Flavor physics in a warped extra dimension

Matthias Neubert
Johannes Gutenberg University Mainz

Beyond the Standard Models of Particle Physics, Cosmology and Astrophysics
Cape Town, South Africa, 1 - 6 February 2010

Many nice memories of WIN 1999 in Cape Town ...

Based on recent work by:

- Csaki, Falsowski, Weiler: arXiv:0804.1954
- Casagrande, Goertz, Haisch, MN, Pfoh: arXiv:0807.4937
- Blanke, Buras, Duling, Gori, Weiler: arXiv:0809.1073
- Bauer, Casagrande, Gründer, Haisch, MN: arXiv:0811.3678
- Blanke, Buras, Duling, Gemmler, Gori: arXiv:0812.3803
- **Bauer, Casagrande, Haisch, MN: arXiv:0912.1625**

  → **due to time restrictions, only cover small fraction of relevant results!**

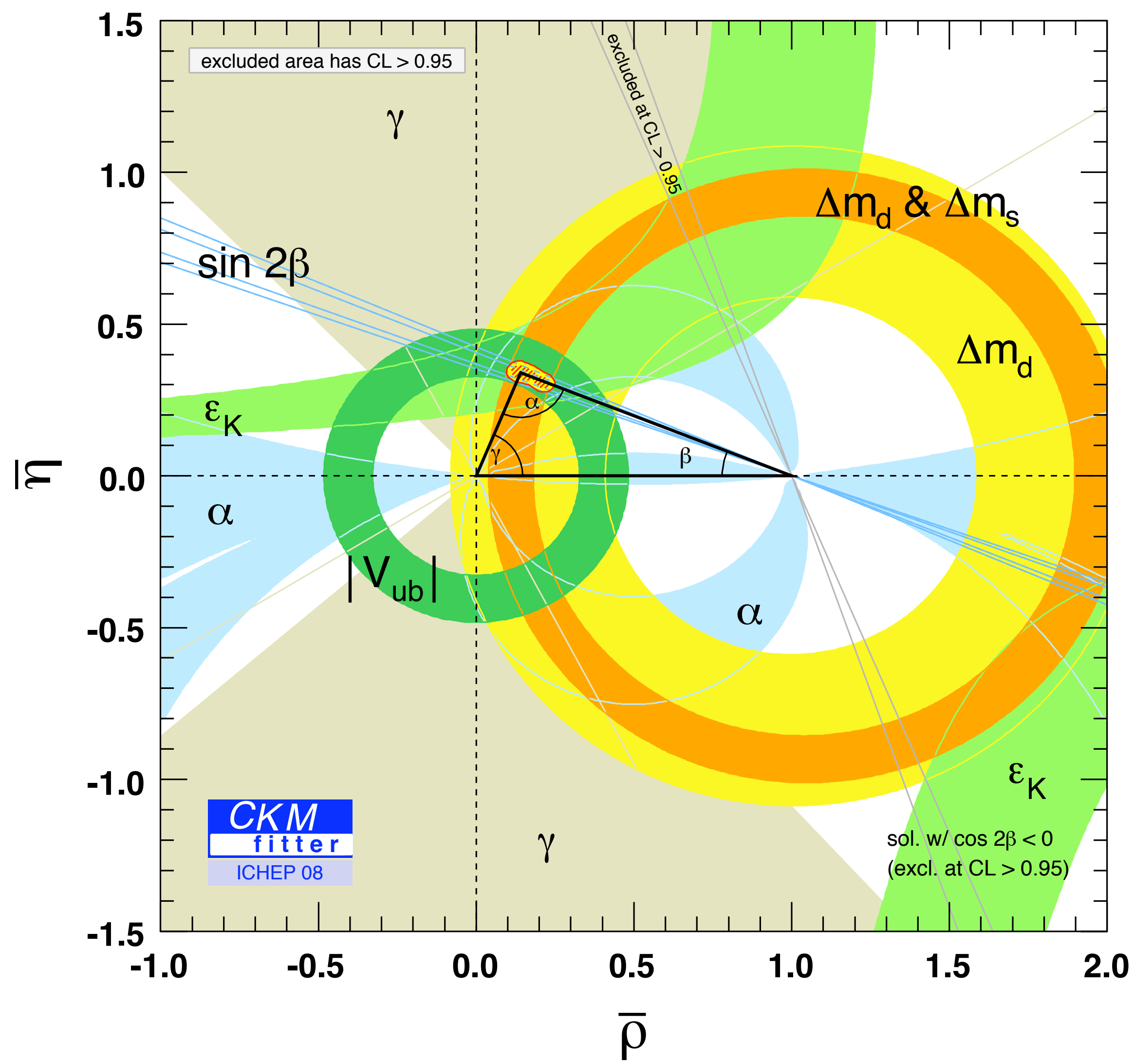
Also lots of previous important work, in particular:

- Huber, hep-ph/0303183
- Agashe, Perez, Soni: hep-ph/0406101, 0408134, 0606293
- Burdman, hep-ph/0205329, 0310144
- and more ...

Main lesson from quark flavor physics

Standard Model of particle physics is very successful in **describing** quark flavor mixing:

Compelling evidence from consistency of various constraints combined in global Cabibbo-Kobayashi-Maskawa (CKM) fit ...



Main lesson from quark flavor physics

Standard Model of particle physics is very successful in **describing** quark flavor mixing:

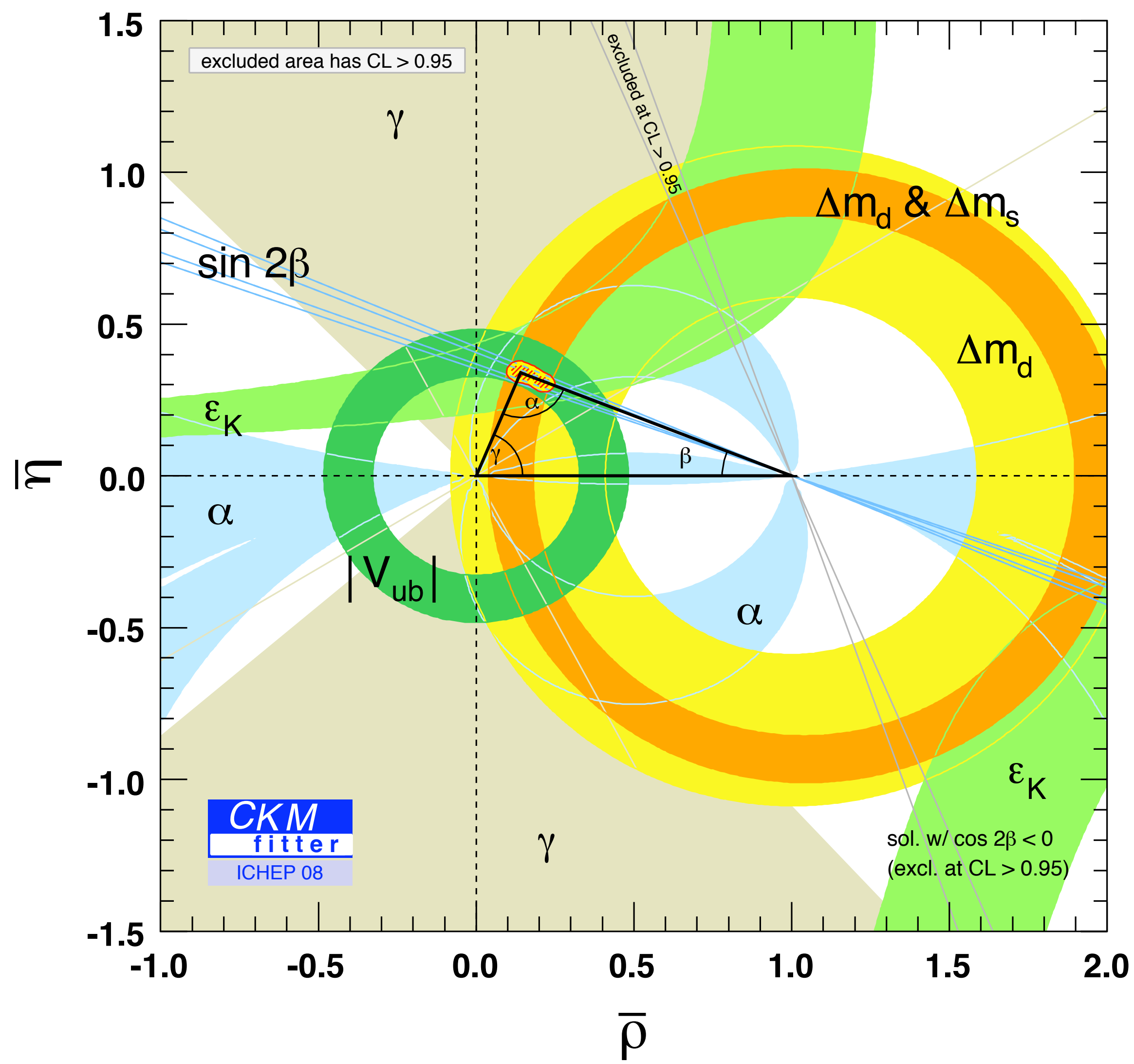
N. Cabibbo

M. Kobayashi

T. Maskawa

Nobel Prize in Physics 2008 awarded to Kobayashi and Maskawa:

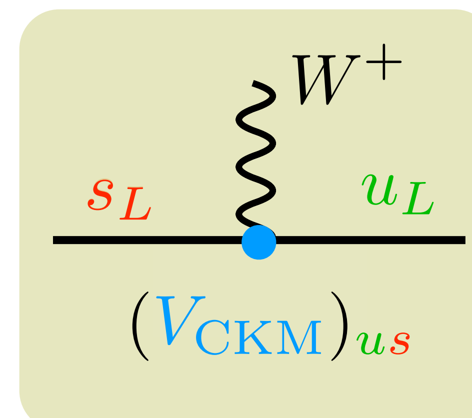
"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"



Main lesson from quark flavor physics

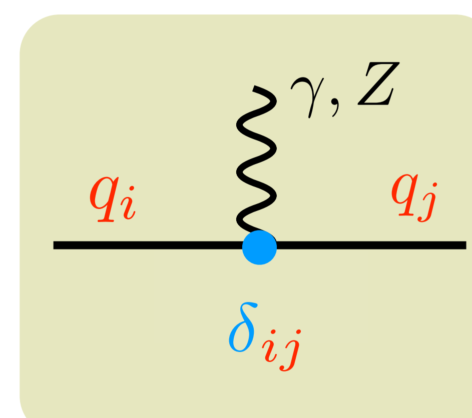
Standard Model of particle physics is very successful in **describing** quark flavor mixing:

... and from absence of excessive flavor-changing neutral currents (FCNCs), such as D–$\bar{D}$ mixing, $K_L \to \mu^+\mu^-$, $B \to X_s\gamma$ *etc*., which are forbidden at tree level in SM



$V_{\rm CKM}$ = CKM matrix

Upshot: effects of beyond SM physics in quark flavor-mixing can only appear as corrections to leading CKM mechanism



δ = diagonal matrix

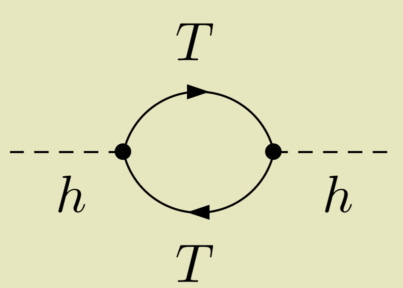
But the SM does not **explain** the hierarchies in flavor physics!

Beyond SM there is another problem of flavor ...

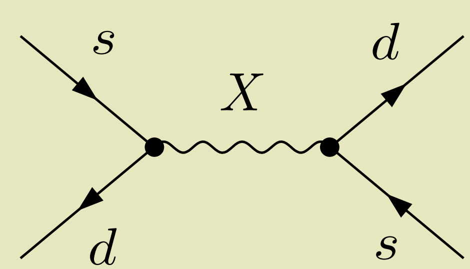
$$\mathcal{L}_{\rm EFT} = \underbrace{\boxed{\Lambda_{\rm UV}^2\, \Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2}} + \mathcal{L}_{\rm SM}^{\rm gauge} + \mathcal{L}_{\rm SM}^{\rm Yukawa} + \underbrace{\boxed{\frac{\mathcal{L}^{(5)}}{\Lambda_{\rm UV}}} + \boxed{\frac{\mathcal{L}^{(6)}}{\Lambda_{\rm UV}^2}}}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

electroweak symmetry breaking $\Downarrow$ Higgs mass

large FCNCs $\Downarrow$ generic flavor structure



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



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

no fine-tuning $\Downarrow$

bounds on flavor mixing $\Downarrow$

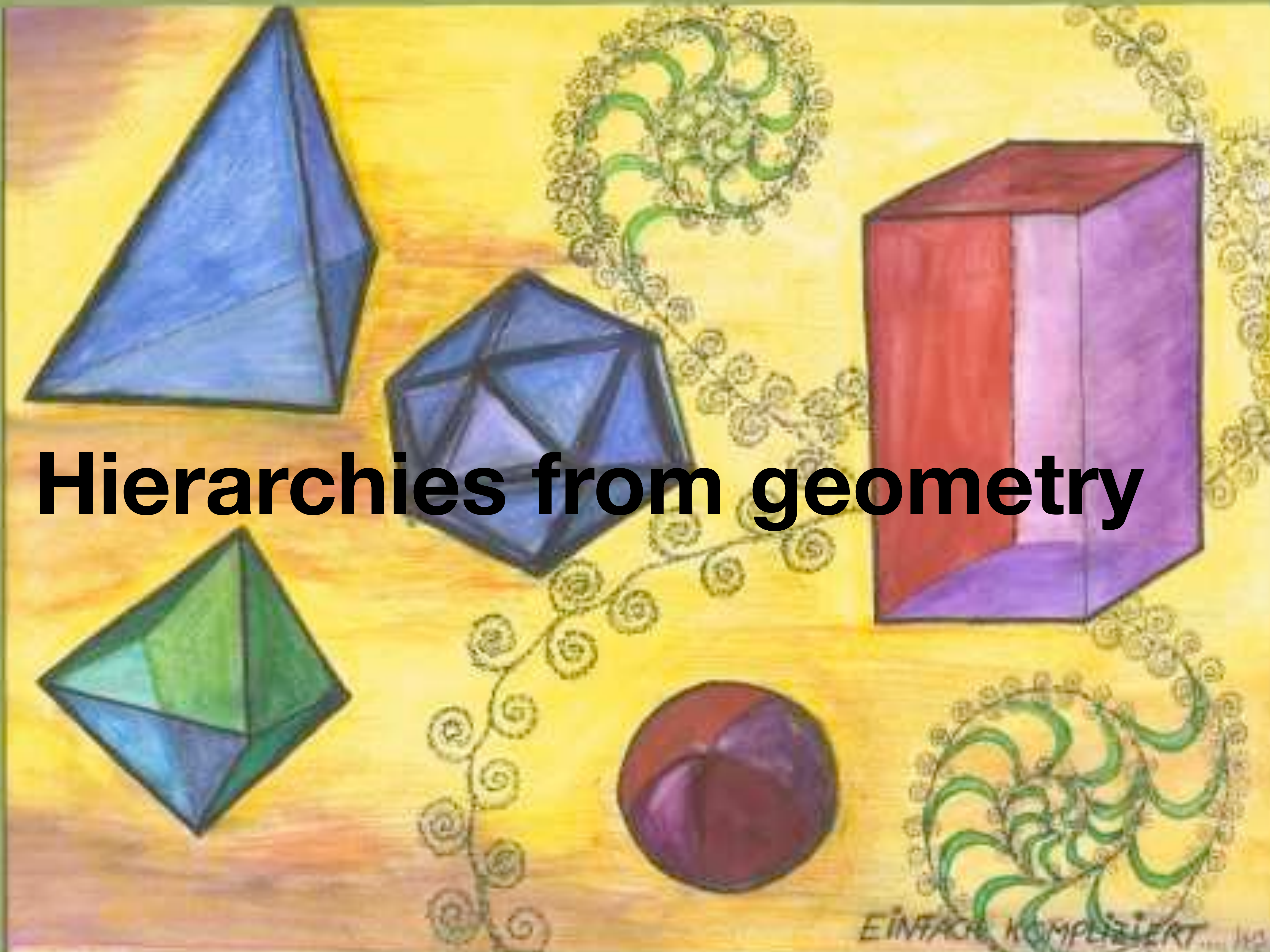
$\Lambda_{\rm Higgs} \lesssim 1$ TeV $\longrightarrow$ increasing energy scale $\longrightarrow$ $\Lambda_{\rm flavor} \gtrsim 10^3$ TeV

- Solutions to flavor problem explaining $\Lambda_{\rm Higgs} << \Lambda_{\rm flavor}$:

