Flavor physics in a warped extra dimension*

Matthias Neubert
Johannes Gutenberg University Mainz

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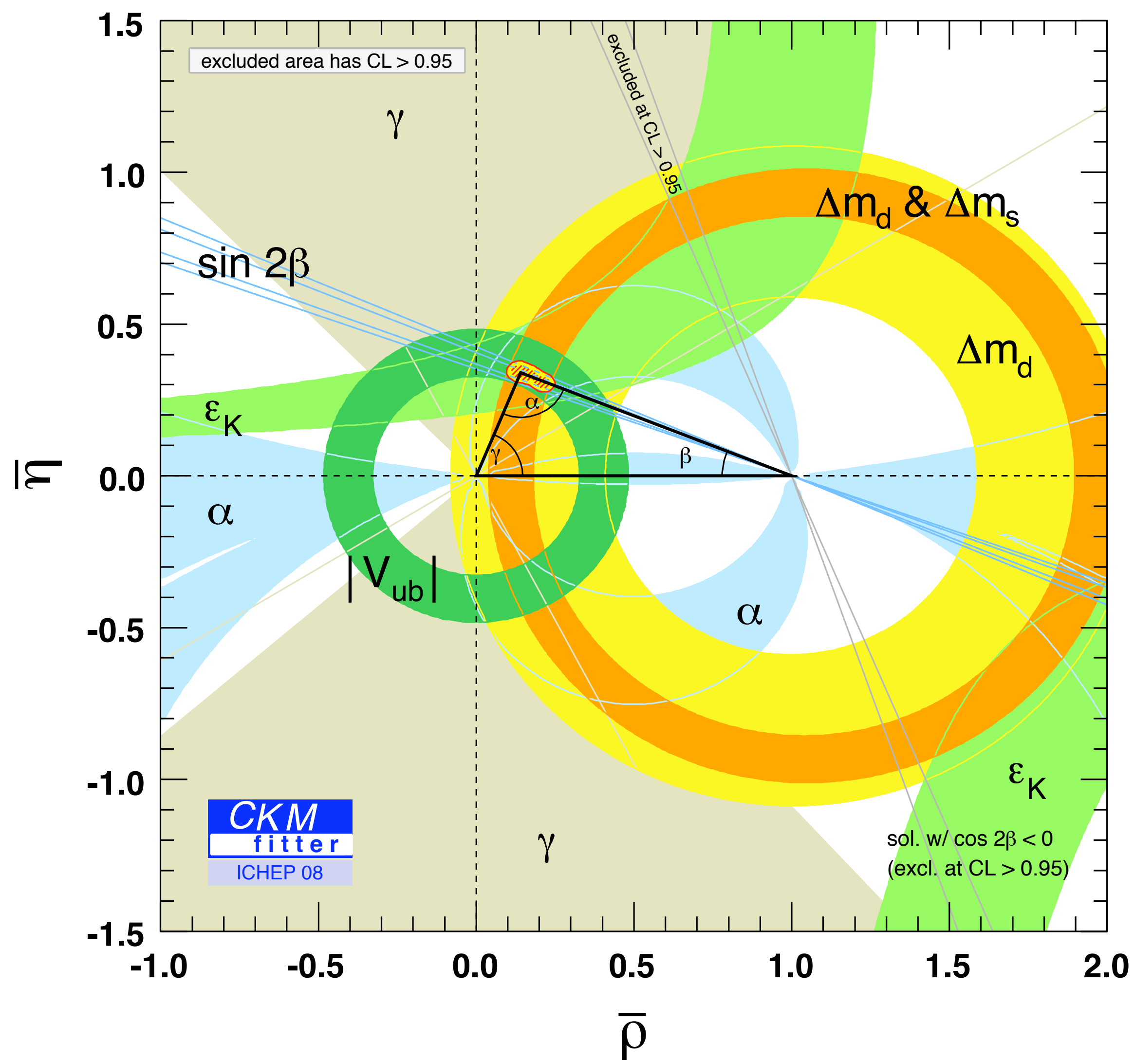
*with M. Bauer, S. Casagrande, F. Goertz, L. Gründer, U. Haisch, T. Pfoh, arXiv:0807.4537, 0811.3678 & in preparation

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

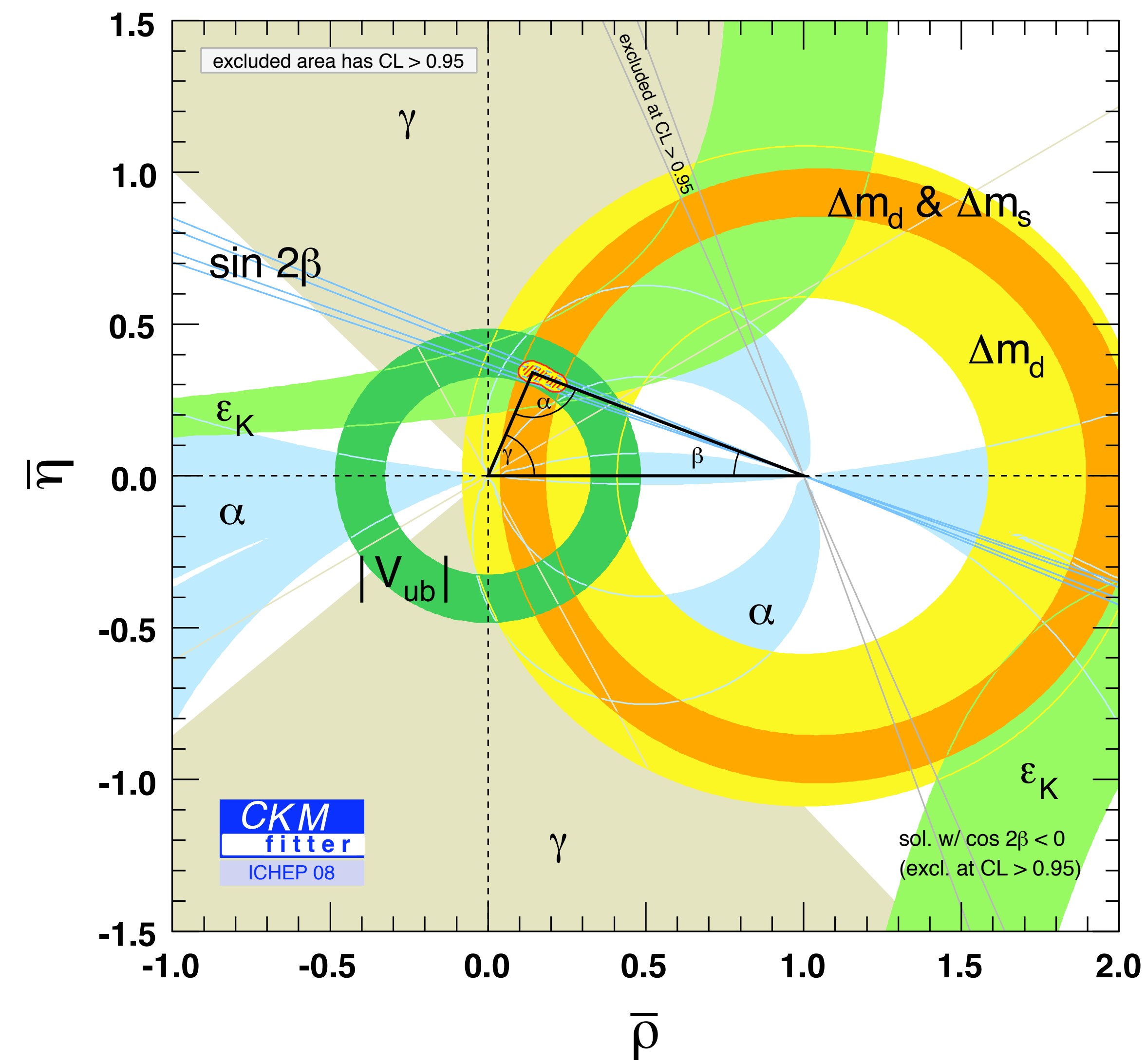
N. Cabibbo

M. Kobayashi

T. Maskawa

Nobel Prize in Physics 2008 awarded to Kobayashi and Maskawa:

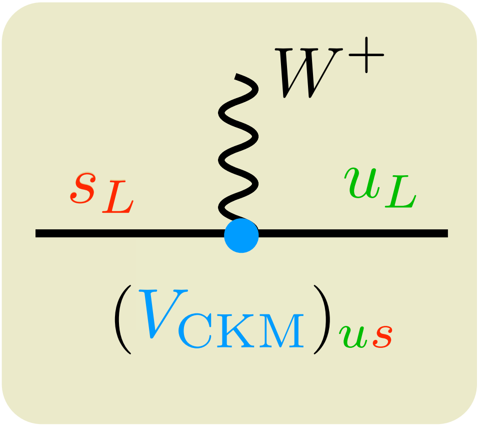
“for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature”



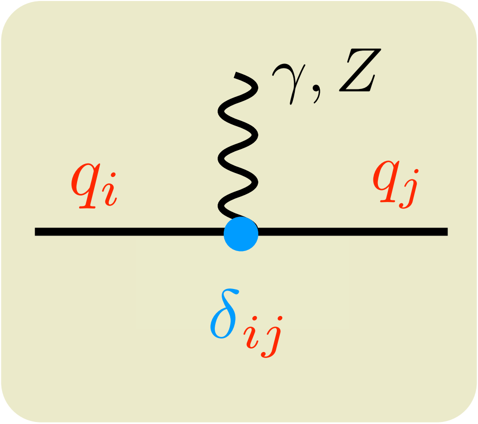
Main lesson from quark flavor physics

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



δ = diagonal matrix

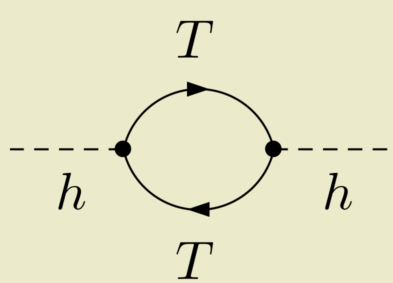
Upshot: effects of beyond SM physics in quark flavor-mixing can only appear as corrections to leading CKM mechanism

Still there is a problem of flavor ...

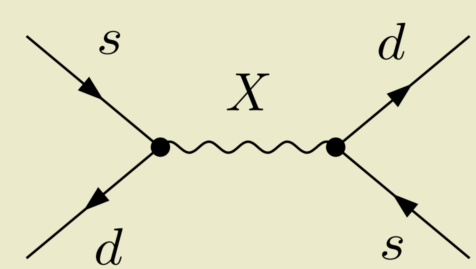
$$\mathcal{L}_{\rm EFT} = \Lambda_{\rm UV}^2 \Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2 + \mathcal{L}_{\rm SM}^{\rm gauge} + \mathcal{L}_{\rm SM}^{\rm Yukawa} + \frac{\mathcal{L}^{(5)}}{\Lambda_{\rm UV}} + \frac{\mathcal{L}^{(6)}}{\Lambda_{\rm UV}^2} + \ldots$$

electroweak symmetry breaking $\Downarrow$ Higgs mass

large FCNCs $\Downarrow$ generic flavor structure



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



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

no fine-tuning $\Downarrow$

bounds on flavor mixing $\Downarrow$

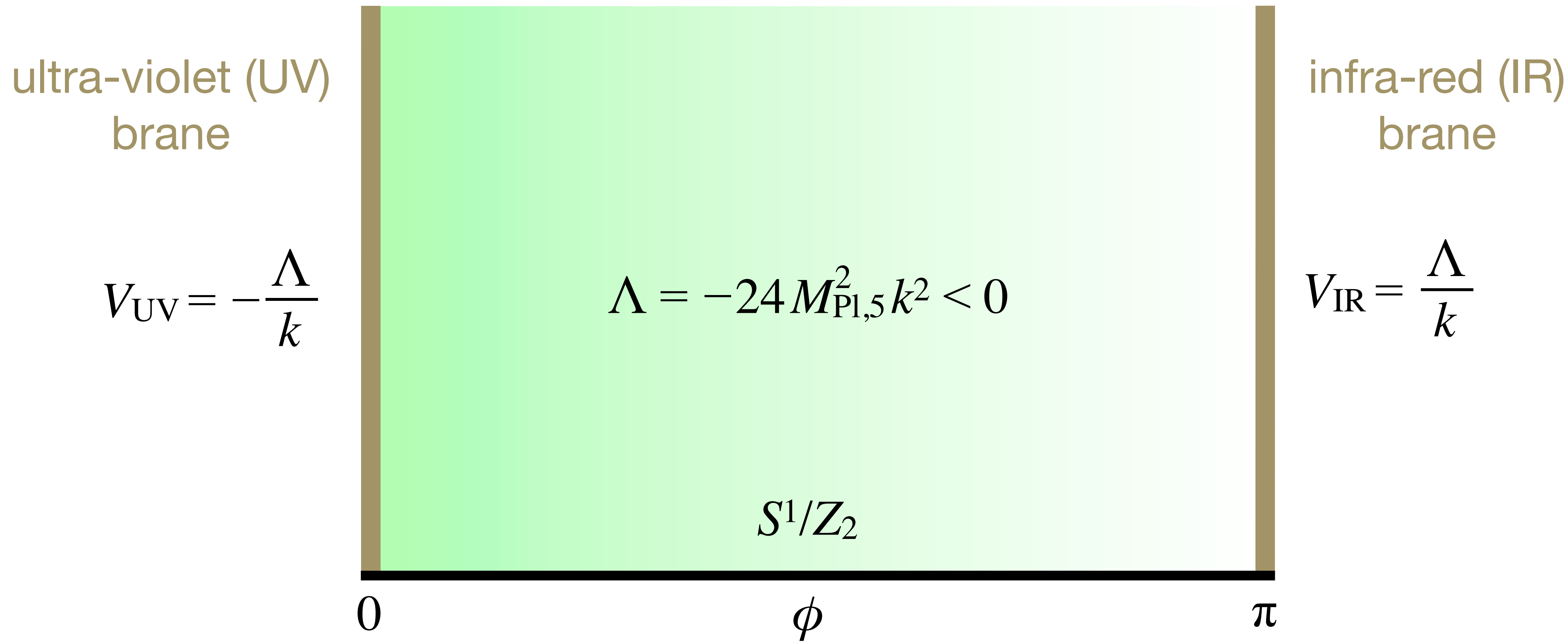
$\Lambda_{\rm Higgs} \lesssim 1$ TeV $\longrightarrow$ increasing energy scale $\longrightarrow$ $\Lambda_{\rm flavor} \gtrsim 10^3$ TeV

- Solutions to flavor problem explaining $\Lambda_{\rm Higgs} << \Lambda_{\rm flavor}$: (see talk by A. Weiler)

  (i) $\Lambda_{\rm UV} >> 1$ TeV: new particles too heavy to be discovered at LHC

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

Hierarchies from geometry: RS model*



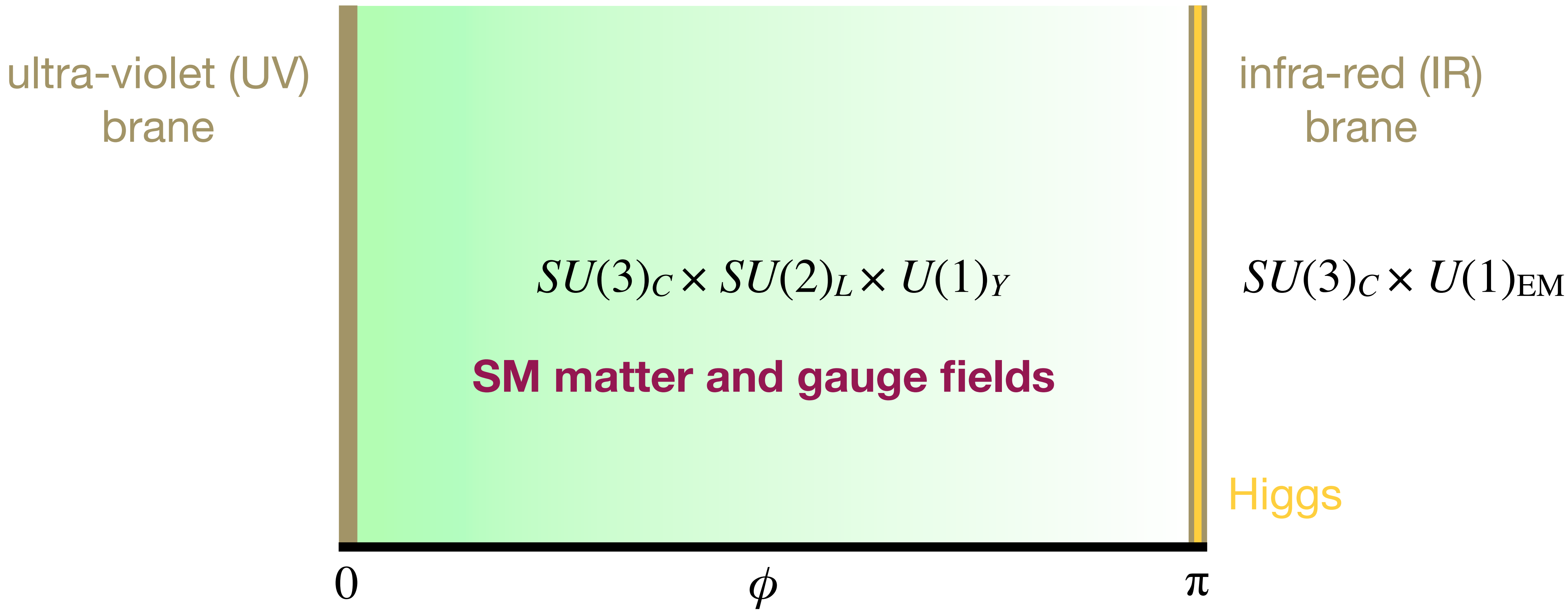
Slice of AdS_5 with curvature k:

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

$$\epsilon = \frac{M_W}{M_{\rm Pl}} = e^{-kr\pi} \approx 10^{-16}\,, \quad L = -\ln\epsilon \approx 37\,, \quad M_{\rm KK} = k\epsilon = \text{few TeV}$$

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

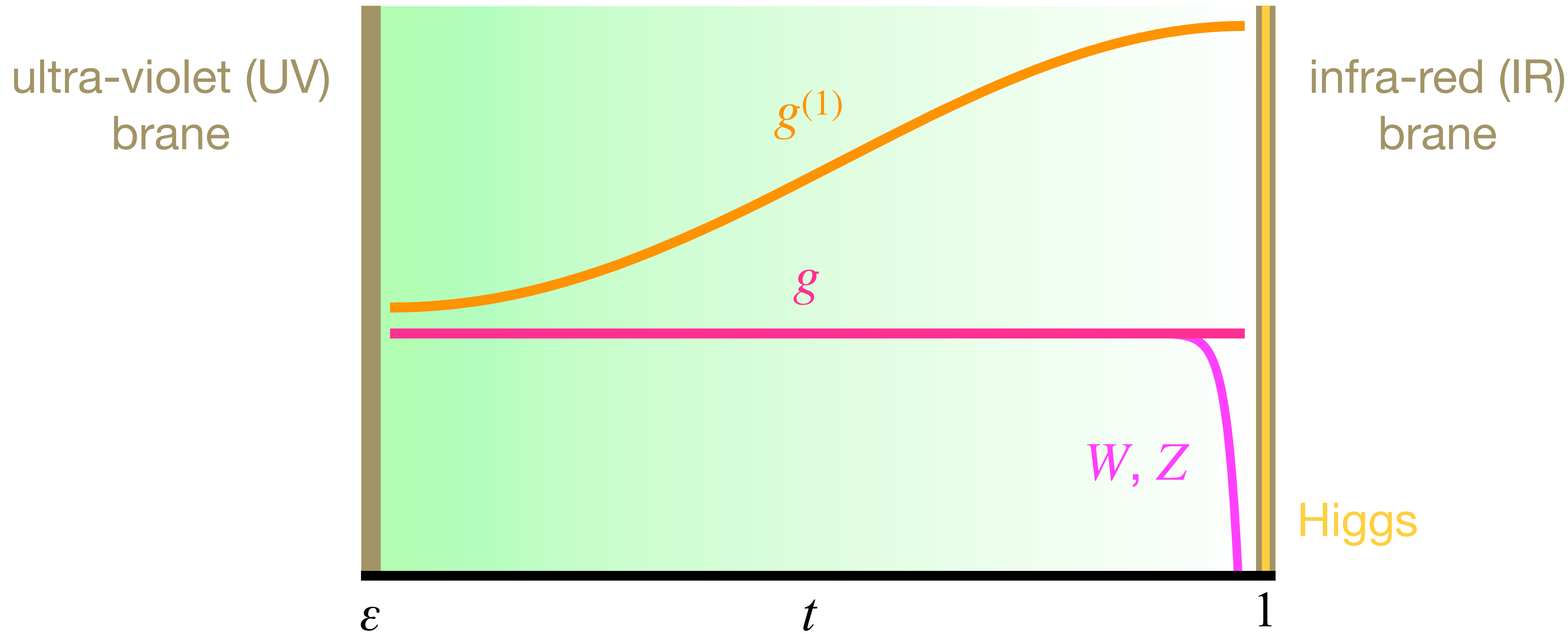
Hierarchies from geometry: RS model



Pattern of symmetry breaking:

- bulk gauge group $SU(2)_L \times U(1)_Y$ broken by IR brane-localized Higgs to $U(1)_{\rm EM}$
- after electroweak symmetry breaking, heavy gauge bosons and their Kaluza-Klein excitations get masses m_0, $m_1 \approx 2.45\, M_{\rm KK}$, ...

RS model: Gauge boson profiles*

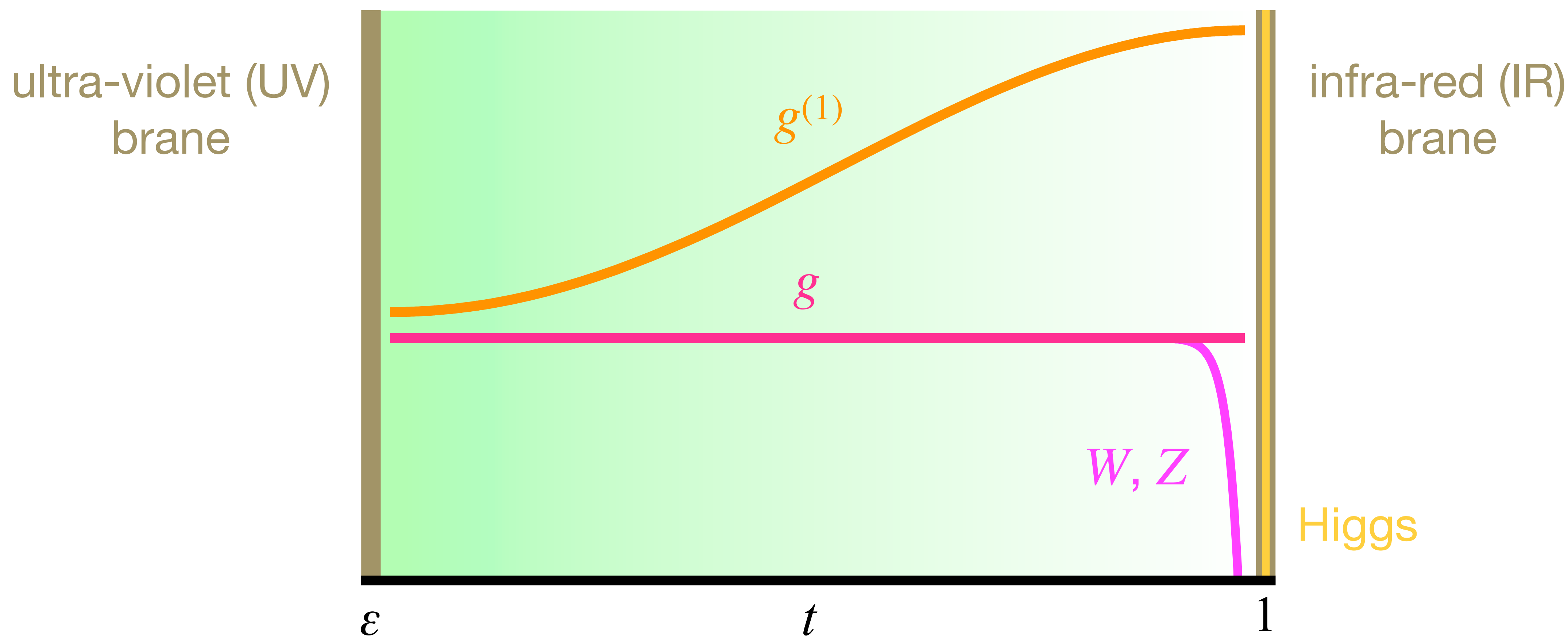


Profiles of gauge fields:

$$\chi_{g,\gamma}(\phi) = \frac{1}{\sqrt{2\pi}}\,, \quad \chi_{W,Z}(\phi) \approx \frac{1}{\sqrt{2\pi}} \left[1 + \frac{m_{W,Z}^2}{M_{\rm KK}^2} \left(1 - \frac{1}{L} + t^2 \left(1 - 2L - 2\ln t \right) \right) \right]$$

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

RS model: Gauge boson profiles*

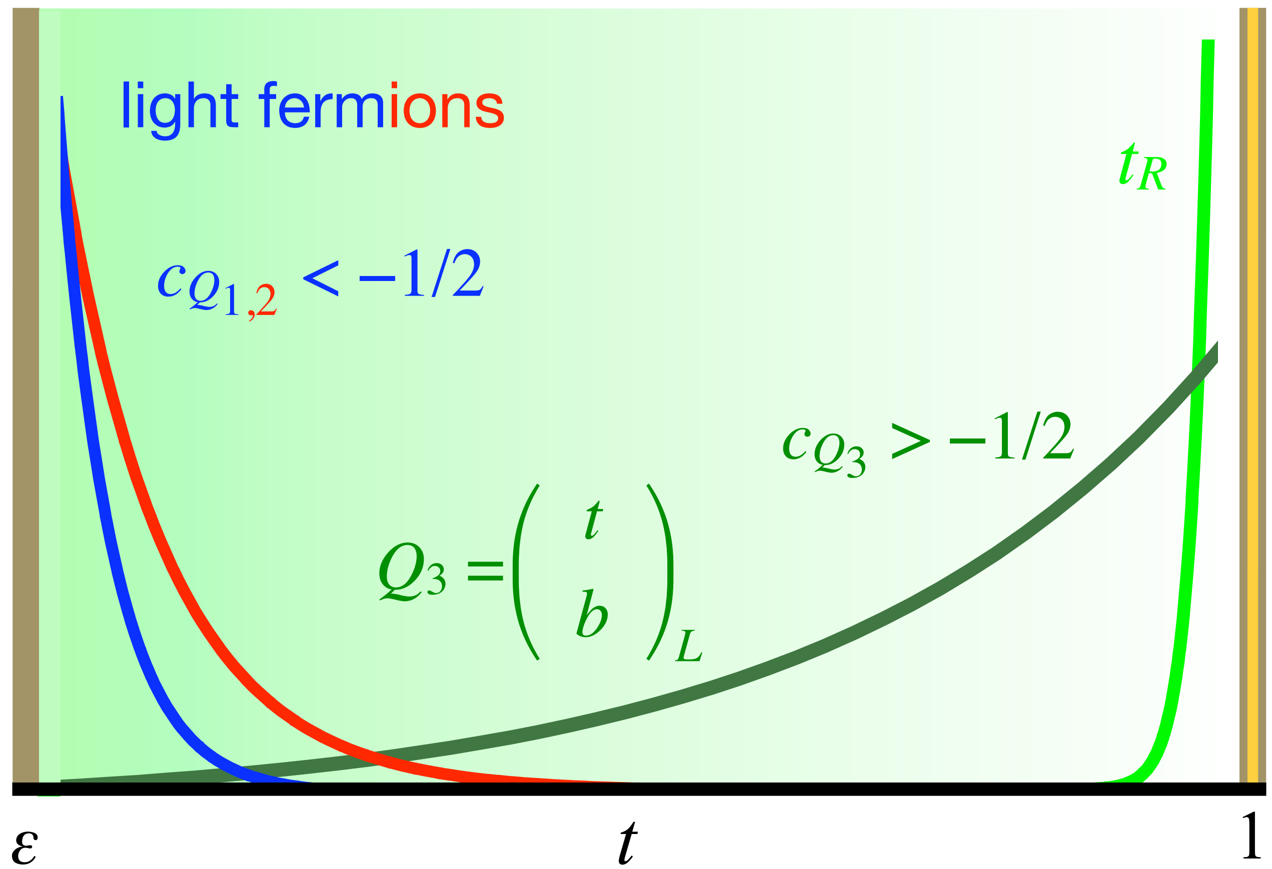


Profiles of gauge fields:

- while profiles of photon and gluon are flat, wave functions of heavy gauge bosons and profiles of KK modes peaked at IR brane
- non-trivial profiles entering overlap integrals alter interactions compared to SM

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

RS model: Fermion profiles*

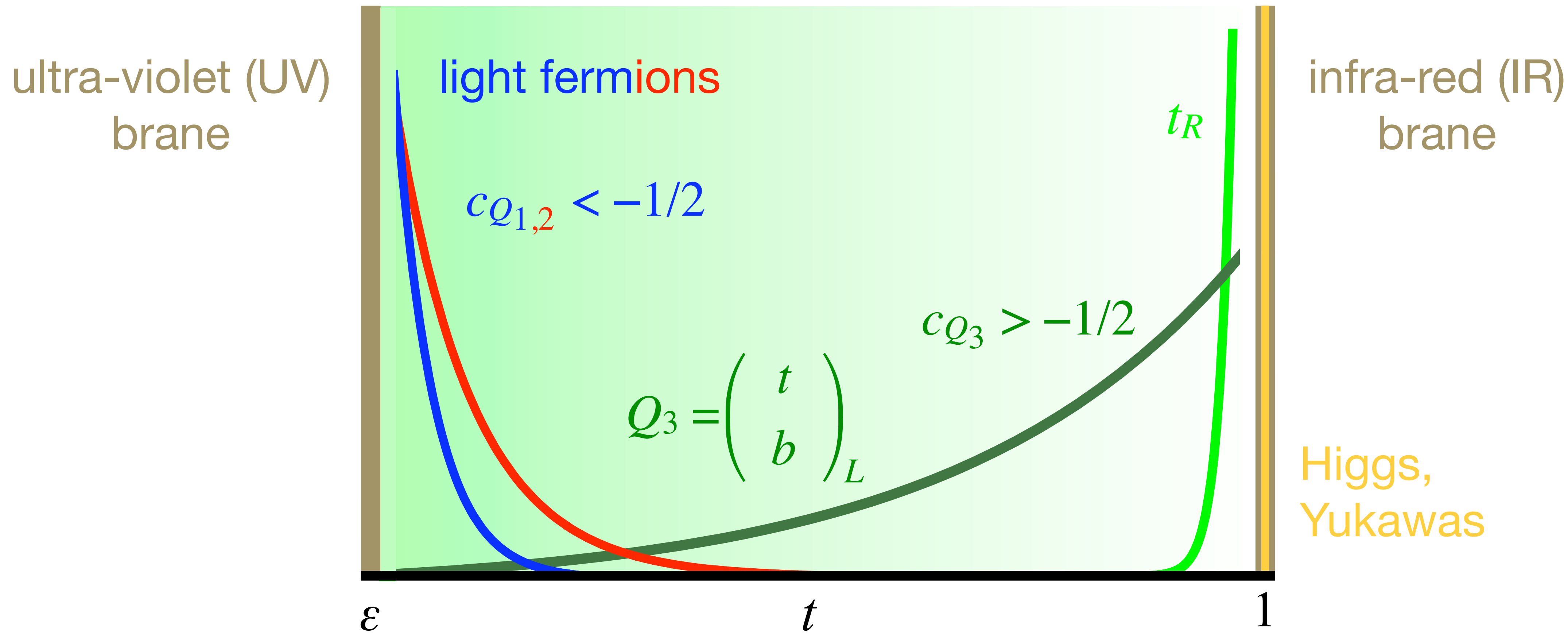


<u>Profiles of fermion fields:</u>

$$C_n^{(A)}(\phi) \approx \sqrt{\frac{L\epsilon}{\pi}}\, F_{c_A}\, t^{c_A}, \quad S_n^{(A)}(\phi) \approx \pm\mathrm{sgn}(\phi)\sqrt{\frac{L\epsilon}{\pi}}\, \frac{m_n}{M_{\mathrm{KK}}}\left(\frac{t^{-c_A}}{F_{c_A}} + \frac{t^{1+c_A} - t^{-c_A}}{1-2c_A}\, F_{c_A}\right)$$

