Higgs Physics in a Warped Extra Dimension

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

Planck 2012
Warsaw, Poland, 31 May 2012

based on: F. Goertz, U. Haisch, MN (1112.5099)
M. Carena, S. Casagrande, F. Goertz, U. Haisch, MN (1204.0008)

Higgs and flavor physics as indirect BSM probes

The **hierarchy problem** (mechanism of EWSB) and the **origin of flavor** are two big, unsolved mysteries of fundamental physics

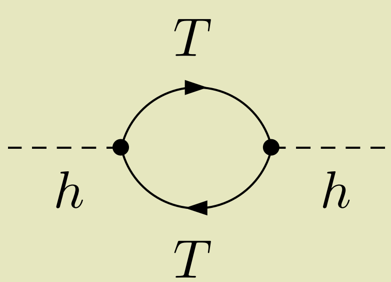
- connected to deep questions such as the **origin of mass** of elementary particles, the **stability of the electroweak scale**, the **matter-antimatter asymmetry** in the Universe, the **origin of fermion generations**, and the reason for the **hierarchies** observed in the spectrum of fermion masses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

Higgs and flavor physics provide unique opportunities to probe the **structure of electroweak interactions at the quantum level**, thereby offering sensitive probes of physics beyond the SM

Higgs and flavor physics as indirect BSM probes

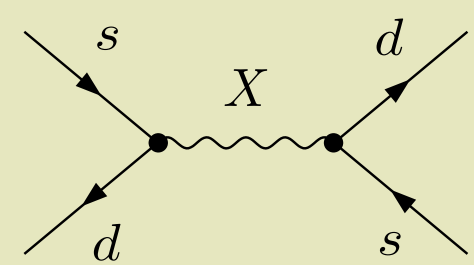
$$\mathcal{L}_{\rm EFT} = \Lambda^2_{\rm UV}\,\Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2 + \mathcal{L}^{\rm gauge}_{\rm SM} + \mathcal{L}^{\rm Yukawa}_{\rm SM} + \frac{\mathcal{L}^{(5)}}{\Lambda_{\rm UV}} + \frac{\mathcal{L}^{(6)}}{\Lambda^2_{\rm UV}} + \dots$$

electroweak symmetry breaking $\Downarrow$ Higgs mass



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

$\Downarrow$



$$\sim \frac{g_X^2}{\Lambda^2_{\rm UV}}$$

no fine-tuning $\Downarrow$

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

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

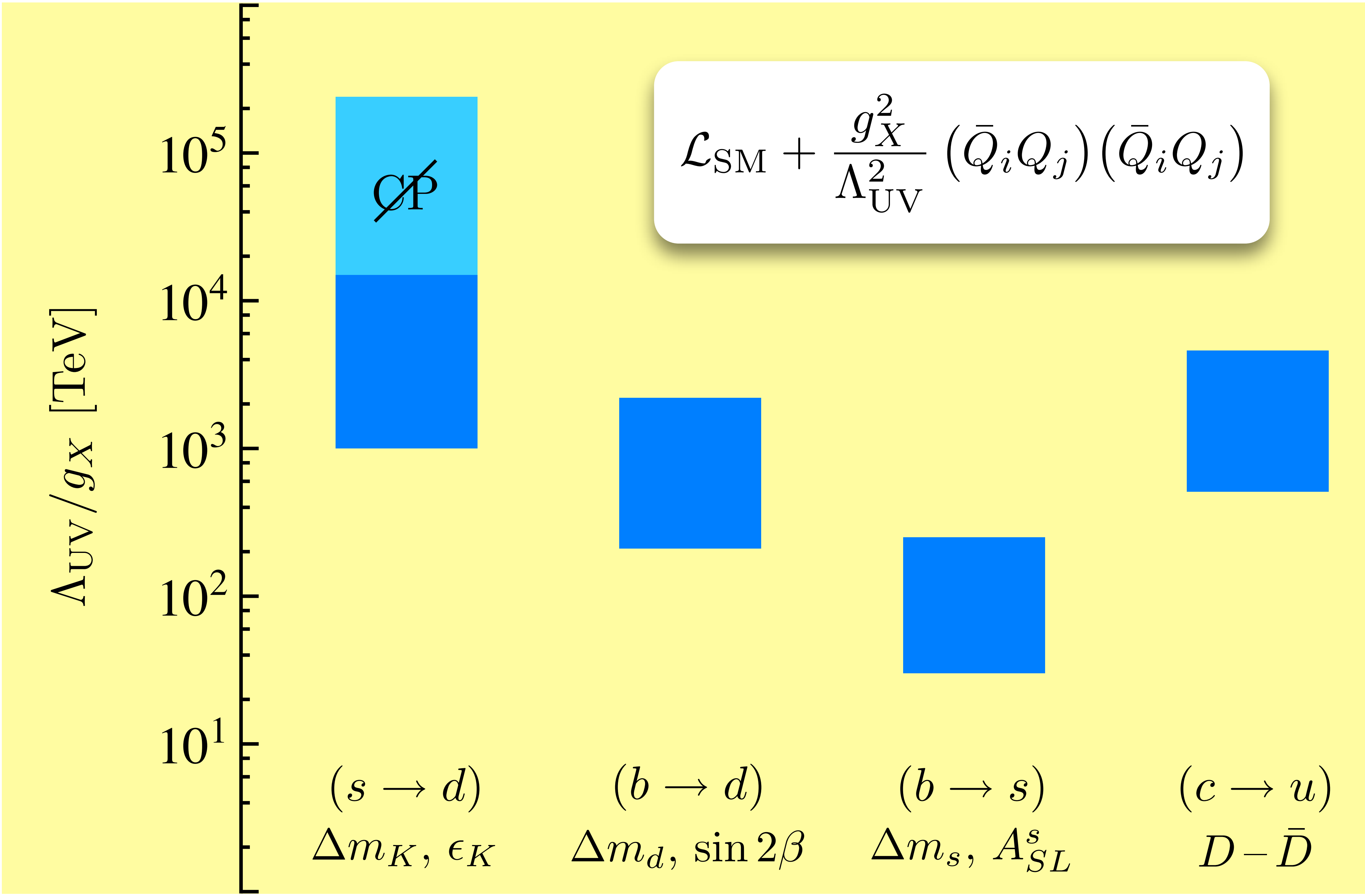
$\Lambda_{\rm flavor} \gtrsim 10^3$ TeV

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

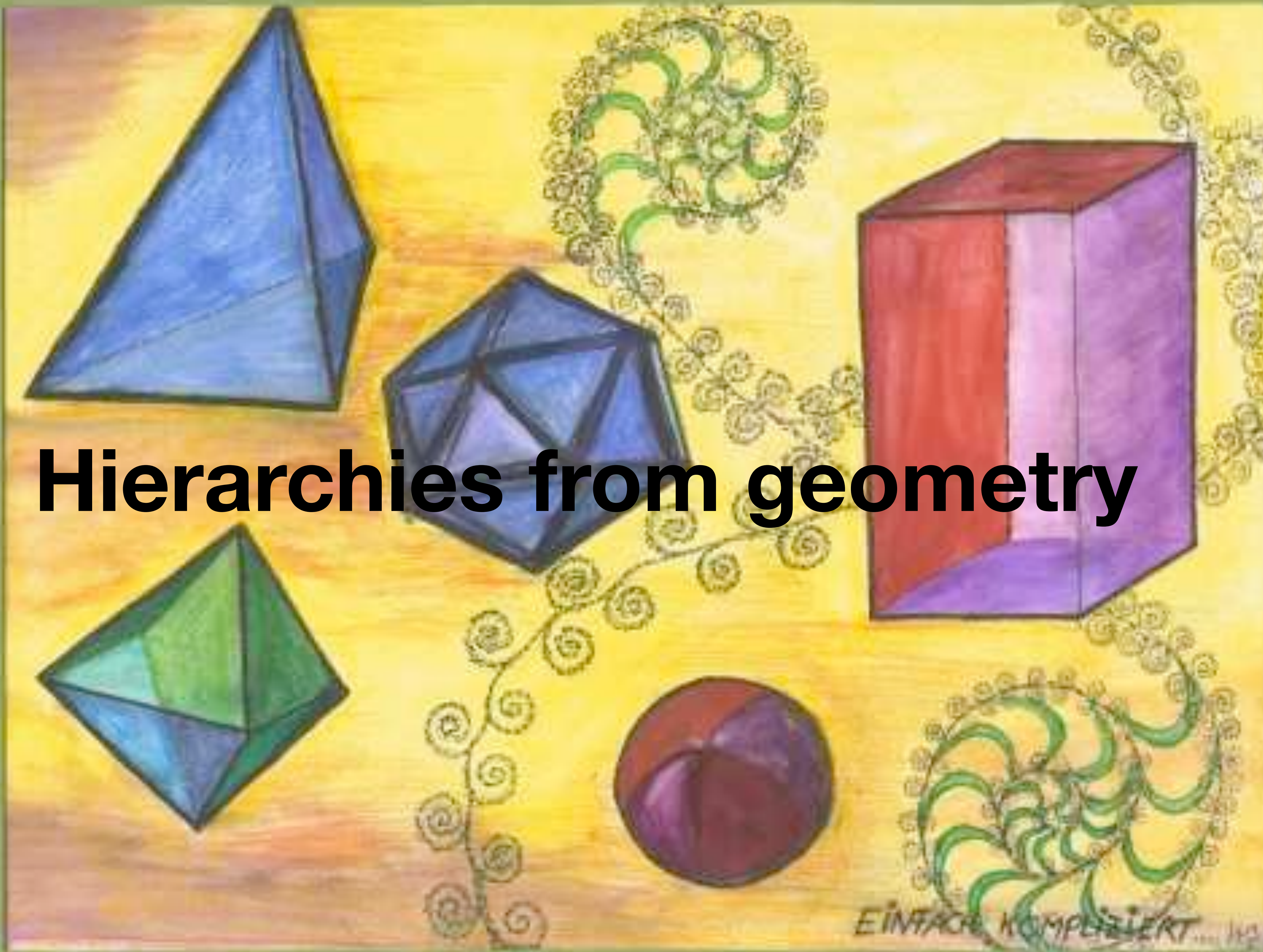
(ii) $\Lambda_{\rm UV} \approx 1$ TeV: quark flavor-mixing protected by a **flavor symmetry**

