Flavor Physics in a Warped Extra Dimension

Matthias Neubert

Institute for Physics, Johannes Gutenberg University Mainz &
Institute for Theoretical Physics, University of Heidelberg

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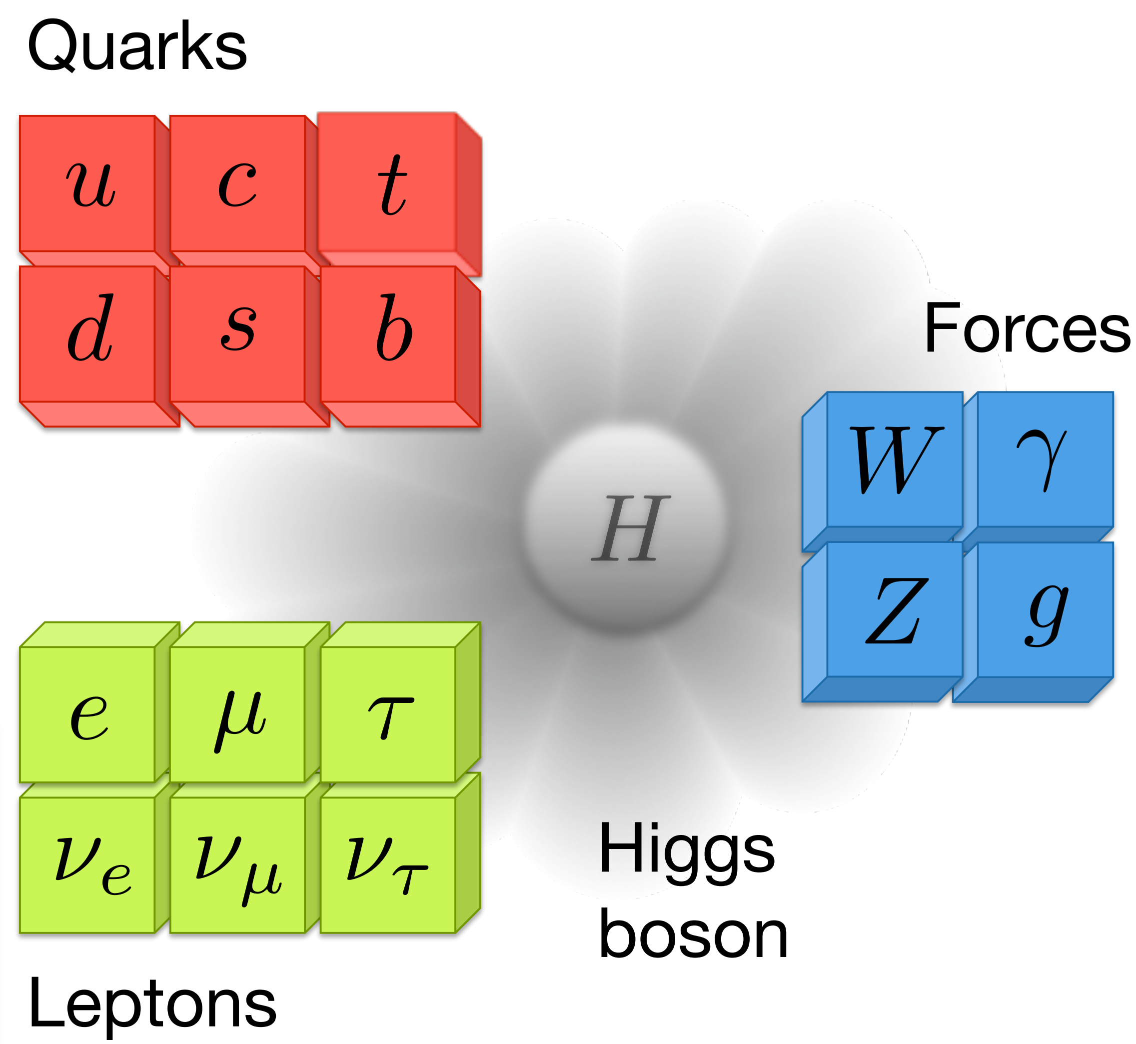
Standard Model and Beyond

Fundamental laws derived from few, basic guiding principles:

- Symmetries (gauge theories)
- Simplicity and beauty (few parameters)
- Naturalness (avoid fine-tuning)
- Anarchy (everything is allowed)



But many questions remain unanswered:

- 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"

Standard Model and Beyond: The Gordian Knot

What is the “New Physics” and how to find it ?

Standard Model and Beyond


4th generation


extended Higgs sectors


extended technicolor


left-right symmetry


leptoquarks


universal extra dimensions


large extra dimensions


warped extra dimensions


gauge-Higgs unification


Higgsless models

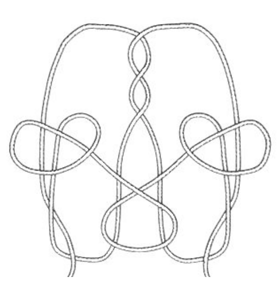

MSSM


CMSSM

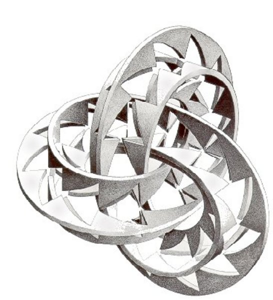

NMSSM


νMSSM


SUSY GUTs


unparticles


Little Higgs


hidden valleys

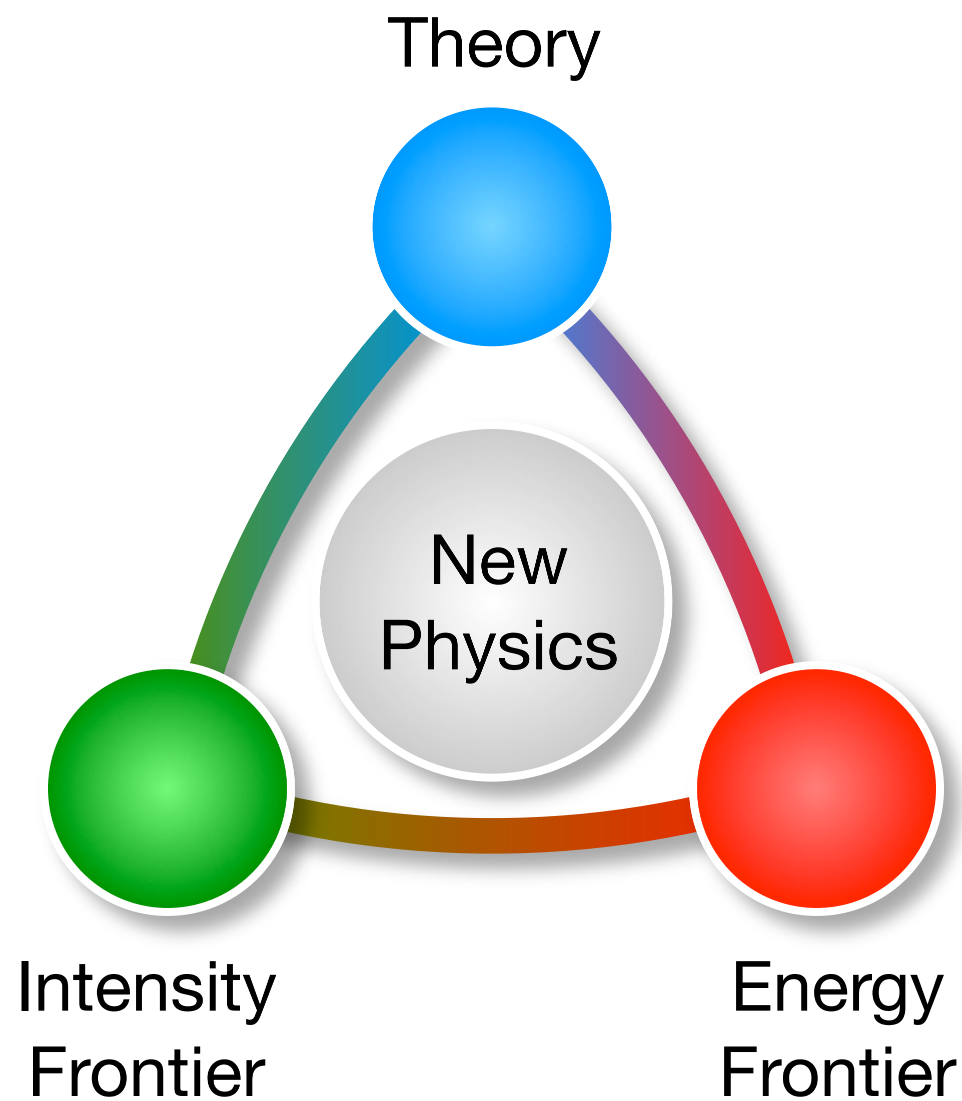

not yet thought of ...

Searches for New Physics: Interplay

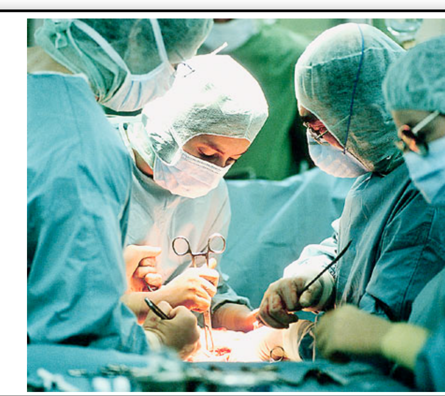
<u>Complementarity and synergy:</u>

Answering the open questions of elementary particle physics requires a joint effort:

- Theory: precision calculations in the SM, studies of New Physics, model-building, ...
- High-energy experiments: Tevatron, LHC, ILC (?), CLIC (?), Muon Collider (?), ...
- Low-energy experiments: BaBar, Belle, Super-*B*, NA62, J-PARC, Project X, neutrino physics, EDMs, $(g-2)_\mu$, ...

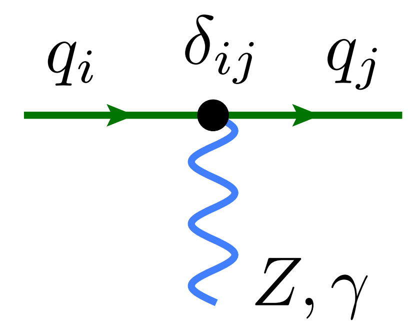


Quark flavor physics is a crucial component in this program, which provides surgical probes of subtle corrections to fundamental interactions

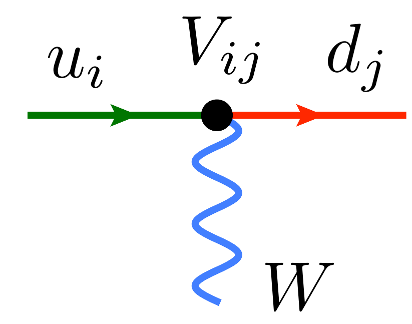


Flavor Structure in the SM and Beyond

Flavor physics means phenomena related to Yukawa couplings and generation-changing interactions in the fermion sector



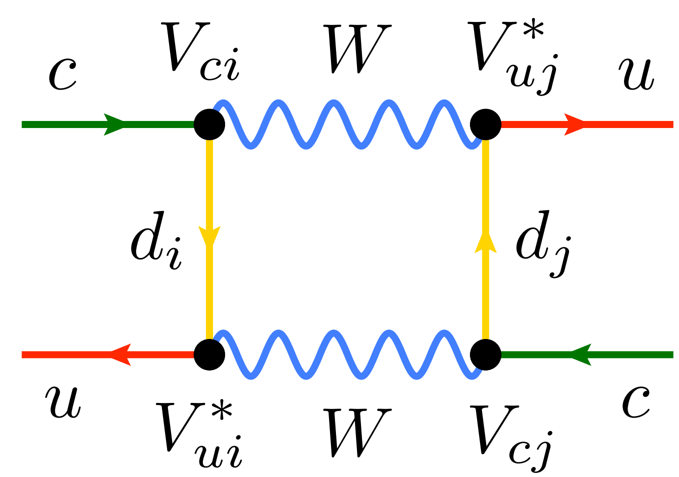
δ: unit matrix



V: CKM matrix

In SM:

- all flavor-violating interactions encoded in Yukawa couplings to Higgs boson
- suppression of flavor-changing neutral currents (FCNCs) and CP violation in quark sector due to unitarity of CKM matrix, small mixing angles, and GIM mechanism



$$\sum_{i,j} \lambda_i \lambda_j \, f(m_i, m_j) \approx \lambda_b^2 \, \frac{m_b^2 - m_d^2}{M_W^2} + \lambda_s^2 \, \frac{m_s^2 - m_d^2}{M_W^2} \approx \lambda_b^2 \, \frac{m_b^2}{M_W^2}, \quad \lambda_i \equiv V_{ui}^* V_{ci}$$

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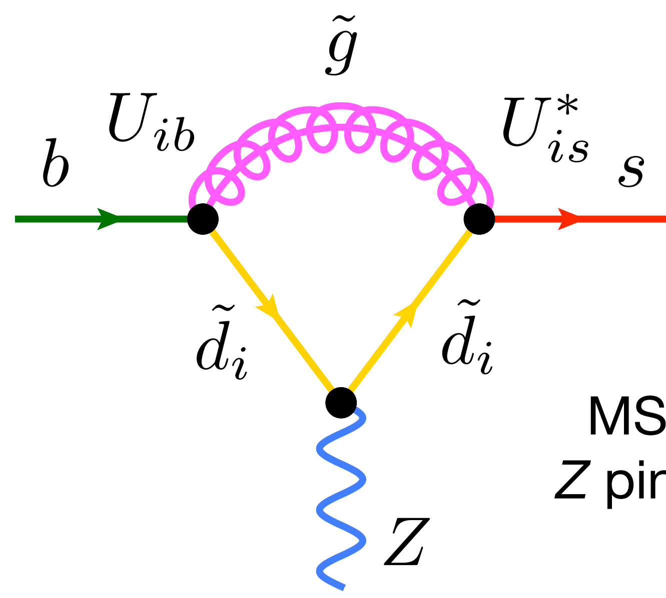
Flavor Structure in the SM and Beyond