*Grossman and Neubert, hep-ph/9912408; Ghergetta and Pomarol, hep-ph/0003129; Casagrande *et al*., arXiv:0807.4537

RS model: Fermion profiles*



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

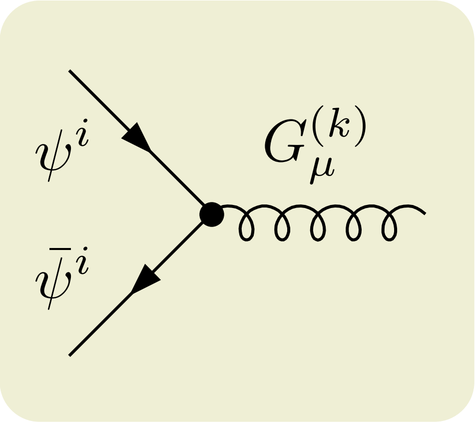
- localization of fermion profiles in extra dimension controlled by bulk mass parameters $c_{Q,q} = \pm M_{Q,q}/k$
- top quark lives in IR to generate its large mass, while light fermions live in UV

*Grossman and Neubert, hep-ph/9912408; Ghergetta and Pomarol, hep-ph/0003129; Casagrande *et al.*, arXiv:0807.4537

RS-GIM mechanism*

- Quark-quark-gluon vertex in flavor eigenbasis:

$$\bar{\psi}^i \, G_\mu^{(k)} \, \psi^i \sim -i g_s^{4\mathrm{D}} \gamma_\mu \sqrt{L} \, F^2_{c_{\psi^i}} \, , \quad F_{c_{\psi^i}} \sim \epsilon^{-c_{\psi^i} - 1/2}$$



- Quark-quark-gluon vertex in mass eigenbasis:

$$\bar{q}_L^i \, G_\mu^{(k)} \, q_L^j \sim -i g_s^{4\mathrm{D}} \gamma_\mu \sqrt{L} \, F_{c_{Q_i}} F_{c_{Q_j}} \, , \quad \bar{q}_R^i \, G_\mu^{(k)} \, q_R^j \sim -i g_s^{4\mathrm{D}} \gamma_\mu \sqrt{L} \, F_{c_{q_i}} F_{c_{q_j}}$$

<u>Important features:</u>

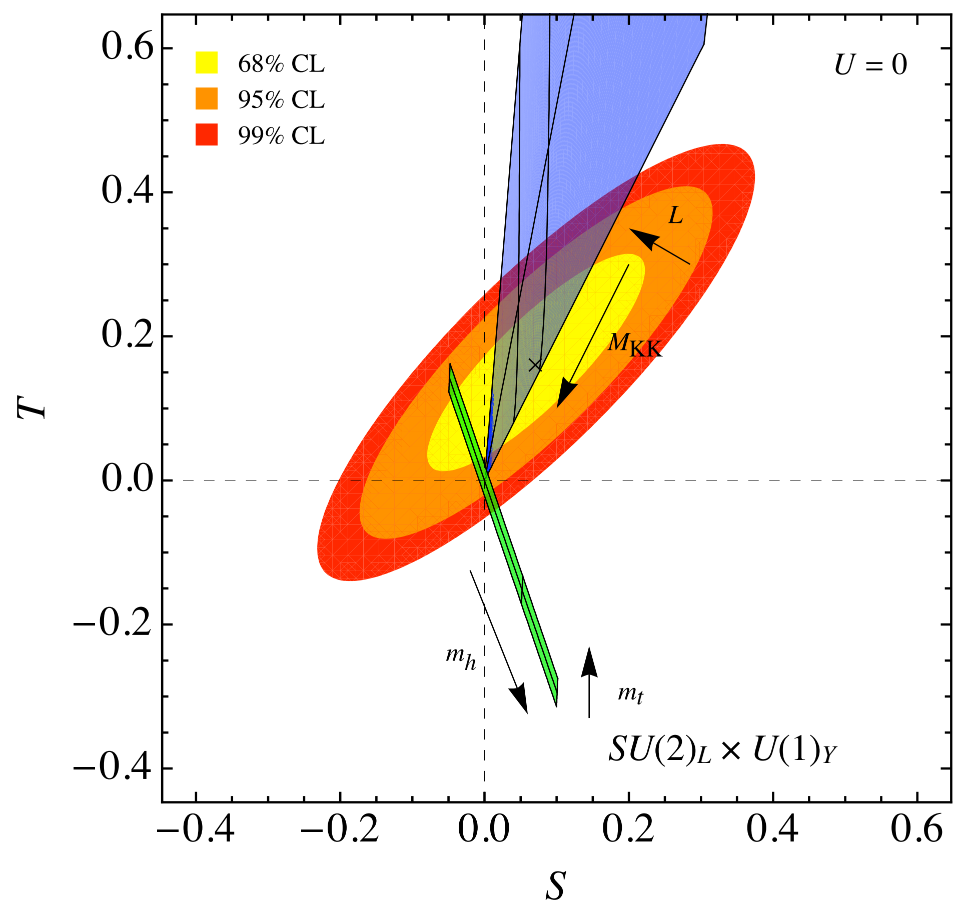
- in flavor eigenbasis KK gluon couples to quarks flavor diagonally but non-universally, so that after rotation to mass eigenstates tree-level FCNCs arise
- since FCNCs are proportional to $F_{c_{A_i}} F_{c_{A_j}}$, exponential suppression of fermion profiles $F_{c_{A_i}}$ at IR brane guarantees flavor protection (RS-GIM)

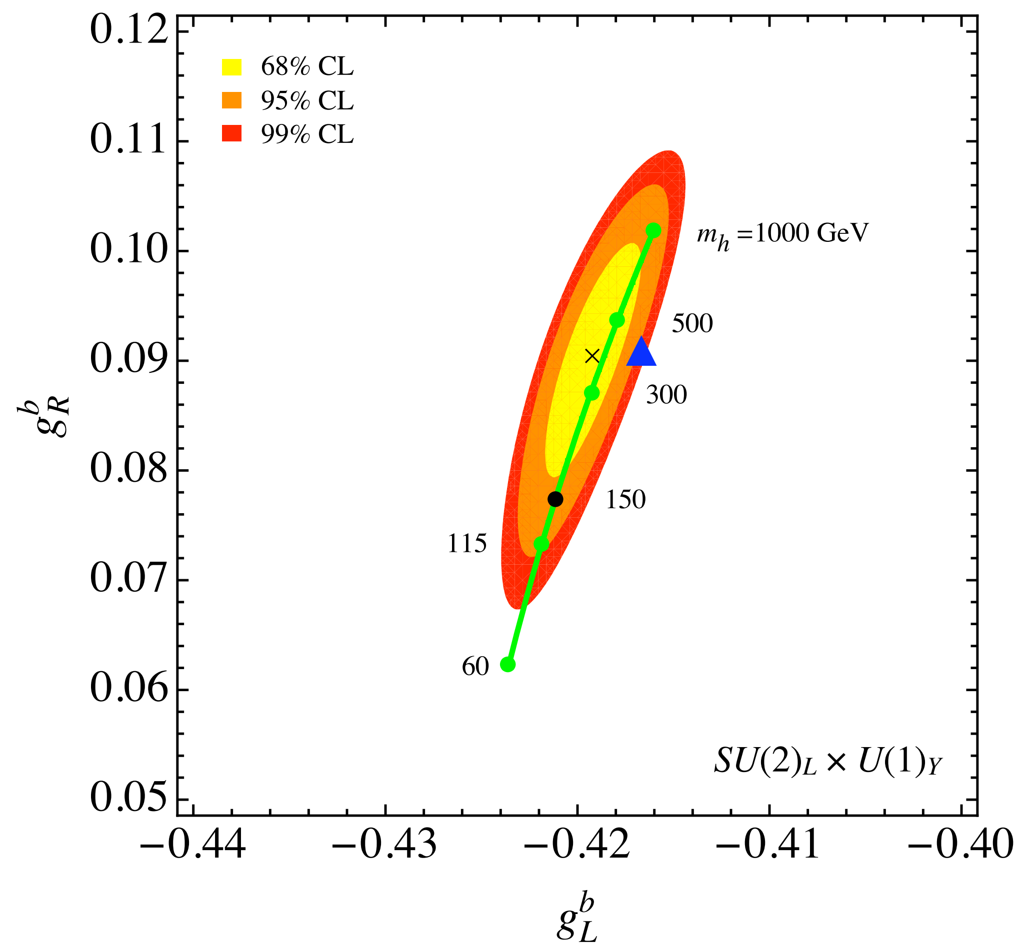
(see talk by A. Weiler)

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

Electroweak precision tests*

- Heavy Higgs boson (natural in RS) helps relaxing constraints from *S* and *T* parameters and *Zbb* couplings





minimal RS prediction for $M_{\rm KK} \in [1, 10]$ TeV and $L \in [5, 37]$

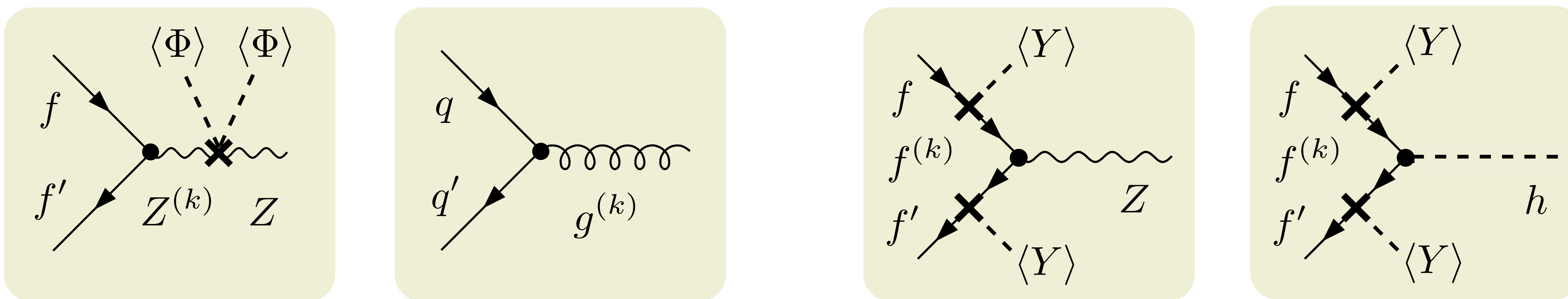
SM reference point for $m_h \in [60, 1000]$ GeV

minimal RS prediction for reference point with $M_{\rm KK} = 1.5$ TeV and $m_h = 400$ GeV

SM prediction for $m_h \in [60, 1000]$ GeV

*Carena *et al.*, hep-ph/0305188; Casagrande *et al.*, arXiv:0807.4537

Sources of flavor violation*



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

- modification of W, Z boson profiles due to electroweak symmetry breaking on IR brane
- non-trivial overlap integrals of KK gauge-boson profiles with SM fermion wave functions
- non-orthonormality of fermion profiles interpreted as mixing of $SU(2)_L$ singlet and doublets via their KK excitations

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

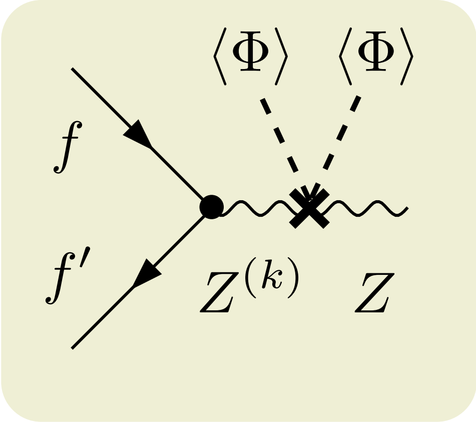
Mixing matrices: Gauge and KK boson effects

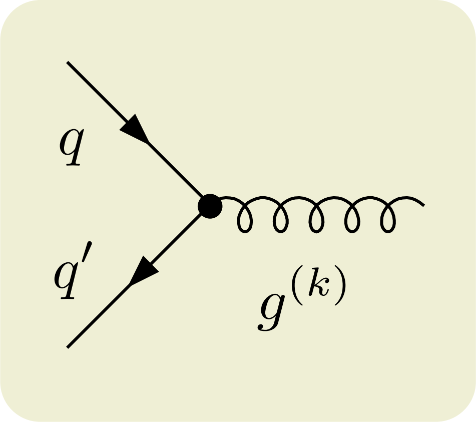
$$(\Delta_Q)_{ij} \to \left(\boldsymbol{U}_q^\dagger \,\mathrm{diag}\left[\frac{F^2_{c_{Q_i}}}{3+2c_{Q_i}} \right] \boldsymbol{U}_q \right)_{ij} , \quad (\Delta_q)_{ij},\, (\Delta'_q)_{ij} : Q_i \to q_i,\, \boldsymbol{U}_q \to \boldsymbol{W}_q \,,$$

$$(\Delta'_Q)_{ij} \to \left(\boldsymbol{U}_q^\dagger \,\mathrm{diag}\left[\frac{5+2c_{Q_i}}{2(3+2c_{Q_i})^2}\, F^2_{c_{Q_i}} \right] \boldsymbol{U}_q \right)_{ij} , \qquad \boldsymbol{V}_{\mathrm{CKM}} \to \boldsymbol{U}_u^\dagger \boldsymbol{U}_d$$

<u>Effects due to gauge-boson profiles*:</u>

- parameterized by four mixing matrices $\boldsymbol{\Delta}_A$, $\boldsymbol{\Delta}'_A$ built out of $F_{c_{A_i}}$ and left- and right-handed rotations $\boldsymbol{U}_q$ and $\boldsymbol{W}_q$
- $\boldsymbol{\Delta}_A$ contributions are enhanced with respect to $\boldsymbol{\Delta}'_A$ corrections by logarithm L of warp factor





*Agashe *et al*., hep-ph/0308036; Burdman, hep-ph/0310144; Casagrande *et al*., arXiv:0807.4537

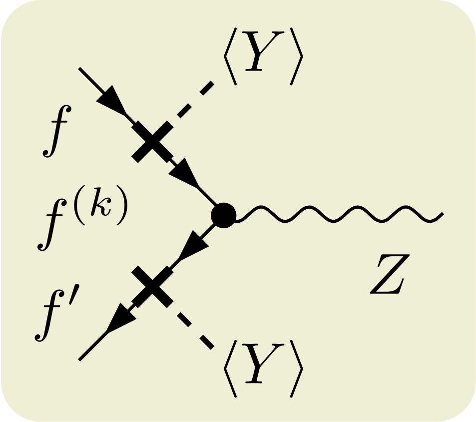
Mixing matrices: Fermion mixing

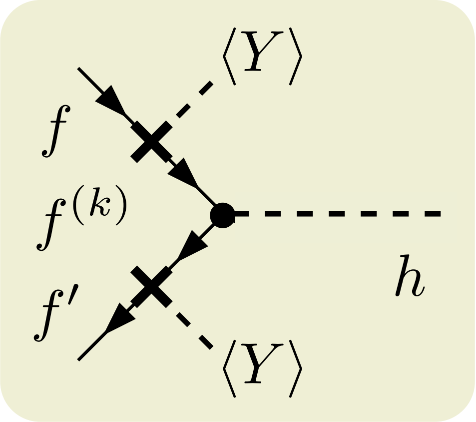
$$(\delta_Q)_{ij} \to \left(\boldsymbol{x}_q \, \boldsymbol{W}_q^\dagger \, \mathrm{diag}\left[\frac{1}{1-2c_{q_i}} \left(\frac{1}{F^2_{c_{q_i}}} - 1 + \frac{F^2_{c_{q_i}}}{3+2c_{q_i}} \right) \right] \boldsymbol{W}_q \, \boldsymbol{x}_q \right)_{ij} ,$$

$$(\delta_q)_{ij} : c_{q_i} \to c_{Q_i} , \; \boldsymbol{W}_q \to \boldsymbol{U}_q \, , \qquad \boldsymbol{x}_q \equiv \frac{\boldsymbol{m}_q}{M_{\mathrm{KK}}} = \frac{\mathrm{diag}\,(m_{q_1}, m_{q_2}, m_{q_3})}{M_{\mathrm{KK}}}$$

Effects due to fermion mixing*:

- mixing matrices $\boldsymbol{\delta}_A$ are parametrically of same order as $\boldsymbol{\Delta}_A$, $\boldsymbol{\Delta}'_A$ as they are not suppressed by v^2/M^2_{KK} in Feynman rules
- fermion mixing is only source of flavor-breaking in Higgs-boson couplings that are proportional to $\boldsymbol{m}_q/v \, \boldsymbol{\delta}_q + \boldsymbol{\delta}_Q \, \boldsymbol{m}_q/v$ (small effect)