Higgs and flavor physics as indirect BSM probes

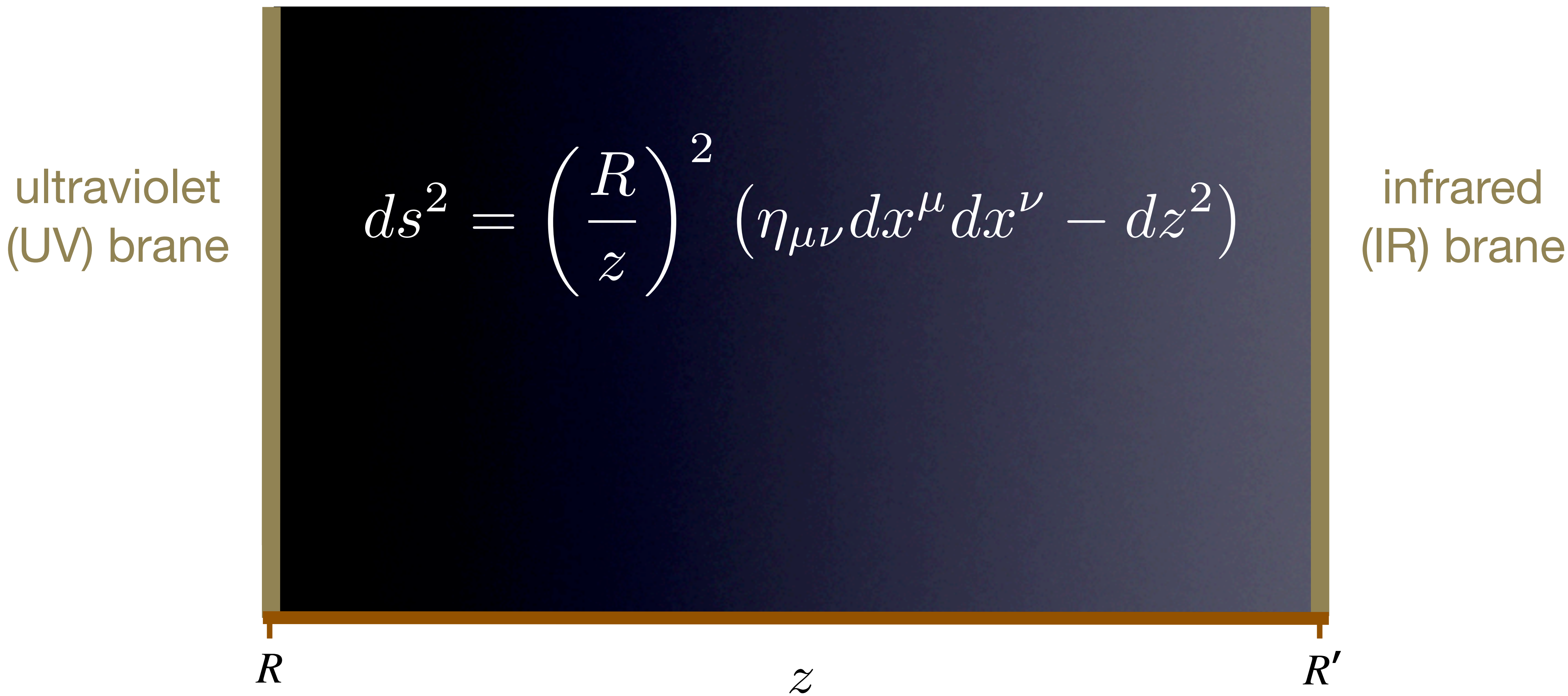


Generic bounds on New Physics scale (for g_X~1)

Hierarchies from geometry



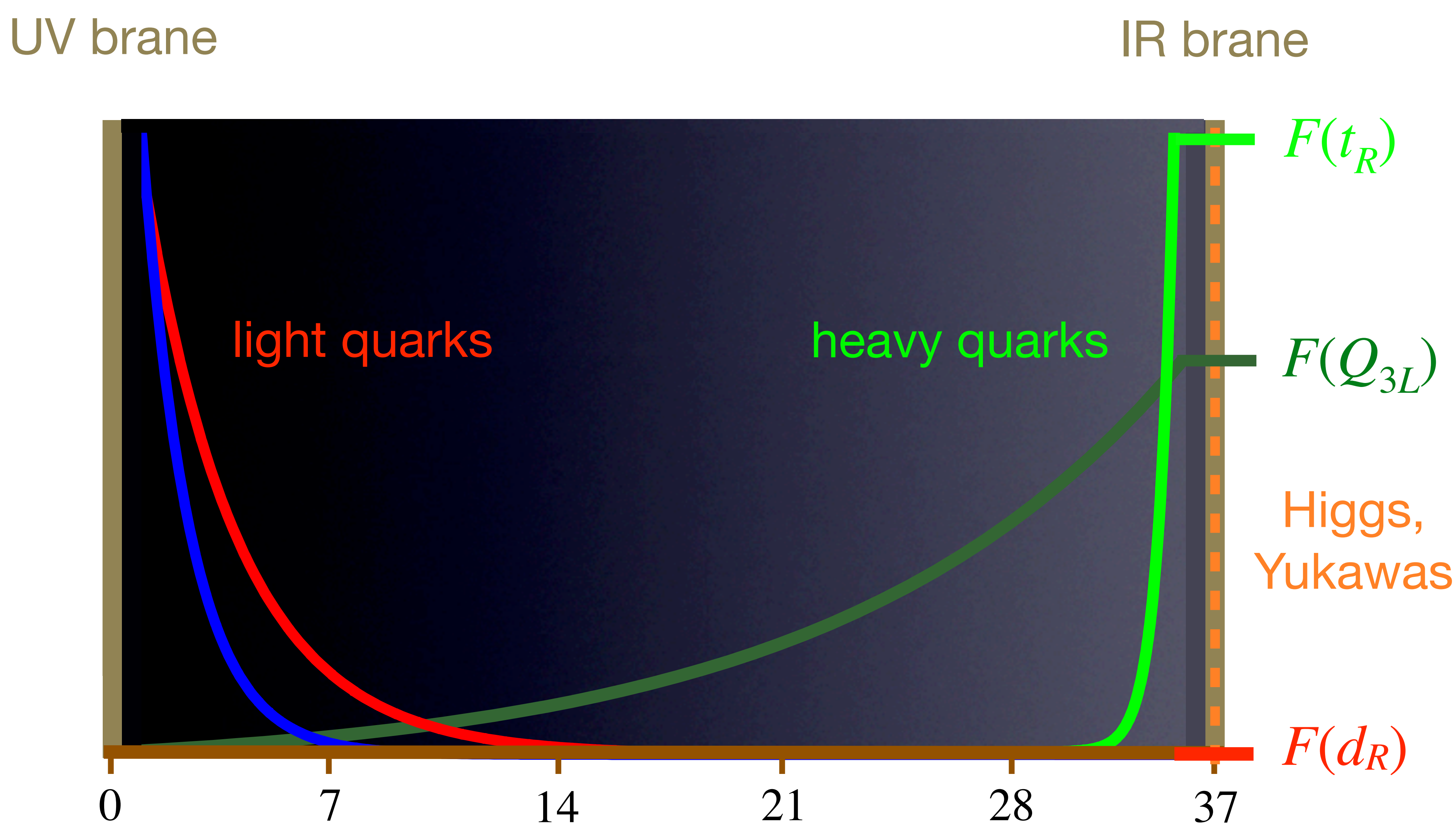
Flavor structure in RS models



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)

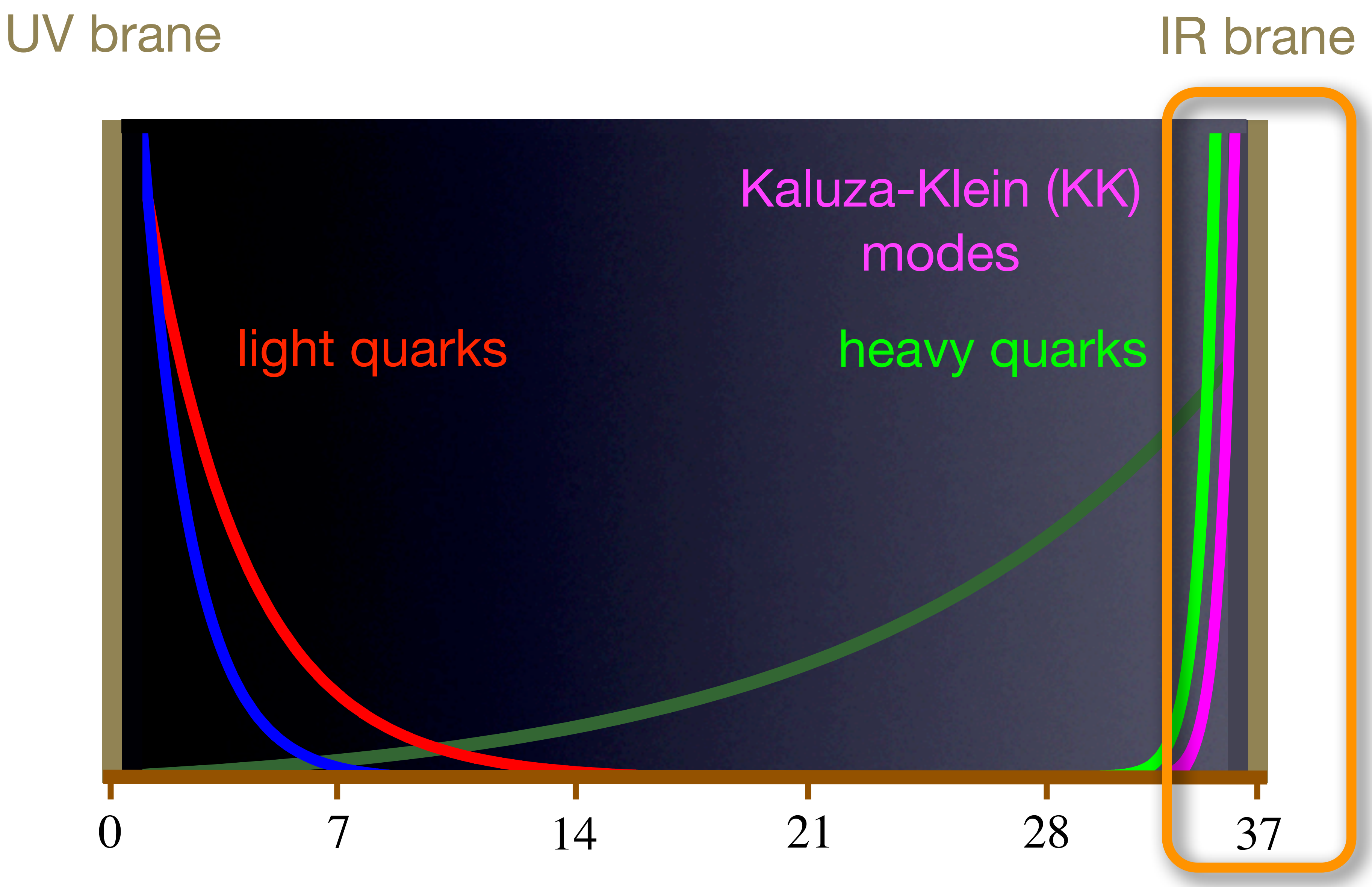
Flavor structure in RS models



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)

