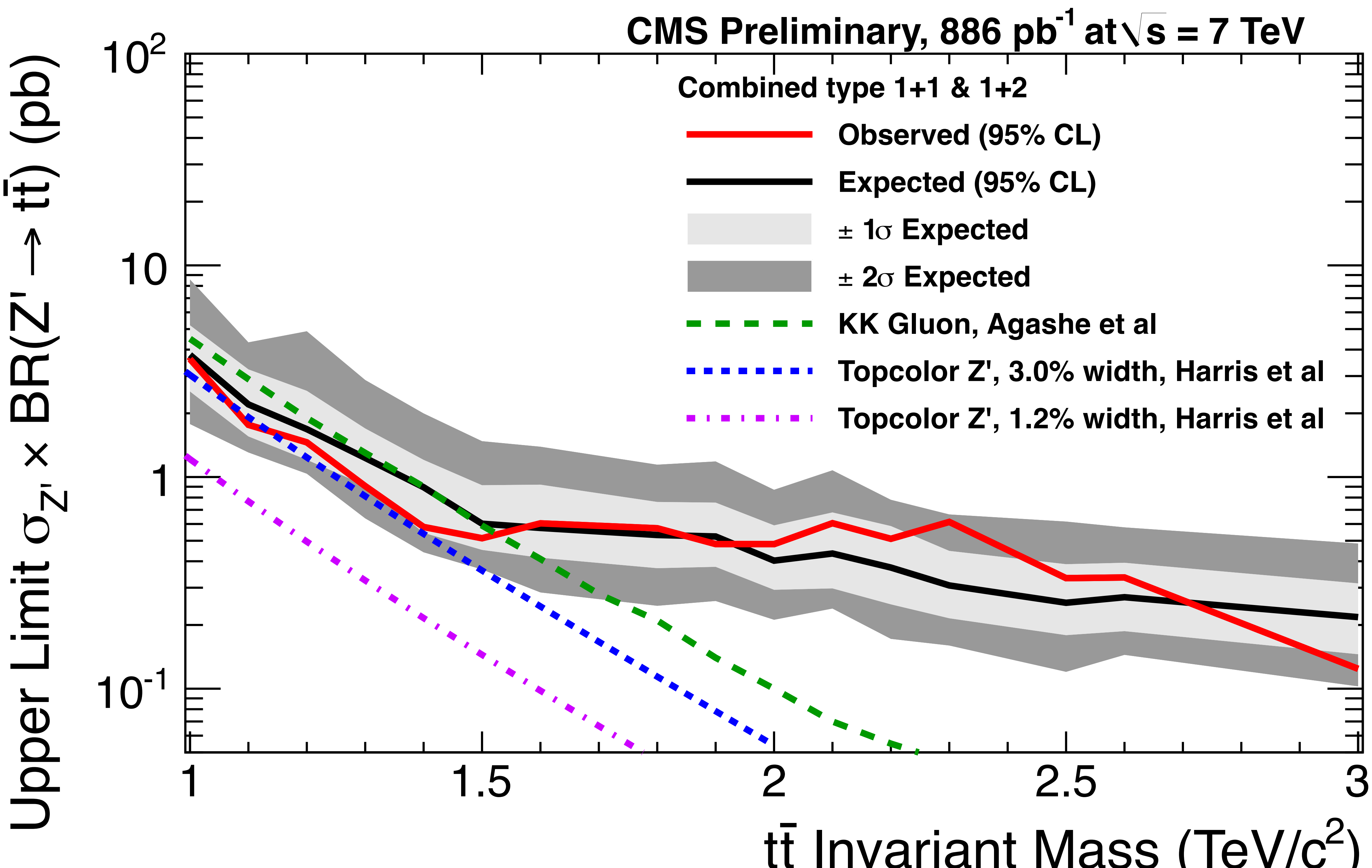
KK (Axi-)Gluon Branching Ratio:



7% bottom

91% top

LHC bounds on $t\bar{t}$ resonances



[CMS ’11]

Conclusions

The first LHC data mark the beginning of a new era for particle physics, which holds promise of ground-breaking discoveries

ATLAS and CMS discoveries alone are unlikely to provide a complete understanding of the observed phenomena

Flavor physics (more generally, low-energy precision physics) will play a key role in unravelling what lies beyond the Standard Model, providing access to energy scales and couplings unaccessible at the energy frontier

Embedding the SM into a warped extra dimension provides an attractive framework for addressing the hierarchy problem and the flavor puzzle in terms of the same geometrical mechanism