*Casagrande *et al*., arXiv:0807.4537

Mixing matrices: Scaling relations

$$(U_q)_{ij} \sim (V_{\rm CKM})_{ij} \sim \begin{cases} \dfrac{F_{c_{Q_i}}}{F_{c_{Q_j}}}\,, & i \le j\,, \\ \dfrac{F_{c_{Q_j}}}{F_{c_{Q_i}}}\,, & i > j\,, \end{cases} \qquad (W_q)_{ij} \sim \begin{cases} \dfrac{F_{c_{q_i}}}{F_{c_{q_j}}}\,, & i \le j\,, \\ \dfrac{F_{c_{q_j}}}{F_{c_{q_i}}}\,, & i > j\,, \end{cases}$$

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

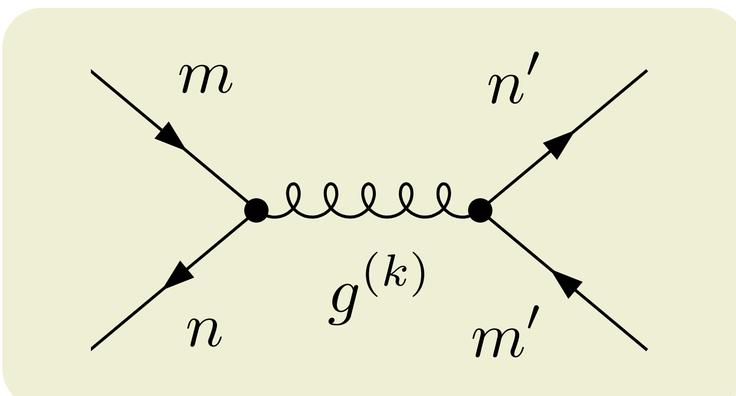
$$(\Delta_q^{(\prime)})_{ij} \sim F_{c_{q_i}} F_{c_{q_j}}\,, \qquad (\delta_q)_{ij} \sim \frac{m_{q_i} m_{q_j}}{M_{\rm KK}^2} \frac{1}{F_{c_{Q_i}} F_{c_{Q_j}}} \sim \frac{v^2 Y_q^2}{M_{\rm KK}^2} F_{c_{Q_i}} F_{c_{Q_j}}$$

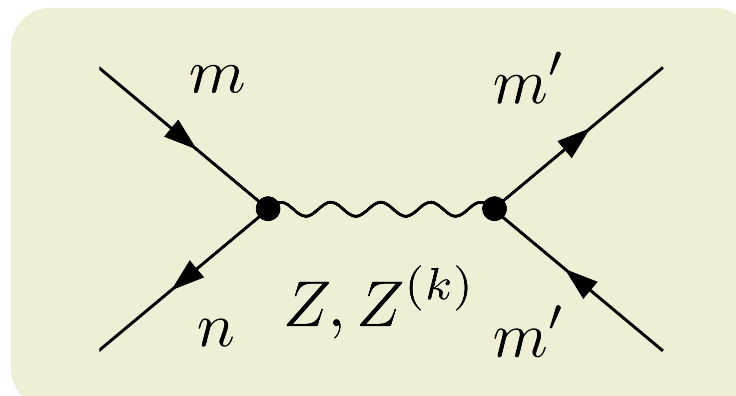
- $F_{c_{A_i}} F_{c_{A_j}}$ factors present in expressions for $\boldsymbol{\Delta}_A$, $\boldsymbol{\Delta}'_A$, and $\boldsymbol{\delta}_A$ mixing matrices makes RS-GIM suppression explicit

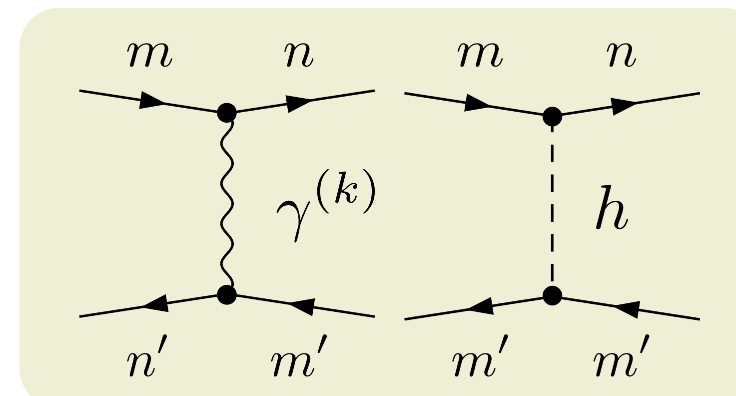
*Casagrande *et al*., arXiv:0807.4537

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

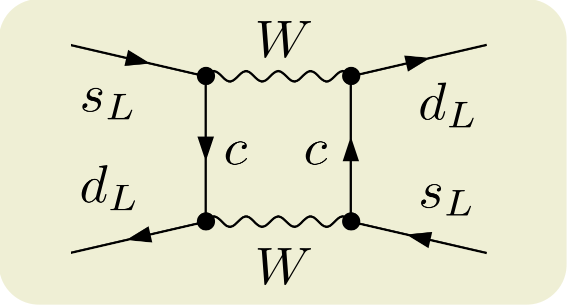
small contributions to $\Delta F = 1, 2$ processes

- Like in SM, dimension-five perators contributing to $B \to X_s \gamma$ or $\mu \to e\gamma$ arise first at one-loop level

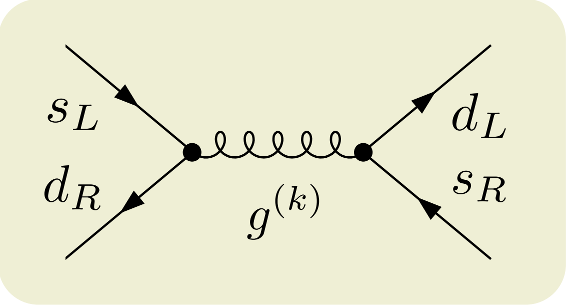
Phenomenology

Meson mixing: Effective Hamiltonian*

SM



RS



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

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

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

$$C_{1,K}^{\rm RS} = \frac{4\pi L}{M_{\rm KK}^2} (\widetilde{\Delta}_D)_{12} \otimes (\widetilde{\Delta}_D)_{12} \left[\frac{\alpha_s}{3} + 1.04\,\alpha\right],$$
$$\tilde{C}_{1,K}^{\rm RS} = \frac{4\pi L}{M_{\rm KK}^2} (\widetilde{\Delta}_d)_{12} \otimes (\widetilde{\Delta}_d)_{12} \left[\frac{\alpha_s}{3} + 0.15\,\alpha\right],$$
$$C_{4,K}^{\rm RS} = \frac{4\pi L}{M_{\rm KK}^2} (\widetilde{\Delta}_D)_{12} \otimes (\widetilde{\Delta}_d)_{12} \left[-2\alpha_s\right],$$
$$C_{5,K}^{\rm RS} = \frac{4\pi L}{M_{\rm KK}^2} (\widetilde{\Delta}_D)_{12} \otimes (\widetilde{\Delta}_d)_{12} \left[\frac{2\alpha_s}{3} + 0.30\,\alpha\right]$$

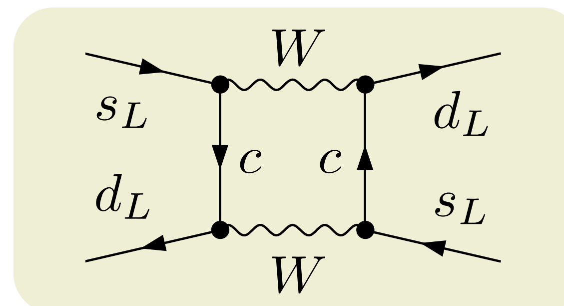
$$(\widetilde{\Delta}_A)_{mn} \otimes (\widetilde{\Delta}_B)_{m'n'} \;\rightarrow\; (\Delta_A)_{mn}\,(\Delta_B)_{m'n'}$$

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

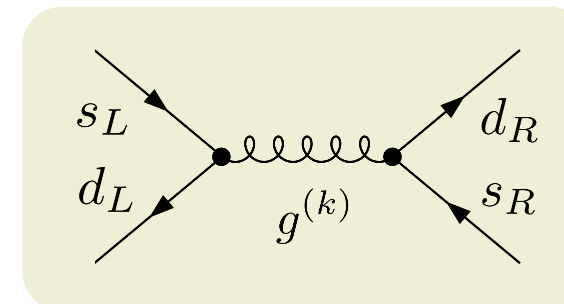
Meson mixing: Effective Hamiltonian

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

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:

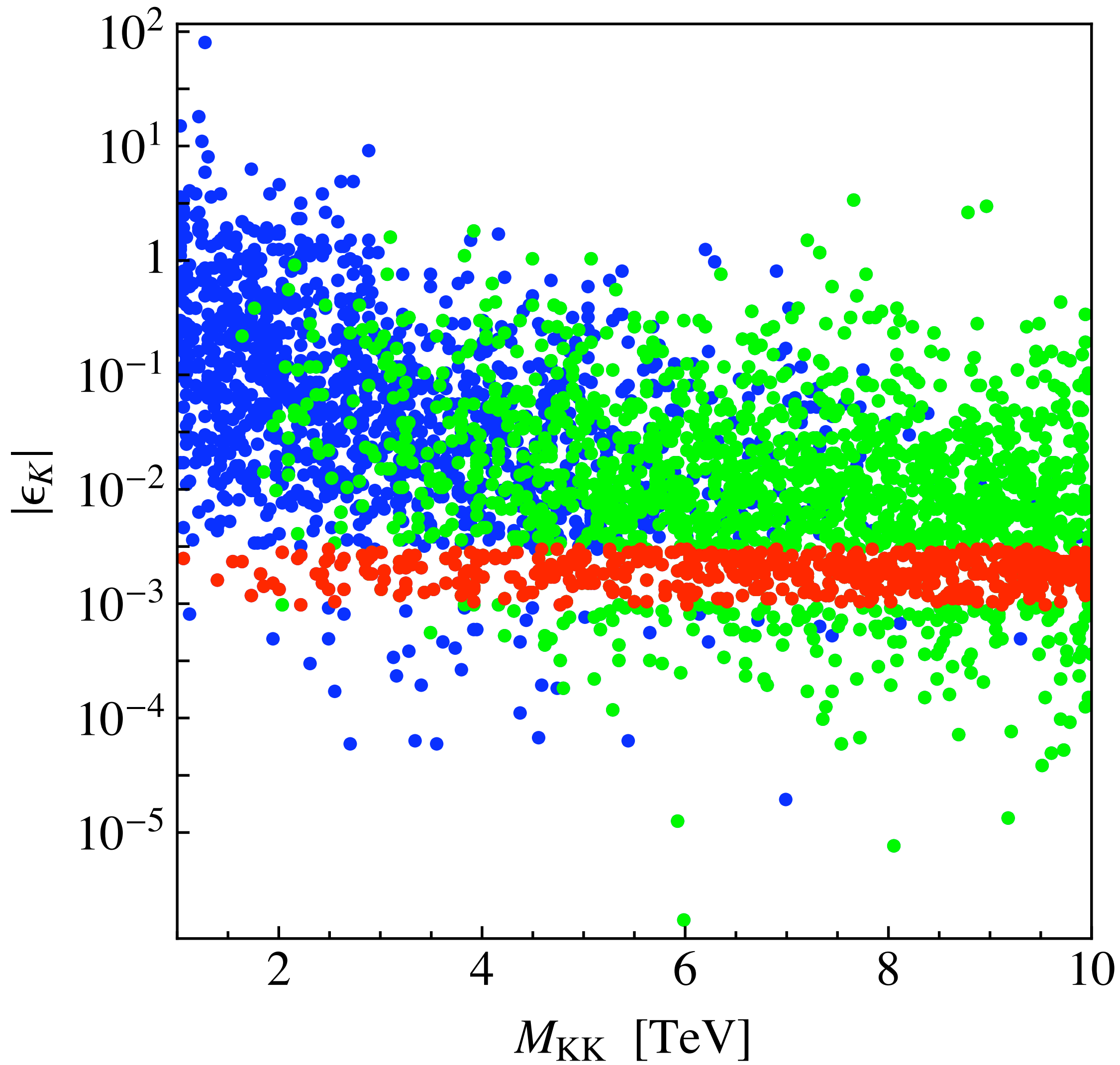
$$|\epsilon_K|_{\text{RS}} \propto \text{Im}\left[C_{1,K}^{\text{RS}} + 115\left(C_{4,K}^{\text{RS}} + \frac{C_{5,K}^{\text{RS}}}{3}\right)\right]$$

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

Meson mixing: Neutral kaons*

- 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 $M_{\rm KK} = 1$ TeV after some fine-tuning

(see talk by A. Weiler)

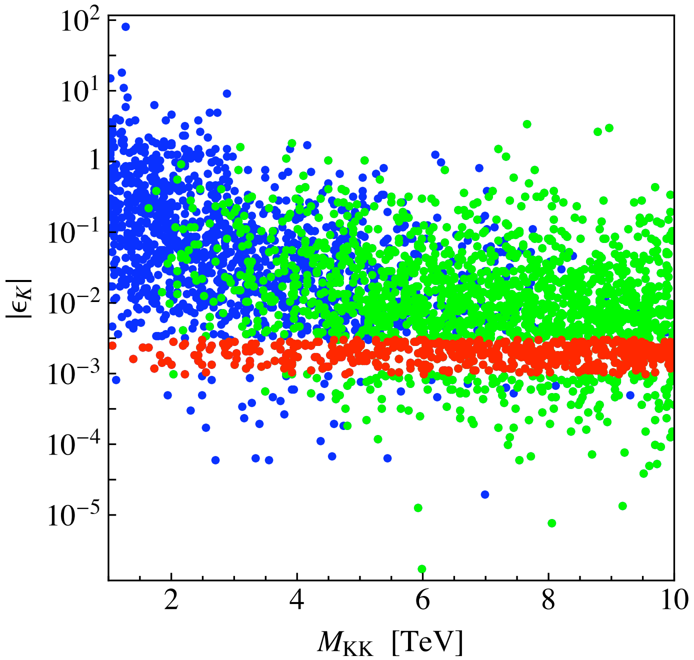


3000 randomly chosen RS points with $|Y_q| < 3$ reproducing quark masses and CKM parameters with $\chi^2/\text{dof} < 11.5/10$ (corresponding to 68% CL)