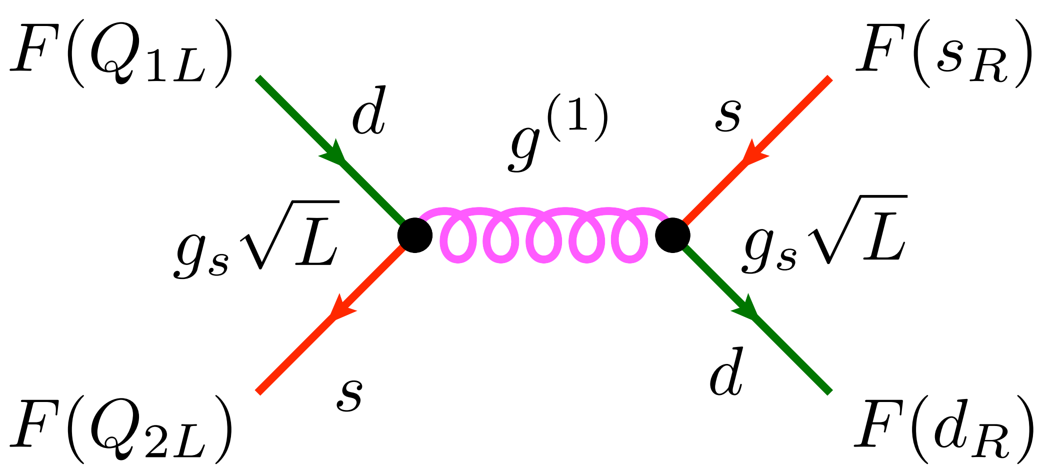
Flavor structure in RS models



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)

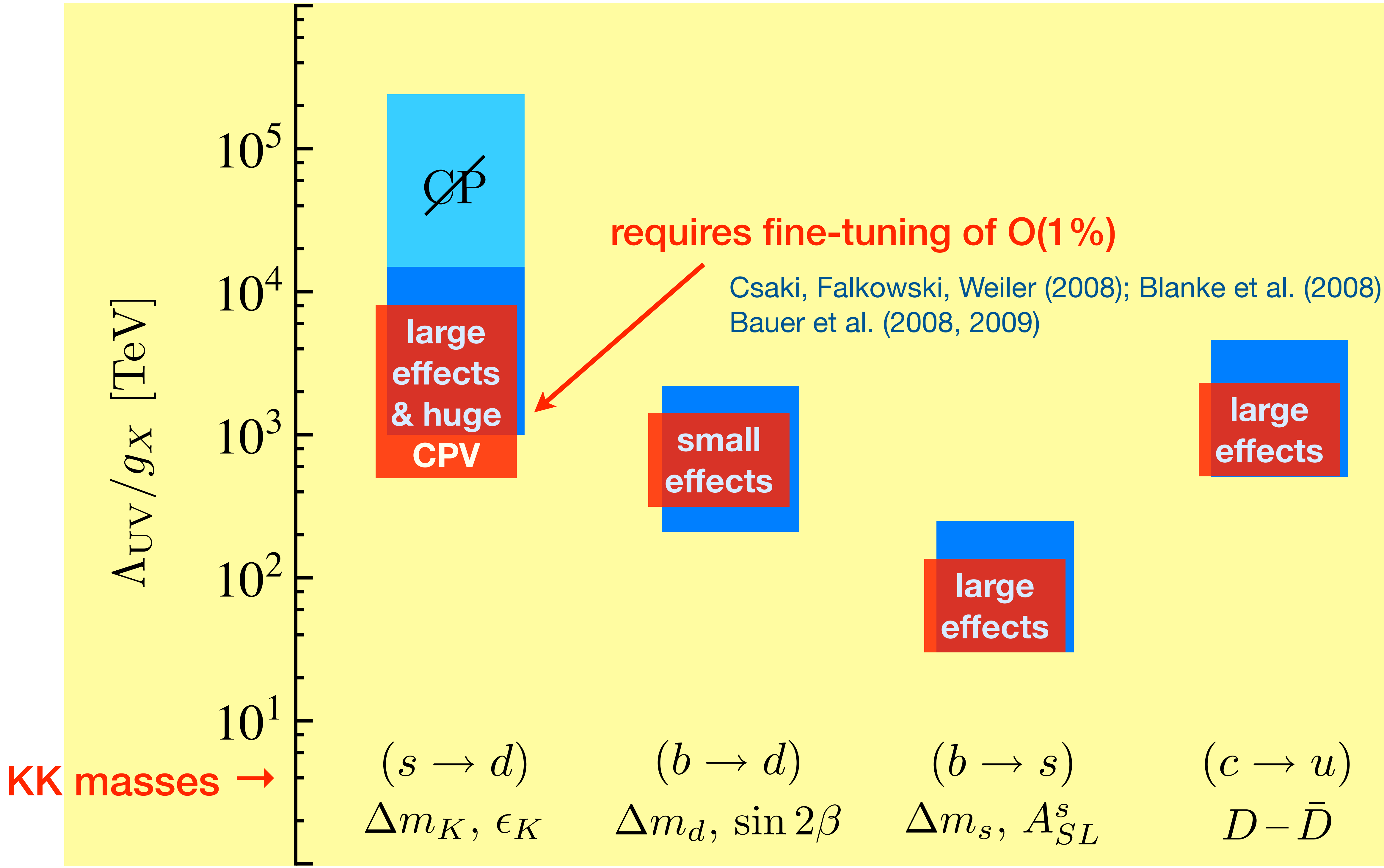
- Resulting FCNC couplings depend on same exponentially small overlap integrals $F(Q_L)$, $F(q_R)$ that generate fermion masses

