Implications of LHC Scalar Searches on Warped Extra Dimensions

Matthias Neubert
Johannes Gutenberg University Mainz

ERC Advanced Grant (EFT4LHC)
An Effective Field Theory Assault on the Zeptometer Scale: Exploring the Origins of Flavor and Electroweak Symmetry Breaking

Rencontres de Moriond
Electroweak Interactions and Unified Theories
La Thuile, Aosta Valley, Italy, 3-10 March 2012

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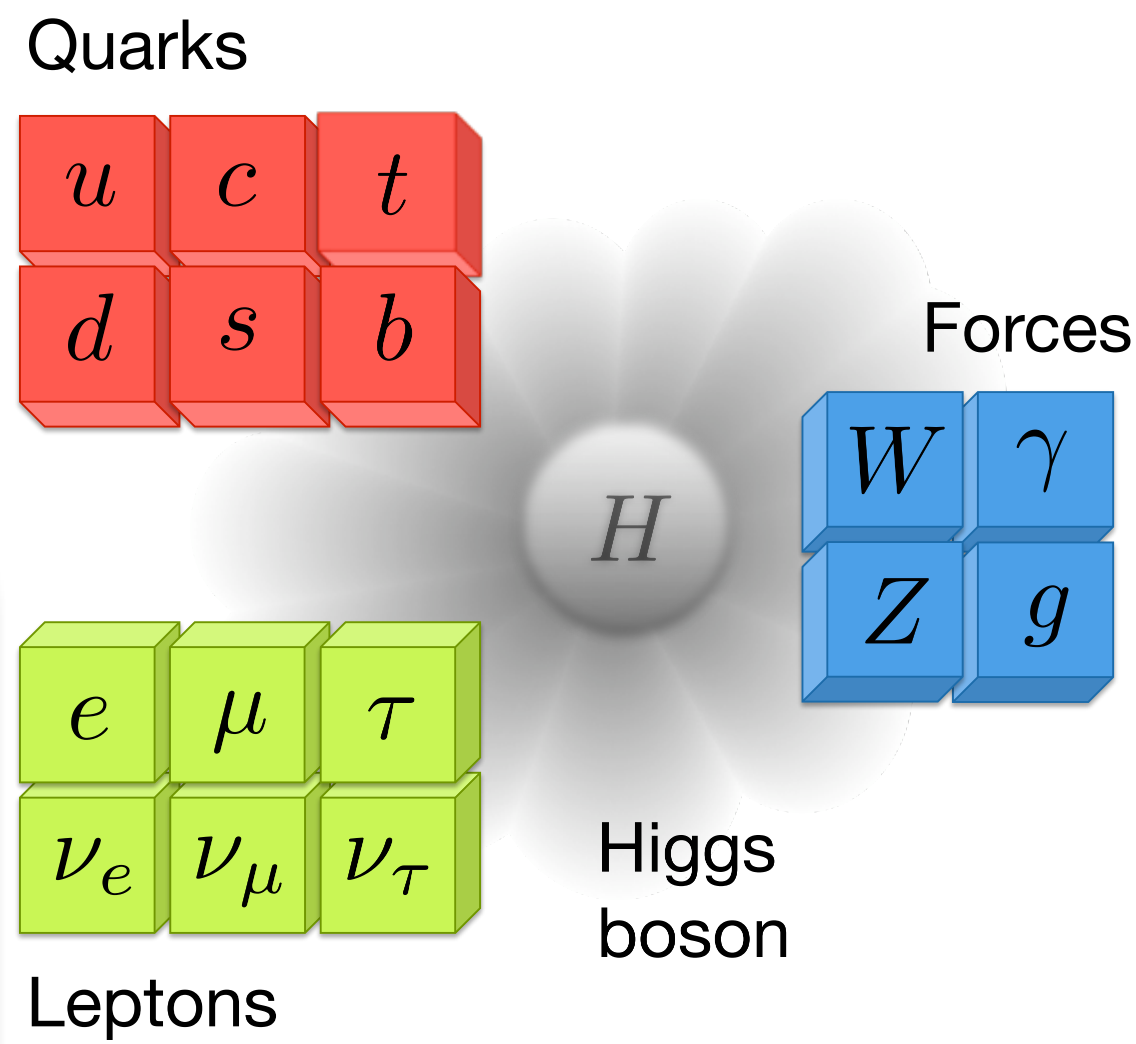
Standard Model and Beyond

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?

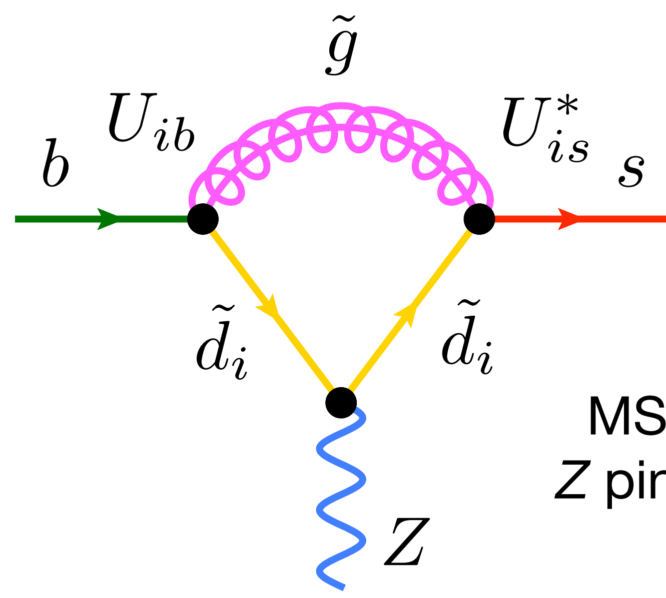


Prejudice that there must be "New Physics"

Flavor Structure in the SM and Beyond

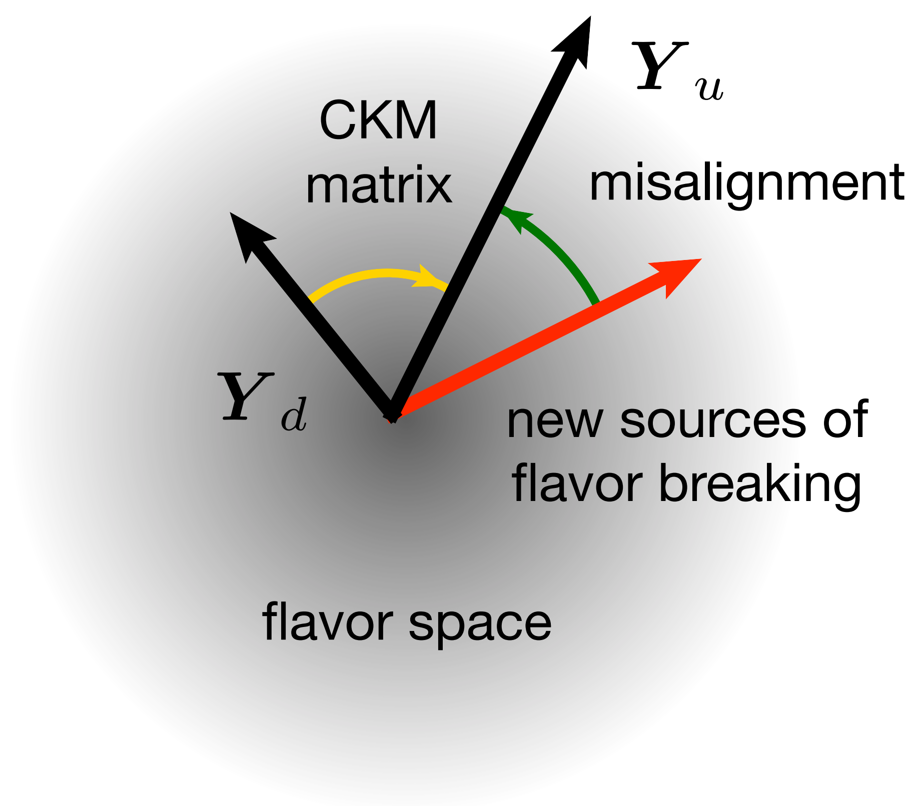
In extensions of SM, additional flavor and CP violation can arise from exchange of new scalar (H^+, $\tilde{q}$, ...), fermionic ($\tilde{g}$, t', $t^{(1)}$, ...), or gauge (Z', $g^{(1)}$, ...) degrees of freedom

- 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: $U_{ij} << 1$



MSSM
Z pinguin

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

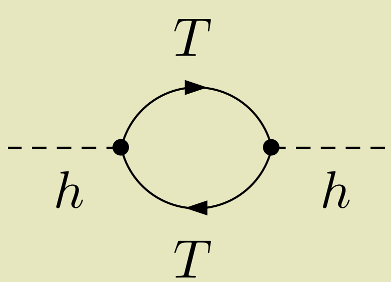


Flavor Structure in the SM and Beyond

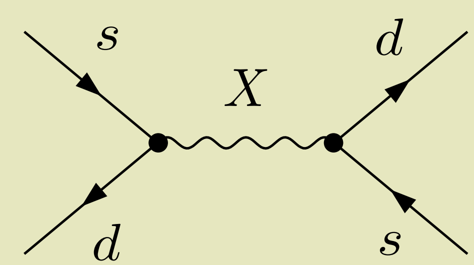
$$\mathcal{L}_{\rm EFT} = \underbrace{\Lambda^2_{\rm UV}\,\Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2}_{} + \mathcal{L}^{\rm gauge}_{\rm SM} + \mathcal{L}^{\rm Yukawa}_{\rm SM} + \underbrace{\frac{\mathcal{L}^{(5)}}{\Lambda_{\rm UV}} + \frac{\mathcal{L}^{(6)}}{\Lambda^2_{\rm UV}}}_{} + \ldots$$