- 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

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

Meson mixing: Ideas to reduce fine-tuning in $|\varepsilon_K|^*$

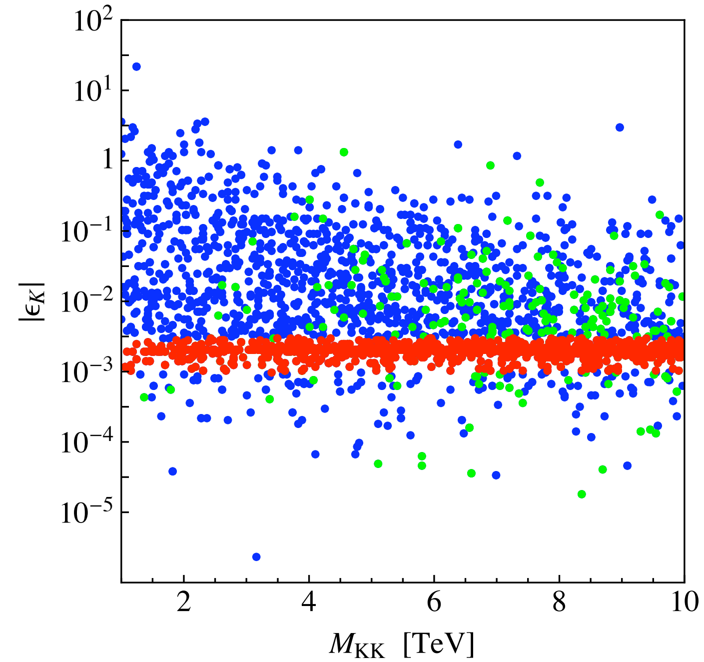


<u>S1: Standard</u>

$|Y_q| < 3$

- 16%
- 59%

13% pass

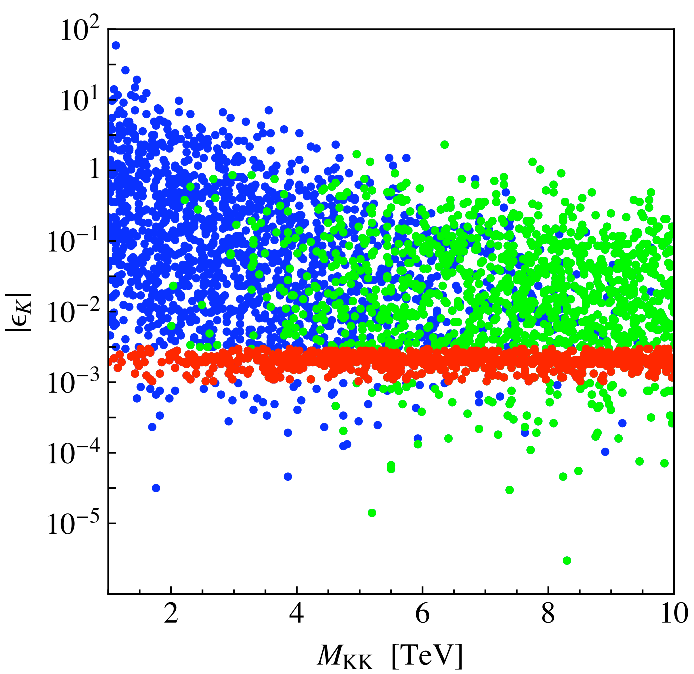


<u>S2: Big Yukawas</u>

$|Y_q| < 12$

- 44%
- 26%

19% pass

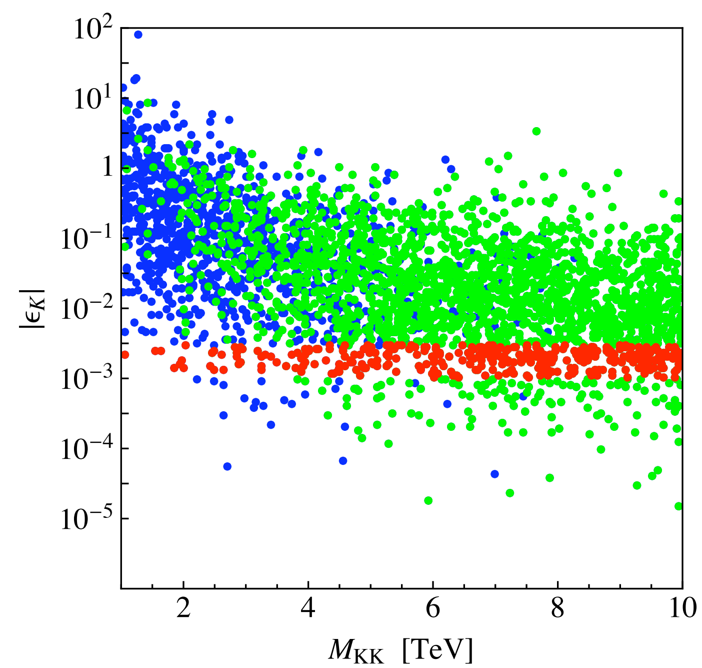


<u>S3: Alignement</u>

$c_{d_1} = c_{d_2} = c_{d_3}$

- 48%
- 24%

16% pass



<u>S4: Little RS</u>

$L = 7$

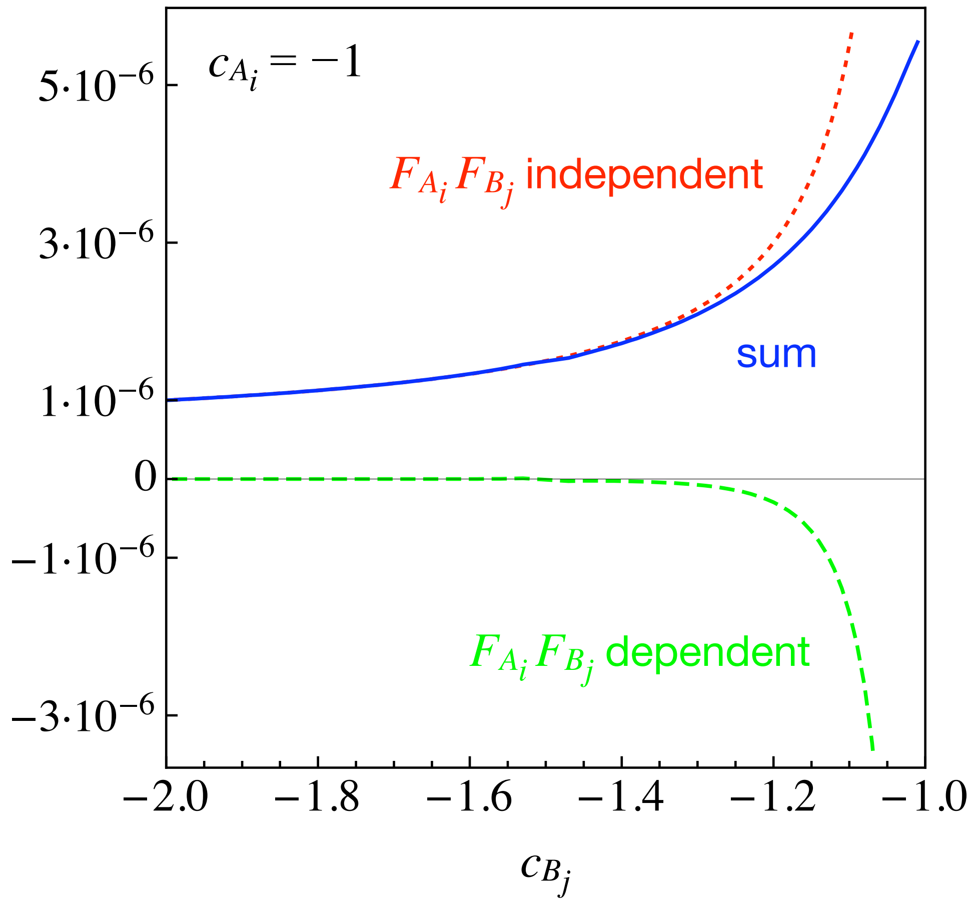
- 11%
- 68%

9% pass

*Davoudiasl *et al.*, arXiv:0802.0203; Santiago, arXiv:0806.1230; Bauer *et al.*, arXiv:0811.3678 & paper in preparation

$|\varepsilon_K|$ in little RS models*

- Since many amplitudes in RS model are enhanced by logarithm of warp factor L, harmful effects can naively be suppressed by volume truncation



Typical bulk parameters for $L = 7$:

$$c_{Q_1} = -1.06\,, \quad c_{Q_2} = -0.77\,, \quad c_{Q_3} = -0.61\,,$$
$$c_{u_1} = -1.92\,, \quad c_{u_2} = -0.96\,, \quad c_{u_3} = +0.34\,,$$
$$c_{d_1} = -1.75\,, \quad c_{d_2} = -1.53\,, \quad c_{d_3} = -0.93$$

- For $c_{A_i} + c_{B_j} < -2$ weight factor $t_<^2$ appearing in overlap integrals of $\widetilde{\mathbf{\Delta}}_A \otimes \widetilde{\mathbf{\Delta}}_B$ not sufficient to suppress light quark profiles in UV.

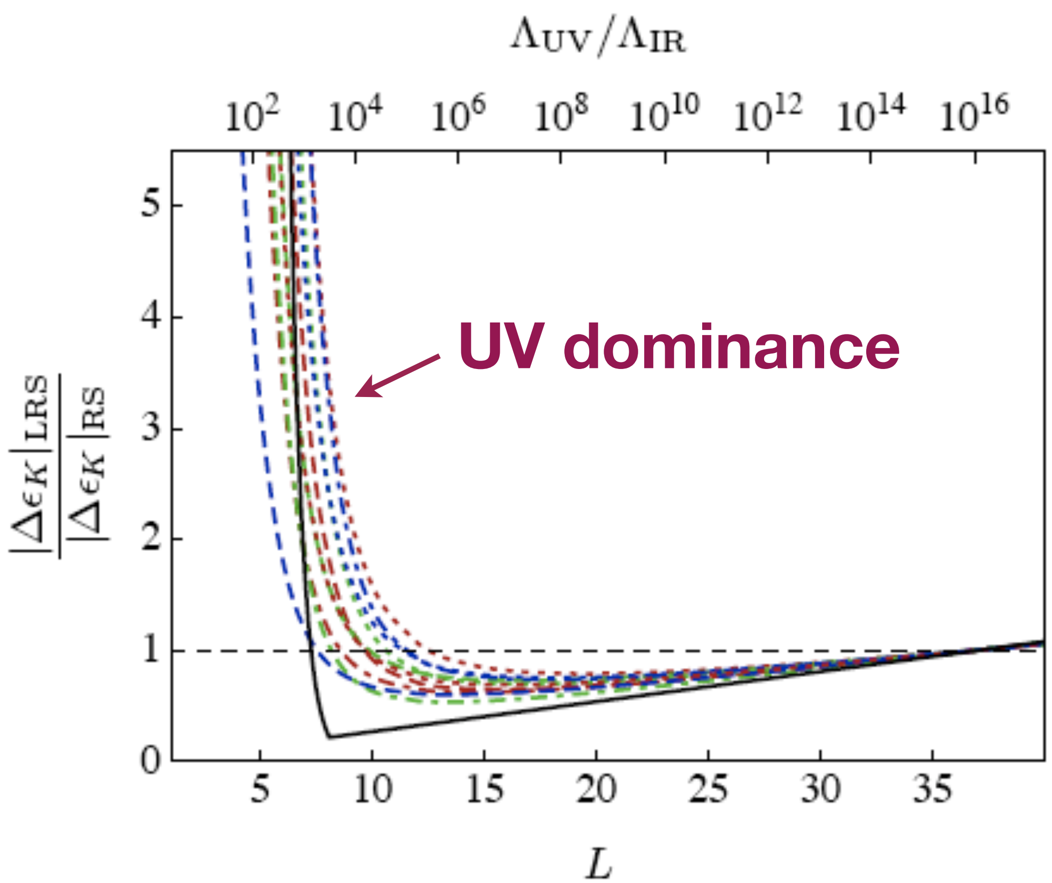
This partially evades RS-GIM suppression!

Bauer *et al.*, arXiv:0811.3678

*Davoudiasl *et al.*, arXiv:0802.0203

$|\varepsilon_K|$ in little RS models*

- Since many amplitudes in RS model are enhanced by logarithm of warp factor L, harmful effects can naively be suppressed by volume truncation



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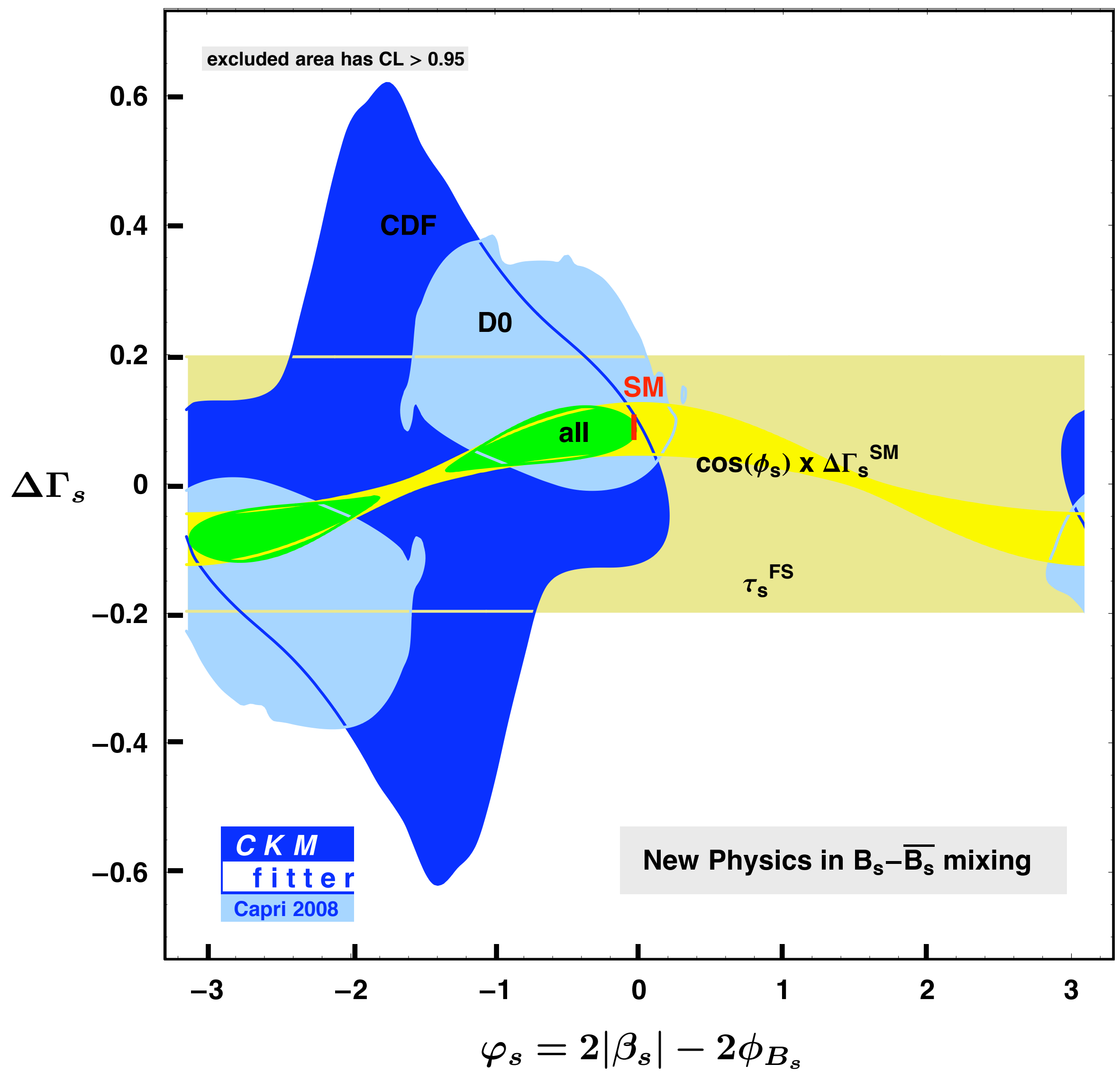
$$c_{d_1} = -1.75\,, \quad c_{d_2} = -1.53\,, \quad c_{d_3} = -0.93$$

- Condition $c_{Q_2} + c_{d_2} > -2$ implies $L > 8.2$, corresponding to $\Lambda_{\rm UV} >$ few 10^3 TeV. UV dominance in $|\varepsilon_K|$ is thus natural feature of little RS models

*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>

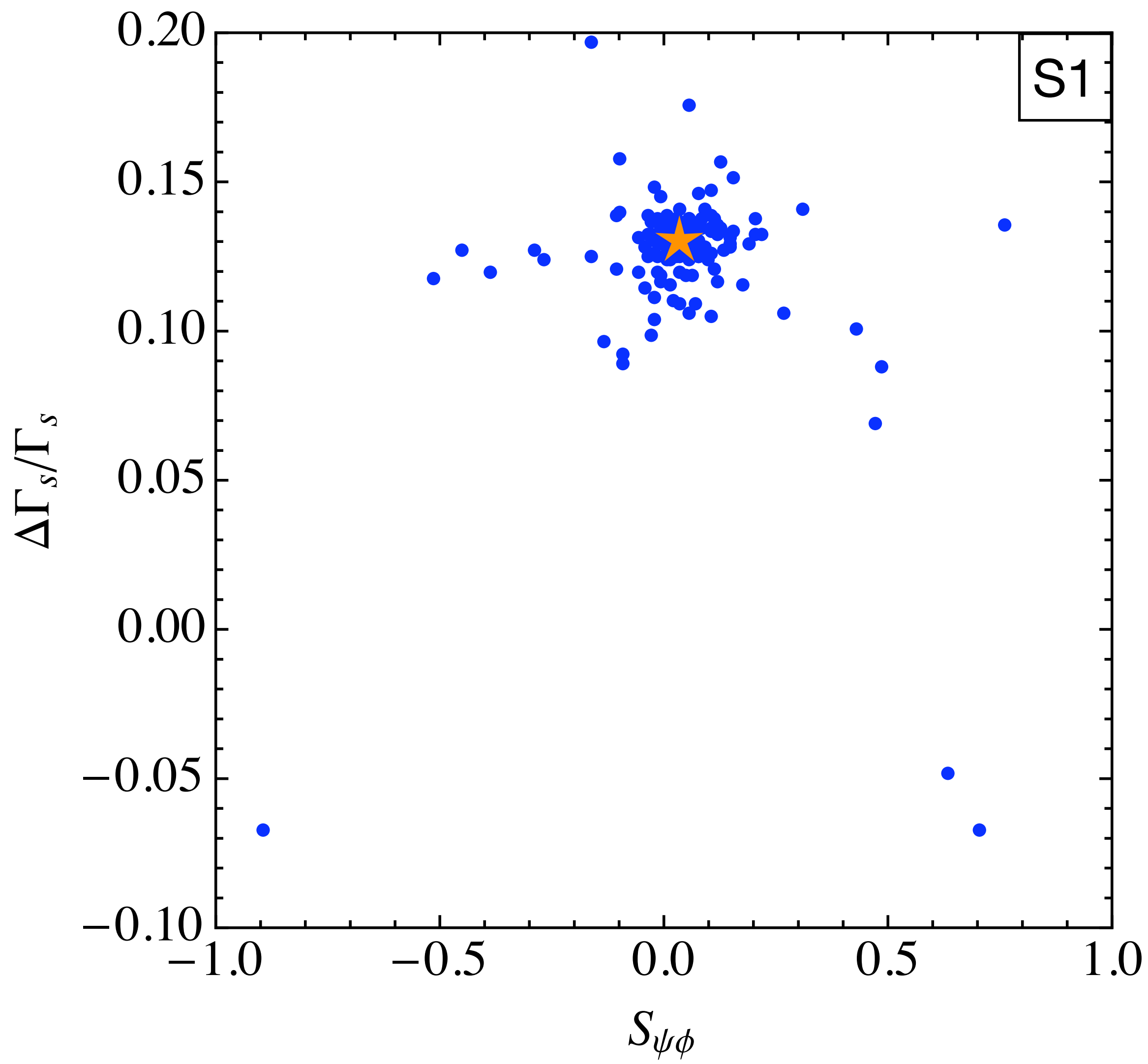
- CDF data only 2.1σ
- DØ data only 1.9σ
- CDF and DØ data 2.7σ
- full BSM physics fit 2.5σ

