# Flavor physics in Randall-Sundrum models*

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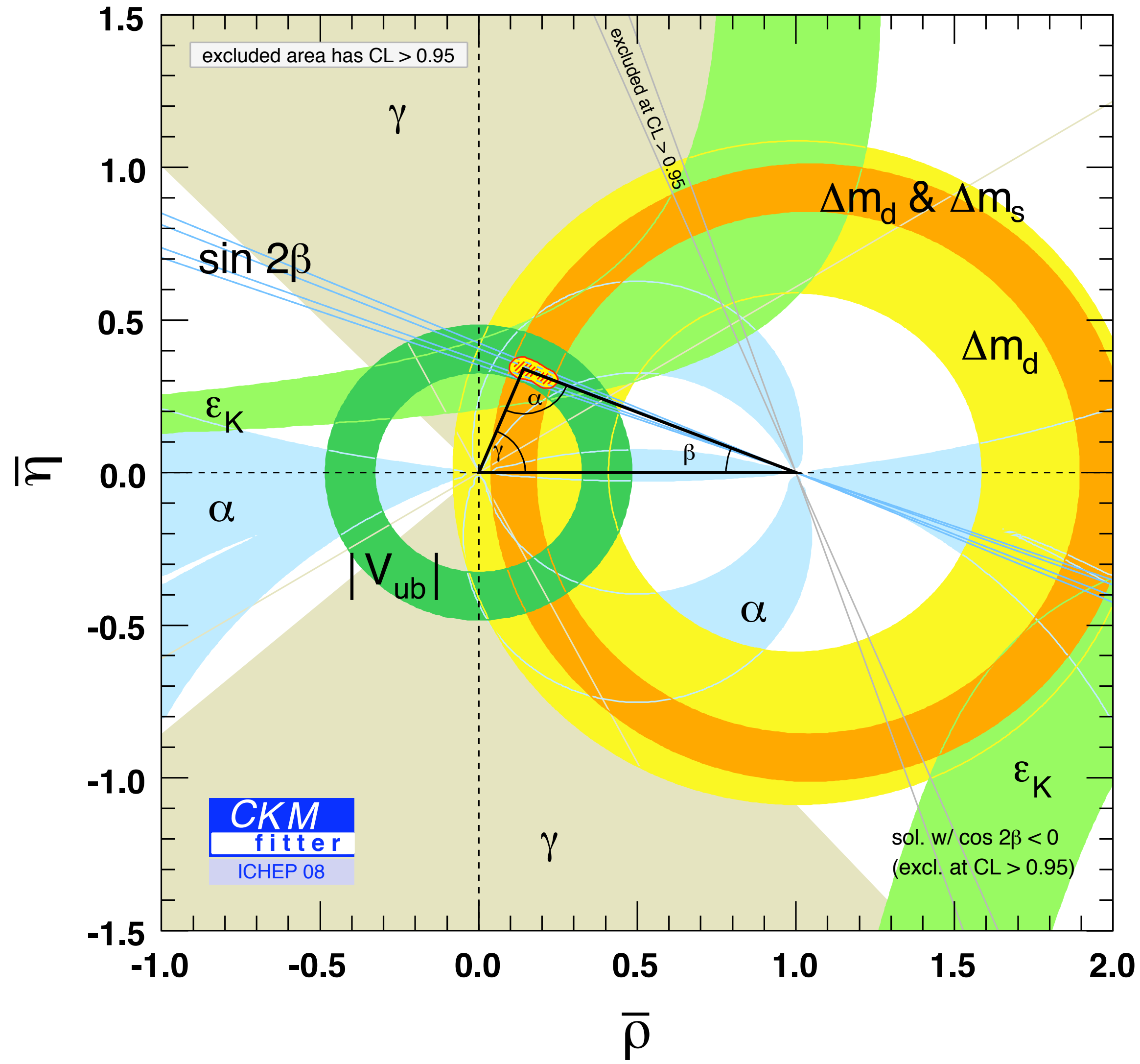
Heidelberg, Germany

*In collaboration with M. Bauer, S. Casagrande, F. Goertz, L. Gründer, M. Neubert, and T. Pfoh, arXiv:0807.4537, arXiv:0811.3678, ...

# Main lesson from quark flavor physics

Standard Model (SM) of particle physics, *i.e.*, theory of electroweak and strong interaction (QCD), is very successful in describing quark flavor-mixing:

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



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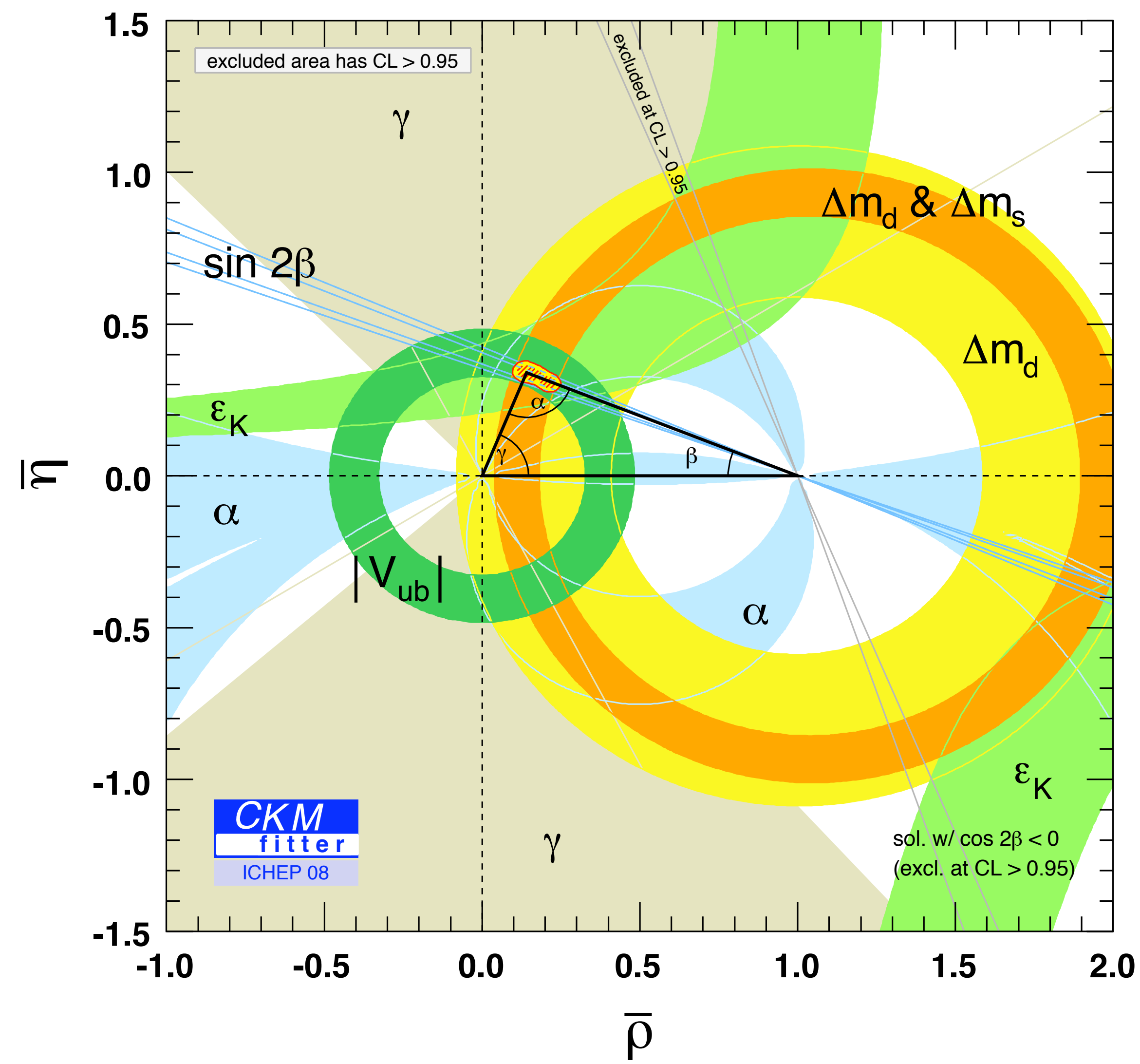
N. Cabibbo

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"**

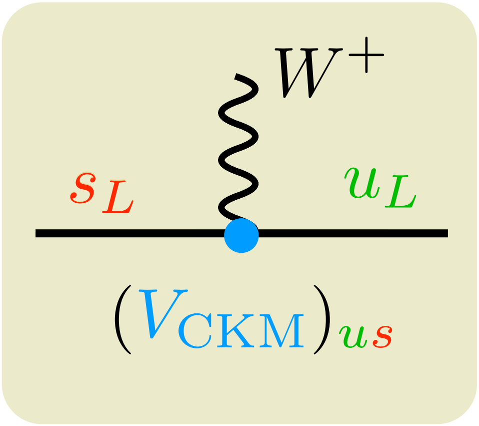



*http://nobelprize.org/nobel_prizes/physics/laureates/2008/

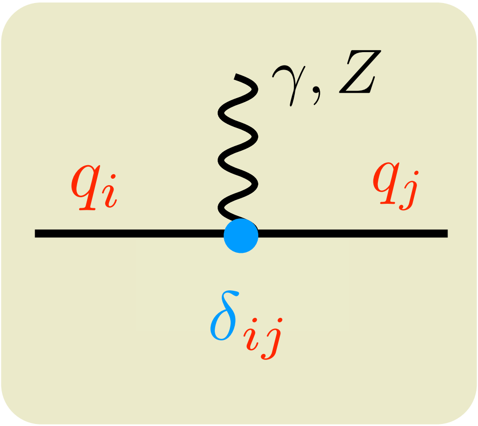
# Main lesson from quark flavor physics

Standard Model (SM) of particle physics, *i.e.*, theory of electroweak and strong interaction (QCD), 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*. that are forbidden at tree level in SM




$V_{\rm CKM}$ = CKM matrix

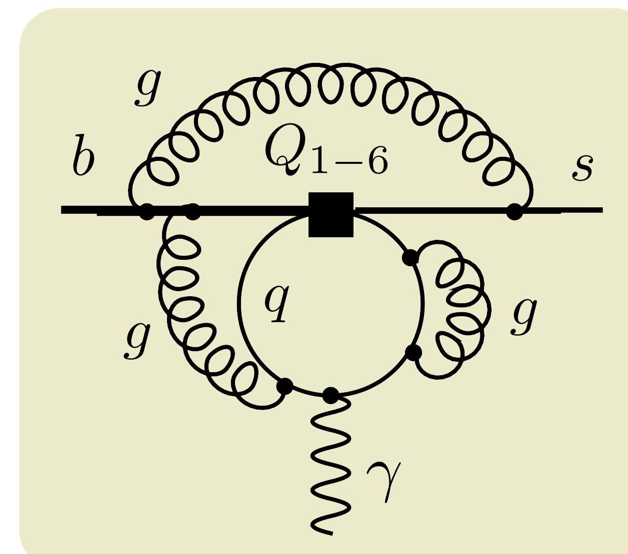



$\delta$ = diagonal matrix

# Main lesson from quark flavor physics

Standard Model (SM) of particle physics, *i.e.*, theory of electroweak and strong interaction (QCD), is very successful in describing quark flavor-mixing:

In case of $B \to X_s \gamma$, highly non-trivial test of SM, since theory prediction at $\mathcal{O}(\alpha_s^2)$, *i.e.*, next-to-next-to-leading order, shows agreement with experiment within errors that amount to less than $10\%$ on each side

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21985 diagrams

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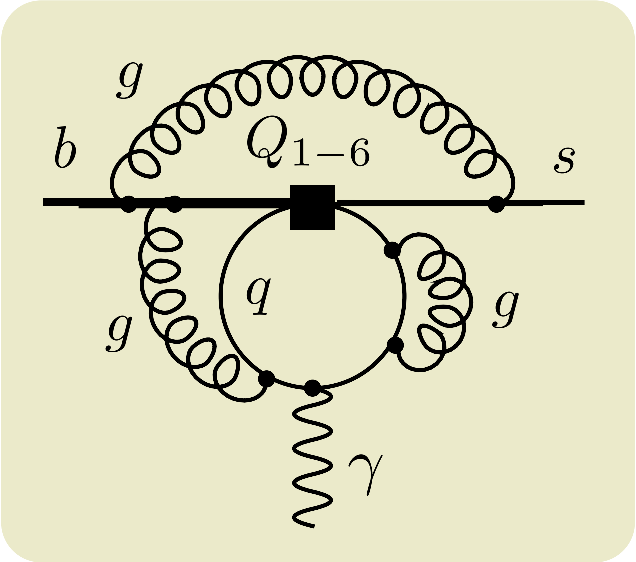


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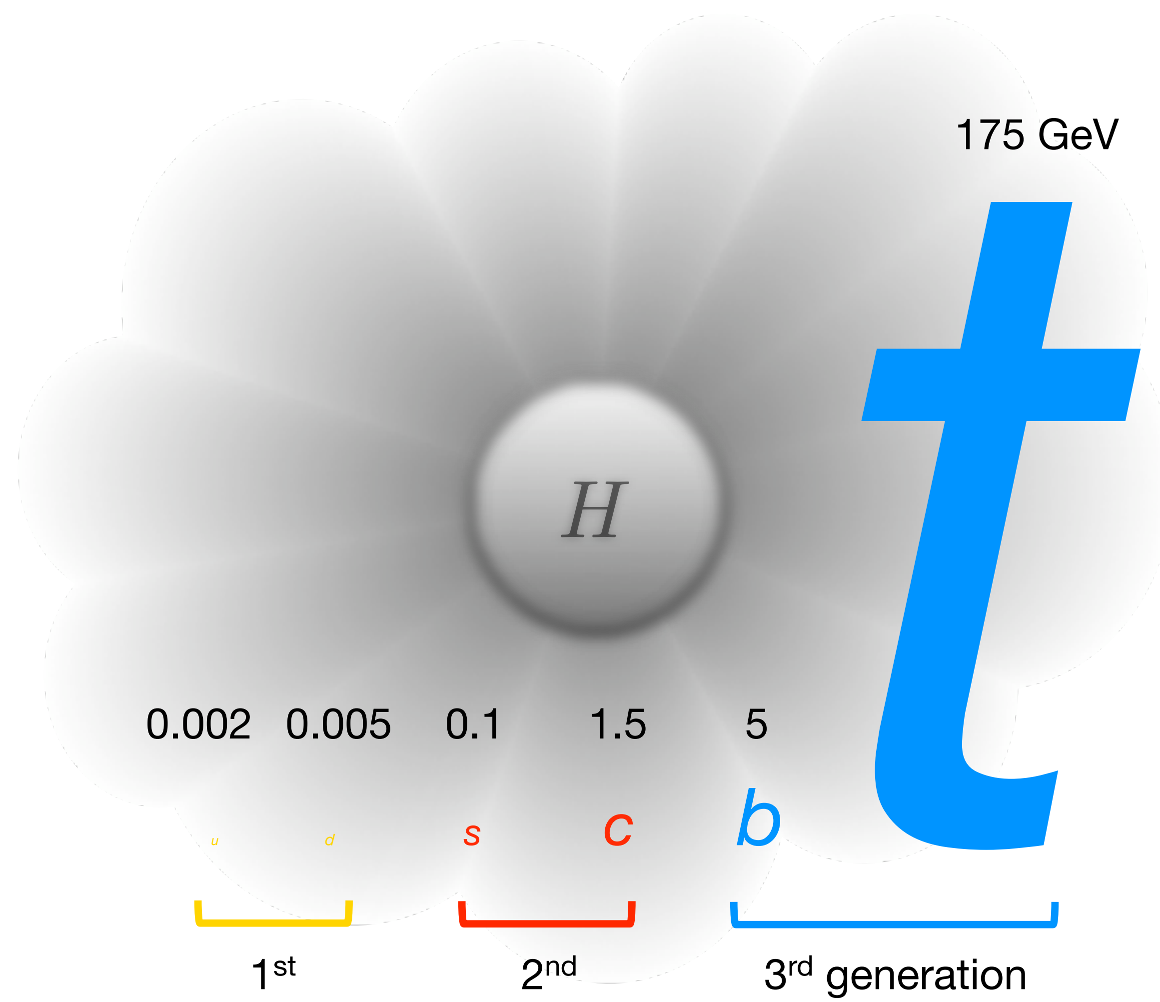
21985 diagrams

Effects of Beyond SM (BSM) physics in quark flavor-mixing can only appear as small corrections to leading CKM mechanism

# But many open questions remain

While Yukawa couplings allow to parametrize masses and mixings, observed hierarchies in quark flavor sector remain unexplained in SM:

- Why do masses of quarks range over 5 orders of magnitude?



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While Yukawa couplings allow to parametrize masses and mixings, observed hierarchies in quark flavor sector remain unexplained in SM:

- Why do masses of quarks range over 5 orders of magnitude?
- Why is there large intra- but small inter-generational mixing?

$$\boldsymbol{V}_{\mathrm{CKM}} \approx \begin{array}{cc} \begin{array}{ccc} d & s & b \end{array} & \\ \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix} & \begin{array}{c} u \\ c \\ t \end{array} \end{array}$$

$\lambda \approx 0.23,$ Cabibbo angle

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While Yukawa couplings allow to parametrize masses and mixings, observed hierarchies in quark flavor sector remain unexplained in SM:

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We will see that Randall-Sundrum (RS) models*, featuring a warped extra dimension, admit natural explanation of SM flavor structure

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$\lambda \approx 0.23,$ Cabibbo angle

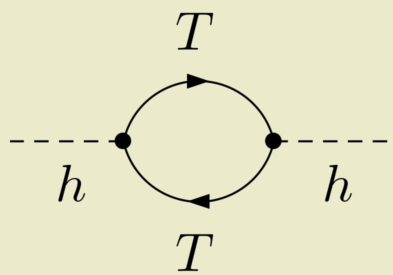
*Randall and Sundrum, hep-ph/9905221

# Beyond SM there is another flavor problem

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

electroweak symmetry breaking $\Downarrow$

Higgs mass

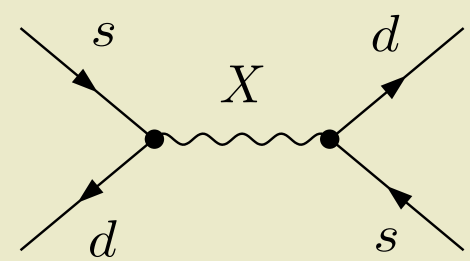



$$\sim \frac{g_T^2}{16\pi^2}\Lambda_{\mathrm{UV}}^2$$

no fine-tuning $\Downarrow$

$\Downarrow$ generic flavor structure

large FCNCs

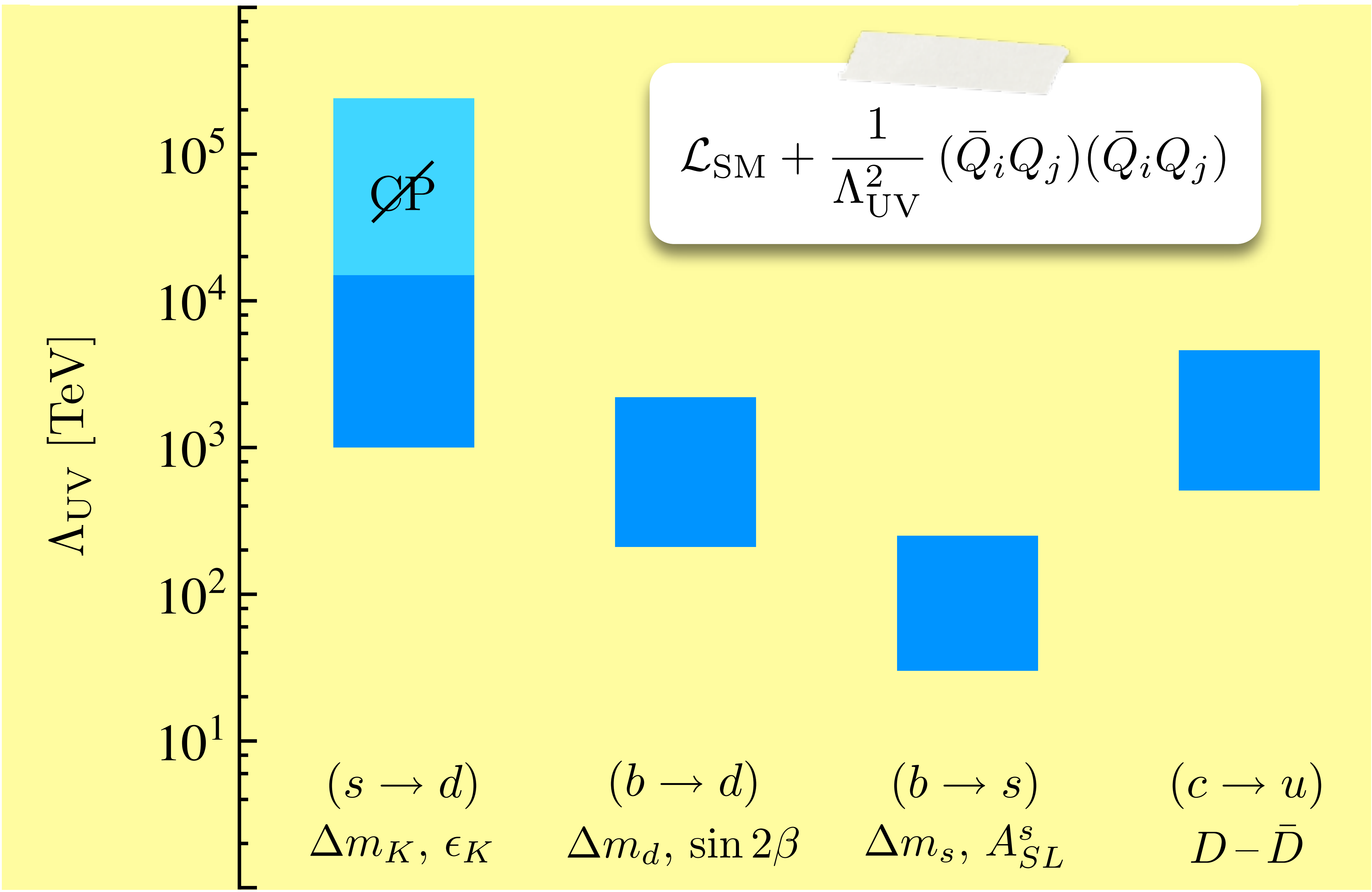



$$\sim \frac{g_X^2}{\Lambda_{\mathrm{UV}}^2}$$

bounds on flavor-mixing $\Downarrow$

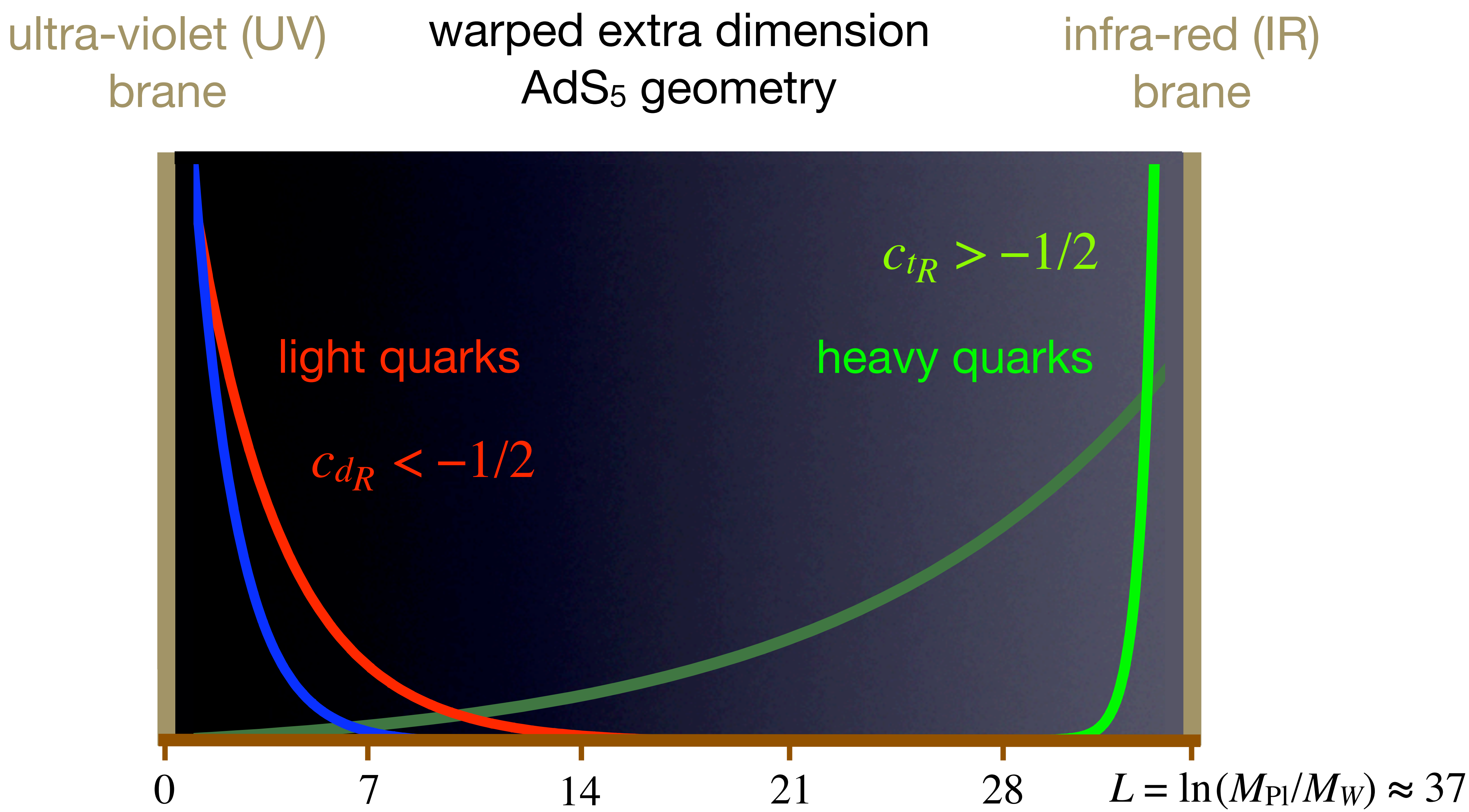
$\Lambda_{\mathrm{Higgs}} \lesssim 1$ TeV $\longrightarrow$ increasing energy scale $\longrightarrow$ $\Lambda_{\mathrm{flavor}} \gtrsim 10^3$ TeV

# Bounds on generic quark flavor-violation*




*UTfit Collaboration, arXiv:0707.0636

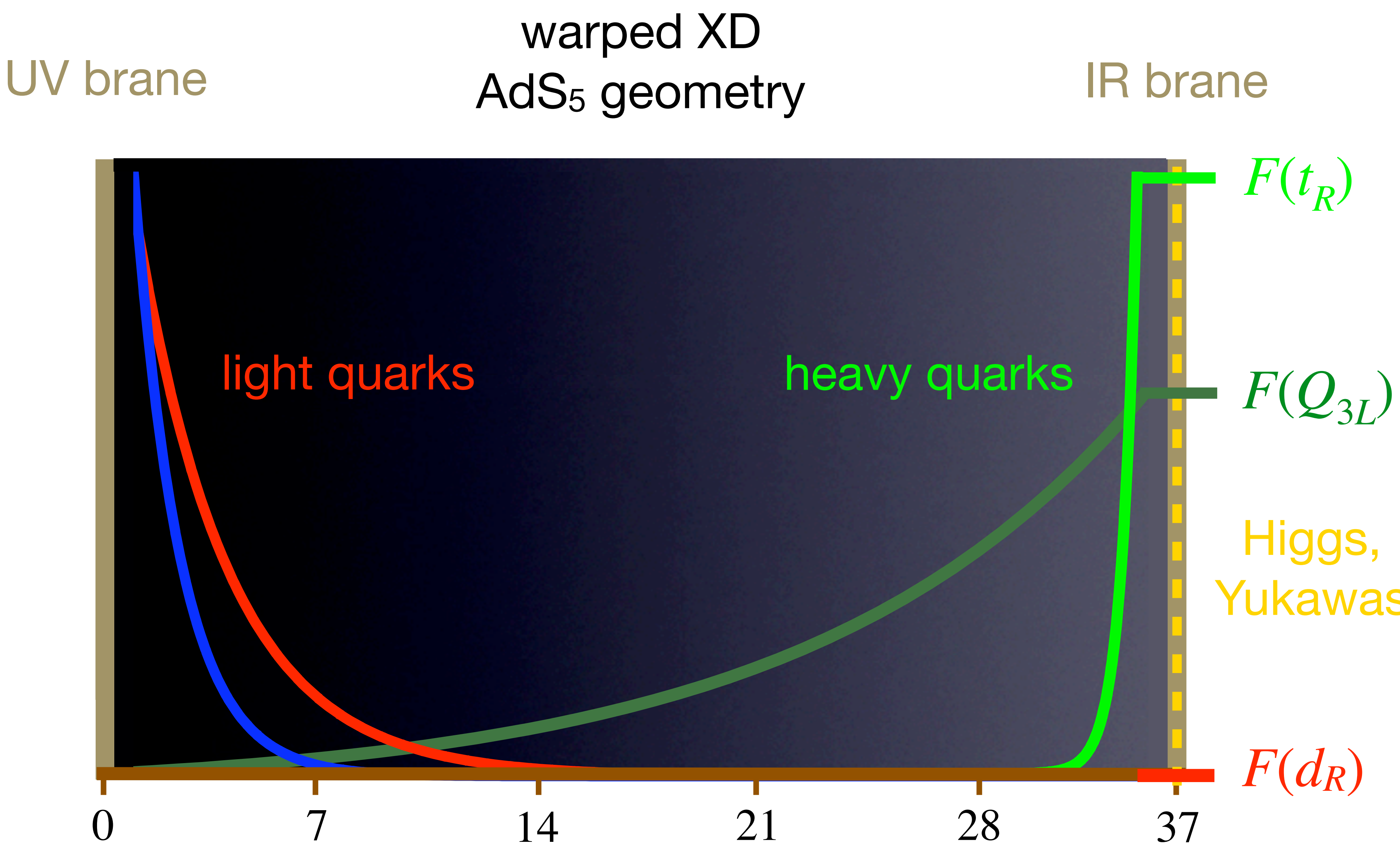
# Origin of quark flavor in RS models




- Localization of quarks fields in extra dimension (XD) depends exponentially on parameters of order 1, *i.e.*, five dimensional (5D) bulk masses parameters $c_q$*