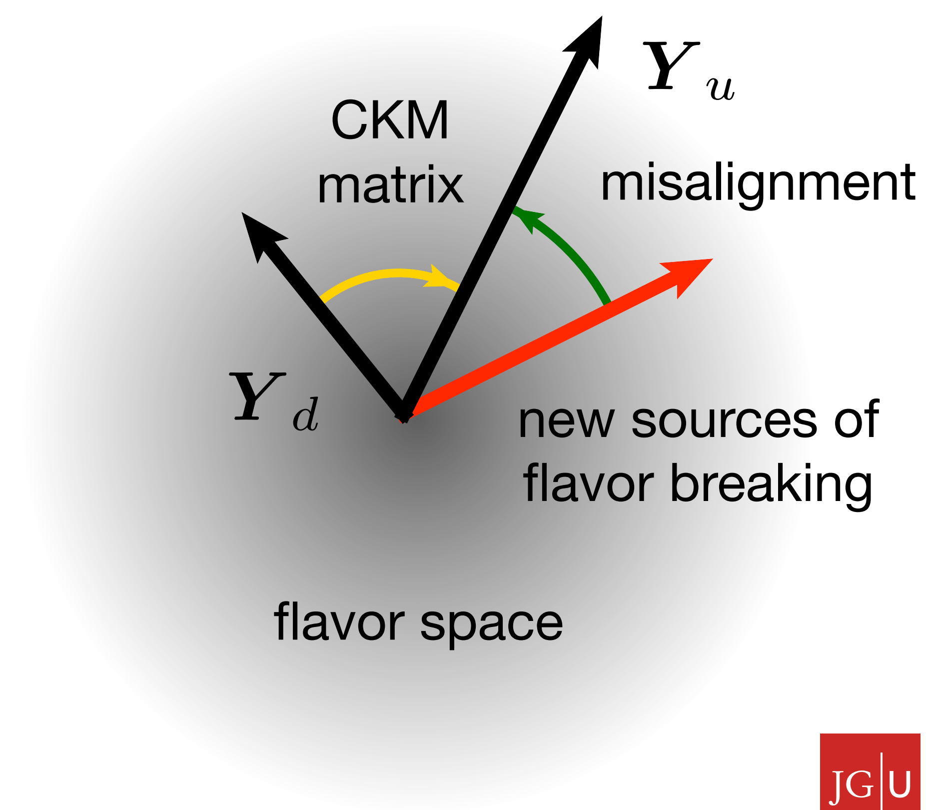
In extensions of SM, additional flavor and CP violation can arise from exchange of new scalar (H^+, $\tilde{q}$, ...), fermionic ($\tilde{g}$, t', $t^{(1)}$, ...), or gauge (Z', $g^{(1)}$, ...) degrees of freedom

- 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)



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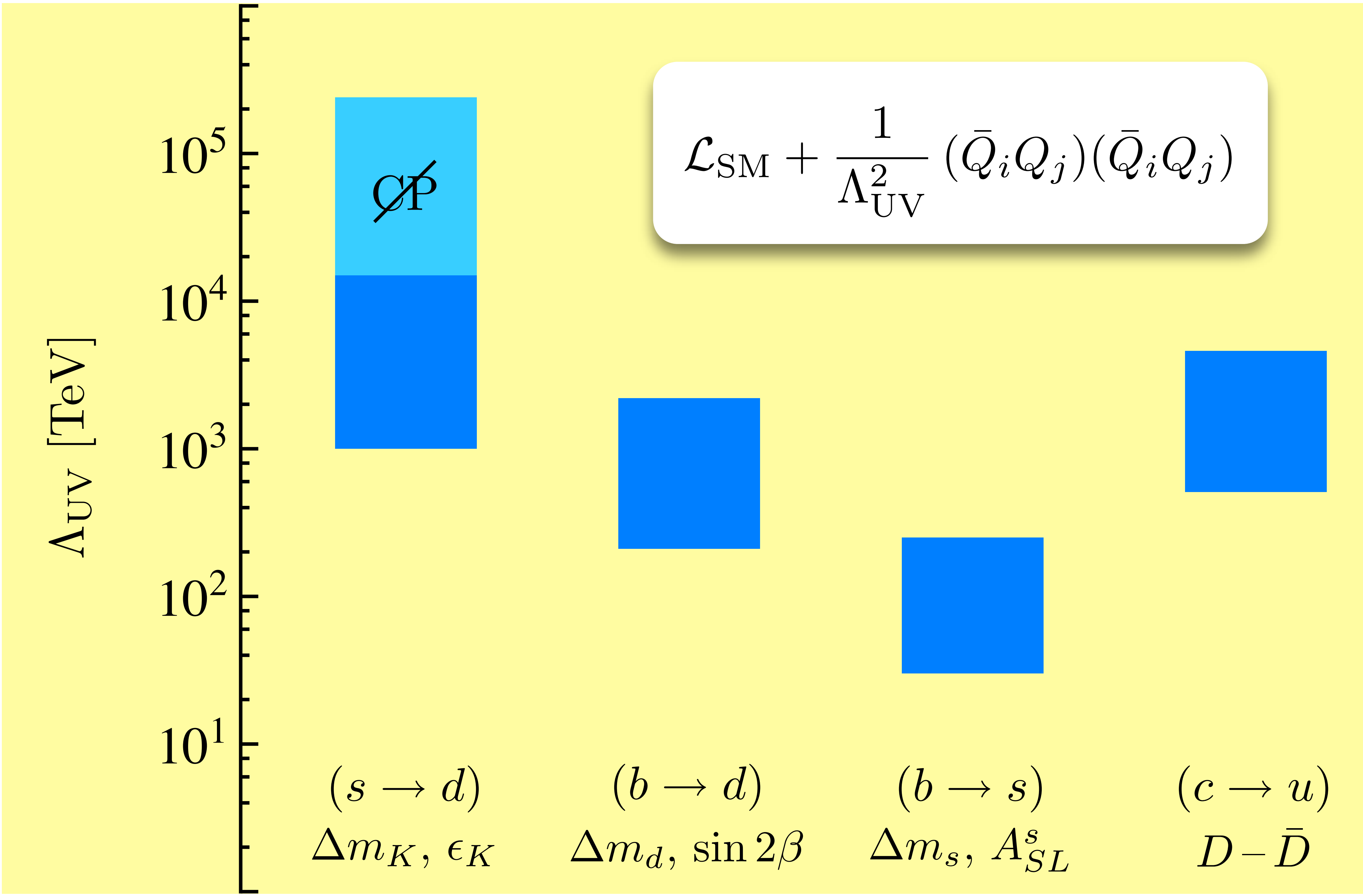
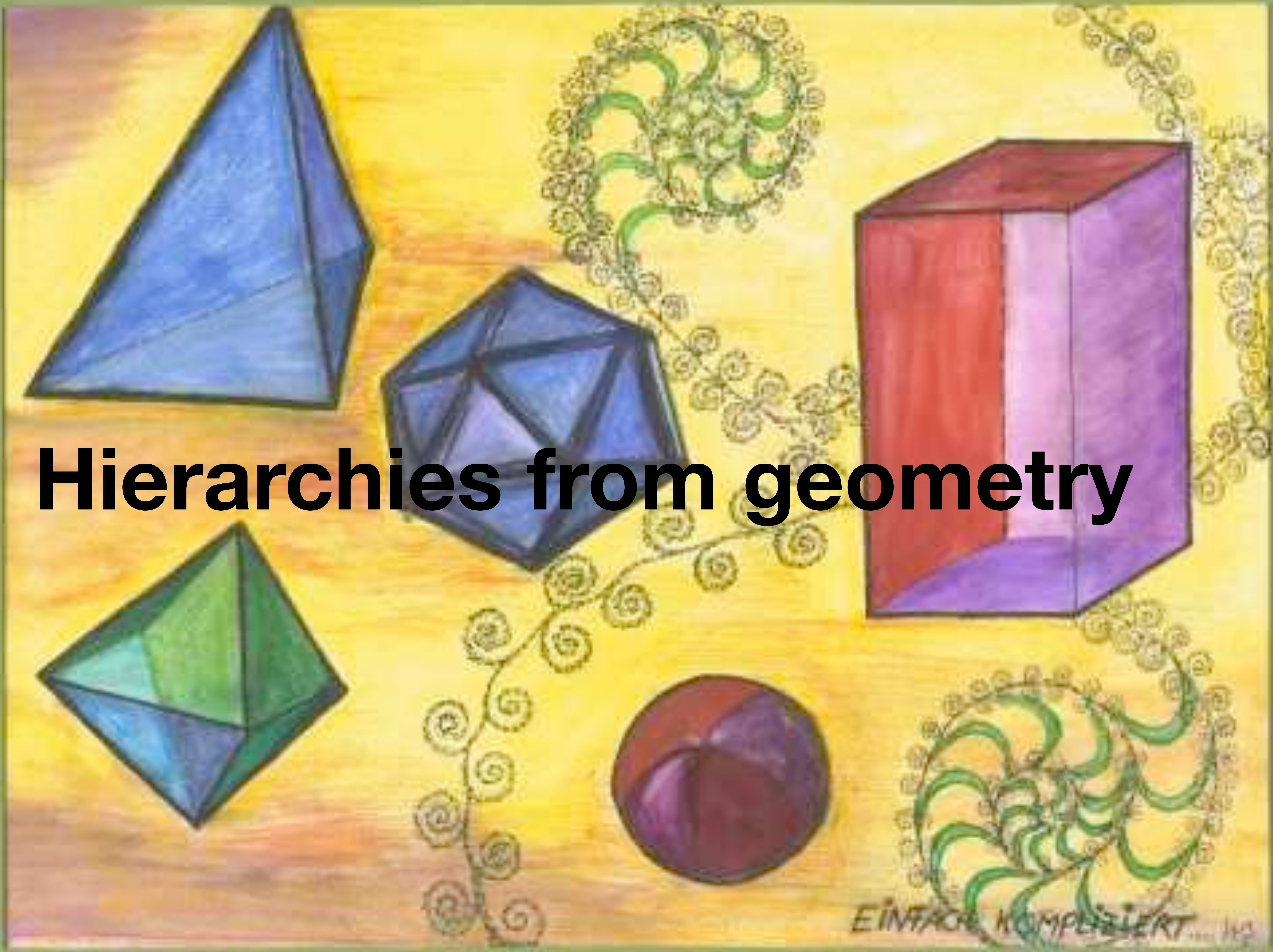
Flavor Structure in the SM and Beyond



Generic bounds without flavor symmetry

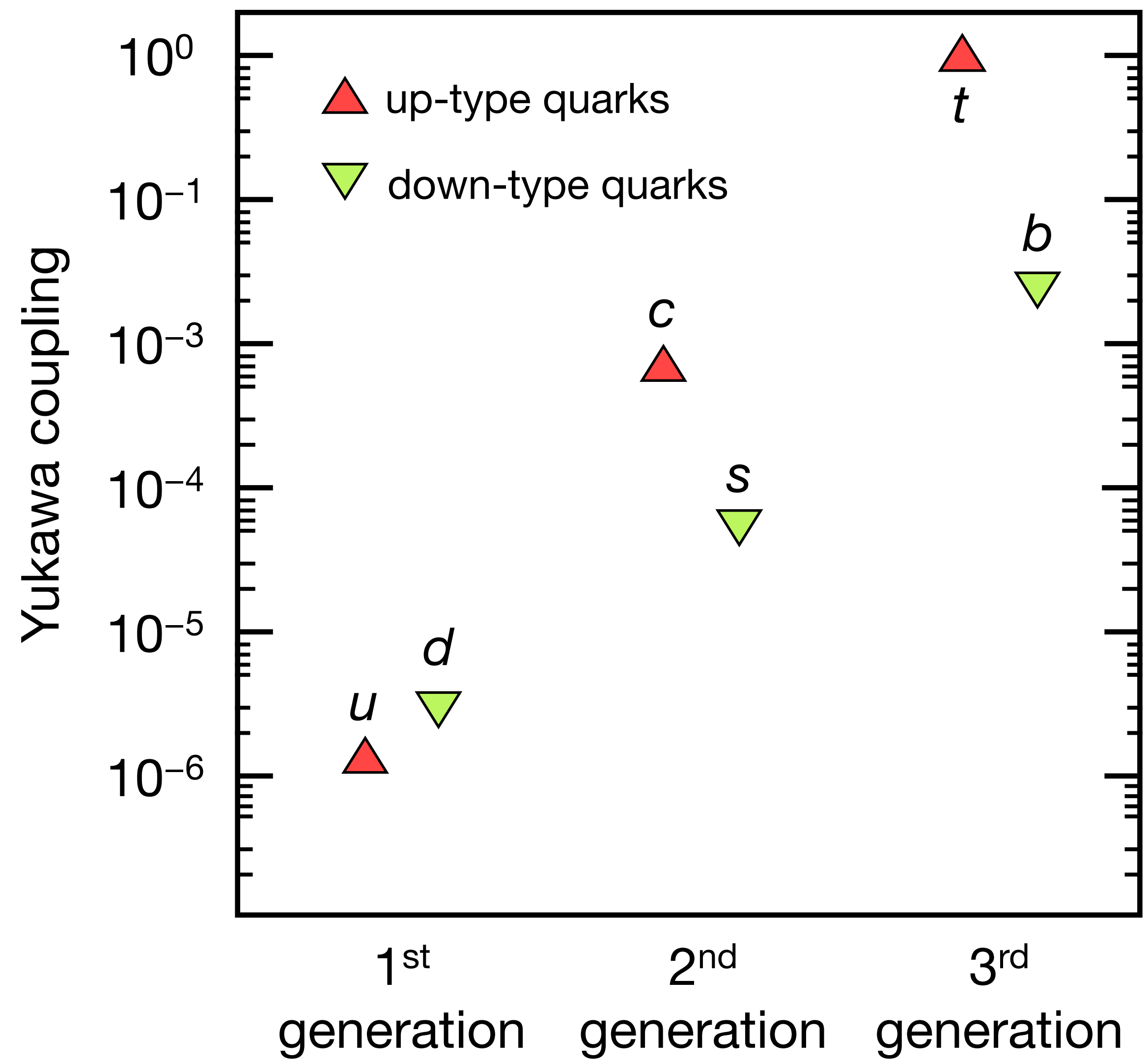
Hierarchies from geometry



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 many orders of magnitude (1st hierarchy)?



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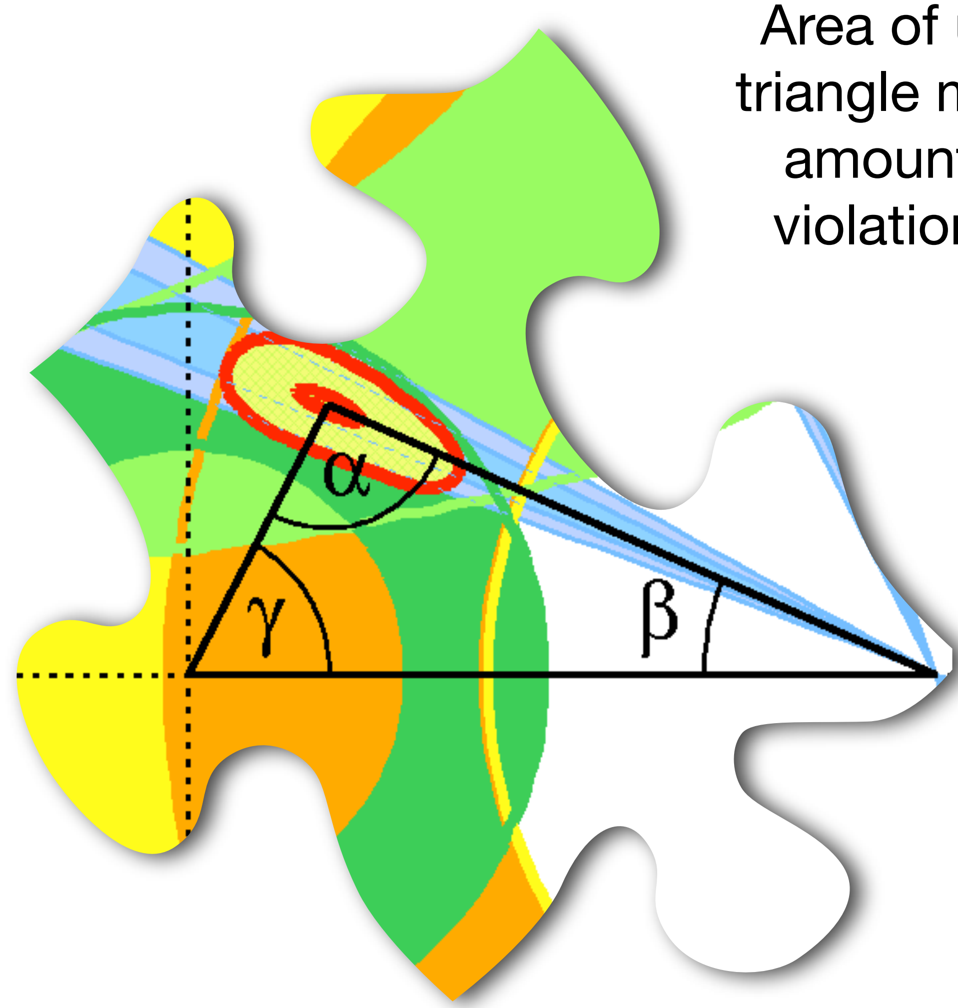
What is the Dynamics of Flavor?