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



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

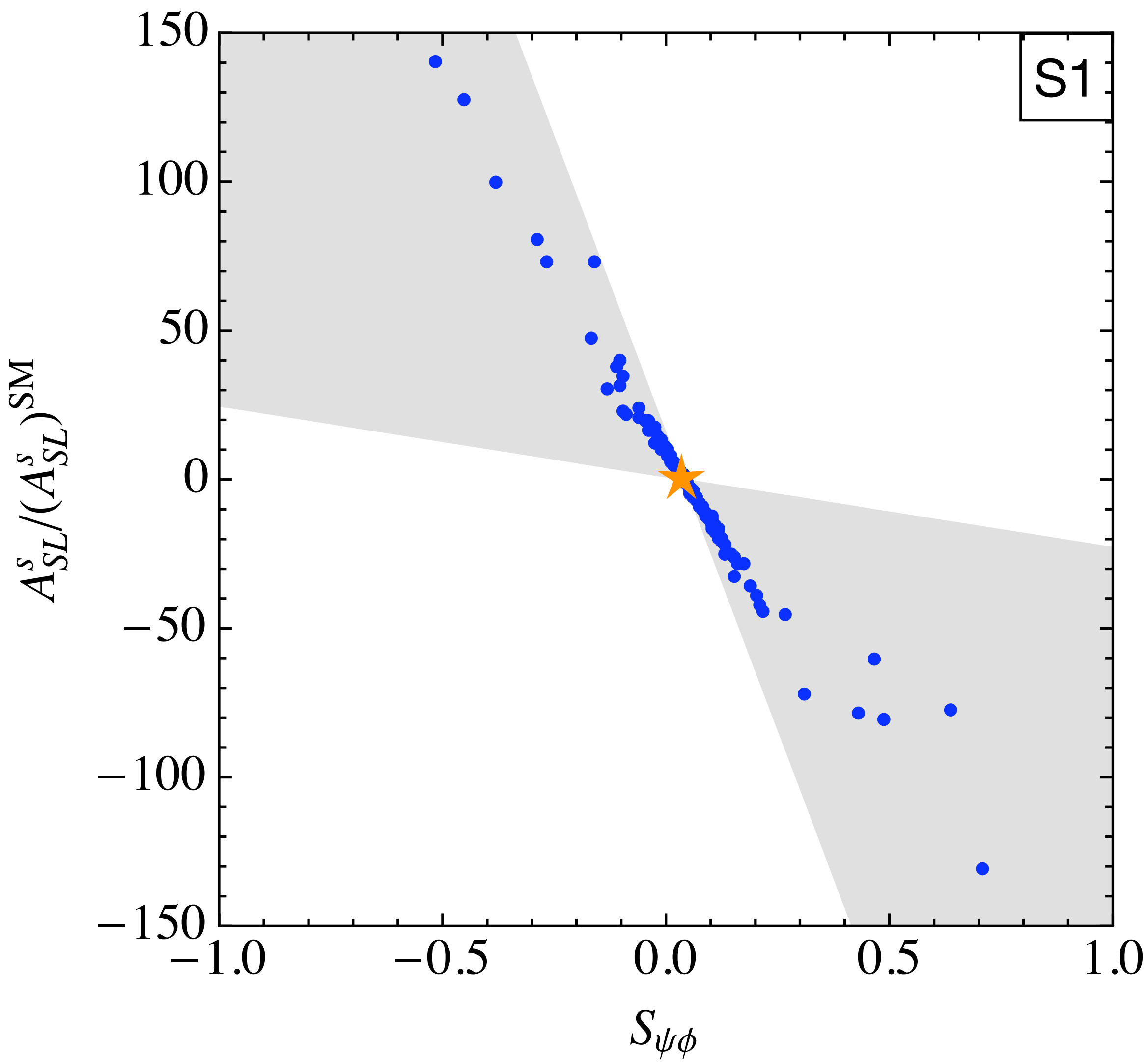
★ SM: $\Delta\Gamma_s/\Gamma_s \approx 0.13$, $S_{\psi\phi} \approx 0.04$

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

*Blanke *et al.*, arXiv:0809.1073; Bauer *et al.*, paper in preparation

Meson mixing: Neutral B_s mesons*

- In RS model significant corrections to semileptonic CP asymmetry A_{SL}^s and $S_{\psi\phi} = \sin(2|\beta_s| - 2\phi_{B_s})$, consistent with $|\varepsilon_K|$, can arise



$$A_{SL}^s = \frac{\Gamma(\bar{B}_s \to l^+ X) - \Gamma(B_s \to l^- X)}{\Gamma(\bar{B}_s \to l^+ X) + \Gamma(B_s \to l^- X)}$$

$$= \mathrm{Im}\left(\frac{\Gamma_{12}^s}{M_{12}^s}\right)$$

★ SM: $A_{SL}^s \approx 2 \cdot 10^{-5}$, $S_{\psi\phi} \approx 0.04$

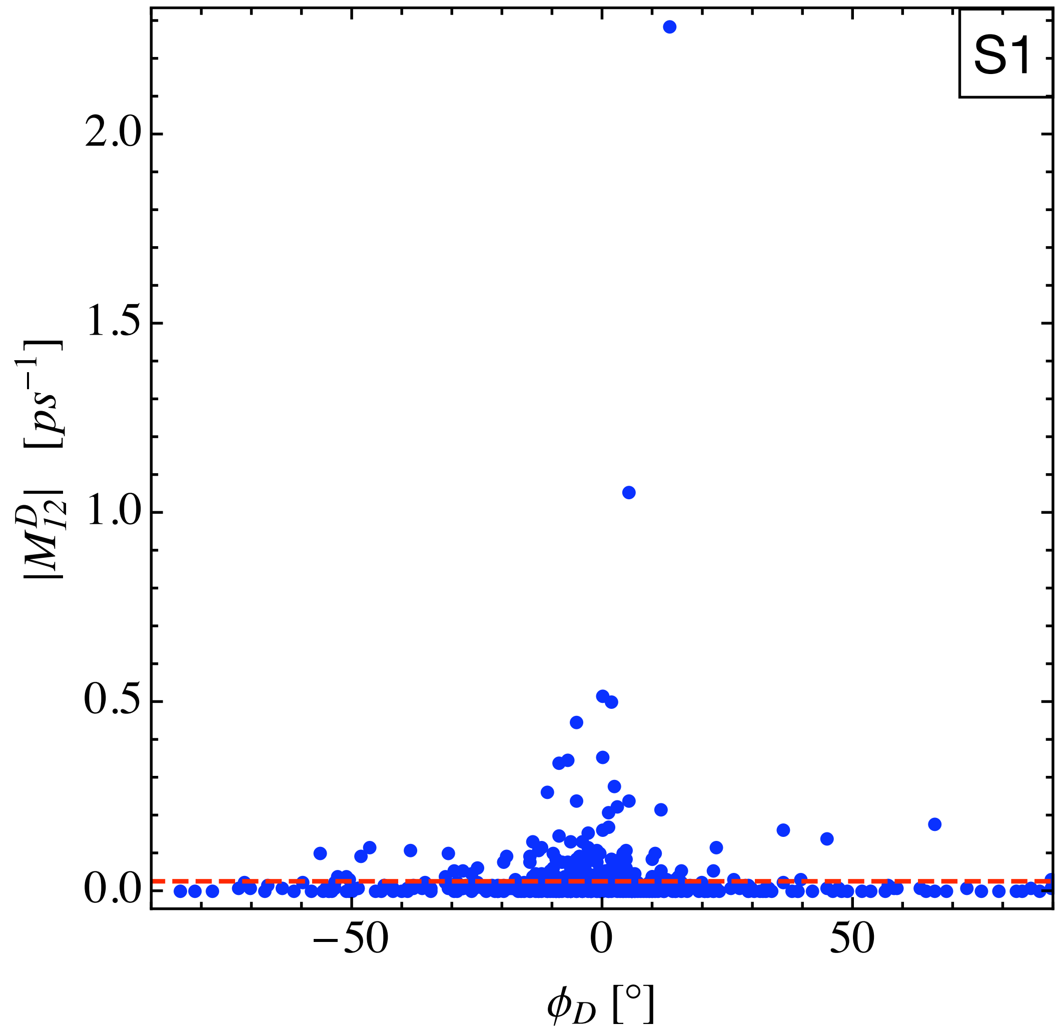
■ model-independent prediction

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

*Blanke *et al.*, arXiv:0809.1073; Bauer *et al.*, paper in preparation

Meson mixing: Neutral D mesons*

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



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

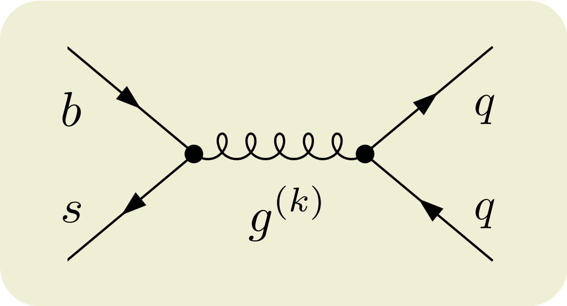
- - maximal allowed SM effect with no significant CP phase

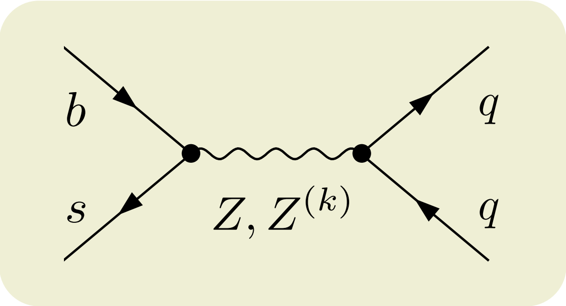
● consistent with quark masses, CKM parameters, and 95% CL limit $|\varepsilon_K| \in [1.3, 3.3] \cdot 10^{-3}$

*Bauer *et al*., paper in preparation

Rare decays: Effective Hamiltonian*

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





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

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

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

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

*Bauer *et al.*, paper in preparation

Rare decays: Effective Hamiltonian*

- Analogous expressions for Wilson coefficients $\widetilde{C}_{3-10}^{\rm RS}$ of opposite-chirality operators

$$C_3^{\rm RS} = \frac{\pi\alpha_s}{M_{\rm KK}^2}\,\frac{(\Delta_D)_{23}}{6} - \frac{\pi\alpha}{6s_w^2 c_w^2\, M_{\rm KK}^2}(\Sigma_D)_{23}\,,$$

$$C_4^{\rm RS} = C_6^{\rm RS} = -\frac{\pi\alpha_s}{2M_{\rm KK}^2}\,(\Delta_D)_{23}\,,$$

$$C_5^{\rm RS} = \frac{\pi\alpha_s}{6\,M_{\rm KK}^2}\,(\Delta_D)_{23}\,,$$

$$C_7^{\rm RS} = \frac{2\pi\alpha}{9M_{\rm KK}^2}\,(\Delta_D)_{23} - \frac{2\pi\alpha}{3c_w^2\, M_{\rm KK}^2}(\Sigma_D)_{23}\,,$$

$$C_8^{\rm RS} = C_{10}^{\rm RS} = 0\,,$$

$$C_9^{\rm RS} = \frac{2\pi\alpha}{9M_{\rm KK}^2}\,(\Delta_D)_{23} + \frac{2\pi\alpha}{3s_w^2\, M_{\rm KK}^2}(\Sigma_D)_{23}\,,$$

<u>Only four couplings:</u>

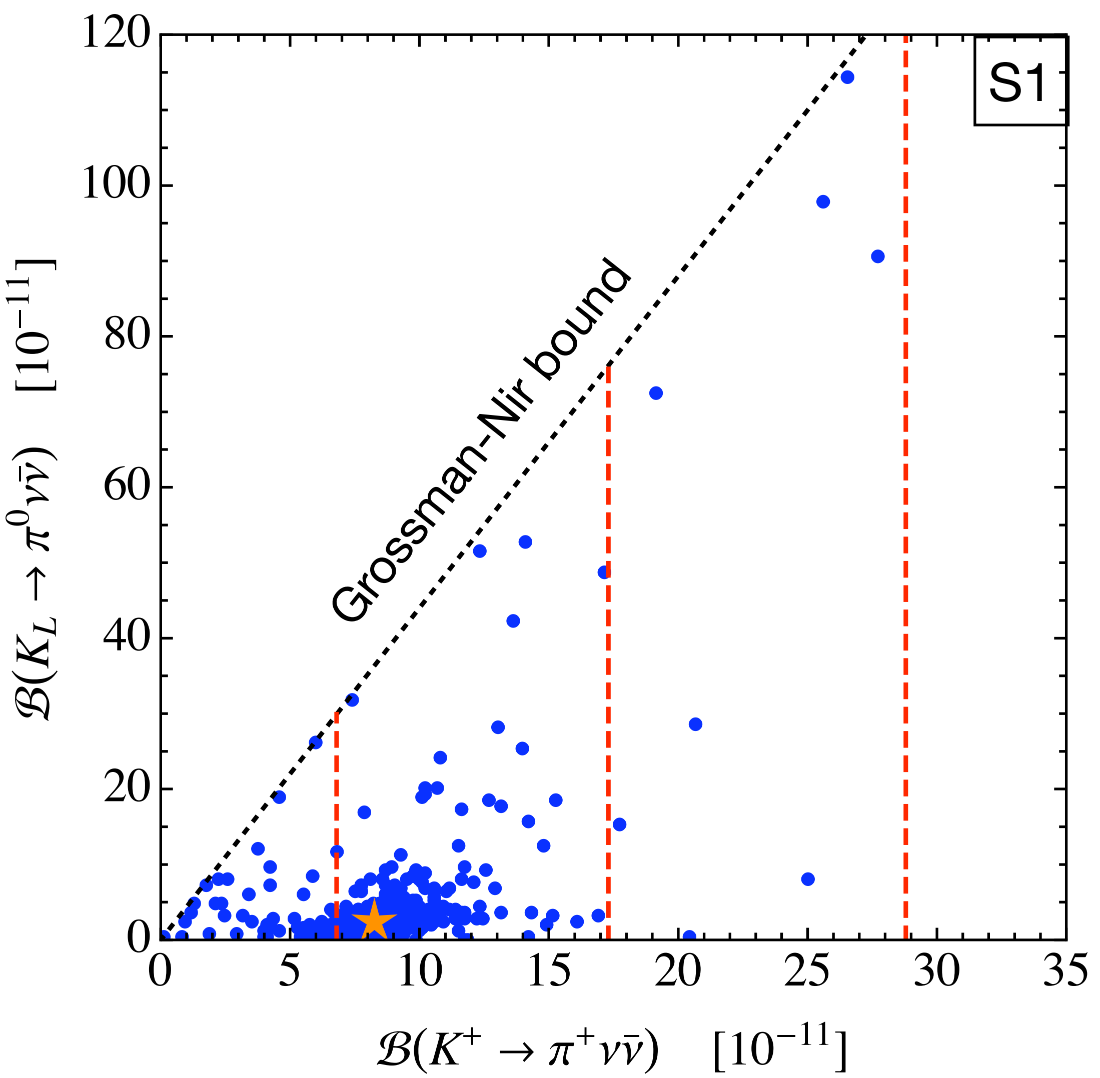
- $\boldsymbol{\Delta}_Q$, $\boldsymbol{\Delta}_q$ arising from $g^{(k)}$, $\gamma^{(k)}$ and $\boldsymbol{\Sigma}_Q$, $\boldsymbol{\Sigma}_q$ due to Z, $Z^{(k)}$ exchange
- former two couplings can be made small, but latter ones cannot

$$\boldsymbol{\Sigma}_Q = L\left(\frac{1}{2} - \frac{s_w^2}{3}\right)\boldsymbol{\Delta}_Q' + \frac{M_{\rm KK}^2}{m_Z^2}\,\boldsymbol{\delta}_Q$$

