Higgs and Flavor Physics in a Warped Extra Dimension

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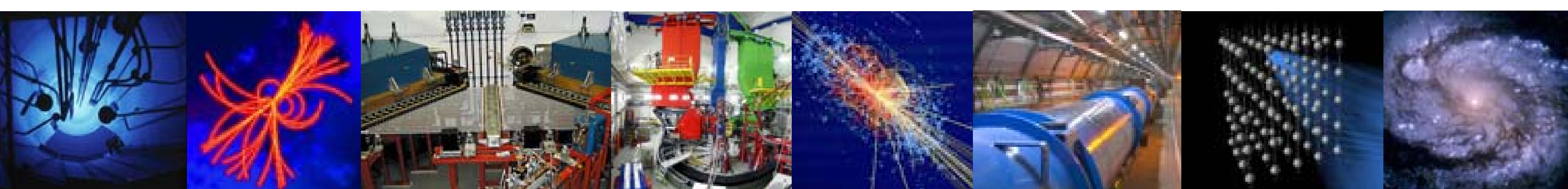
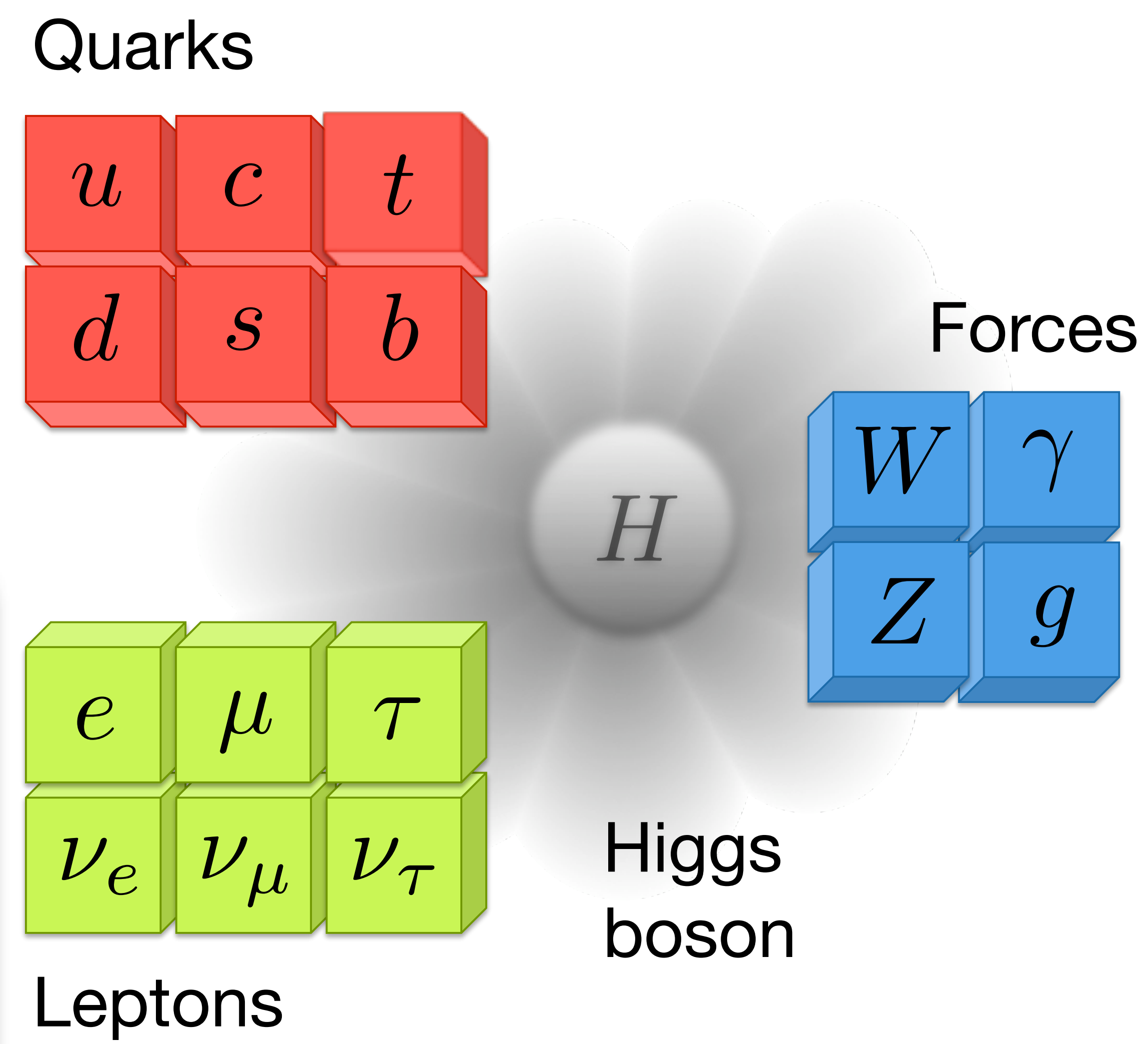


Standard Model and Beyond

Standard Model of particle physics works beautifully, explaining all experimental phenomena to date with great precision:

- no compelling hints for deviations
- triumph of 20th century science



But many questions remain unanswered:

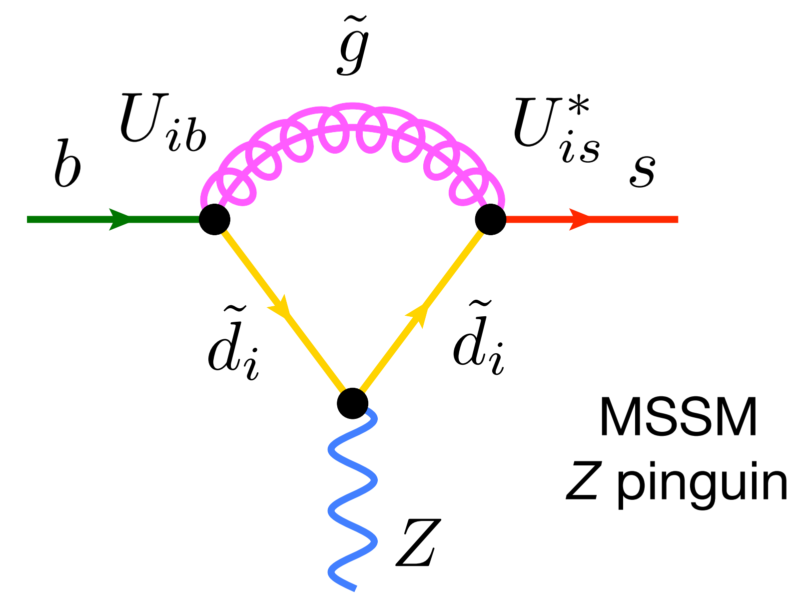
- Origin of electroweak sym. breaking?
- Origin of generations and structure of Yukawa interactions?
- Matter-antimatter asymmetry?
- Unification of forces? Neutrino masses?
- Dark matter and dark energy?

Strong prejudice that there must be "New Physics"

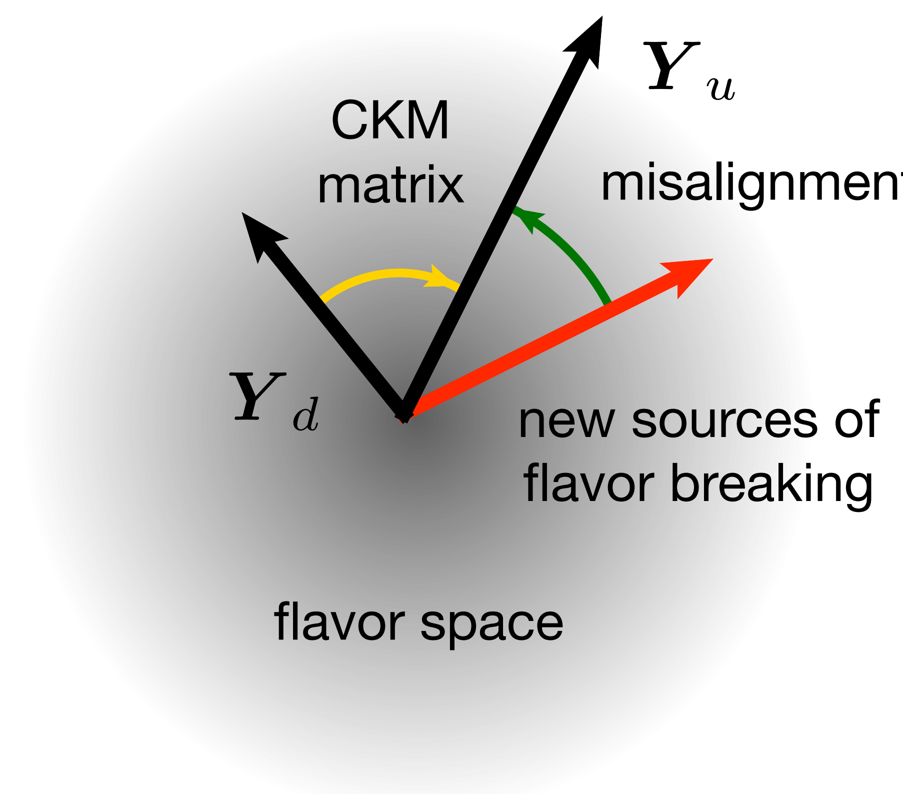
Flavor Structure in the SM and Beyond

In extensions of SM, additional flavor and CP violation can arise from exchange of new scalar (H^+, $\tilde{q}$, ...), fermionic ($\tilde{g}$, t', $t^{(1)}$, ...), or gauge (Z', $g^{(1)}$, ...) degrees of freedom

- new flavor-violating terms in general not aligned with SM Yukawa couplings $\boldsymbol{Y}_u$, $\boldsymbol{Y}_d$
- can lead to excessive FCNCs, unless:
  - new particles are heavy: $\tilde{m}_i >> 1$ TeV
  - masses are degenerate: $\Delta\tilde{m}_{ij} << \tilde{m}_i$
  - mixing angles are very small: $U_{ij} << 1$



Absence of clear New Physics signals in FCNCs implies strong constraints on flavor structure of TeV-scale physics (if it exists)