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 many orders of magnitude (1st hierarchy)?
- Why is the mixing between different generation governed by small mixing angles (2nd hierarchy)?
- Why is the CP-violating phase of the CKM matrix unsuppressed?

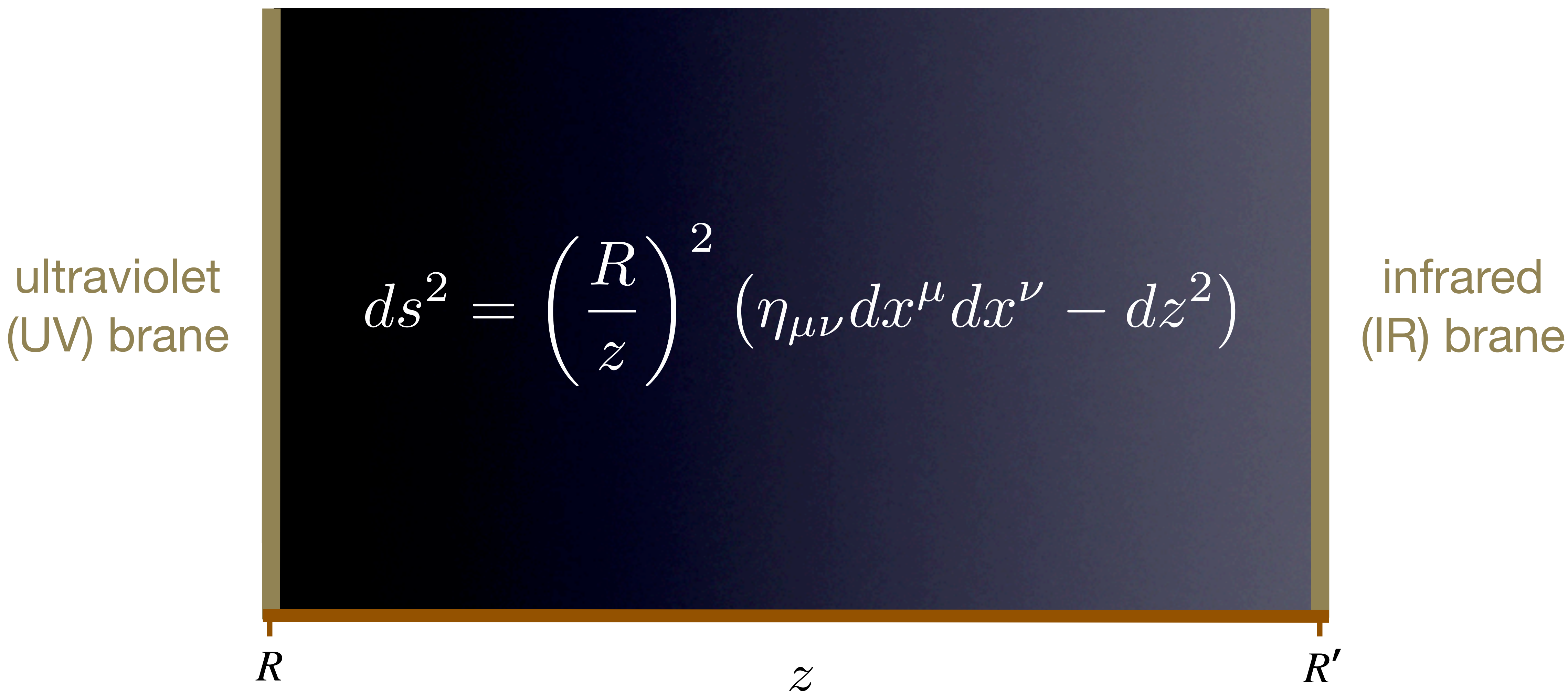


Area of unitarity triangle measures amount of CP violation in SM

Answers to these questions necessarily require going beyond the SM -- an interesting approach is offered by Randall-Sundrum models with warped extra dimensions

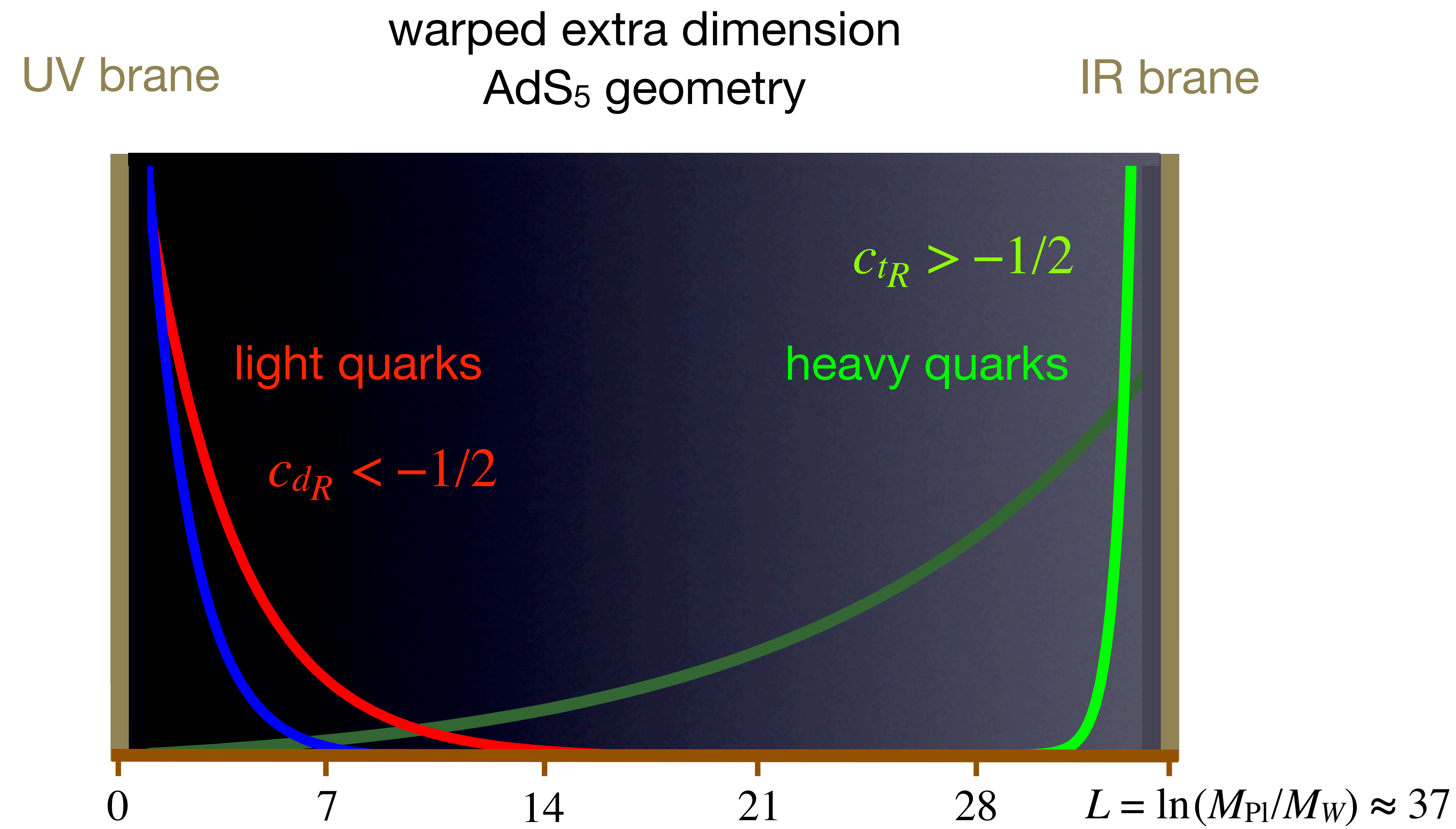
Flavor Structure in RS Models

Randall, Sundrum (1999)



- Solution to gauge hierarchy problem via gravitational redshift
- AdS/CFT calculable strong electroweak-symmetry breaking: holographic technicolor, composite Higgs
- Unification possible due to logarithmic running of couplings

Flavor Structure in RS Models



Localization of fermions in extra dimension depends exponentially on O(1) parameters: five-dimensional bulk masses parameters c_q

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

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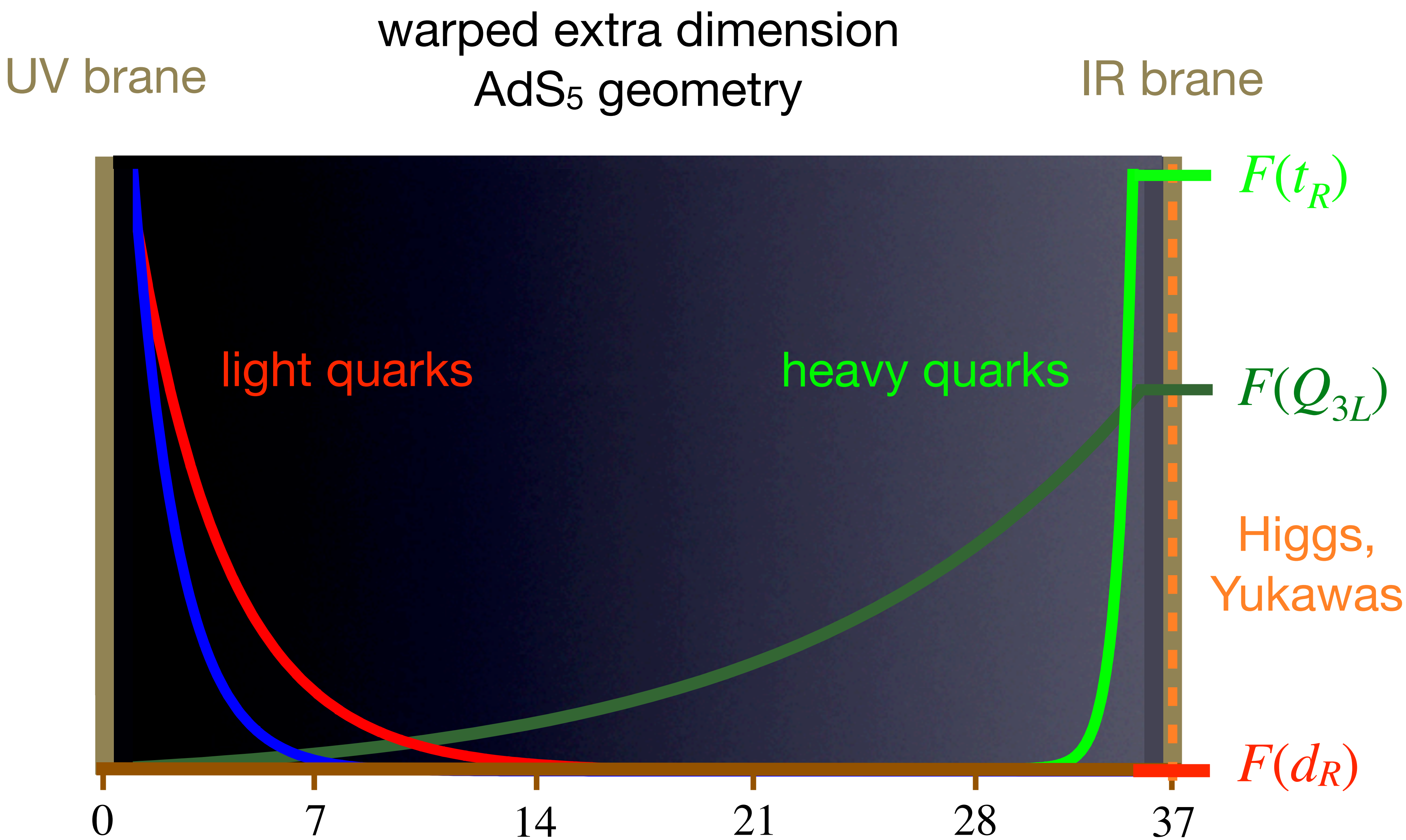
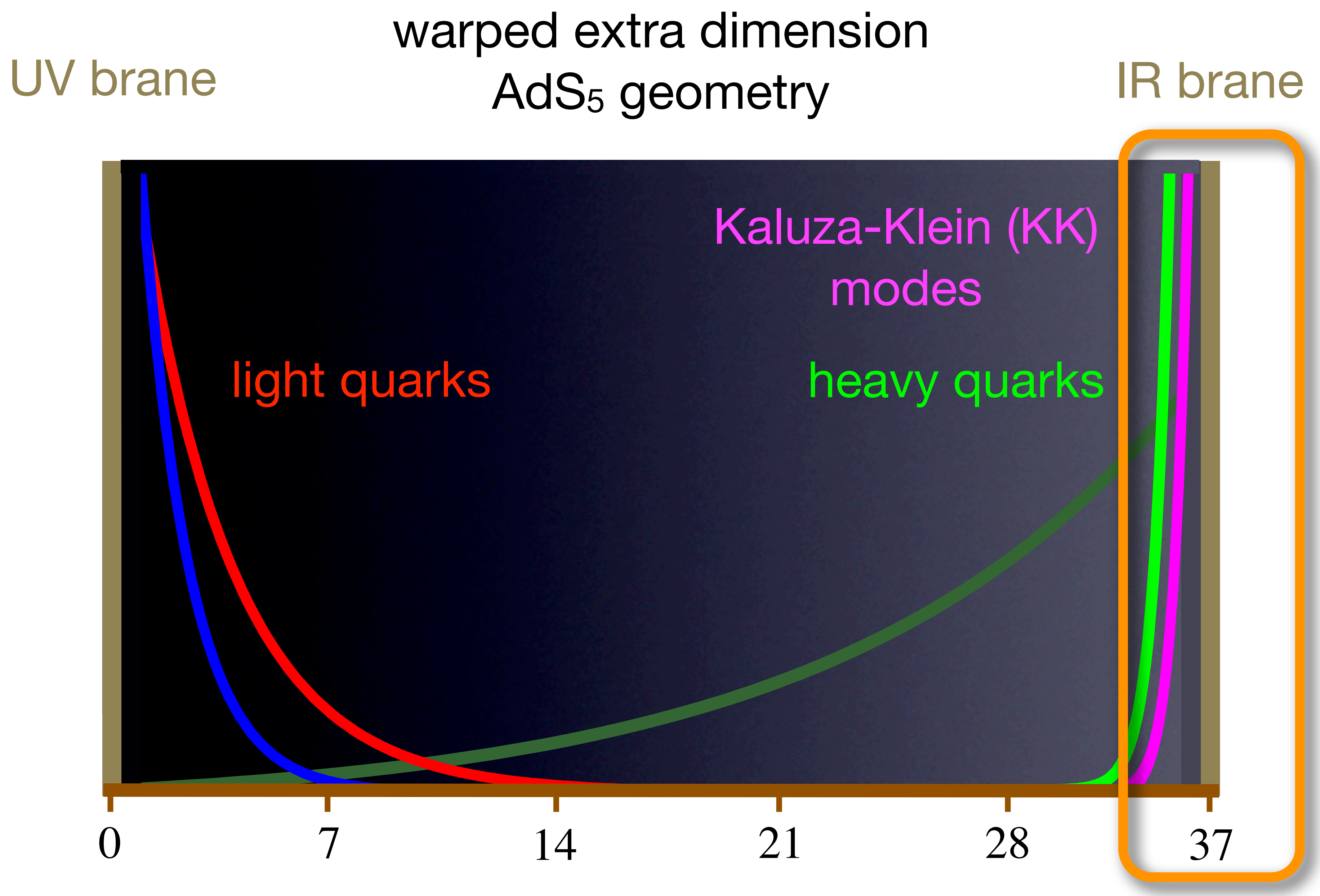
Flavor Structure in RS Models