electroweak symmetry breaking $\Downarrow$ Higgs mass

$\Downarrow$



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



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

no fine-tuning $\Downarrow$

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

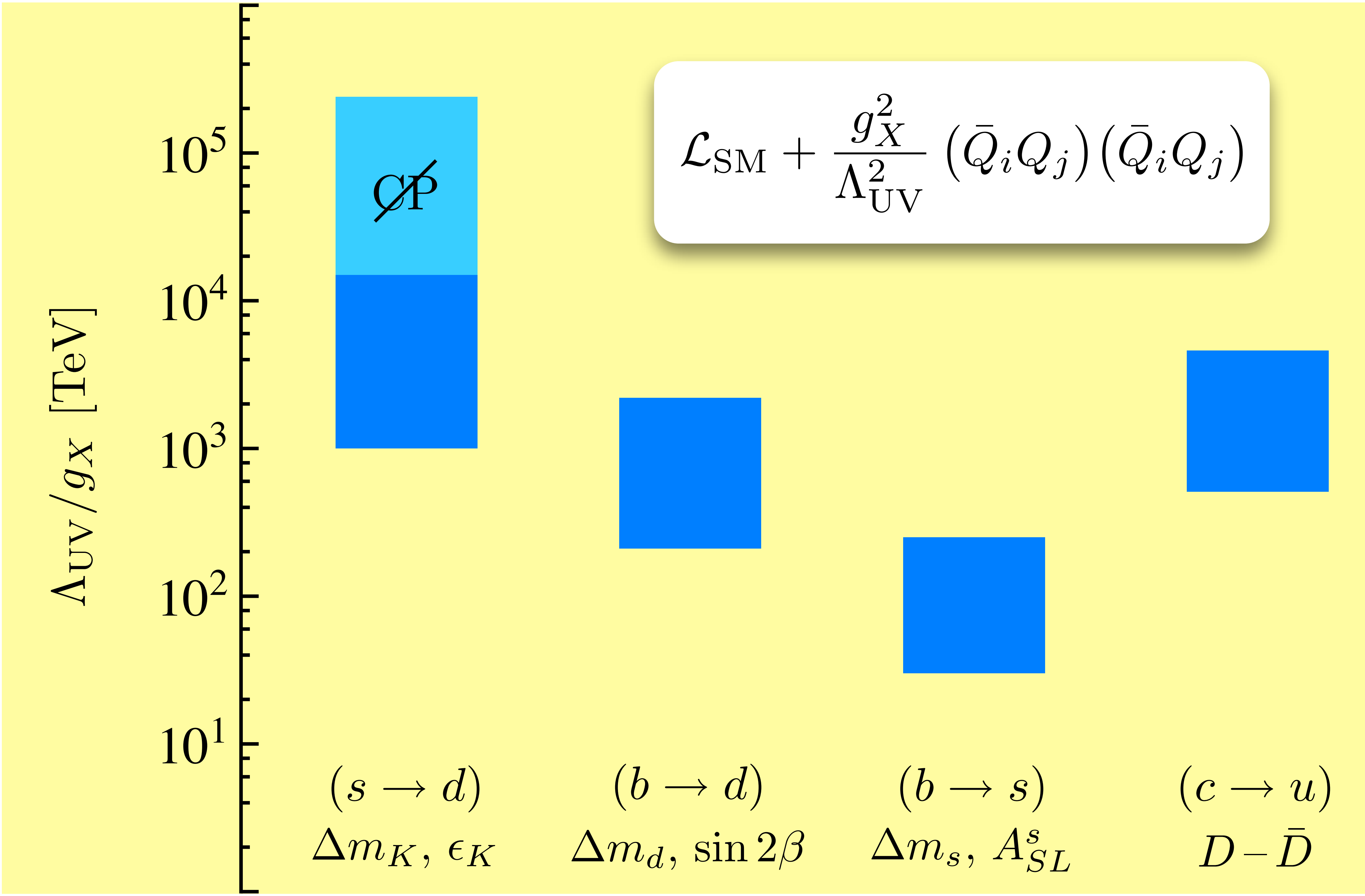
$\Lambda_{\rm Higgs} \lesssim 1$ TeV $\qquad$ $\Lambda_{\rm flavor} \gtrsim 10^3$ TeV

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

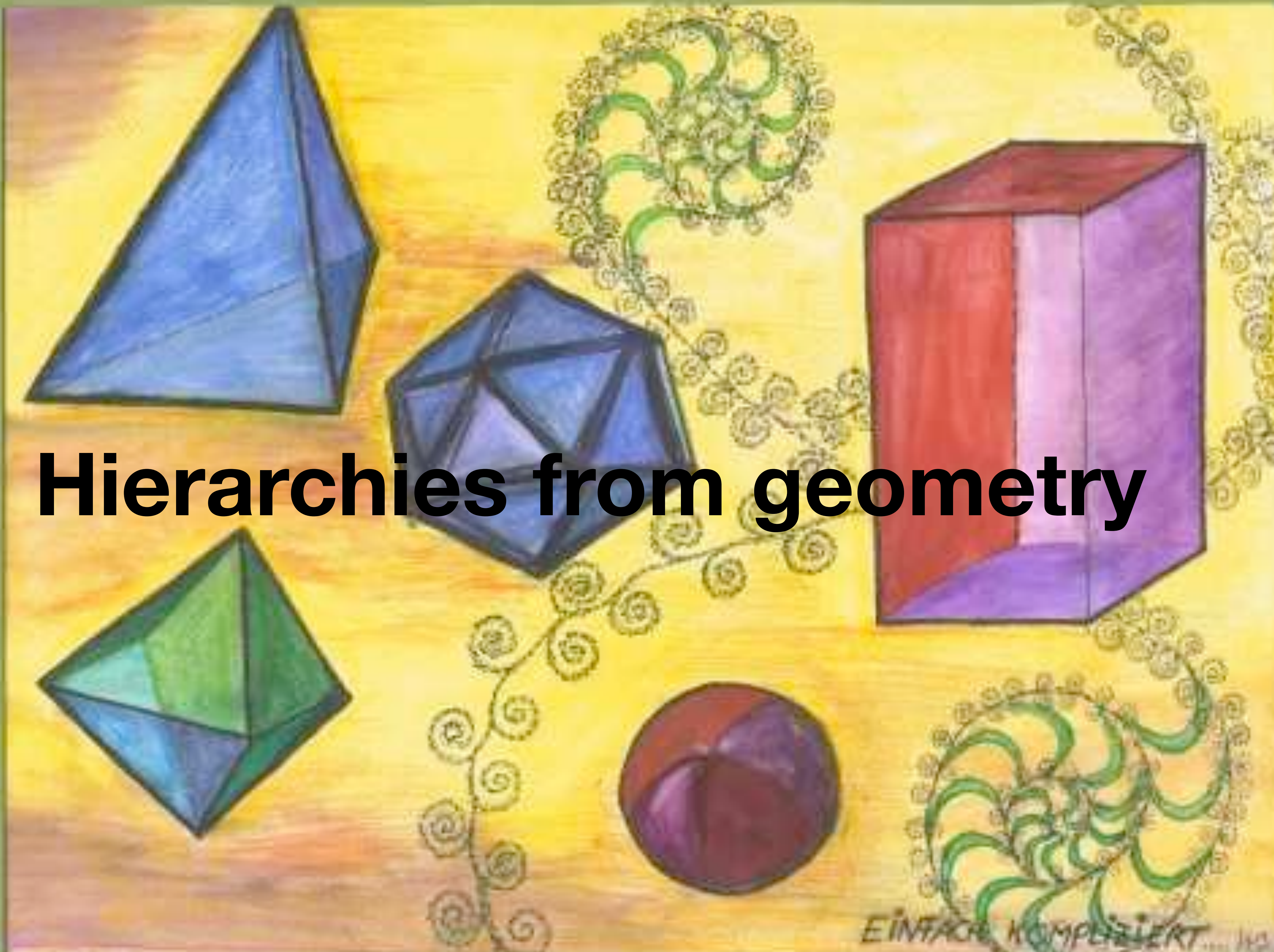
(ii) $\Lambda_{\rm UV} \approx 1$ TeV: quark flavor-mixing protected by a **flavor symmetry**