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

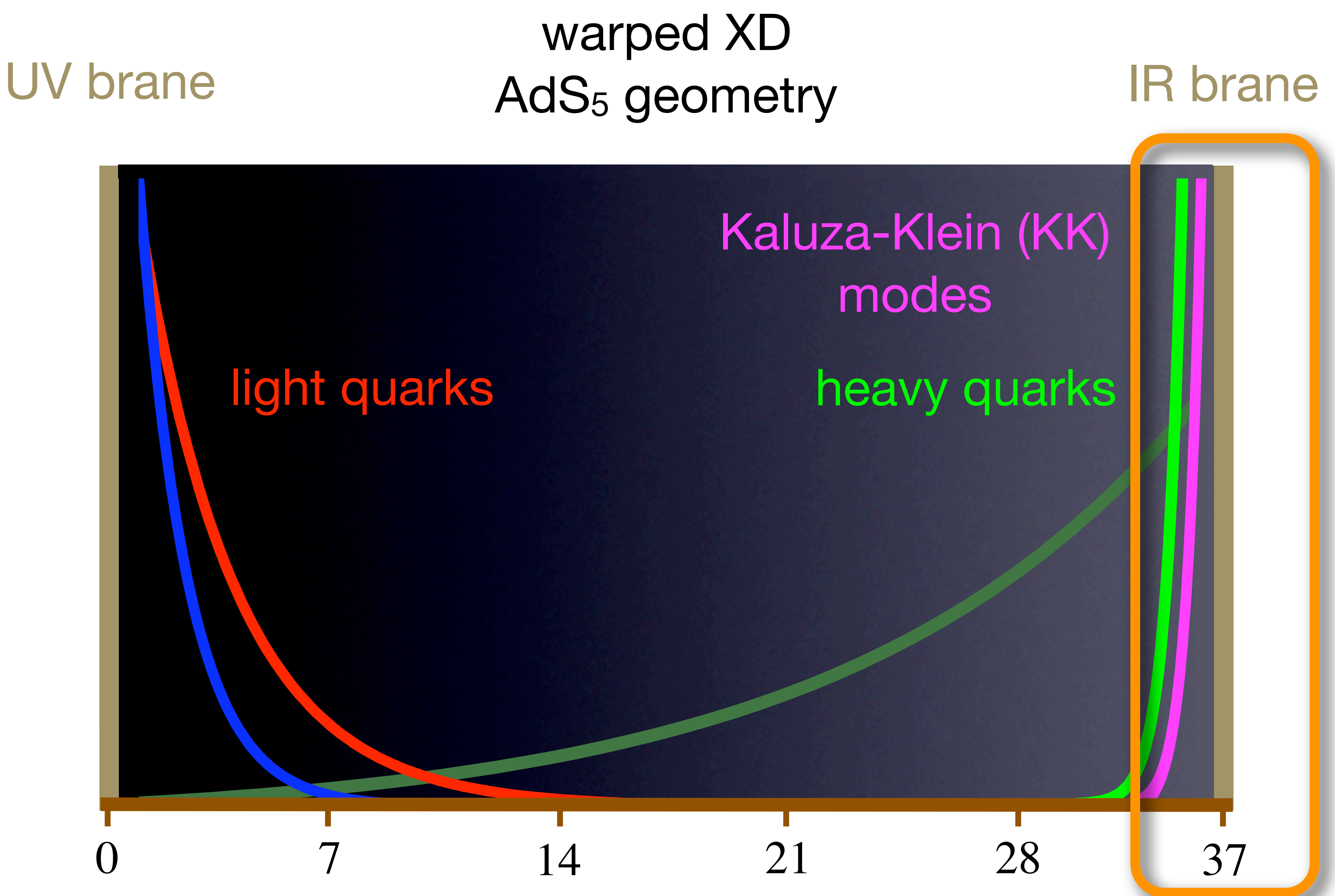
# Origin of quark flavor in RS models




- Overlaps of profiles $F(Q_L)$, $F(q_R)$ with IR-localized Higgs sector and Yukawa couplings are exponentially small for light quarks while of order 1 for top*

*Ghergetta & Pomarol, hep-ph/0003129

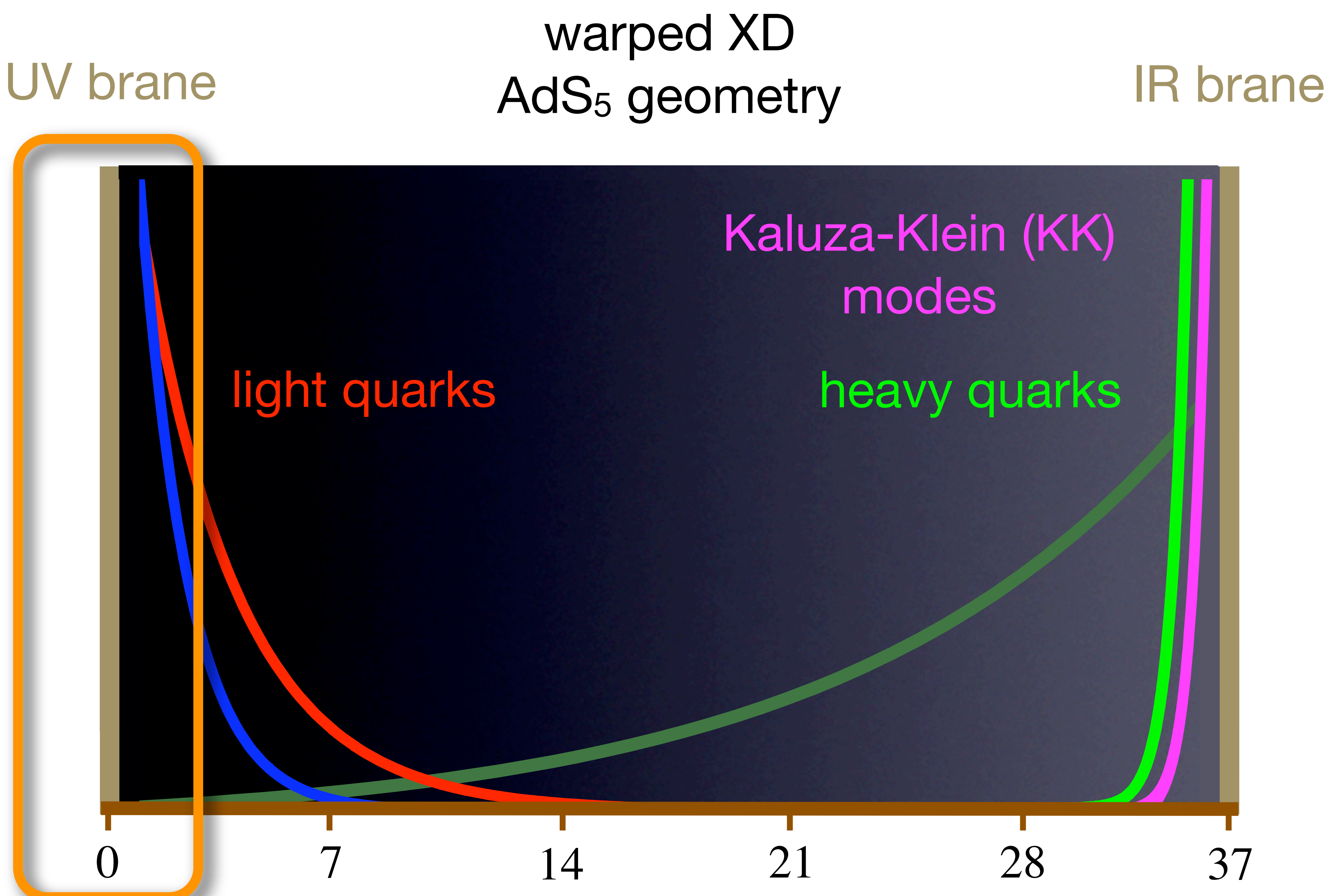
# Origin of quark flavor in RS models




- All KK modes live in IR. In case of gluon this leads to enhancement of coupling by a factor of $L^{1/2}$ relative to zero mode, *i.e.*, SM gluon*

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

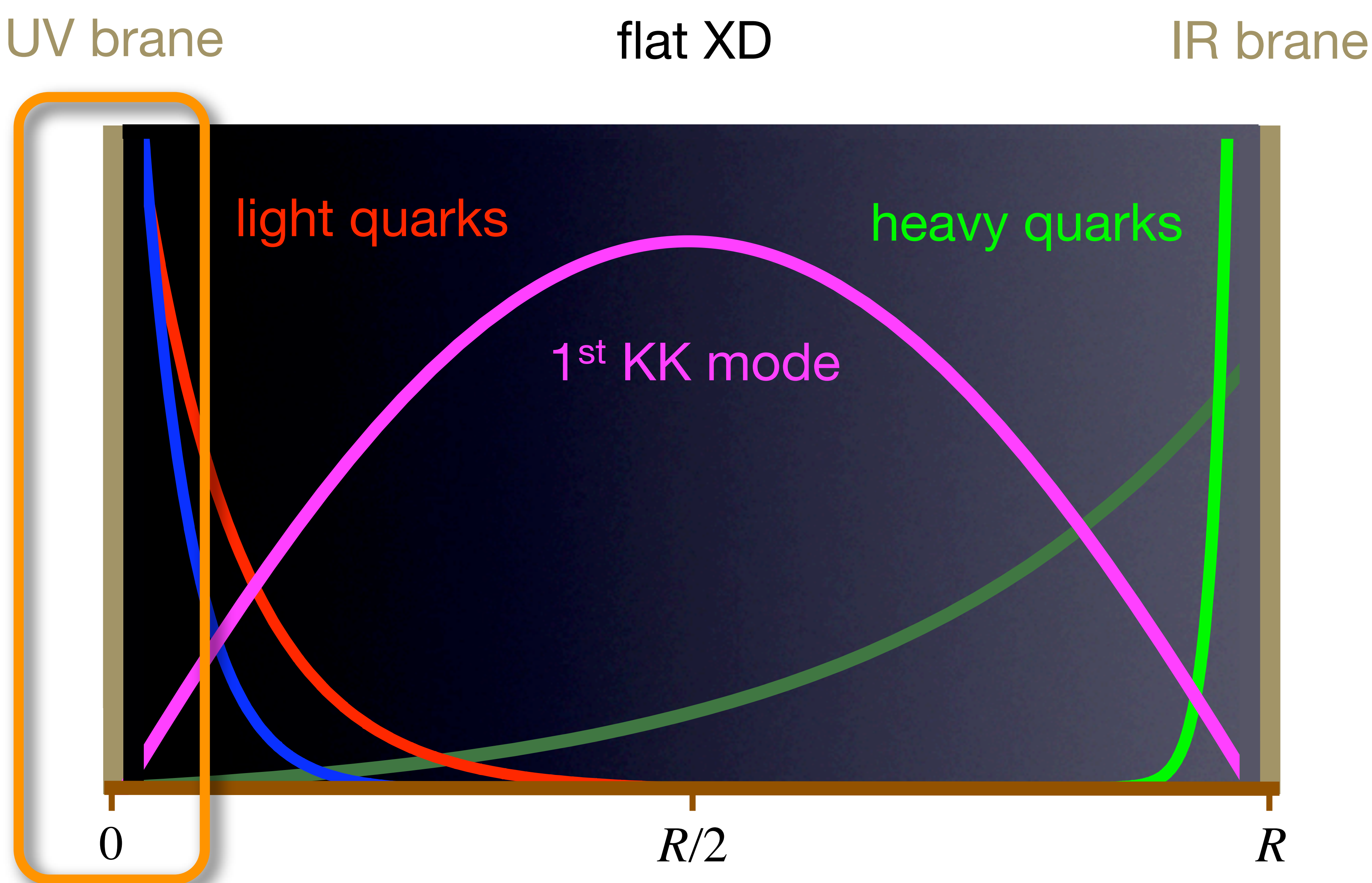
# Origin of quark flavor in RS models




- Since all light quark generations live in UV, their couplings to $W$ and $Z$ bosons as well as KK gluons are almost universal, *i.e.*, flavor-independent*

*Ghergetta & Pomarol, hep-ph/0003129

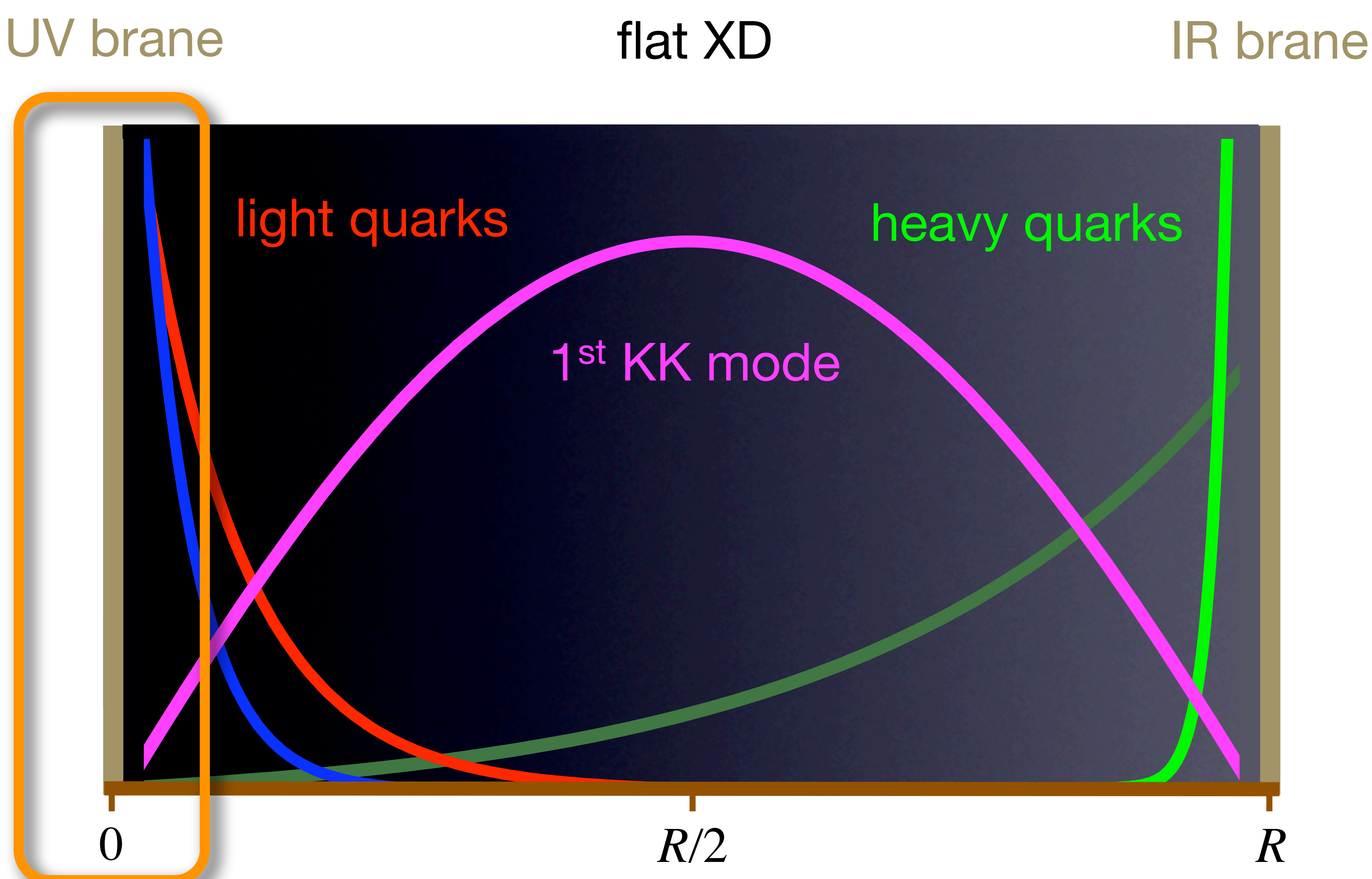
# Flavor problem in flat XDs




- Light quarks couple generation-dependent to KK modes, which leads to large FCNCs unless KK scale $M_{\mathrm{KK}} \approx 1/R > 5000\ \mathrm{TeV}^*$

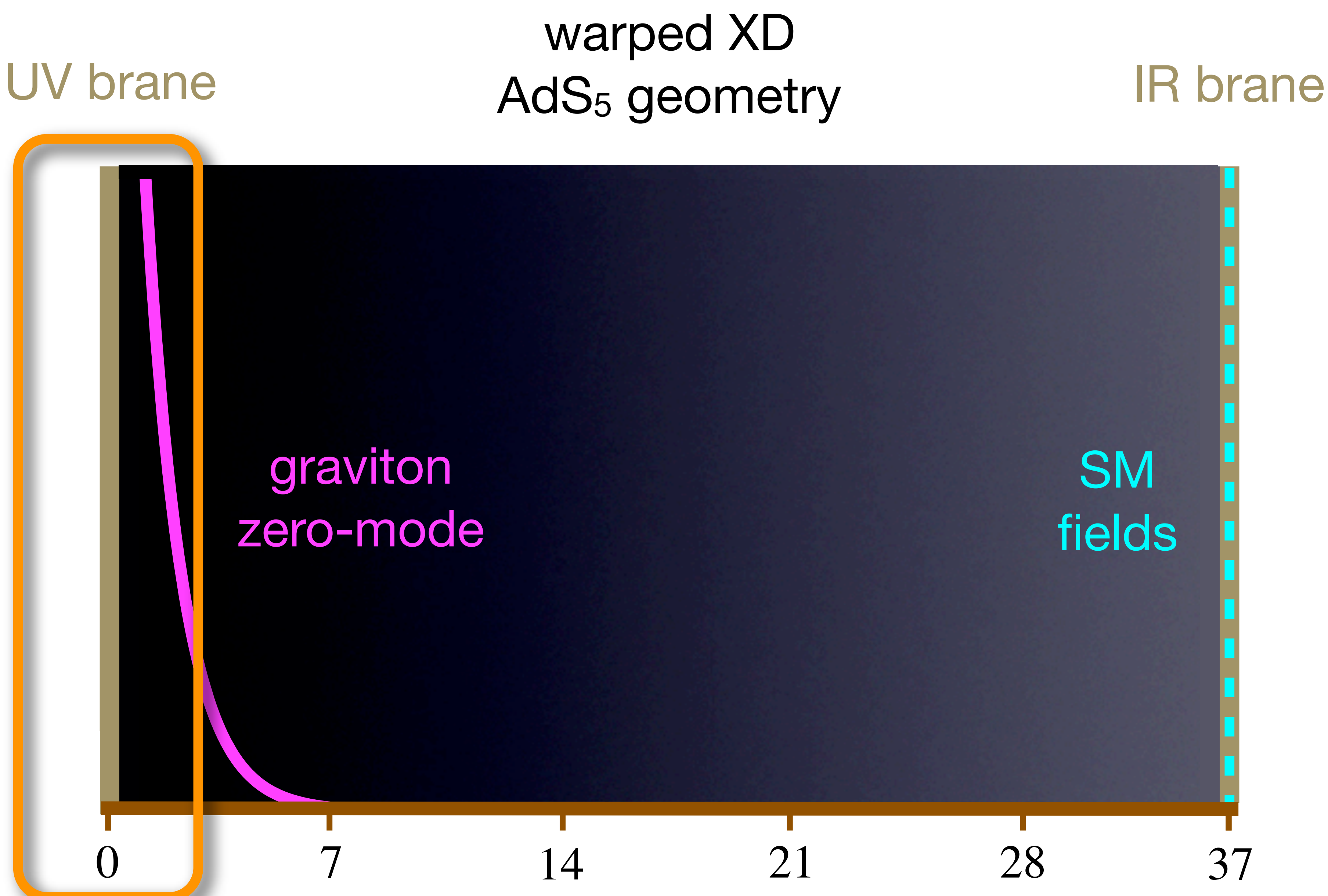
*Delgado, Pomarol & Quiros, hep-ph/9911252

# Flavor problem in flat XDs




- Even if KK modes couple flavor-independent, as in universal XDs (UEDs), huge suppression of $1/\Lambda_{\mathrm{UV}}^2\,(\bar{s}d)(\bar{d}s)$ unnatural since $\Lambda_{\mathrm{UV}} = \mathcal{O}(10/R)$ in flat models

# Problems in RS model with SM on IR brane

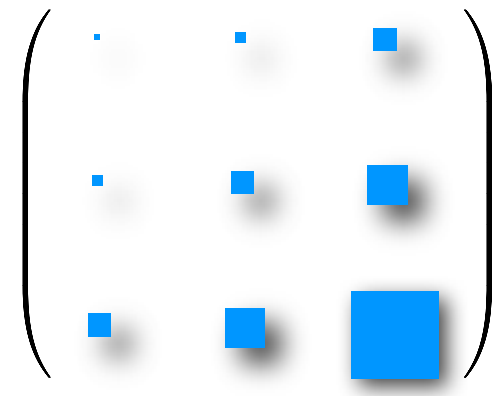



- Fields confined to IR brane feel cut-off scale $\Lambda_{\rm UV} = \text{few TeV}$. Contributions from higher-dimensional operators to $S$, $T$, ... are thus generically much too big

# RS explanation of quark masses and CKM angles*

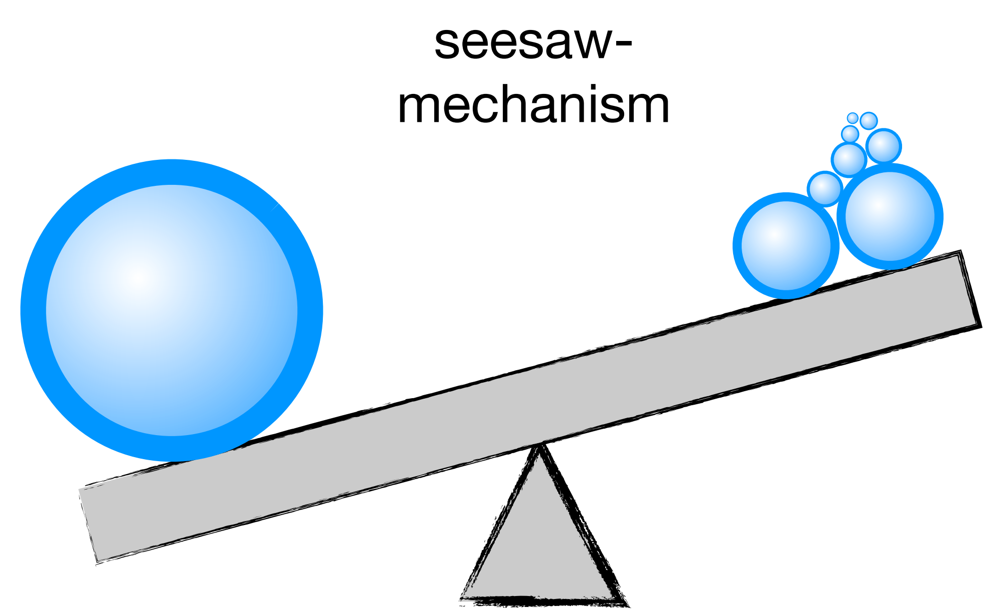
- SM mass matrices can be written as

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



where $\boldsymbol{Y}_q$ with $q = u,d$ structureless, complex Yukawa matrices with elements of order 1, called anarchic, and $F(Q_i) << F(Q_j)$, $F(q_i) << F(q_j)$ for $i < j$

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

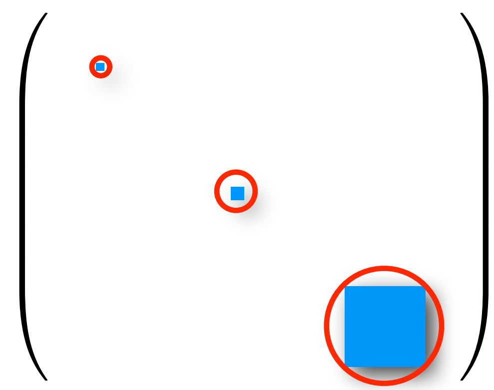



*Huber, hep-ph/0303183

# RS explanation of quark masses and CKM angles*

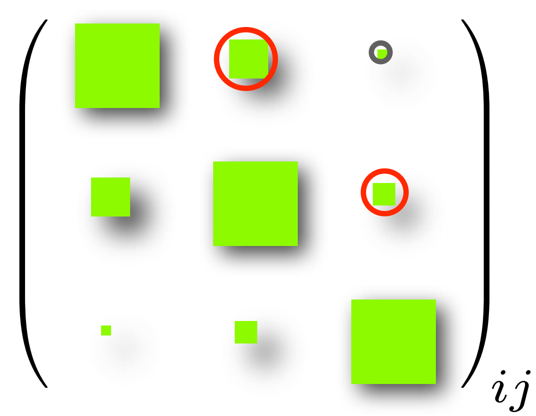
- Thus

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



precisely predicted in RS model

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

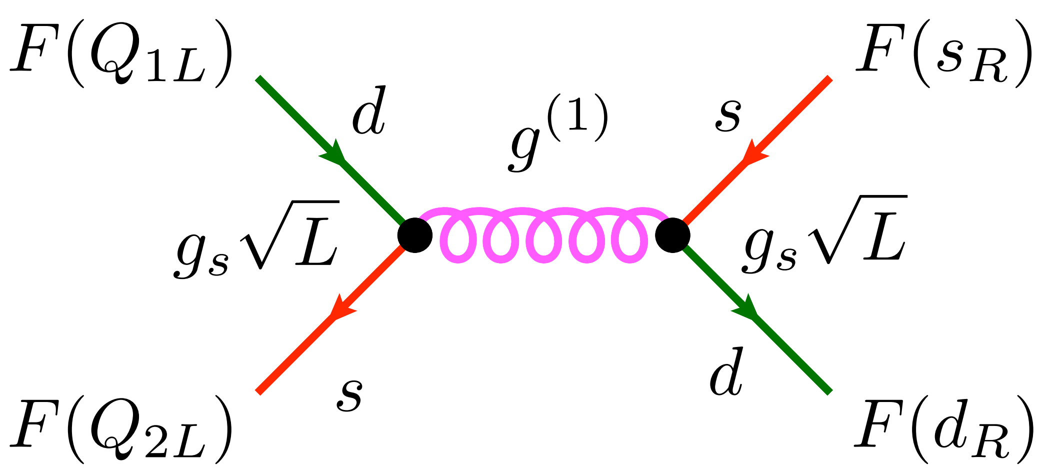


predicted in RS model up to a factor of order 1

- 9 profiles $F(Q_i)$, $F(q_i)$ are chosen so that 8 conditions following from $m_u$, ..., $m_t$ and $(V_{\rm CKM})_{us}$, $(V_{\rm CKM})_{cs}$ are satisfied. Exact amount of CP-violation, which enters element $(V_{\rm CKM})_{ub}$, is predicted in RS model only up to $\mathcal{O}(1)$

*Huber, hep-ph/0303183

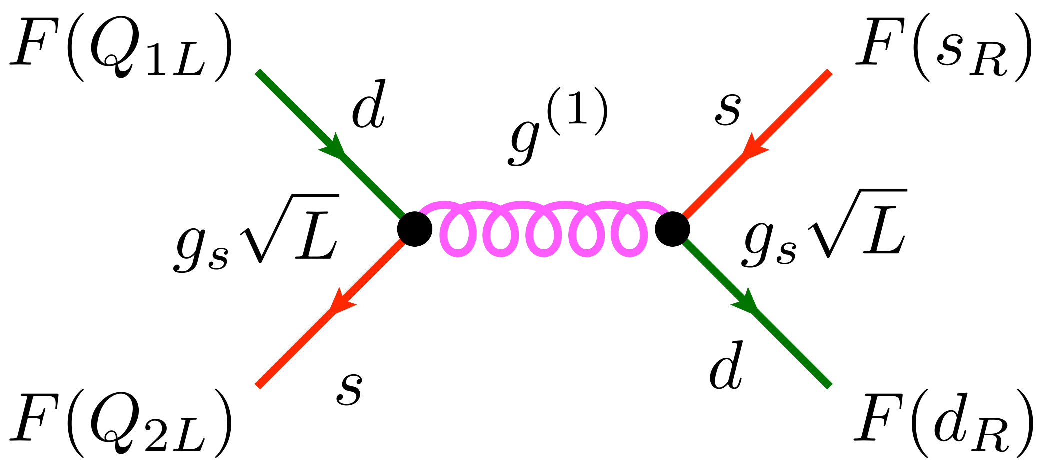
# Quark FCNCs in RS model




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

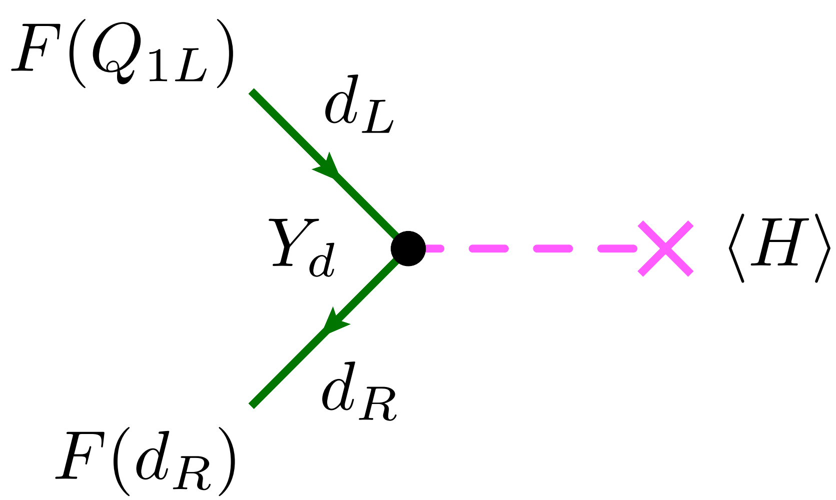
- In RS model, quark FCNCs are already induced at tree level through virtual exchange of *e.g.* KK-gluon excitations ($g^{(1)}$, ...)