- 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

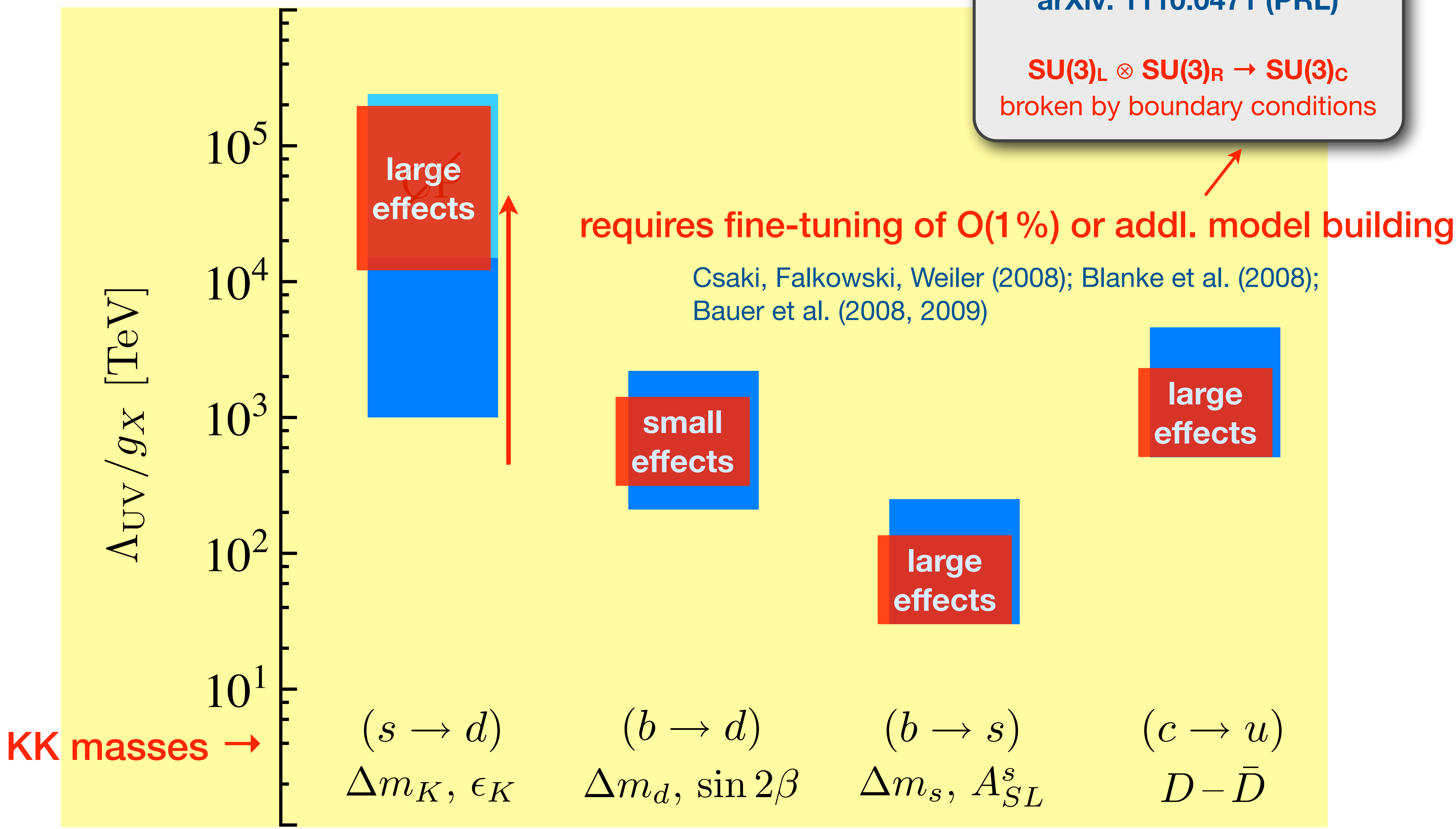


RS-GIM protection with KK masses of order few TeV

RS-GIM protection of FCNCs

M. Bauer, R. Malm, MN
arXiv: 1110.0471 (PRL)

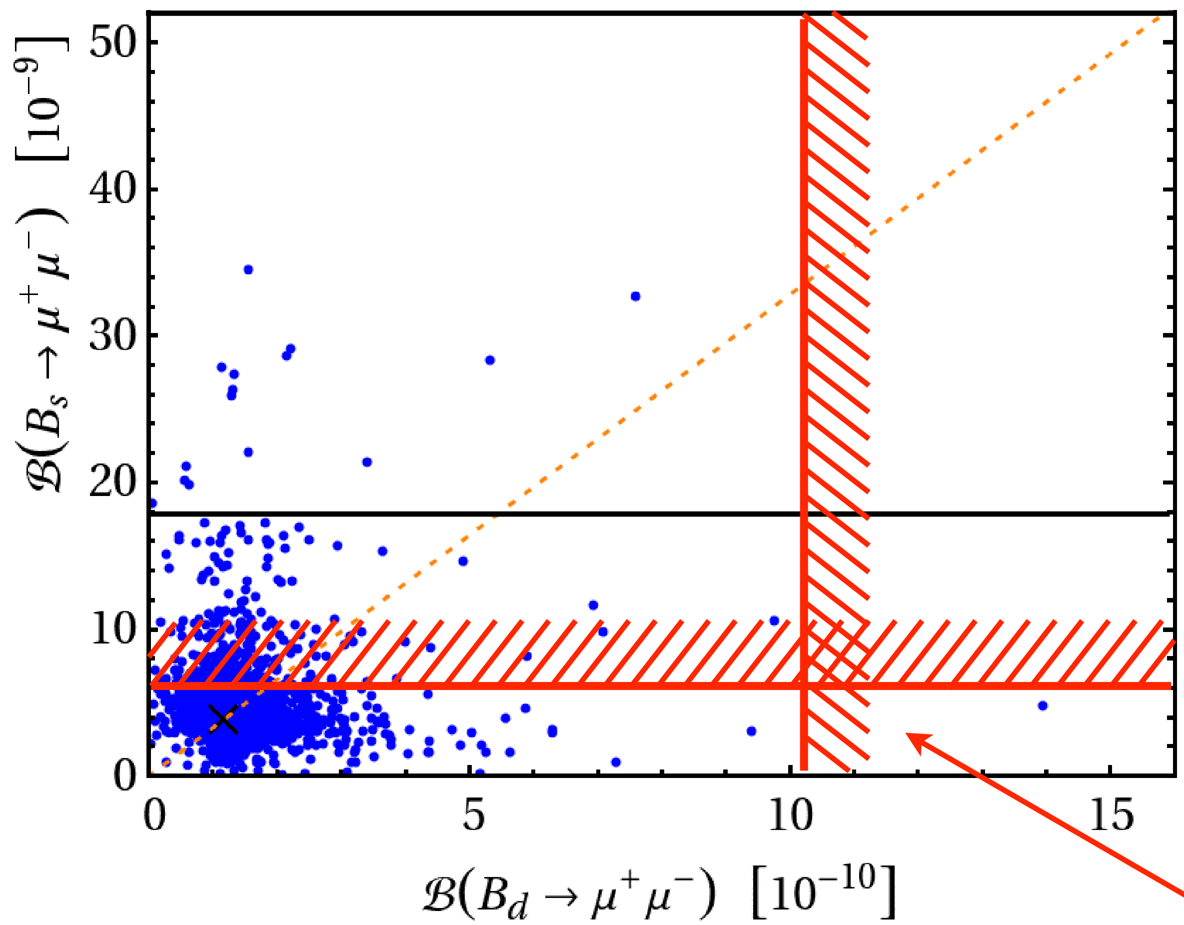
SU(3)$_L$ ⊗ SU(3)$_R$ → SU(3)$_C$
broken by boundary conditions



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:

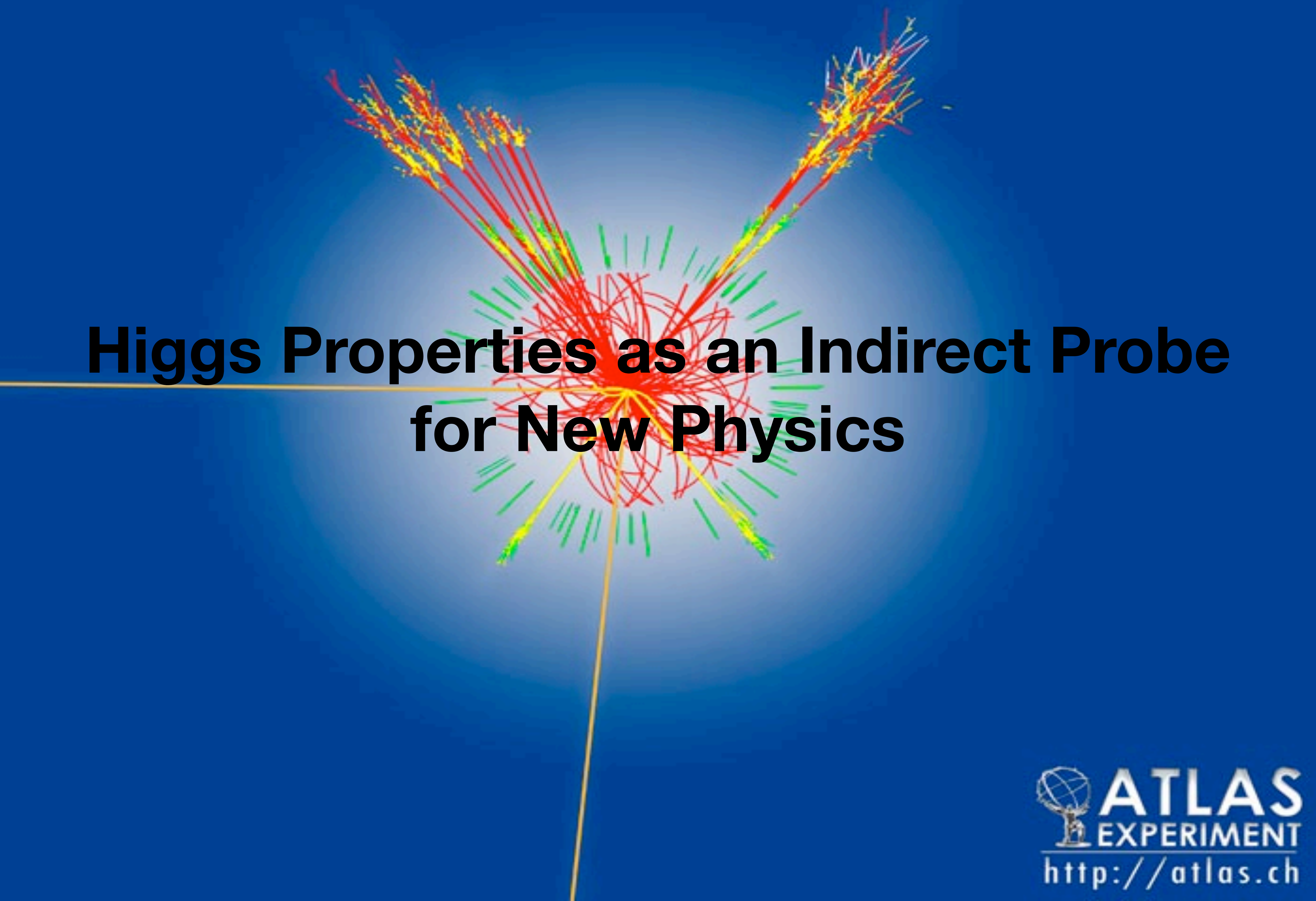


Bauer, Casagrande, Haisch, MN (2009);
see also: Blanke et al. (2008)

LHCb upper bounds (95% CL) @ Moriond EW 2012

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

Higgs Properties as an Indirect Probe for New Physics

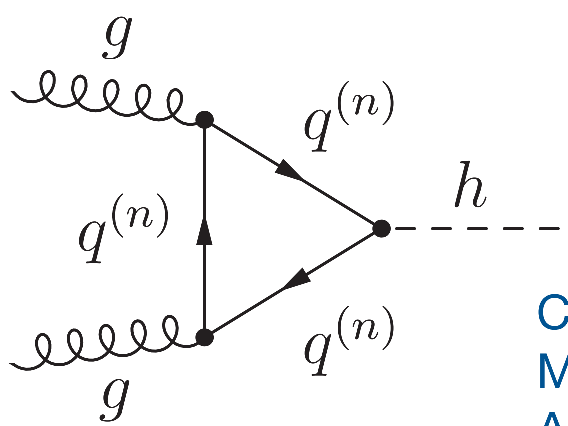


Higgs physics as an indirect BSM probe

Higgs discovery will mark the birth of the **hierarchy problem**:

- one of the main motivations for physics beyond the SM
- detailed study of **Higgs properties** (mass, width, cross section, branching fractions) will help to probe whether the Higgs sector is as simple as predicted by the SM
- **Higgs couplings to photons and gluons** are loop-suppressed in the SM and hence are **particularly sensitive** to the presence of new particles

In RS models, **large number of bulk fermionic fields** in 5D theory gives rise to large loop effects, which change the effective hγγ and hgg couplings



Casagrande, Goertz, Haisch, MN, Pfoh (2010); Azatov, Toharia, Zhu (2010)

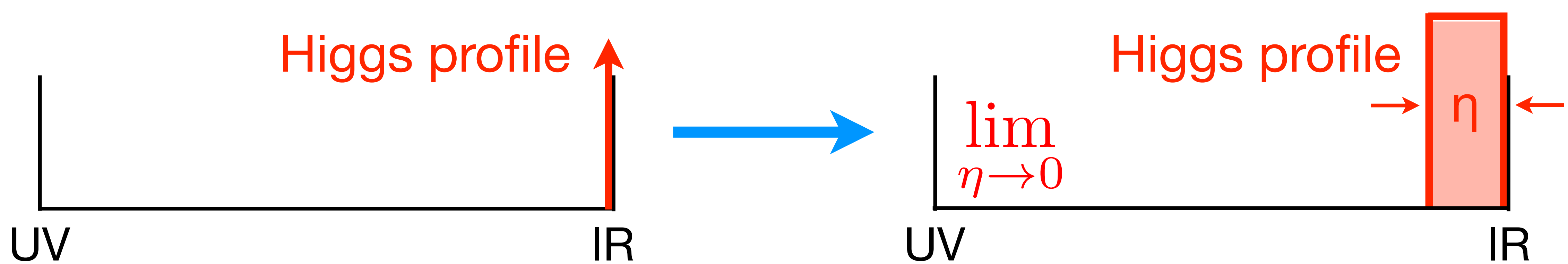
- KK towers of light quarks contribute as much as those of heavy quarks
- effect even more pronounced in models with custodial protection

Much like flavor physics, precision Higgs physics probes quantum effects of new particles!