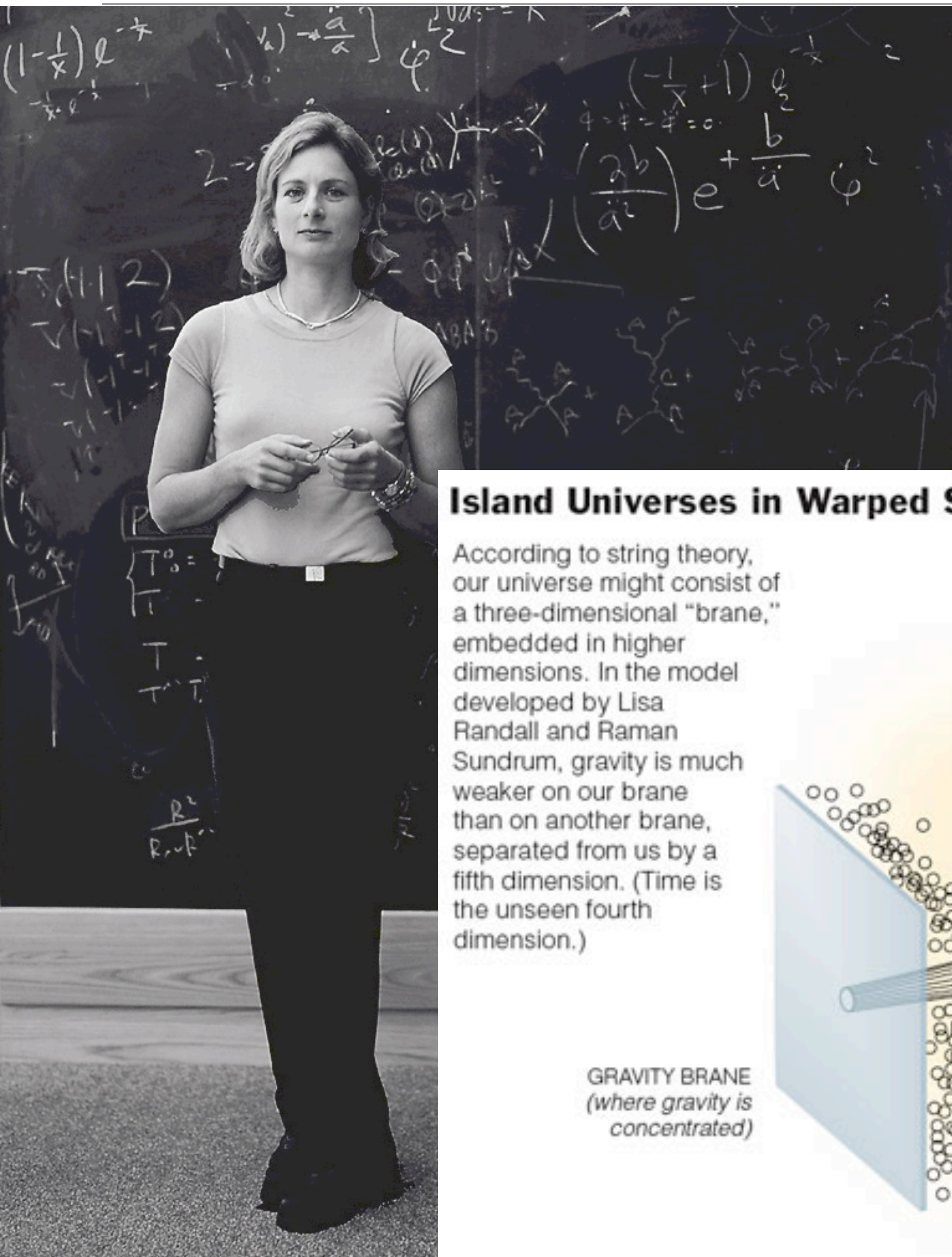
  (i) $\Lambda_{\rm UV} >> 1$ TeV: Higgs fine tuned, new particles too heavy for LHC

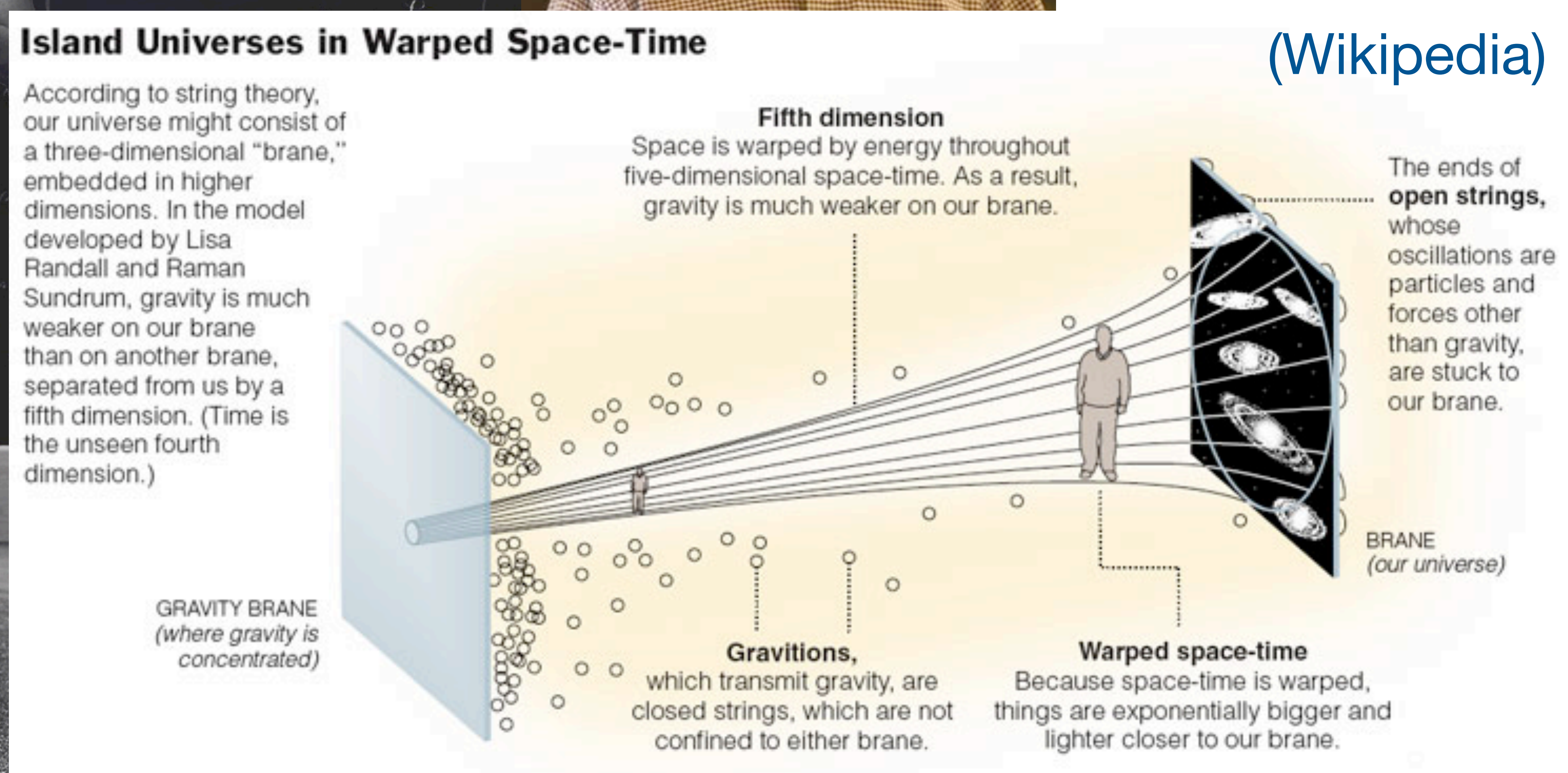
  (ii) $\Lambda_{\rm UV} \approx 1$ TeV: quark flavor mixing protected by flavor symmetry

Hierarchies from geometry



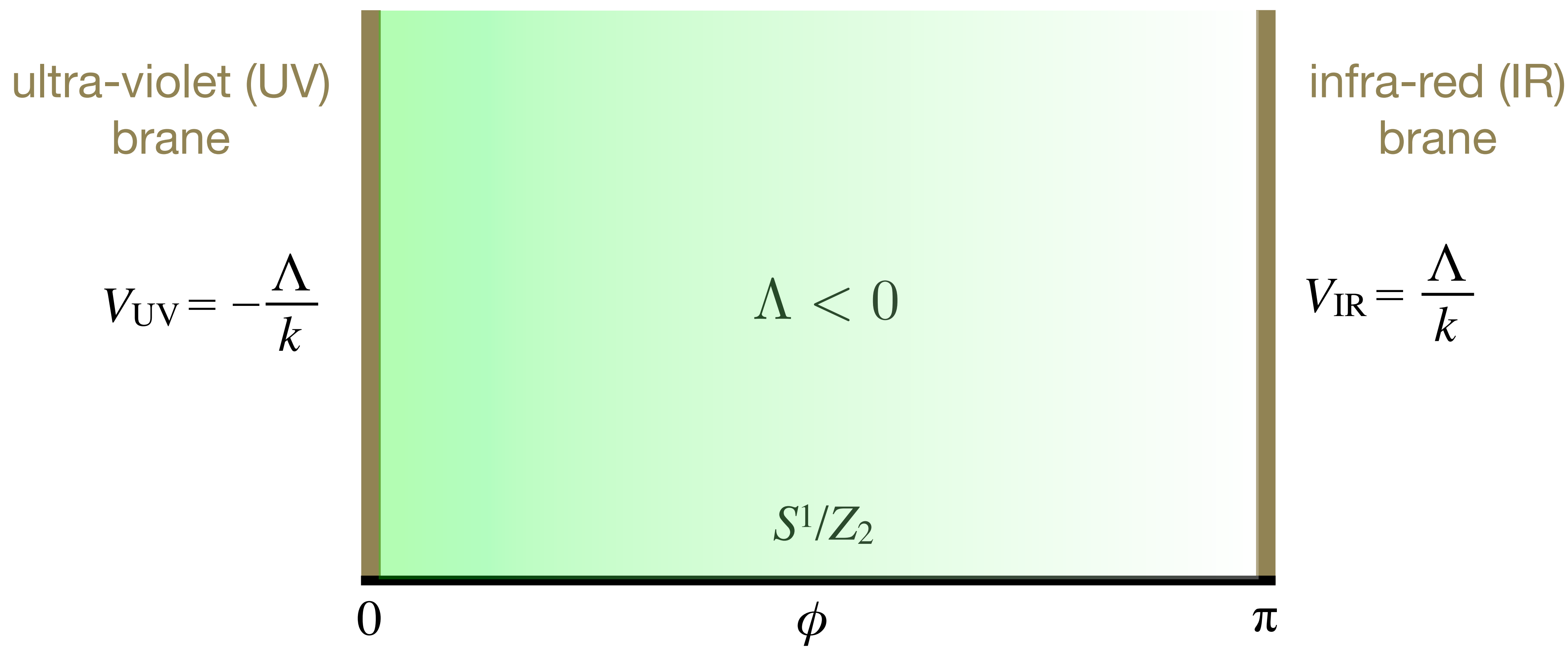
The Randall-Sundrum (RS) idea





(Wikipedia)

Hierarchies from geometry: RS model*



Slice of AdS_5 with curvature k:

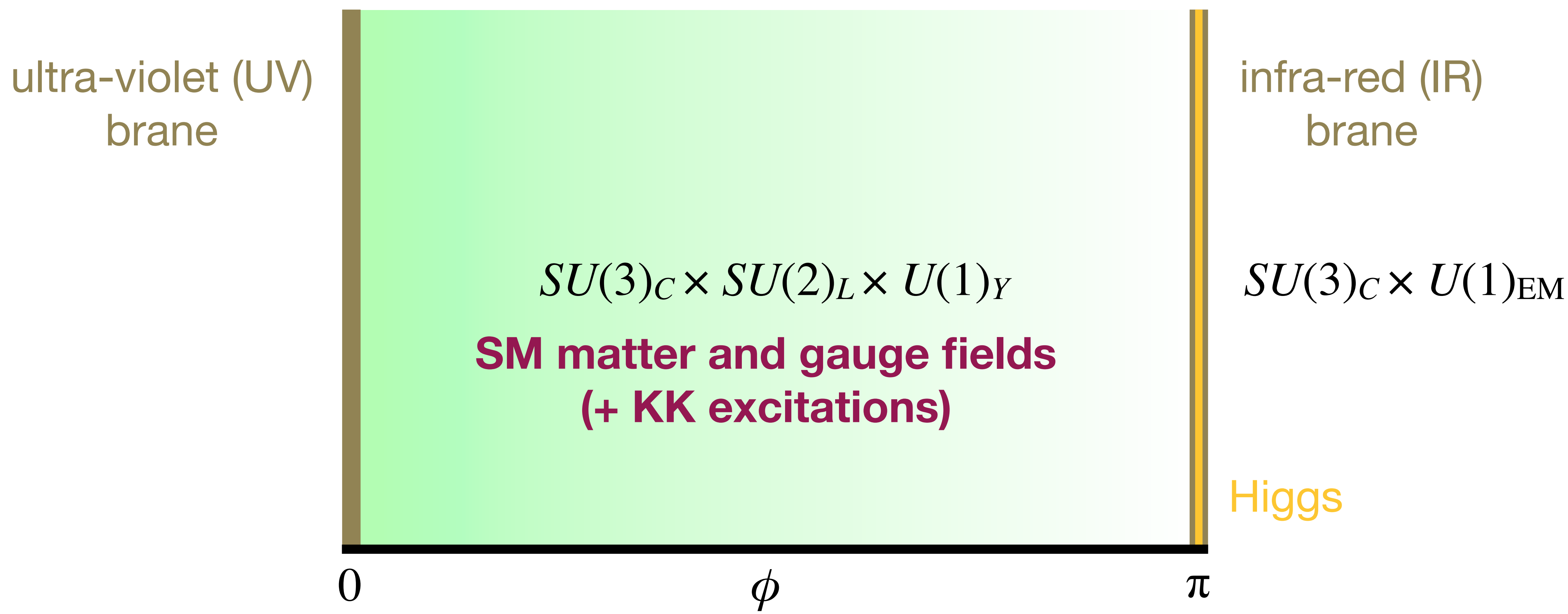
warp factor
(solution to Einstein's equations)

$$ds^2 = e^{-2\sigma}\eta_{\mu\nu}dx^\mu dx^\nu - r^2 d\phi^2\,, \quad \sigma = kr|\phi|$$

$$\epsilon = \frac{M_{\rm weak}}{M_{\rm Planck}} = e^{-kr\pi} \approx 10^{-16}\,, \qquad M_{\rm KK} = k\epsilon = \text{few TeV}$$

*Randall and Sundrum, hep-ph/9905221, hep-th/9906064

Hierarchies from geometry: RS model

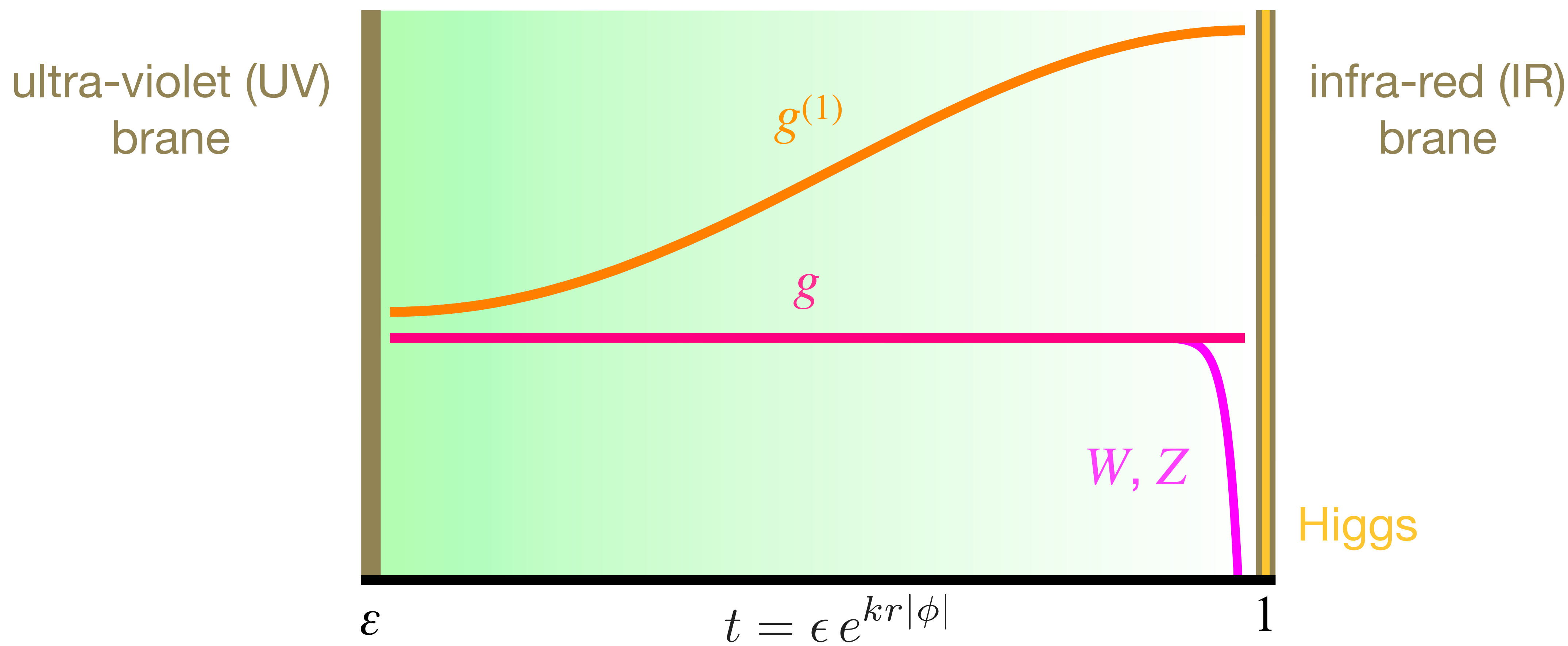


<u>Pattern of gauge-symmetry breaking:</u>

- bulk gauge group $SU(2)_L \times U(1)_Y$ broken by IR brane-localized Higgs to $U(1)_{\mathrm{EM}}$
- more complicated patterns (custodial symmetry) have also been considered*