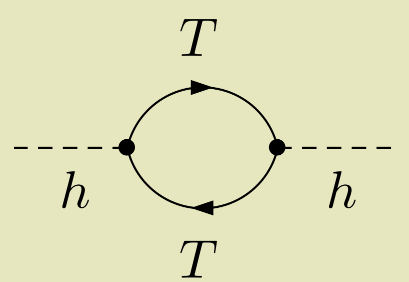


Flavor Structure in the SM and Beyond

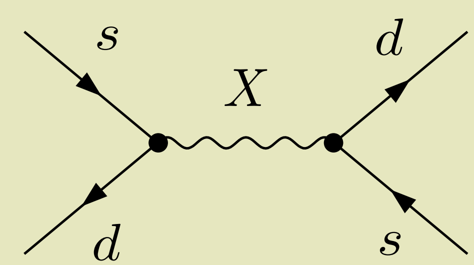
$$\mathcal{L}_{\mathrm{EFT}} = \underbrace{\Lambda_{\mathrm{UV}}^2 \Phi^\dagger \Phi - \lambda(\Phi^\dagger\Phi)^2}_{} + \mathcal{L}_{\mathrm{SM}}^{\mathrm{gauge}} + \mathcal{L}_{\mathrm{SM}}^{\mathrm{Yukawa}} + \underbrace{\frac{\mathcal{L}^{(5)}}{\Lambda_{\mathrm{UV}}} + \frac{\mathcal{L}^{(6)}}{\Lambda_{\mathrm{UV}}^2}}_{}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

electroweak symmetry breaking $\Downarrow$ Higgs mass

$\Downarrow$



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



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

no fine-tuning $\Downarrow$

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

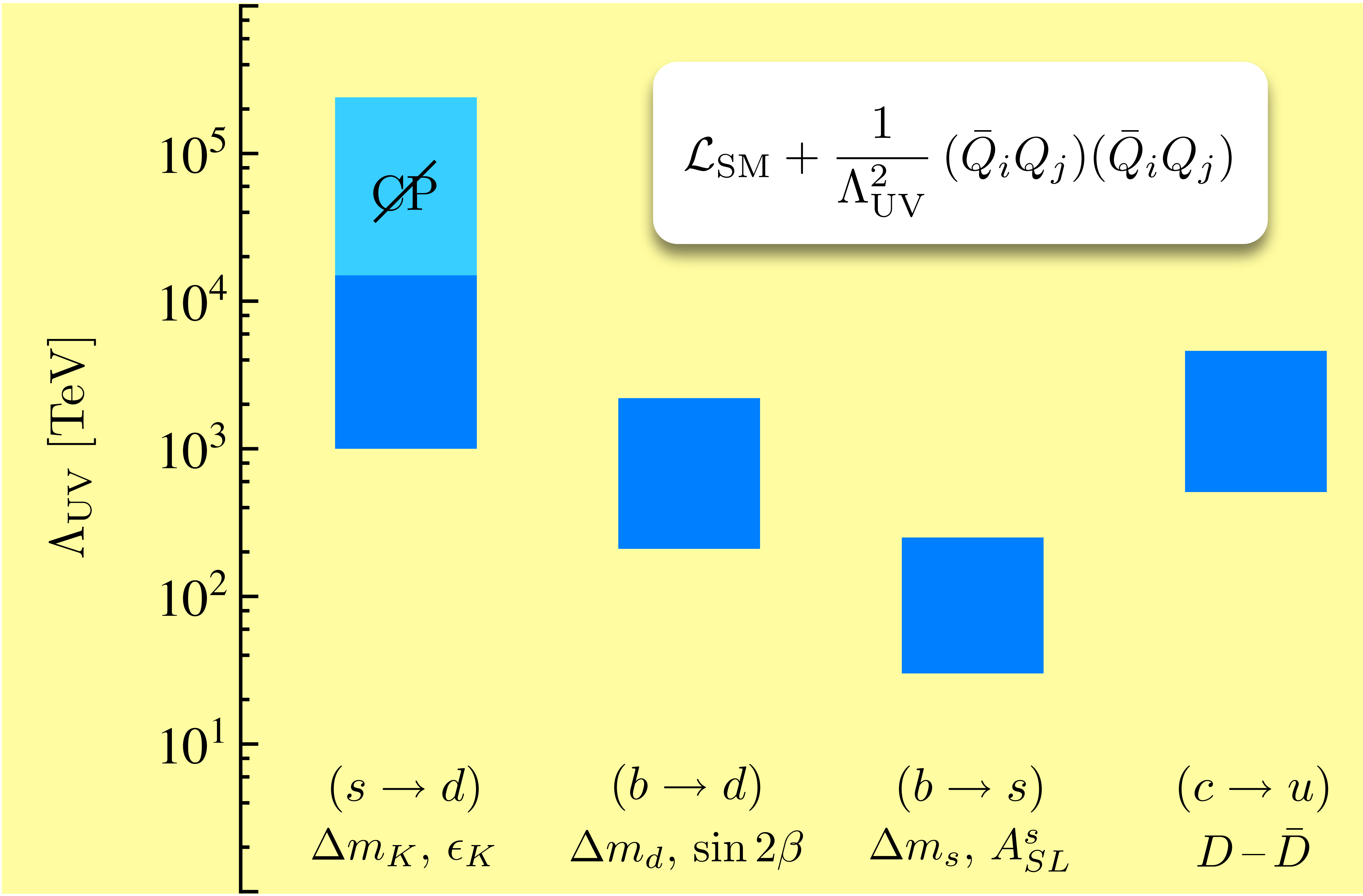
$\Lambda_{\mathrm{Higgs}} \lesssim 1\ \mathrm{TeV}$ $\qquad$ $\Lambda_{\mathrm{flavor}} \gtrsim 10^3\ \mathrm{TeV}$

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

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

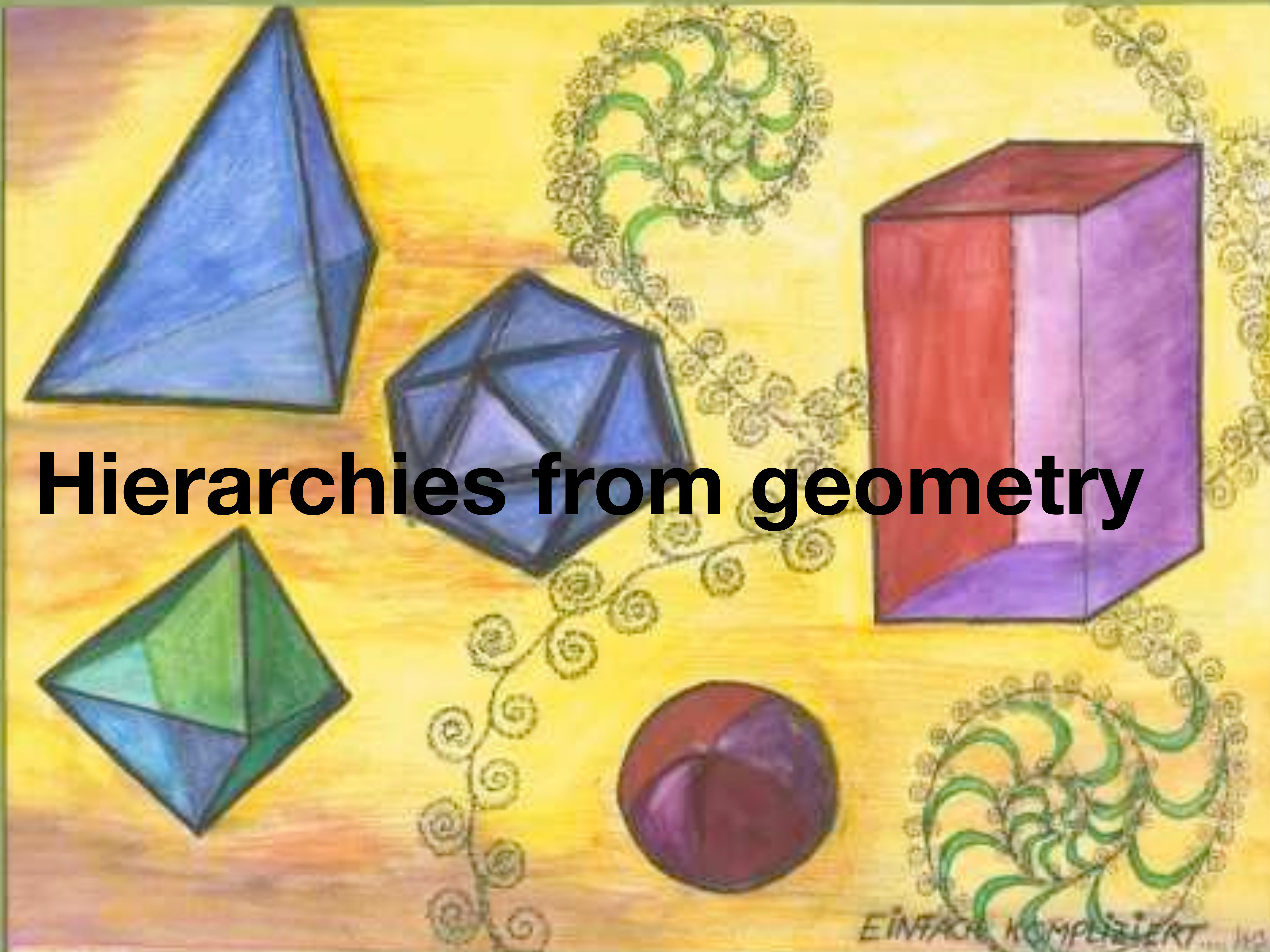
(ii) $\Lambda_{\mathrm{UV}} \approx 1\ \mathrm{TeV}$: quark flavor-mixing protected by a **flavor symmetry**