Flavor Structure in the SM and Beyond



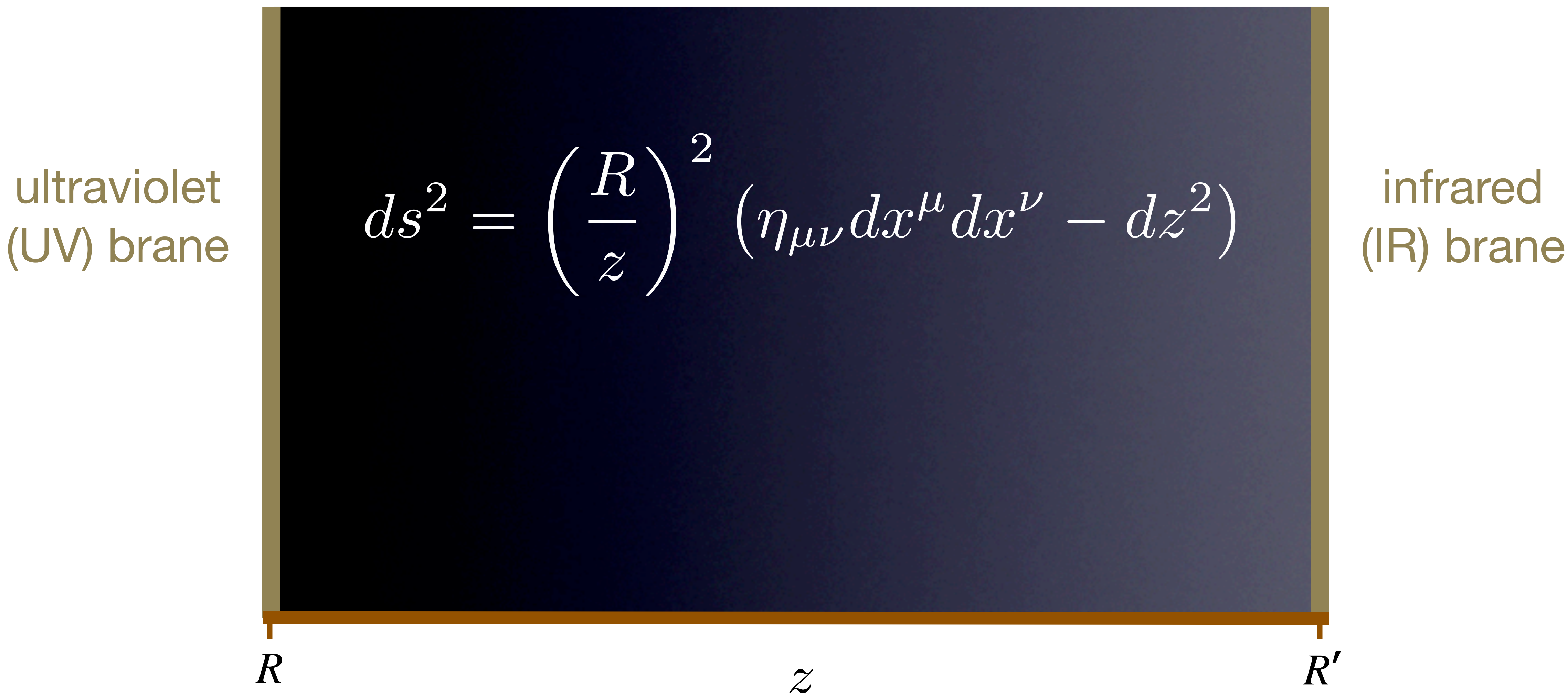
Generic bounds without flavor symmetry

Hierarchies from geometry



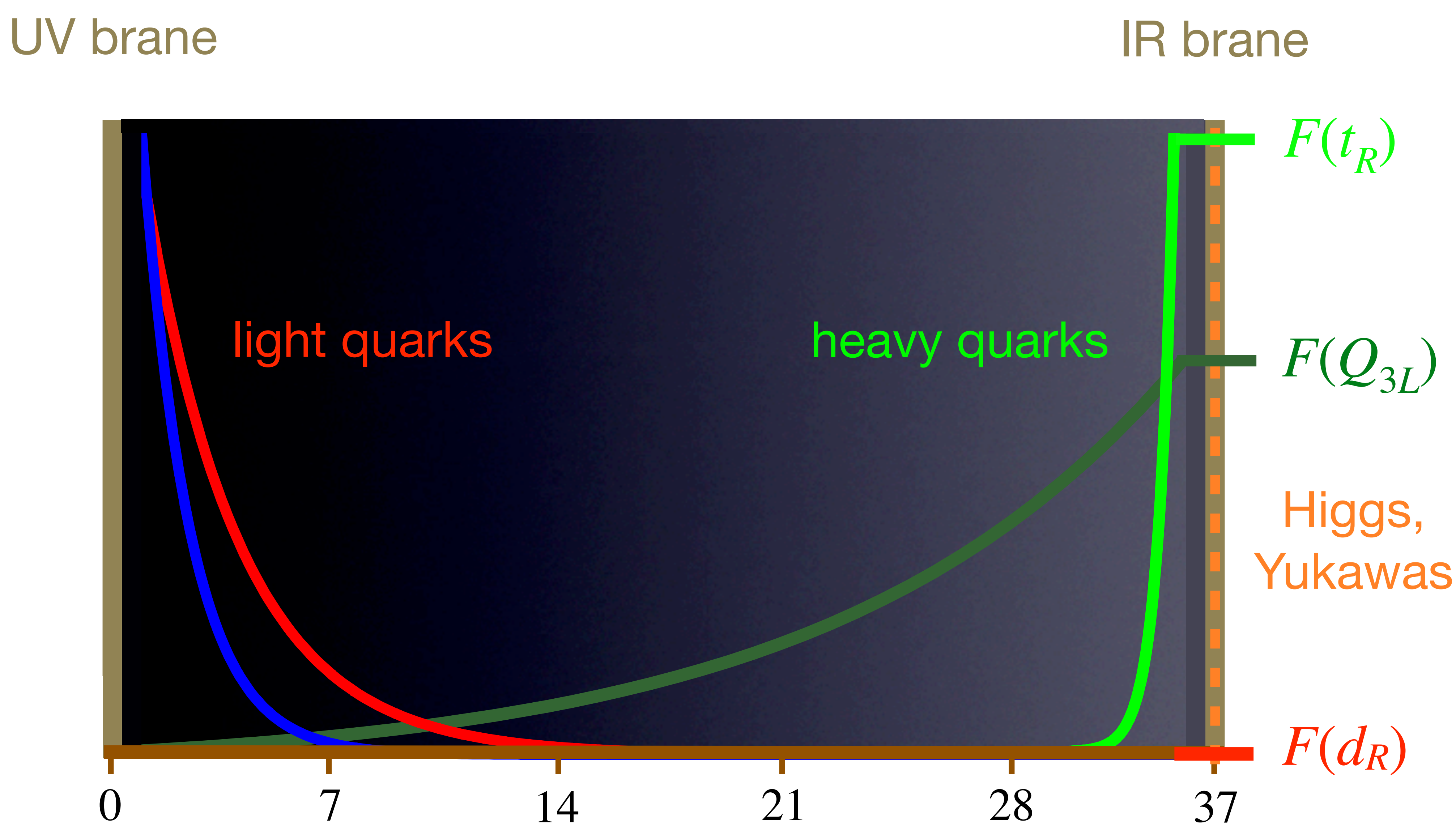
Embedding the SM in a warped extra dimension

Randall, Sundrum (1999)



RS models featuring 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)

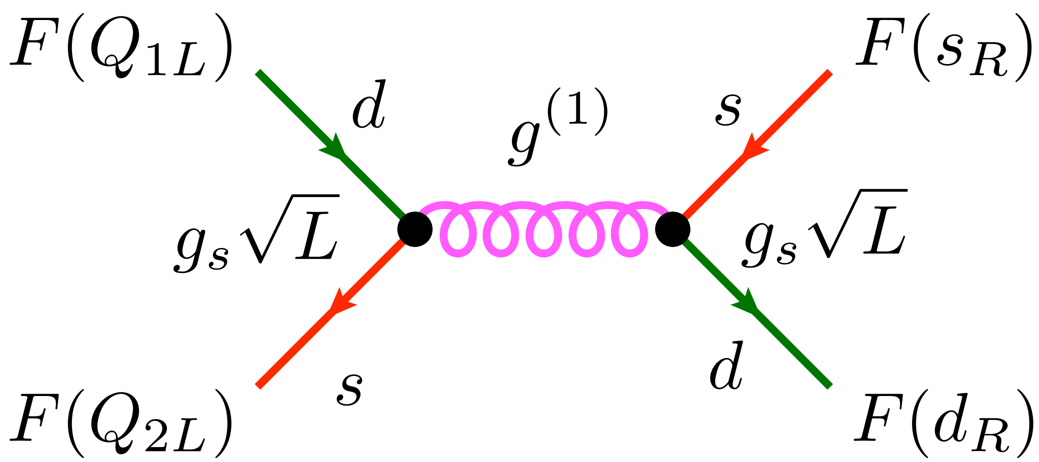
Flavor structure in RS models



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 IR-localized Higgs sector are **exponentially small** for light quarks, while O(1) for top quark: effective Yukawa couplings exhibit **realistic hierarchies**

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

RS-GIM protection of FCNCs



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

- 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)

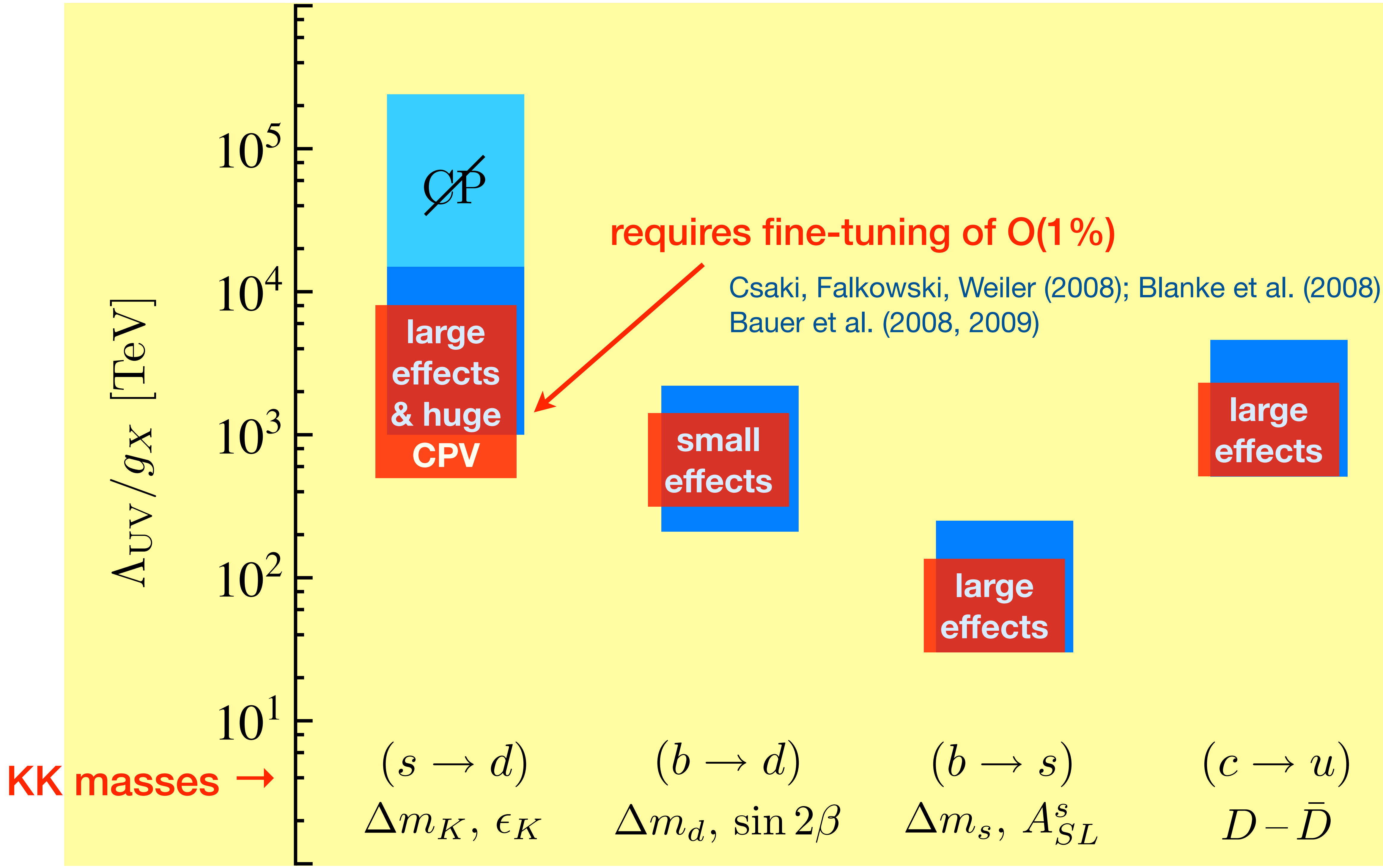
- Resulting FCNC couplings depend on same exponentially small overlap integrals $F(Q_L)$, $F(q_R)$ that generate fermion masses