# Quark FCNCs in RS model




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

$$\sim \frac{g_s^2}{M_{\mathrm{KK}}^2}\, L\, \frac{m_d m_s}{(vY_d)^2}$$



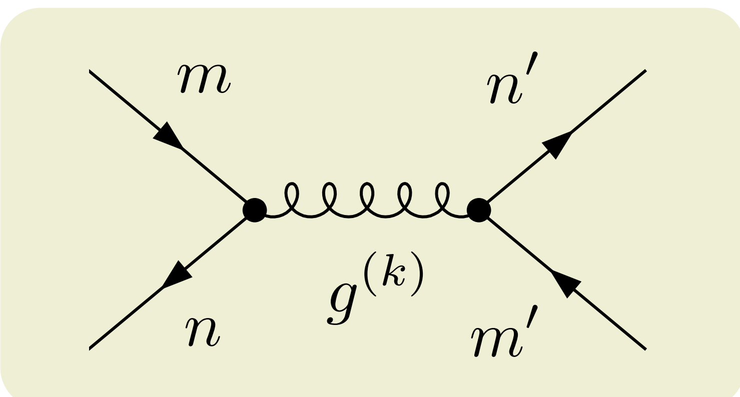

$$m_d \sim v\, F(Q_{1L}) Y_d F(d_R)$$

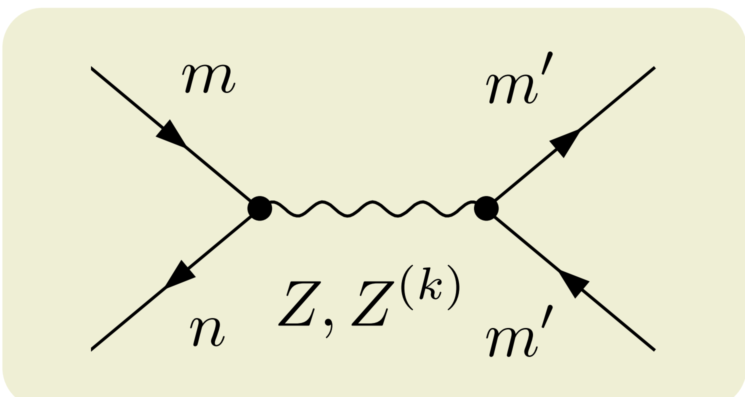
- As flavor-changing vertices depend on same exponentially small overlaps $F(Q_L)$, $F(q_R)$, that generate light quark masses, FCNCs involving quarks of 1st and 2nd family are partially protected. This mechanism is dubbed RS-GIM*

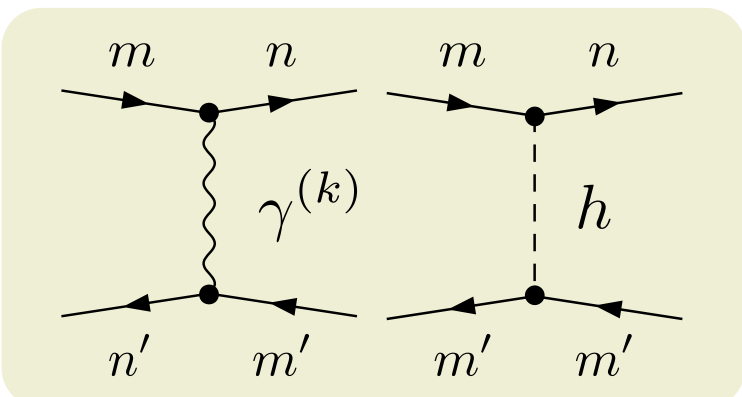
*Agashe, Perez & Soni, hep-ph/0406101, hep-ph/0408134

# 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

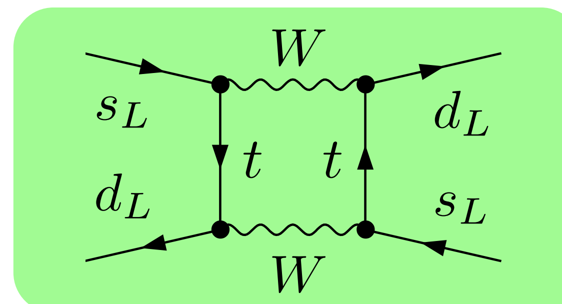
- Like in SM, dimension five dipole-type operators contributing to $B \to X_s\gamma$ or $\mu \to e\gamma$ arise first at one-loop level

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

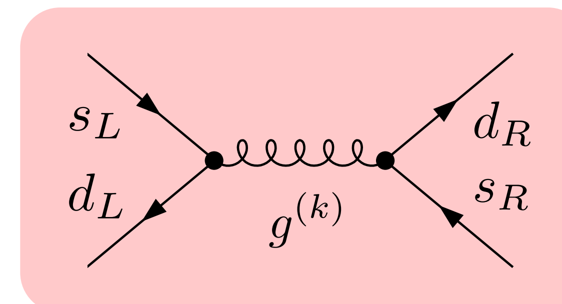
# Meson mixing: Effective Hamiltonian*

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

SM




RS




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

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

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

$$\boxed{\begin{aligned} Q_4 &= (\bar{d}_R^a s_L^a)(\bar{d}_L^b s_R^b)\,,\\ Q_5 &= (\bar{d}_R^a s_L^b)(\bar{d}_L^b s_R^a)\,, \end{aligned}}$$

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

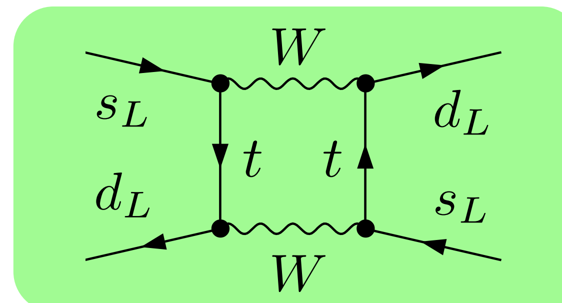
- Contribution from Wilson coefficient of $Q_4$ to CP-violating quantity $\varepsilon_K$ strongly enhanced through renormalization group evolution and chiral factor $(m_K/m_s)^2$ in matrix element:

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

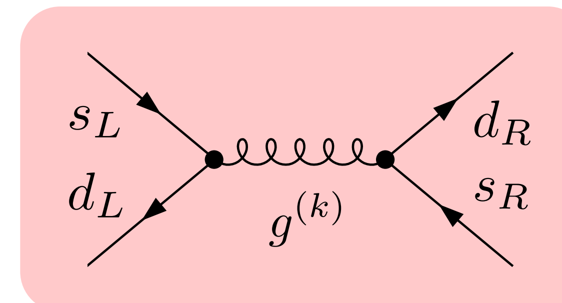
*Csaki, Falkowski & Weiler, arXiv:0804.1954; Blanke *et al.*, arXiv:0809.1073; Bauer *et al.*, arXiv:0811.3678

# Meson mixing: Effective Hamiltonian*

SM




RS




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

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

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

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

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

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

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

$$C_{1,K}^{\text{RS}} \sim \frac{4\pi L}{M_{\text{KK}}^2}\left[\frac{\alpha_s}{3} + 1.12\,\alpha\right] F^2(Q_{1L})F^2(Q_{2L})\,,$$

$$C_{4,K}^{\text{RS}} \sim \frac{4\pi L}{M_{\text{KK}}^2}\,[-2\alpha_s]\; F(Q_{1L})F(d_R)F(Q_{2L})F(s_R)$$

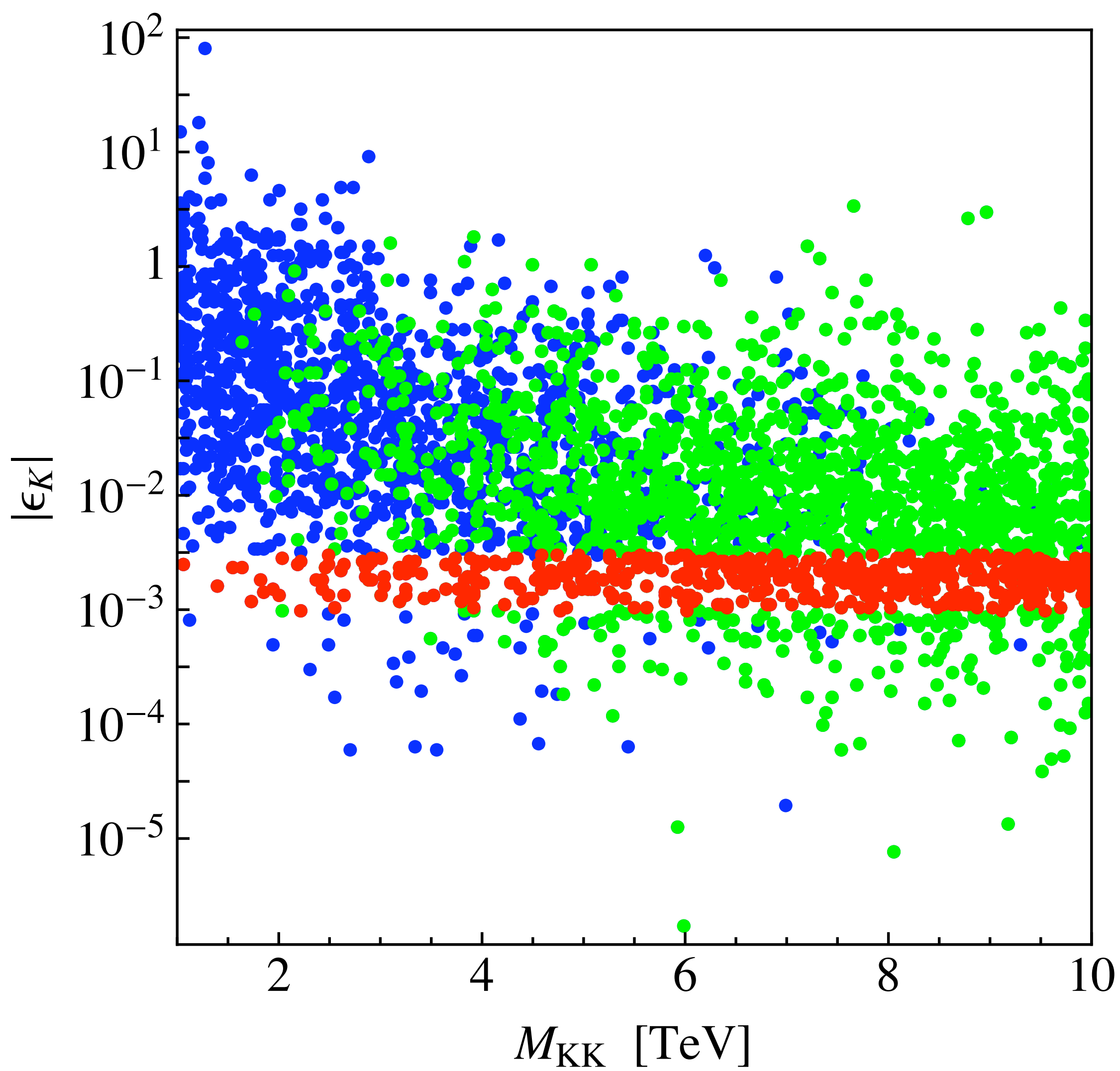
$$\sim \frac{4\pi L}{M_{\text{KK}}^2}\,[-2\alpha_s]\,\frac{2\,m_d m_s}{(vY_d)^2}$$

- Size of $C_{4,K}^{\text{RS}}$ can be reduced (enhanced) by making $L$ ($Y_d$) smaller (larger)

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

# Meson mixing: Neutral kaons*

- Generically $|\varepsilon_K|/|\varepsilon_K|_{\rm exp} = \mathcal{O}(50)$ in RS model with $|\varepsilon_K|_{\rm exp} = (2.23 \pm 0.01) \cdot 10^{-3}$. But $|\varepsilon_K| \approx |\varepsilon_K|_{\rm exp}$ possible even for $M_{\rm KK} = 1$ TeV after percent tuning



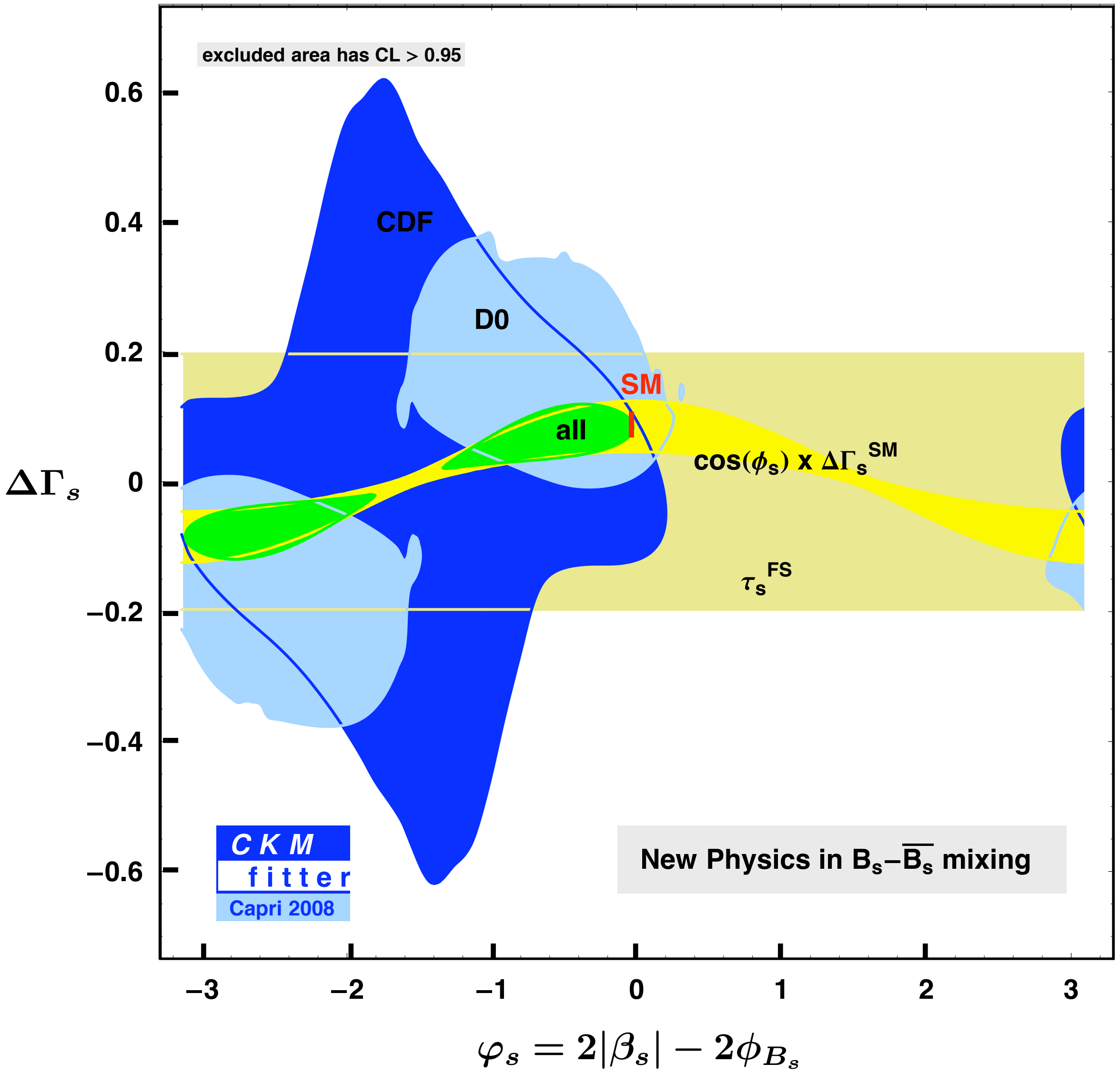

3000 randomly chosen RS points with $|Y_q| < 3$ reproducing quark masses and CKM parameters with $\chi^2/\text{dof} < 11.5/10$ corresponding to 68% CL

- 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:09xx.xxxx

# 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




CKMfitter combination:

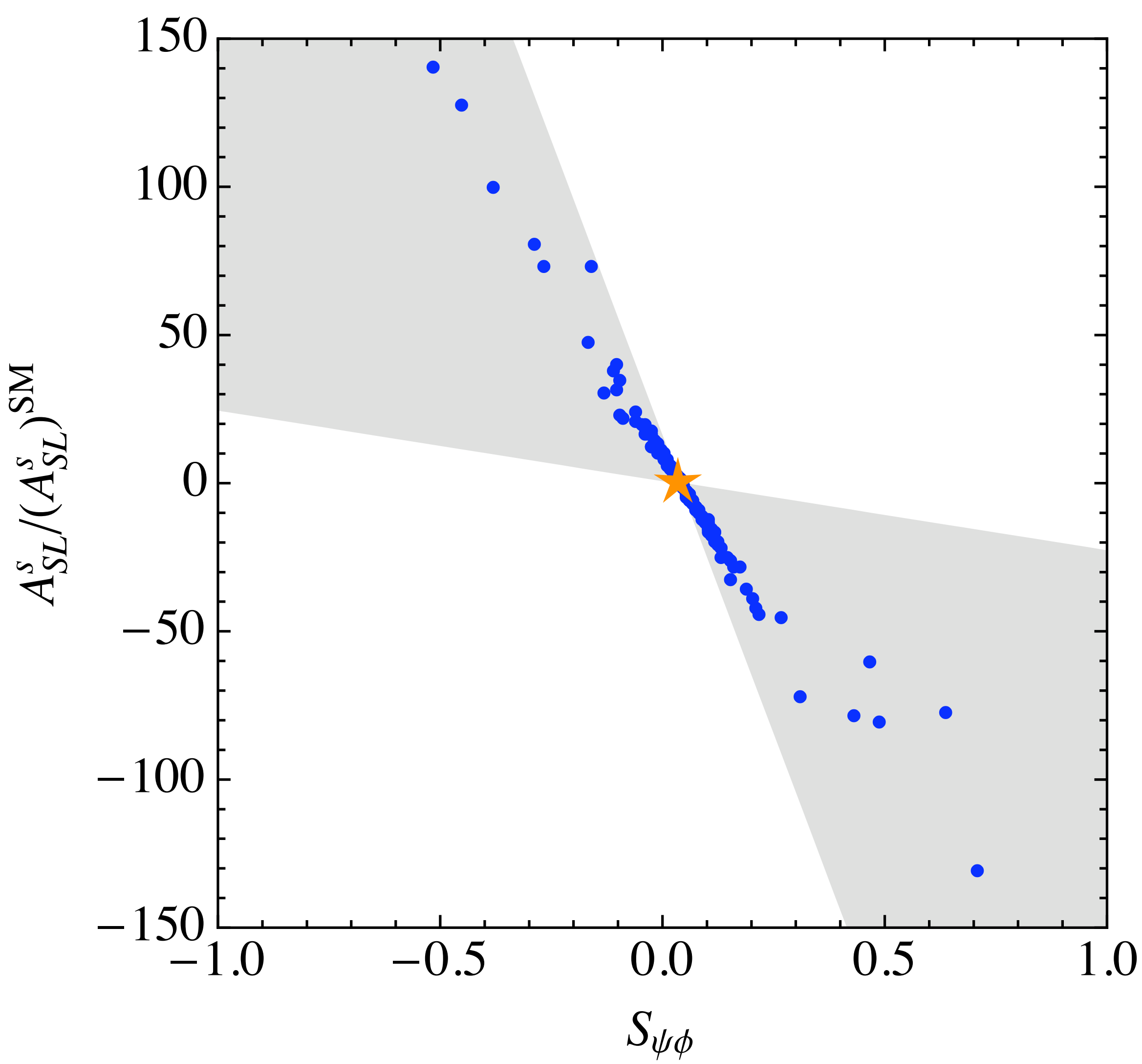
- CDF data only $2.1\sigma$
- DØ data only $1.9\sigma$
- CDF and DØ data $2.7\sigma$
- full BSM physics fit $2.5\sigma$

Discrepancy of $\varphi_s = 2|\beta_s| - 2\phi_{B_s}$ with respect to SM value $\varphi_s \approx 2_\circ$ at around $2\sigma$ 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*

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

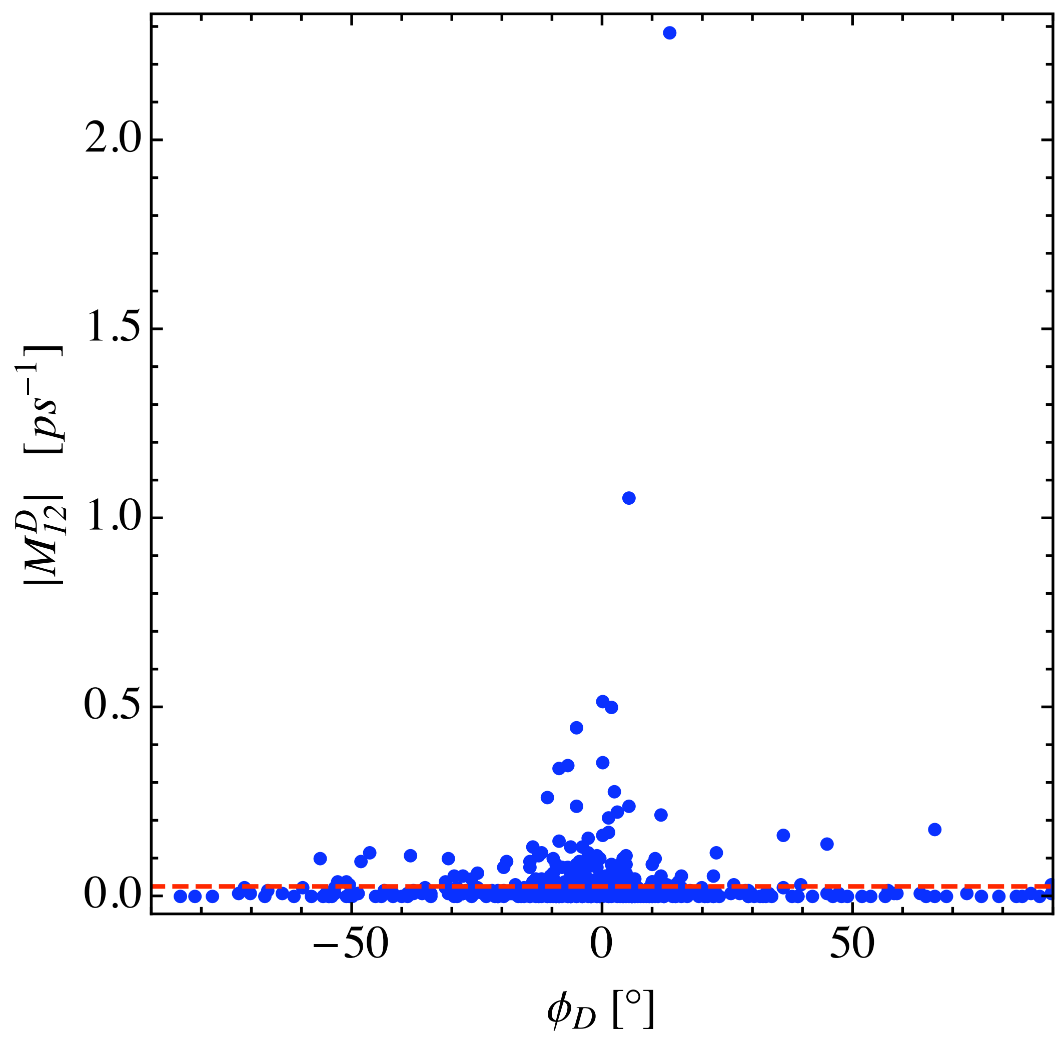
■ model-independent prediction

● 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.*, arXiv:09xx.xxxx

# Meson mixing: Neutral $D$ mesons*

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



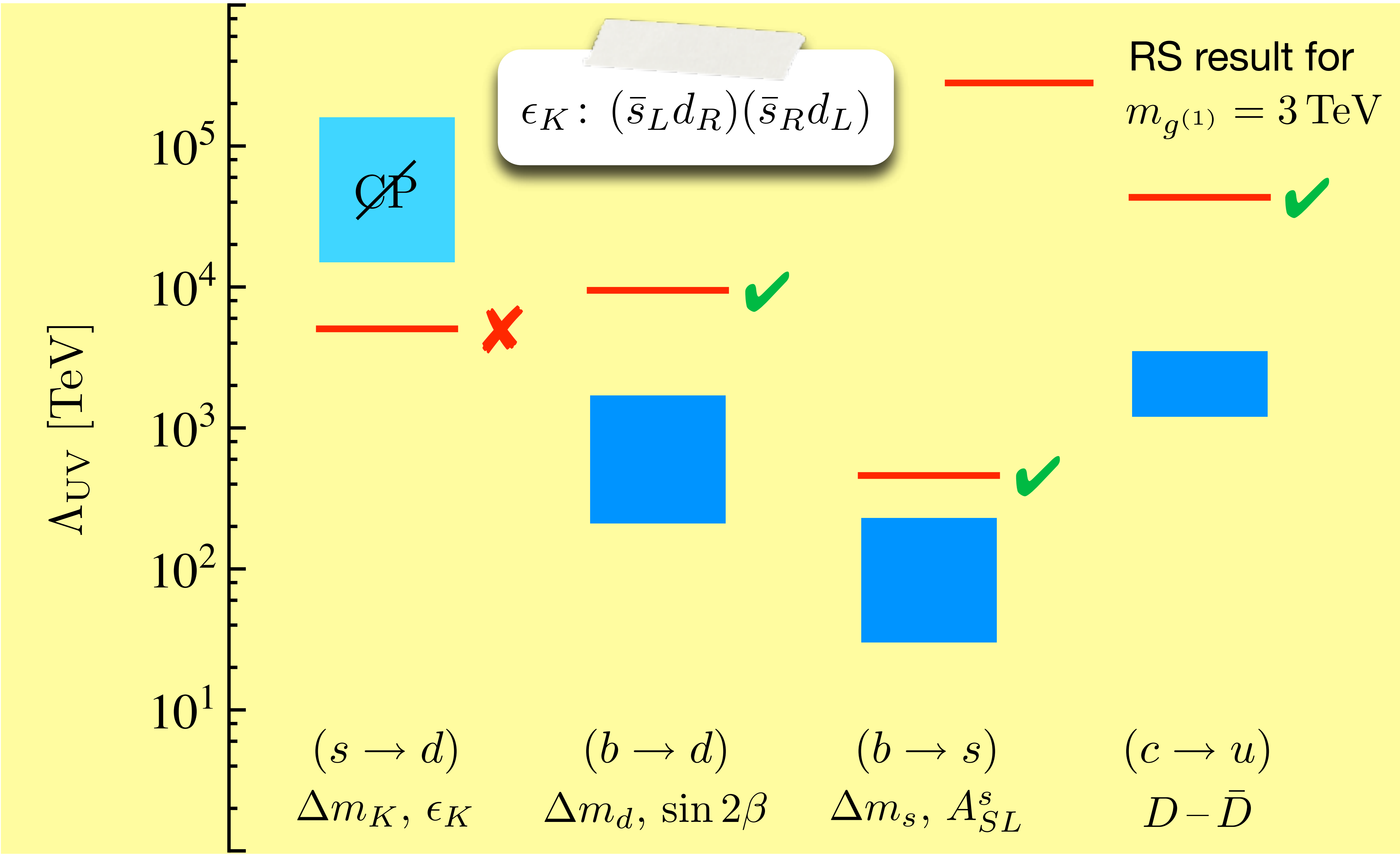

$$(M_{12}^D)^* = \langle \bar{D} | \mathcal{H}_{\text{eff,RS}}^{\Delta C=2} | D \rangle$$
$$= |M_{12}^D| \, e^{2i\phi_D}$$