Flavor Structure in the SM and Beyond



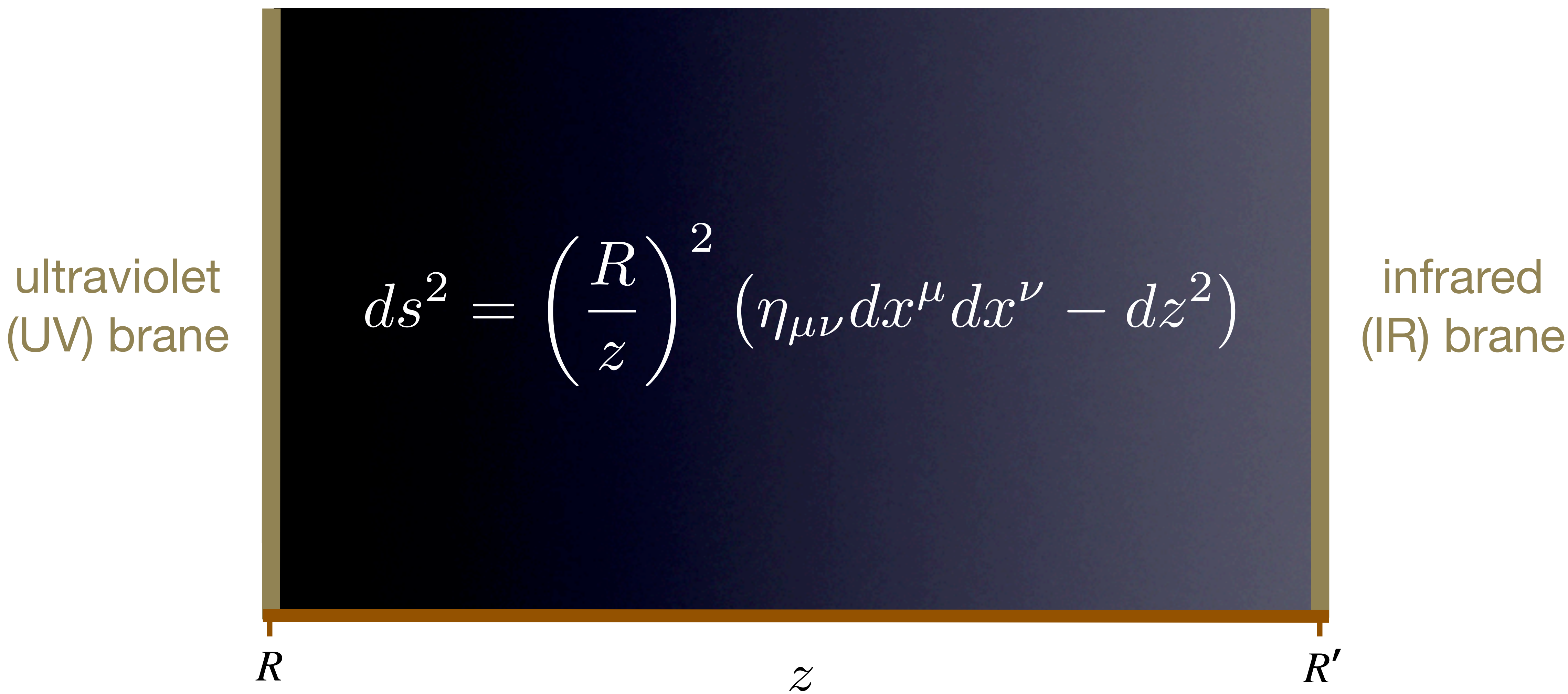
Generic bounds without flavor symmetry

Hierarchies from geometry



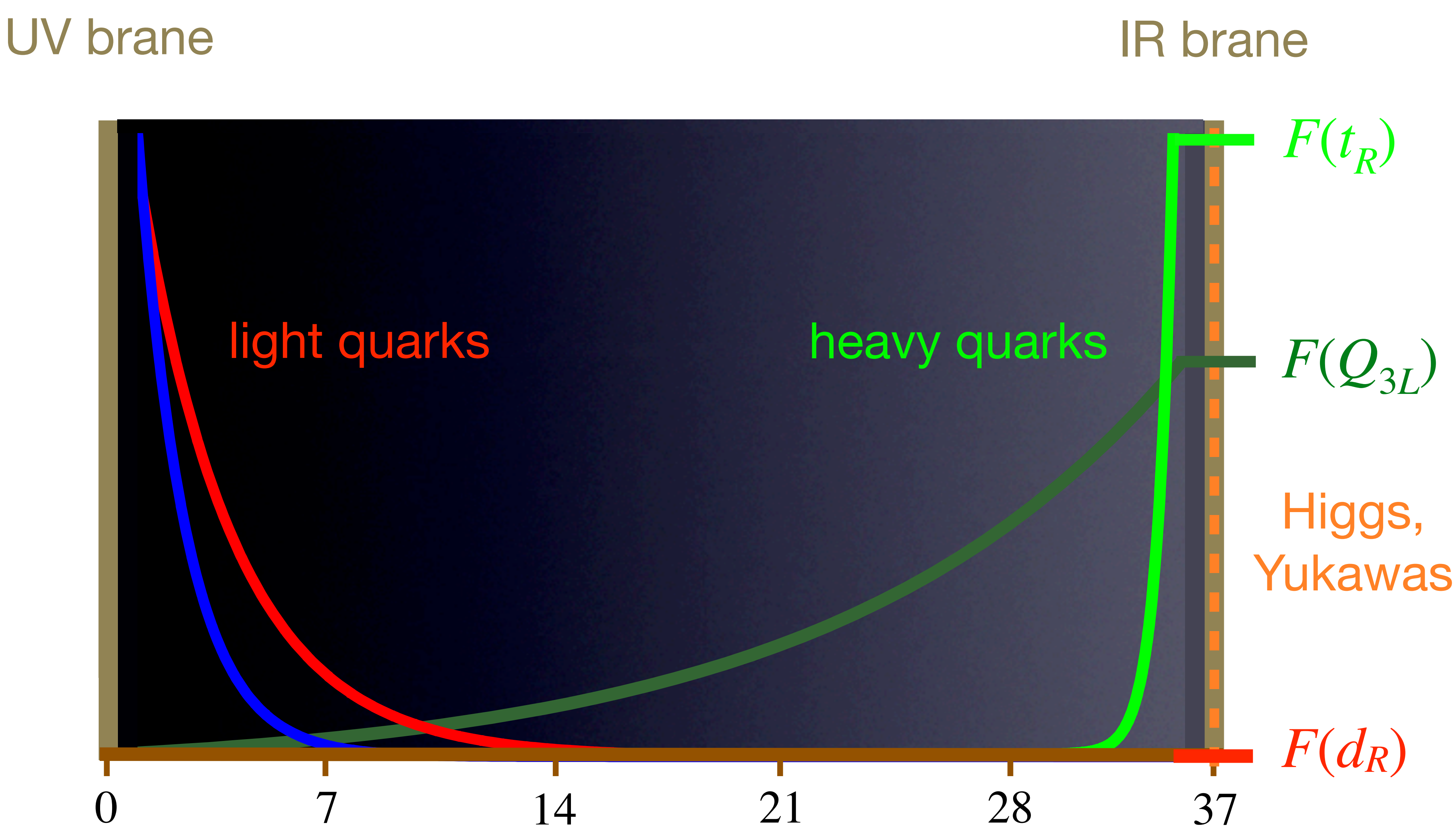
Embedding the SM in a warped extra dimension

Randall, Sundrum (1999)



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

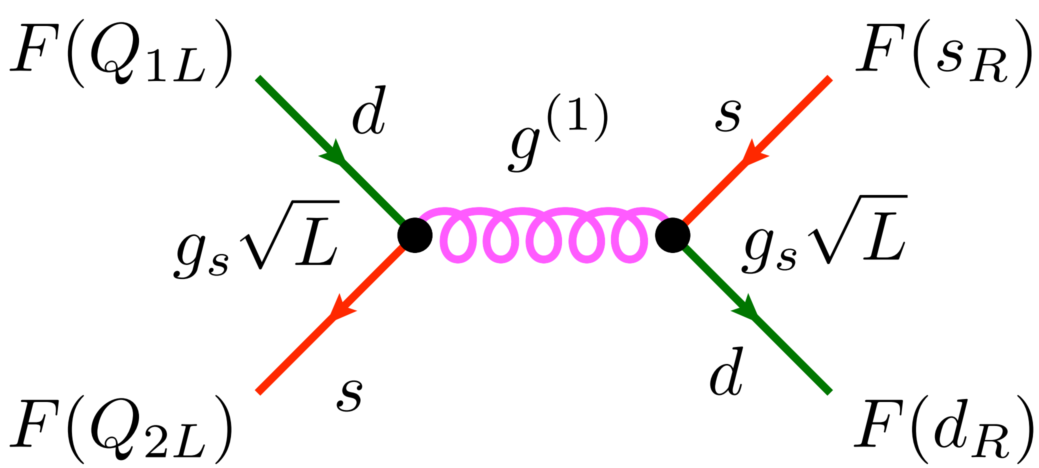
Flavor structure in RS models



Localization of fermions in extra dimension depends exponentially on **O(1) parameters** related to the five-dimensional **bulk masses.** Overlaps $F(Q_L)$, $F(q_R)$ with IR-localized Higgs sector and Yukawa couplings are **exponentially small** for light quarks, while O(1) for top quark