- 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



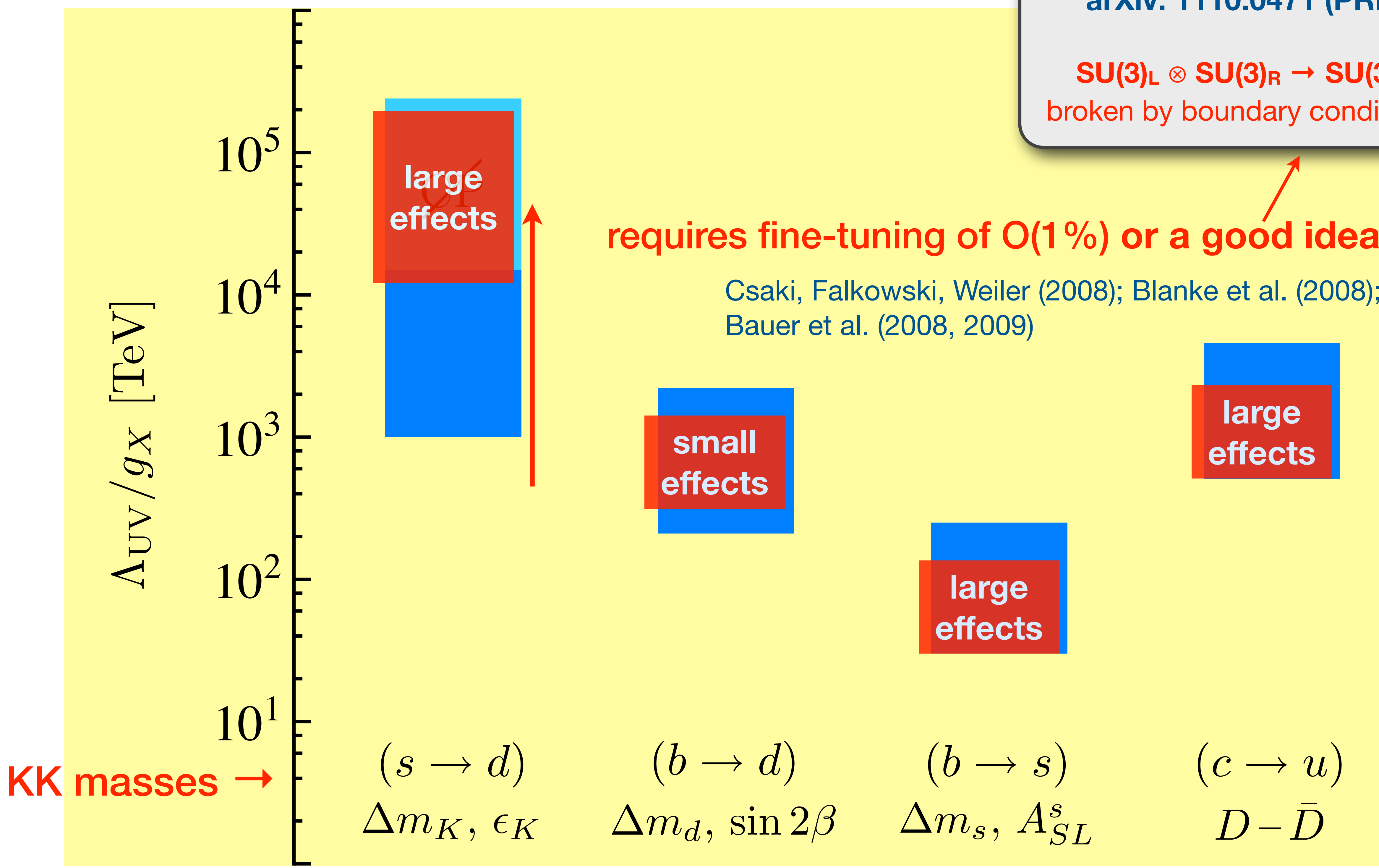
RS-GIM protection with KK masses of order few TeV

RS-GIM protection of FCNCs

talk at Moriond EW 2012
(Monday session)

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

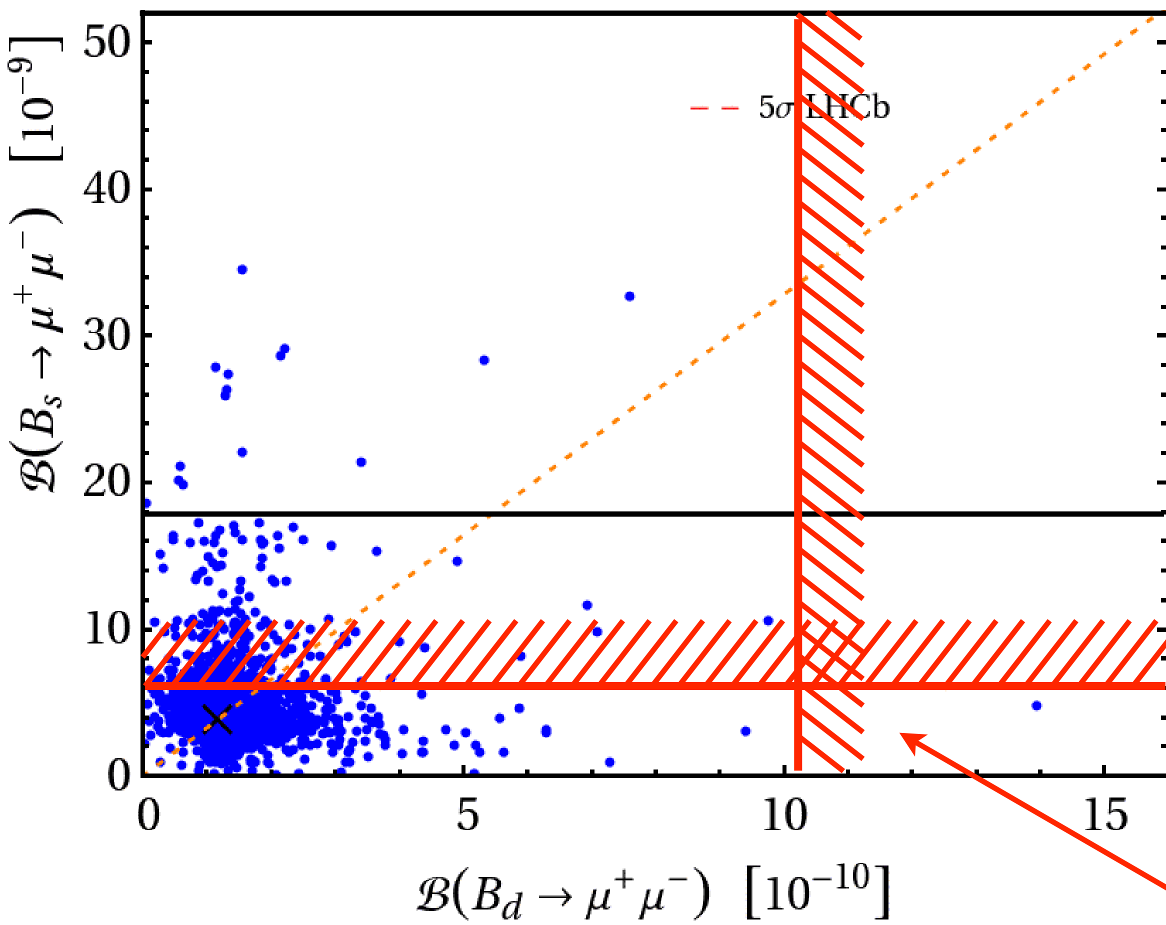
$SU(3)_L \otimes SU(3)_R \to SU(3)_C$
broken by boundary conditions

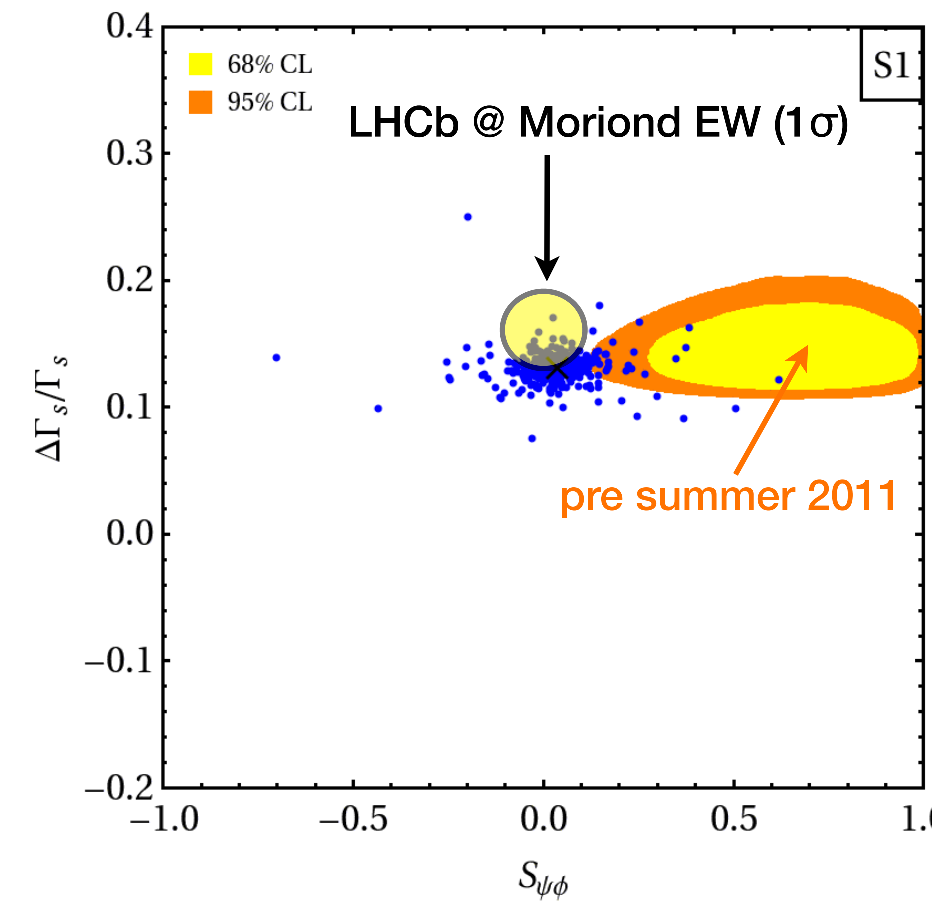


RS-GIM protection with KK masses of order few TeV

Example: New physics in B_s system

Rare decays $B_{d,s} \to \mu^+\mu^-$ and B_s mixing could be significantly affected, but very large deviations from SM are not generic:



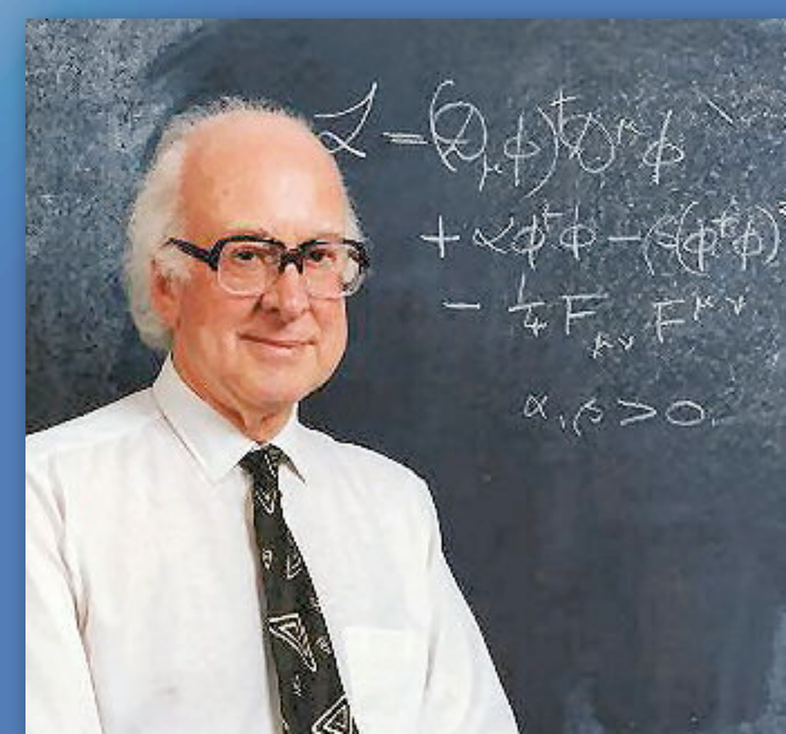


Bauer, Casagrande, Haisch, MN (2009);
see also: Blanke et al. (2008)