*Bauer *et al.*, paper in preparation

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



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

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

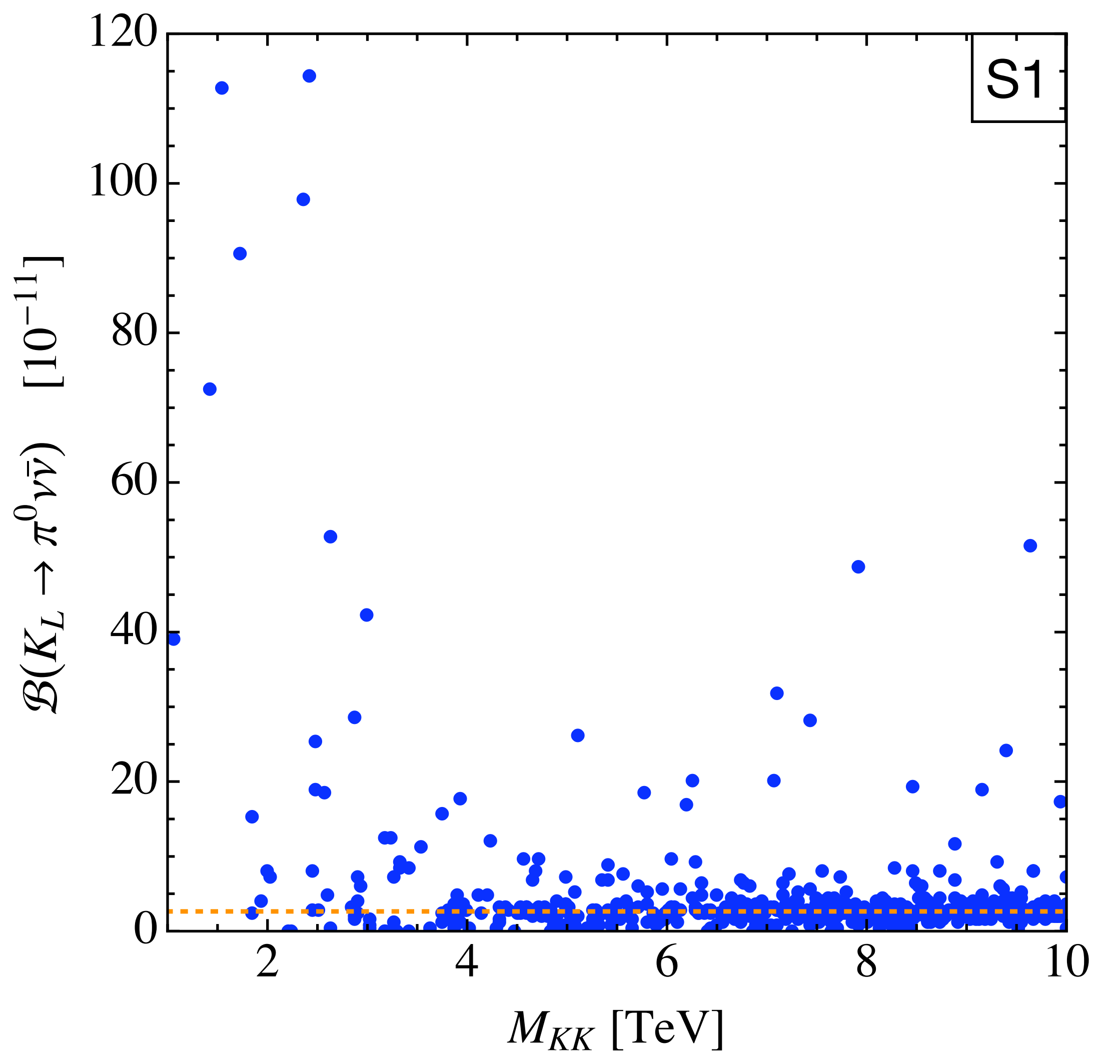
- - central value and 68% CL limit $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \cdot 10^{-11}$ from E949

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

*Grossman and Nir, hep-ph/9701313; Bauer *et al*., paper in preparation

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



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

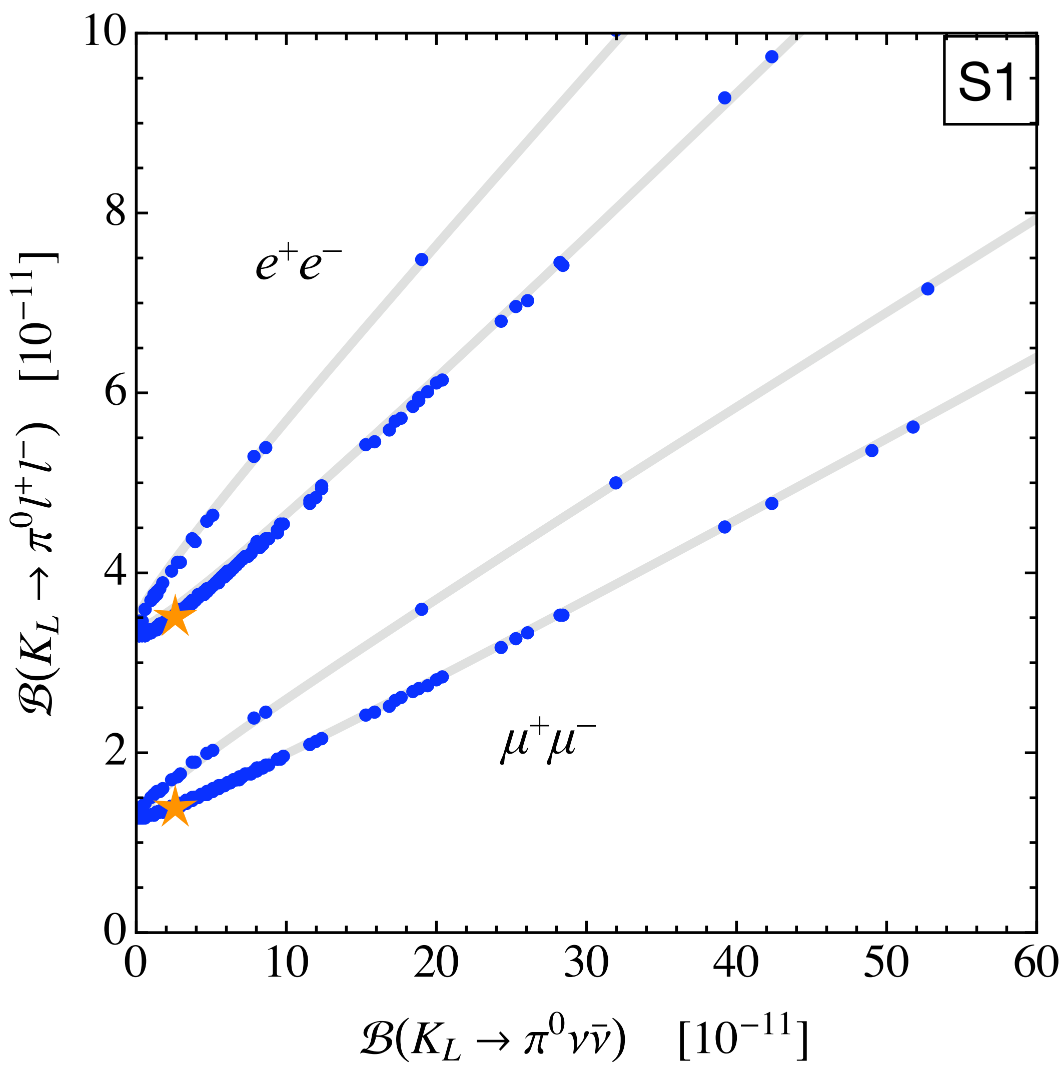
SM: $\mathcal{B}(K_L \to \pi^0 \nu \bar{\nu}) \approx 2.7 \cdot 10^{-11}$

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

*Bauer *et al.*, paper in preparation

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

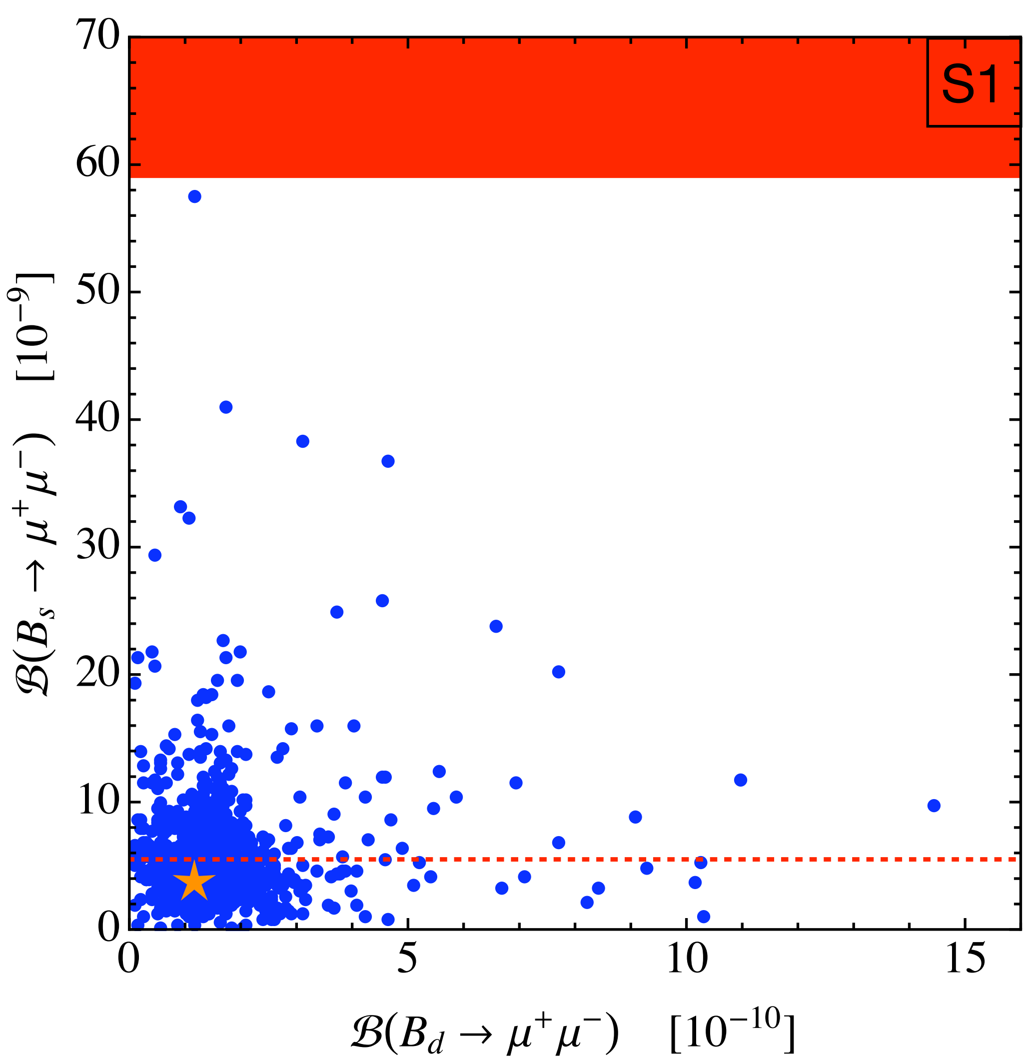
— model-independent prediction

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

*Bauer *et al.*, paper in preparation

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, $2\ \mathrm{fb}^{-1}$

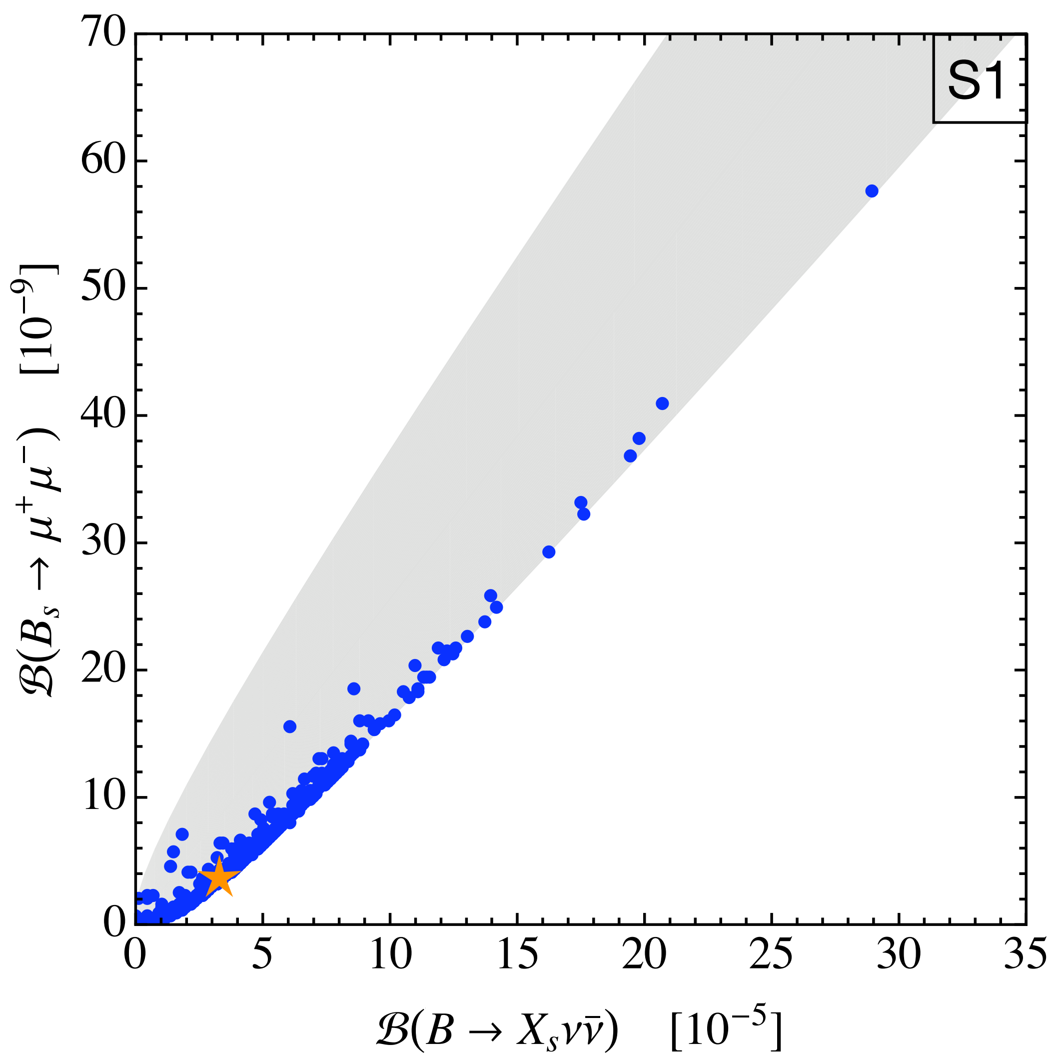
95% CL upper limit from CDF $\mathcal{B}(B_s \to \mu^+\mu^-) < 5.8 \cdot 10^{-8}$

● consistent with quark masses, CKM parameters, and 95% CL limit of $Z \to b\bar{b}$