- - maximal allowed SM effect with no significant CP phase

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

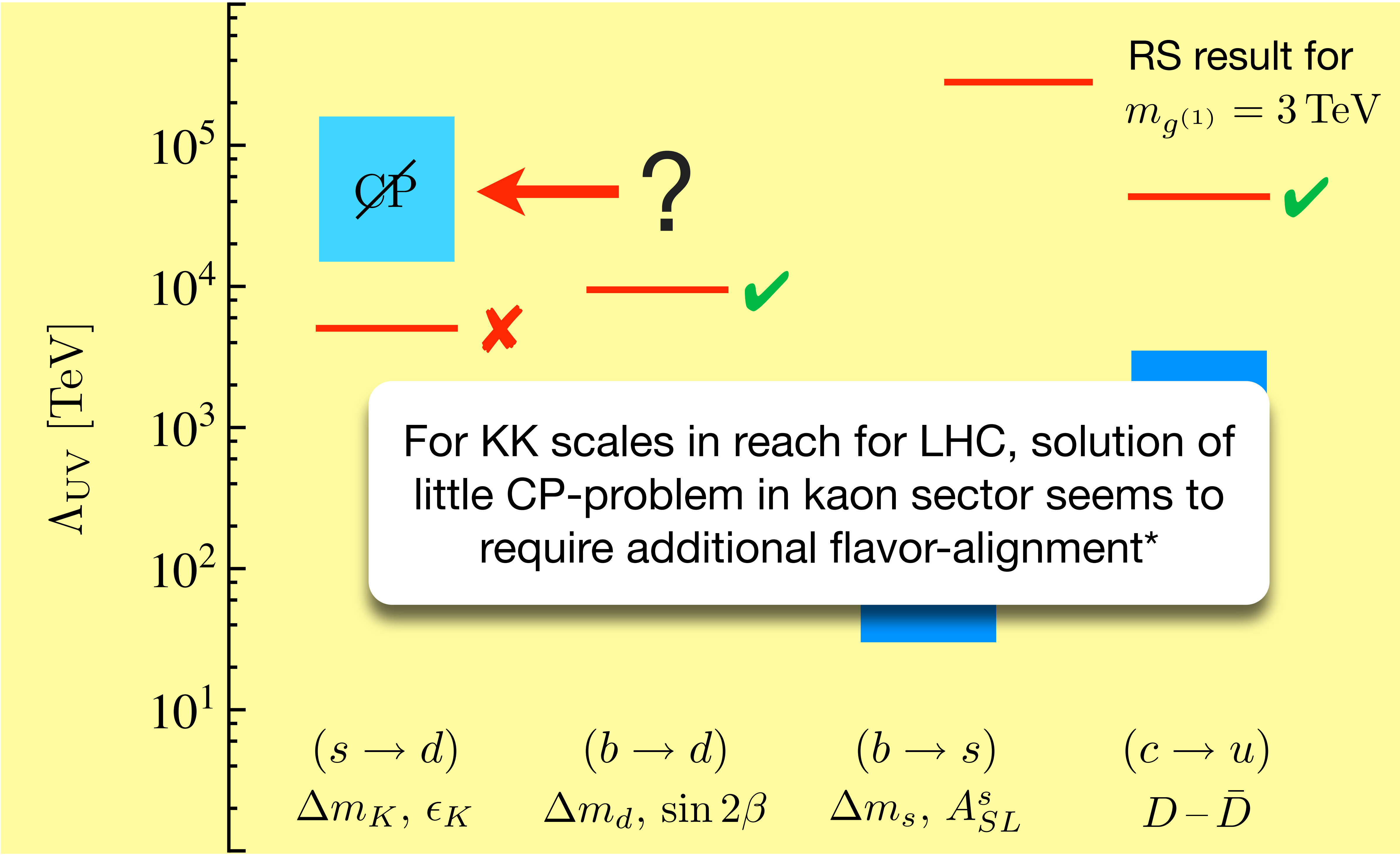
*Bauer *et al*., arXiv:09xx.xxxx

# $\Delta F = 2$ sector: RS model almost works*




*Csaki, Falkowski & Weiler, arXiv:0804.1954

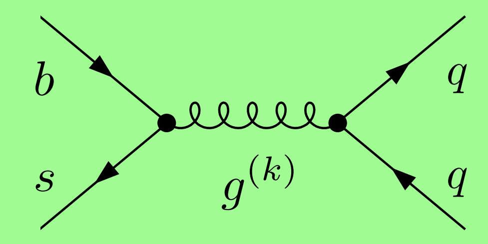
# $\Delta F = 2$ sector: RS model almost works*

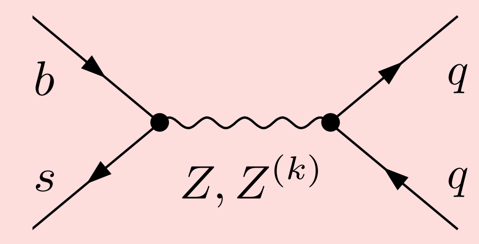



*Fitzpatrick *et al.*, arXiv:0710.1869; Santiago, arXiv:0806.1230; Csaki *et al.*, arXiv:0709.1714, arXiv:0806.3757, arXiv:0907.0474

# Rare decays: Effective Hamiltonian*

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




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

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

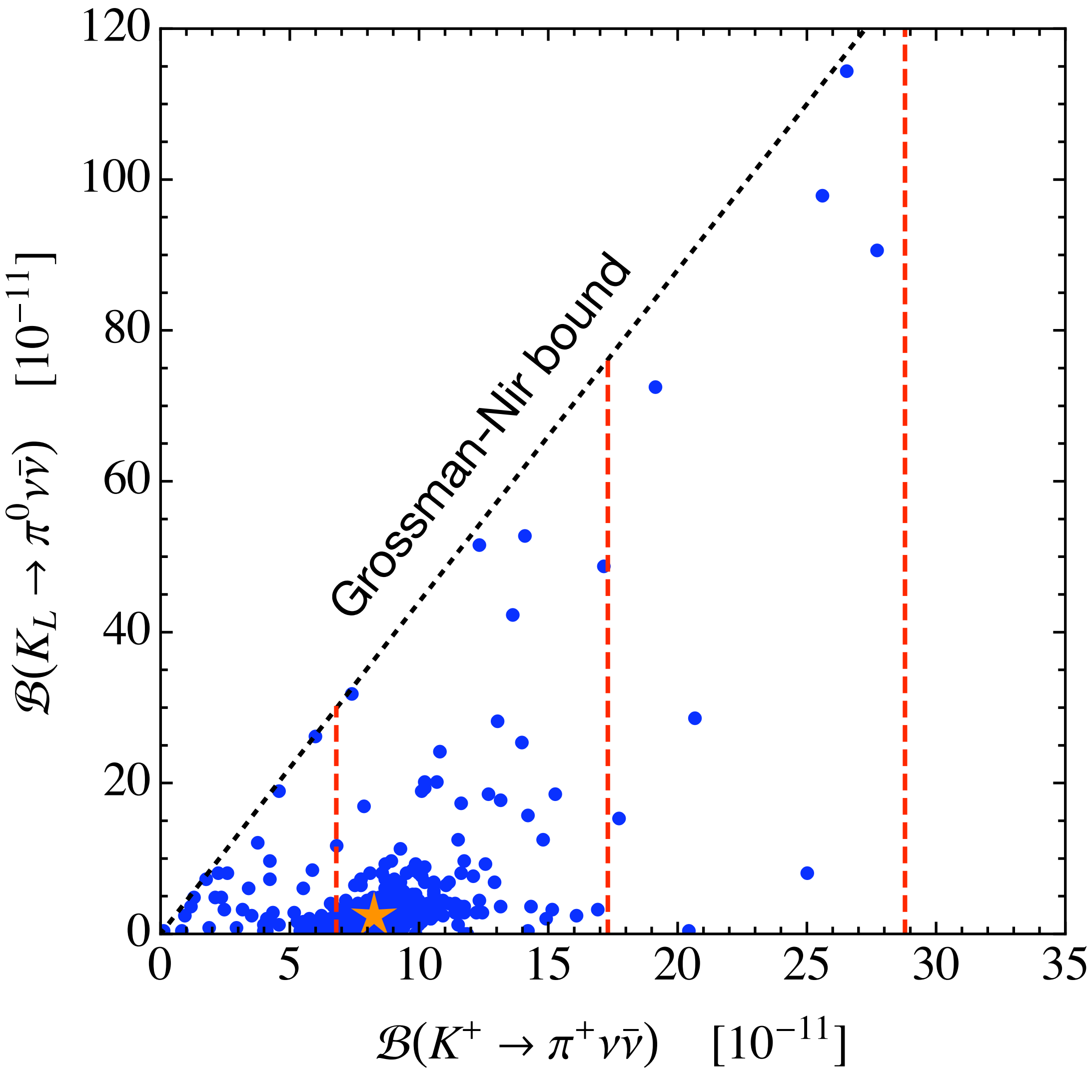
$$\tilde{Q}_{3-10} : L \leftrightarrow R$$

- 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

*Blanke *et al.*, arXiv:0812.3803; Bauer *et al.*, arXiv:09xx.xxxx

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

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

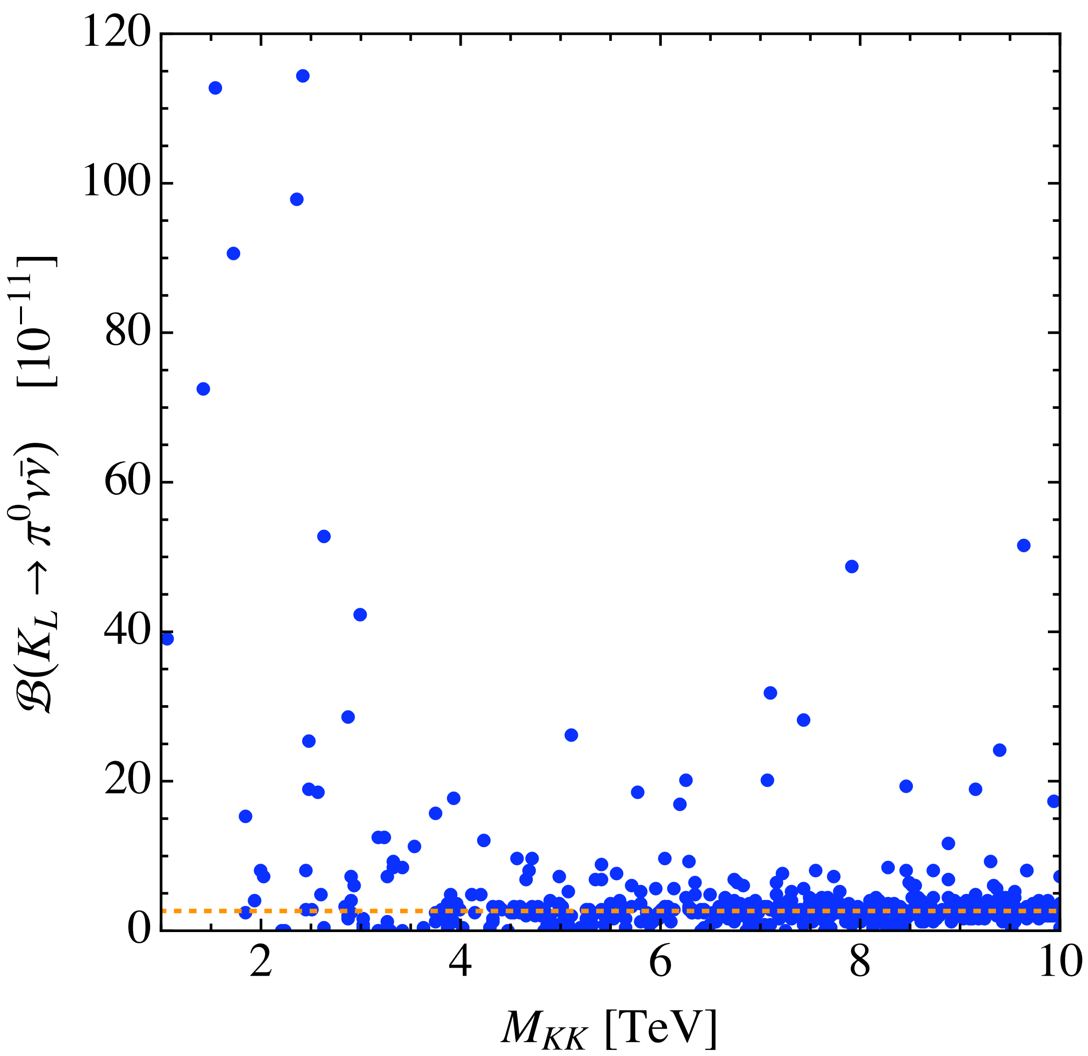
- - central value and 68% CL limit $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \cdot 10^{-11}$ from E949

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

*Grossman & Nir, hep-ph/9701313; Bauer *et al.*, arXiv:09xx.xxxx

# 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 terascale




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

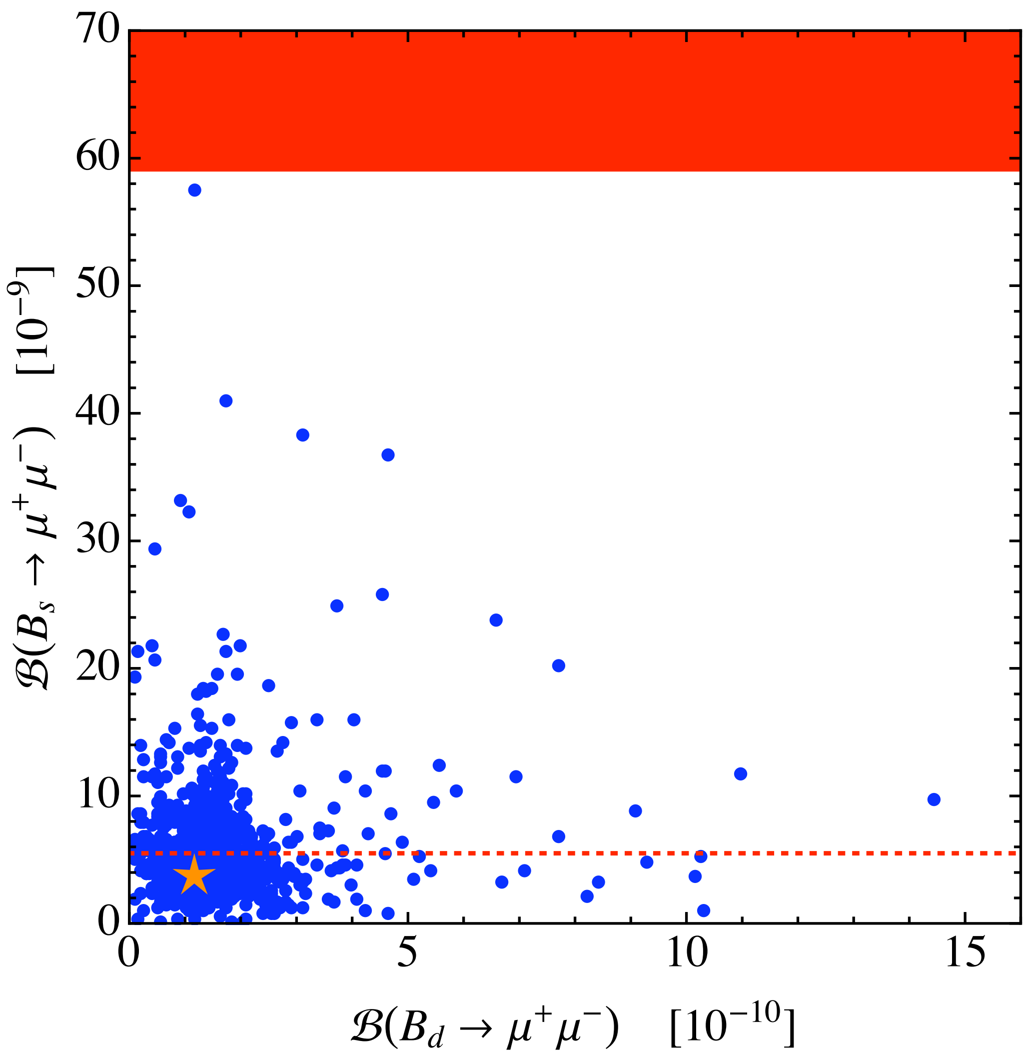
SM: $\mathcal{B}(K_L \to \pi^0 \nu \bar{\nu}) \approx 2.7 \cdot 10^{-11}$

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

*Bauer *et al.*, arXiv:09xx.xxxx

# Rare $B$ decays: Purely leptonic modes*

- Factor ten 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 $5\sigma$ discovery by LHCb, $2\ \mathrm{fb}^{-1}$

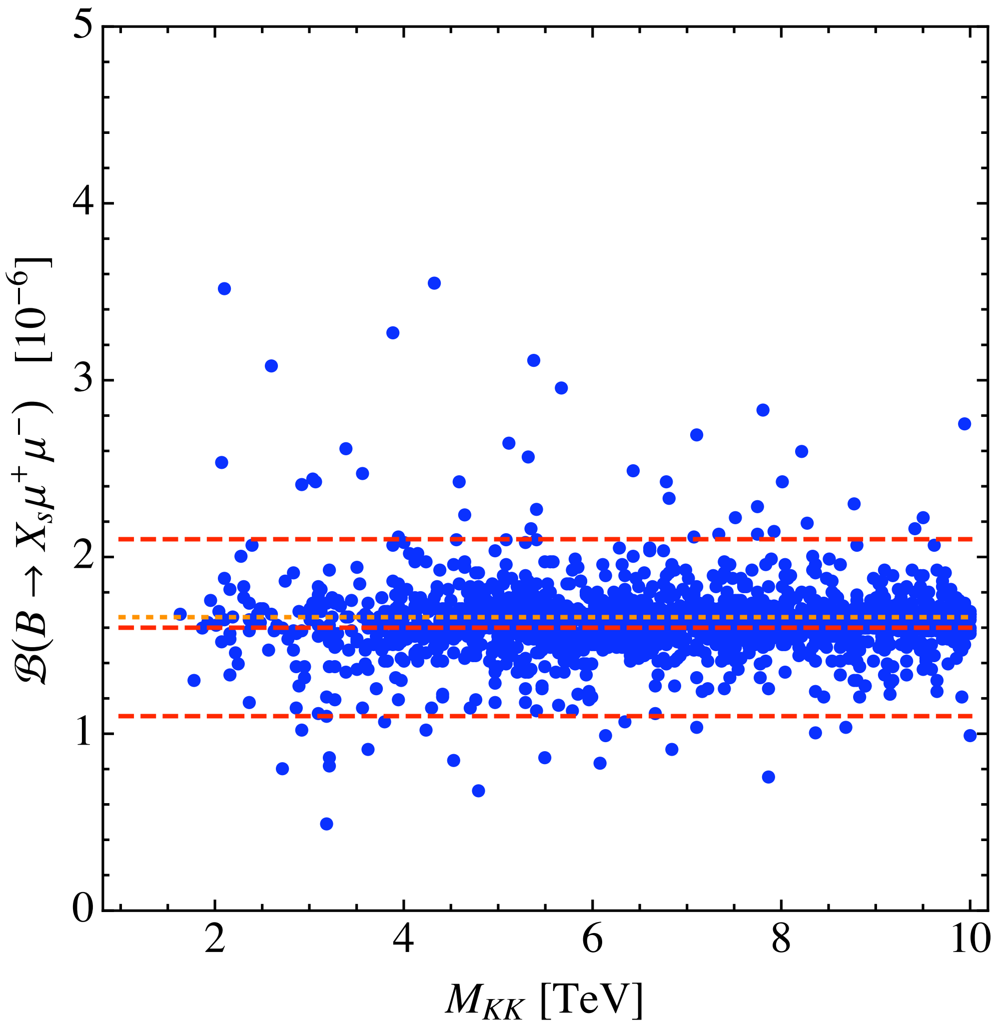
$95\%$ CL upper limit from CDF $\mathcal{B}(B_s \to \mu^+\mu^-) < 5.8 \cdot 10^{-8}$

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

*Bauer *et al.*, arXiv:09xx.xxxx

# Rare $B$ decays: Inclusive semileptonic modes*

- Once $Z \to b\bar{b}$ constraint is 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$^2$

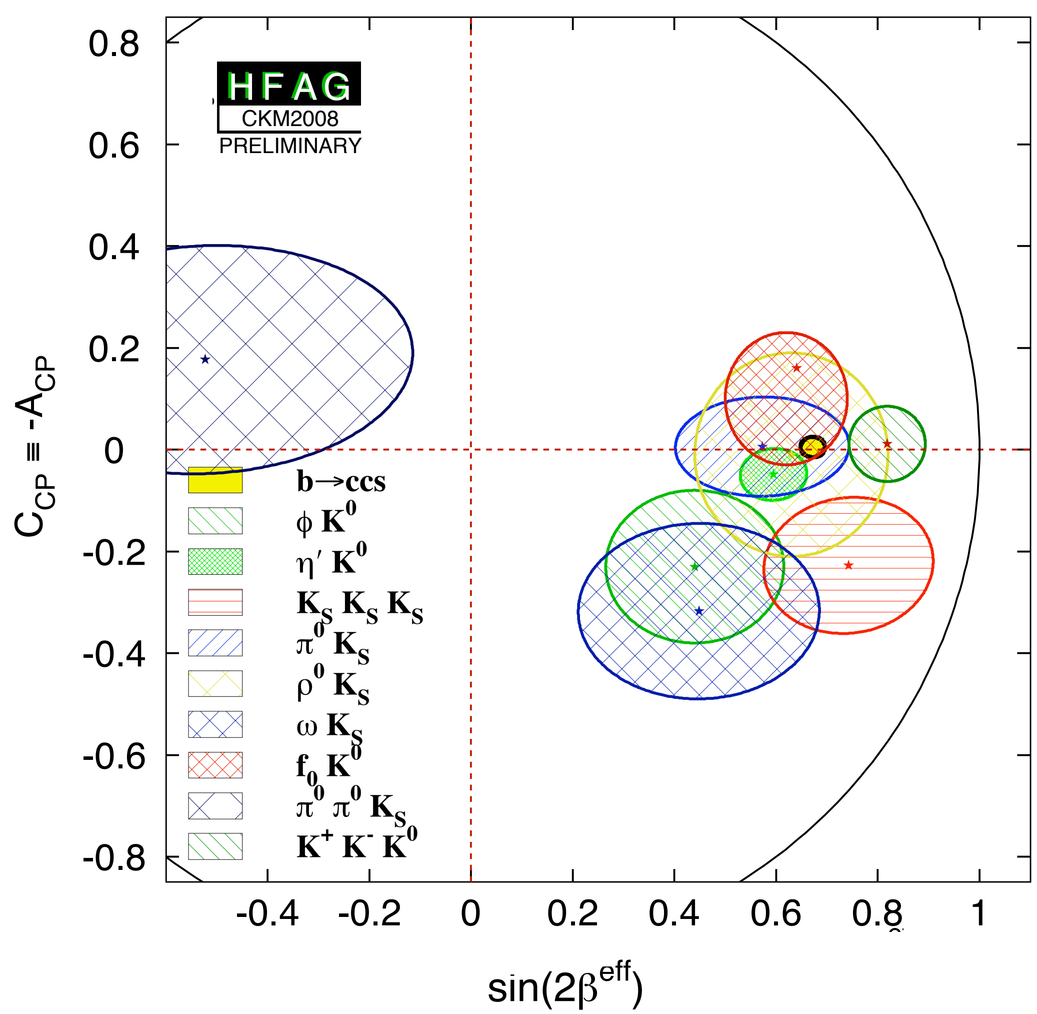
central value and 68% CL limit $\mathcal{B}(B \to X_s \mu^+\mu^-) = (1.6 \pm 0.5) \cdot 10^{-6}$ from BaBar and Belle

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

*Bauer *et al.*, arXiv:09xx.xxxx

# Non-leptonic $B$ and $K$ decays*

- Electroweak penguin effects in rare hadronic decays such as $B \to K\pi$ or $B \to \phi K$ can be of same size as SM contributions and can introduce new large CP-violating phases. Similar effects can occur in $K \to \pi\pi$



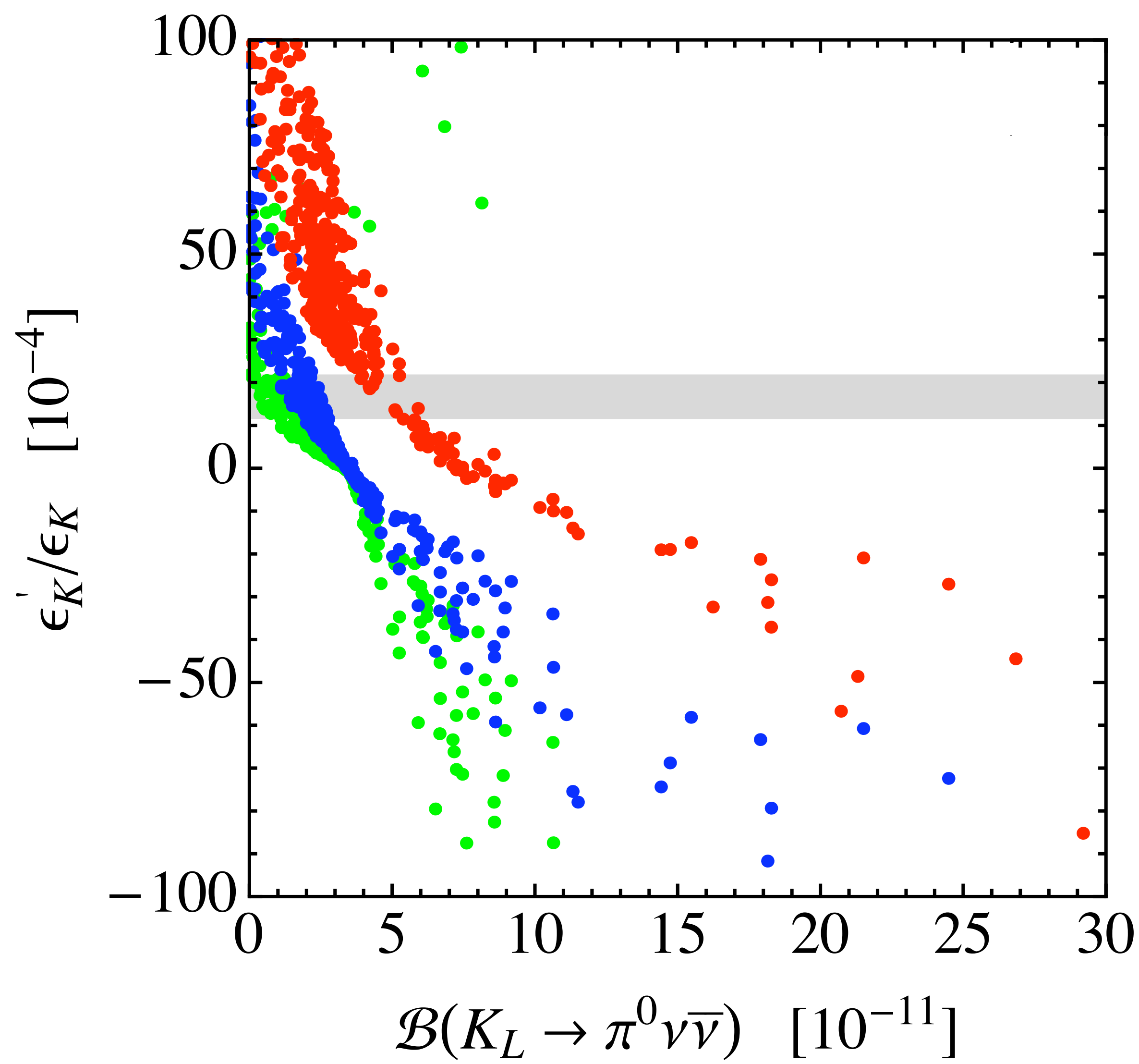

<u>Potentially relevant for:</u>

- explaining large CP asymmetries in $B \to K\pi$ and determining of $\sin(2\beta^{\rm eff})$ from penguin-dominated modes
- studying of 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.*, arXiv:09xx.xxxx