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)

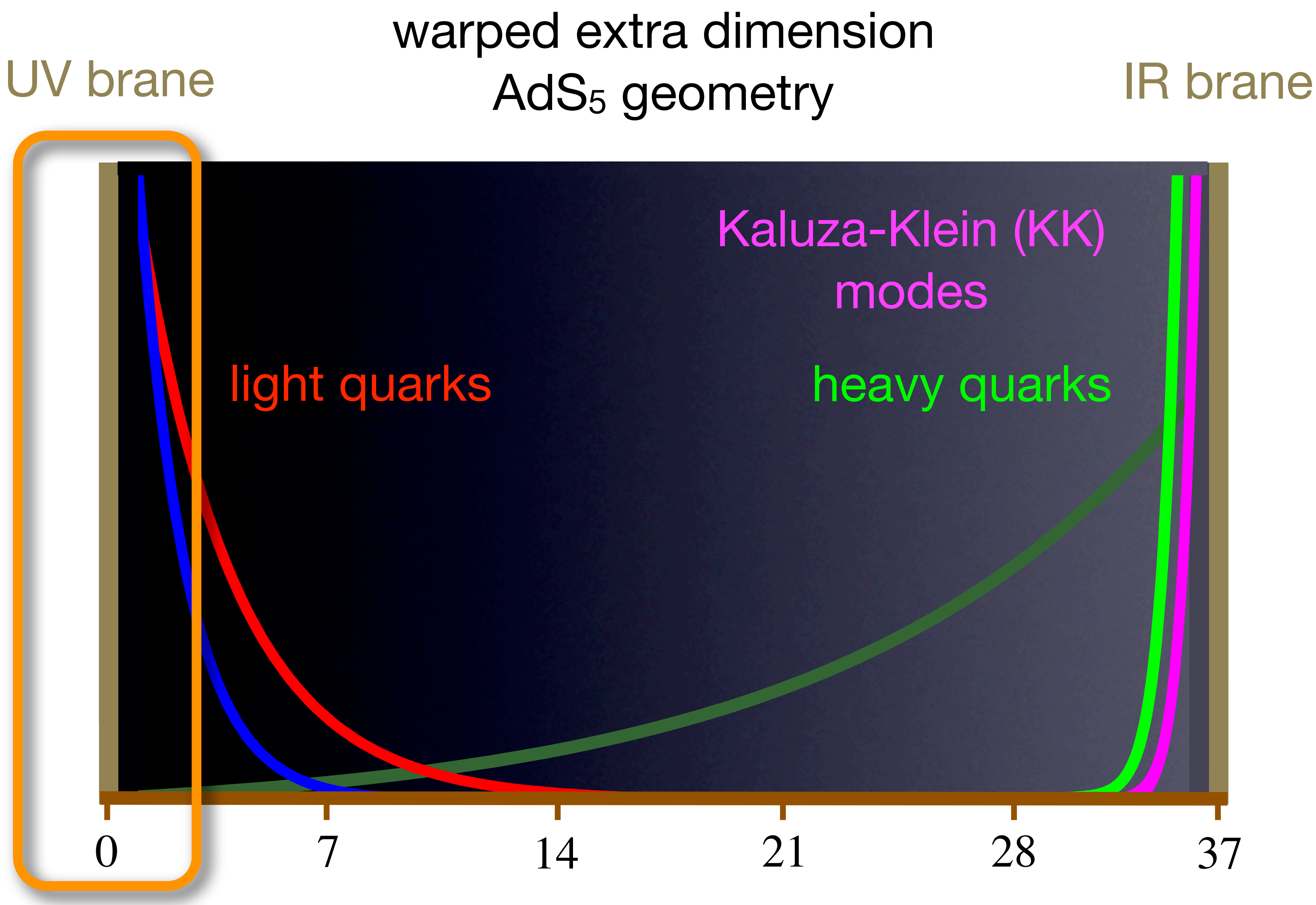
Flavor Structure in RS Models



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

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

Flavor Structure in RS Models



Since light quarks live in UV, their couplings to W and Z bosons, as well as to KK gauge bosons, are almost flavor-independent Gherghetta, Pomarol (2000)

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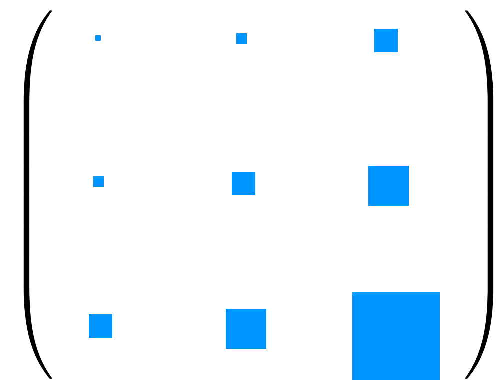
Hierarchies of Quark Masses and CKM Angles

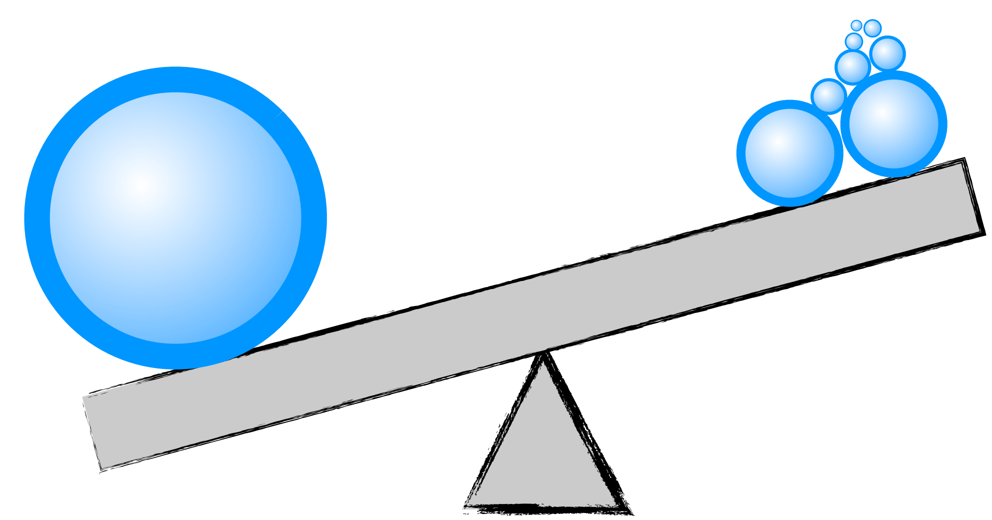
- SM mass matrices can be written as Huber (2003)

$$\boldsymbol{m}_q^{\rm SM} = \frac{v}{\sqrt{2}}\,\mathrm{diag}\,[F(Q_i)]\,\boldsymbol{Y}_q\,\mathrm{diag}\,[F(q_i)] =$$



where $\boldsymbol{Y}_q$ with $q = u,d$ are structureless, complex Yukawa matrices with O(1) entries, and $F(Q_i) << F(Q_j)$, $F(q_i) << F(q_j)$ for $i < j$

- In analogy to seesaw mechanism for neutrinos, matrices of this form give rise to hierarchical mass eigenvalues and mixing matrices



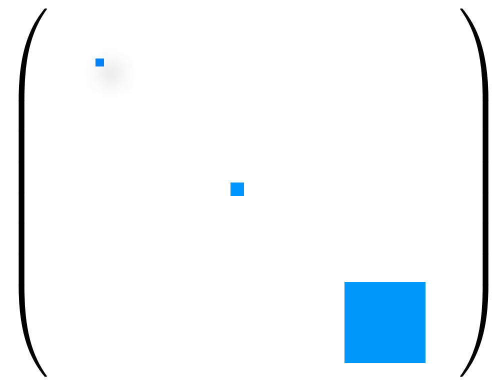
Warped-space Froggatt-Nielsen mechanism!

Froggatt, Nielsen (1979); Casagrande *et al*. (2008); Blanke *et al*. (2008)

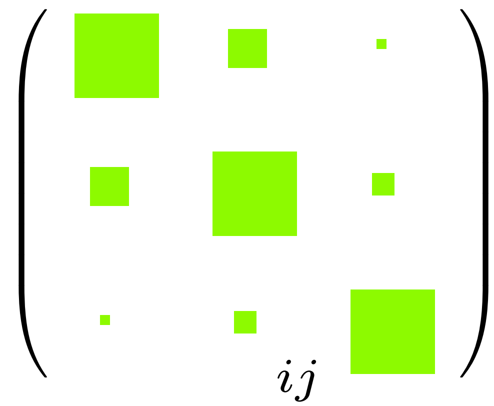
Hierarchies of Quark Masses and CKM Angles

- Thus:

$$\boldsymbol{m}_q \sim \frac{v}{\sqrt{2}}\,\mathrm{diag}\left[F(Q_i)F(q_i)\right] =$$

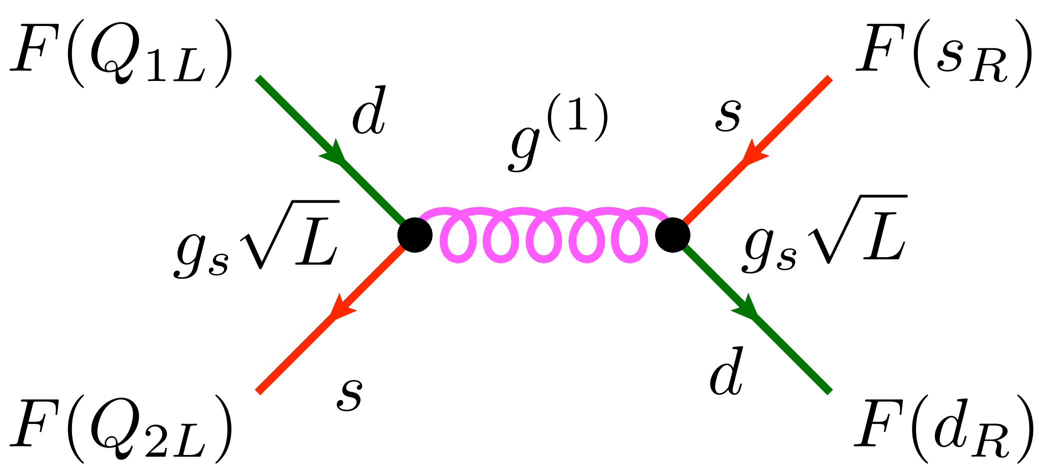


$$(V_{\mathrm{CKM}})_{ij} \sim \begin{cases} \dfrac{F(Q_i)}{F(Q_j)}, & i \le j \\[2ex] \dfrac{F(Q_j)}{F(Q_i)}, & i > j \end{cases} =$$



- Hierarchies predicted and readily adjusted by O(1) variations of bulk masses
- CP violating phase is predicted to be unsuppressed! Casagrande *et al*. (2008); Blanke *et al*. (2008)