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

RS-GIM protection of FCNCs

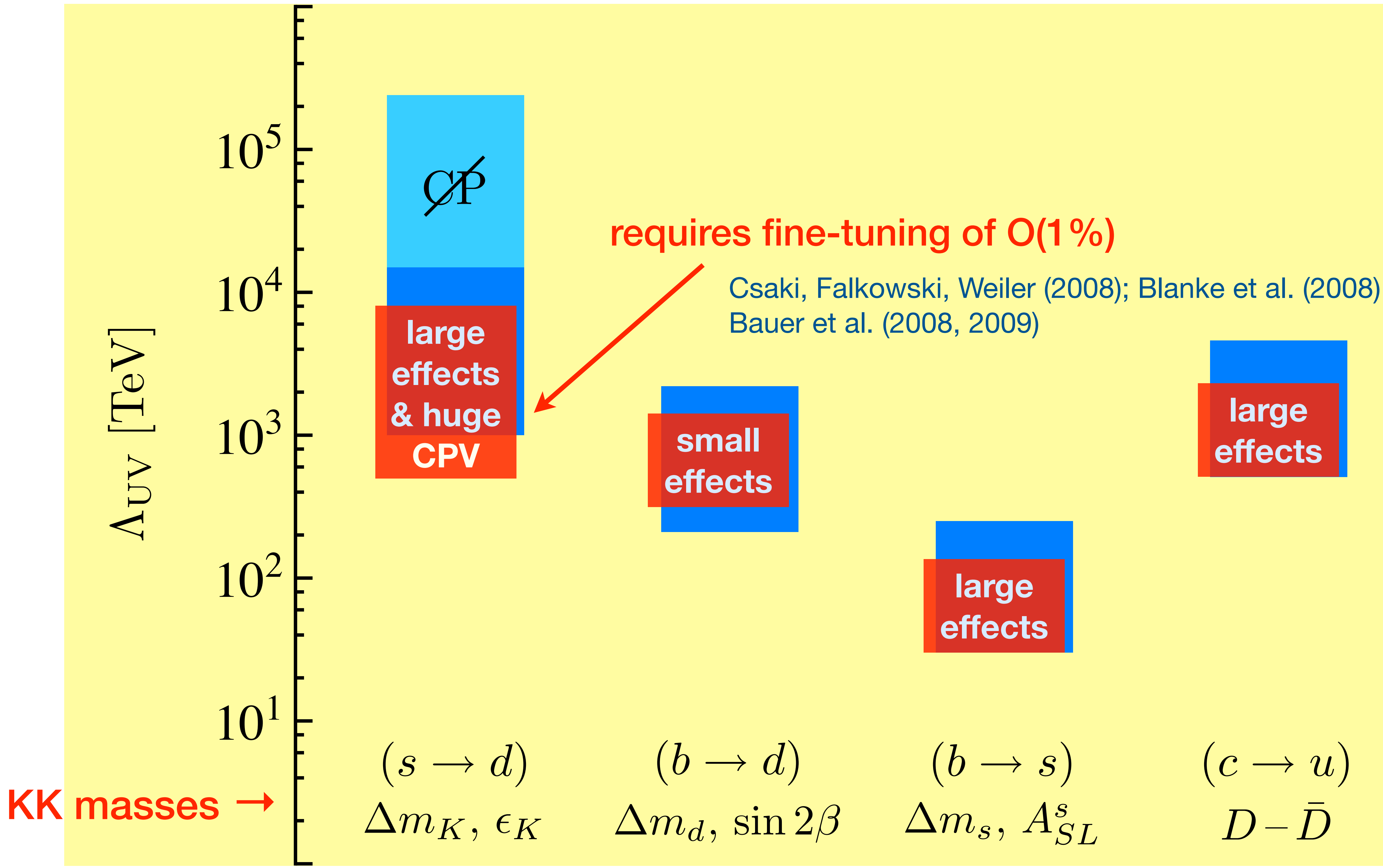


$$\sim \frac{g_s^2}{M_{\mathrm{KK}}^2}\, L\, F(Q_{1L})F(d_R)\, F(Q_{2L})F(s_R)$$

- Quark FCNCs are induced at tree-level through virtual exchange of KK gauge bosons (including KK gluons!) Huber (2003); Burdman (2003); Agashe et al. (2004); Casagrande et al. (2008)
- Resulting FCNC couplings depend on same exponentially small overlaps $F(Q_L)$, $F(q_R)$ that generate fermion masses
- FCNCs involving quarks other than top are strongly suppressed (true for all induced FCNC couplings) Agashe et al. (2004)

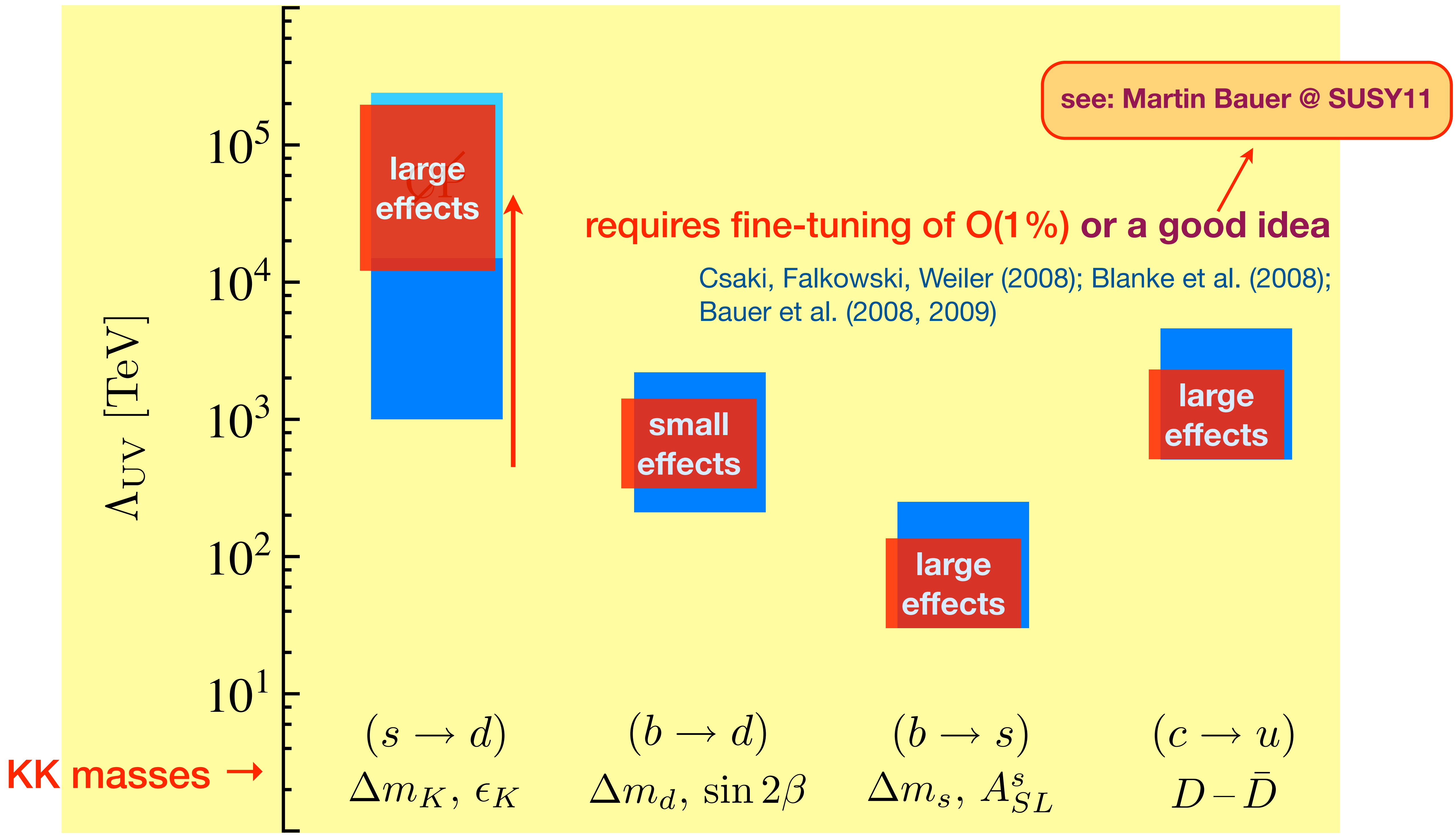
This mechanism suffices to suppress all but one of the dangerous FCNC couplings!

RS-GIM protection of FCNCs



RS-GIM protection with KK masses of order few TeV

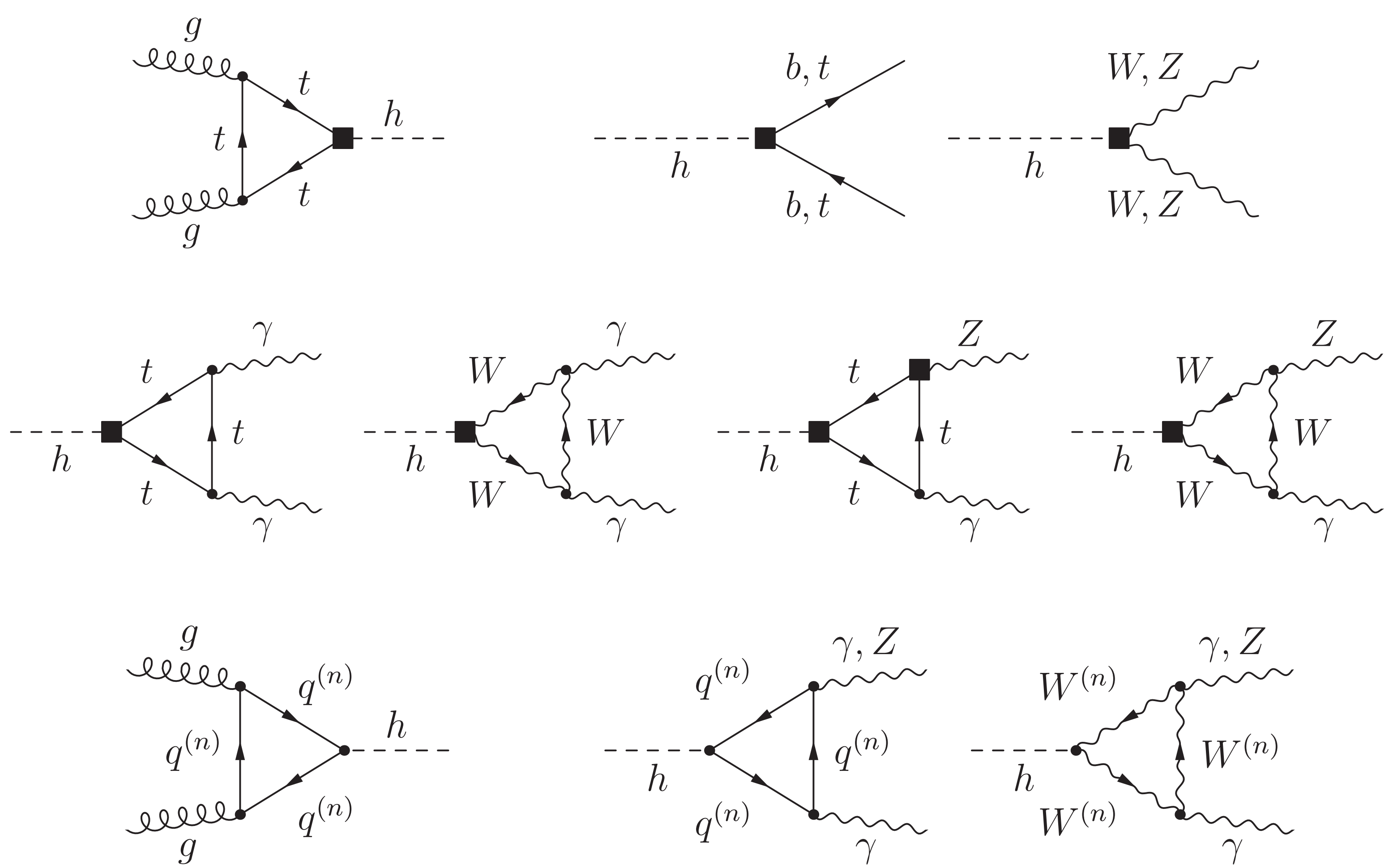
RS-GIM protection of FCNCs



RS-GIM protection with KK masses of order few TeV

Correlations with Higgs physics

- Properties of the Higgs boson offer alternative ways to **indirectly probe**, via **modifications of SM couplings** and **virtual effects from heavy KK states,** the structure of warped extra-dimension models
- Recently, we have performed the first complete one-loop analysis of Higgs production and decays in the RS model with custodial symmetry