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

- New results on $B_s \to \mu^+\mu^-$ begin cutting into the interesting parameter space
- Expected effects in B_s mixing are compatible with new LHCb range

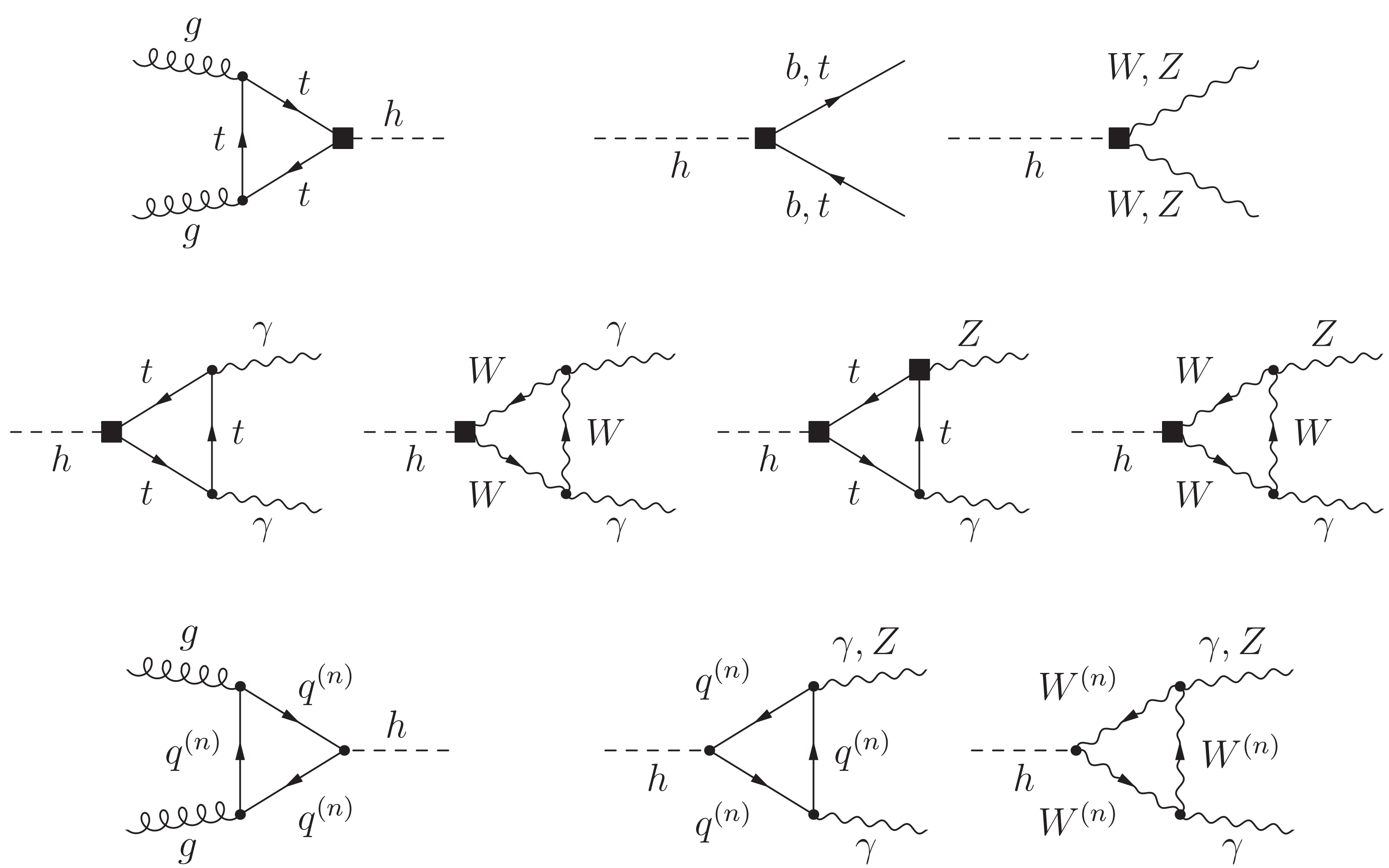
Higgs Properties as an Indirect Probe for New Physics



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

- In 2010, we have performed the first complete one-loop analysis of **Higgs production and decays** in the RS model with custodial symmetry

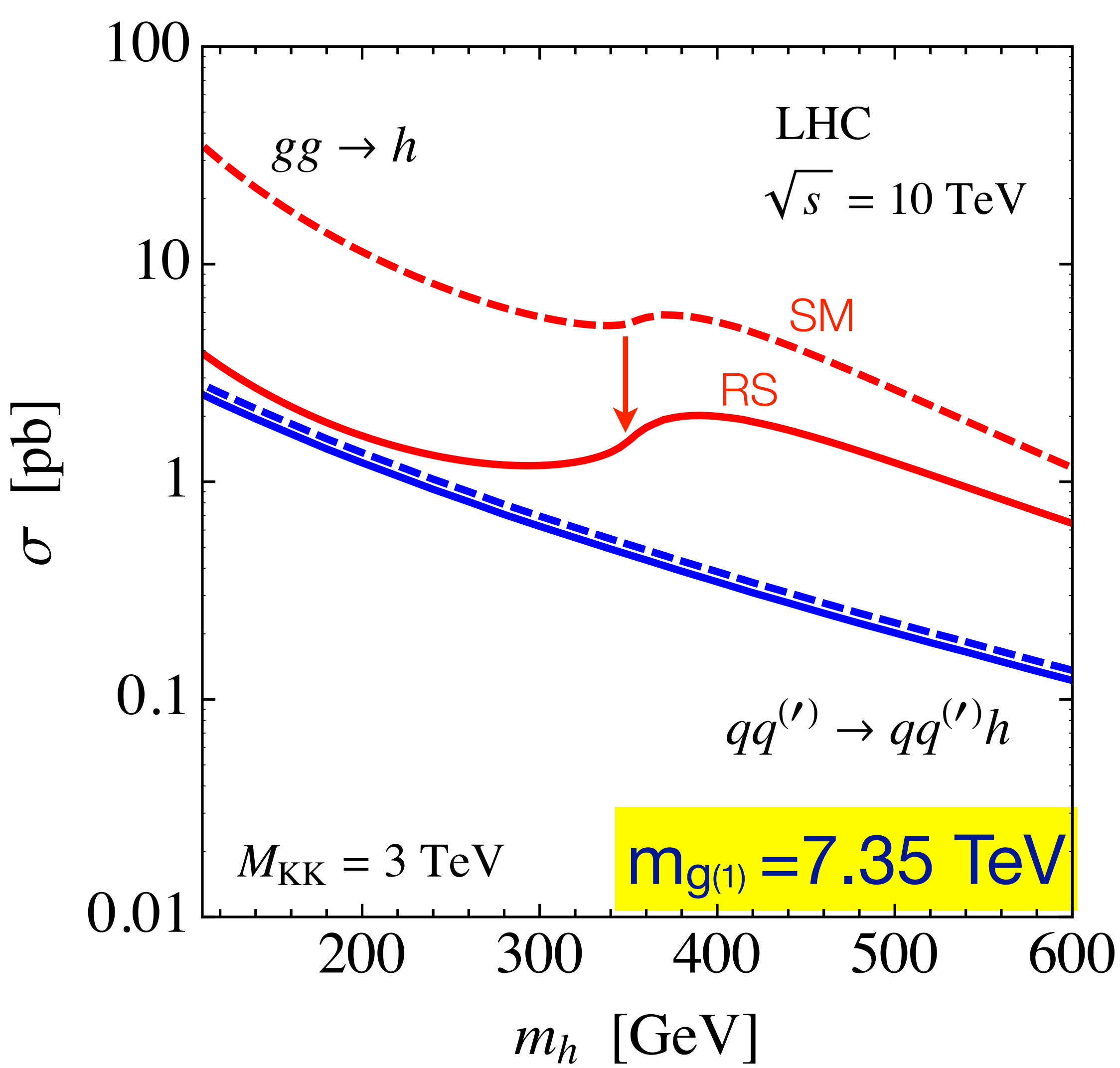


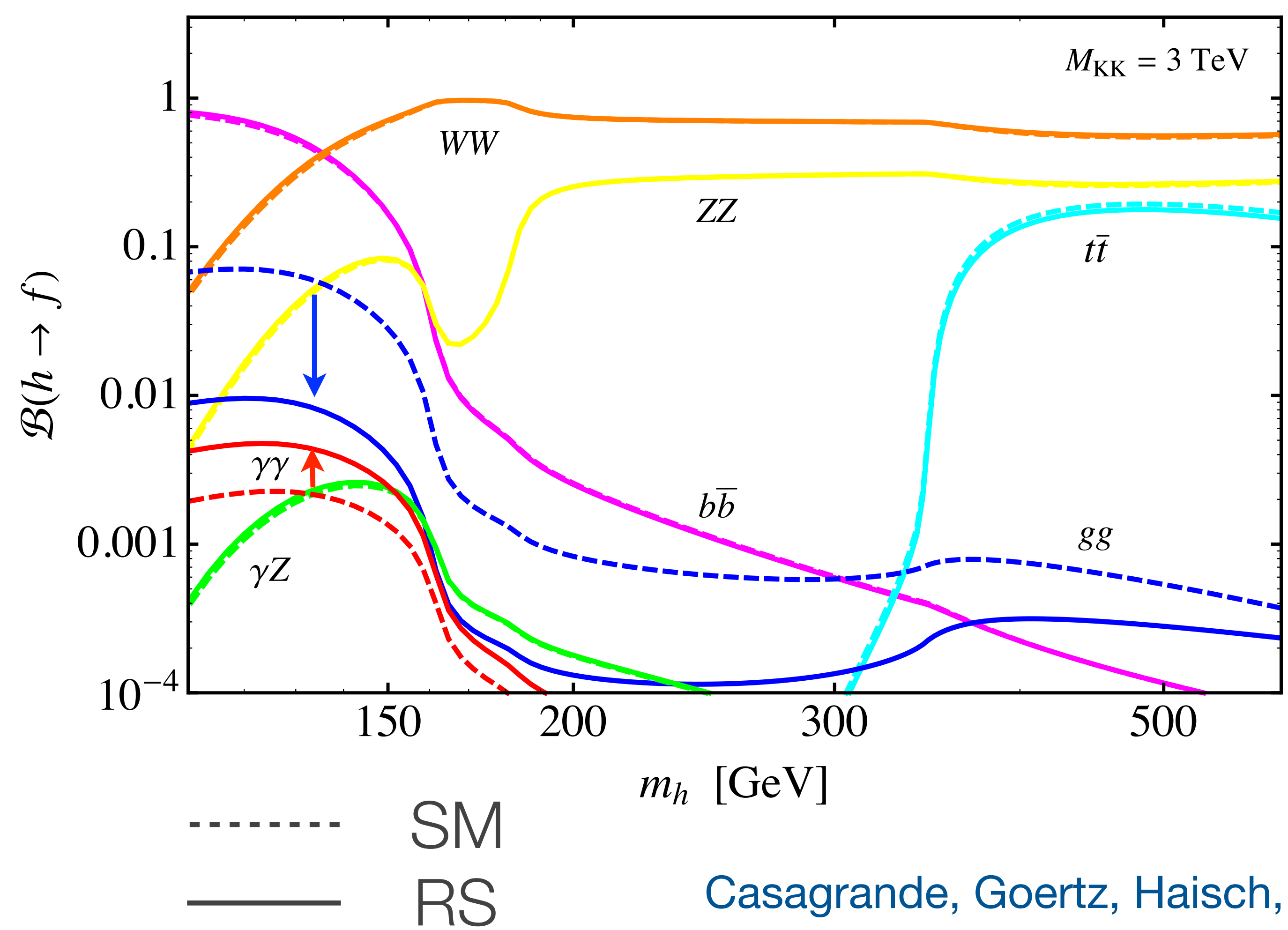
Casagrande, Goertz, Haisch, MN, Pfoh (2010)