Higgs physics as an indirect BSM probe

- Have recently obtained closed, **analytic expressions** for the Higgs production cross section as well as the main Higgs decay rates in minimal RS model, obtained by summing the infinite towers of KK states
- Work with a IR brane-localized Higgs sector, but regularize the Higgs profile carefully in an intermediate step:

Azatov, Toharia, Zhu (2009)

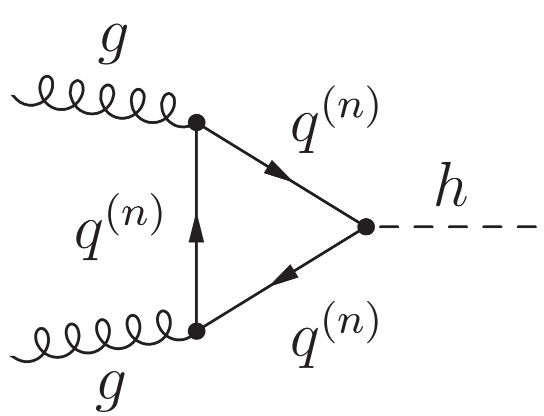


- Despite of the fact that the **sum over KK modes converges** (and is well approximated by the sum over the first few modes), it is important to implement the (physical) **UV cutoff** inherent in RS models

Higgs physics as an indirect BSM probe

RS model is an effective theory defined with a **physical, 5D position-dependent cutoff**, the warped Planck scale: $\Lambda_{\rm UV} \sim M_{\rm Pl}\, e^{-\sigma(\phi)}$

- for loop graphs including a Higgs boson, the cutoff lies in the **several TeV range**



UV regularization needed for:

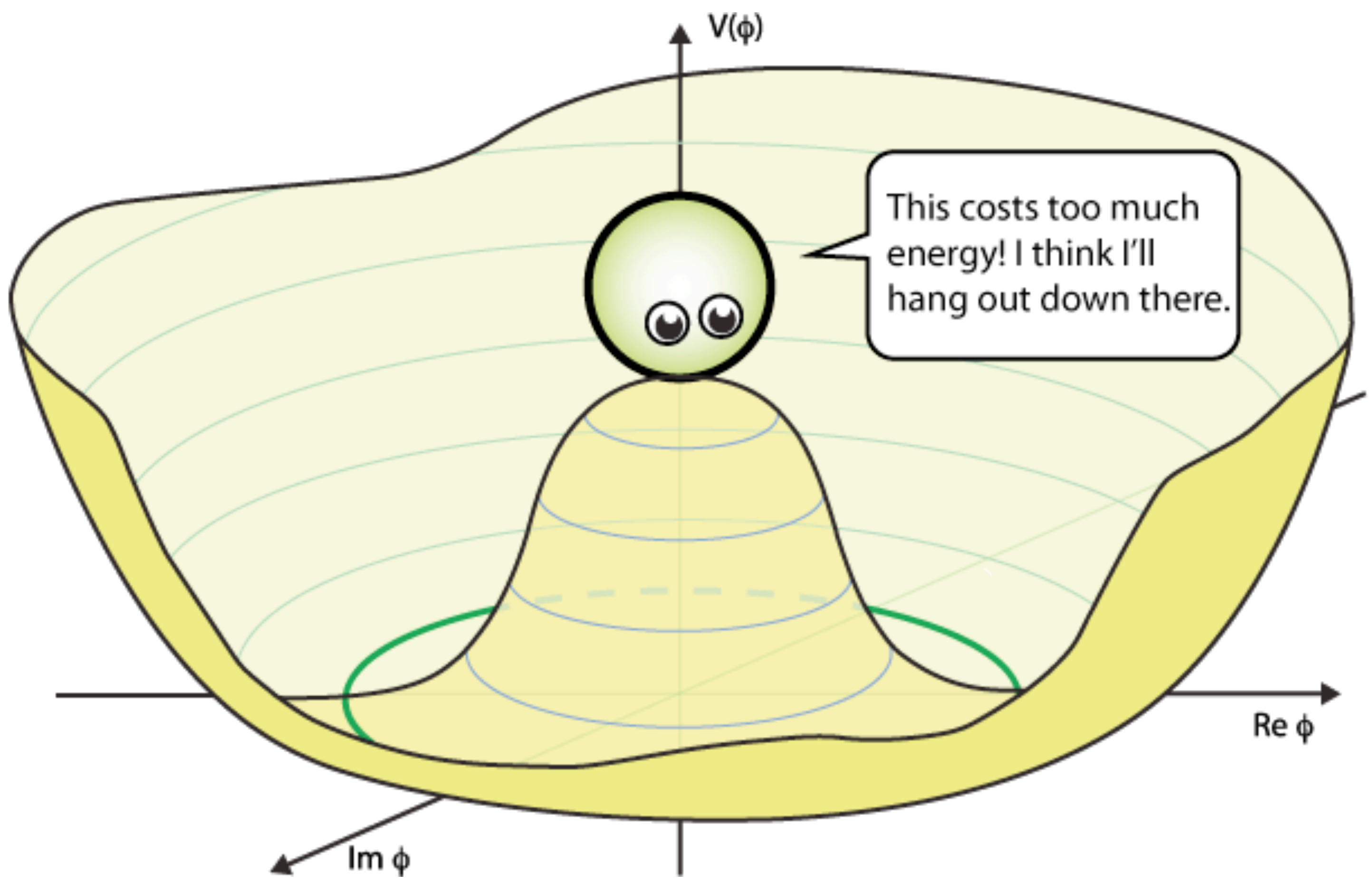
- gauge invariance (even in 4D)
- regularization of KK sum (superficially logarithmic divergence)
- eliminating UV contributions from super-massive KK states ~M_{KK}/η

Have explored dimensional regularization & hard momentum cutoff, both in 4D picture (KK sum) and 5D loop calculation

- find same results in all cases!