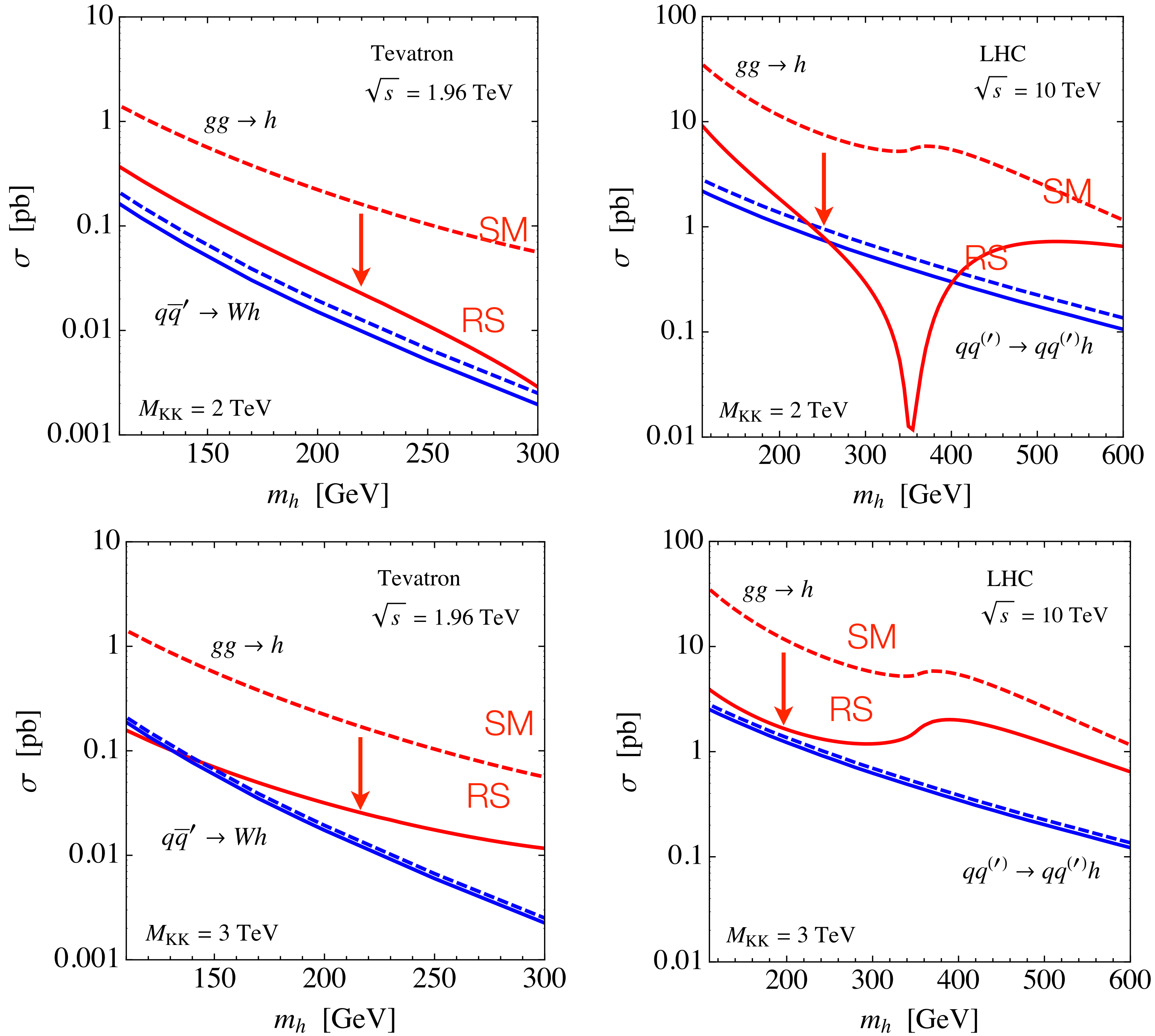
Casagrande, Goertz, Haisch, MN, Pfoh (2010)

Higgs production cross sections

Find possibly **spectacular effects** on Higgs production via gluon fusion, even for KK masses out of production reach at the LHC ($m_{G^{(1)}_{\mathrm{KK}}} \approx 2.45 M_{\mathrm{KK}}$):

M_{KK}=2 TeV:

M_{KK}=3 TeV:



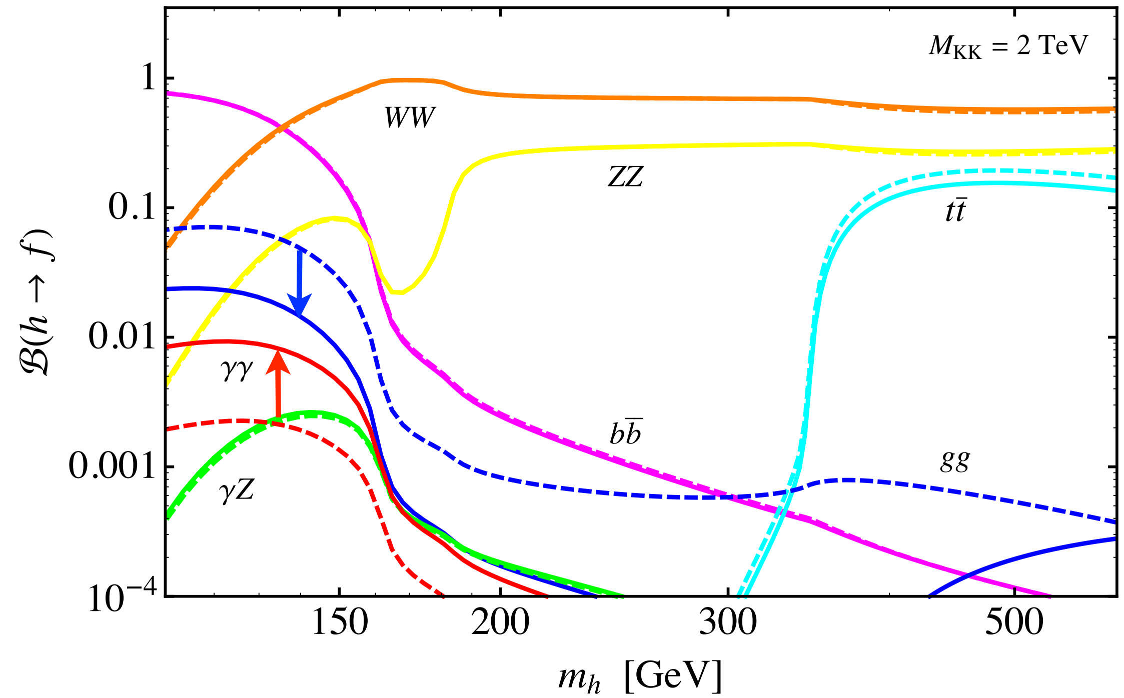
SM
RS

Casagrande, Goertz, Haisch, MN, Pfoh (2010)

Higgs decay branching fractions

Correspondingly, find possibly significant impact on $h \to gg$ and $h \to \gamma\gamma$ branching ratios:

M$_{KK}$=2 TeV:

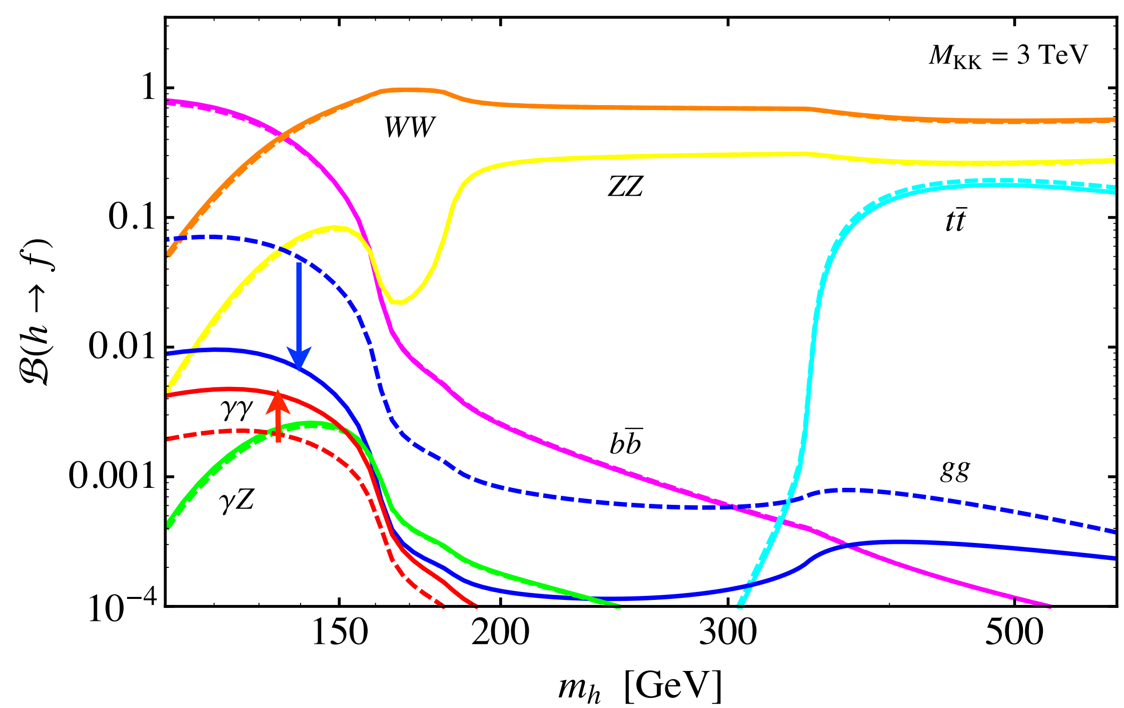


SM

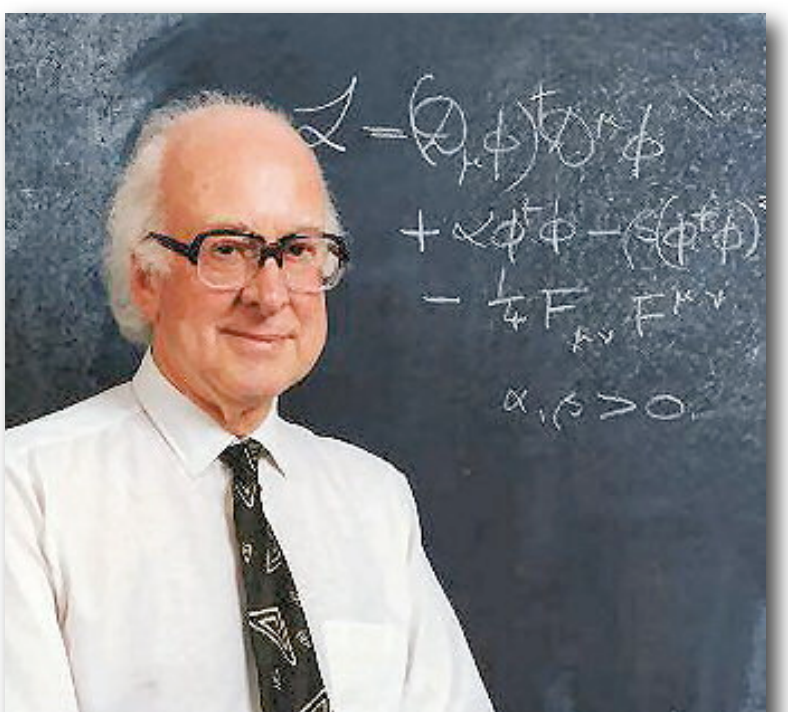
RS

Casagrande, Goertz, Haisch, MN, Pfoh (2010)

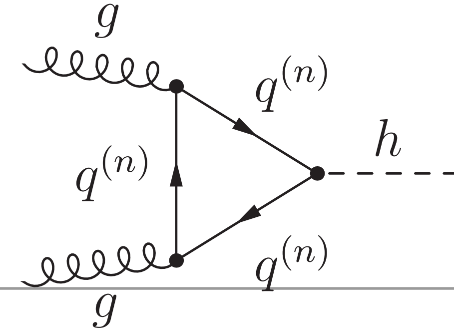
M$_{KK}$=3 TeV:



The RS Higgs Puzzle



RS Higgs puzzle



Two independent calculations of Higgs production and decay in the RS model (with custodial symmetry) predict **opposite effects**

Casagrande, Goertz, Haisch, MN, Pfoh (arXiv:1005.4315):

- sum over first few KK modes numerically, then extrapolate to $N_{max} \to \infty$ (convergent sum)
- all-order treatment in v/M_{KK}
- find **suppression** of $gg \to h$ and $h \to gg$, but **enhancement** of $h \to \gamma\gamma$

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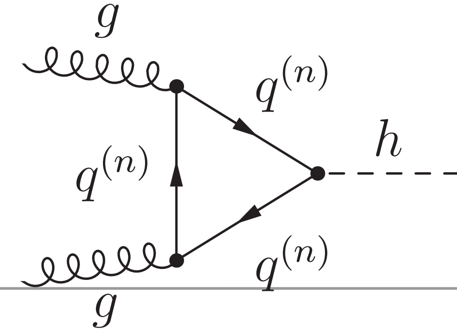
In both calculations, the $hq\bar{q}$ couplings are derived by **regularizing the Higgs profile** by smearing it out over an **interval of width η**, e.g.:

$$\boxed{\delta(1-t) \to \delta_\eta(1-t) = \frac{1}{\eta}\,\theta(1-\eta < t < 1)} \quad (\eta \to 0^+)$$

RS Higgs puzzle



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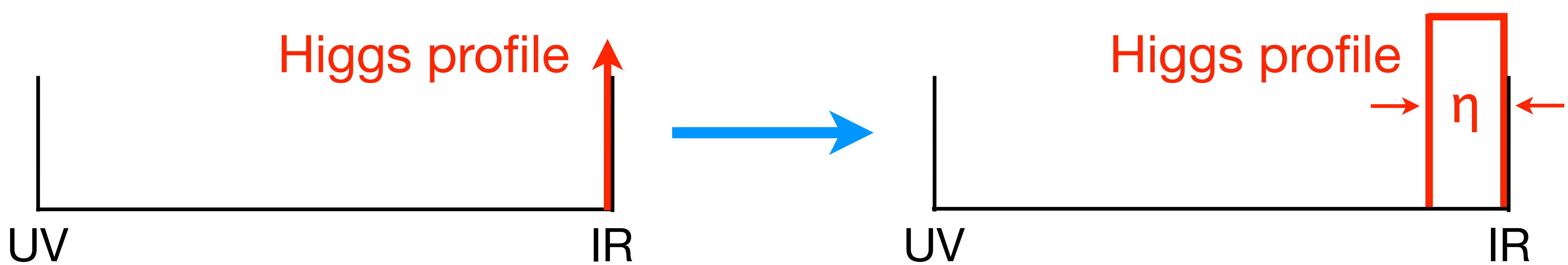

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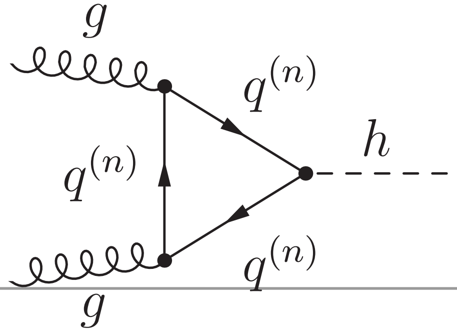
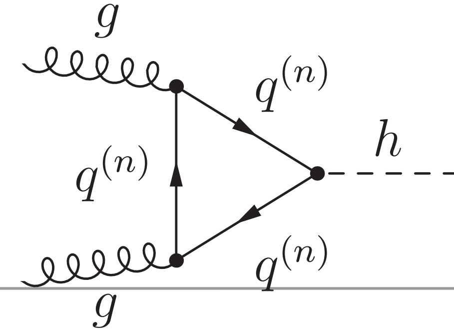


How can these results be reconciled?

⇒ work in progress with M. Carena, S. Casagrande, U. Haisch

RS Higgs puzzle



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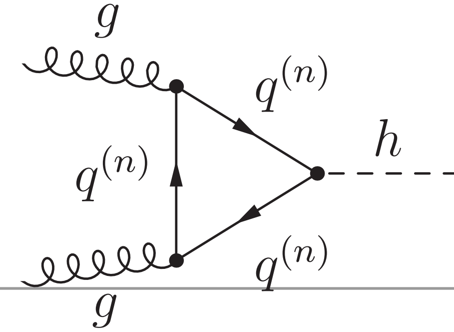
- Find that both calculations are correct!
- Difference from **noncommutativity** of limits $\mathbf{N_{max} \to \infty}$ and $\boldsymbol{\eta \to 0}$
- Consider the contribution ν_q of the KK tower of 3 generations of heavy quarks (light modes would need to be subtracted → trivial modification), in units where the top contribution equals 1:

$$\boxed{\nu_q = v \sum_n \frac{\mathrm{Re}(g_h^q)_{nn}}{m_n^q}}$$

$$\lim_{N_{\max}\to\infty} v \sum_{n=1}^{N_{\max}} \frac{\mathrm{Re}(g_h^q)_{nn}\big|_{\eta\to 0}}{m_n^q} \qquad\qquad \lim_{\eta\to 0} v \sum_{n=1}^{\infty} \frac{\mathrm{Re}(g_h^q)_{nn}\big|_{\eta}}{m_n^q}$$

RS Higgs puzzle



- Consider the contribution ν_q of the KK tower of 3 generations of heavy q-type quarks (light modes need to be subtracted → trivial modification), in units where the top contribution equals 1:

$$\boxed{\nu_q = v \sum_n \frac{\mathrm{Re}(g_h^q)_{nn}}{m_n^q}}$$

$$X^2 = \frac{v^2}{2M_{\mathrm{KK}}^2} Y_q Y_q^\dagger$$

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$$\lim_{N_{\max}\to\infty} v \sum_{n=1}^{N_{\max}} \frac{\mathrm{Re}(g_h^q)_{nn}\big|_{\eta\to 0}}{m_n^q} = \mathrm{Tr}\left[1 - \frac{5X^2}{3} + \frac{119X^4}{45} \mp \dots\right]$$

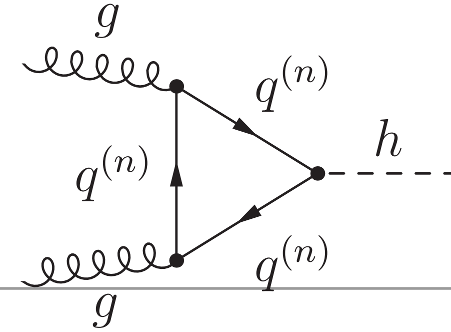
suppression

$$\lim_{\eta\to 0} v \sum_{n=1}^{\infty} \frac{\mathrm{Re}(g_h^q)_{nn}\big|_{\eta}}{m_n^q} = \mathrm{Tr}\left[1 + \frac{X^2}{3} - \frac{X^4}{45} \pm \dots\right]$$