Higgs production cross sections

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

Correspondingly, find **significant enhancement** (suppression) of the **h→γγ** (h→gg) branching ratios:





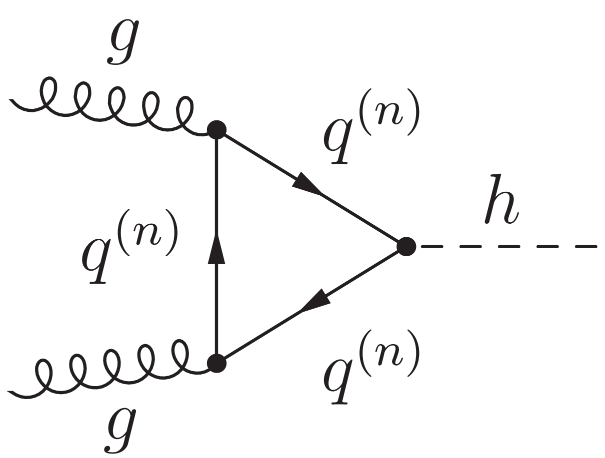
Casagrande, Goertz, Haisch, MN, Pfoh (2010)

Higgs physics as a probe of BSM physics

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

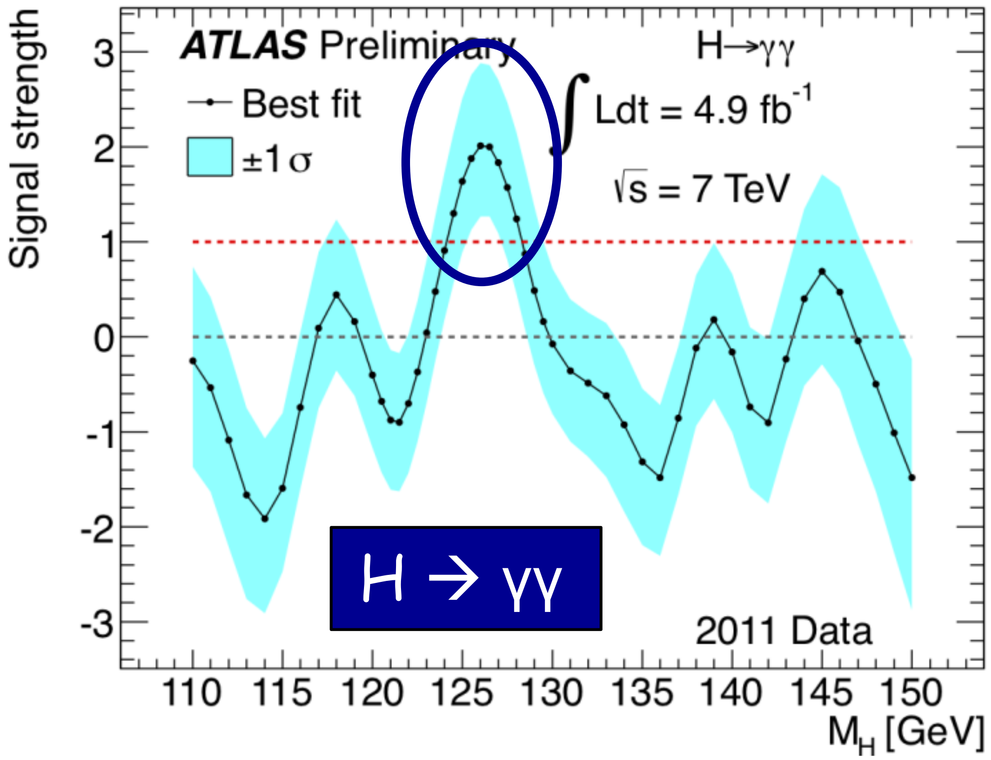
In RS models, the **large number of bulk fermionic fields** in the 5D theory give rise to large loop effects, which change the effective $h\gamma\gamma$ and hgg couplings significantly

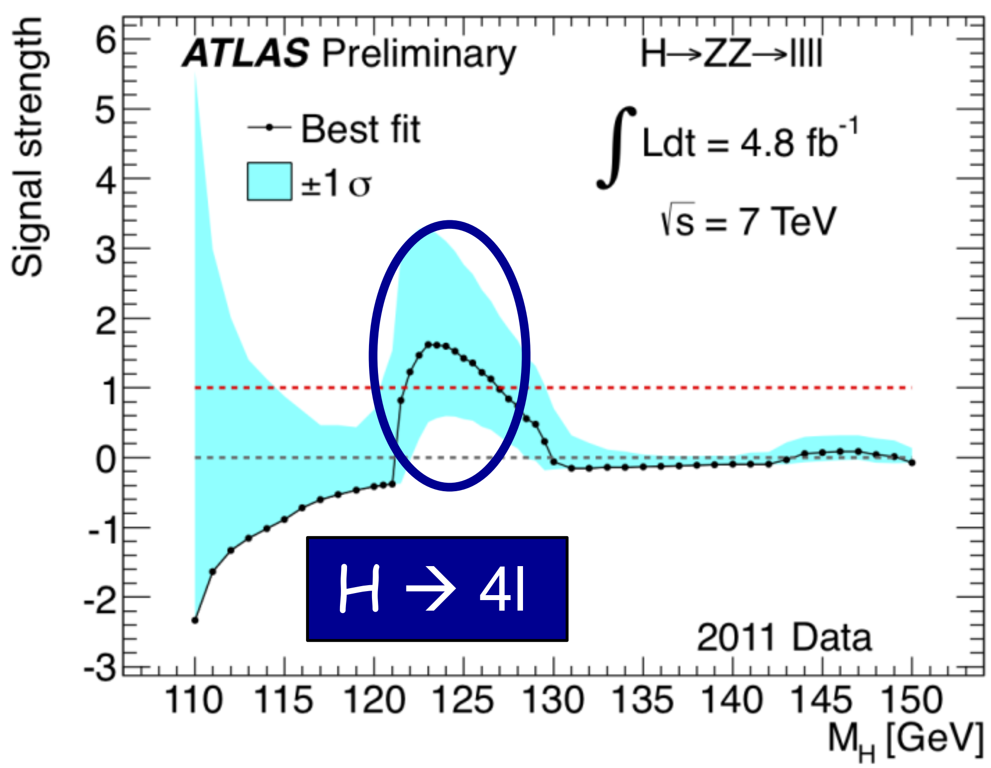


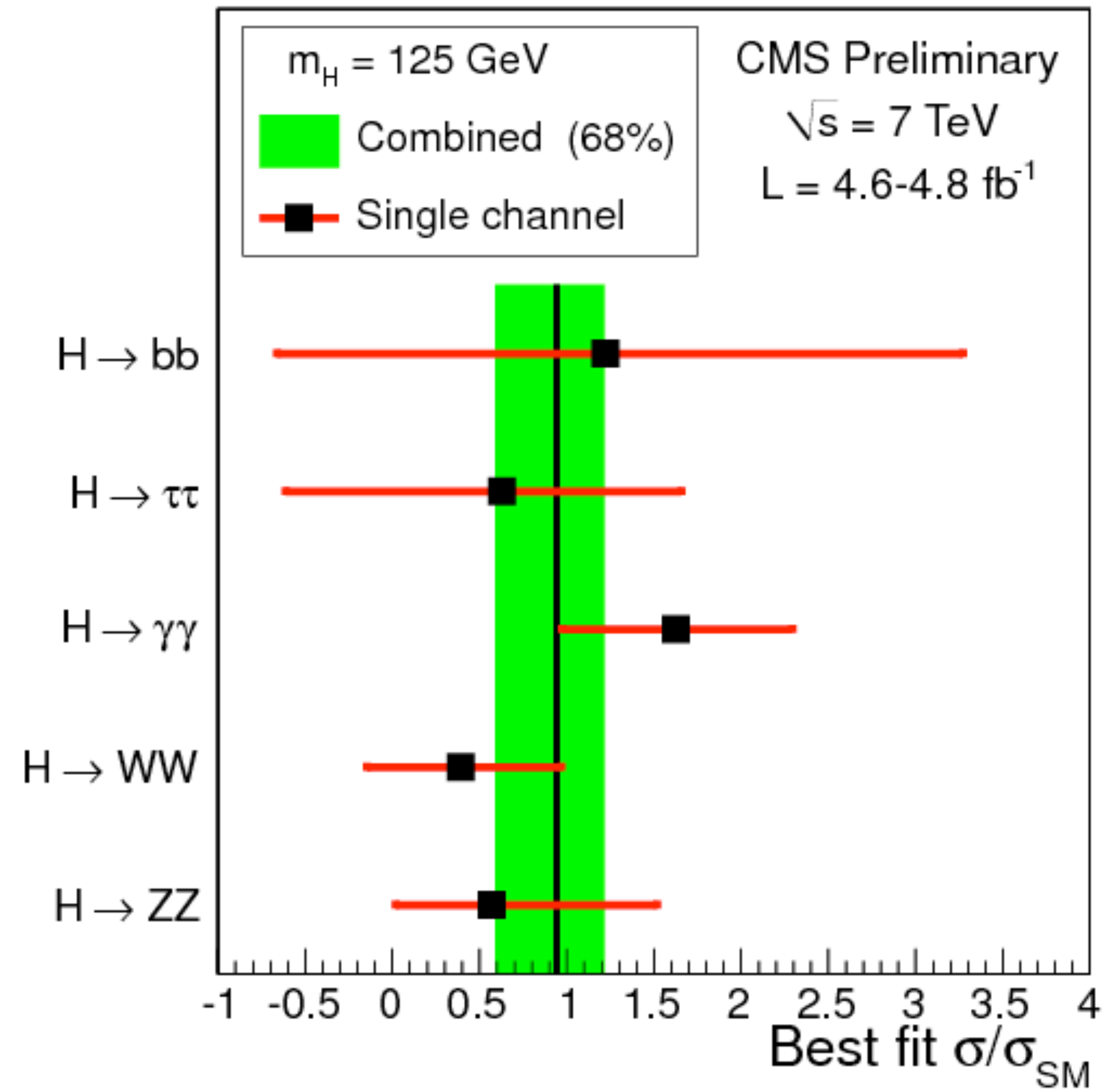
- KK towers of light quarks contribute as much as those of heavy quarks
- effect even more pronounced in models with custodial protection