Carena, Casagrande, Goertz, Haisch, MN: arXiv:1204.0008
& work in preparation

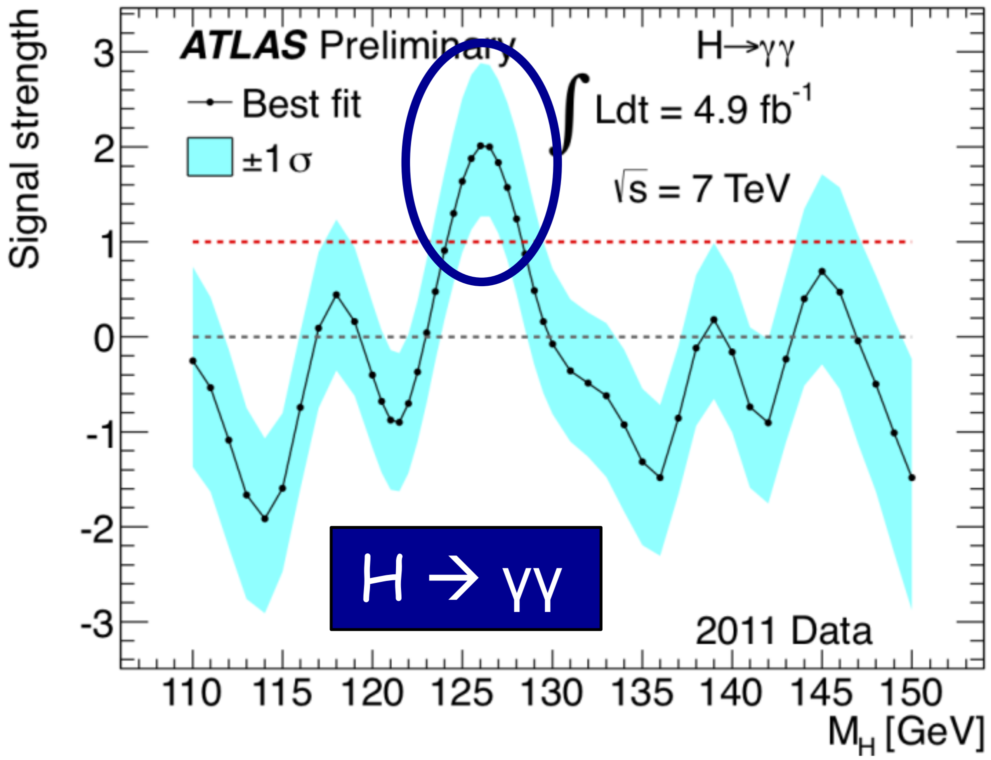
Phenomenology

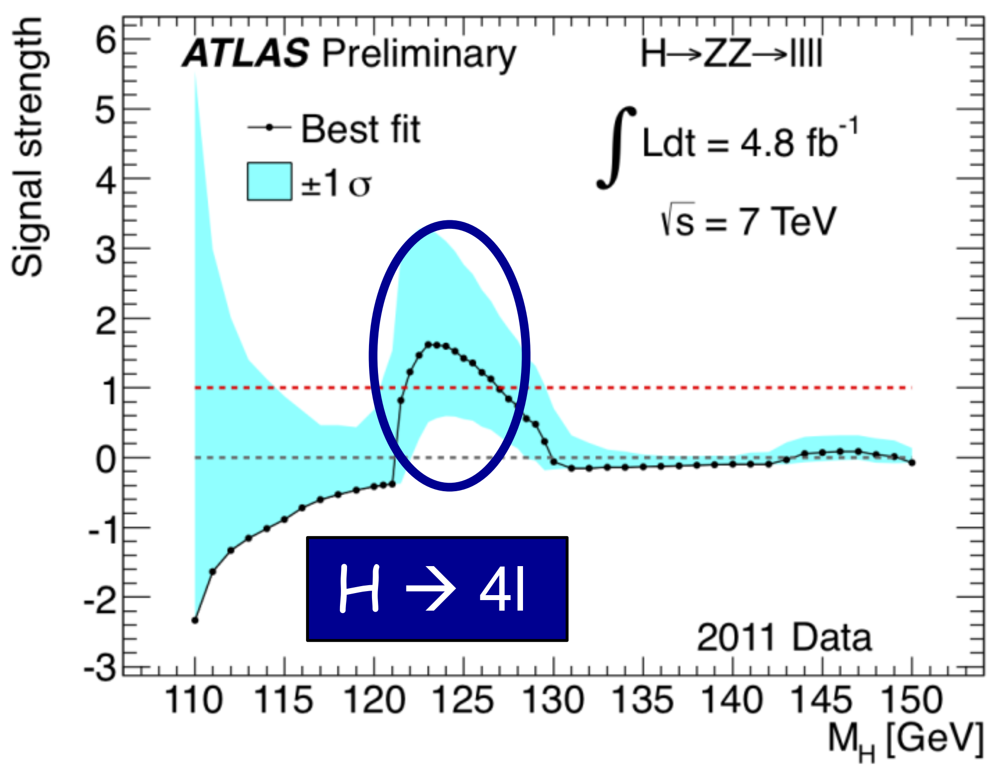


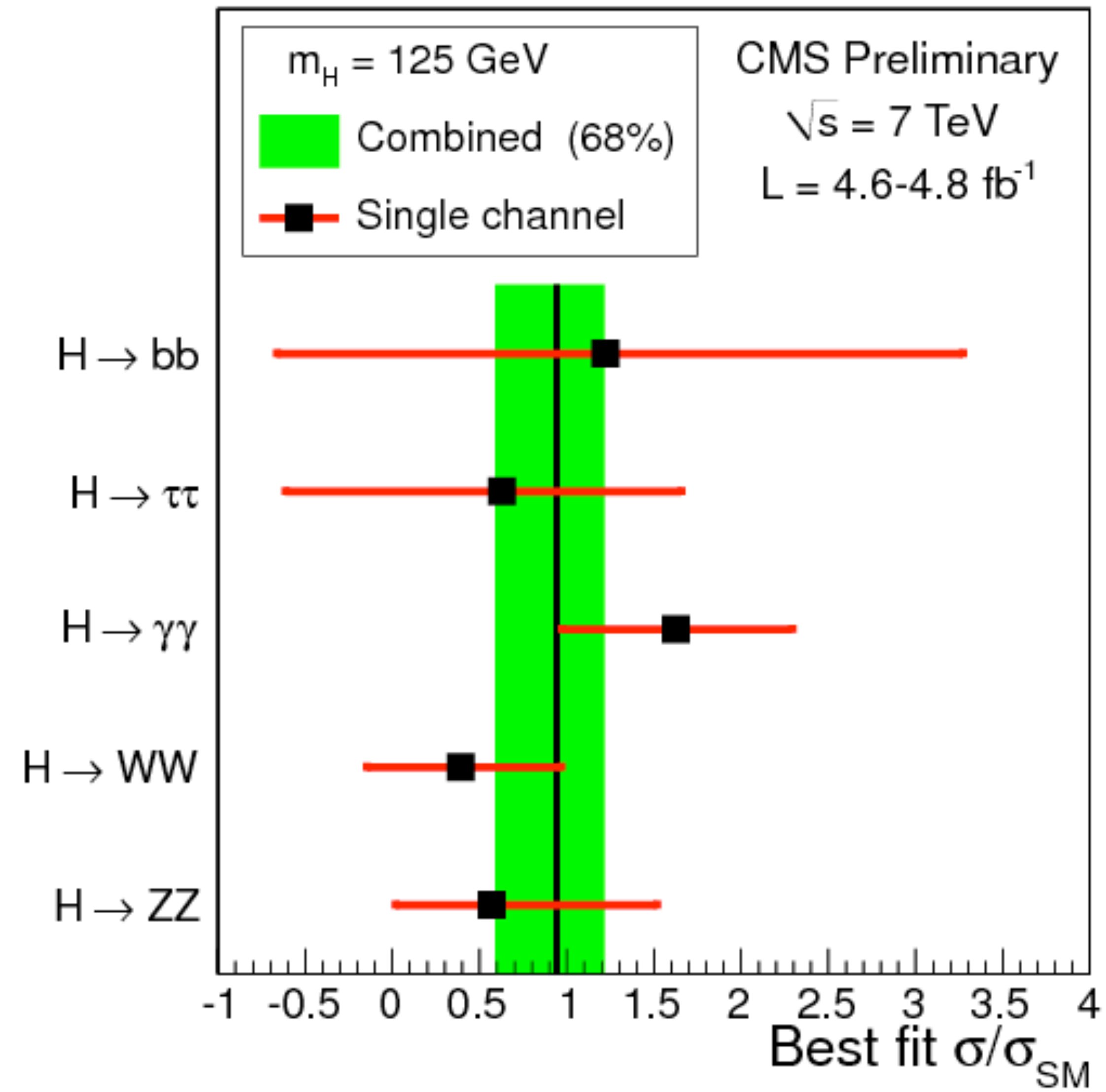
Goertz, Haisch, MN: arXiv:1112.5099

Carena, Casagrande, Goertz, Haisch, MN: arXiv:1204.0008

Implications of recent LHC data







Decays to di-bosons particularly interesting:

- clean signatures, good mass resolution (Z,γ)
- tree-dominated (h→ZZ, h→WW) vs. loop-dominated modes (h→γγ)

Higgs phenomenology in RS: production

Higgs production cross section:

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

- Modifications due to top Yukawa and Kaluza-Klein tower of quark states:

$$\kappa_g \approx \mathrm{Re}(\kappa_t) - \sum_{q=u,d} \mathrm{Tr}\, f(\boldsymbol{X}_q)$$

modified top contribution: **reduced!**

$$\kappa_t \approx 1 - \frac{v_{\rm RS}^2}{3M_{\rm KK}^2} \frac{\left(\boldsymbol{Y}_u \boldsymbol{Y}_u^\dagger \boldsymbol{Y}_u\right)_{33}}{\left(\boldsymbol{Y}_u\right)_{33}}$$

➡ dominant effect described by 5D Yukawa matrices!

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effect of KK tower: **destructive!**

$$f(x) = \frac{x \tanh x}{\cosh 2x}$$

$$\boldsymbol{X}_q = \frac{v_{\rm RS}}{\sqrt{2} M_{\rm KK}} \sqrt{\boldsymbol{Y}_q \boldsymbol{Y}_q^\dagger}$$

anarchical 5D Yukawa matrices

➡ **equal contributions** for KK modes of all SM fermions !

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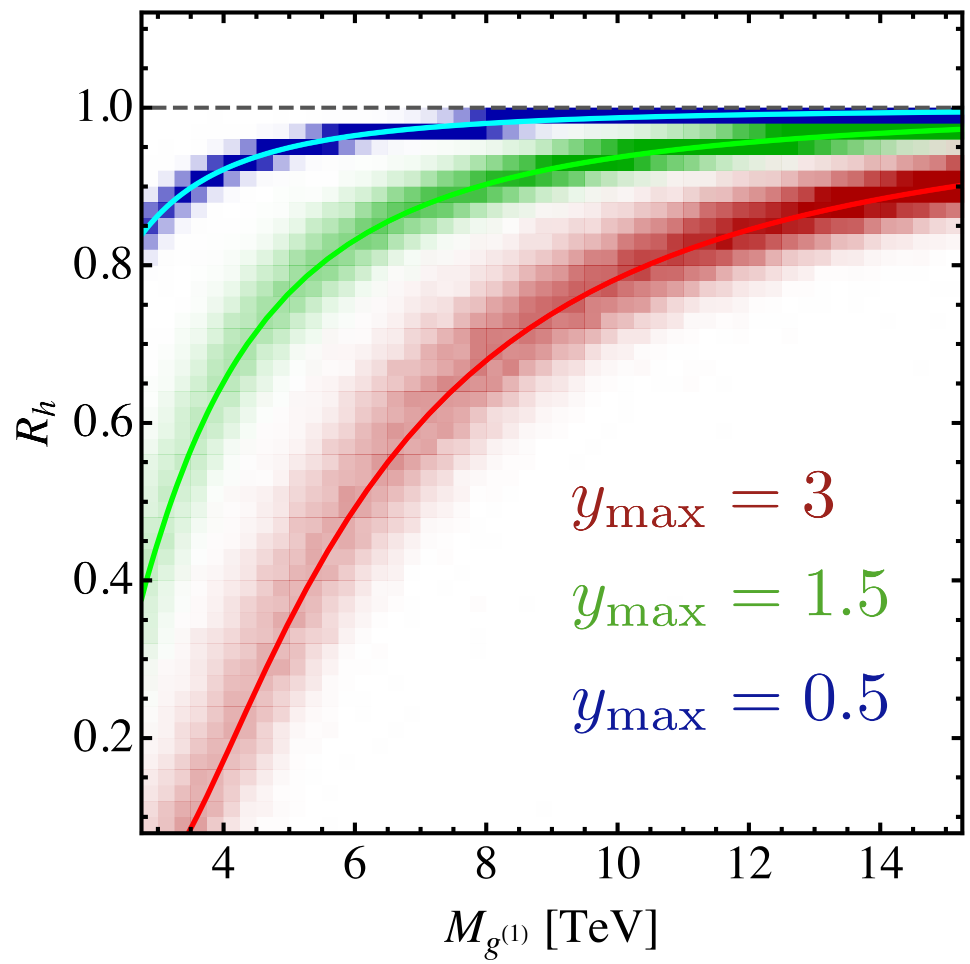
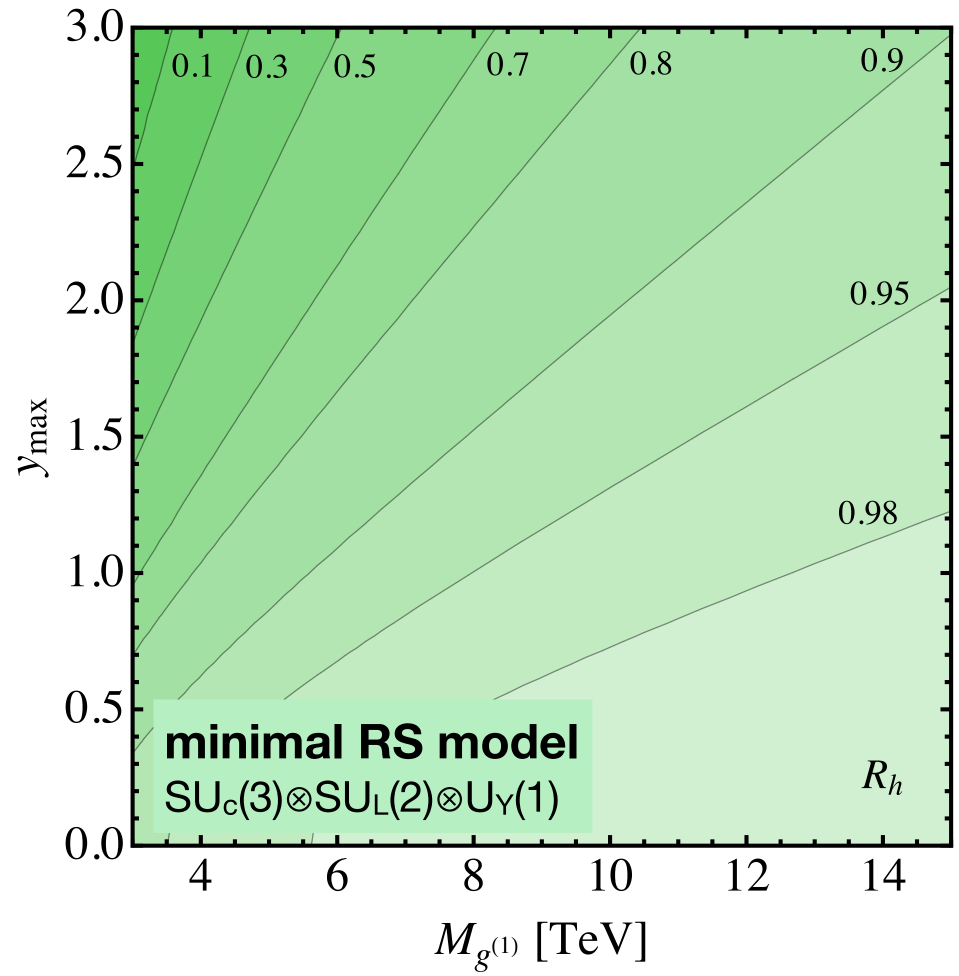
$$\kappa_g \approx \mathrm{Re}(\kappa_t) - \sum_{q=u,d} \mathrm{Tr}\, f(\boldsymbol{X}_q)$$