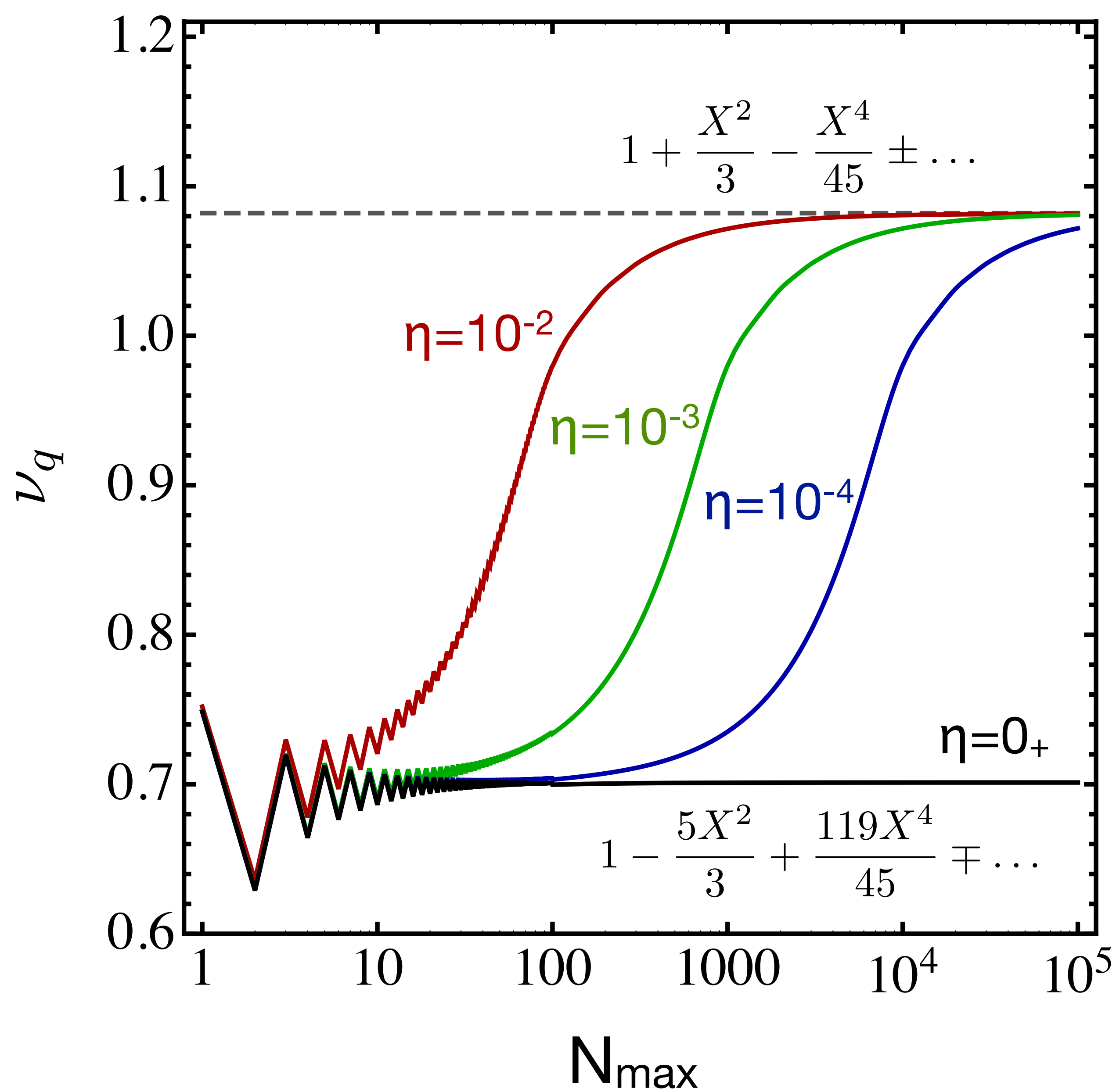
enhancement

Difference is due to **very heavy KK modes**, with masses $\mathbf{m_n \sim M_{KK}/\eta}$!

RS Higgs puzzle



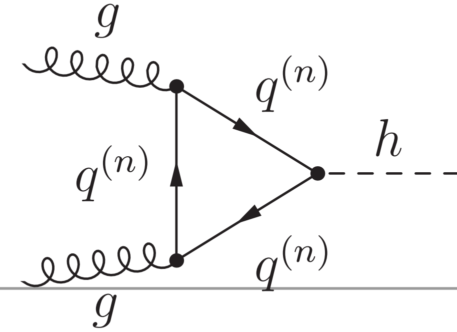
Consider numerical results for the partial sum of the first N_{max} KK modes for the case of 1 generation, for different values of η:



Observations:

- difference arises from very heavy KK modes with masses in the range between 0.1 M_{KK}/η and 10 M_{KK}/η
- the smaller the regulator η, the heavier are these masses (far above TeV scale)
- for smaller masses the sum converges to the result of Casagrande et al.
- **How is this possible, given that KK sum is convergent?**
- **Violation of decoupling?**

RS Higgs puzzle

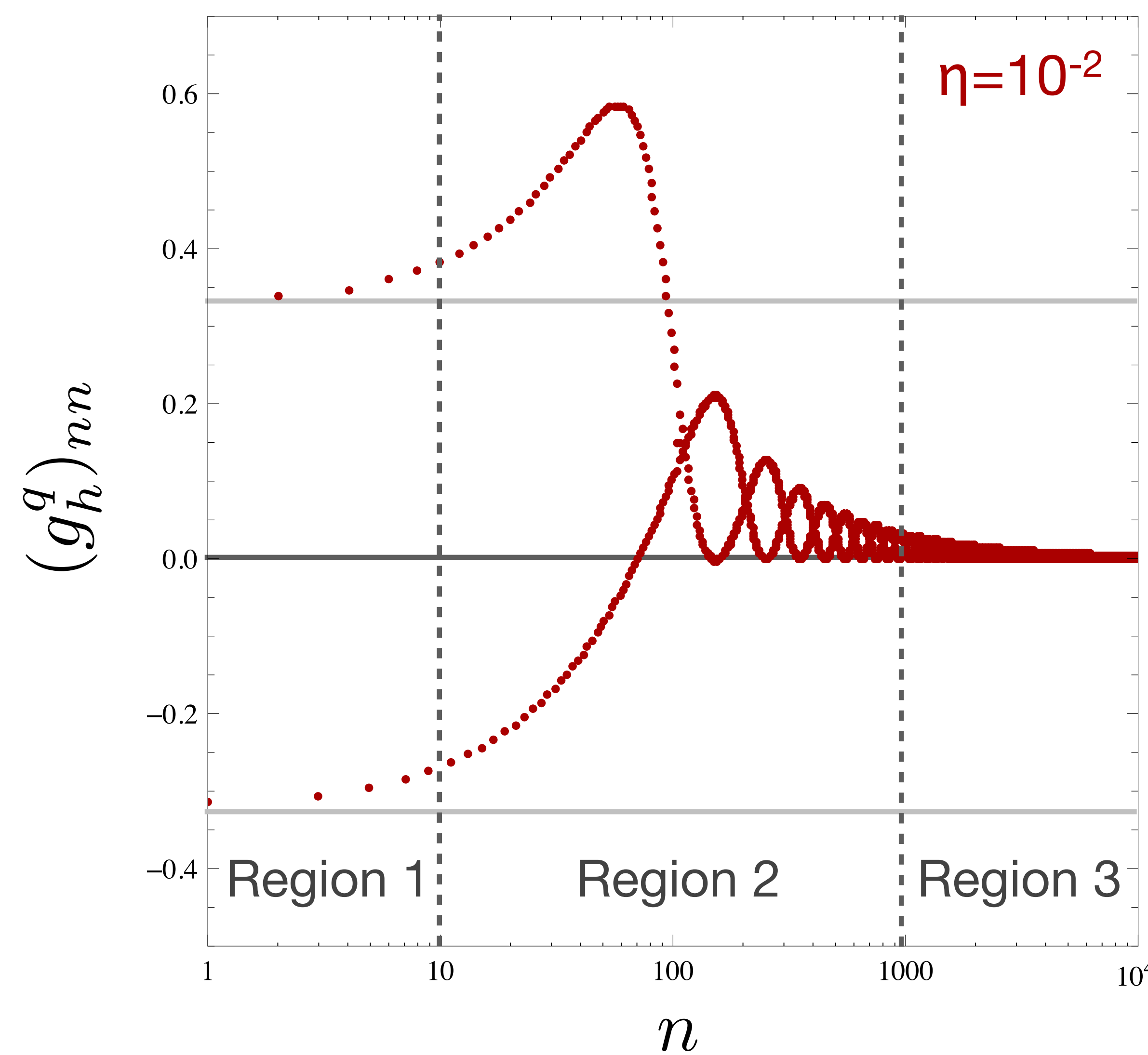


Note that KK sum

$$\nu_q = v \sum_n \frac{\mathrm{Re}(g_h^q)_{nn}}{m_n^q}\,, \text{ with } \quad m_n^q \sim n M_{\mathrm{KK}}\,, \quad (g_h^q)_{nn} = O(1)$$

is **logarithmically divergent** by naive power counting, but it converges since couplings $(g_h^q)_{nn}$ have **alternating sign** as long as $m_n^q \ll M_{KK}/\eta$ (region 1)

For $0.1\ M_{KK}/\eta < m_n^q < 10\ M_{KK}/\eta$ (region 2) this behavior changes, giving rise to an intermediate region with **logarithmic evolution**



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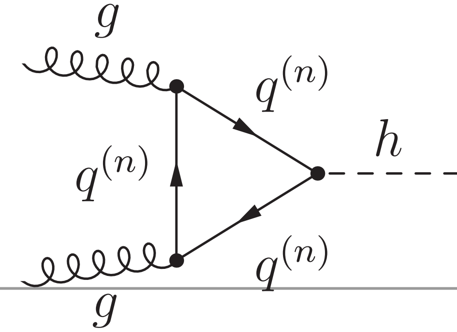