# 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
- central
- lower value

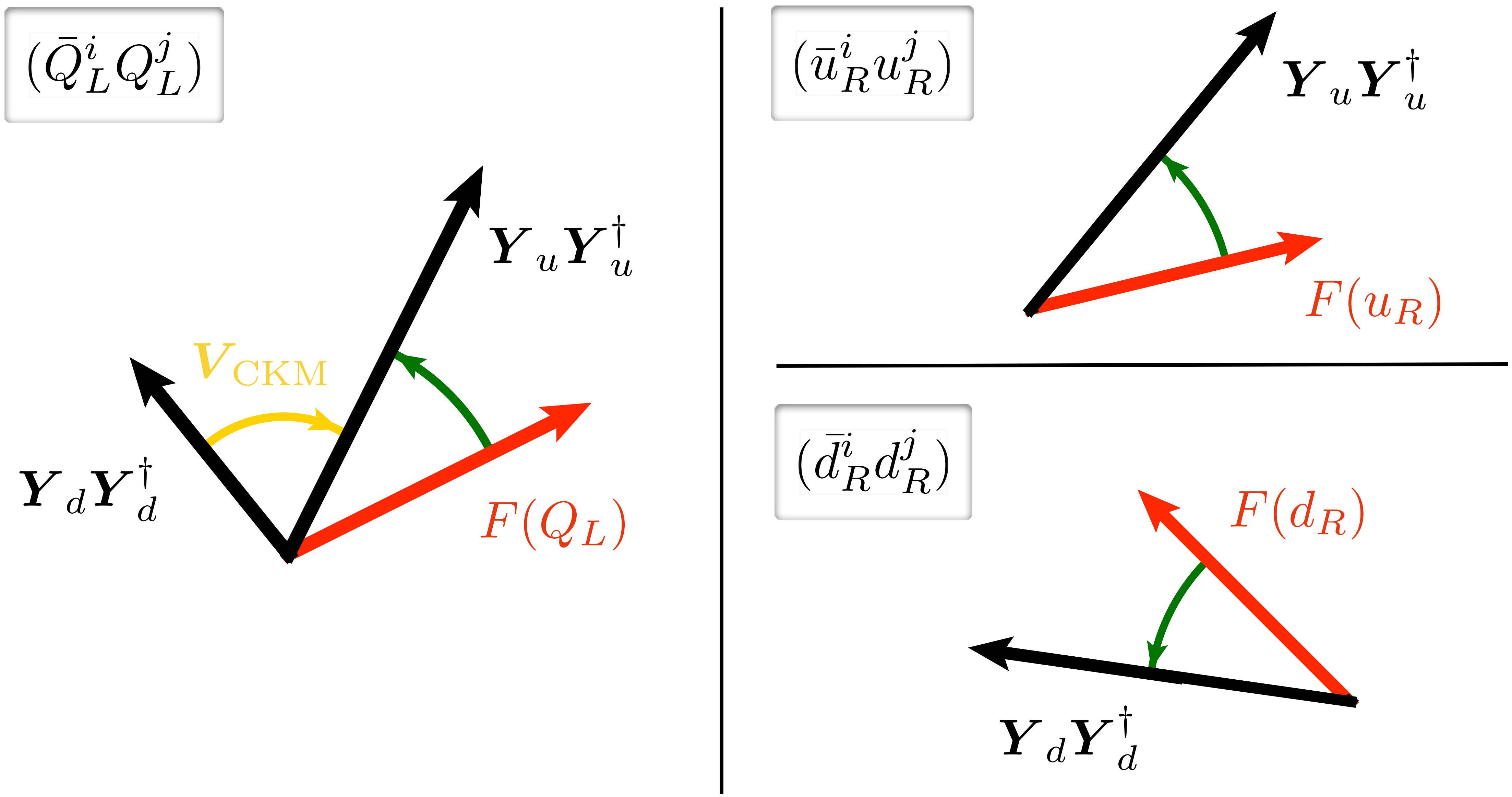
consistent with quark masses, CKM parameters, and 95% CL limit $|\varepsilon_K| \in [1.3, 3.3] \cdot 10^{-3}$

*Bauer *et al.*, arXiv:09xx.xxxx

# Conclusions

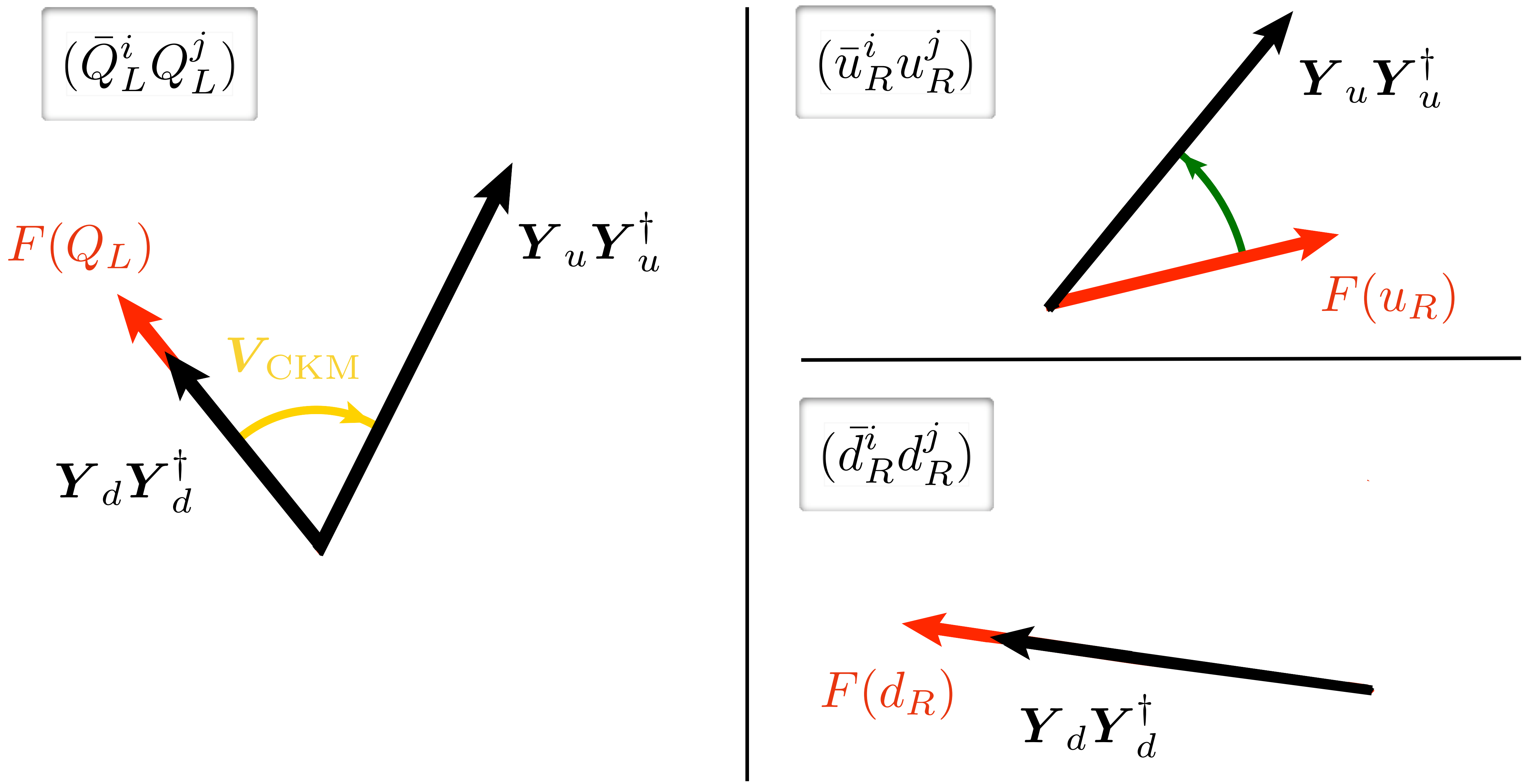
- LHC is there (maybe, sometime soon ...), but LHC discoveries alone unlikely to allow for full understanding of new phenomena observed
- Flavor physics can play key role in this respect, since it offers unique window to BSM physics at and beyond terascale
- Warped extra dimensions offer compelling geometrical 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
- Flavor-anarchy models need tuning to survive constraints from CP-violation in kaon sector, which calls for additional flavor structure

# Remarks on flavor alignment in RS models




- In case of flavor-anarchy, $F(Q_L)$, $F(q_R)$ are not aligned with $\boldsymbol{Y}_q \boldsymbol{Y}_q^\dagger$ which are only source of flavor-breaking in SM. This misalignment leads to FCNCs

# Remarks on flavor alignment in RS models




- Most dangerous contributions, *i.e.*, those that plague $\varepsilon_K$, can be tamed by aligning down-type quark sector. Up-type quark sector remains misaligned

# Remarks on flavor alignment in RS models*

- Suitable alignment is realized if

$$\boldsymbol{c}_Q \sim \boldsymbol{Y}_d \boldsymbol{Y}_d^\dagger + \epsilon \, \boldsymbol{Y}_u \boldsymbol{Y}_u^\dagger \,, \qquad \boldsymbol{c}_d \sim \boldsymbol{Y}_d \boldsymbol{Y}_d^\dagger \,, \qquad \boldsymbol{c}_u \sim \boldsymbol{Y}_u \boldsymbol{Y}_u^\dagger$$

  and $\varepsilon \to 0$

- Latter conditions can be achieved by introducing a gauged $SU(3)_Q \times SU(3)_d$ bulk flavor group and promoting $F(Q_L)$, $F(d_R)$ to dynamical dofs

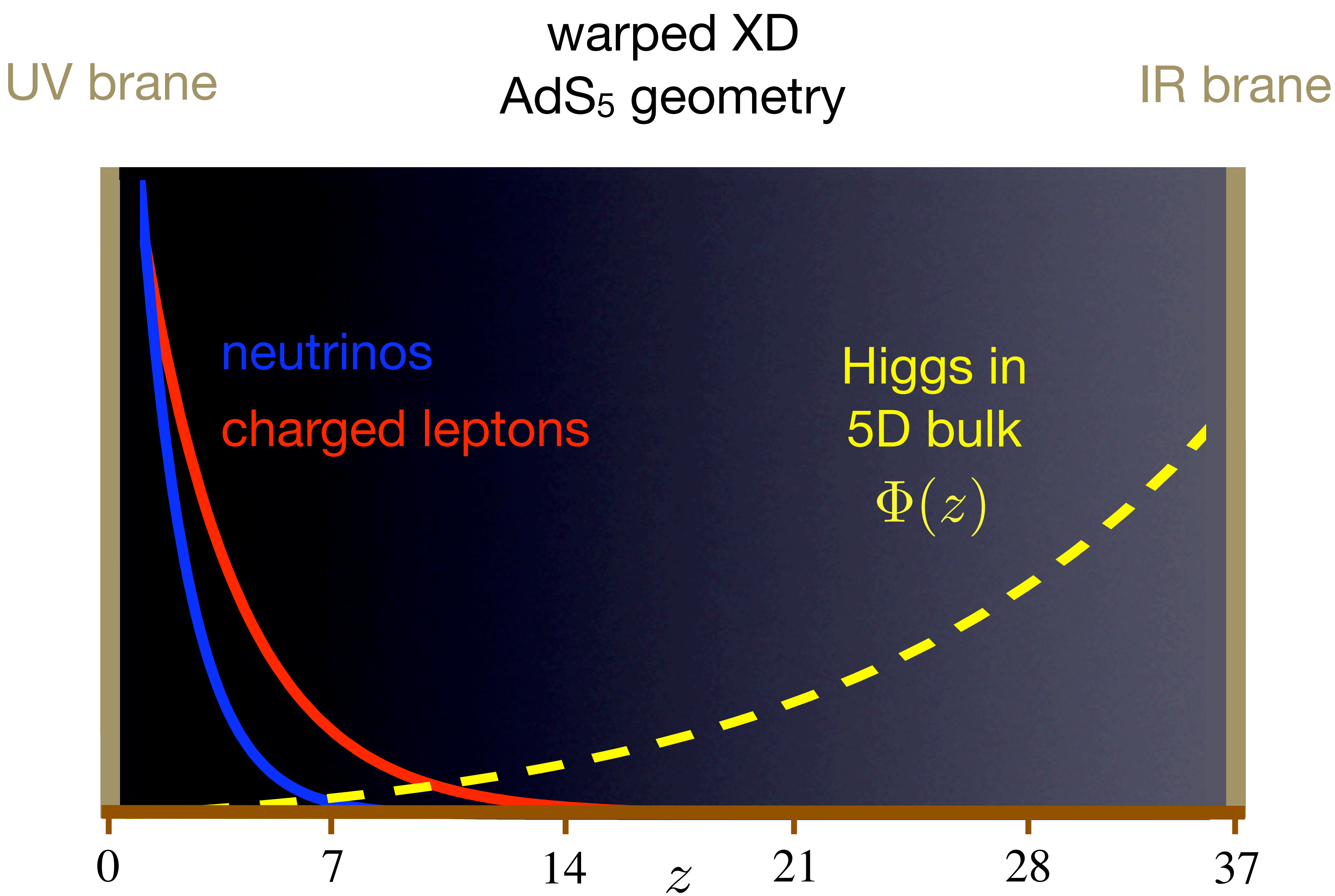
$$F(Q_L) = F(\boldsymbol{Y}_{*d} \boldsymbol{Y}_{*d}^\dagger) \,, \qquad F(d_R) = F(\boldsymbol{Y}_{*d}^\dagger \boldsymbol{Y}_{*d})$$

- Symmetry broken by vacuum expectation value of bulk field $\boldsymbol{Y}_{*d}$ on UV brane. Shining via marginal operator guarantees that flavor-breaking remains small

- Since aligning both down- and up-type quark sector simultaneously is not possible, CP-violating effects in $D$ system are expected in such a set-up

*Rattazzi & Zaffaroni, hep-th/0012248; Fitzpatrick *et al.*, arXiv:0710.1869; Csaki *et al.*, arXiv:0907.0474

# Remarks on leptons in RS models*




- Neutrino wave function picks up UV tail of Higgs. Exponential suppression of overall mass scale, but $\mathcal{O}(1)$ neutrino mixing angles, as required by experiment

*Agashe, Sundrum & Okui, arXiv:0810.1277

# Remarks on leptons in RS models*

$$\left(Y_{4\mathrm{D}}\right)_{ij} \sim \int_0^L dz\, \left(Y_{5\mathrm{D}}(z)\right)_{ij}\, e^{-(M_{L_i}+M_{R_j})z+M_H(z-L)}$$

$M_{L_i} + M_{R_j} > M_H$

$M_{L_i} + M_{R_j} < M_H$

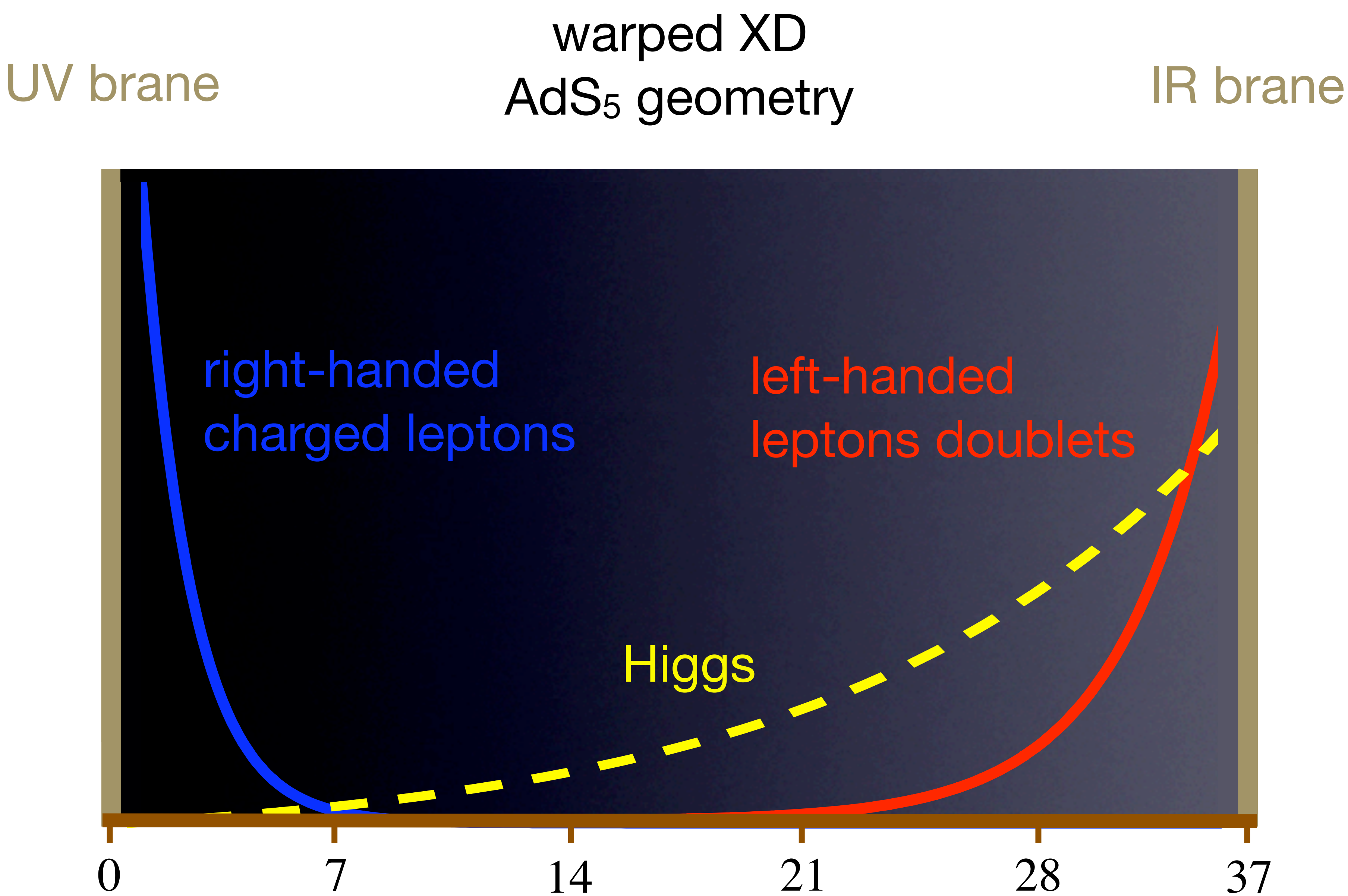
$$\sim \left(\tilde{Y}_0\right)_{ij} e^{-M_H L} \quad \ll \quad \sim \left(\tilde{Y}_L\right)_{ij} e^{-(M_{L_i}+M_{R_j})L}$$

for $M_H < \infty$, Dirac neutrinos can be implemented in this way by choosing $M_{\nu_{R_j}}$ sufficiently large

charged leptons are implemented in this way; *btw.* only possibility for brane-Higgs, *i.e.*, $M_H \to \infty$

*Agashe, Sundrum & Okui, arXiv:0810.1277

# Remarks on leptons in RS models*




- Smallness of Majorana $m_\nu$ due to its non-renormalizable origin, $1/\Lambda_M\,(L_L\Phi)^2$, and leaning left- (right-) handed charged leptons toward (away from) Higgs

*Agashe, Sundrum & Okui, arXiv:0810.1277

# Large hierarchy from gravitational red-shifting

- Metric of Black Hole (BH) is given as function of radial component $r$ by

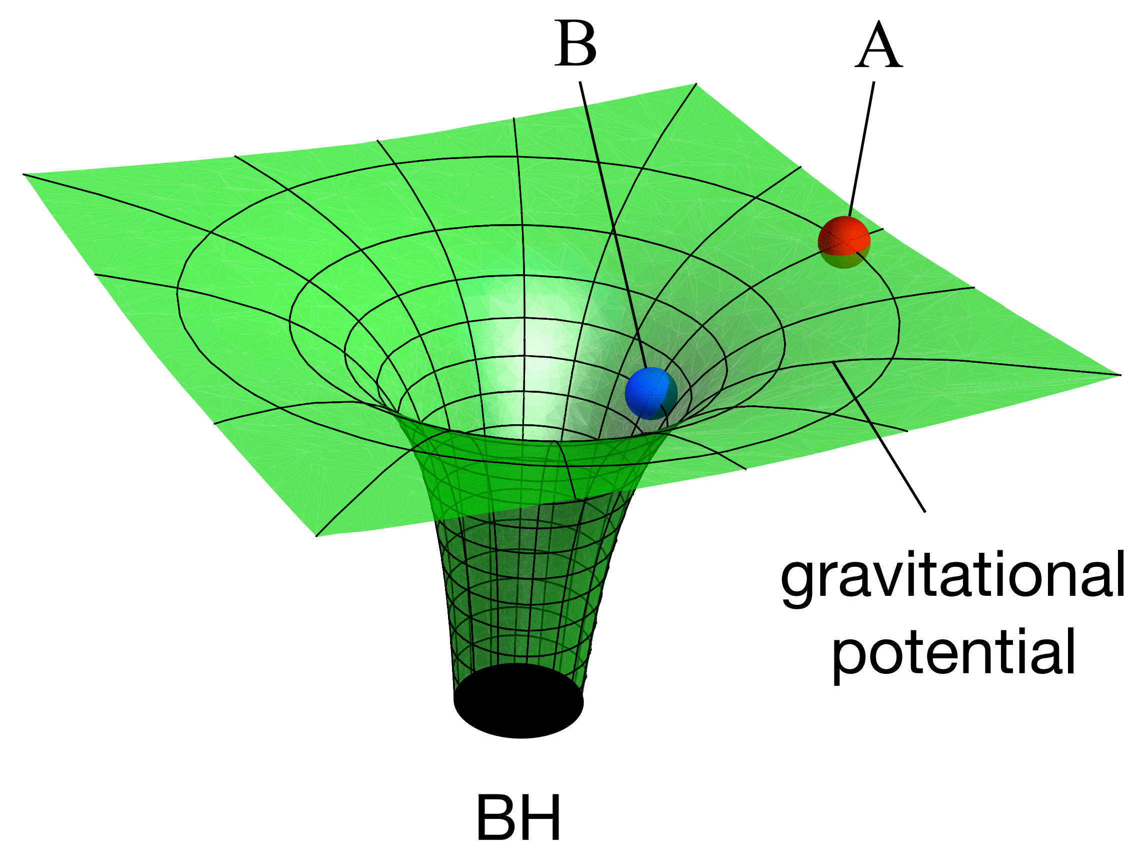
$$g_{00} = -1 + \frac{2G_N M}{r} = -1 + \frac{r_s}{r}$$

where $M$ denotes mass of BH and $G_N = M_{\rm Pl}^{-2} = 6.7 \cdot 10^{-39}\ \mathrm{GeV}^{-2}$

- Ratio of frequencies reads

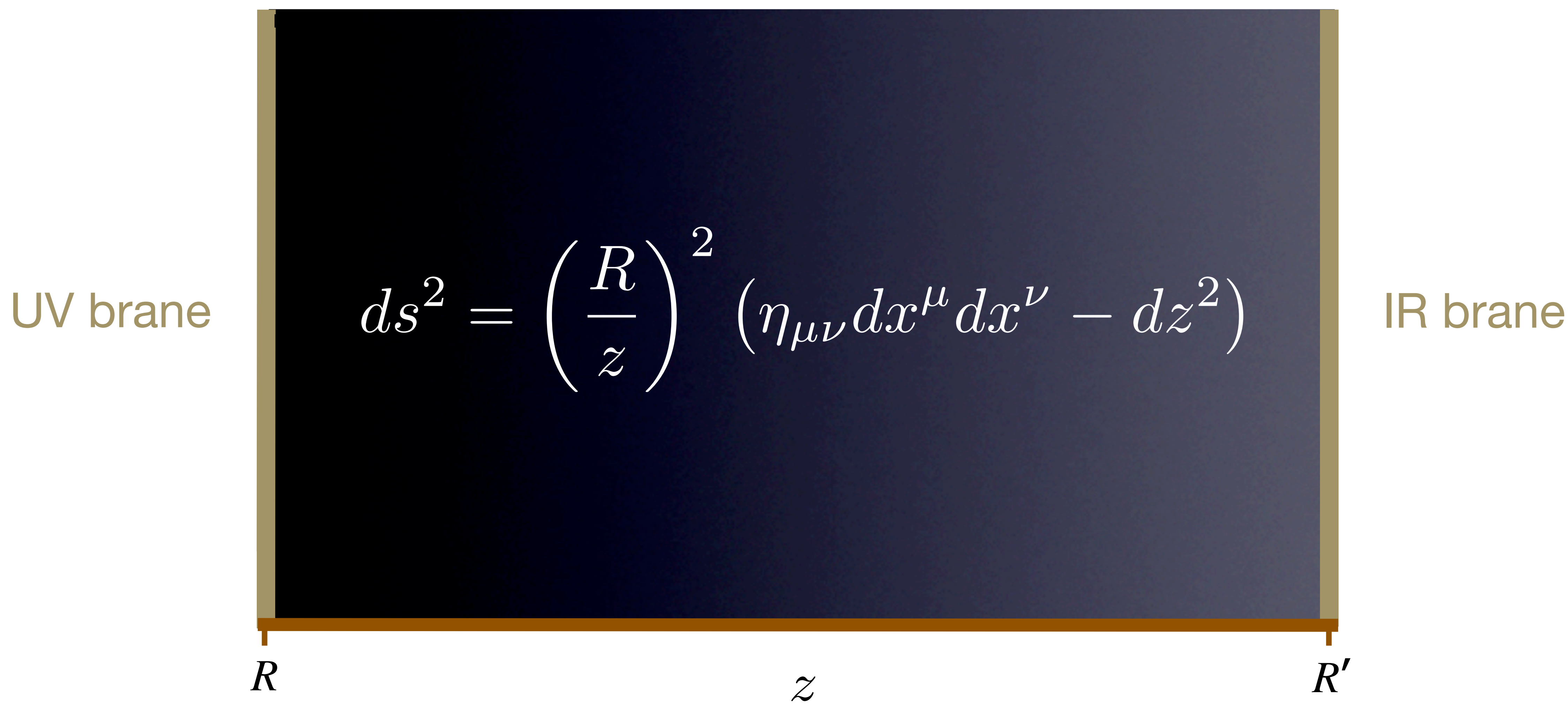
$$\frac{\omega_{\rm B}}{\omega_{\rm A}} = \sqrt{\frac{g_{00}(\mathrm{B})}{g_{00}(\mathrm{A})}} < 1$$

which implies that observer at $\mathrm{A}$ (B) measures light emitted from $\mathrm{B}$ (A) red (blue) -shifted




- Moving emitter $\mathrm{B}$ close to event horizon $r_s$ allows to generate large hierarchy between energies $\omega_{\rm A}$ and $\omega_{\rm B}$

# Virtues of RS framework




- ✓ Solution to gauge hierarchy problem via gravitational red-shifting
- ✓ AdS/CFT calculable strong electroweak symmetry breaking: holographic technicolor, composite Higgs, pseudo-Goldstone-boson composite Higgs
- ✓ High-scale unification due to logarithmic running of gauge couplings

# Physical parameters in quark sector*

Flavor is violated by:

- bulk parameters $c_Q$, $c_u$, $c_d$ — $3\times6$ real parameters
  - $3\times3$ hermitian matrices — $3\times3$ complex phases
- Yukawa couplings $Y_u$, $Y_d$ — $2\times9$ real parameters
  - $3\times3$ complex matrices — $2\times9$ complex phases

36 real parameters

27 complex phases

- global $U(3)^3$ flavor symmetry can be used to remove — 9 real parameters, $18 - 1_B = 17$ complex phases

Physical parameters: $6_m + 12_\alpha + 9_c = 27$ moduli and $1_{\text{CKM}} + 9_\phi = 10$ phases