RS-GIM Protection of FCNCs

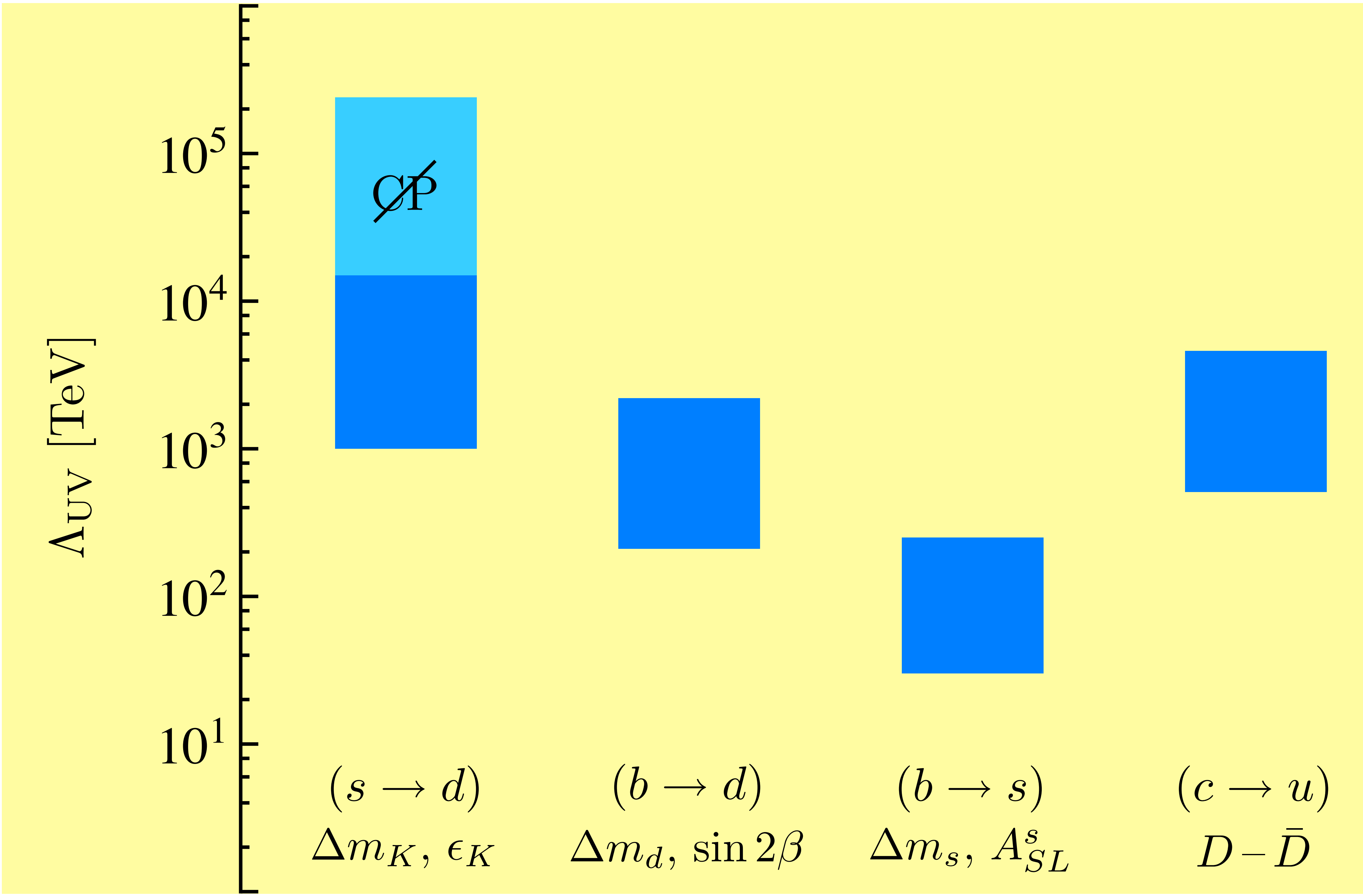


$$\sim \frac{g_s^2}{M_{\rm KK}^2}\, L\; F(Q_{1L})F(d_R)\, F(Q_{2L})F(s_R)$$

- 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

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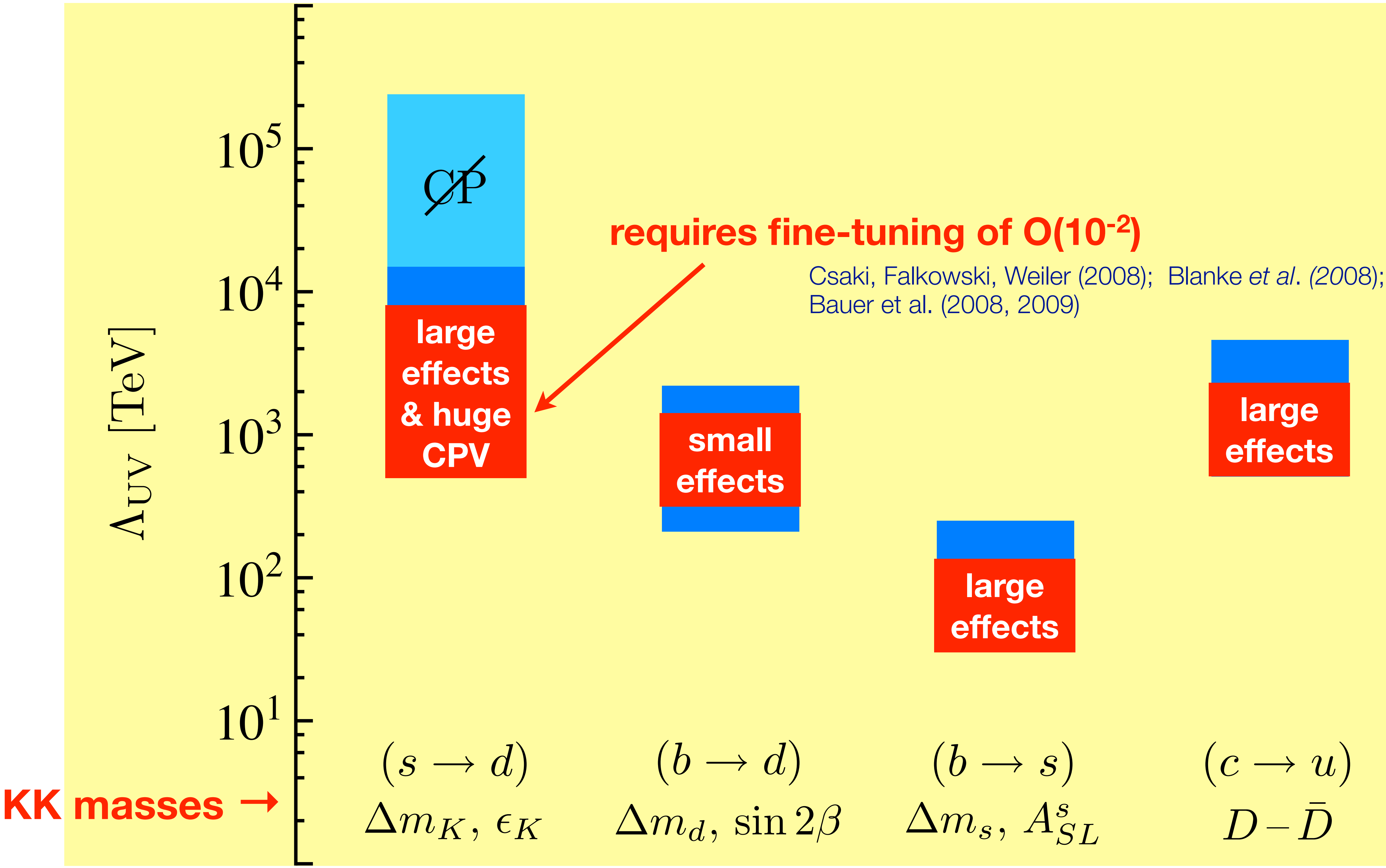
RS-GIM Protection of FCNCs



RS-GIM protection with KK masses of order few TeV

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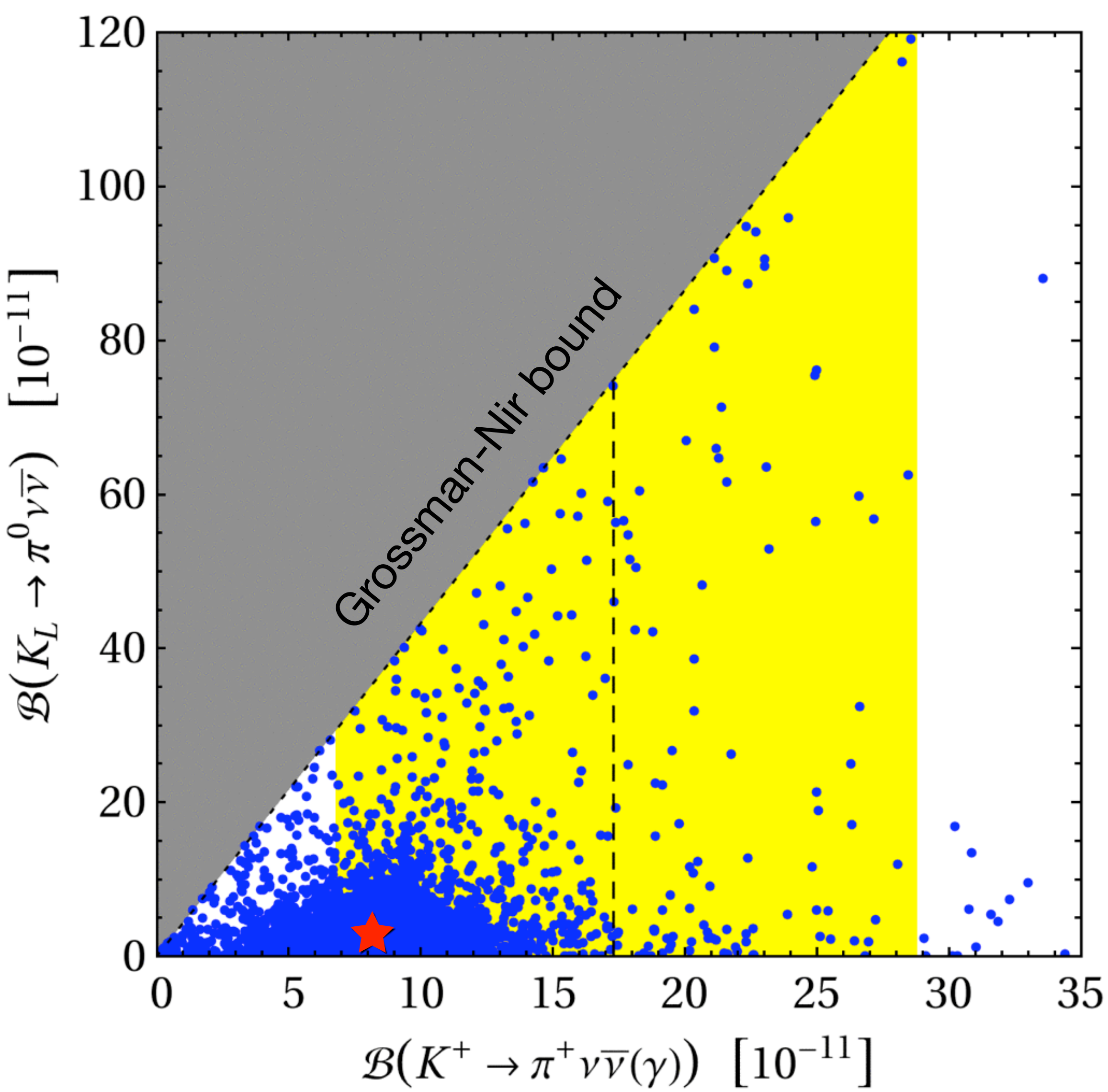
Golden Modes: Rare Kaon Decays

- Spectacular corrections are possible in very clean $K \to \pi\nu\bar{\nu}$ decays, even saturating the Grossman-Nir bound, $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) < 4.4\,\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$

Blanke *et al*. (2008); Bauer et al. (2009)



★ SM: $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) \approx 8.3 \cdot 10^{-11}$,

$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) \approx 2.7 \cdot 10^{-11}$

- - central value and 68% CL limit $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \cdot 10^{-11}$ from E949

● consistent with quark masses, CKM parameters, and 95% CL limit $|\varepsilon_K| \in [1.3, 3.3] \cdot 10^{-3}$

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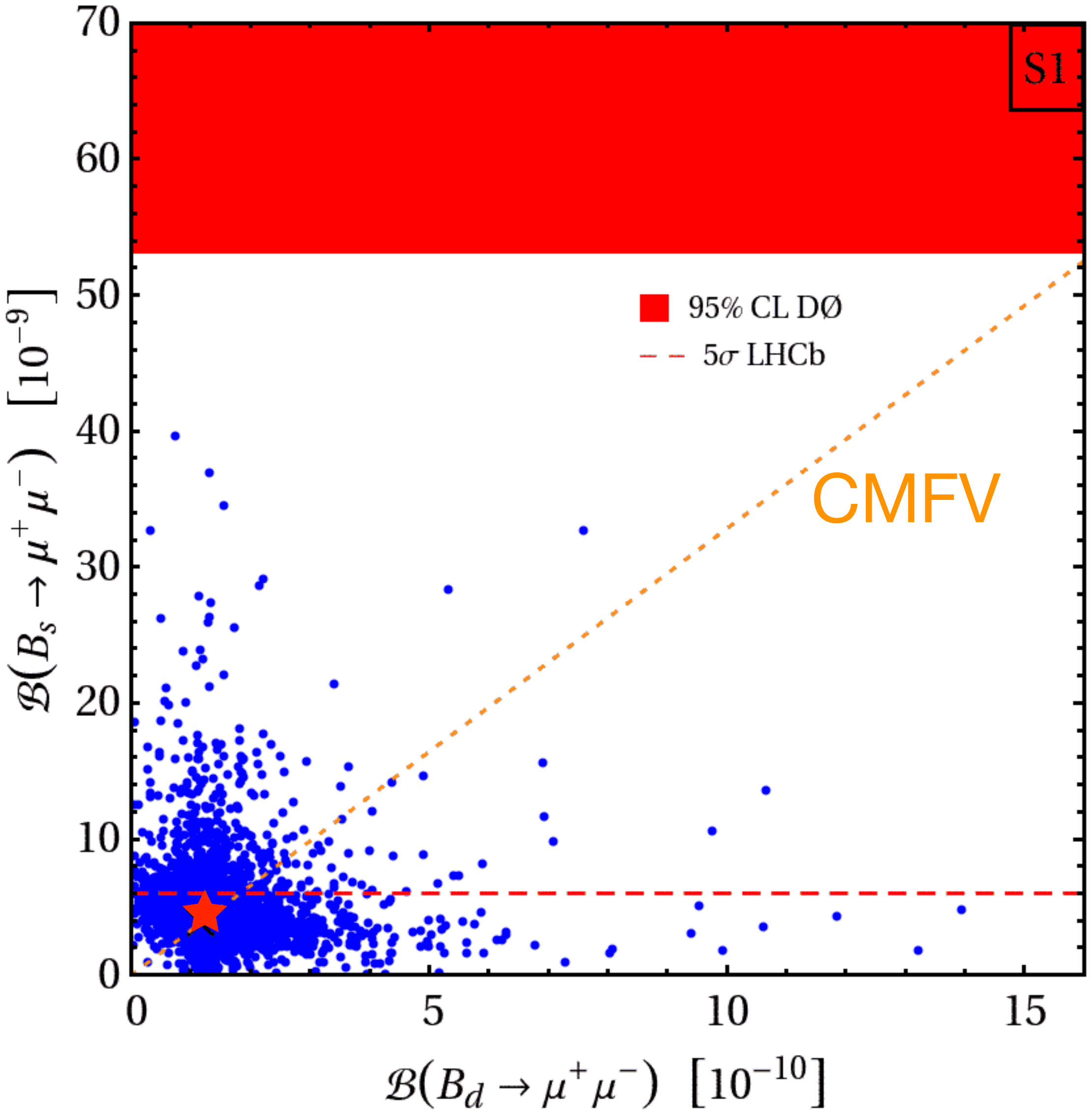
Golden Modes: Rare B Decays

- Factor ~10 enhancements possible in rare $B_{d,s} \to \mu^+\mu^-$ modes without violation of $Z \to b\bar{b}$ constraints; effects largely uncorrelated with $|\varepsilon_K|$

Blanke *et al*. (2008); Bauer et al. (2009)



★ SM: $\mathcal{B}(B_d \to \mu^+\mu^-) \approx 1.2 \cdot 10^{-10}$,
$\mathcal{B}(B_s \to \mu^+\mu^-) \approx 3.9 \cdot 10^{-9}$

- - - minimum of $5.5 \cdot 10^{-9}$ for 5σ discovery by LHCb, $2\ \mathrm{fb}^{-1}$

■ 95% CL upper limit from CDF: $\mathcal{B}(B_s \to \mu^+\mu^-) < 5.8 \cdot 10^{-8}$