- Both effects described in terms of **fundamental 5D parameters**
- For **random Yukawa matrices**, the matrix-valued functions are to a good approximation determined by the **maximum value** allowed for the random variables $0 < |(Y_q)_{ij}| < y_{max}$ (most previous analyses assumed y_{max}=3)
- Results can therefore be displayed as functions of y_{max} and the mass of the lightest Kaluza-Klein gluon ($m_{g^{(1)}} \approx 2.45 M_{\rm KK}$)

Higgs phenomenology in RS: production

Find a **significant suppression** of the cross section:





- If a strong suppression is observed, then this can be interpreted as a **hint for existence of WEDs** and translated into parameter space of such models
- If σ(gg→h) is close to SM prediction, this would imply **tight bounds** on model parameters, perhaps moving KK masses out of LHC reach for direct production

Higgs phenomenology in RS: decays

Higgs decays:

$$\frac{\Gamma(h \to VV)_{\rm RS}}{\Gamma(h \to VV)_{\rm SM}} = \kappa_V^2 \,, \qquad \frac{\Gamma(h \to \gamma\gamma)_{\rm RS}}{\Gamma(h \to \gamma\gamma)_{\rm SM}} = \kappa_\gamma^2$$

- Modification for massive vector bosons (V = Z,W) is a small effect:

$$\kappa_V \approx 1 - \frac{m_V^2}{M_{\rm KK}^2}\,(L-1)$$

$$L = \ln \frac{M_{\rm Pl}}{10\,{\rm TeV}} \approx 35$$

- Modification for photons can be significant ($A_W = 6.27$ is a loop function):

$$\kappa_\gamma \approx \frac{1}{A_W - \frac{4N_c}{9}} \left[\kappa_W A_W + \frac{21}{8}\,\frac{m_W^2}{M_{\rm KK}^2}\,(L-1) - N_c \left(\frac{4}{9}\,\kappa_g + \frac{1}{3}\,{\rm Tr}\, f(\boldsymbol{X}_d) - \frac{1}{N_c}\,{\rm Tr}\, f(\boldsymbol{X}_l) \right) \right]$$

modified W contribution

effect of KK modes $W^{(n)}$

effect of SM quarks and KK fermions (quarks and leptons)

Higgs phenomenology in RS: rate ratios

Production cross section times branching fraction:

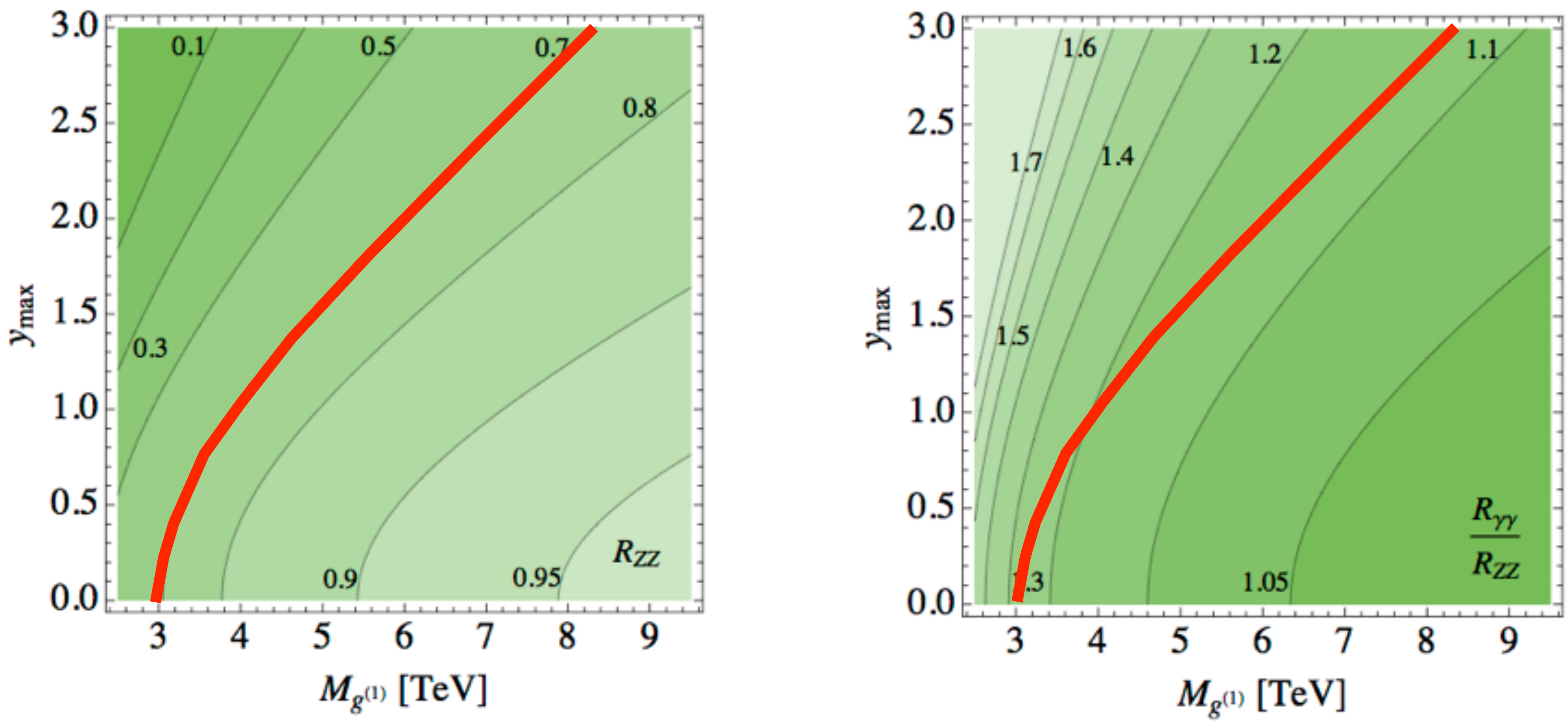
$$R_f = \frac{\left[\sigma(pp\to h)\,\mathrm{Br}(h\to f)\right]_{\mathrm{RS}}}{\left[\sigma(pp\to h)\,\mathrm{Br}(h\to f)\right]_{\mathrm{SM}}}$$

- Phenomenologically, the most interesting ratios are $R_{\gamma\gamma},\ R_{ZZ}$ and their ratio (experimentally clean signatures, good mass resolution)
- ZZ mode probes loop effects via Higgs production, while di-photon mode is sensitive to loop effects in both production and decay
- Preliminary LHC data (if interpreted invoking a Higgs hypothesis) may indicate that $R_{ZZ} \lesssim 1$, while $R_{\gamma\gamma}/R_{ZZ} > 1$

Caveat: Discussion below is illustrative -- serious analysis must await Higgs discovery and reliable rate measurements!

Higgs phenomenology in RS: rate ratios

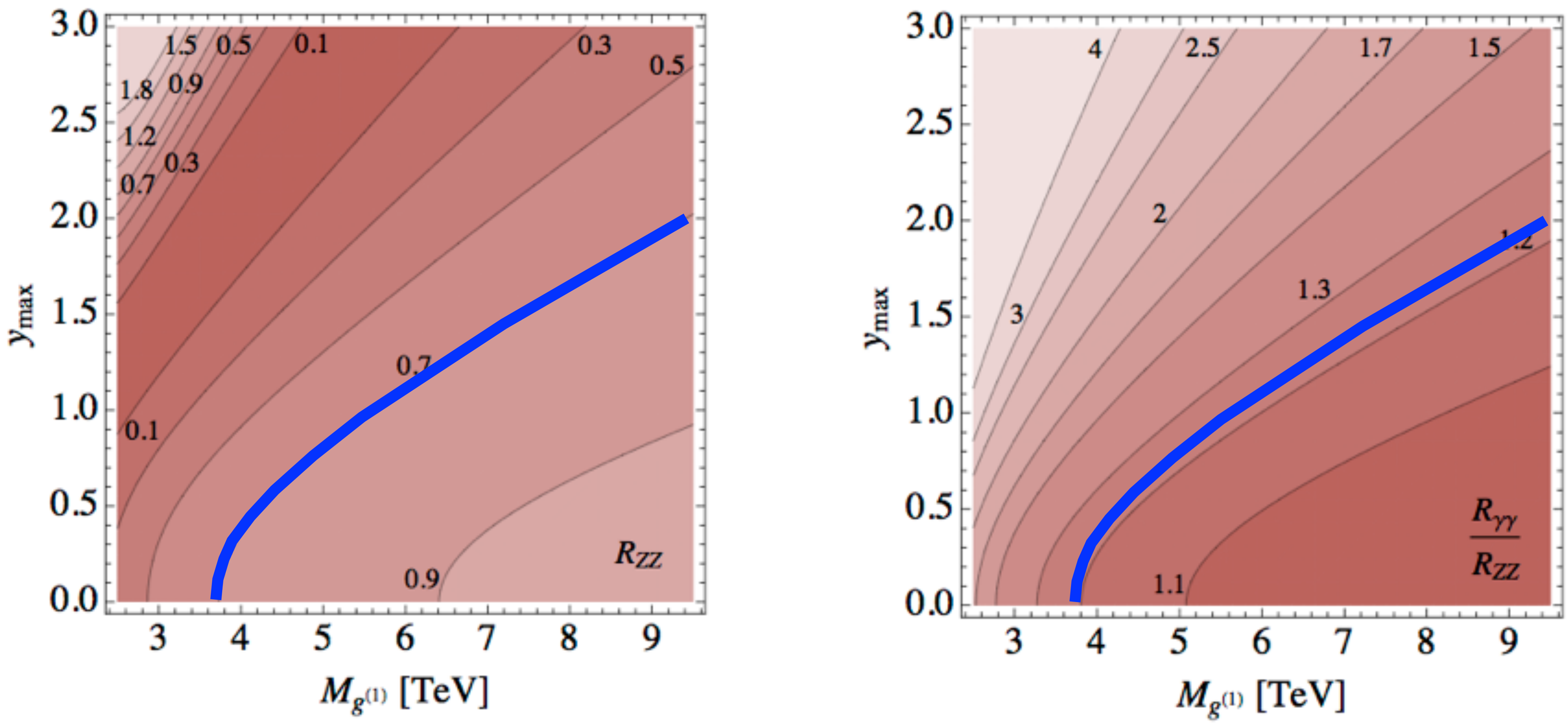
Minimal RS model with bulk fermions and gauge fields:



- Assuming y_{max}=3, a measurement **$R_{ZZ} \approx$ 0.7** along with a slight enhancement of the di-photon over the ZZ channel would then imply **KK masses ≈ 8 TeV**, far outside reach for direct production at the LHC (a lower bound $R_{ZZ} > 0.7$ would imply very strong bounds)

Higgs phenomenology in RS: rate ratios

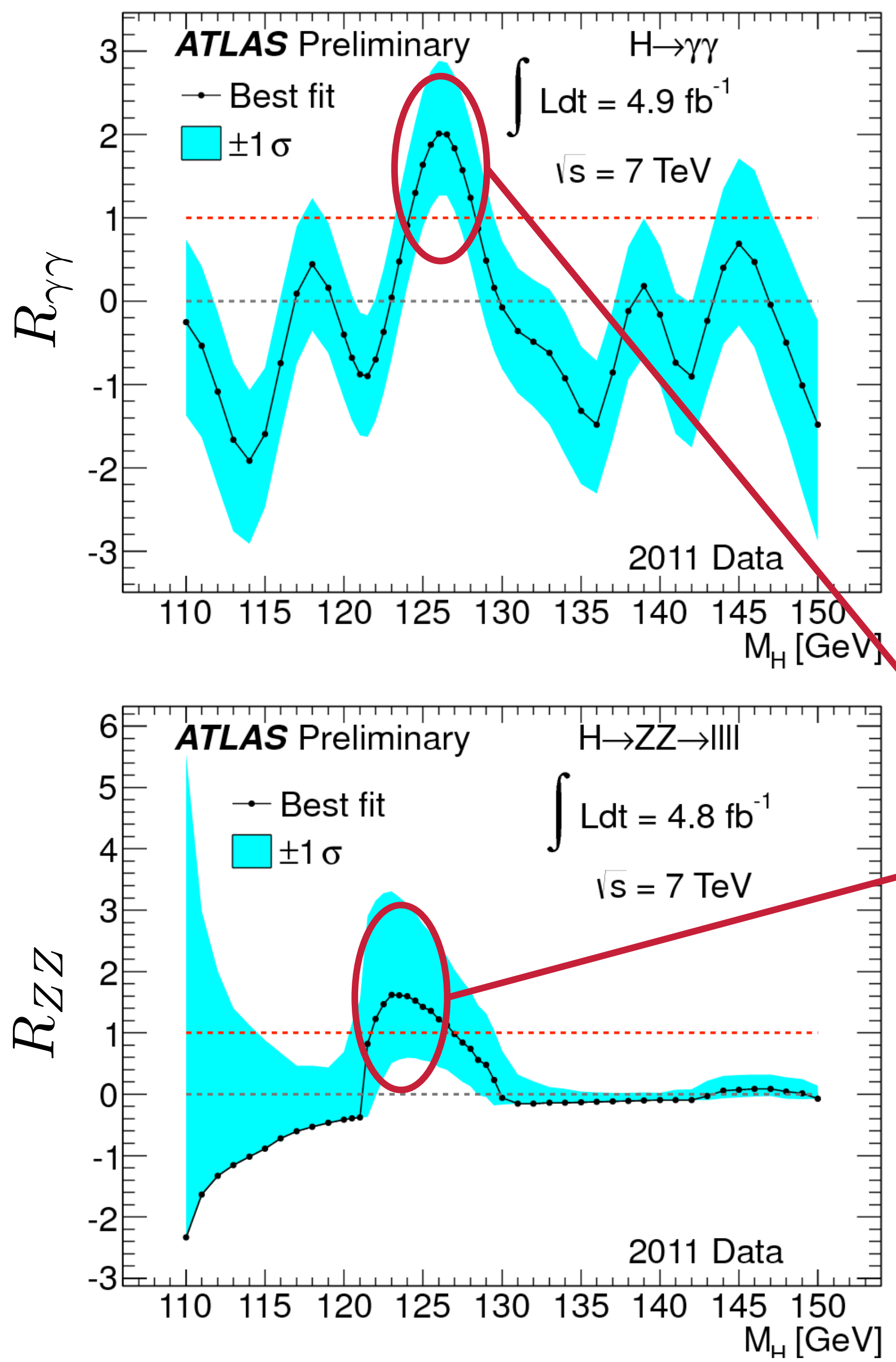
Extended RS model with custodial symmetry:



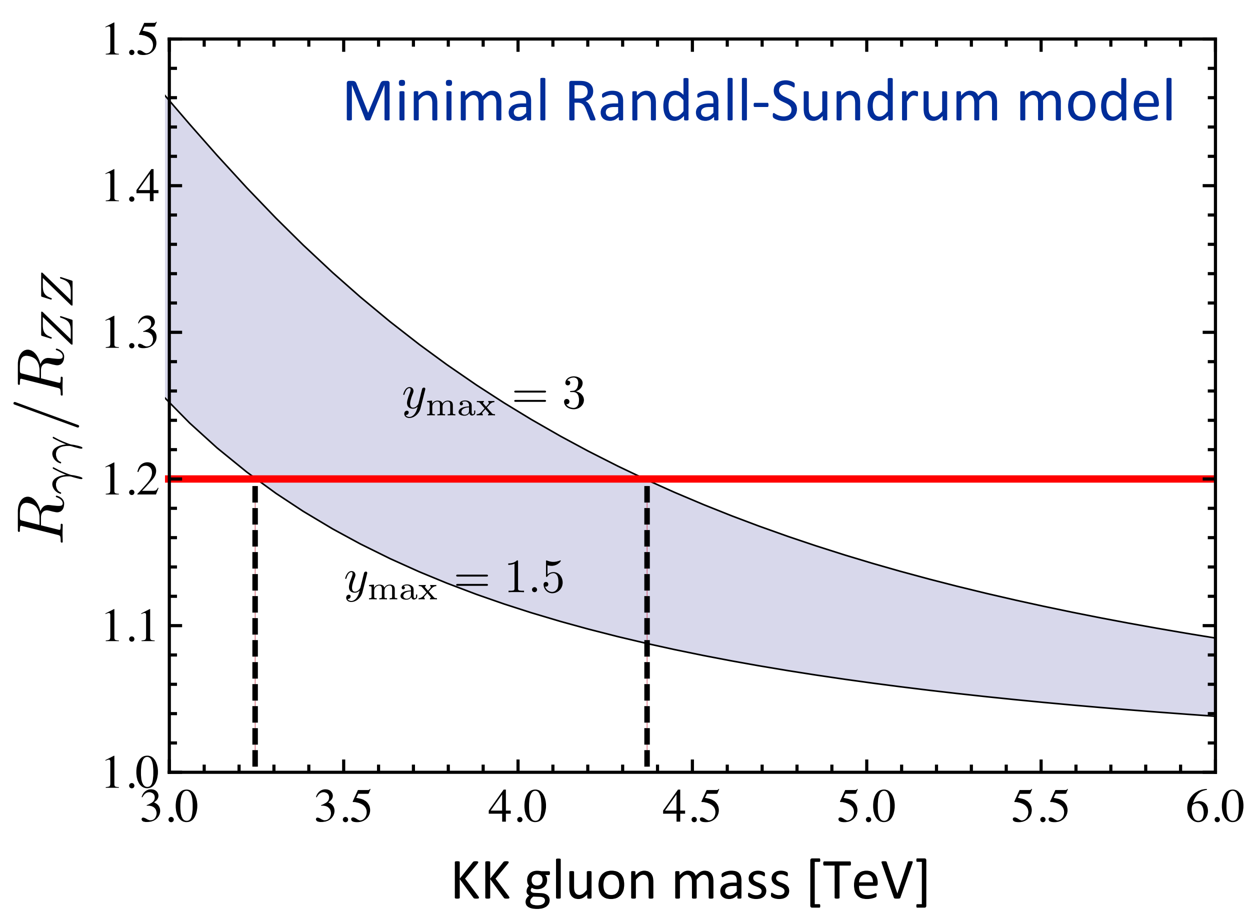
- Even with reduced y_{max}=2, a measurement **$R_{ZZ} \approx$ 0.7** along with a slight enhancement of the di-photon over the ZZ channel would then imply **KK masses ≈ 10 TeV**, far outside reach for direct production at the LHC (a lower bound $R_{ZZ} > 0.7$ would imply very strong bounds)

Higgs phenomenology in RS: rate ratios

A possible future game to play:



Consider **double ratios**, which are insensitive to New Physics effects in Higgs production, e.g.:



F. Goertz, U. Haisch, M. Neubert (2011)

Conclusions

- **Warped extra-dimension models** provide an appealing framework for addressing the **hierarchy problem** and the **flavor puzzle** within the same geometrical approach

- Much like rare FCNC processes, **Higgs production** in gluon-gluon fusion and **Higgs decays** into the di-photon final state are **loop-suppressed processes**, which are sensitive to new heavy particles and probe EWSB sector at the quantum level

- Find that the contribution of the Kaluza-Klein towers of SM quarks is **independent** of the quark mass and given in terms of fundamental **5D Yukawa matrices**

- Effects are enhanced by the **large multiplicity** of 5D fermion states and probe regions of parameter space **not accessible to direct searches**

- Interesting to study other WED models: bulk Higgs, gauge-Higgs unification, generalized Yukawa couplings ... → model dependence?