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

# Warped-space Froggatt-Nielsen mechanism*

<u>Bulk fermions in RS:</u>

$$(Y_q^{\mathrm{eff,RS}})_{ij} \propto (Y_q)_{ij}\, e^{-kr\pi(c_{Q_i}-c_{q_j})}$$

- self-similarity along $\phi$
- bulk parameter $c_{Q_i,q_i}$
- IR brane at $\phi = \pi$
- warp factor $e^{-2kr\pi}$

<u>Froggatt-Nielsen (FN) symmetry:</u>

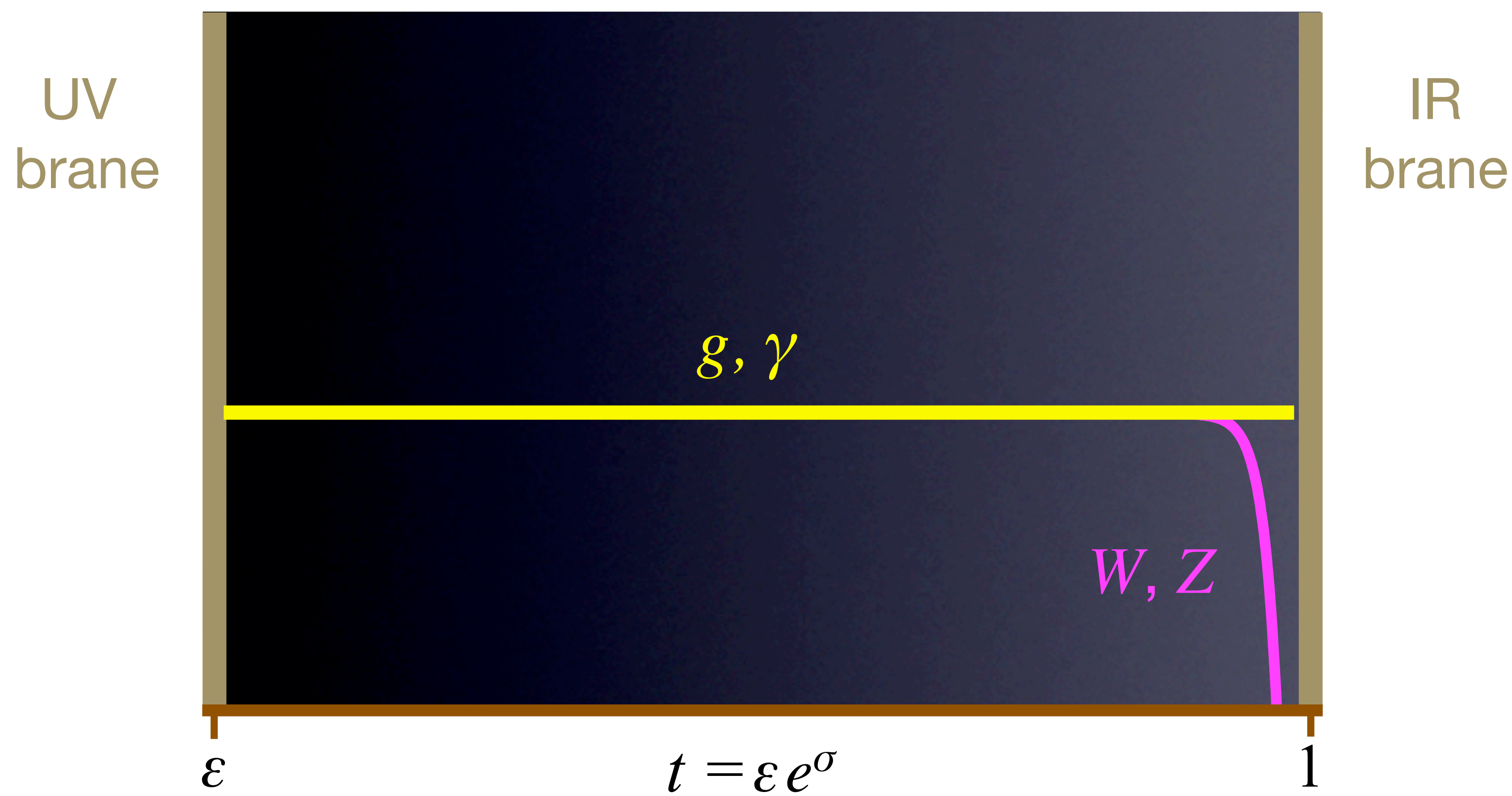
$$(Y_q^{\mathrm{eff,FN}})_{ij} \propto (Y_q)_{ij}\, e^{(a_i-b_{q_j})}$$

- $U(1)_F$ symmetry
- $U(1)_F$ charges $Q_F = a_i, b_{q_i}$
- $\langle\varphi\rangle \neq 0$ of scalar $\varphi$, $Q_F = 1$
- $\varepsilon = \langle h\rangle/\langle\varphi\rangle << 1$

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

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

# RS gauge-boson wave functions*




Profiles of gauge fields:

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

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

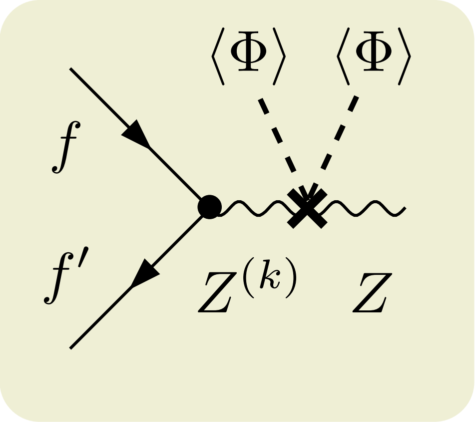
# Mixing matrices: Gauge and KK boson effects

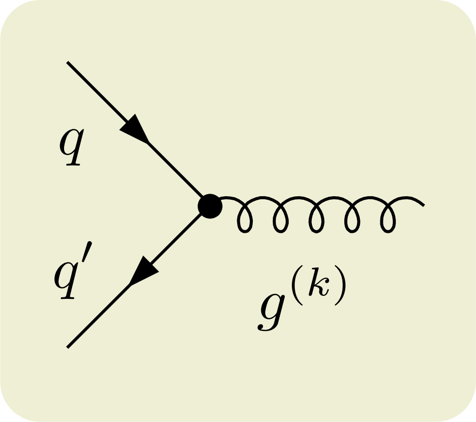
$$(\Delta_Q)_{ij} \to \left( \boldsymbol{U}_q^\dagger \, \mathrm{diag}\left[ \frac{F^2_{c_{Q_i}}}{3 + 2c_{Q_i}} \right] \boldsymbol{U}_q \right)_{ij} , \quad (\Delta_q)_{ij}, \, (\Delta'_q)_{ij} : Q_i \to q_i, \, \boldsymbol{U}_q \to \boldsymbol{W}_q \, ,$$

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

Effects due to gauge-boson profiles*:

- parametrized by four mixing matrices $\boldsymbol{\Delta}_A$, $\boldsymbol{\Delta}'_A$ build 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

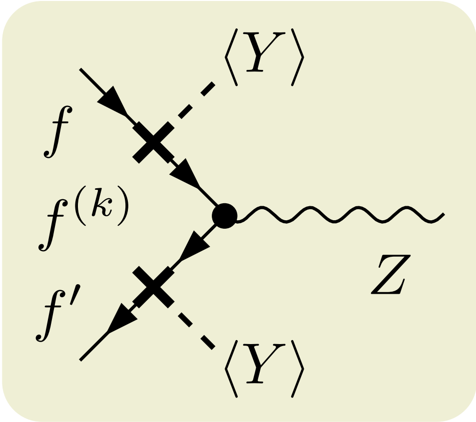
# Mixing matrices: Fermion mixing

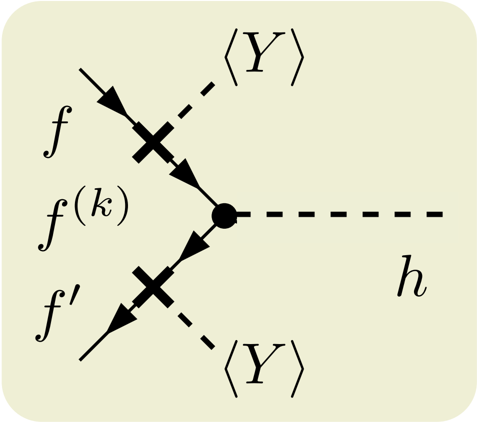
$$(\delta_Q)_{ij} \to \left( \boldsymbol{x}_q \, \boldsymbol{W}_q^\dagger \, \mathrm{diag}\left[ \frac{1}{1-2c_{q_i}} \left( \frac{1}{F^2_{c_{q_i}}} - 1 + \frac{F^2_{c_{q_i}}}{3+2c_{q_i}} \right) \right] \boldsymbol{W}_q \, \boldsymbol{x}_q \right)_{ij} ,$$

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

<u>Effects due to fermion mixing*:</u>

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




*Casagrande *et al.*, arXiv:0807.4537

# Mixing matrices: Scaling relations

$$(U_q)_{ij} \sim (V_{\rm CKM})_{ij} \sim \begin{cases} \dfrac{F_{c_{Q_i}}}{F_{c_{Q_j}}}\,, & i \le j\,, \\[2mm] \dfrac{F_{c_{Q_j}}}{F_{c_{Q_i}}}\,, & i > j\,, \end{cases} \qquad (W_q)_{ij} \sim \begin{cases} \dfrac{F_{c_{q_i}}}{F_{c_{q_j}}}\,, & i \le j\,, \\[2mm] \dfrac{F_{c_{q_j}}}{F_{c_{q_i}}}\,, & i > j\,, \end{cases}$$

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

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

- $F_{c_{A_i}} F_{c_{A_j}}$ 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

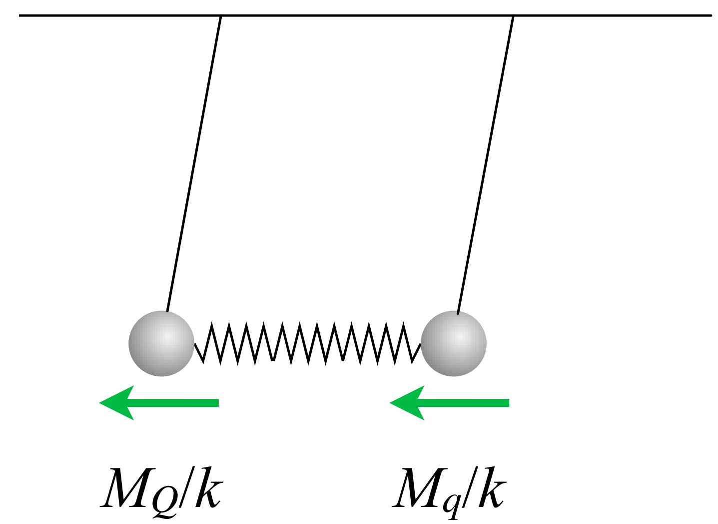
# Reparametrization invariance*

- Expressions for quark masses and mixing matrices are invariant under two reparametrizations RPI-1 and RPI-2

RPI-1:

$$F_{c_Q} \to e^{-\xi} F_{c_Q}\,, \qquad \left[c_Q \to c_Q - \frac{\xi}{L}\right],$$

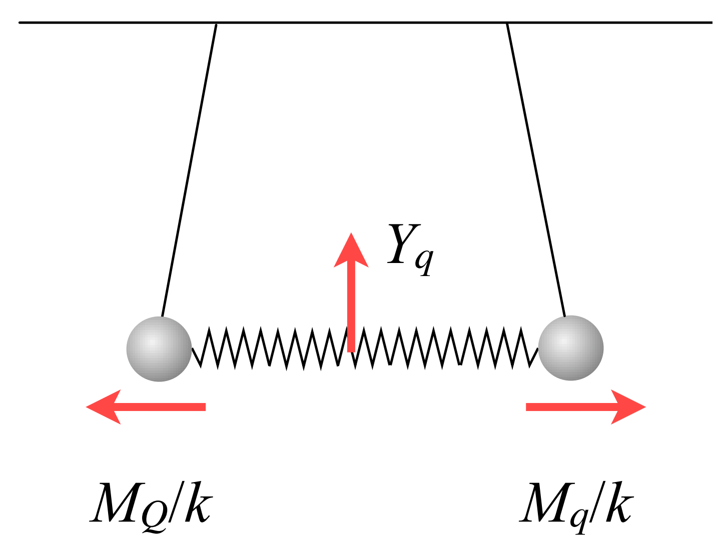
$$F_{c_q} \to e^{+\xi} F_{c_q}\,, \qquad \left[c_q \to c_q + \frac{\xi}{L}\right]$$




RPI-2:

$$F_{c_A} \to \zeta\, F_{c_A}\,, \qquad \left[c_A \to c_A - \frac{\ln\zeta}{L}\right],$$

$$\boldsymbol{Y}_q \to \frac{1}{\zeta^2}\,\boldsymbol{Y}_q$$




*Casagrande *et al.*, arXiv:0807.4537

# Mixing matrices: Transformation properties

<u>RPI-1:</u>

$$\mathbf{\Delta}_Q \to e^{-2\xi}\,\mathbf{\Delta}_Q\,, \qquad \mathbf{\Delta}_q \to e^{+2\xi}\,\mathbf{\Delta}_q\,,$$
$$\boldsymbol{\delta}_Q \to e^{+2\xi}\,\boldsymbol{\delta}_Q\,, \qquad \boldsymbol{\delta}_q \to e^{-2\xi}\,\boldsymbol{\delta}_q\,,$$

<u>RPI-2:</u>

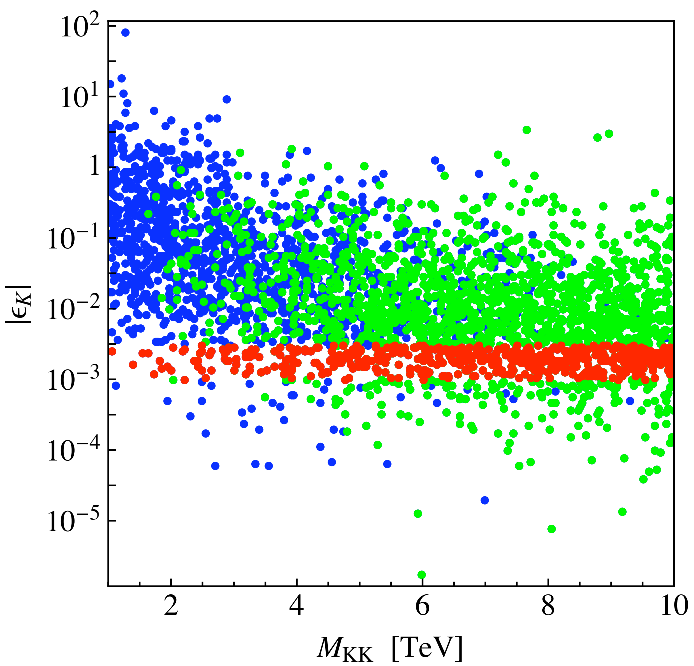
$$\mathbf{\Delta}_Q \to \zeta^2\,\mathbf{\Delta}_Q\,, \qquad \mathbf{\Delta}_q \to \zeta^2\,\mathbf{\Delta}_q\,,$$
$$\boldsymbol{\delta}_Q \to \frac{1}{\zeta^2}\,\boldsymbol{\delta}_Q\,, \qquad \boldsymbol{\delta}_q \to \frac{1}{\zeta^2}\,\boldsymbol{\delta}_q\,,$$

<u>Reparametrization transformations imply*:</u>

- relative importance of left- and right-handed couplings, $\mathbf{\Delta}_Q$, $\boldsymbol{\delta}_Q \leftrightarrow \mathbf{\Delta}_q$, $\boldsymbol{\delta}_q$, as well as contributions due to non-trivial gauge-boson profiles and fermion mixing, $\mathbf{\Delta}_{Q,q} \leftrightarrow \boldsymbol{\delta}_{Q,q}$, can be reshuffled
- but it is not possible to make all contributions simultaneously small

*Casagrande *et al.*, arXiv:0807.4537

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

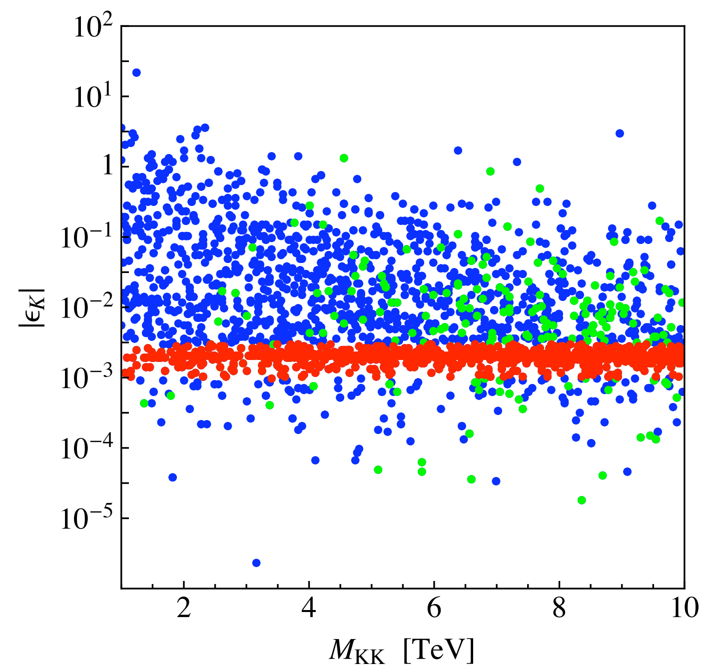



**S1: Standard**

$|Y_q| < 3$

- 16%
- 59%

13% pass

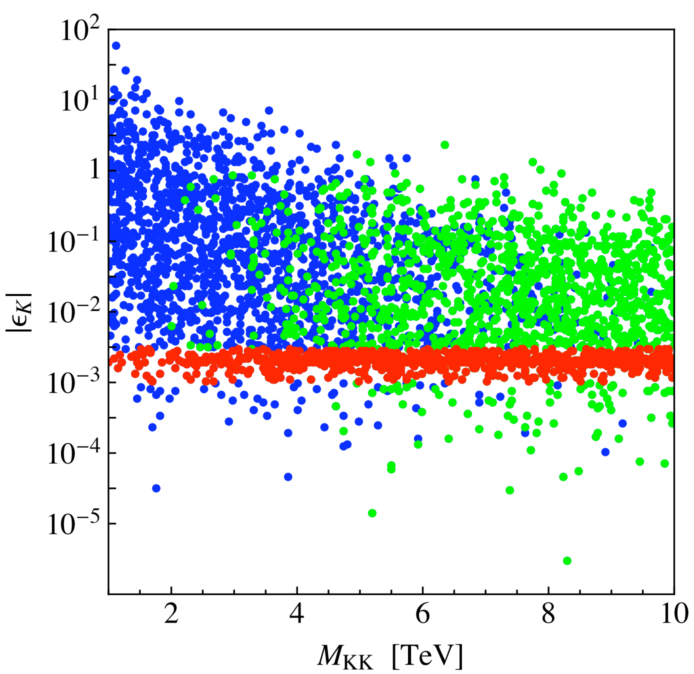



**S2: Big Yukawas**

$|Y_q| < 12$

- 44%
- 26%

19% pass

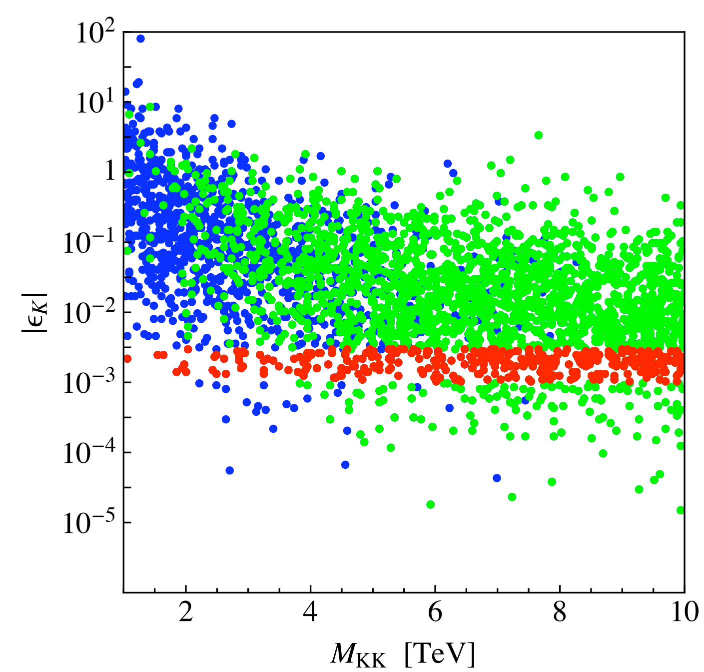



**S3: Alignement**

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

- 48%
- 24%

16% pass




**S4: Little RS**

$L = 7$

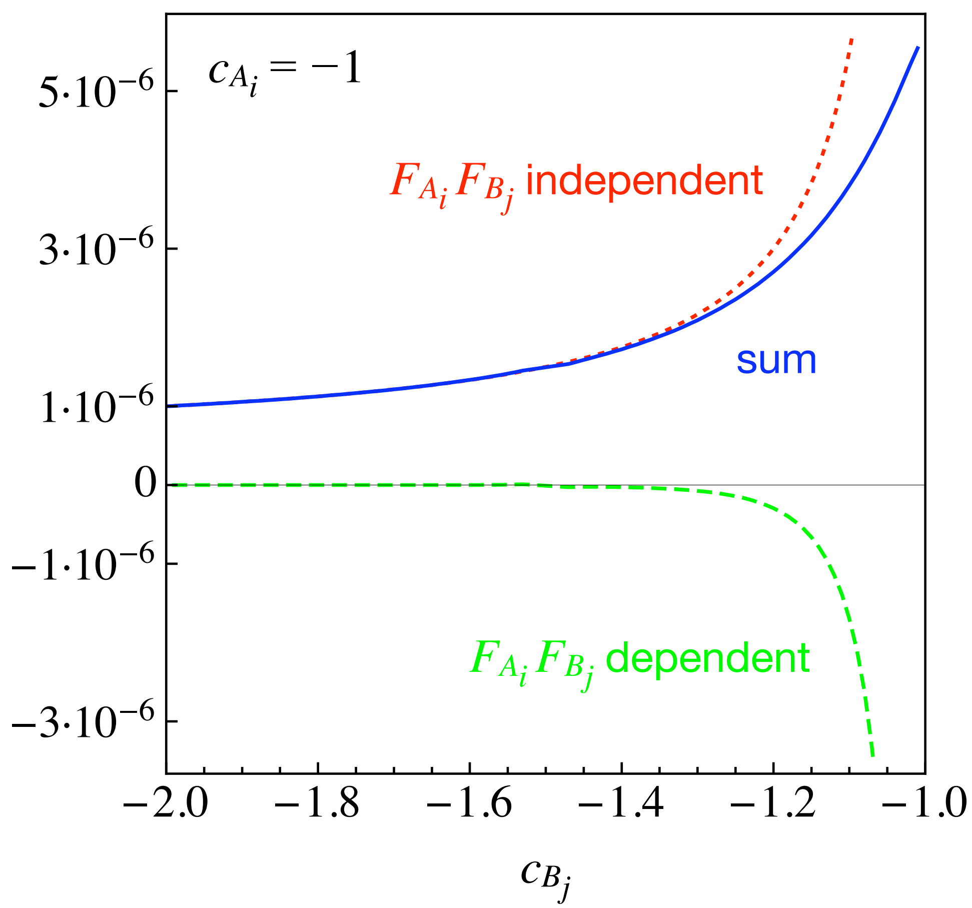
- 11%
- 68%

9% pass

*Davoudiasl *et al.*, arXiv:0802.0203; Santiago, arXiv:0806.1230; Bauer *et al.*, arXiv:0811.3678, arXiv:09xx.xxxx

# $|\varepsilon_K|$ 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




<u>Typical bulk parameters for $L = 7$:</u>

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

- 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

*Davoudiasl *et al.*, arXiv:0802.0203; Bauer *et al.*, arXiv:0811.3678

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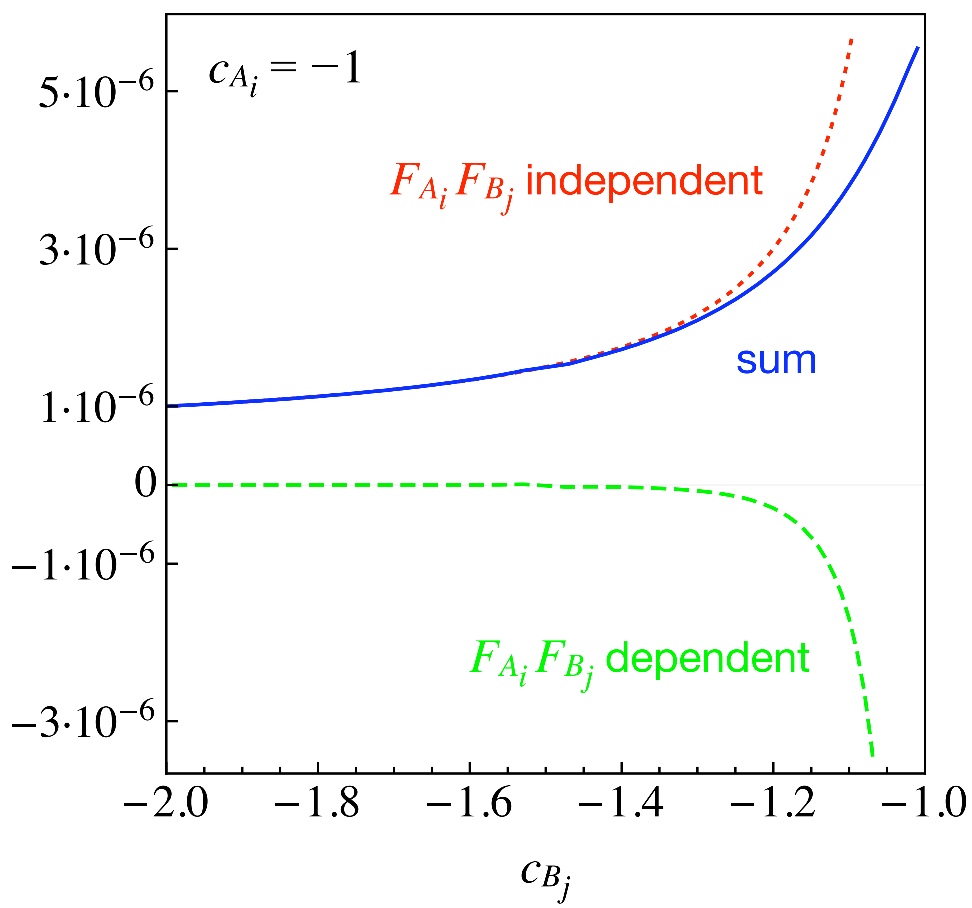



Typical bulk parameters for $L = 7$:

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

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

*Davoudiasl *et al.*, arXiv:0802.0203; Bauer *et al.*, arXiv:0811.3678

# Non-unitarity of CKM matrix*

- Typical RS prediction:

$$
\begin{aligned}
1-\left(|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2\right) &= -0.00048\,, \\
1+\frac{V_{ub}^*V_{ud}}{V_{cb}^*V_{cd}}+\frac{V_{tb}^*V_{td}}{V_{cb}^*V_{cd}} &= -0.0068+0.0209\,i
\end{aligned}
$$

- Effects of similar magnitude as current uncertainties of global CKM fit:

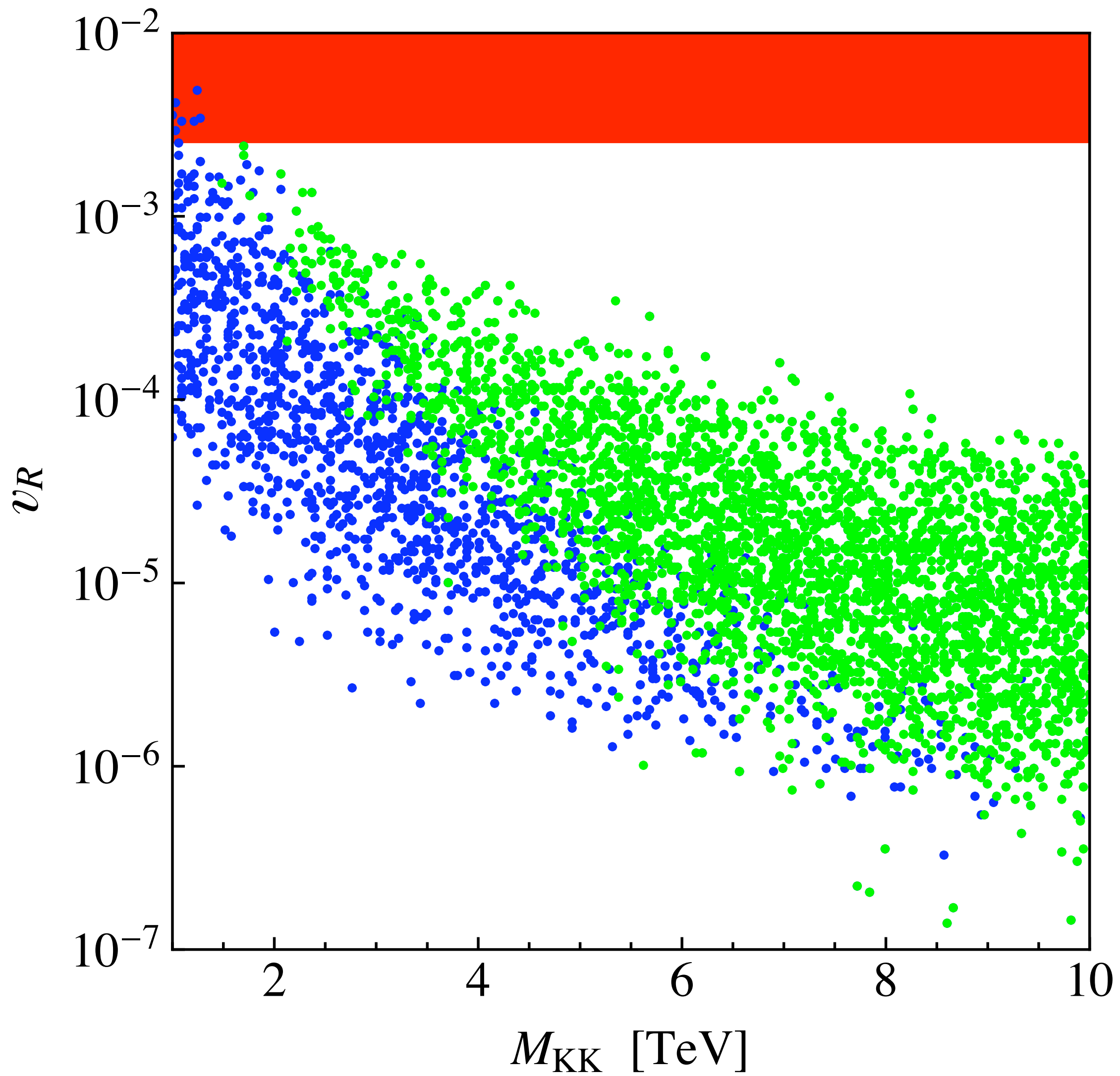
$$
1-\left(|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2\right) = 0.00022 \pm 0.00051_{V_{ud}} \pm 0.00041_{V_{us}}\,,
$$

$$
\bar\rho = 0.147 \pm 0.029\,, \qquad \bar\eta = 0.343 \pm 0.016
$$

*Huber, hep-ph/0303183; Cheung *et al.*, arXiv:0806.0667; Casagrande *et al.*, arXiv:0807.4537

# Right-handed charged current couplings*

- Induced right-handed charged current couplings are too small to lead to observable effects. Most pronounced effects occur in $Wtb$ coupling $v_R$




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

■ $v_R \in [-0.0007, 0.0025]$ at $95\%$ CL exclusion bound from $B \to X_s\gamma$

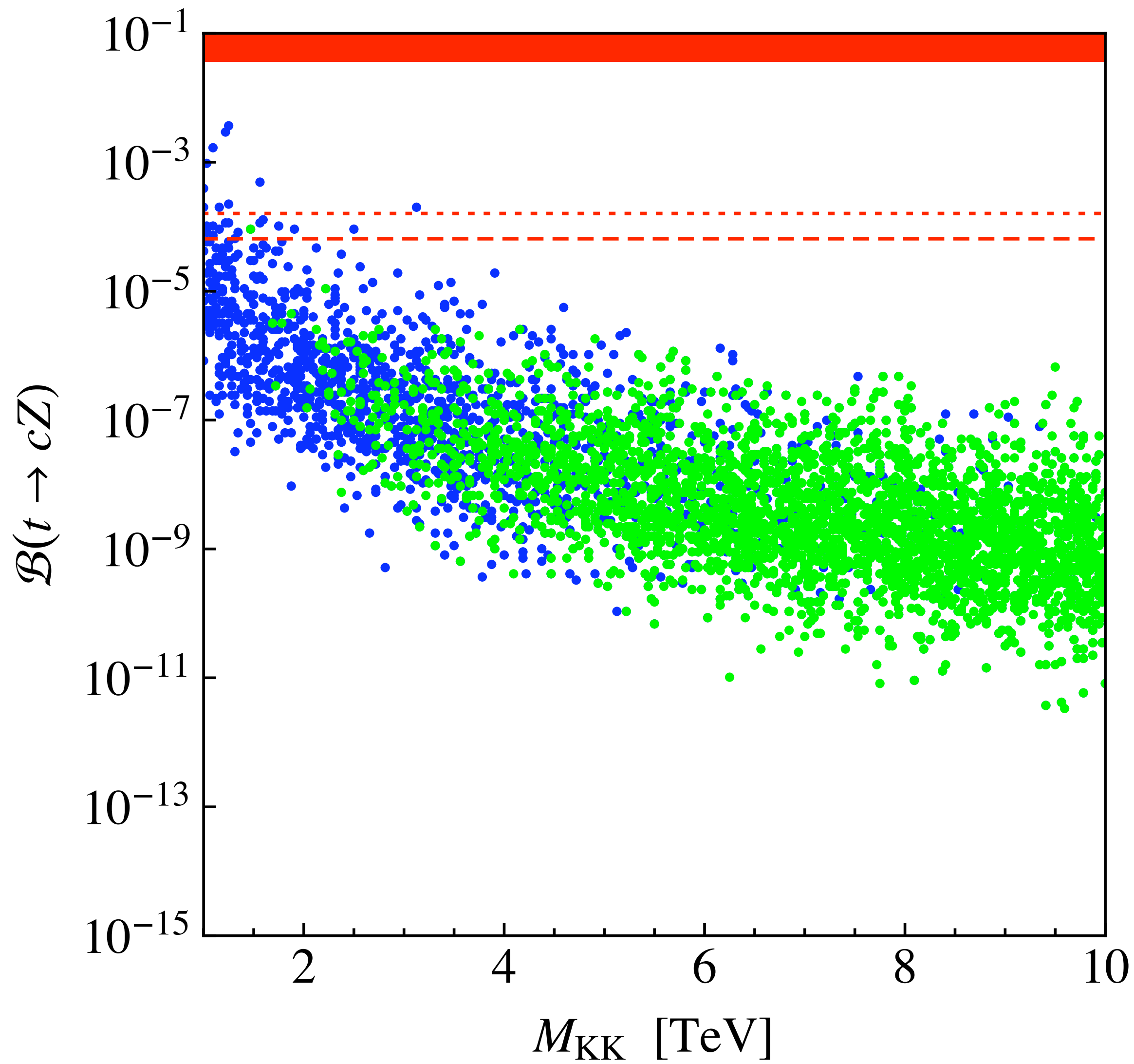
● without $Z \to b\bar{b}$ constraint

● with $Z \to b\bar{b}$ constraint at $95\%$ CL

*Casagrande *et al.*, arXiv:0807.4537

# Rare FCNC top decays*

- Predictions of branching ratios for $t \to cZ$ and $t \to ch$ in minimal RS model typically below LHC sensitivity




minimum of $1.6 \cdot 10^{-4}$ for $5\sigma$ discovery by ATLAS, $100\ \text{fb}^{-1}$

95% CL limit of $6.5 \cdot 10^{-5}$ from ATLAS, $100\ \text{fb}^{-1}$

95% CL upper bound from CDF $B(t \to u(c)Z) < 3.7\%$

without $Z \to b\bar{b}$ constraint

with $Z \to b\bar{b}$ constraint at 95% CL

*Agashe *et al*., hep-ph/0606293; Chang *et al*., arXiv:0806.0667; Casagrande *et al*., arXiv:0807.4537

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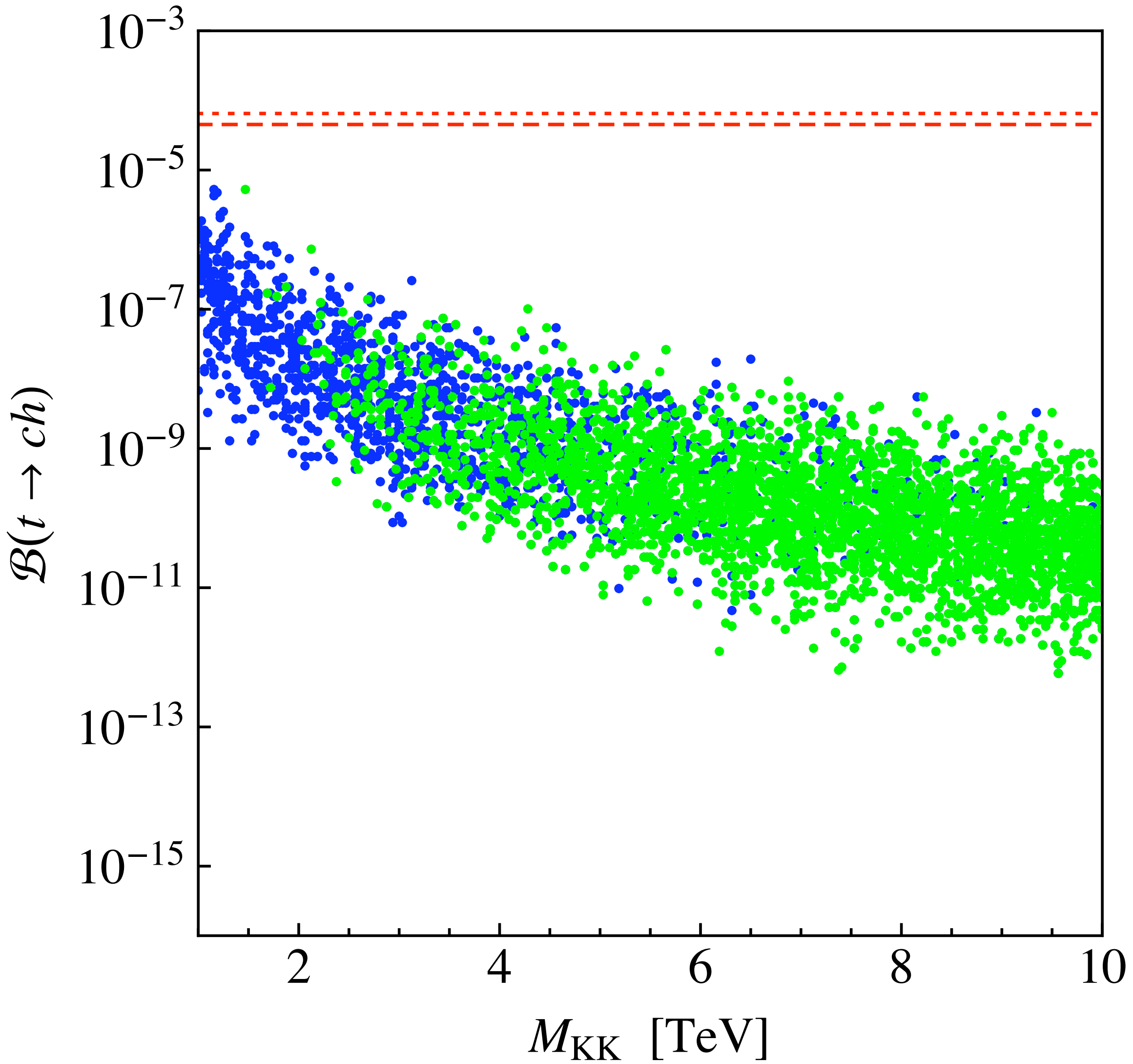
- Predictions of branching ratios for $t \to cZ$ and $t \to ch$ in minimal RS model typically below LHC sensitivity




minimum of $6.5 \cdot 10^{-4}$ for $3\sigma$ evidence by LHC

95% CL limit from LHC $\mathcal{B}(t \to ch) < 4.5 \cdot 10^{-5}$

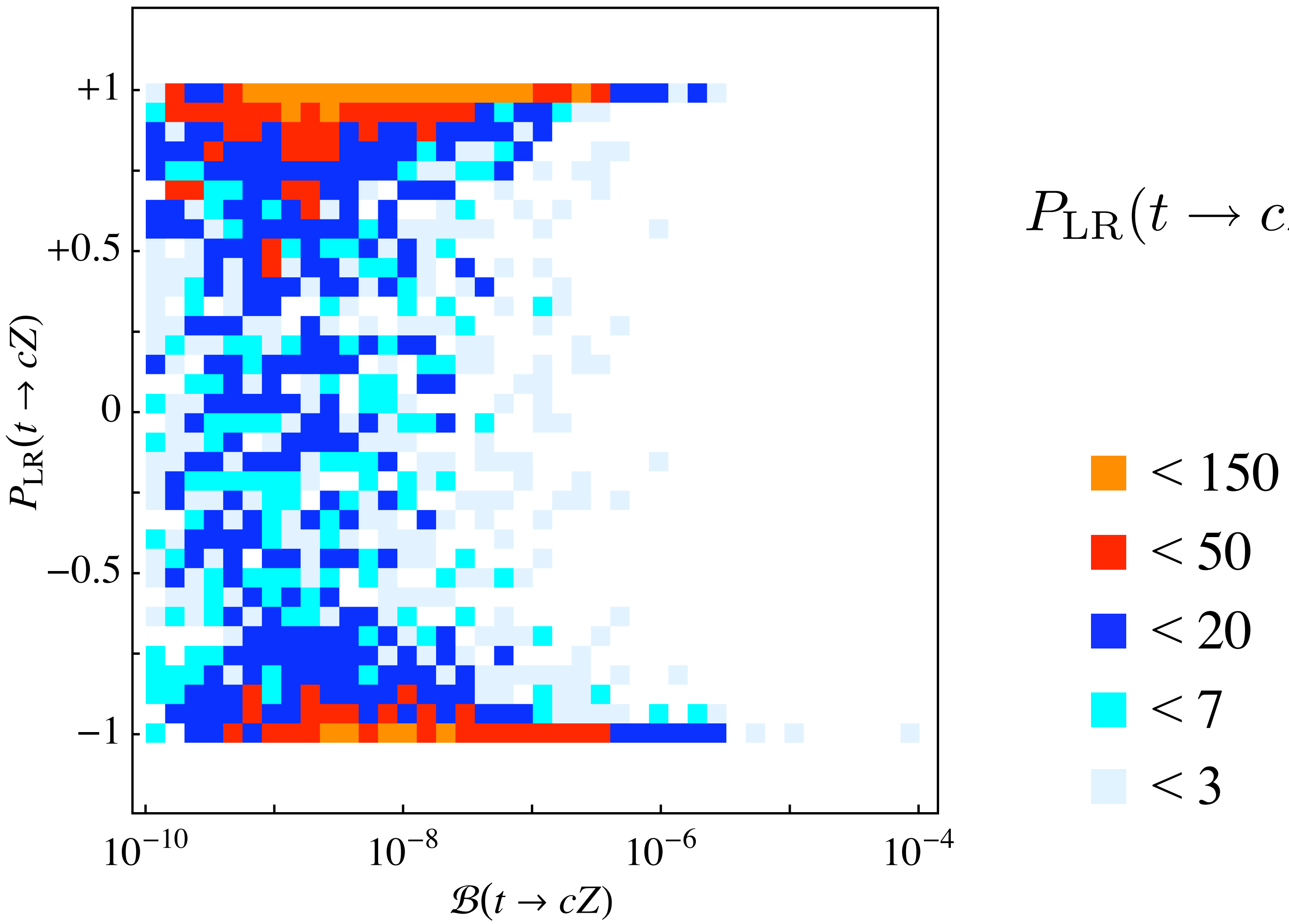
without $Z \to b\bar{b}$ constraint

with $Z \to b\bar{b}$ constraint at 95% CL

*Casagrande *et al.*, arXiv:0807.4537

# Rare FCNC top decays*

- RS model does not lead to firm prediction for chirality of $Ztc$ interactions, although $Z \to b\bar{b}$ constraint restricts more strongly left-handed coupling



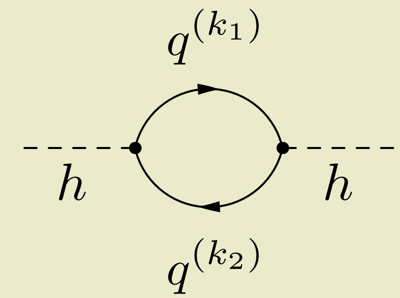

$$P_{\mathrm{LR}}(t \to cZ) = \frac{\Gamma_L(t \to cZ) - \Gamma_R(t \to cZ)}{\Gamma_L(t \to cZ) + \Gamma_R(t \to cZ)}$$

events in bin after imposing $Z \to b\bar{b}$ constraint at 95% CL

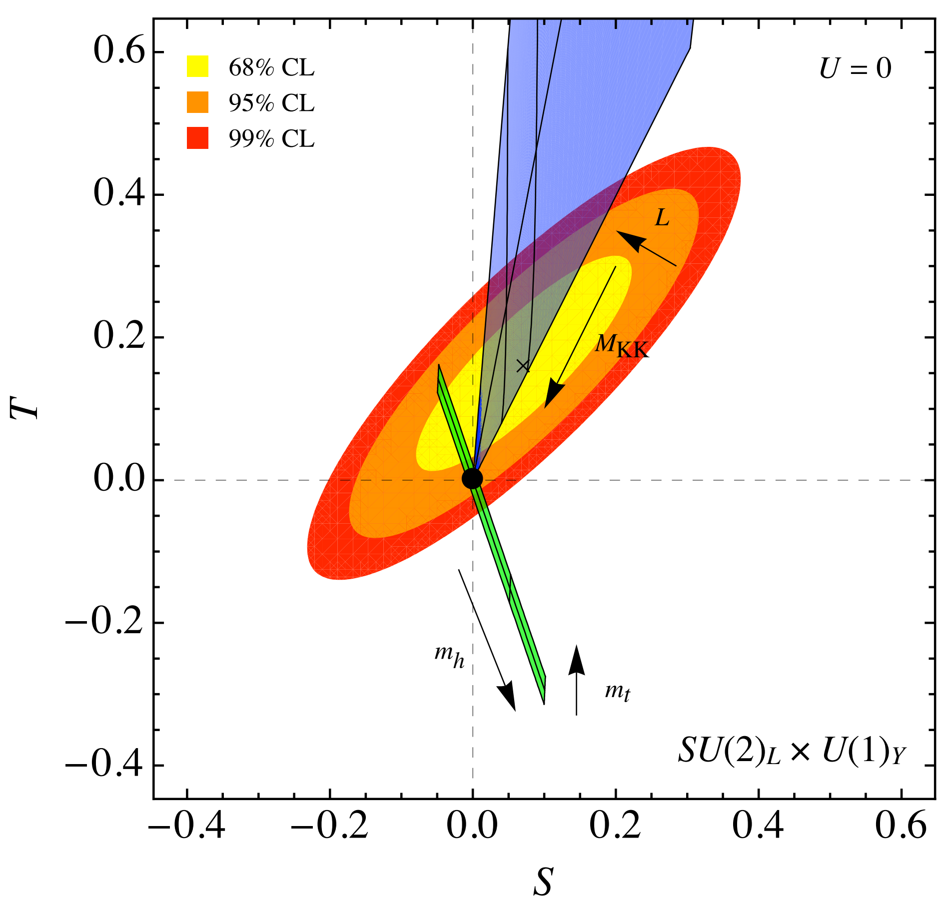
*Agashe *et al.*, hep-ph/0606293; Chang *et al.*, arXiv:0806.0667; Casagrande *et al.*, arXiv:0807.4537

# $S$ and $T$ parameters in minimal RS model*

- In warped models with brane-localized Higgs sector, $m_h$ naturally of order $M_{\text{KK}}$. Heavy Higgs allows for $M_{\text{KK}} > 2.6$ TeV at 99% CL consistent with $S$ and $T$




$$\sim \Lambda_{\text{UV}}^2 \frac{|Y_q|^2}{16\pi^2} \frac{\Lambda_{\text{UV}}^2}{M_{\text{KK}}^2}$$




$$\Delta S = \frac{1}{6\pi} \ln \frac{m_h}{m_h^{\text{ref}}}\,, \qquad \Delta T = -\frac{3}{8\pi c_w^2} \ln \frac{m_h}{m_h^{\text{ref}}}$$

- minimal RS prediction for $M_{\text{KK}} \in [1, 10]$ TeV and $L \in [5, 37]$
- SM reference point for $m_h \in [60, 1000]$ GeV and $m_t = (172.6 \pm 1.4)$ GeV
- SM reference point for $m_h = 150$ GeV

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

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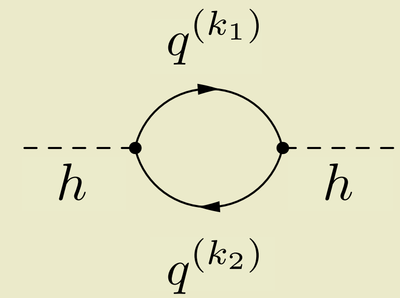
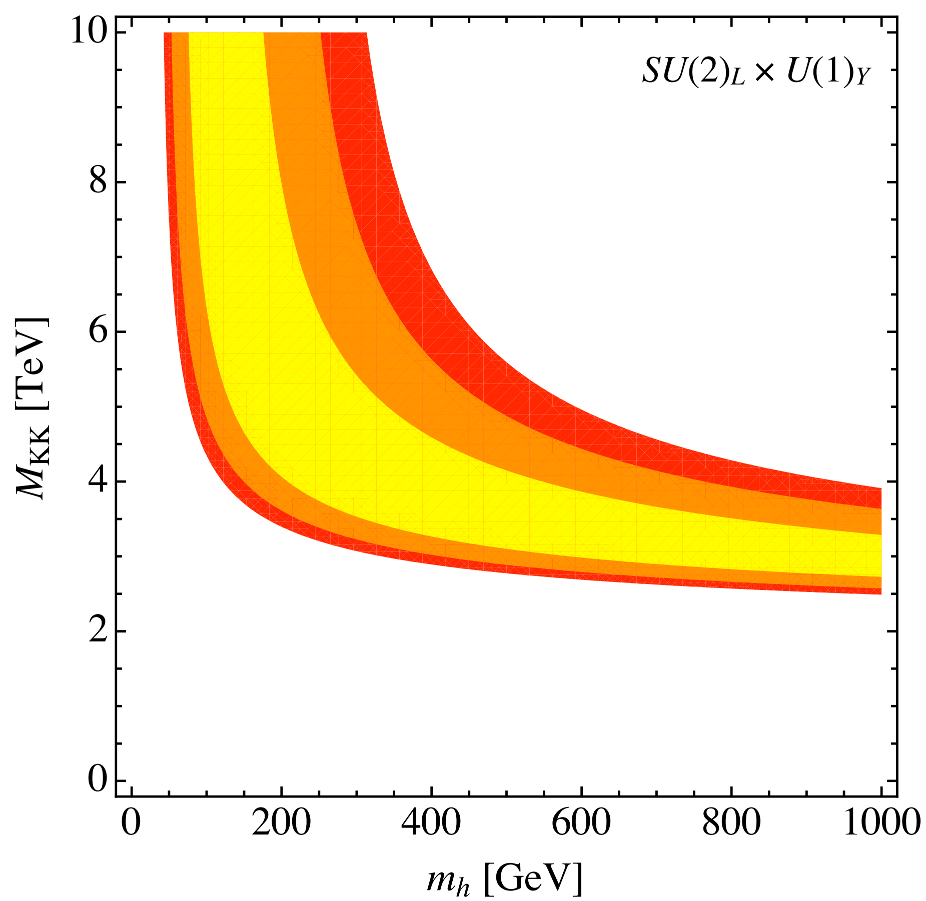



$$\sim \Lambda_{\rm UV}^2 \frac{|Y_q|^2}{16\pi^2} \frac{\Lambda_{\rm UV}^2}{M_{\rm KK}^2}$$




$$\Delta S = \frac{1}{6\pi} \ln \frac{m_h}{m_h^{\rm ref}}\,, \qquad \Delta T = -\frac{3}{8\pi c_w^2} \ln \frac{m_h}{m_h^{\rm ref}}$$

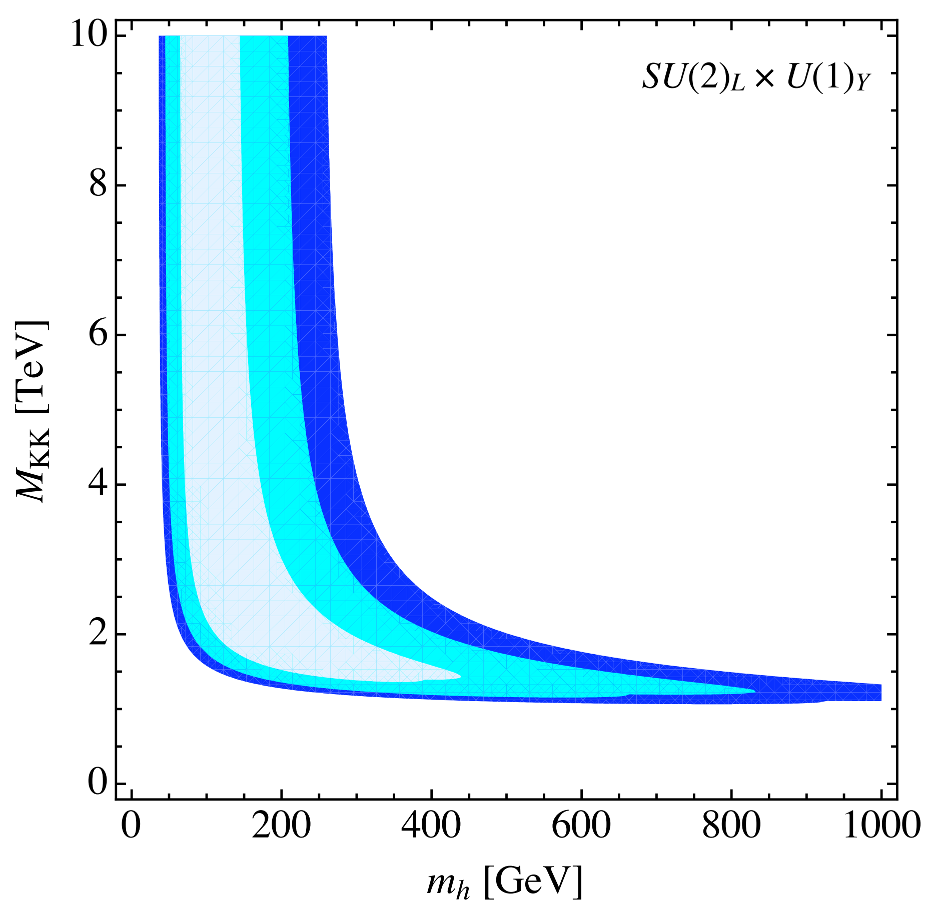
68% CL
95% CL
99% CL

regions from $S$ and $T$ in minimal RS model for $L = \ln(10^{16}) \approx 37$

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

# $S$ and $T$ parameters in little RS model*

- Another way to protect $T$ from vast corrections consists in giving up on solution to full gauge hierarchy problem by working in volume-truncated RS background. For $L = \ln(10^3) \approx 7$, allowed KK scale is lowered to $M_{\mathrm{KK}} > 1.5$ TeV at 99% CL for $m_h = 150$ GeV




$$S = \frac{2\pi v^2}{M_{\mathrm{KK}}^2}\left(1 - \frac{1}{L}\right),$$

$$T = \frac{\pi v^2}{2c_w^2 M_{\mathrm{KK}}^2}\left(L - \frac{1}{2L}\right)$$

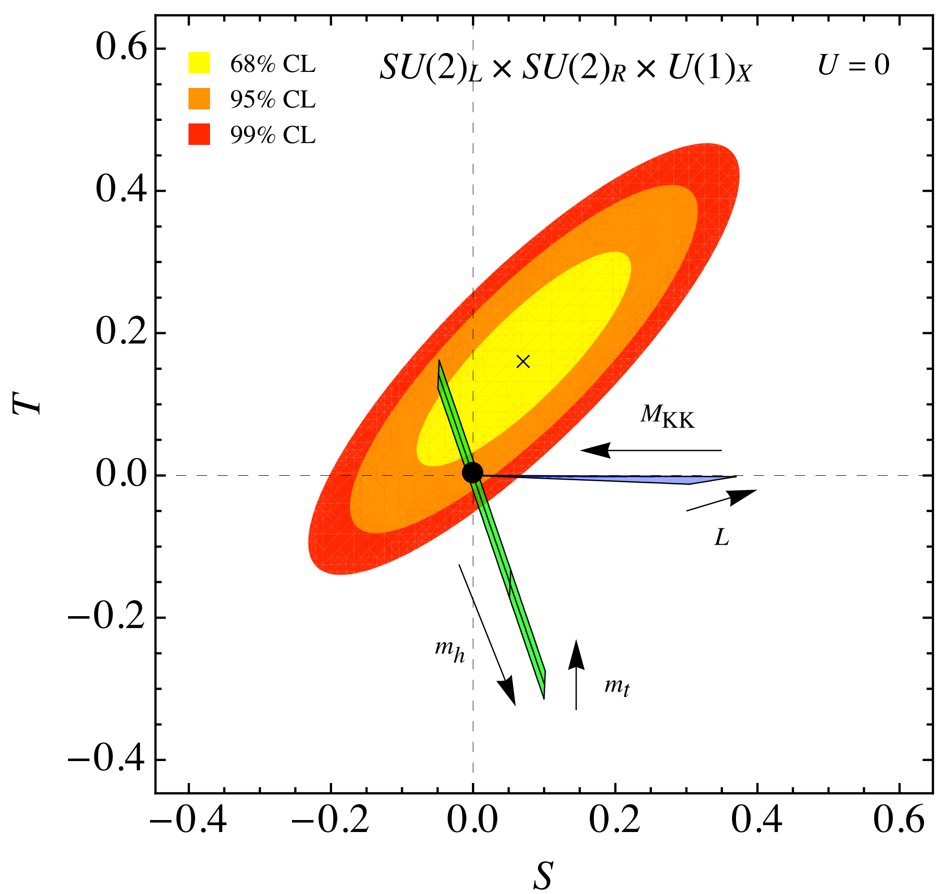
68% CL
95% CL
99% CL

regions from $S$ and $T$ in little RS model for $L = \ln(10^3) \approx 7$

*Davoudiasl *et al.*, arXiv:0802.0203; Casagrande *et al.*, arXiv:0807.4537

# $S$ and $T$ parameters in extended RS model*

- Most elegant cure for excessive contributions to $T$ parameter is custodial $SU(2)_R$ symmetry. Lower bound of KK scale follows then from constraint on $S$. For $m_h = 150$ GeV one finds $M_{\mathrm{KK}} > 2.4$ TeV at 99% CL. Yet presence of heavy Higgs boson could spoil global electroweak fit