● consistent with quark masses, CKM parameters, $Z \to b\bar{b}$, and 95% CL limit $|\varepsilon_K| \in [1.3, 3.3] \cdot 10^{-3}$

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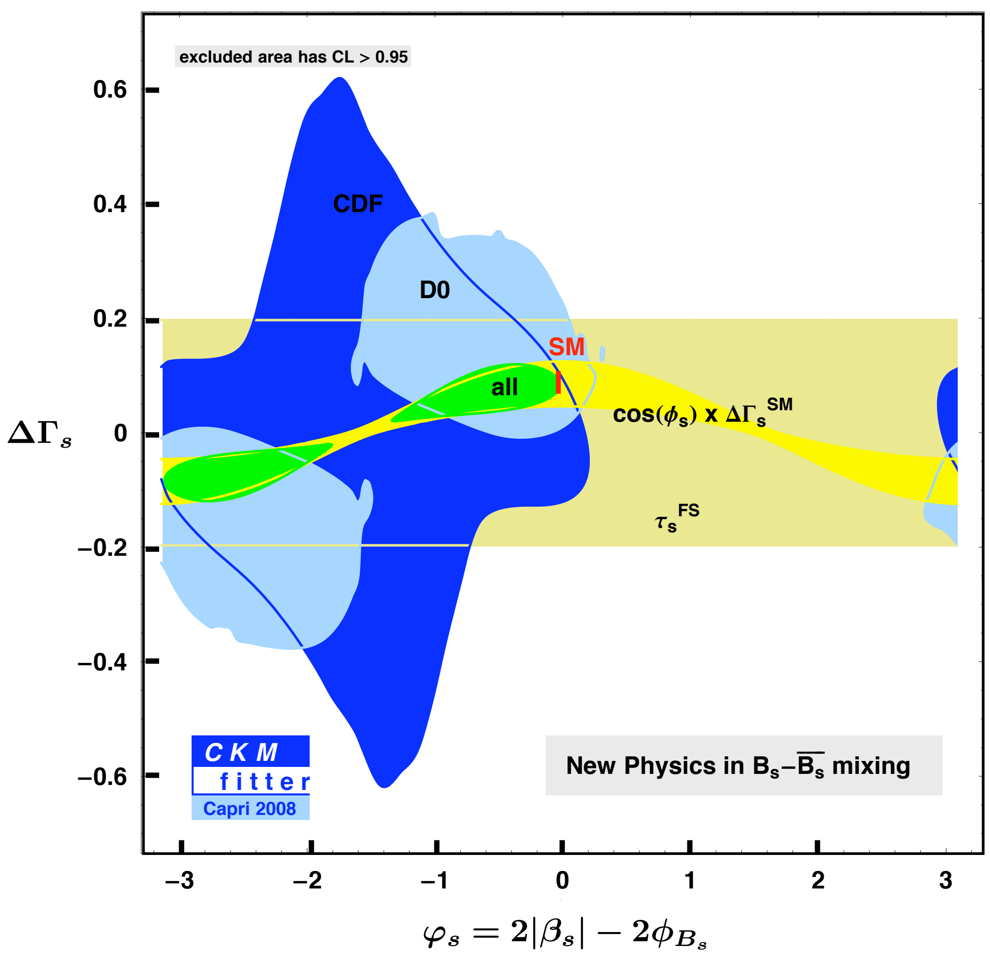
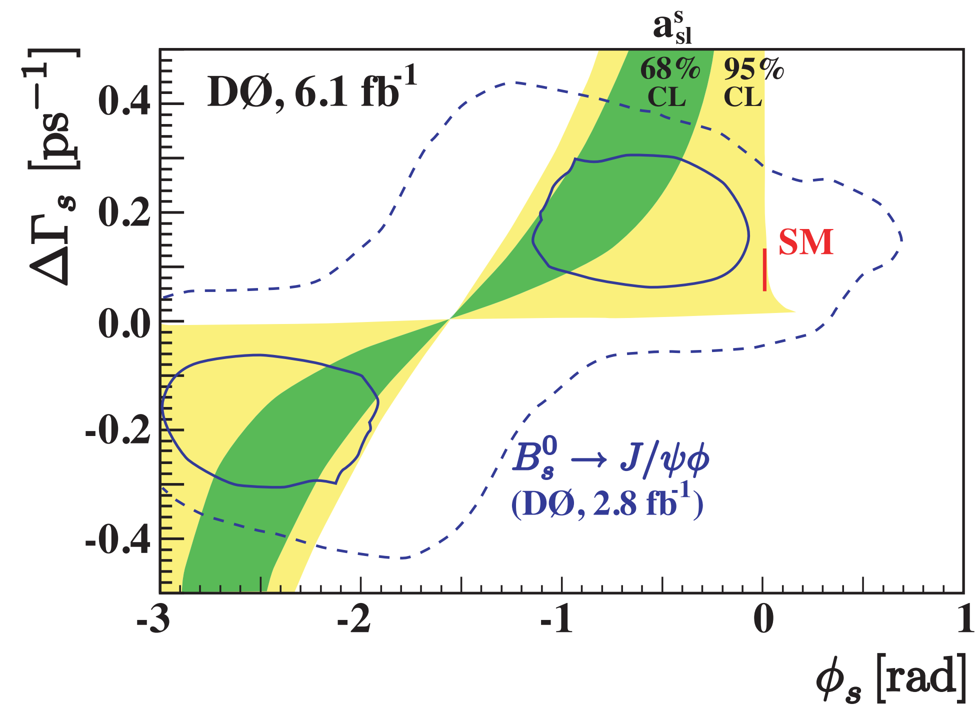
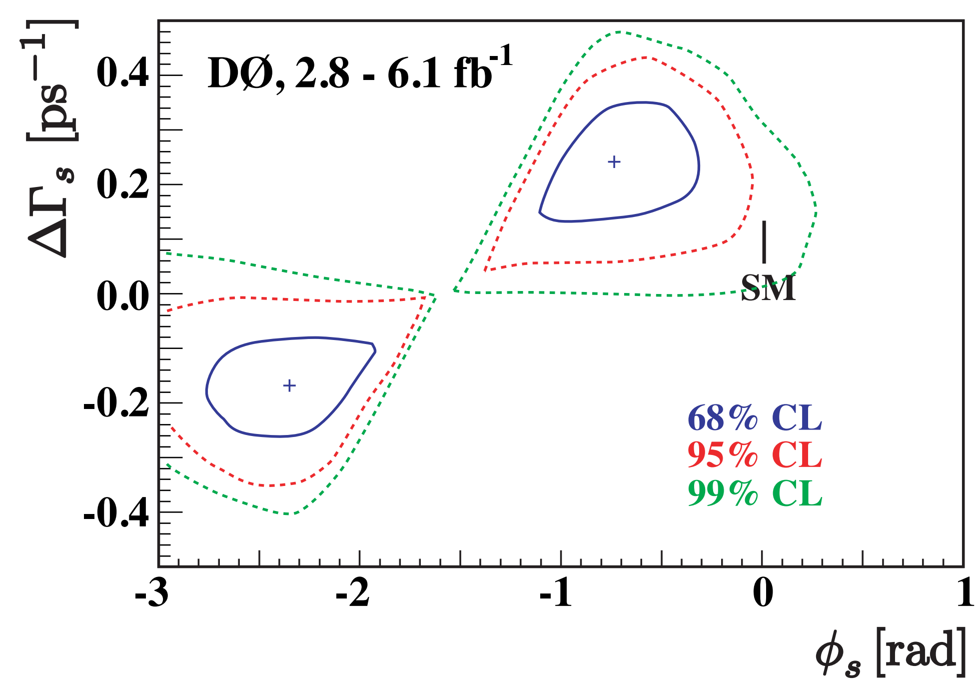
New Physics in B_s-$\bar{B}_s$ mixing?

- Tantalizing hints for new physics phase in $B_s - \bar{B}_s$ mixing from flavor-tagged analysis of mixing-induced CP violation in $B_s \rightarrow J/\psi\phi$ by CDF and DØ, and more recently from anomalous like-sign di-muon charge asymmetry at DØ



Discrepancy of $\varphi_s = 2|\beta_s| - 2\phi_{B_s}$ with respect to SM value $\varphi_s \approx 2^\circ$ at around 2-3σ level

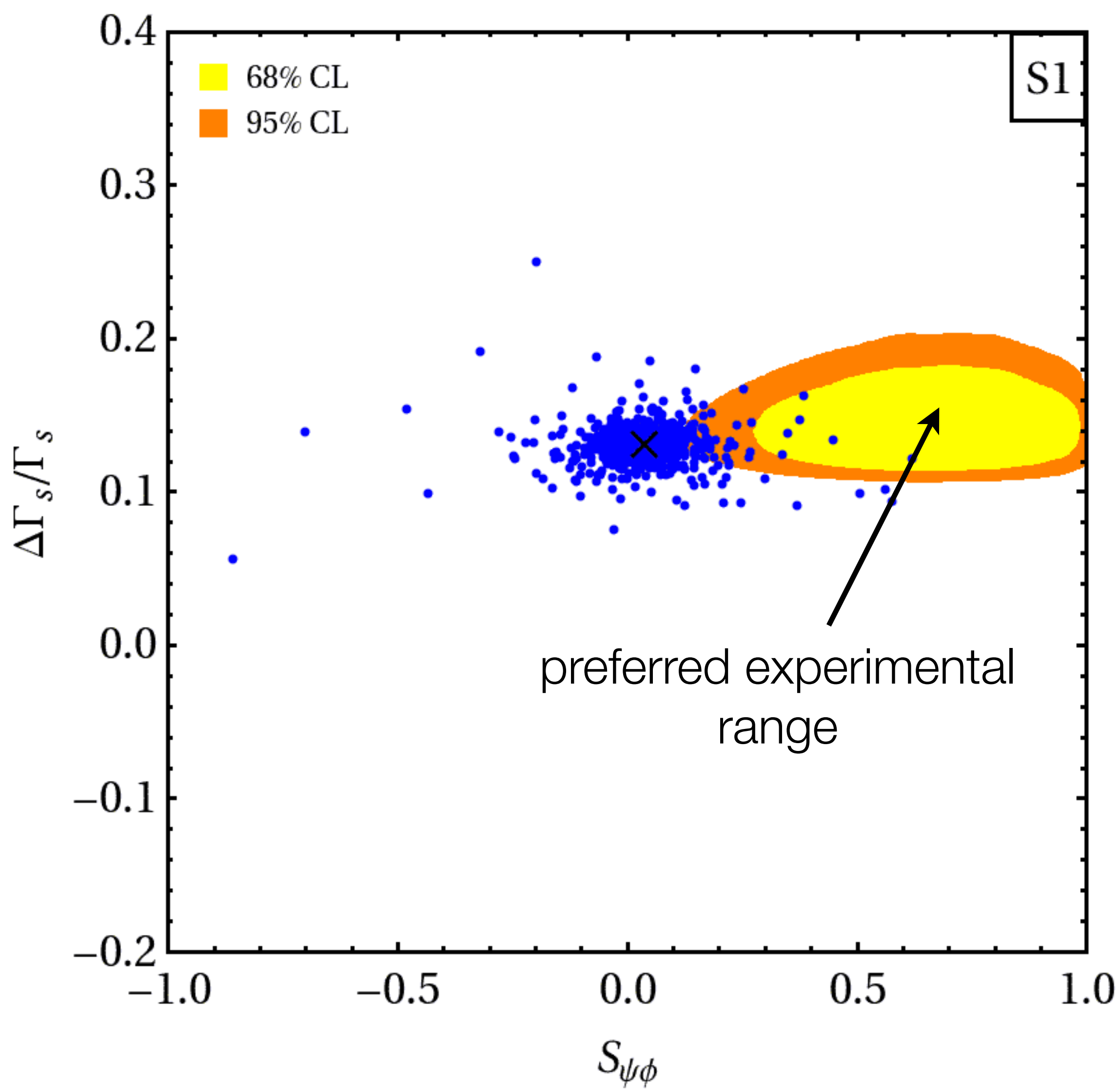




New Physics in B_s-$\bar{B}_s$ mixing?

- Constraint from $|\varepsilon_K|$ does not exclude O(1) effects in width difference $\Delta\Gamma_s/\Gamma_s$ of B_s system, but difficult to account for central values of data

Blanke *et al*. (2008); Bauer et al. (2009)



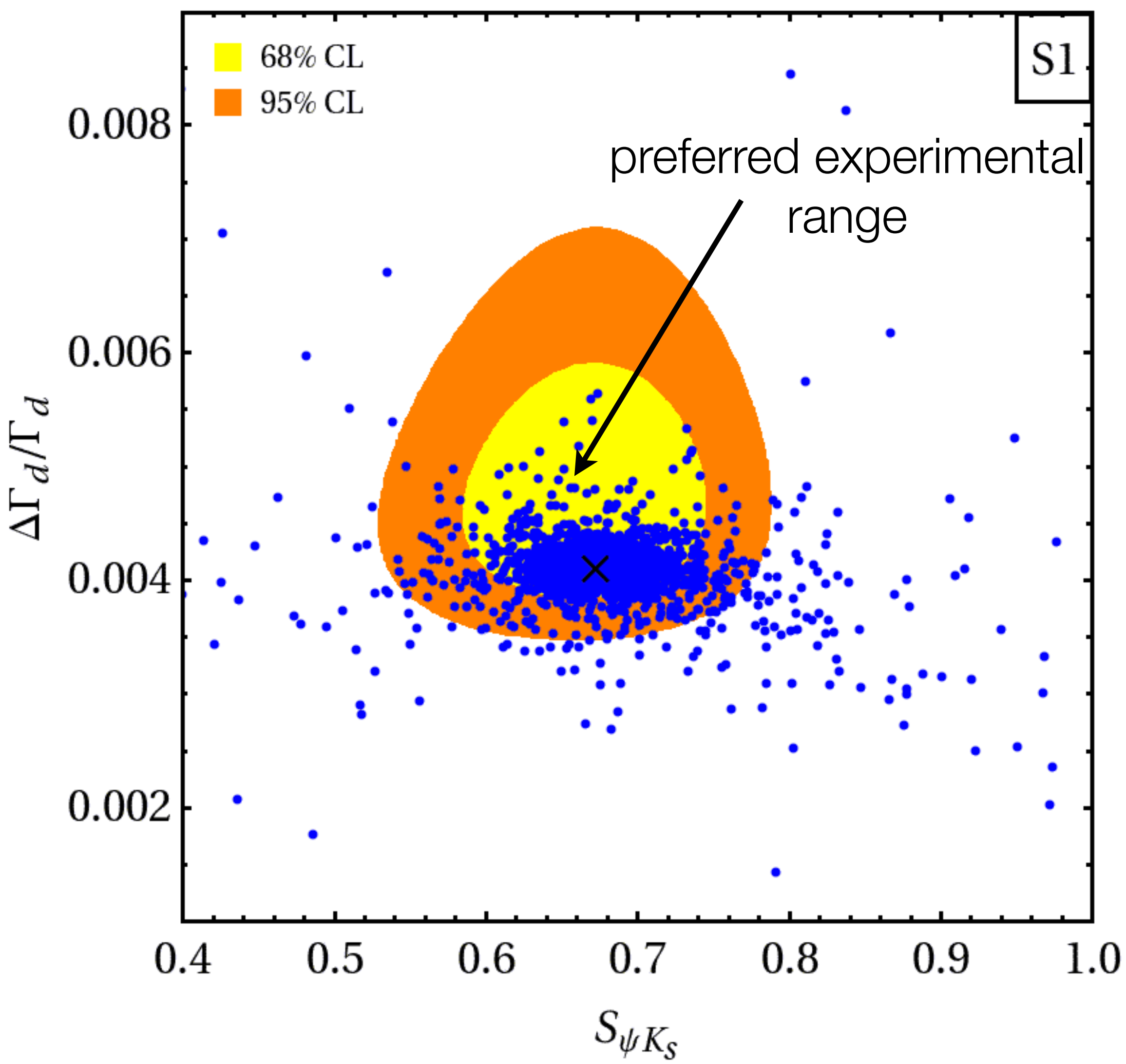
x SM: $\Delta\Gamma_s/\Gamma_s \approx 0.13$, $S_{\psi\phi} \approx 0.04$