*Agashe, Delgado, May, Sundrum, hep-ph/0308036; Agashe, Contino, Da Rold, Pomarol, hep-ph/0605341

RS model: Gauge boson profiles*

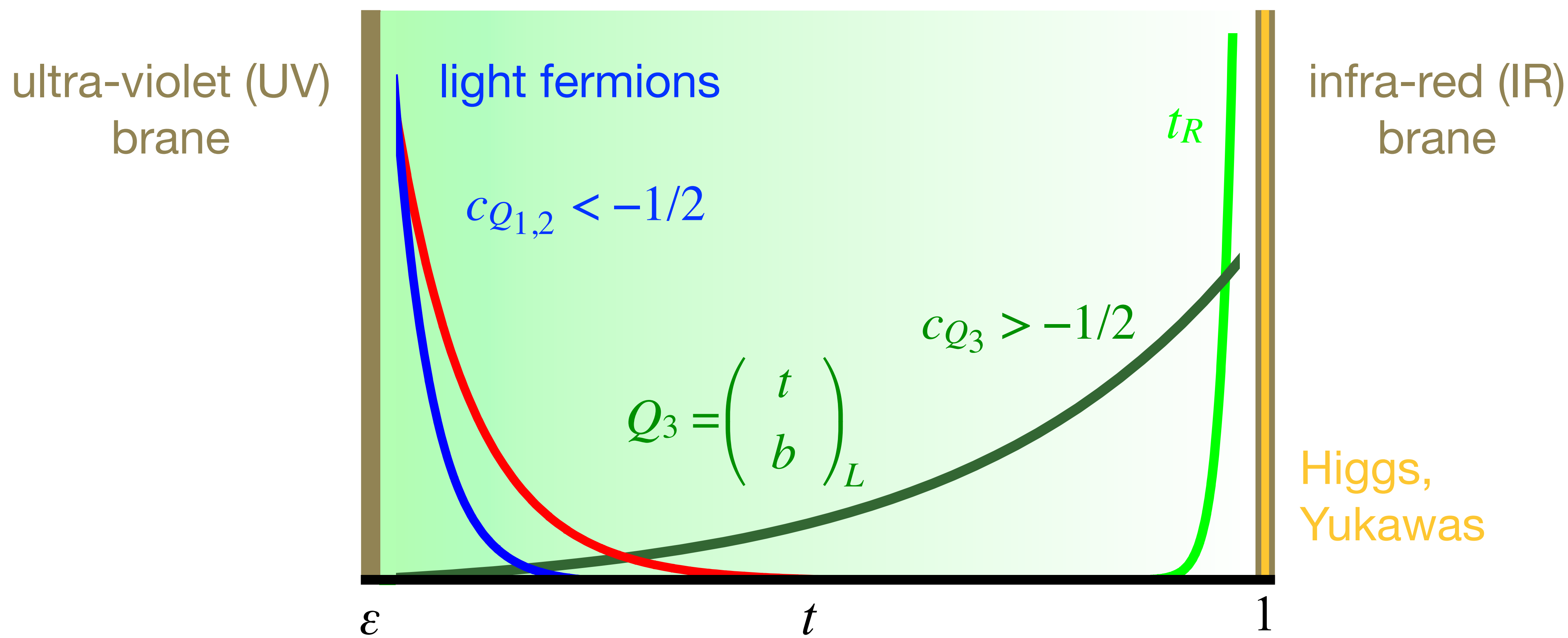


<u>Profiles of gauge fields:</u>

- while profiles of photon and gluon are flat, wave functions of heavy gauge bosons and KK modes are peaked near IR brane

*Davoudiasl *et al.*, hep-ph/9911262; Pomarol, hep-ph/9911294; Chang *et al.*, hep-ph/9912498

RS model: Fermion profiles*



Profiles of fermion fields:

- localization of fermion profiles in extra dimension controlled by bulk mass parameters $c_{Q,q} = \pm M_{Q,q}/k$
- wave functions on IR brane: $$\boxed{F_{c_A} = \sqrt{\frac{1+2c}{1-\epsilon^{1+2c}}} \sim \epsilon^{-\frac{1}{2}-c}} \quad (c < -\frac{1}{2})$$

$(\epsilon = e^{-kr\pi} \approx 10^{-16})$

*Grossman and Neubert, hep-ph/9912408; Ghergetta and Pomarol, hep-ph/0003129

Quark masses and mixings in RS model*

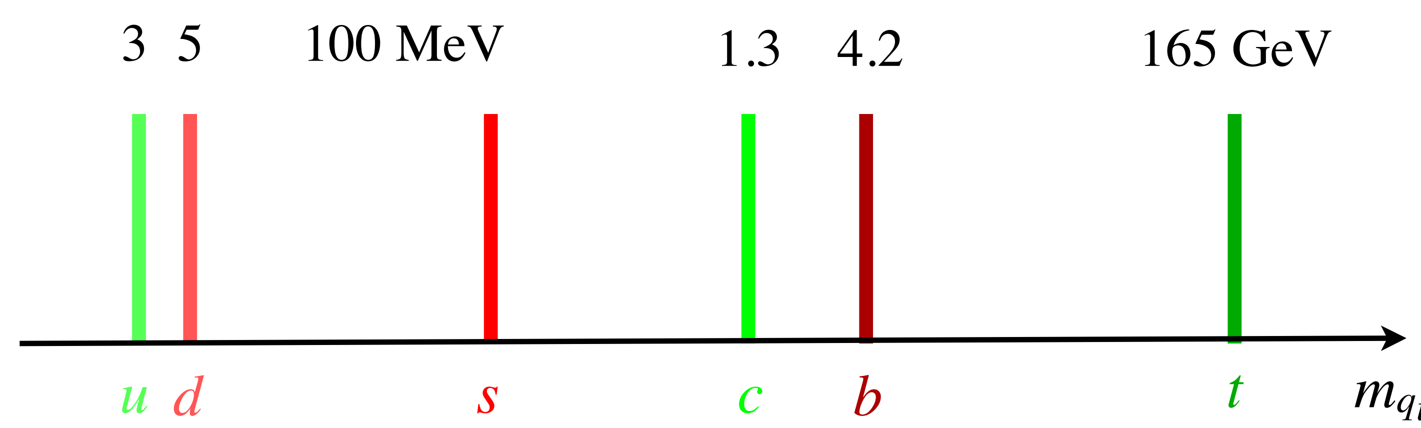
Scaling laws:

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

$$\lambda = \mathcal{O}(1)\,\frac{F_{c_{Q_1}}}{F_{c_{Q_2}}}$$

$$A = \mathcal{O}(1)\,\frac{F^3_{c_{Q_2}}}{F^2_{c_{Q_1}}F_{c_{Q_3}}}$$

$$\bar\rho - i\bar\eta = \mathcal{O}(1)$$



$$\begin{aligned}
c_{Q_1} &= -0.579\,, & c_{Q_2} &= -0.517\,, & c_{Q_3} &= -0.473\\
c_{u_1} &= -0.742\,, & c_{u_2} &= -0.558\,, & c_{u_3} &= +0.339\\
c_{d_1} &= -0.711\,, & c_{d_2} &= -0.666\,, & c_{d_3} &= -0.553
\end{aligned}$$

(+ anarchic Yukawa matrices)

- Hierarchy in quark masses and mixings can be naturally generated from anarchic complex 3×3 matrices $Y_q = \mathcal{O}(1)$ entering $Y_q^{\rm eff} = F_{c_{Q_i}}\,(Y_q)_{ij}\,F_{c_{q_j}}$

*Huber, hep-ph/0303183

Warped-space Froggatt-Nielsen mechanism*

Bulk fermions in RS:

$$(Y_q^{\text{eff,RS}})_{ij} \propto (Y_q)_{ij}\, \epsilon^{c_{Q_i} - c_{q_j}}$$

- bulk parameter c_{Q_i, q_i}
- warp factor $\epsilon = e^{-kr\pi}$

Froggatt-Nielsen (FN) symmetry:

$$(Y_q^{\text{eff,FN}})_{ij} \propto (Y_q)_{ij}\, \epsilon^{a_{Q_i} - b_{q_j}}$$

- $U(1)_F$ charges $Q_F = a_{Q_i},\, b_{q_j}$
- model parameter $\epsilon \ll 1$ set by VEVs

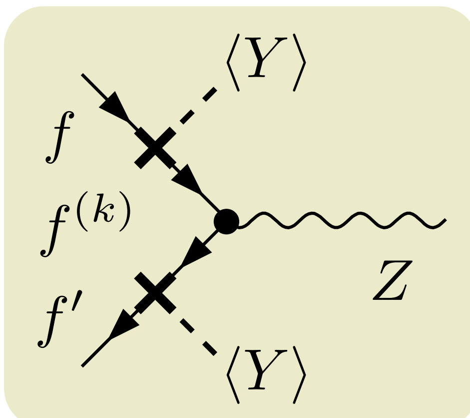
- Models with warped spatial extra dimension provide compelling geometrical interpretation of flavor symmetry

RS is a **theory** of flavor!

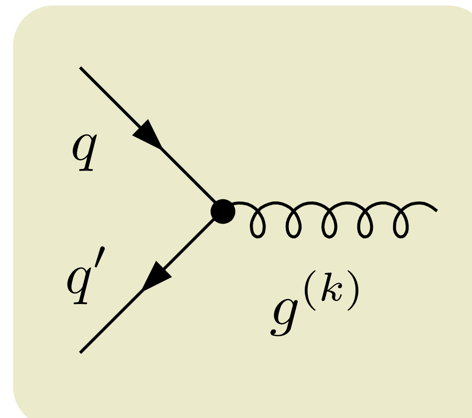
(to a good extent)

*Froggatt and Nielsen, Nucl. Phys, B147 (1979) 277; Casagrande *et al.*, arXiv:0807.4537; Blanke *et al.*, arXiv:0809.1073

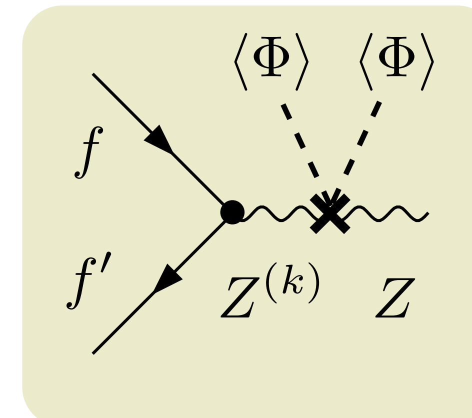
Sources of flavor violation*



also: *W*, *h*



also: $Z^{(k)}$, $\gamma^{(k)}$



<u>Flavor violation arises from:</u>

- modification of W, Z , and Higgs boson profiles due to electroweak symmetry breaking on IR brane: mixing matrices $\mathbf{\Delta}_A$, $\mathbf{\Delta}_A$ with A=Q,q
- non-trivial overlap integrals of KK gauge-boson profiles with SM fermion wave functions: mixing matrices $\mathbf{\Delta}_A$, $\mathbf{\Delta}'_A$
- non-orthonormality of fermion profiles interpreted as mixing of $SU(2)_L$ singlet and doublets via their KK excitations: mixing matrices $\boldsymbol{\delta}_A$

*Huber, hep-ph/0303183; Burdman, hep-ph/0310144; Agashe *et al*., hep-ph/0408134; Casagrande *et al*., arXiv:0807.4537

Mixing matrices: Scaling relations

- In all cases one finds:

$$(\Delta_Q^{(\prime)})_{ij} \sim F_{c_{Q_i}} F_{c_{Q_j}} \,, \qquad (\delta_Q)_{ij} \sim \frac{m_{q_i} m_{q_j}}{M_{\rm KK}^2} \frac{1}{F_{c_{q_i}} F_{c_{q_j}}} \sim \frac{v^2 Y_q^2}{M_{\rm KK}^2} F_{c_{q_i}} F_{c_{q_j}}$$

$$(\Delta_q^{(\prime)})_{ij} \sim F_{c_{q_i}} F_{c_{q_j}} \,, \qquad (\delta_q)_{ij} \sim \frac{m_{q_i} m_{q_j}}{M_{\rm KK}^2} \frac{1}{F_{c_{Q_i}} F_{c_{Q_j}}} \sim \frac{v^2 Y_q^2}{M_{\rm KK}^2} F_{c_{Q_i}} F_{c_{Q_j}}$$

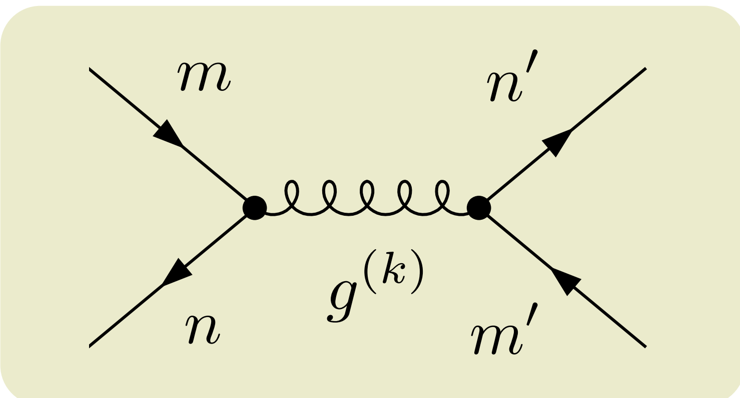
Implications of scaling relations:

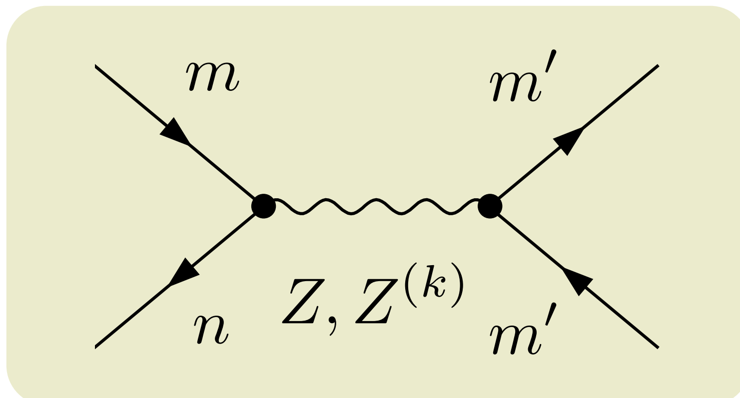
- all effects are proportional to $F_{c_{A_i}} F_{c_{A_j}}$, so that all flavor-violating vertices involving light, UV-localized fermions are suppressed
- this suppression of dangerous FCNCs involving light quarks is called the RS-GIM mechanism*

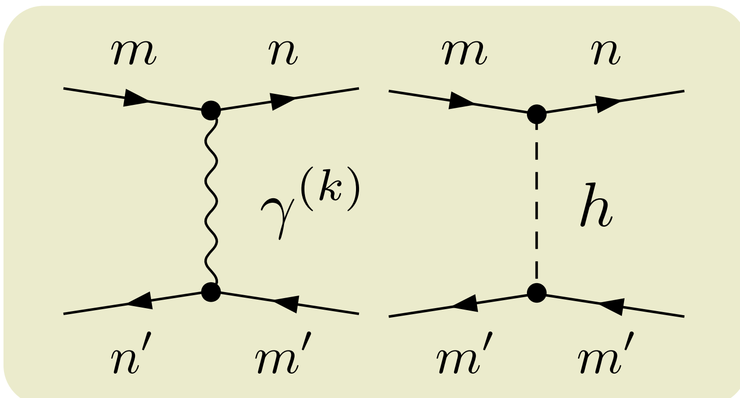
*Agashe *et al*., hep-ph/0406101, hep-ph/0408134