*Bauer *et al*., paper in preparation

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



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

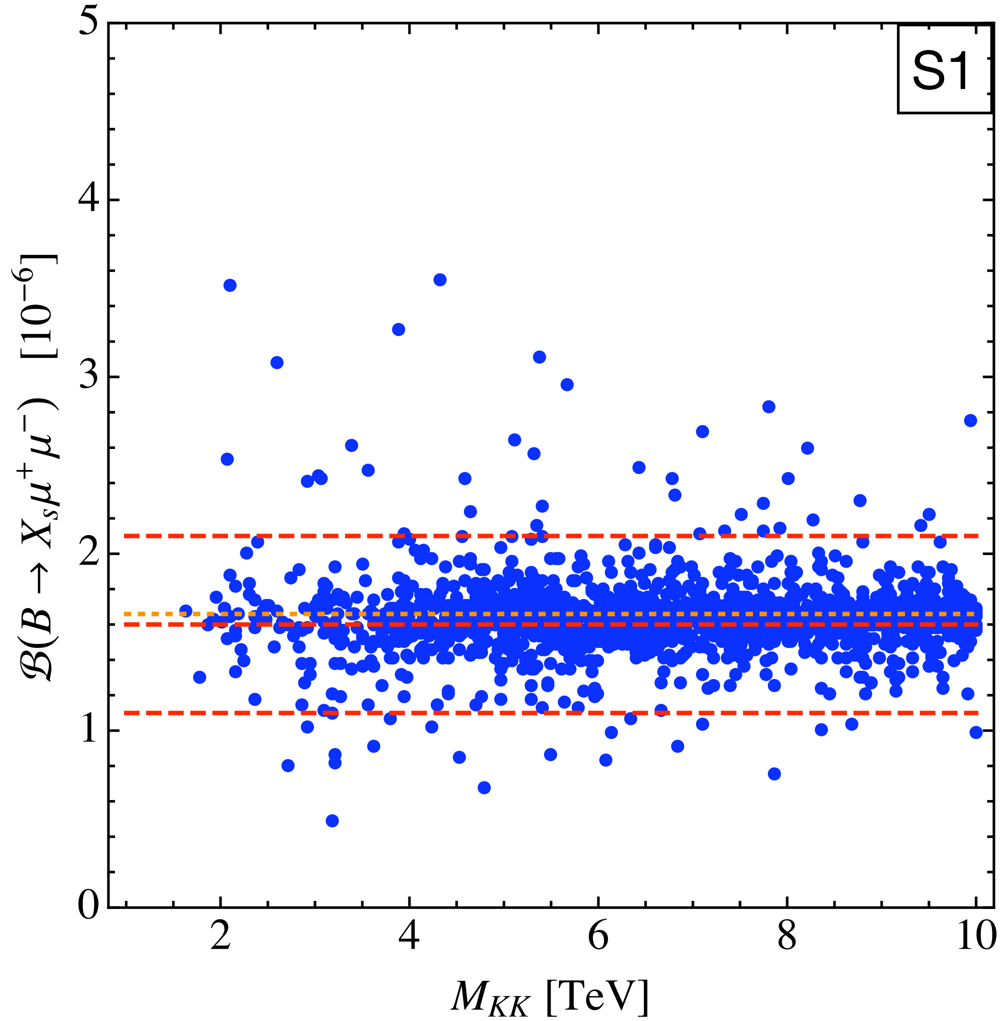
■ model-independent prediction

● consistent with quark masses, CKM parameters, and 95% CL limit of $Z \to b\bar{b}$

*Bauer *et al.*, paper in preparation

Rare B decays: Inclusive semileptonic modes*

- Once $Z \to b\bar{b}$ constraints are satisfied, values for $B \to X_s \mu^+ \mu^-$ branching ratio arising from Z and $Z^{(k)}$ exchange are typically within experimental limits



SM: $\mathcal{B}(B \to X_s \mu^+ \mu^-) \approx 1.7 \cdot 10^{-6}$ for $q^2 \in [1, 6]$ GeV^2

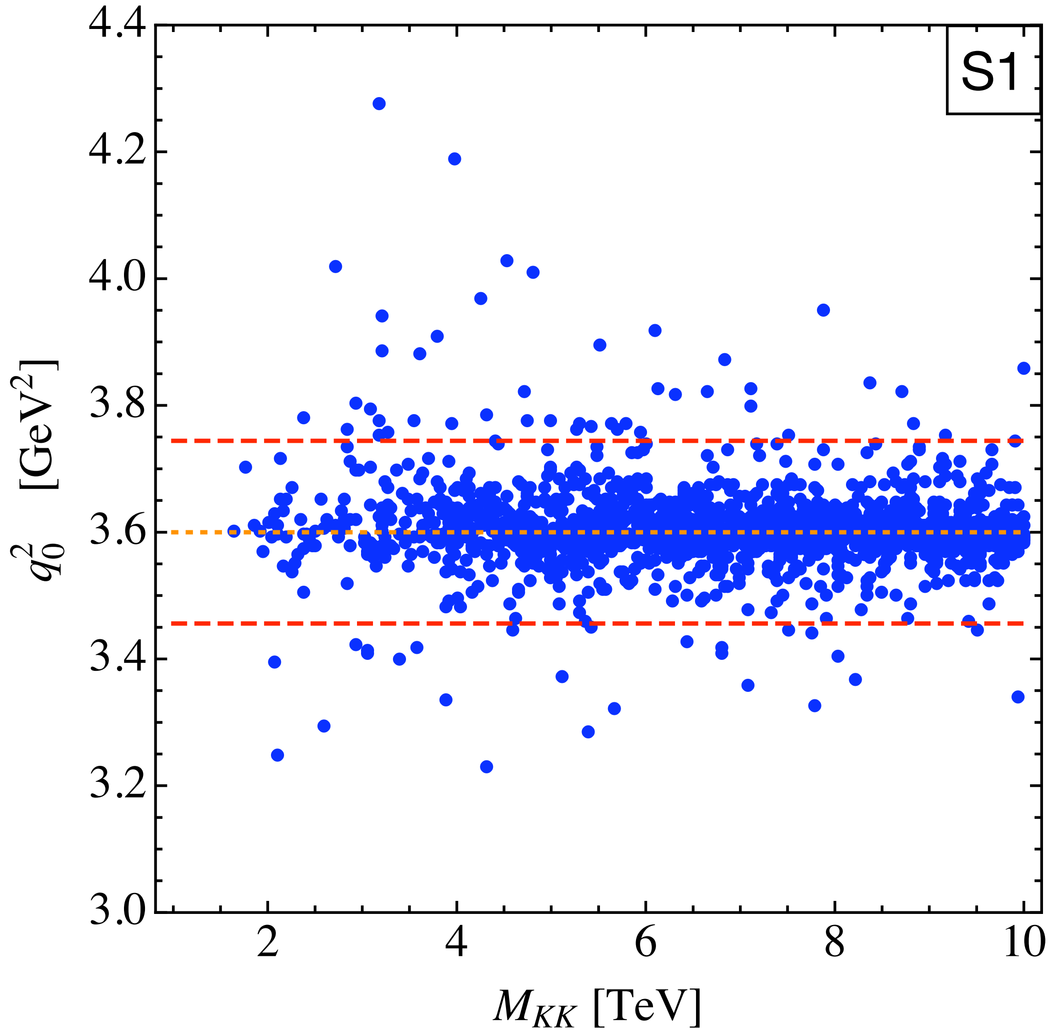
central value and 68% CL limit $\mathcal{B}(B \to X_s \mu^+ \mu^-) = (1.6 \pm 0.5) \cdot 10^{-6}$ from BaBar and Belle

consistent with quark masses, CKM parameters, and 95% CL limit of $Z \to b\bar{b}$

*Bauer *et al.*, paper in preparation

Rare B decays: Inclusive semileptonic modes*

- Deviations of zero in forward-backward asymmetry, q_0^2, in $B \to X_s \mu^+\mu^-$ from SM prediction might be observable at high-luminosity flavor factory



SM: $q_0^2 \approx 3.6\,\mathrm{GeV}^2$

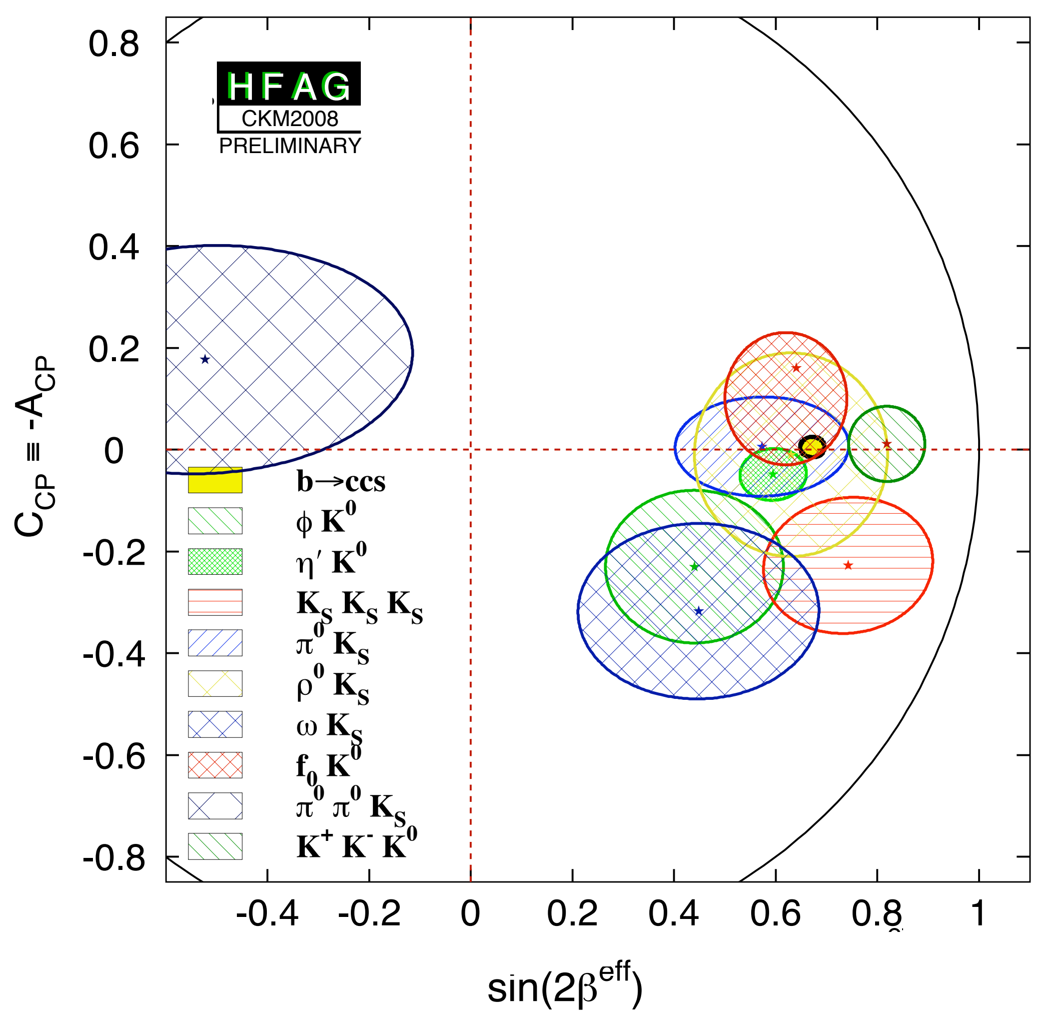
expected sensitivity at SuperB factory, 75 ab^{-1}

consistent with quark masses, CKM parameters, and 95% CL limit of $Z \to b\bar{b}$

*Bauer *et al.*, paper in preparation

Non-leptonic B and K decays*

- Electroweak penguin effects in rare hadronic decays such as $B \to K\pi$ or $B \to \phi K$ are naturally of O(1) compared to SM and can introduce new large CP-violating phases. Similar effects can occur in $K \to \pi\pi$



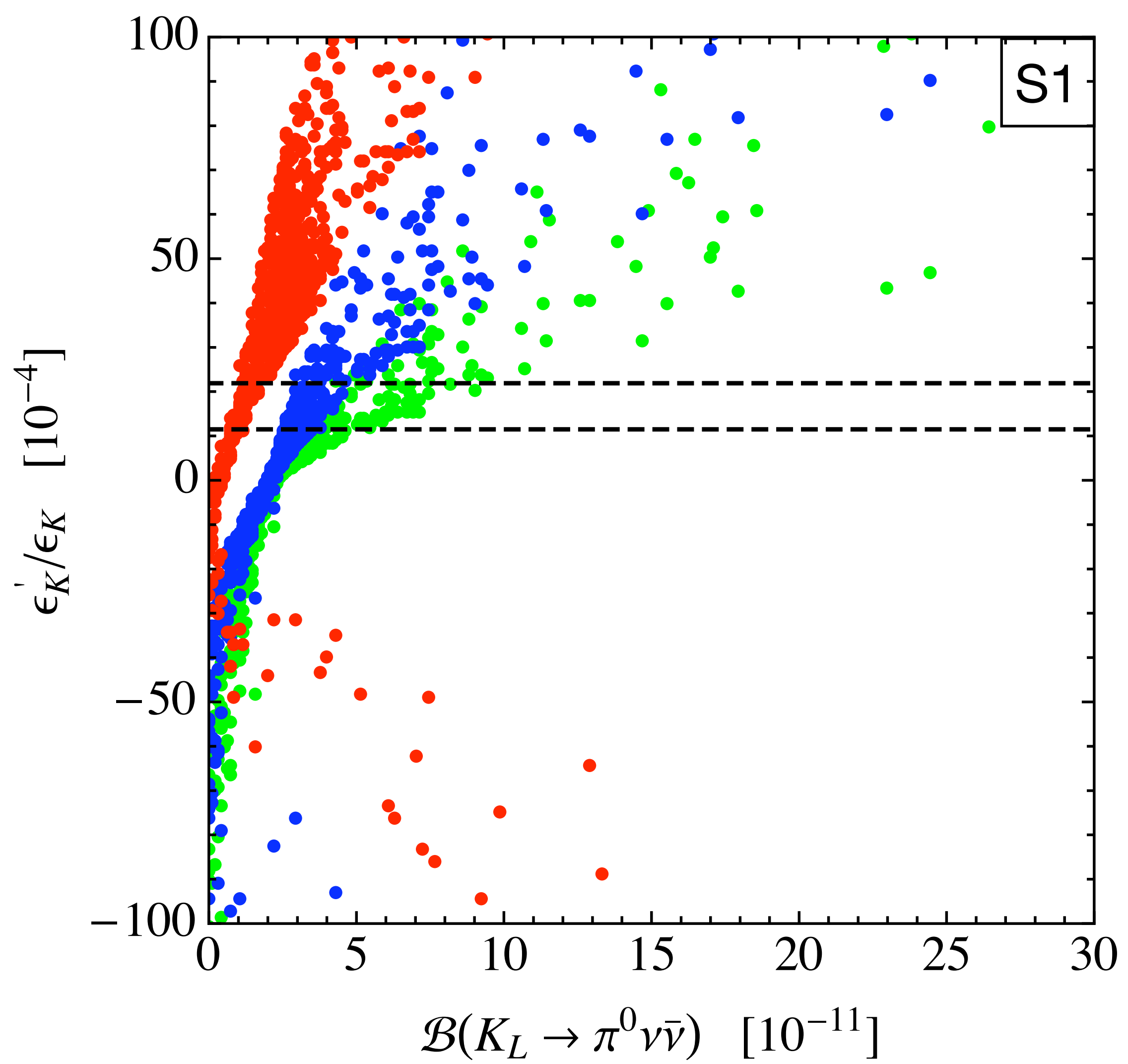
<u>Potentially relevant for:</u>

- explaining large CP asymmetries in $B \to K\pi$ and determining of $\sin(2\beta^{\rm eff})$ from penguin-dominated modes
- studying correlations between ratio $\varepsilon'_K/\varepsilon_K$ measuring direct and indirect CP violation in $K \to \pi\pi$ and large effects in rare K decays

*Bauer *et al.*, paper in preparation

Correlations between $\varepsilon'_K/\varepsilon_K$ and rare K decays*

- Even in view of large theoretical uncertainties, data on $\varepsilon'_K/\varepsilon_K$ imply non-trivial constraints on possible BSM effects in rare K decay



- - experimental 95% CL limit $\varepsilon'_K/\varepsilon_K \in [11.5, 21.9] \cdot 10^{-4}$

- upper value (theory parameter var.)
- central values (default theory pars.)
- lower value (theory parameter var.)

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

*Bauer *et al.*, paper in preparation

Conclusions

- LHC is there (maybe, sometime ...), 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