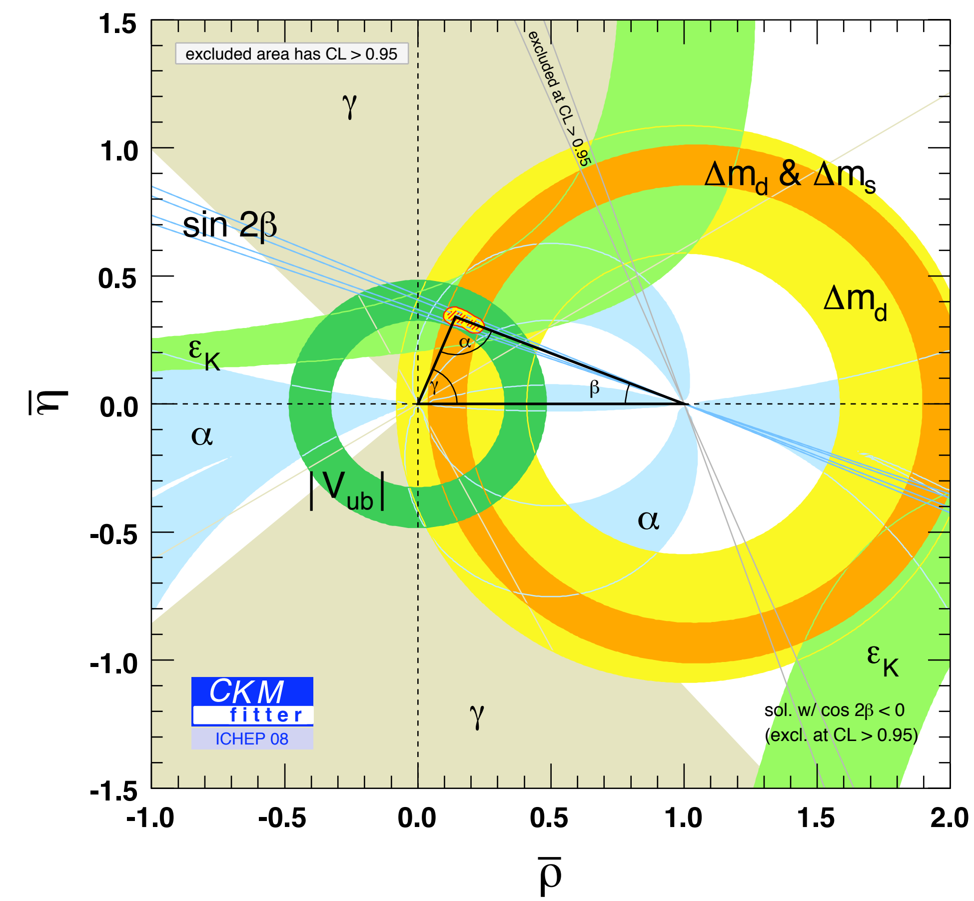
● consistent with quark masses, CKM parameters, $Z \to b\bar{b}$, and 95% CL limit $|\varepsilon_K| \in [1.3, 3.3] \cdot 10^{-3}$

New Physics in B_d-$\bar{B}_d$ mixing?

- Constraint from $|\varepsilon_K|$ does not exclude significant modifications of the CP asymmetry in $B \to \psi\, K_S$, which could relax the $|V_{ub}|$ - sin2β tension

Blanke *et al*. (2008); Bauer et al. (2009)





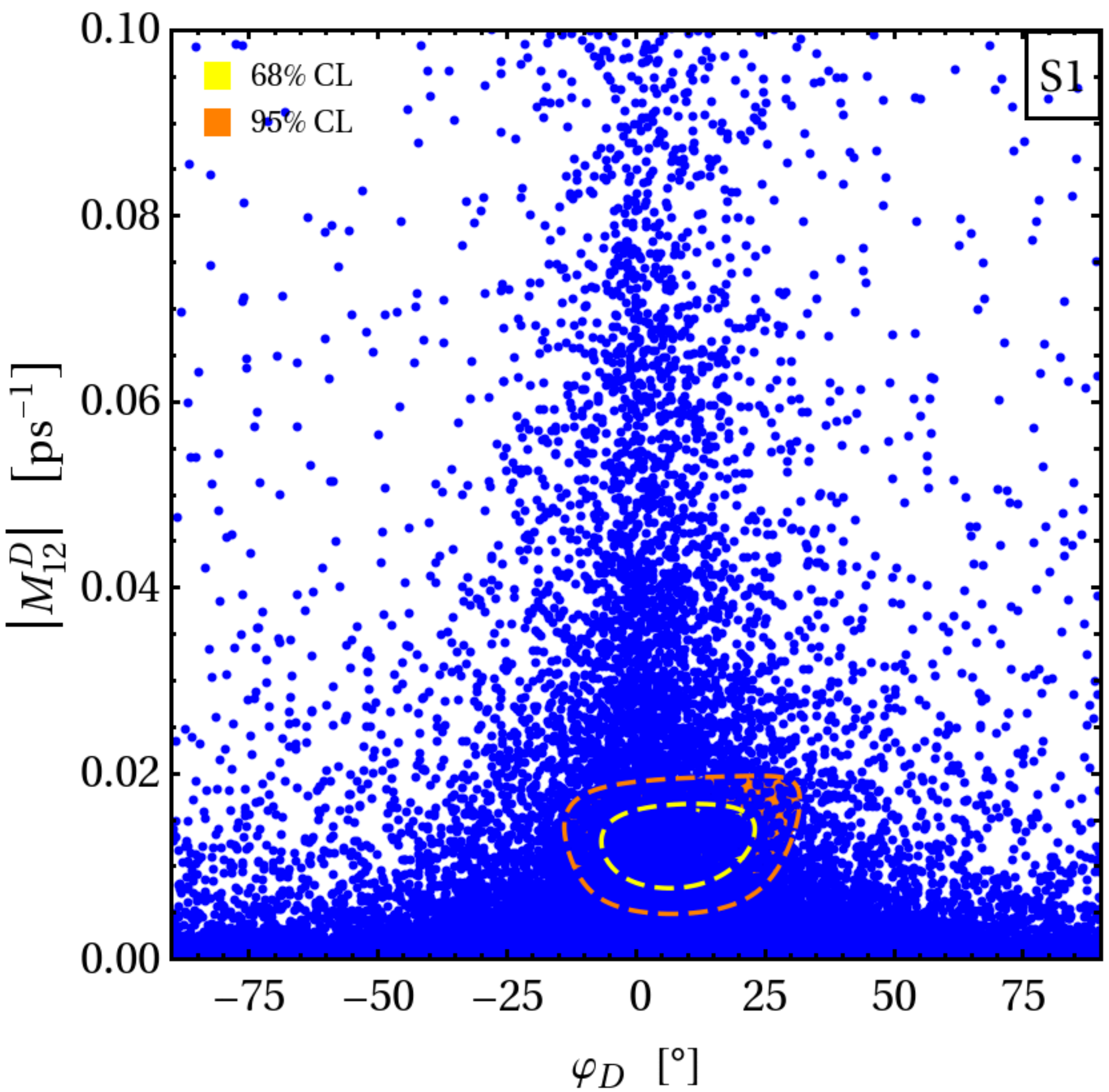
X SM

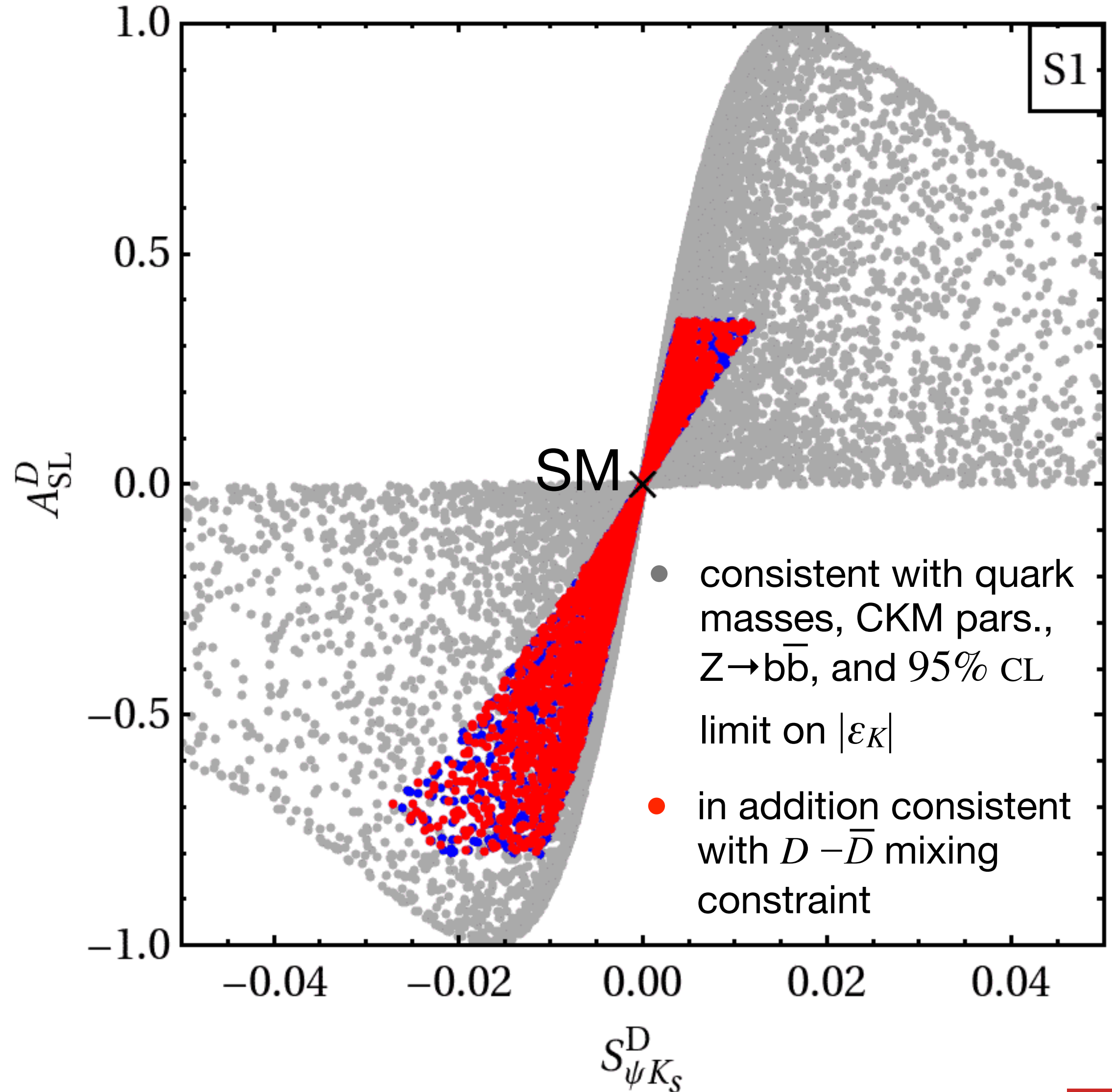
- consistent with quark masses, CKM parameters, $Z \to b\bar{b}$, and 95% CL limit $|\varepsilon_K| \in [1.3, 3.3] \cdot 10^{-3}$

D-D̄ Mixing

- Very large effects possible, including large CP violation; predictions might be testable at LHCb

Bauer et al. (2009)





- consistent with quark masses, CKM parameters, Z→b$\bar{b}$, and 95% CL limit $|\varepsilon_K| \in [1.3, 3.3] \cdot 10^{-3}$

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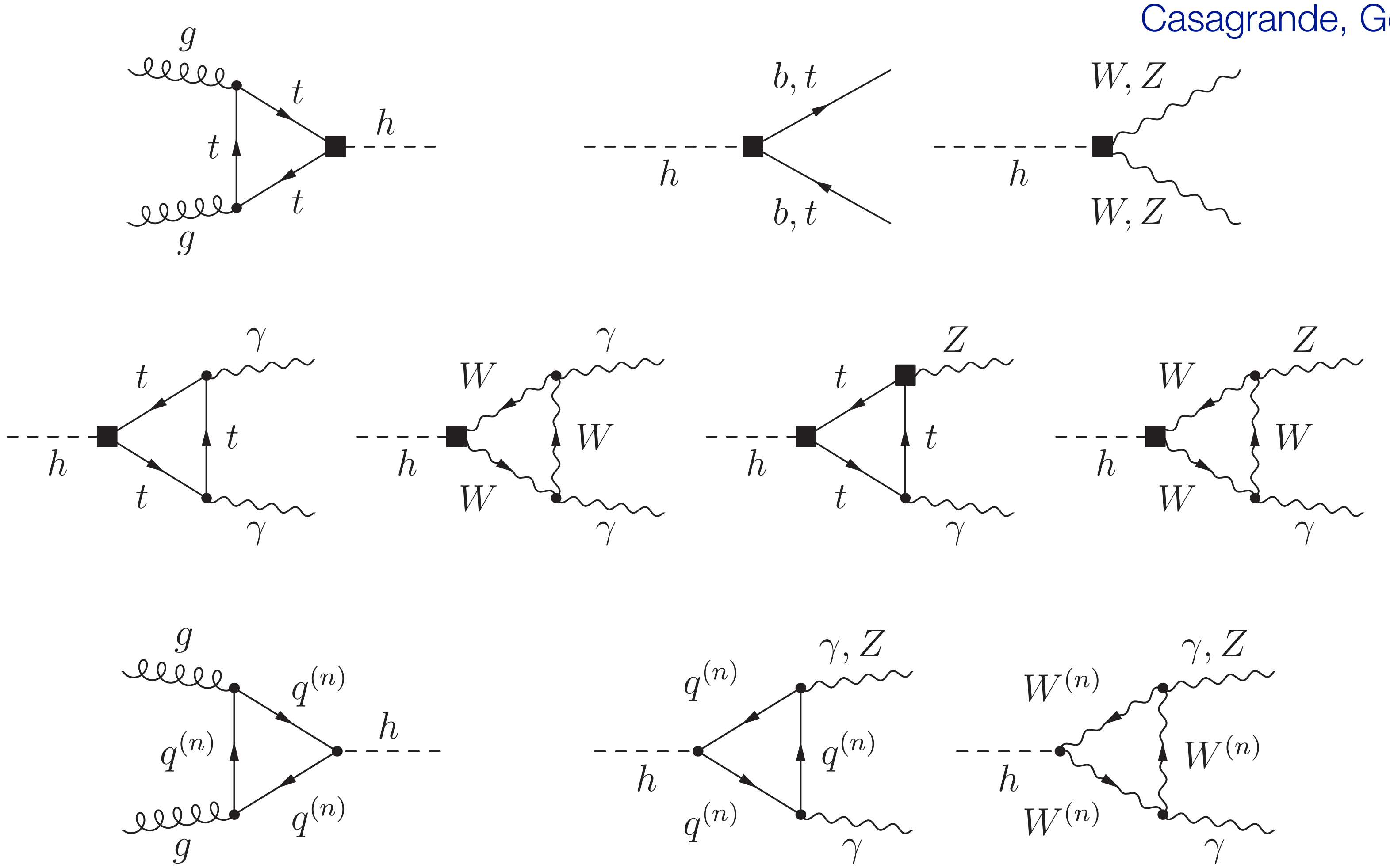
Correlations with Higgs physics