Anatomy of tree-level FCNC processes

- Three types of generic contributions to dimension-six operators:







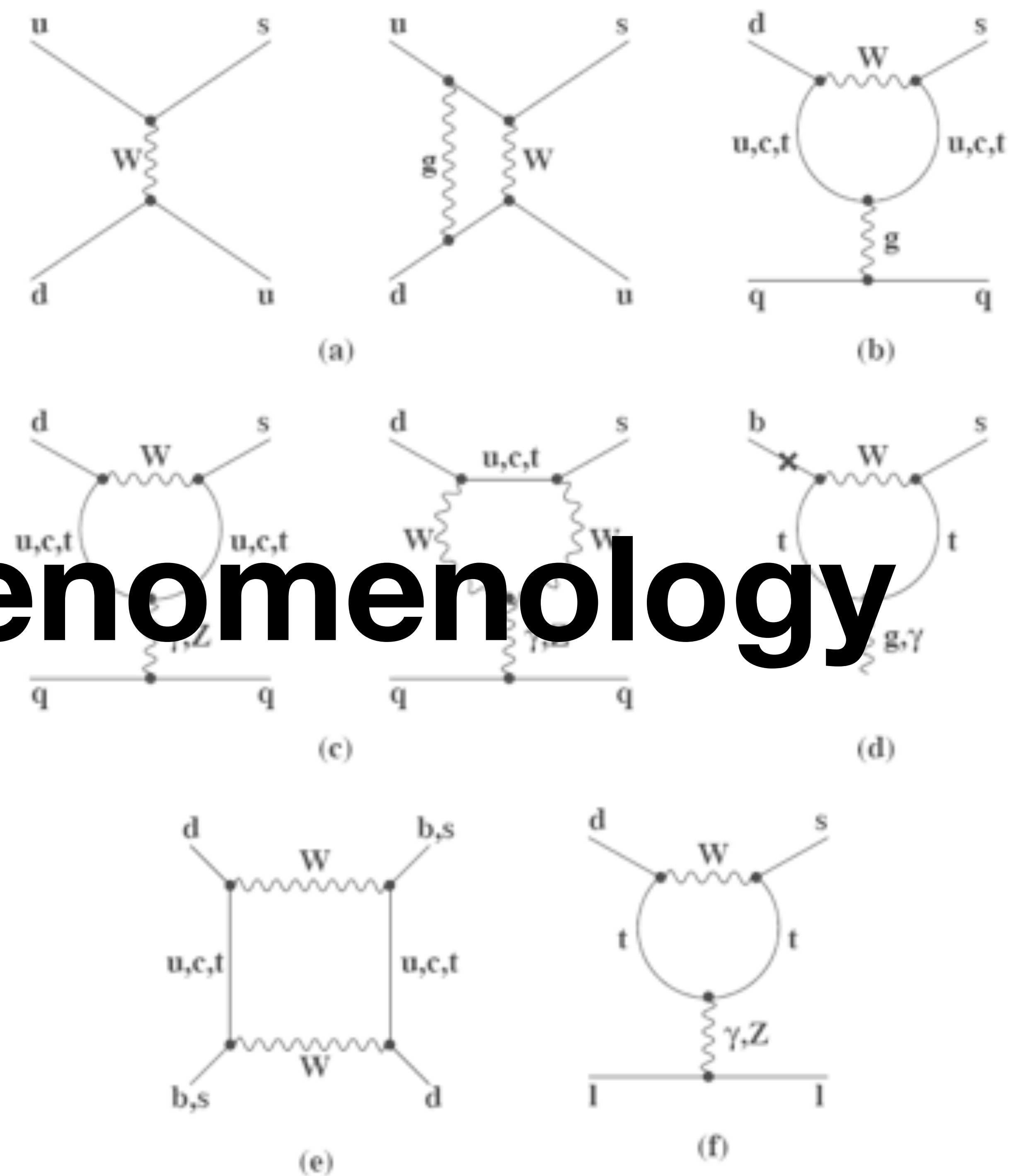
dominant contribution to $\Delta F = 2$ processes

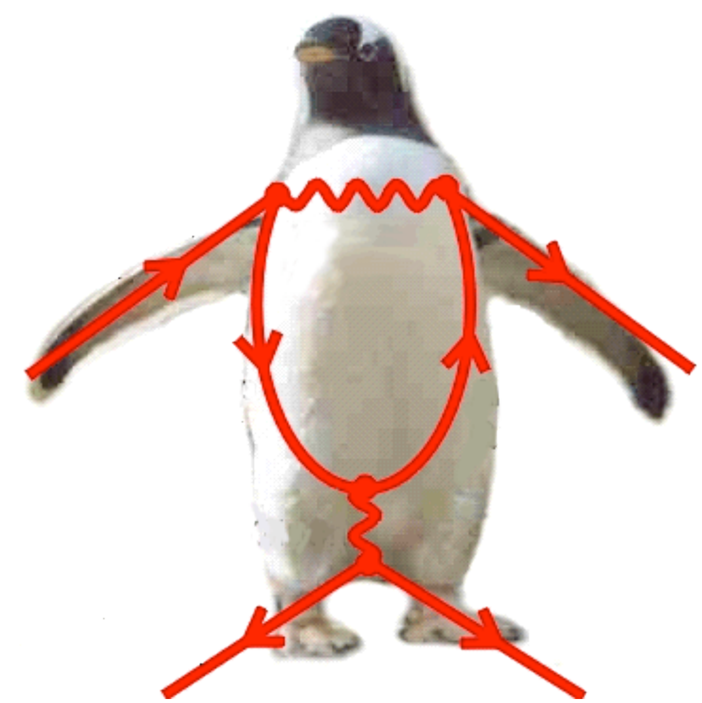
dominant contribution to $\Delta F = 1$ processes

small contributions to $\Delta F = 1, 2$ processes

- Neutral meson mixing is insensitive to electroweak gauge structure!
- Like in SM, dimension-five perators contributing to $B \to X_s \gamma$ or $\mu \to e\gamma$ arise first at one-loop level

Phenomenology

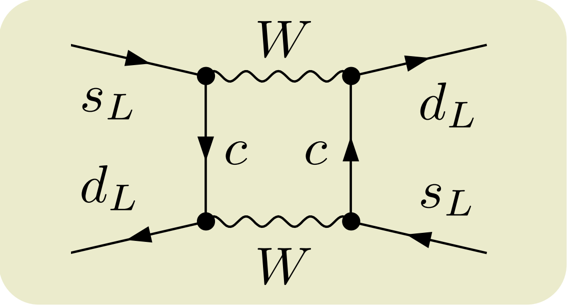




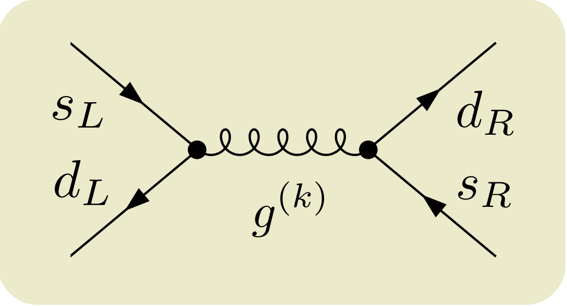
Meson mixing: Effective Hamiltonian*

$$\mathcal{H}_{\text{eff}}^{\Delta S=2} = \sum_{i=1}^{5} C_i Q_i + \sum_{i=1}^{3} \tilde{C}_i \tilde{Q}_i$$

SM



RS



$$Q_1 = (\bar{d}_L^a \gamma_\mu s_L^a)(\bar{d}_L^b \gamma^\mu s_L^b)\,,$$
$$Q_2 = (\bar{d}_R^a s_L^a)(\bar{d}_R^b s_L^b)\,,$$
$$Q_3 = (\bar{d}_R^a s_L^b)(\bar{d}_R^b s_L^a)\,,$$
$$Q_4 = (\bar{d}_R^a s_L^a)(\bar{d}_L^b s_R^b)\,,$$
$$Q_5 = (\bar{d}_R^a s_L^b)(\bar{d}_L^b s_R^a)\,,$$

$$\tilde{Q}_{1,2,3} : L \leftrightarrow R$$

$$C_{1,K}^{\text{RS}} = \frac{4\pi L}{M_{\text{KK}}^2} \big(\widetilde{\Delta}_D\big)_{12} \otimes \big(\widetilde{\Delta}_D\big)_{12} \left[\frac{\alpha_s}{3} + 1.04\,\alpha\right],$$

$$\tilde{C}_{1,K}^{\text{RS}} = \frac{4\pi L}{M_{\text{KK}}^2} \big(\widetilde{\Delta}_d\big)_{12} \otimes \big(\widetilde{\Delta}_d\big)_{12} \left[\frac{\alpha_s}{3} + 0.15\,\alpha\right],$$

$$C_{4,K}^{\text{RS}} = \frac{4\pi L}{M_{\text{KK}}^2} \big(\widetilde{\Delta}_D\big)_{12} \otimes \big(\widetilde{\Delta}_d\big)_{12} \left[-2\alpha_s\right],$$

$$C_{5,K}^{\text{RS}} = \frac{4\pi L}{M_{\text{KK}}^2} \big(\widetilde{\Delta}_D\big)_{12} \otimes \big(\widetilde{\Delta}_d\big)_{12} \left[\frac{2\alpha_s}{3} + 0.30\,\alpha\right]$$

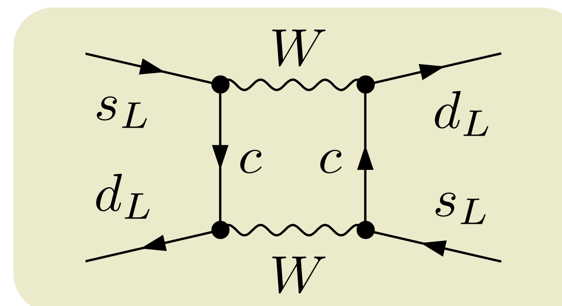
$$\big(\widetilde{\Delta}_A\big)_{mn} \otimes \big(\widetilde{\Delta}_B\big)_{m'n'} \;\rightarrow\; \big(\Delta_A\big)_{mn}\,\big(\Delta_B\big)_{m'n'}$$

*Csaki, Falkowski, Weiler, arXiv:0804.1954; Blanke *et al.*, arXiv:0809.1073; Bauer et al., arXiv:0811.3678

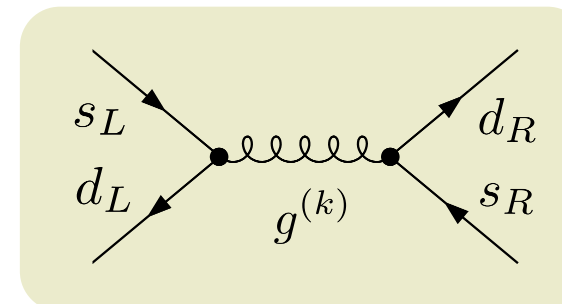
Meson mixing: Effective Hamiltonian*

$$\mathcal{H}_{\text{eff}}^{\Delta S=2} = \sum_{i=1}^{5} C_i Q_i + \sum_{i=1}^{3} \tilde{C}_i \tilde{Q}_i$$

SM



RS



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

$$Q_2 = (\bar{d}_R^a s_L^a)(\bar{d}_R^b s_L^b)\,,$$

$$Q_3 = (\bar{d}_R^a s_L^b)(\bar{d}_R^b s_L^a)\,,$$

$$Q_4 = (\bar{d}_R^a s_L^a)(\bar{d}_L^b s_R^b)\,,$$

$$Q_5 = (\bar{d}_R^a s_L^b)(\bar{d}_L^b s_R^a)\,,$$

$$\tilde{Q}_{1,2,3} : L \leftrightarrow R$$

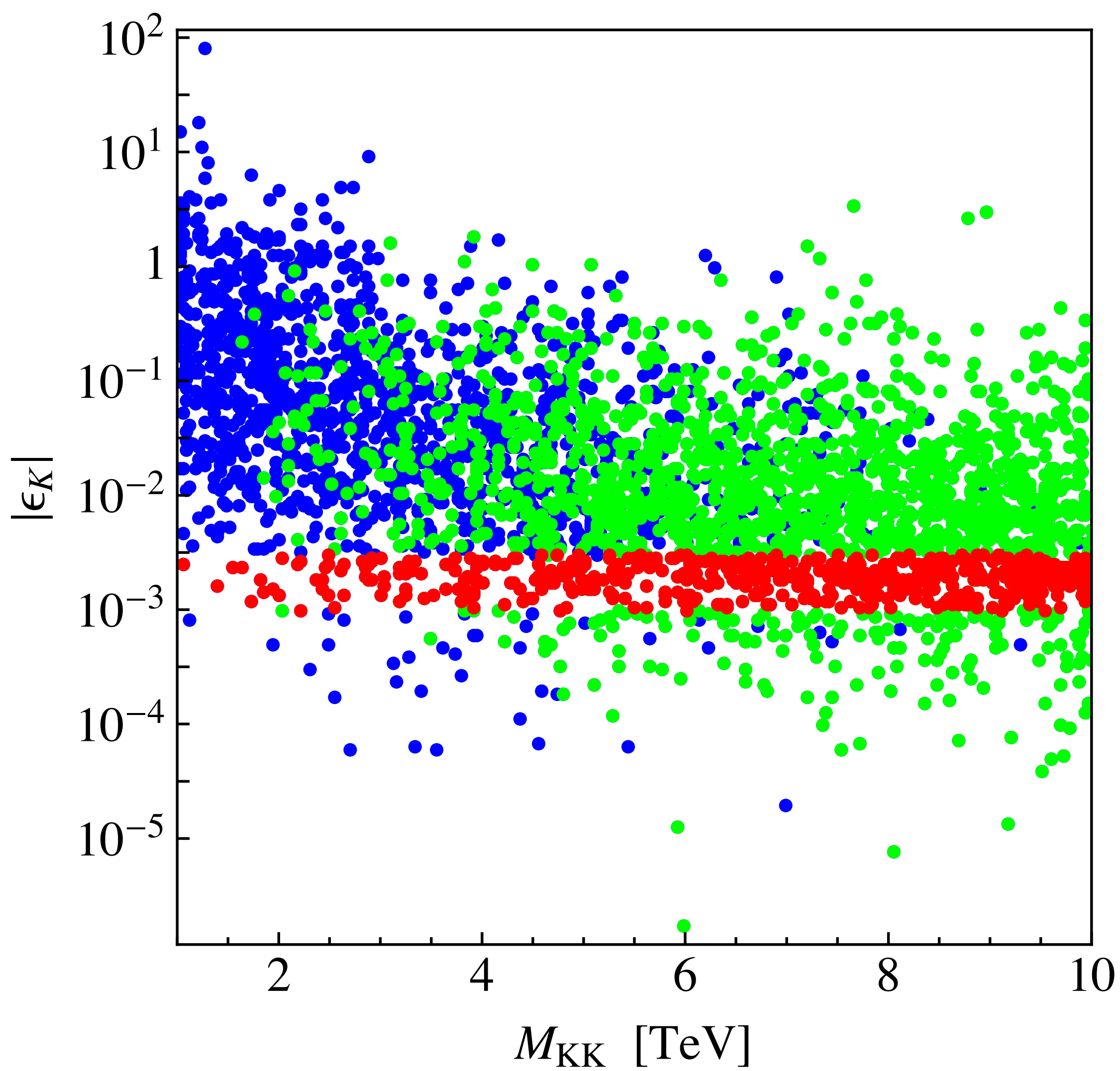
- Contribution from Wilson coefficient of Q_4 to CP-violating quantity ε_K strongly enhanced through renormalization-group evolution and chiral factor $(m_K/m_s)^2$ in matrix element:

$$|\epsilon_K|_{\text{RS}} \propto \text{Im}\left[C_{1,K}^{\text{RS}} + 115\left(C_{4,K}^{\text{RS}} + \frac{C_{5,K}^{\text{RS}}}{3}\right)\right]$$

*Csaki, Falkowski, Weiler, arXiv:0804.1954; Bauer *et al.*, arXiv:0811.3678

Meson mixing: Neutral kaons* (not all is well ...)