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

Implications of recent LHC data







Preliminary hints:

- rate for **h→γγ** may be somewhat enhanced w.r.t. SM (about 1 standard deviation)
- rate for **h→ZZ** may be somewhat smaller

Higgs phenomenology in RS

- Have recently obtained closed, **analytic expressions** for the Higgs production cross section as well as the main Higgs decay rates, obtained after summing over the infinite towers of KK states

- Work with a brane-localized Higgs sector, but regularize the Higgs profile carefully

- Despite of the fact that the sum over KK modes converges, it is nevertheless important to implement the (physical) UV cutoff inherent in RS models, which require UV completions (quantum gravity)

Carena, Casagrande, Goertz, Haisch, MN (in preparation)

- Now present a phenomenological analysis of these results

Goertz, Haisch, MN: arXiv:1112.5099

Higgs phenomenology in RS: production

Goertz, Haisch, MN: arXiv:1112.5099

Higgs production cross section:

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

small modification due to change of Higgs VEV: κ_v=1.014

- Modification due to effect of infinite 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!

Higgs phenomenology in RS: production

Goertz, Haisch, MN: arXiv:1112.5099

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➡ dominant effect described by 5D Yukawa matrices!

effect of KK tower: **destructive!**

$$f(x) = \frac{x(1-x^2)}{1+x^2} \tanh^{-1} x$$

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

anarchical 5D Yukawa matrices

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

Higgs phenomenology in RS: production

Goertz, Haisch, MN: arXiv:1112.5099

Higgs production cross section:

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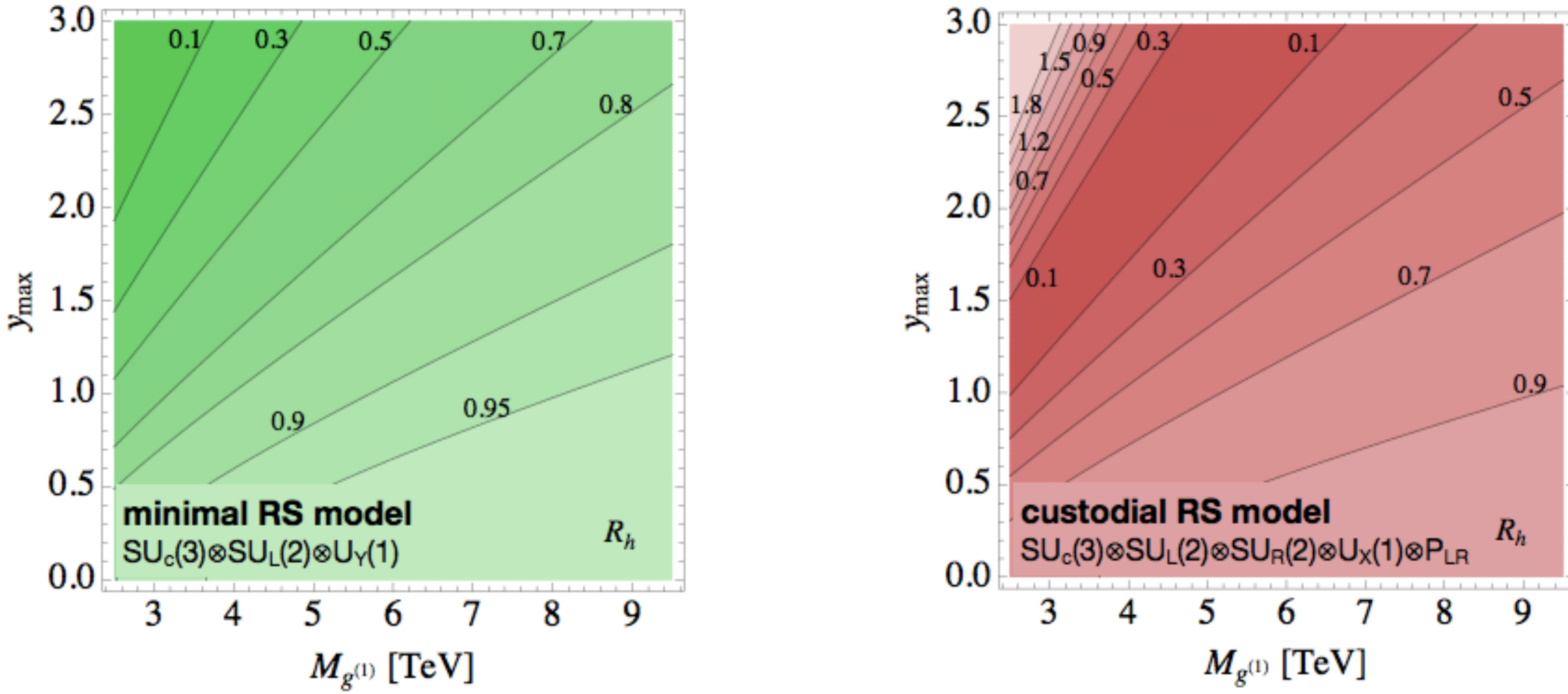
- Modification due to effect of infinite Kaluza-Klein tower of quark states:

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

- 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 $\mathbf{y_{max}=3}$)
- All 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:

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

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

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

$$L = \ln\frac{M_{\rm Pl}}{1\ {\rm TeV}} \approx 37$$

- 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:

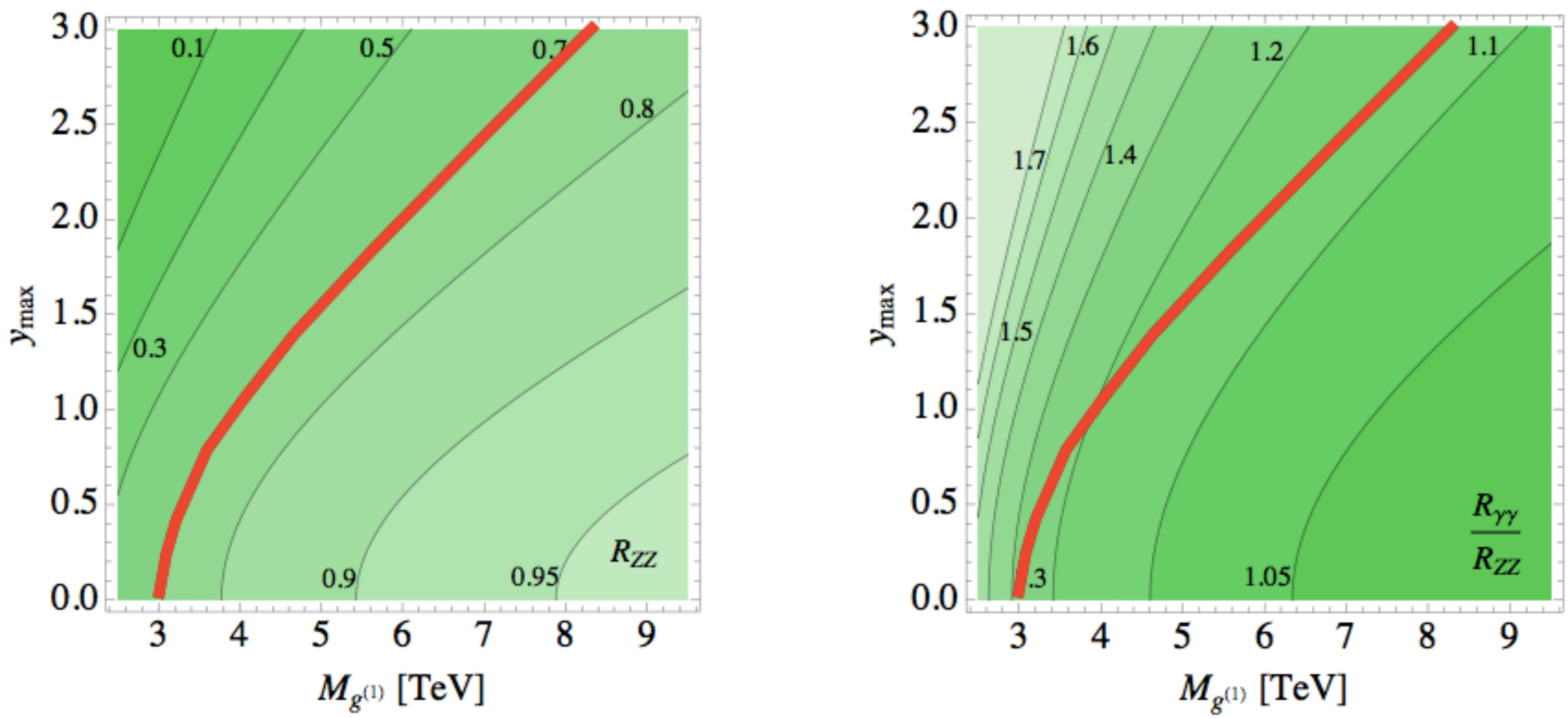
$$\boxed{R_f = \frac{\big[\sigma(pp\to h)\,\mathrm{Br}(h\to f)\big]_{\mathrm{RS}}}{\big[\sigma(pp\to h)\,\mathrm{Br}(h\to f)\big]_{\mathrm{SM}}}}$$