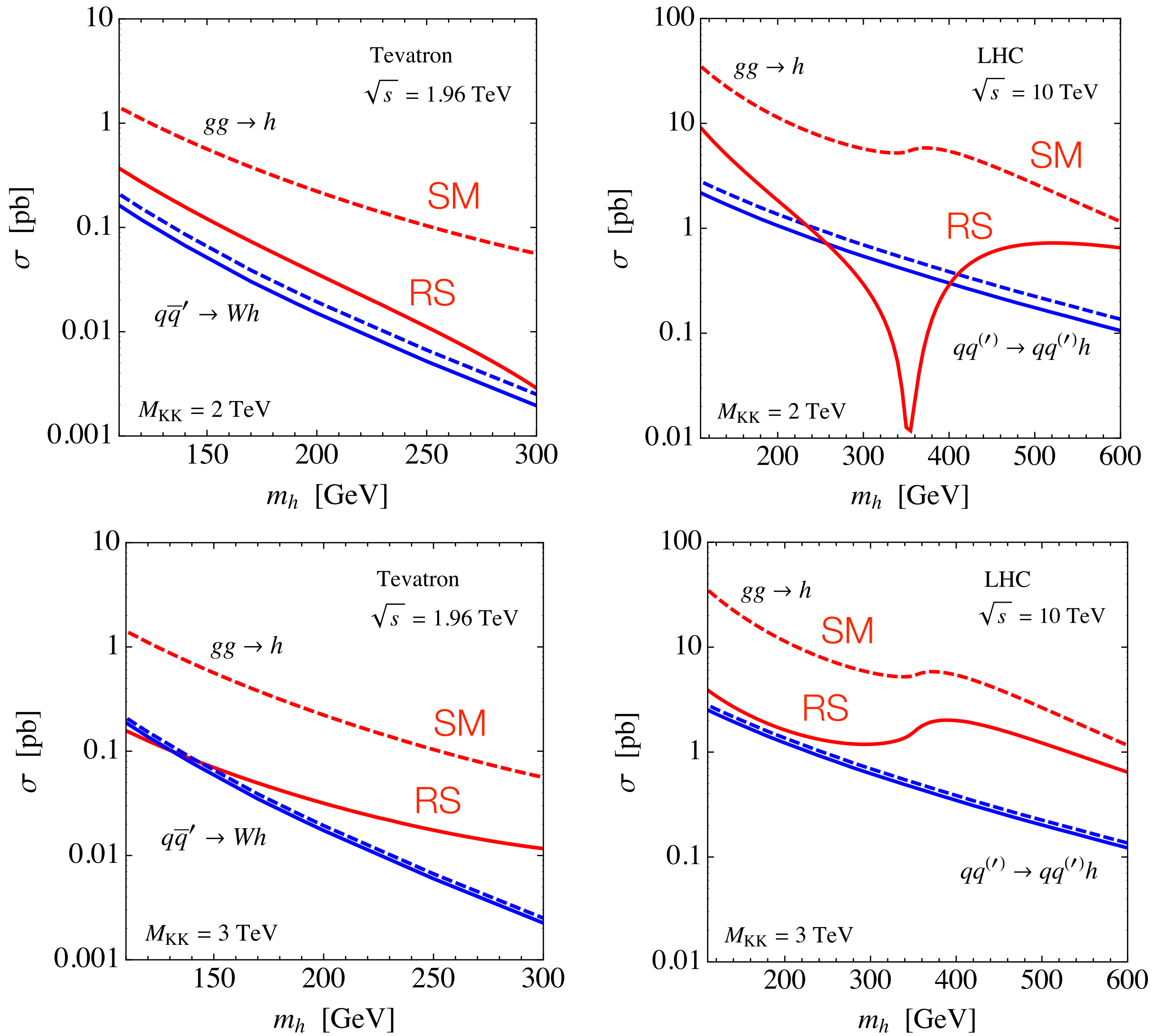
- Properties of the Higgs boson offer alternative ways to probe, via modifications of SM couplings and virtual effects from heavy KK states, the structure of warped extra-dimension models
- Recently, we have performed the first complete one-loop analysis of Higgs production and decays in the RS model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

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



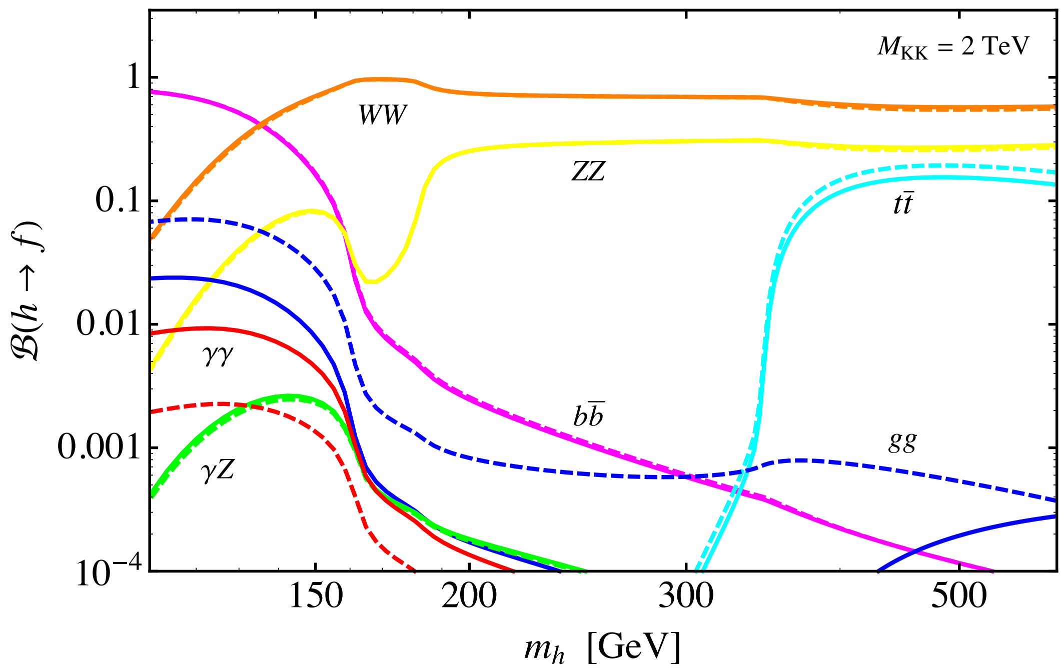
Higgs production cross sections

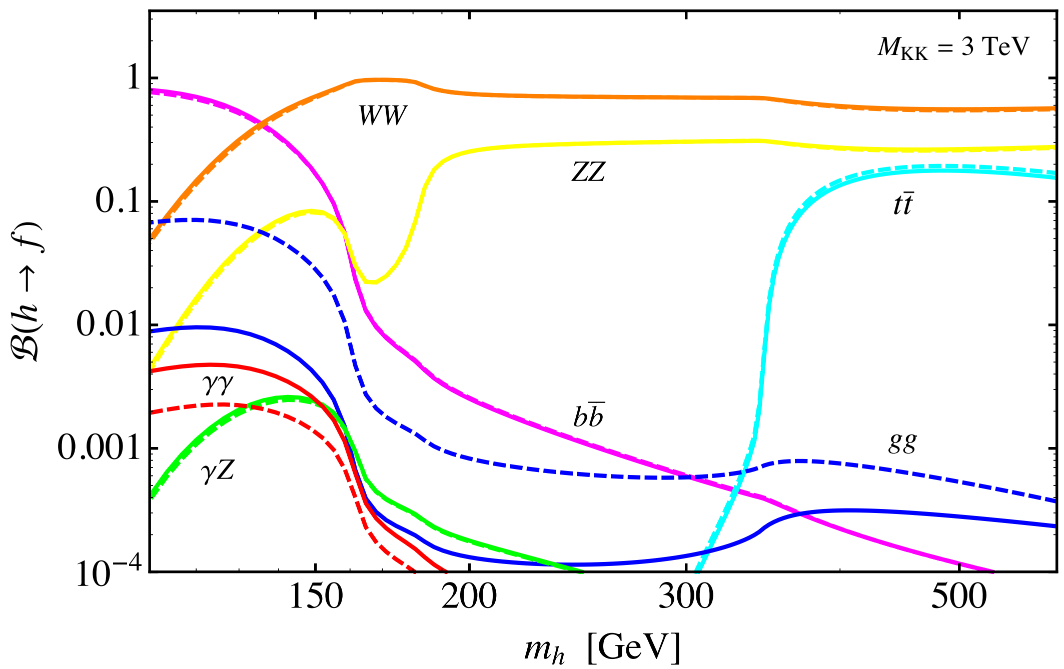
- Find possibly spectacular effects on Higgs production via gluon fusion, even for high KK masses ($m_{G^{(1)}_{\rm KK}} \approx 2.45 M_{\rm KK}$):



Higgs decay branching fractions

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





Puzzles in the Flavor Sector: **Facts or Fiction?**

Several observables don’t look quite right ... (~2σ effects)

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Puzzles in the Flavor Sector: **Facts or Fiction?**

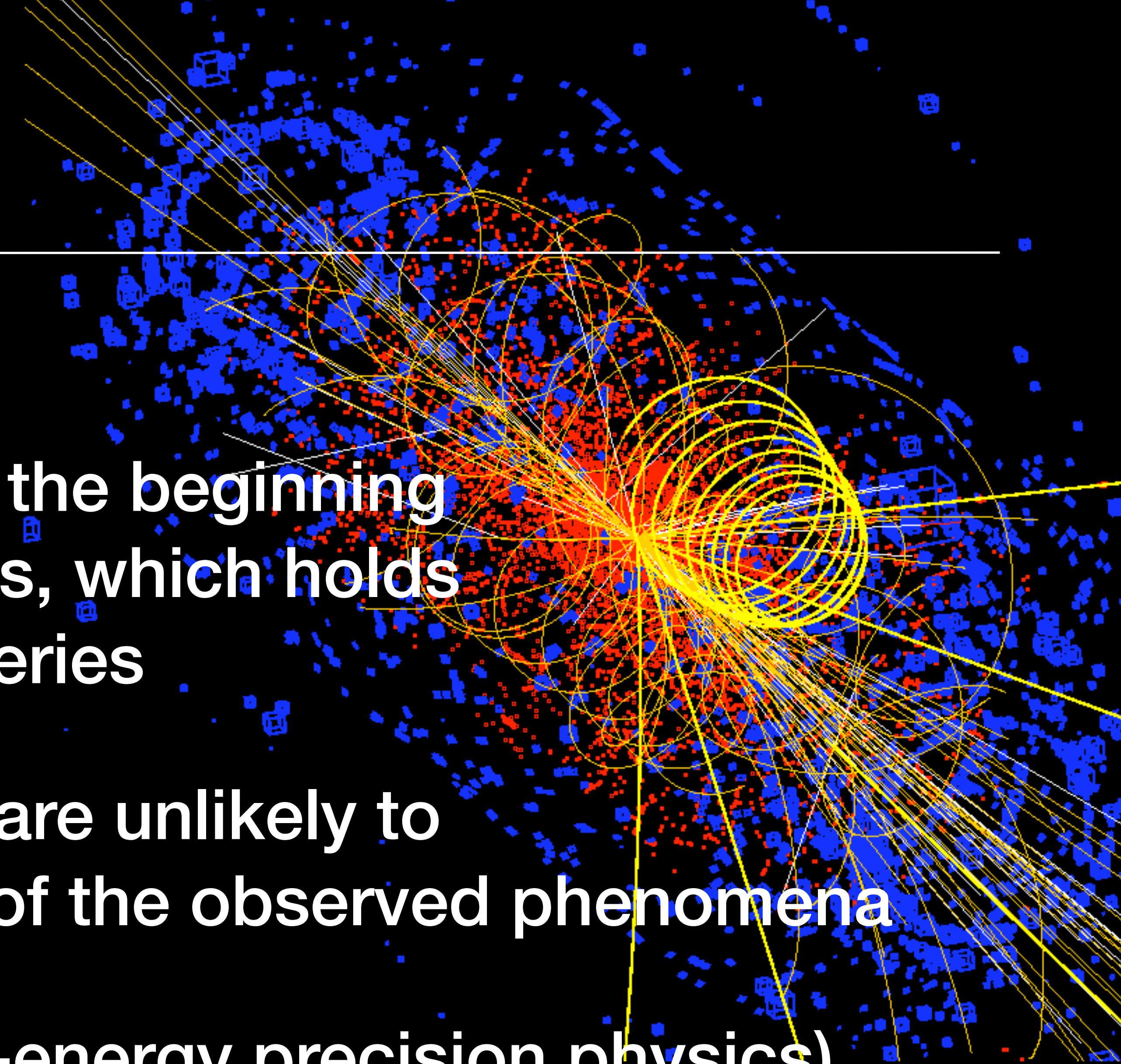
- $\sin 2\beta$ from tree vs. loop processes
- $|V_{cb}|$ and $|V_{ub}|$ exclusive vs. inclusive
- $|V_{ub}|$ vs. $\sin 2\beta$ and ε_K
- $\Delta A_{CP}(B \to \pi K)$ puzzle

Perhaps, one of these hints will solidify and point us the way beyond the SM!

- CP violation in B_s mixing
- enhanced $B \to \tau\nu$ rate
- A_{FB} asymmetry in $B \to K^* l^+ l^-$
- not yet measured ...

Several observables don't look quite right ... (~2σ effects)

Summary and Outlook



The first collisions at the LHC mark the beginning of a fantastic 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

Only the synergy of LHC and high-precision experiments may give us the key to solving the puzzles of fundamental physics