- Generically $|\varepsilon_K|/|\varepsilon_K|_{\rm exp} = \mathcal{O}(10)$ in RS model, where $|\varepsilon_K|_{\rm exp} = (2.23 \pm 0.01) \cdot 10^{-3}$. But $|\varepsilon_K| \approx |\varepsilon_K|_{\rm exp}$ possible even for $M_{\rm KK} = 1\ {\rm TeV}$ after some fine-tuning



3000 randomly chosen RS points with $|Y_q| < 3$ reproducing quark masses and CKM parameters with $\chi^2/{\rm dof} < 11.5/10$ (corresponding to 68% CL)

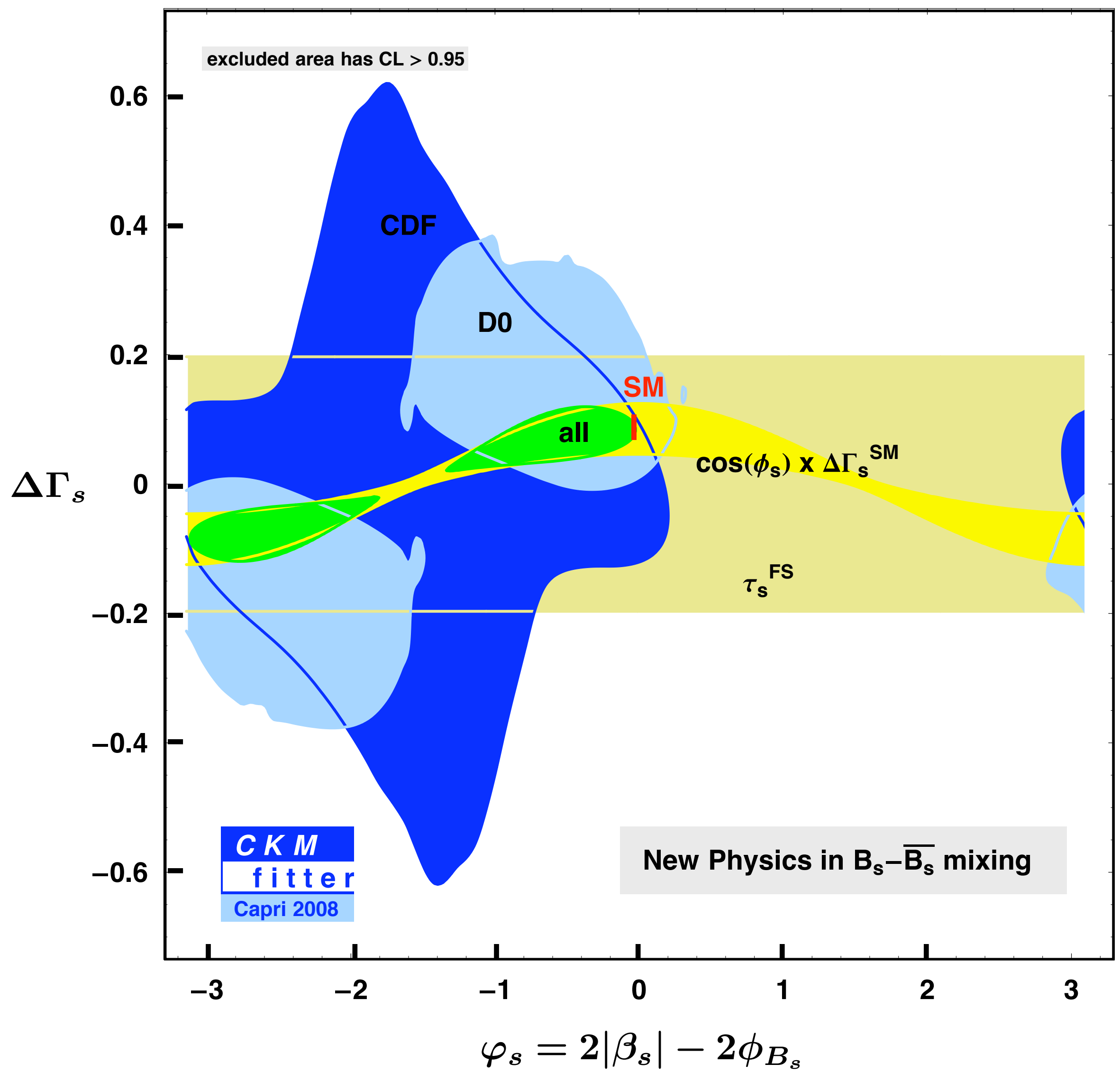
- satisfying 95% CL limit $|\varepsilon_K| \in [1.3, 3.3] \cdot 10^{-3}$
- without $Z \to b\bar{b}$ constraint
- with $Z \to b\bar{b}$ constraint at 95% CL

Upshot: some fine-tuning kaon sector appears to be required!

*Csaki, Falkowski, Weiler, arXiv:0804.1954; Blanke *et al.*, arXiv:0809.1073; Bauer *et al.*, arXiv:0811.3678

BSM physics in 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 $B_s \to J/\psi\phi$ by CDF and DØ



<u>CKMfitter combination:</u>

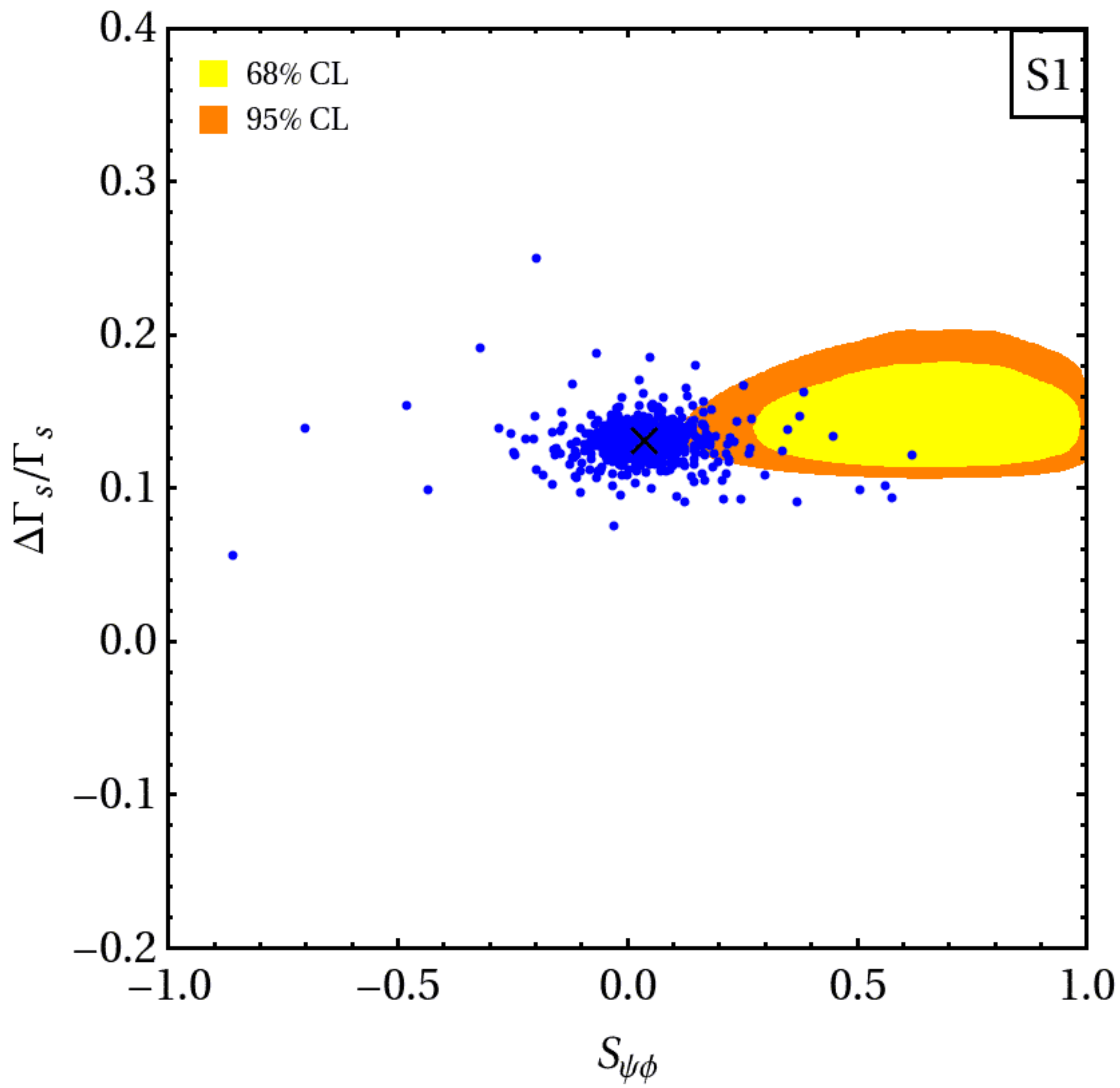
- CDF data only 2.1σ
- DØ data only 1.9σ
- CDF and DØ data 2.7σ
- full BSM physics fit 2.5σ

Discrepancy of $\varphi_s = 2|\beta_s| - 2\phi_{B_s}$ with respect to SM value $\varphi_s \approx 2^\circ$ at around 2σ level. Issue will be clarified at LHCb

*Aaltonen *et al*. [CDF Collaboration], arXiv:0712.2397; Abazov *et al*. [DØ Collaboration], arXiv:0802.2255

Meson mixing: Neutral B_s mesons*

- 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



$$\Delta\Gamma_s = \Gamma_L^s - \Gamma_S^s$$
$$= 2\,|\Gamma_{12}^s|\cos(2|\beta_s| - 2\phi_{B_s})$$

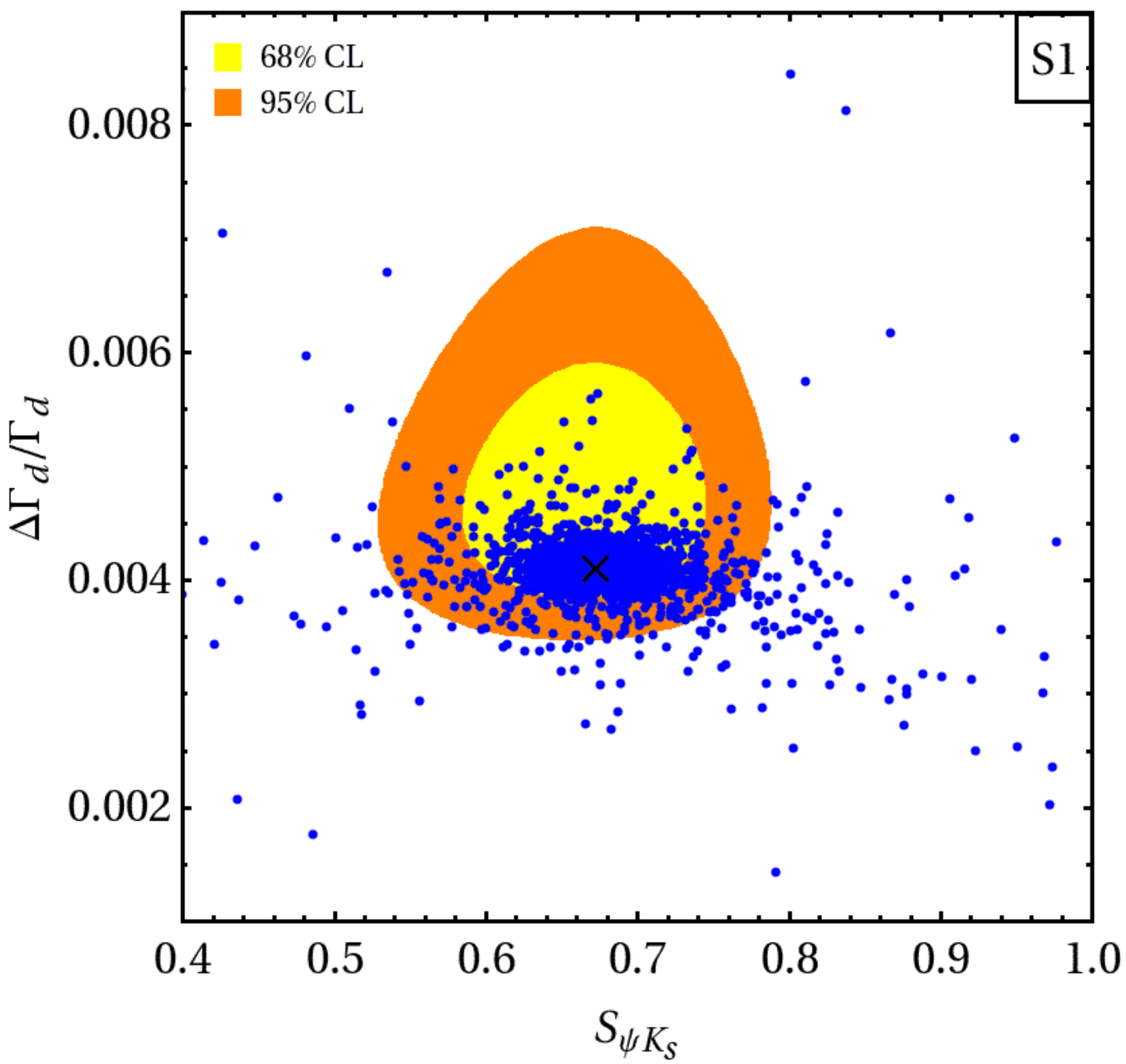
x SM: $\Delta\Gamma_s/\Gamma_s \approx 0.13$, $S_{\psi\phi} \approx 0.04$

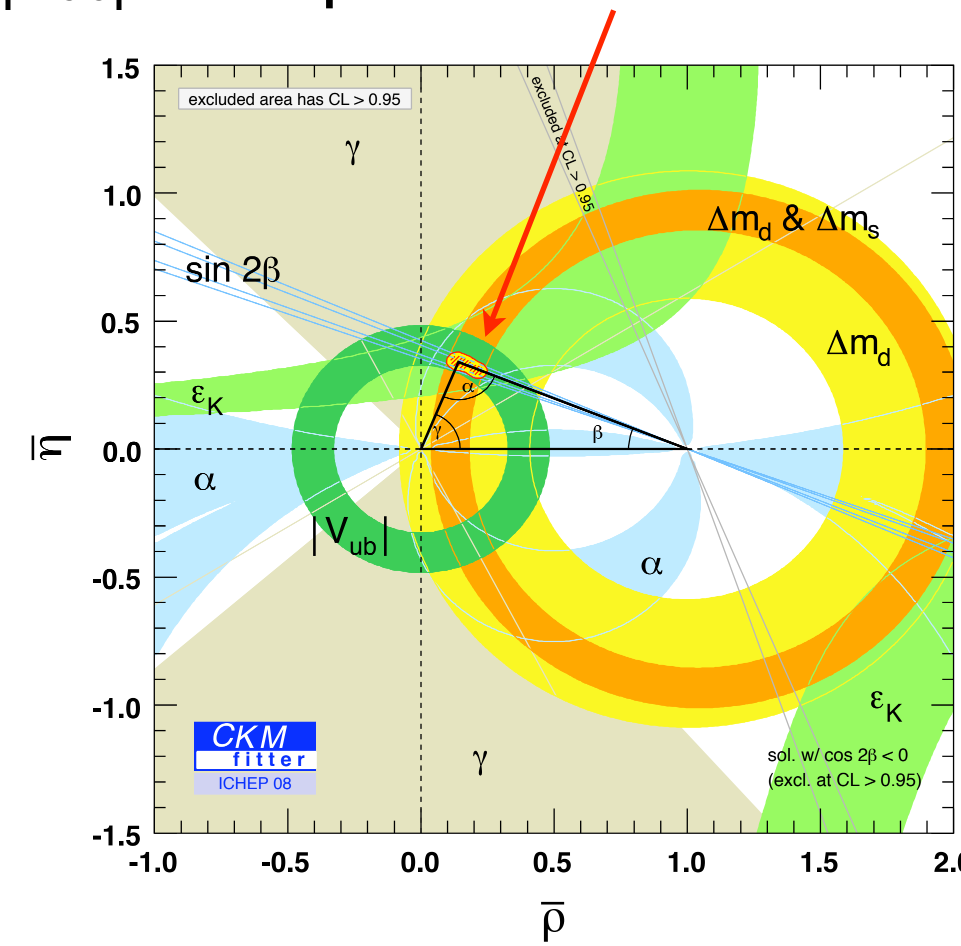
- consistent with quark masses, CKM parameters, Z→b$\bar{\text{b}}$, and 95% CL limit $|\varepsilon_K| \in [1.3, 3.3] \cdot 10^{-3}$

*Blanke *et al.,* arXiv:0809.1073; Bauer *et al.*, arXiv:0912.1625

Meson mixing: Neutral B_d mesons*

- Constraint from $|\varepsilon_K|$ does not exclude significant modifications of the CP asymmetry in $B \to \psi K_S$, which could relax the $|V_{ub}|$ - $\sin 2\beta$ tension