- 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

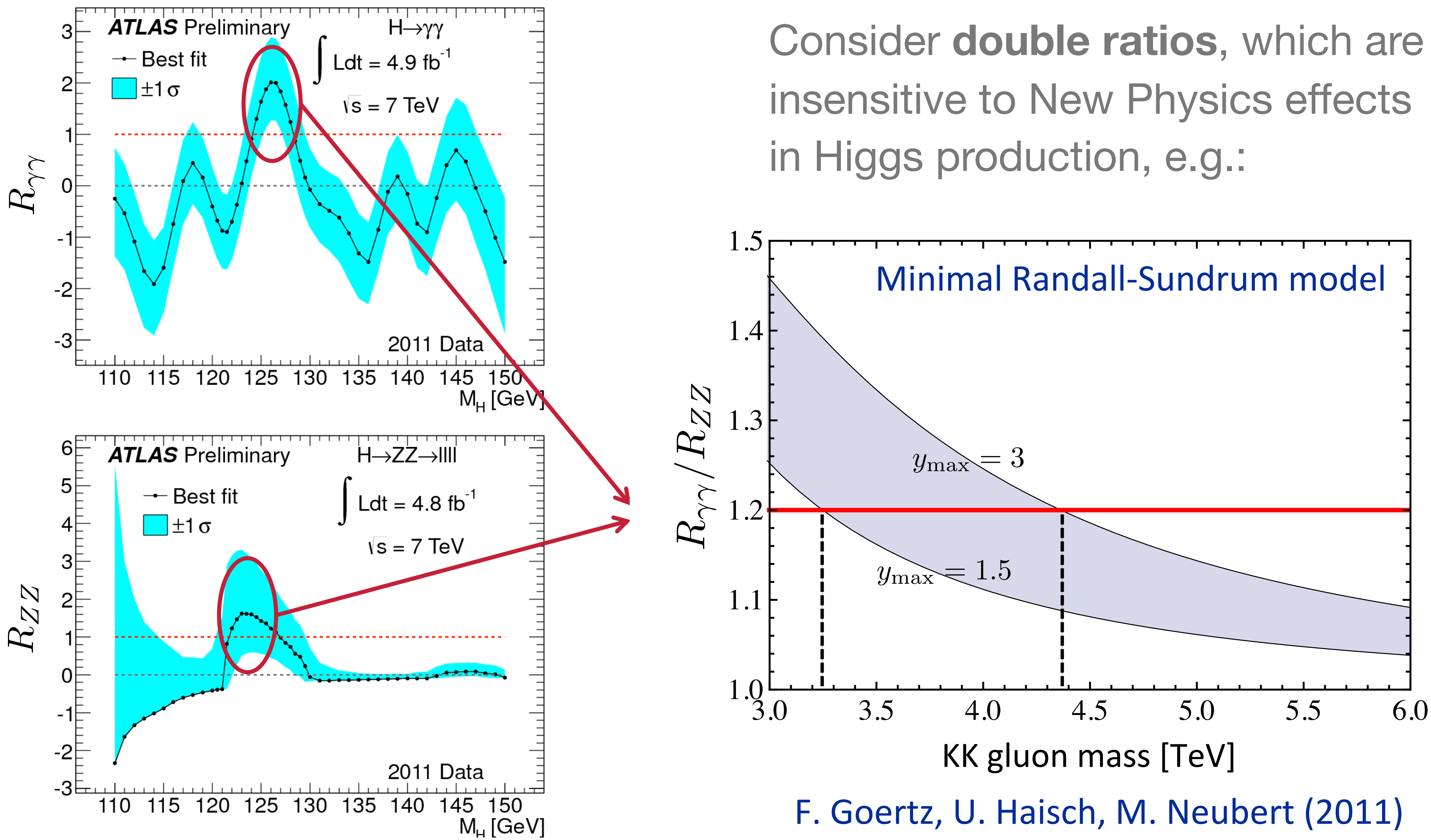
Minimal RS model with bulk fermions and gauge fields:



- Most previous studies of RS models assumed y_{max}=3
- A measurement $\mathbf{R_{ZZ} \approx 0.7}$ 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

A possible future game to play:

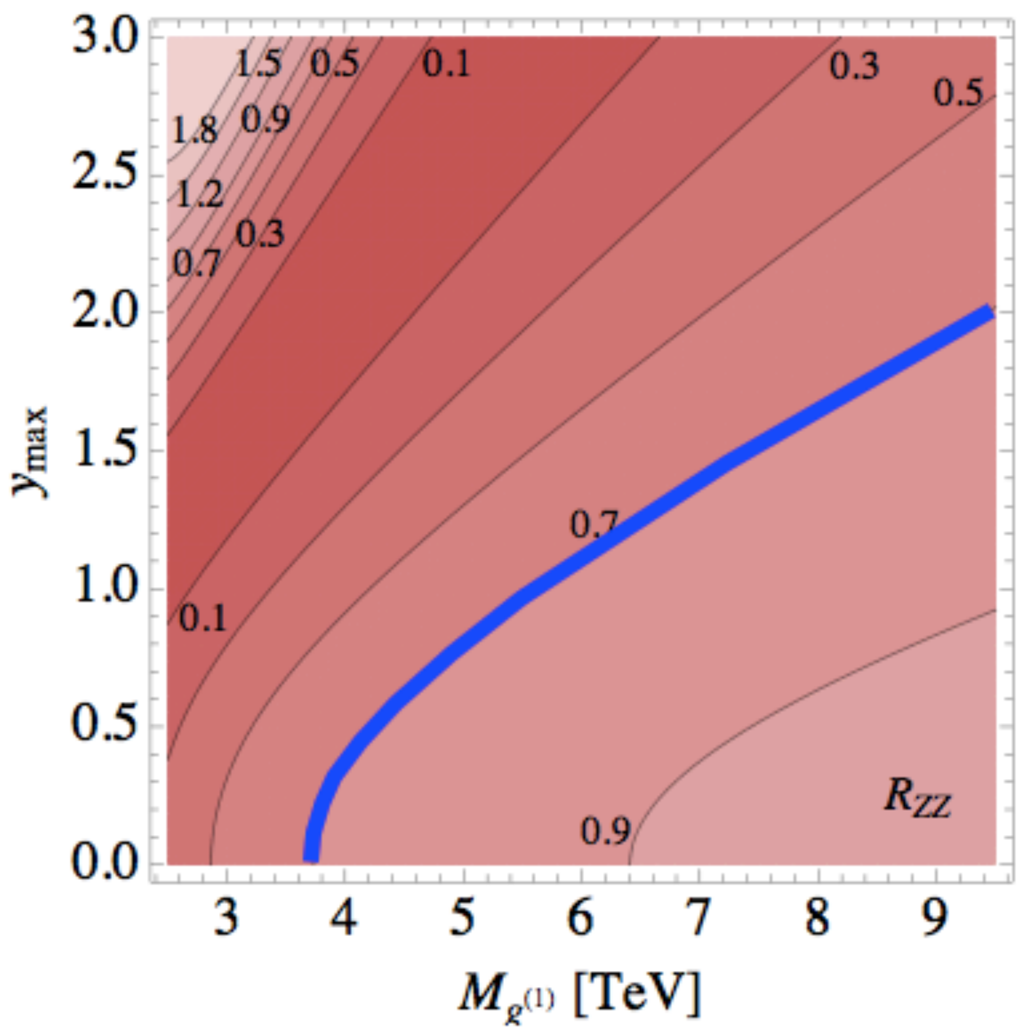


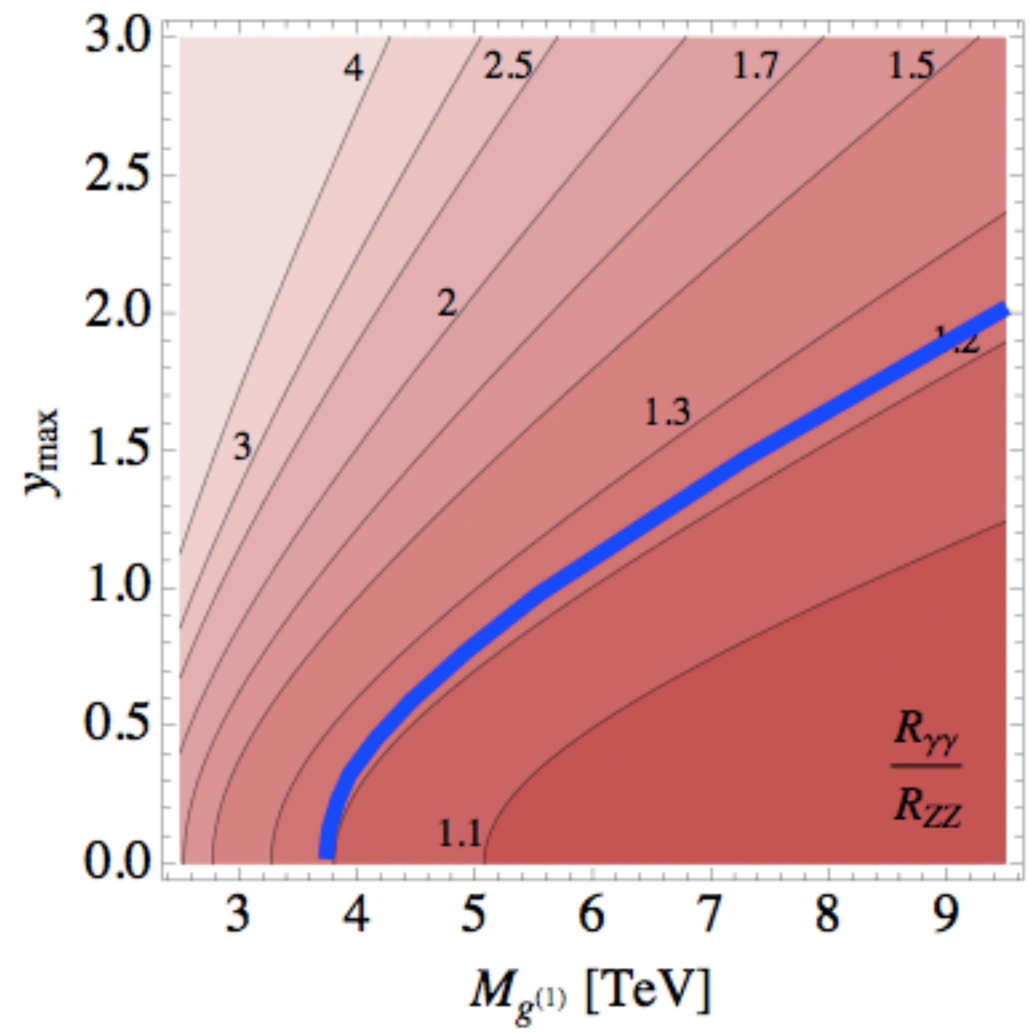
Consider **double ratios**, which are insensitive to New Physics effects in Higgs production, e.g.:

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

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)

Conclusions

- **Higgs phenomenology** provides a **superb laboratory for probing new physics** in the EWSB sector at the quantum level
- 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
- **Warped extra-dimension models** provide an appealing framework for addressing the **hierarchy problem** and the **flavor puzzle** within the same geometrical approach
- Find that the contribution of the Kaluza-Klein towers of SM quarks is **independent** of the quark mass and given entirely 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**