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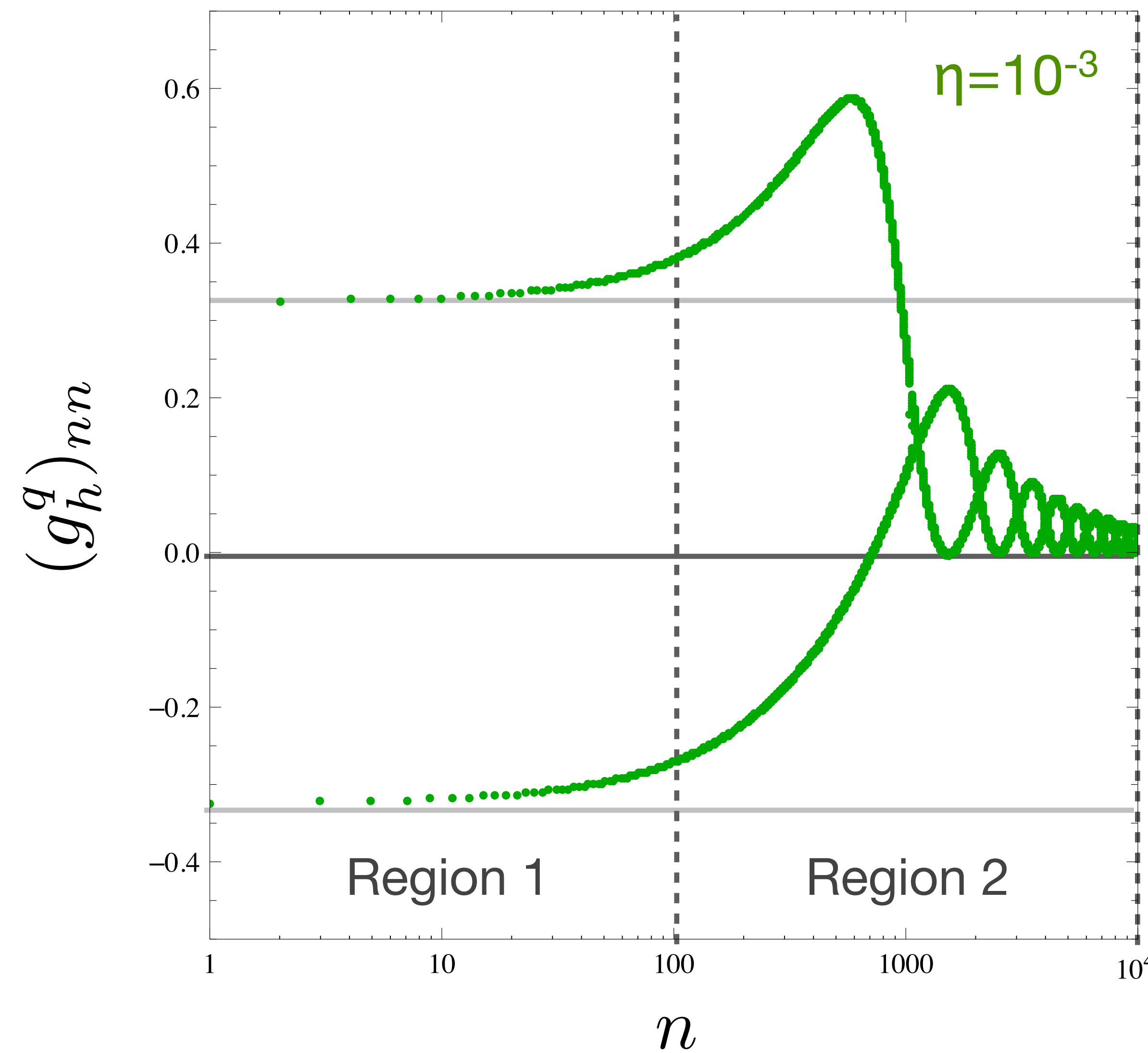

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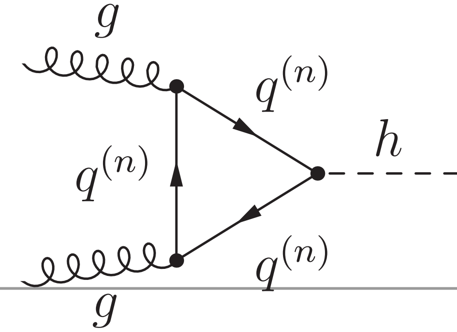

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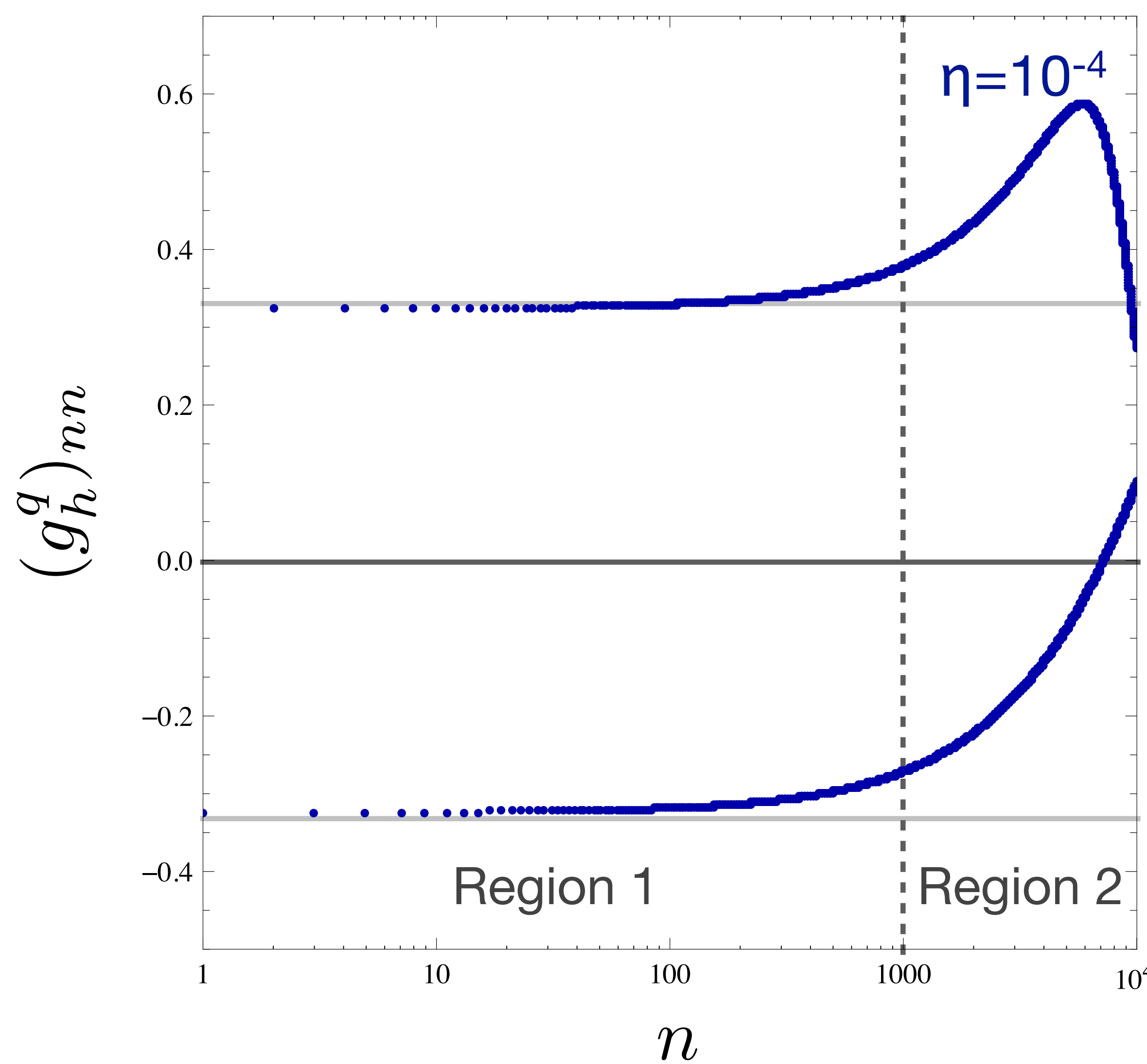

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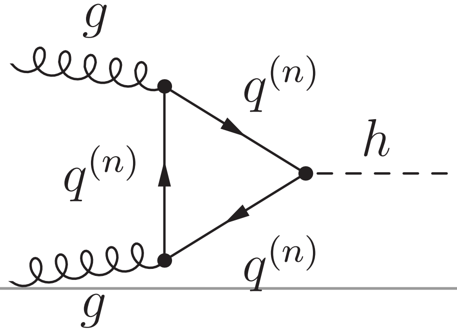

What to conclude from all this?

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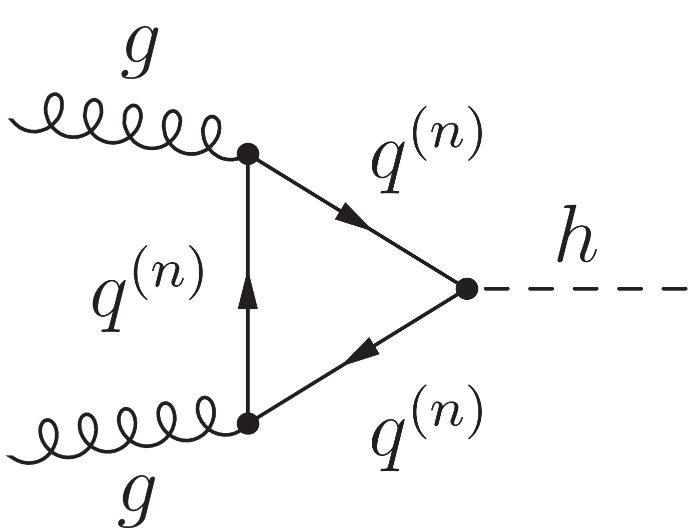
RS Higgs puzzle

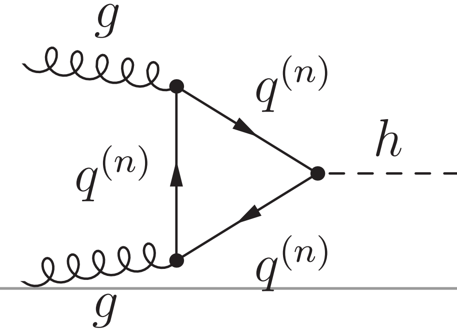
What to conclude from all this?

- Remember that RS model is an effective theory defined with a **physical, 5D position-dependent cutoff**, the warped Planck scale
- For loop graphs including a Higgs boson as an external particle, the warped Planck scale is the **few TeV scale**



- Hence, KK modes with masses M_{KK}/η (with η<<1) lie far above the cutoff and must be omitted from the effective theory for consistency
- Their contribution would correspond to a logarithmic evolution of the effective hgg coupling arising at **trans-Planckian** energy scales

RS Higgs puzzle



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Correct result in the physical RS model defined with a cutoff (UV completion must contain quantum gravity)

Correct result in an RS model that is treated as a "theory of everything", valid at arbitrarily short distance scales

Conclusions

Randall-Sundrum models provide an appealing framework for addressing the gauge hierarchy problem and the flavor puzzle within the same geometrical approach

These models intimately link the physics of electroweak symmetry breaking with flavor physics

Besides the obvious goal of producing Kaluza-Klein excitations of SM particles at the LHC, RS models can be tested by probing virtual effects of KK particles in flavor and Higgs physics

These observables provide sensitivity to KK scales far above the direct LHC reach