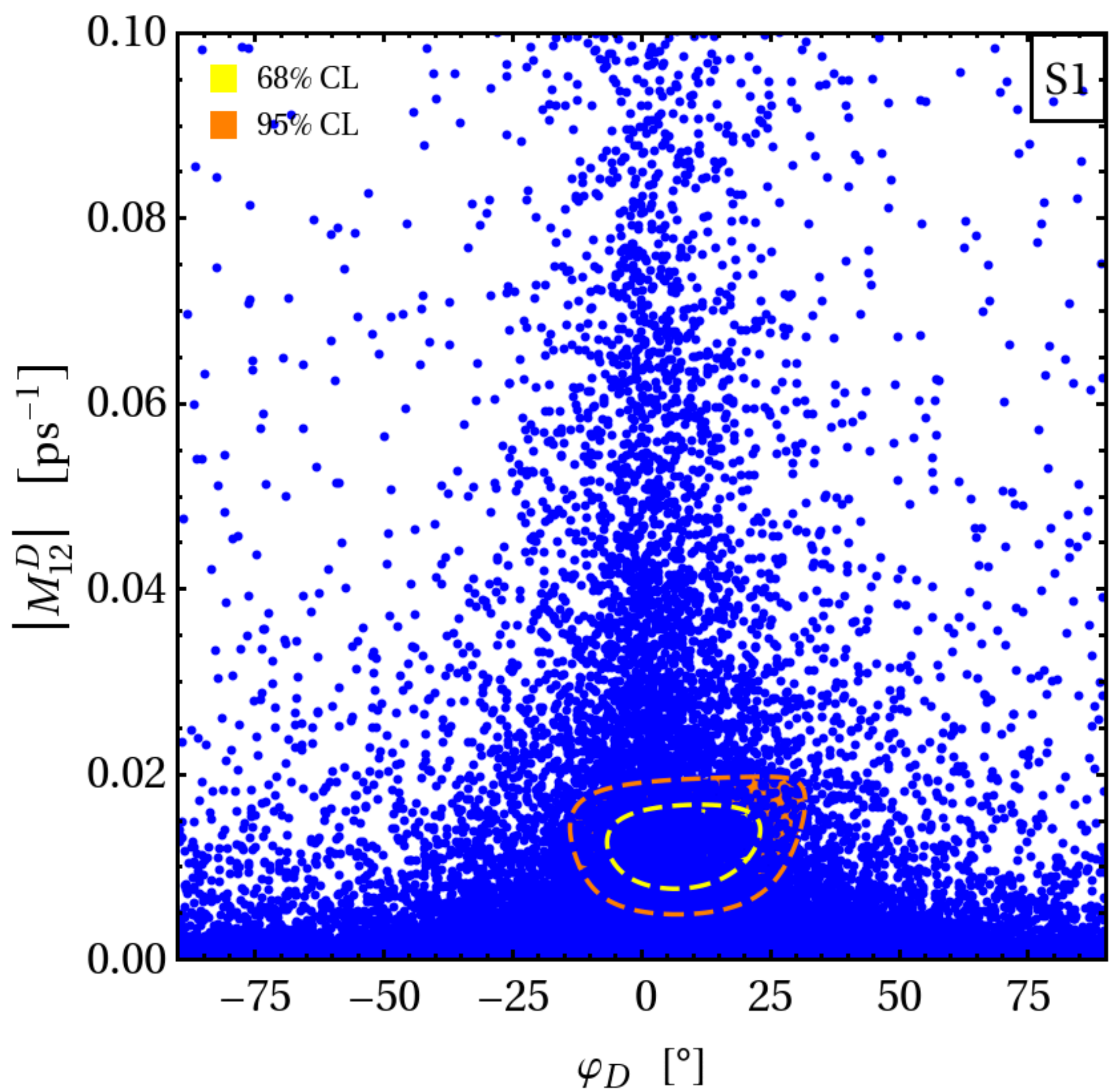
× SM

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

*Blanke *et al.*, arXiv:0809.1073; Bauer *et al.*, arXiv:0912.1625

Meson mixing: Neutral D mesons*

- Very large effects possible in $D - \bar{D}$ mixing, including large CP violation; prediction might be testable at LHCb



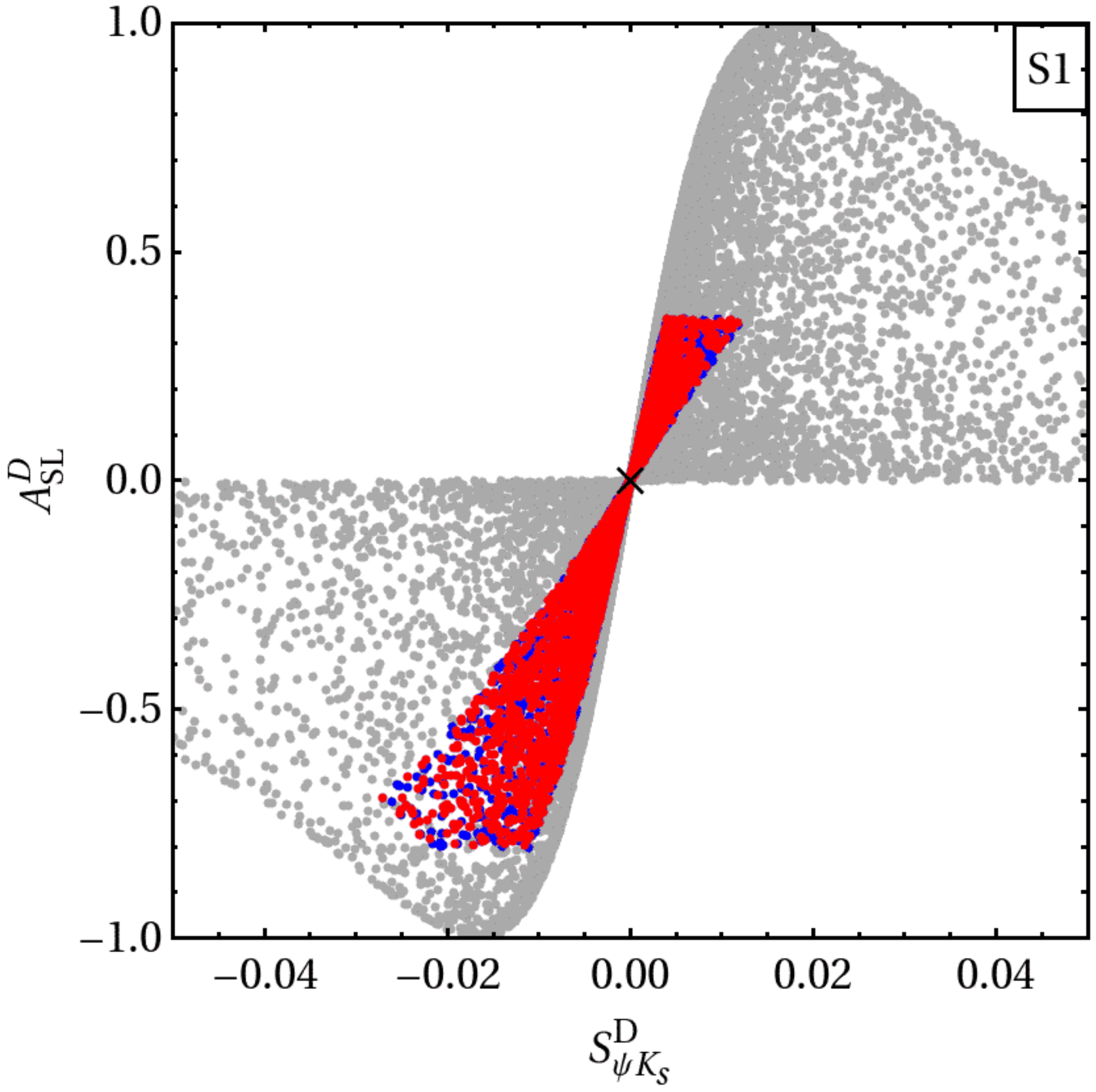
$$
\begin{aligned}
(M_{12}^D)^* &= \langle \bar{D} | \mathcal{H}_{\text{eff,RS}}^{\Delta C=2} | D \rangle \\
&= |M_{12}^D|\, e^{2i\phi_D}
\end{aligned}
$$

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

*Bauer *et al*., arXiv:0912.1625

Meson mixing: Neutral D mesons*

- Large CP-violation effects possible, in particular in $D \to \phi K_S$ mode



x SM

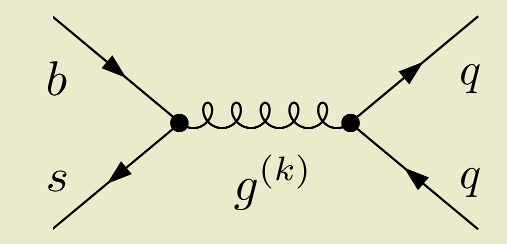
- consistent with quark masses, CKM parameters, $Z \to b\bar{b}$, and 95% CL limit $|\varepsilon_K| \in [1.3, 3.3] \cdot 10^{-3}$

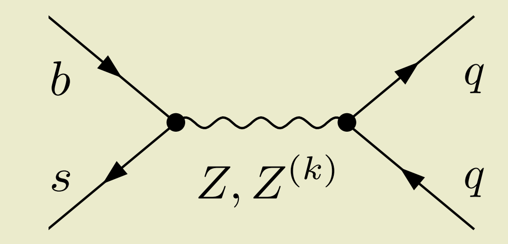
- in addition consistent with $D - \overline{D}$ mixing constraint

*Bauer *et al.*, arXiv:0912.1625

Rare decays: Effective Hamiltonian*

$$\mathcal{H}_{\text{eff,RS}}^{b\to sq\bar{q}} = \sum_{i=3}^{10} \left(C_i^{\text{RS}} Q_i + \tilde{C}_i^{\text{RS}} \tilde{Q}_i \right)$$





$$Q_3 = 4\, (\bar{s}_L^a \gamma^\mu b_L^a) \sum\nolimits_q (\bar{q}_L^b \gamma_\mu q_L^b)\,,$$
$$\vdots$$
$$Q_6 = 4\, (\bar{s}_L^a \gamma^\mu b_L^b) \sum\nolimits_q (\bar{q}_R^b \gamma_\mu q_R^a)\,,$$

$$Q_7 = 6\, (\bar{s}_L^a \gamma^\mu b_L^a) \sum\nolimits_q Q_q\, (\bar{q}_R^b \gamma_\mu q_R^b)\,,$$
$$\vdots$$
$$Q_{10} = 6\, (\bar{s}_L^a \gamma^\mu b_L^b) \sum\nolimits_q Q_q\, (\bar{q}_L^b \gamma_\mu q_L^a)\,,$$

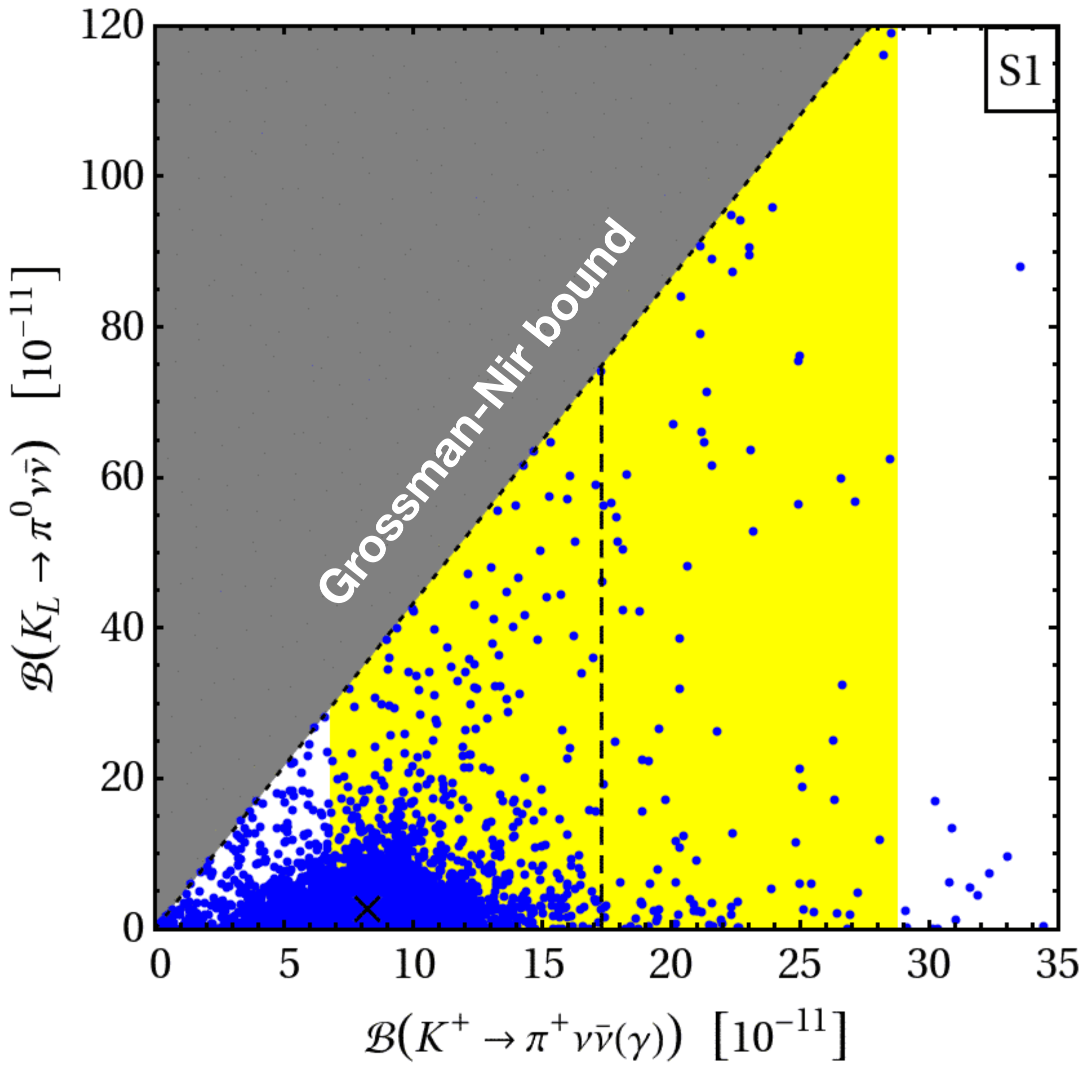
$\tilde{Q}_{3-10}: L \leftrightarrow R$

- KK gluons give dominant contribution to QCD penguins Q_{3-6}. Electroweak penguins Q_{7-10} arise almost entirely from exchange of Z and its KK modes

*Bauer *et al.*, arXiv:0912.1625

Rare K decays: Golden modes*

- Spectacular corrections in very clean $K \to \pi\nu\bar{\nu}$ decays. Even Grossman-Nir bound, $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) < 4.4\,\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$, can be saturated



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

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

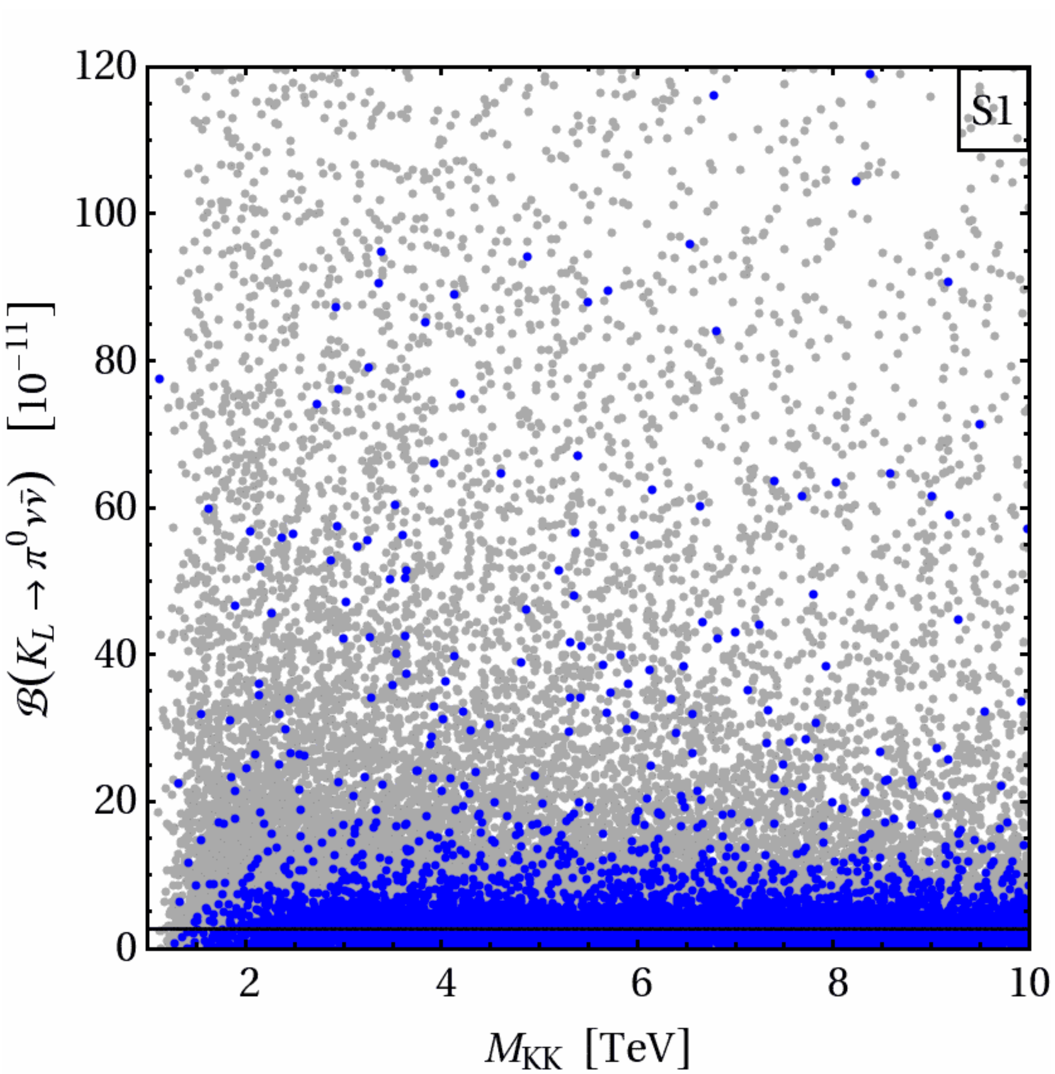
- - - central value and 68% CL limit $\mathcal{B}(K^+ \to \pi^+\nu\nu) = (17.3^{+11.5}_{-10.5}) \cdot 10^{-11}$ from E949

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

*Grossman and Nir, hep-ph/9701313; Bauer *et al*., arXiv:0912.1625

Rare K decays: Golden modes*

- Sensitivity to KK scale extends far beyond LHC reach; $K \to \pi\nu\bar{\nu}$ modes offer unique window to BSM physics at and beyond TeV scale



$$m_{Z^{(1)}} \approx 2.50\, M_{\rm KK}\,,$$
$$m_{Z^{(2)}} \approx 5.59\, M_{\rm KK}\,,$$
$$\vdots$$

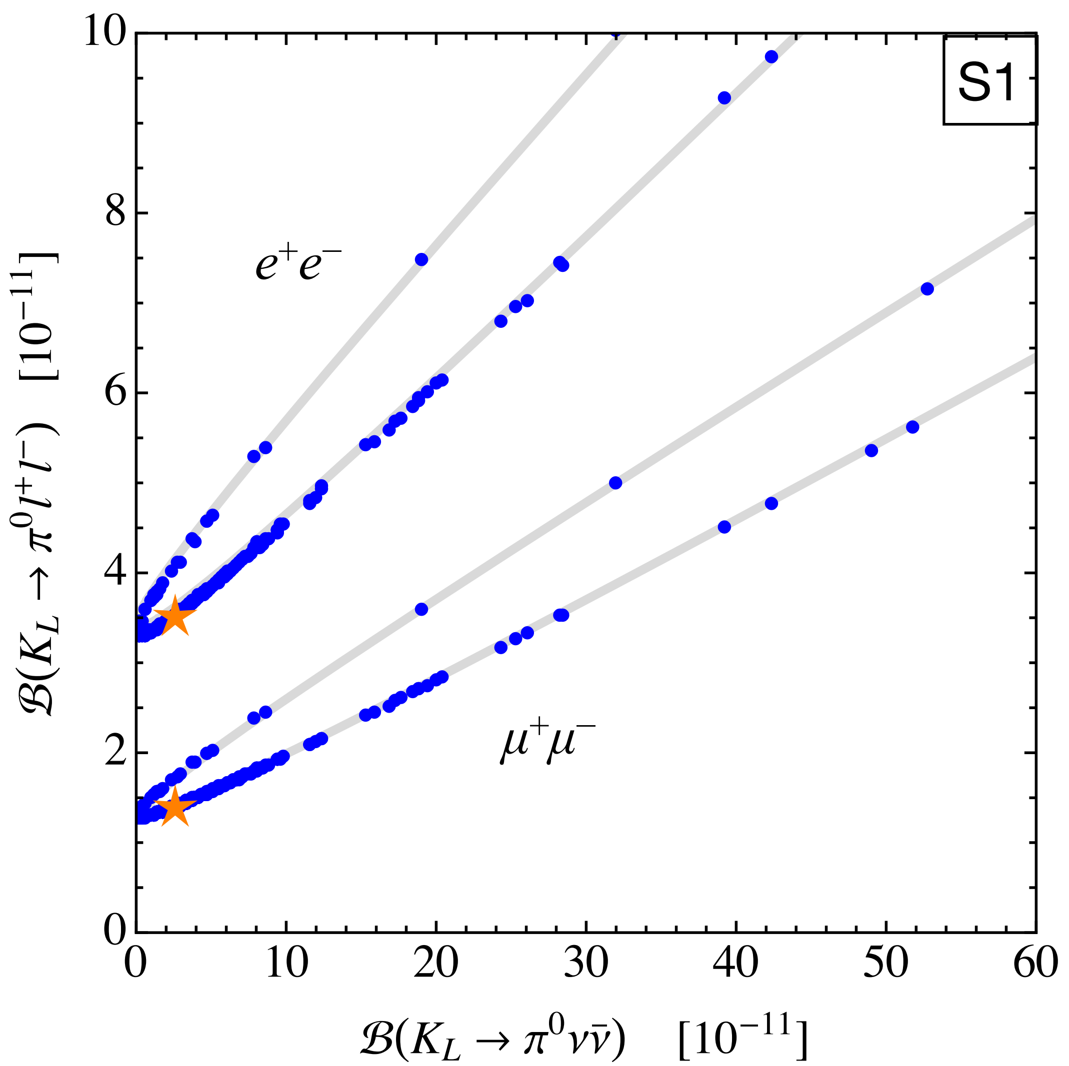
— SM: $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) \approx 2.7 \cdot 10^{-11}$

- consistent with quark masses, CKM parameters, $Z \to b\bar{b}$, and 95% CL limit $|\varepsilon_K| \in [1.3, 3.3] \cdot 10^{-3}$
- same, but without $|\varepsilon_K|$ constraint

*Bauer *et al.*, arXiv:0912.1625

Rare K decays: Silver modes*

- Deviations from SM expectations in $K_L \longrightarrow \pi^0 \nu\bar{\nu}$ and $K_L \longrightarrow \pi^0 l^+ l^-$ follow specific pattern, arising from smallness of vector and scalar contributions



★ SM: $\mathcal{B}(K_L \longrightarrow \pi^0 \nu\bar{\nu}) \approx 2.7 \cdot 10^{-11}$,
$\mathcal{B}(K_L \longrightarrow \pi^0 e^+ e^-) \approx 3.6 \cdot 10^{-11}$,
$\mathcal{B}(K_L \longrightarrow \pi^0 \mu^+ \mu^-) \approx 1.4 \cdot 10^{-11}$
for constructive interference

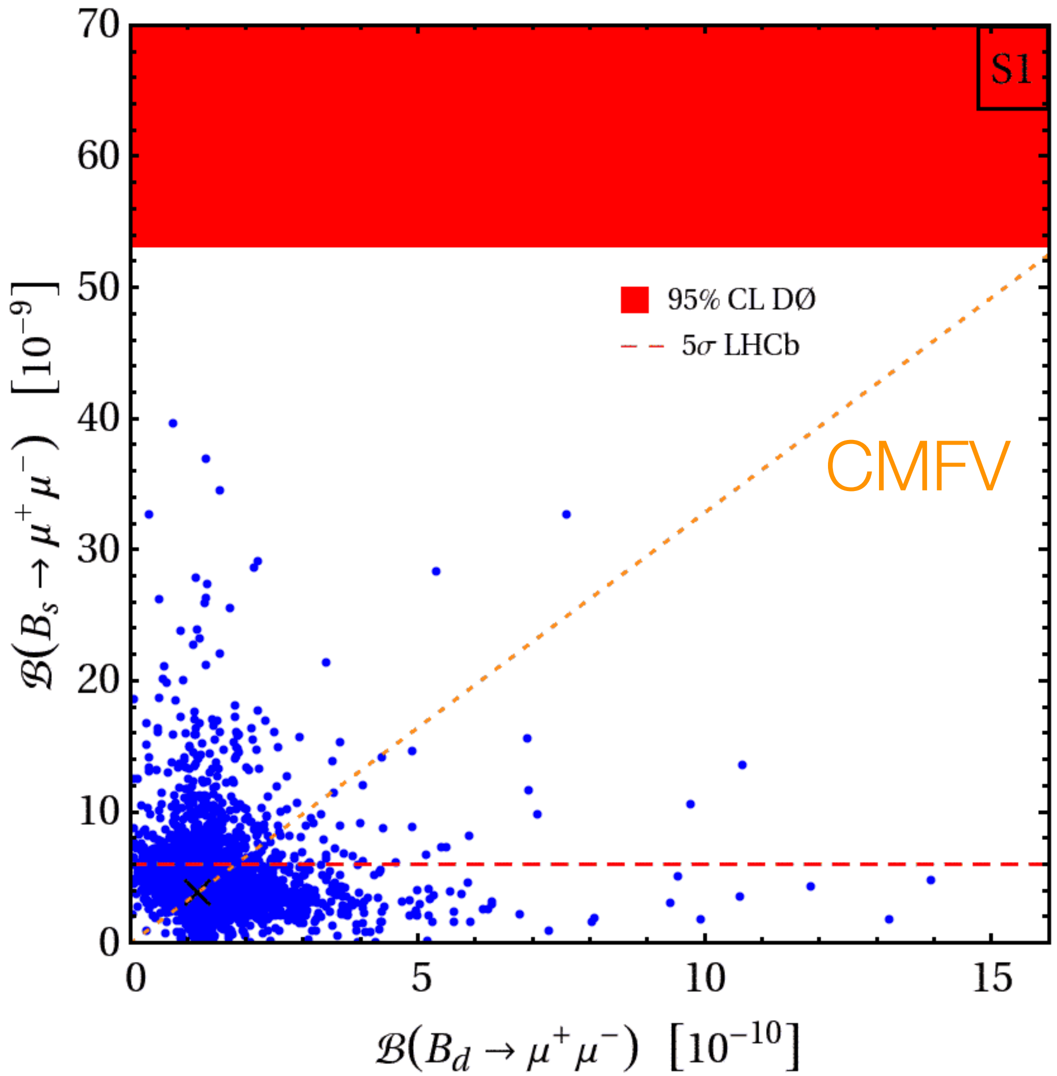
— model-independent prediction

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

*Bauer *et al.*, arXiv:0912.1625

Rare B decays: Purely leptonic modes*

- 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 $|\varepsilon_K|$



× 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, $2\ \mathrm{fb}^{-1}$

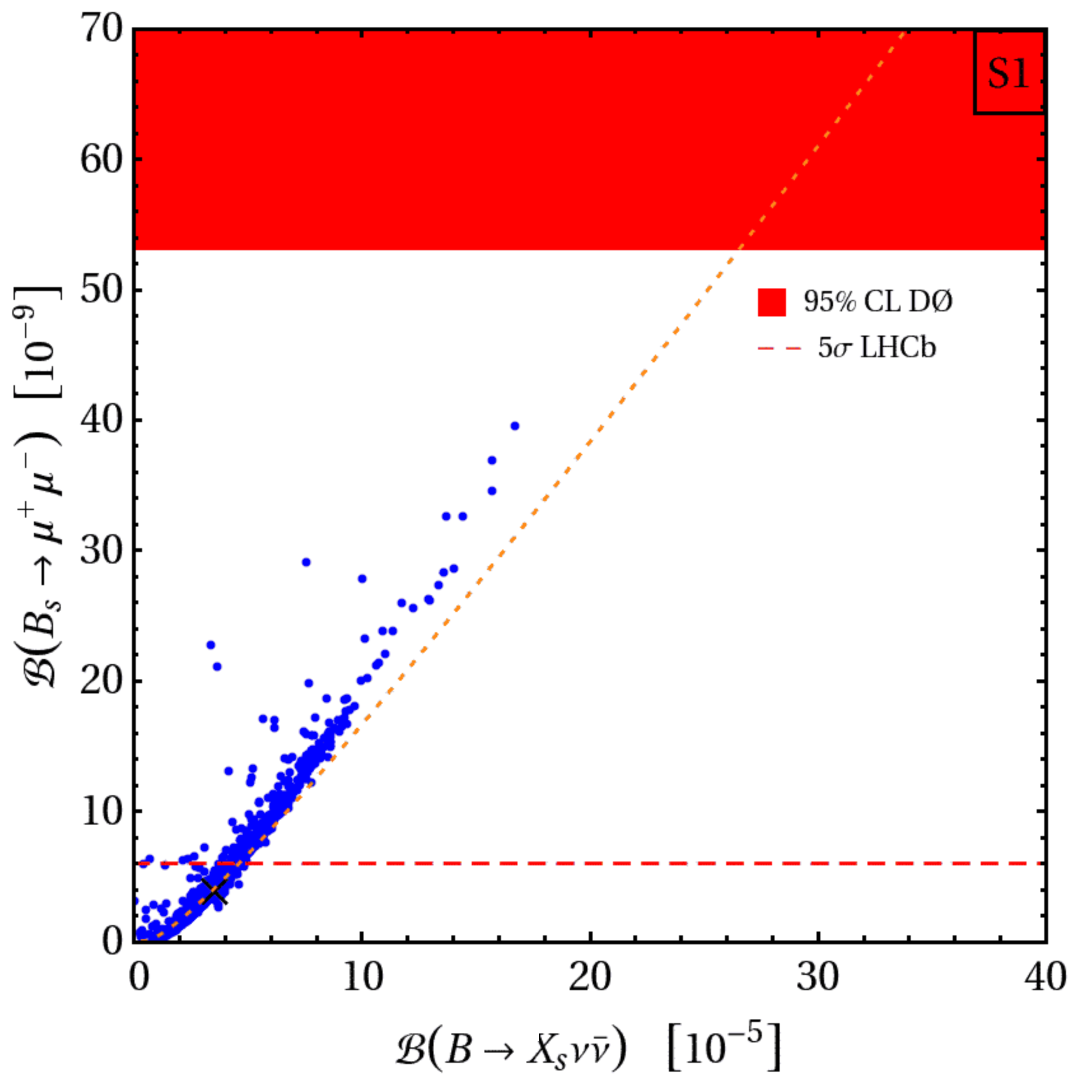
95% CL upper limit from CDF $\mathcal{B}(B_s \to \mu^+\mu^-) < 5.8 \cdot 10^{-8}$

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

*Bauer *et al.*, arXiv:0912.1625

Rare B decays: Purely leptonic modes*

- Enhancements in $B_{d,s} \to \mu^+\mu^-$ strongly correlated with ones in very rare decays $B \to X_{d,s} \nu\bar{\nu}$; pattern again result of axial-vector dominance



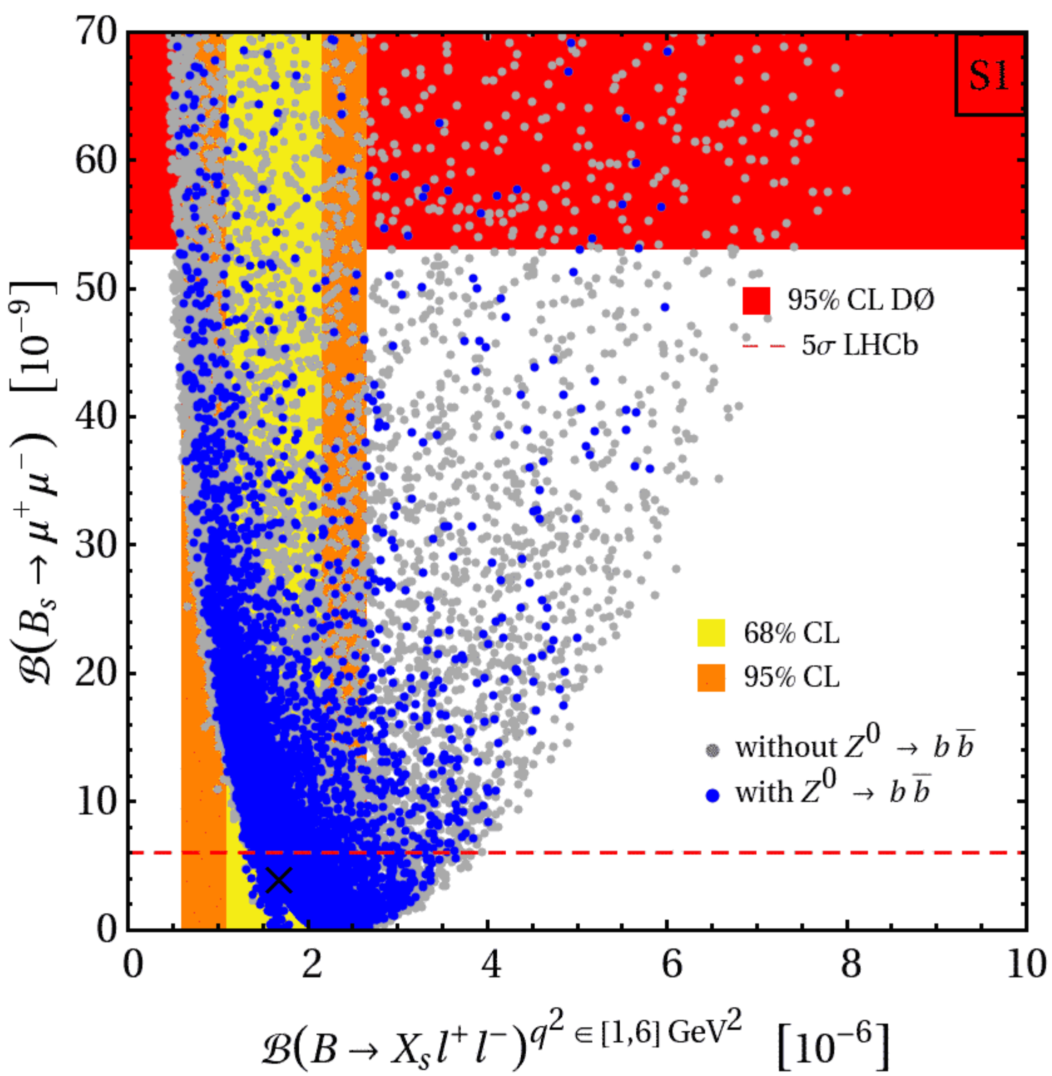
x SM: $\mathcal{B}(B_s \to \mu^+\mu^-) \approx 3.9 \cdot 10^{-9}$,
$\mathcal{B}(B \to X_s \nu\bar{\nu}) \approx 3.5 \cdot 10^{-5}$

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

*Bauer *et al.*, arXiv:0912.1625

Rare B decays: Inclusive semileptonic modes*

- Significant deviations possible in $B \to X_s \mu^+\mu^-$ branching ratio and forward-backward asymmetry



x SM

expected sensitivity at LHCb

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

*Bauer *et al*., arXiv:0912.1625

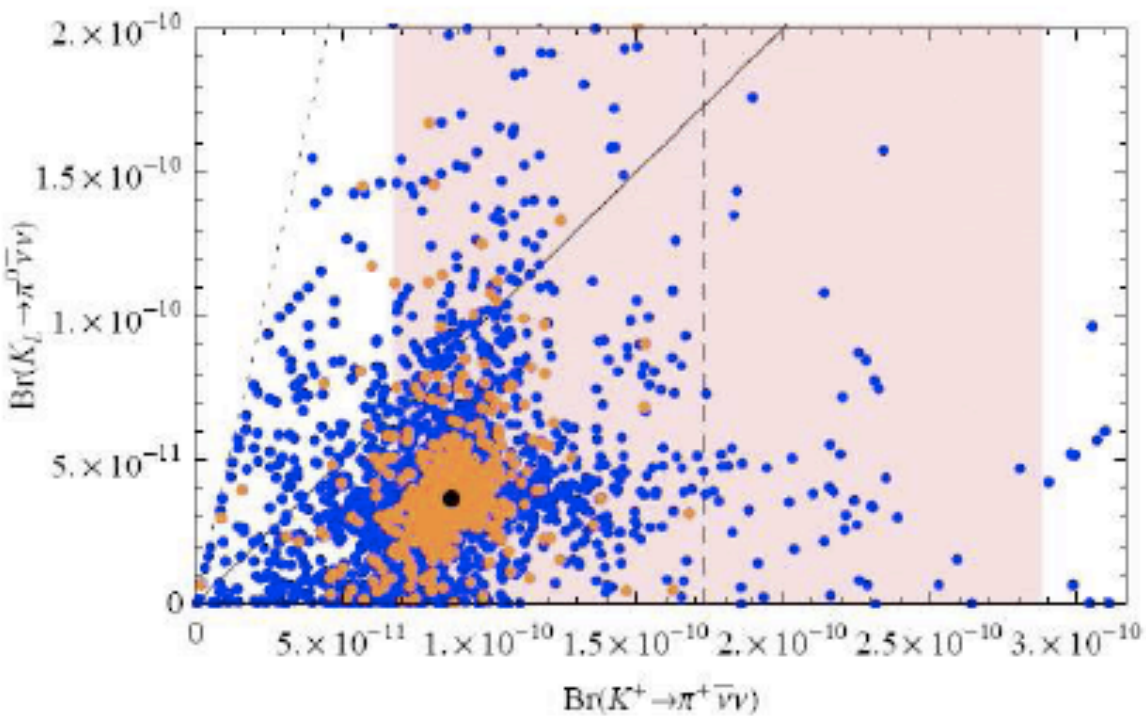
Conclusions

- LHC is finally there, but LHC discoveries alone unlikely to allow for a full understanding of new phenomena observed
- Flavor physics can play a key role in this respect, since it offers a unique window to BSM physics at and beyond the TeV scale
- Warped extra dimensions offer a compelling geometrical explanation of gauge and fermion hierarchy problem, mysteries left unexplained in SM
- Flavor-changing tree-level transitions of K and B_s mesons particularly interesting, as their sensitivity to KK scale extends beyond LHC reach

Backup slides

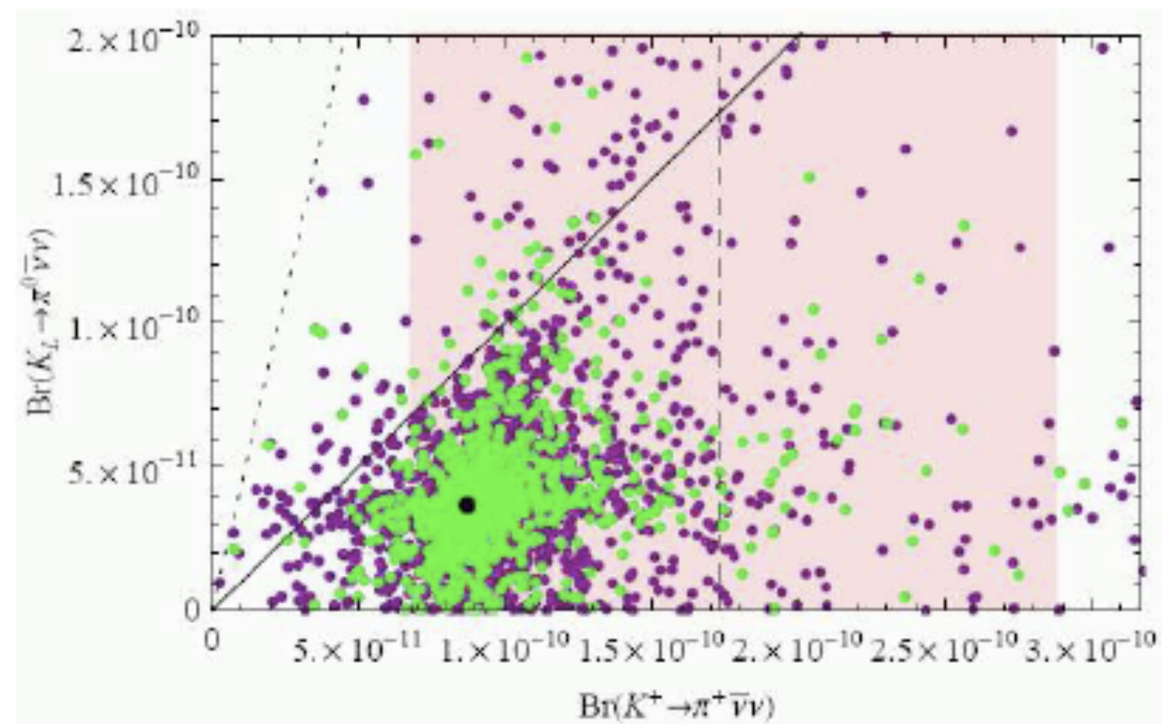
Rare K decays: Golden modes

- Spectacular corrections in very clean $K \to \pi\nu\bar{\nu}$ decays. Even Grossman-Nir bound, $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) < 4.4\,\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$, can be saturated



with custodial protection
(extended gauge symmetry)

orange = moderate fine-tuning for $|\varepsilon_K|$



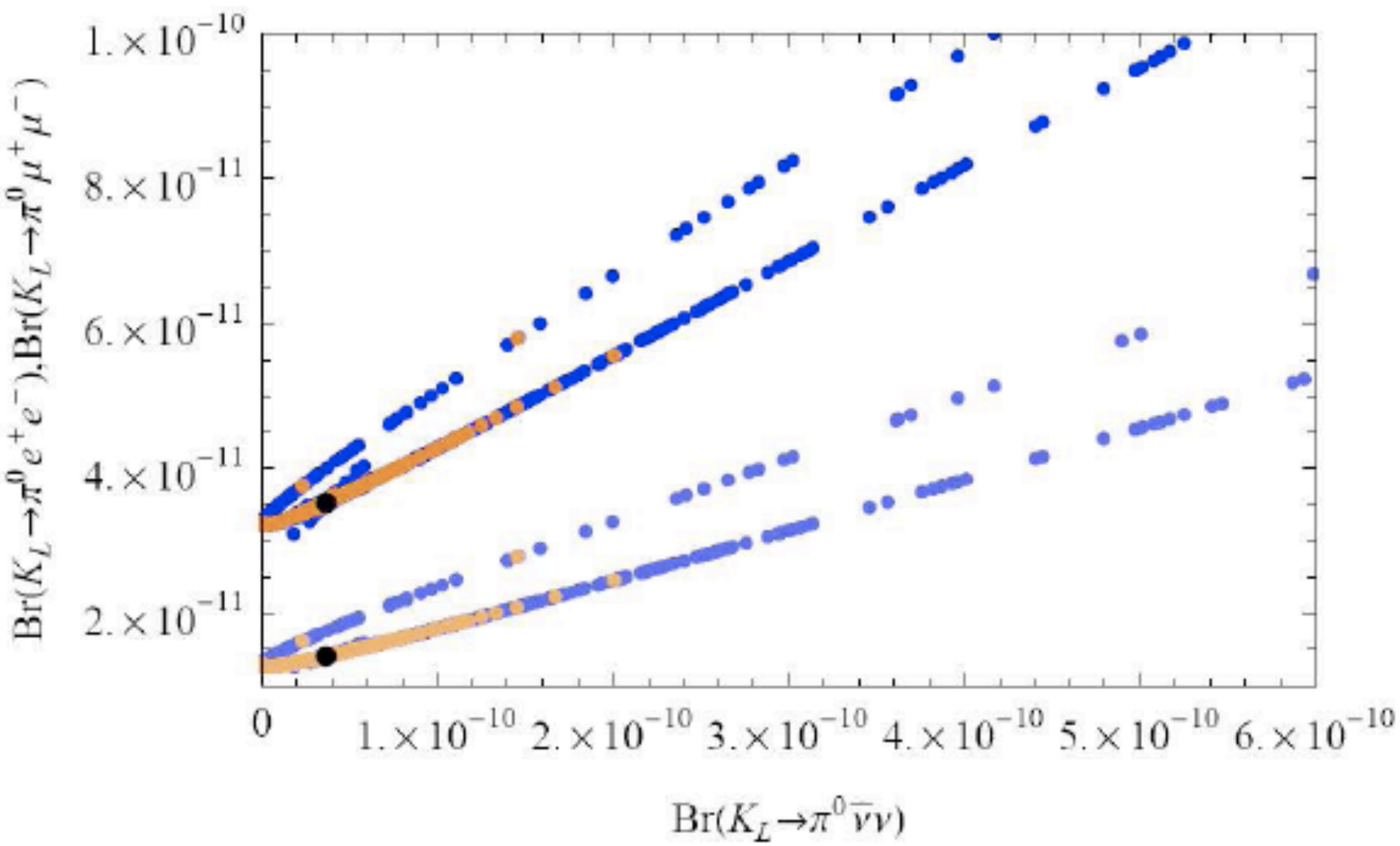
without custodial protection
(minimal model)

green = moderate fine-tuning for $|\varepsilon_K|$

Blanke, Buras, Duling, Gemmler, Gori: arXiv:0812.3803

Rare K decays: Silver modes

- Deviations from SM expectations in $K_L \to \pi^0 \nu\bar{\nu}$ and $K_L \to \pi^0 l^+ l^-$ follow specific pattern, arising from smallness of vector and scalar contributions



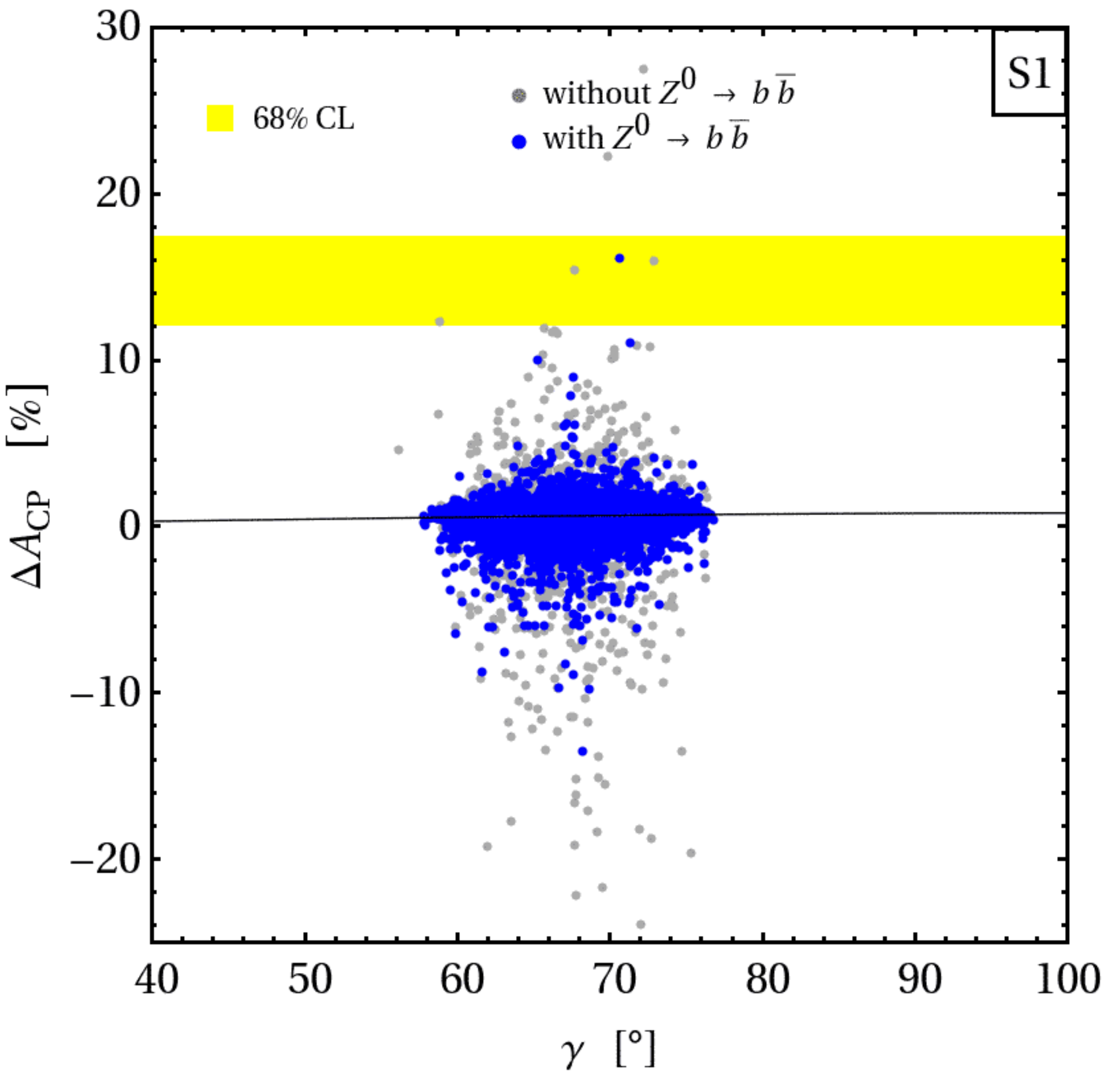
with custodial protection (extended gauge symmetry)

orange = moderate fine-tuning for $|\varepsilon_K|$

Blanke, Buras, Duling, Gemmler, Gori: arXiv:0812.3803

Non-leptonic B decays: A_{CP} puzzle*

- New electroweak penguin effects in RS model can affect the difference in the direct CP asymmetries in $B \to \pi K$ decays, but they cannot explain the large, experimentally observed difference ΔA_{CP} between the asymmetries for $B \to \pi^0 K^-$ and $B \to \pi^+ K^-$



- remains a puzzling effect
- underestimate of hadronic uncertainties?

*Bauer *et al*., arXiv:0912.1625