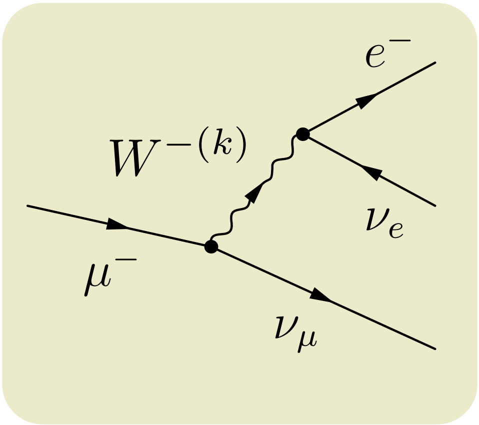

$$S = \frac{2\pi v^2}{M_{\mathrm{KK}}^2}\left(1 - \frac{1}{L}\right), \quad T = -\frac{\pi v^2}{4c_w^2 M_{\mathrm{KK}}^2}\frac{1}{L}$$

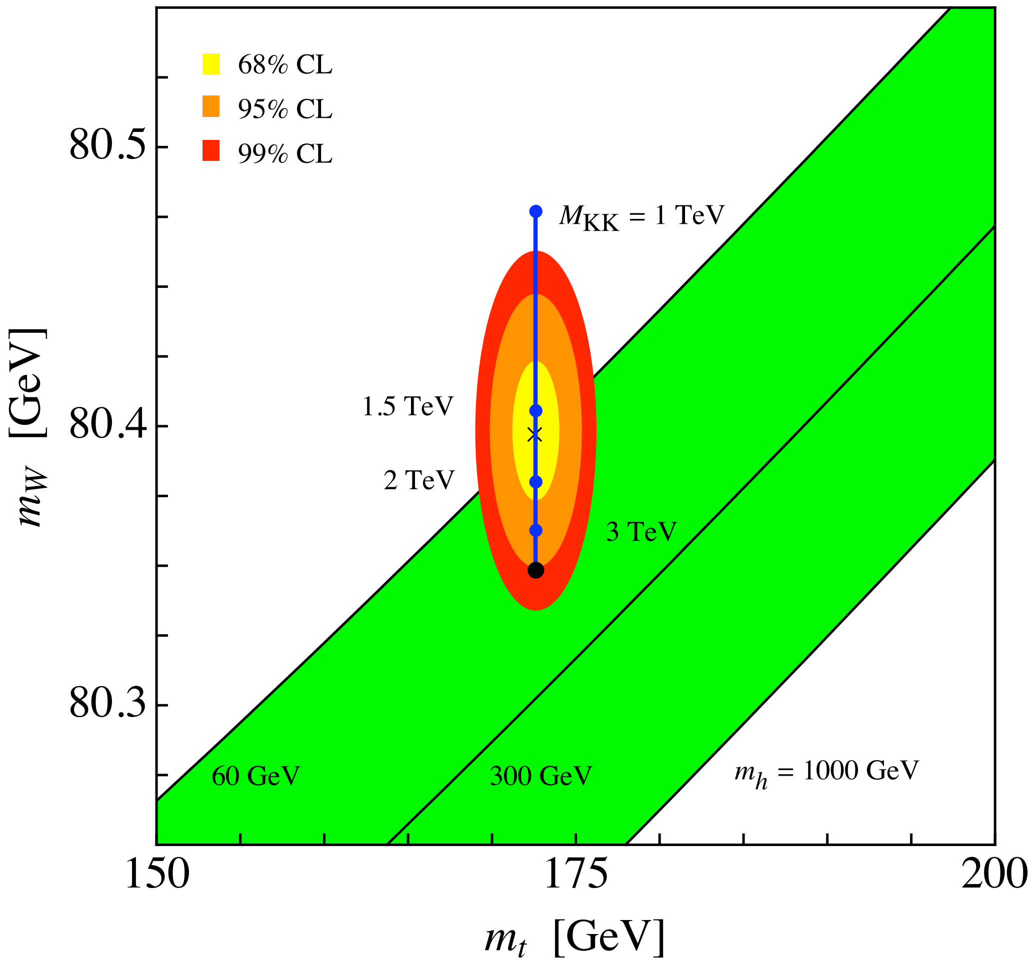
- prediction in extended RS model for $M_{\mathrm{KK}} \in [1, 10]$ TeV and $L \in [5, 37]$
- SM reference point for $m_h \in [60, 1000]$ GeV and $m_t = (172.6 \pm 1.4)$ GeV
- SM reference point for $m_h = 150$ GeV

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

# Mass of $W$ boson*

- RS model allows to explain 50 MeV difference between direct and indirect extractions of $W$–boson mass $m_W \approx 80.40$ GeV and $(m_W)_{\rm ind} \approx 80.35$ GeV



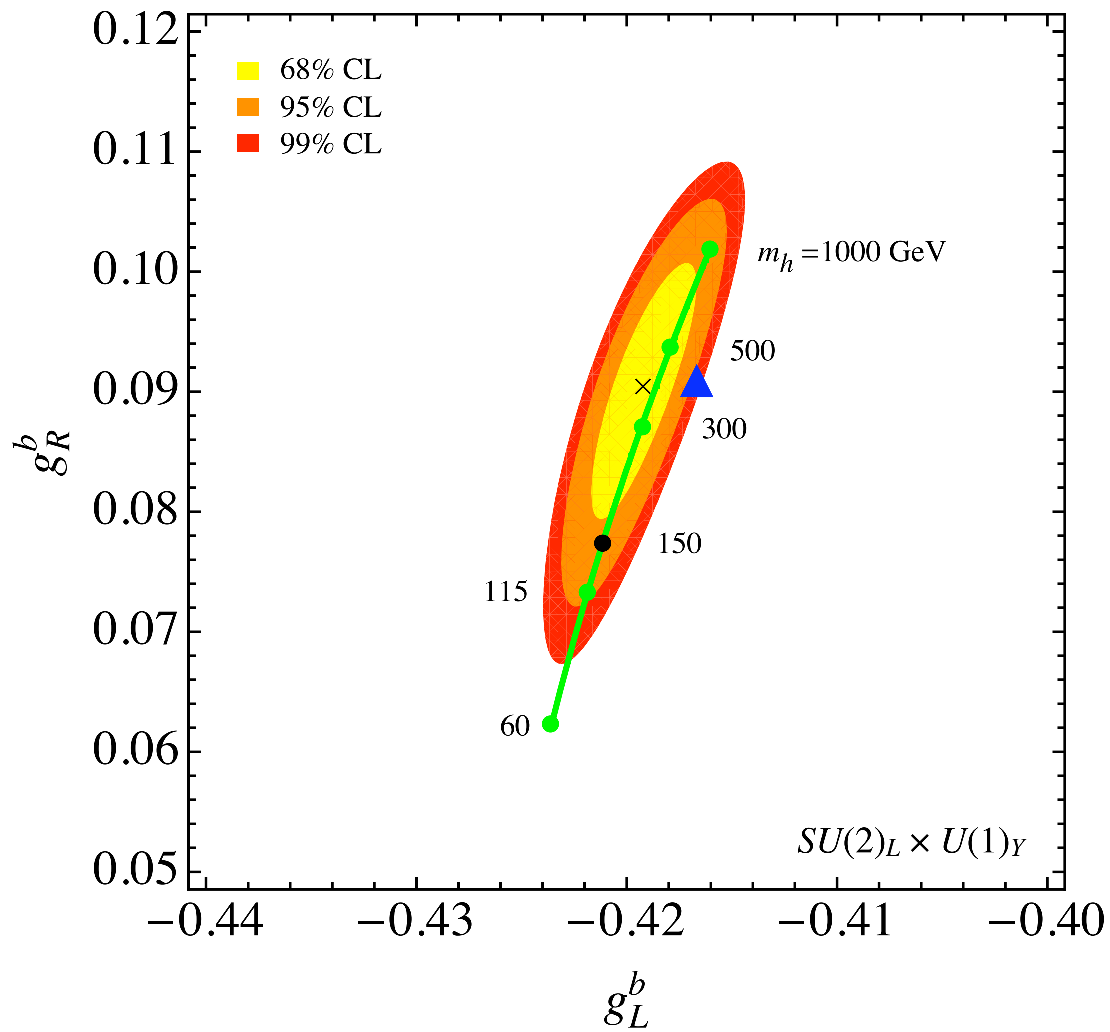

$$(m_W)_{\rm ind} \approx m_W \left[ 1 - \frac{m_W^2}{4M_{\rm KK}^2} \left( 1 - \frac{1}{2L} \right) \right]$$

- (green square) $(m_W)_{\rm ind}$ in SM for $m_h \in [60, 1000]$ GeV
- (black dot) $(m_W)_{\rm ind}$ in SM for $m_h = 150$ GeV
- (blue dot) $(m_W)_{\rm ind}$ in RS model for $M_{\rm KK} \in [1, 3]$ TeV

*Casagrande *et al.*, arXiv:0807.4537

# $Z \to b\bar{b}$ in minimal RS model*

- Heavy Higgs boson improves quality of fit to pseudo observables $R_b^0$, $A_b$, and $A_{\rm FB}^{0,b}$. Minimal RS model thus offer indirect explanation of $2.1\sigma$ anomaly in $A_{\rm FB}^{0,b}$ since in this setup Higgs-boson mass is expected to be large



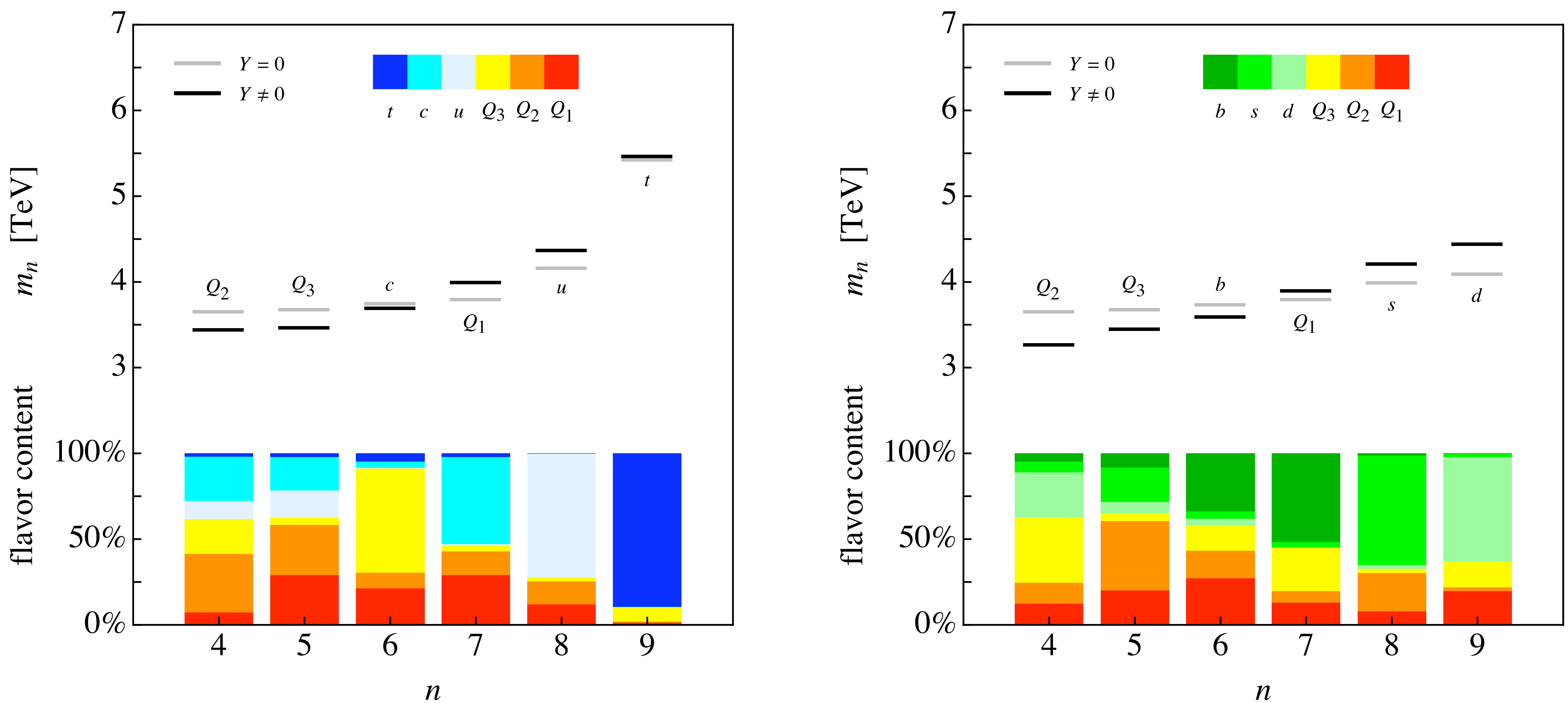

$$\Delta A_{\rm FB}^{0,b} = -2.7 \cdot 10^{-3} \ln \frac{m_h}{m_h^{\rm ref}}$$

- ▲ 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
- ● SM prediction for $m_h = 150$ GeV

*Casagrande *et al.*, arXiv:0807.4537

# Mass and mixing of KK fermions*

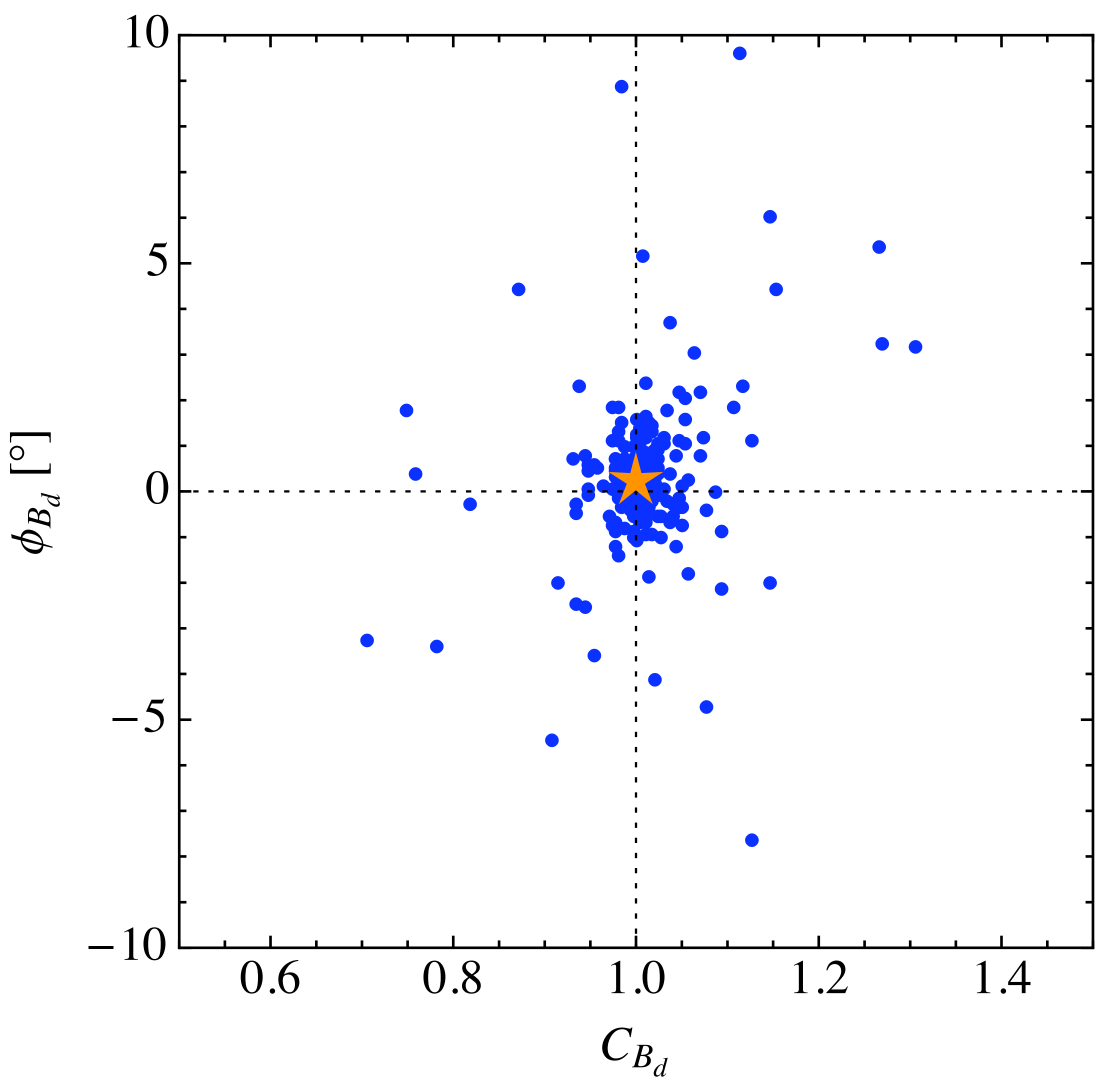
- Since mass splittings of undisturbed KK states typical of order $100\ \mathrm{GeV}$ order, Yukawa couplings introduce large mixings among KK modes of same level. Mixings give rise to FCNCs when inserted into loop diagrams




*Casagrande *et al.*, arXiv:0807.4537

# Meson mixing: Neutral $B_d$ mesons*

- Even after imposing $|\varepsilon_K|$ constraint, sizable effects in magnitude and phase of $B_d$ meson mixing amplitude possible




$$C_{B_d}\, e^{2i\phi_{B_d}} = \frac{\langle B_d | \mathcal{H}_{\text{eff,full}}^{\Delta B=2} | \bar{B}_d \rangle}{\langle B_d | \mathcal{H}_{\text{eff,SM}}^{\Delta B=2} | \bar{B}_d \rangle}$$

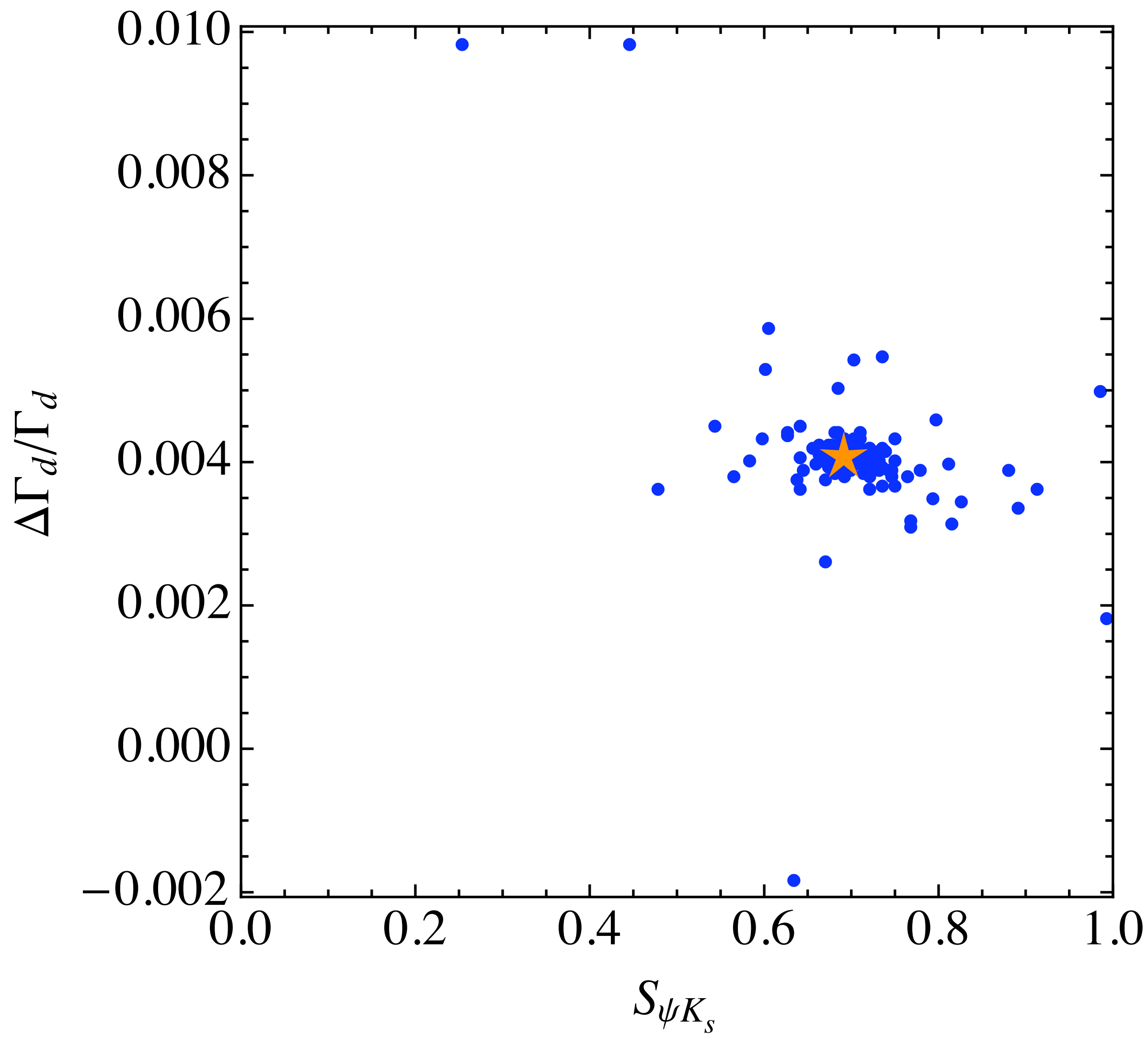
★ SM: $C_{B_d} = 1$, $\phi_{B_d} = 0^\circ$

● 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.*, arXiv:09xx.xxxx

# Meson mixing: Neutral $B_d$ mesons*

- Constraint from $|\varepsilon_K|$ does not exclude order one effects in width difference $\Delta\Gamma_d/\Gamma_d$ of $B_d$ system




$$\Delta\Gamma_d = \Gamma_L^d - \Gamma_S^d$$
$$= 2\,|\Gamma_{12}^d|\cos(2\beta + 2\phi_{B_d})$$

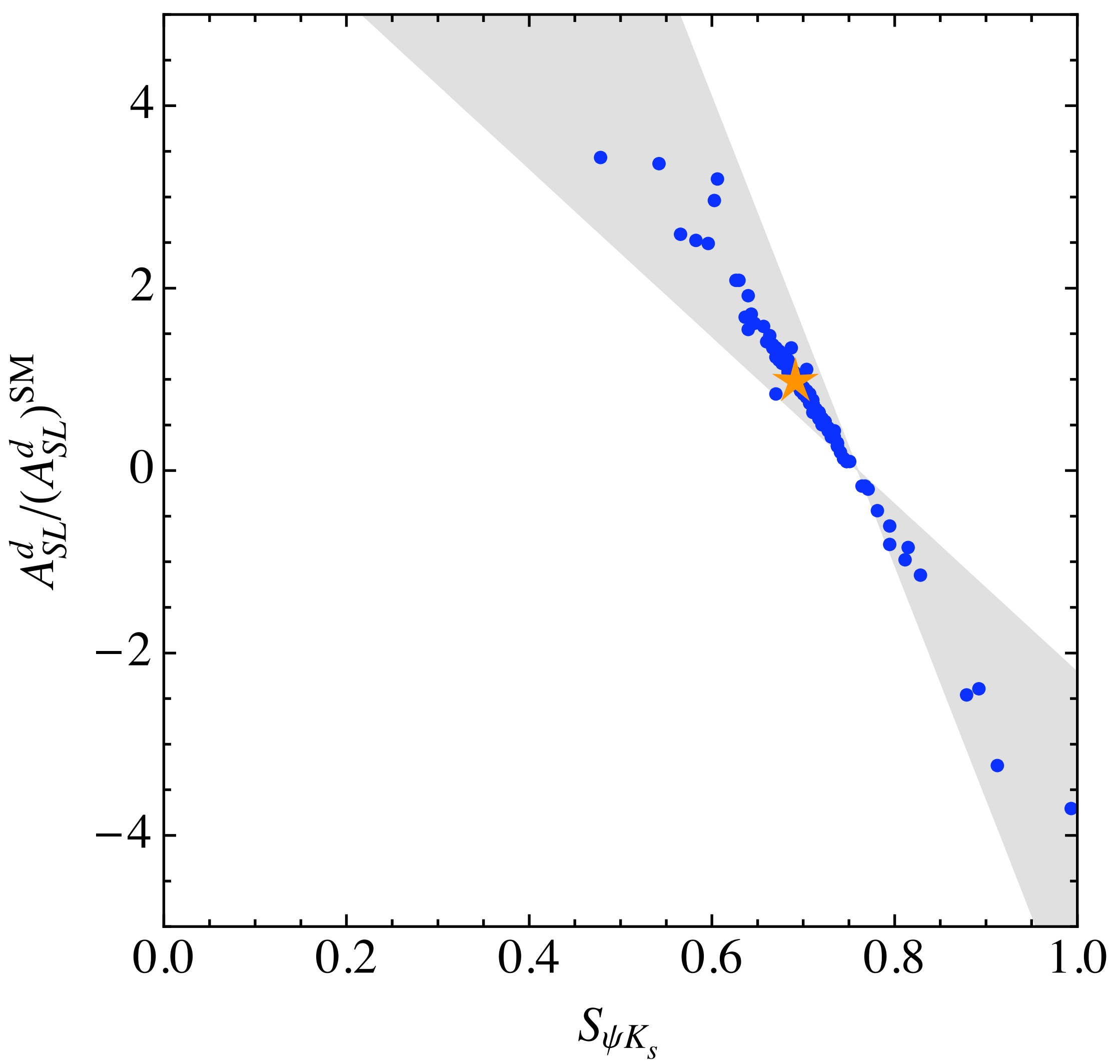
★ SM: $\Delta\Gamma_d/\Gamma_d \approx 0.004$, $S_{\psi K_s} \approx 0.69$

● 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.*, arXiv:09xx.xxxx

# Meson mixing: Neutral $B_d$ mesons*

- In RS model, significant corrections to semileptonic CP asymmetry $A_{SL}^d$ and $S_{\psi K_s} = \sin(2\beta + 2\phi_{B_d})$ consistent with $|\varepsilon_K|$ can arise




$$A_{SL}^d = \frac{\Gamma(\bar{B}_d \to l^+ X) - \Gamma(B_d \to l^- X)}{\Gamma(\bar{B}_d \to l^+ X) + \Gamma(B_d \to l^- X)}$$

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

★ SM: $A_{SL}^d \approx -5 \cdot 10^{-4}$, $S_{\psi K_s} \approx 0.69$

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.*, arXiv:09xx.xxxx

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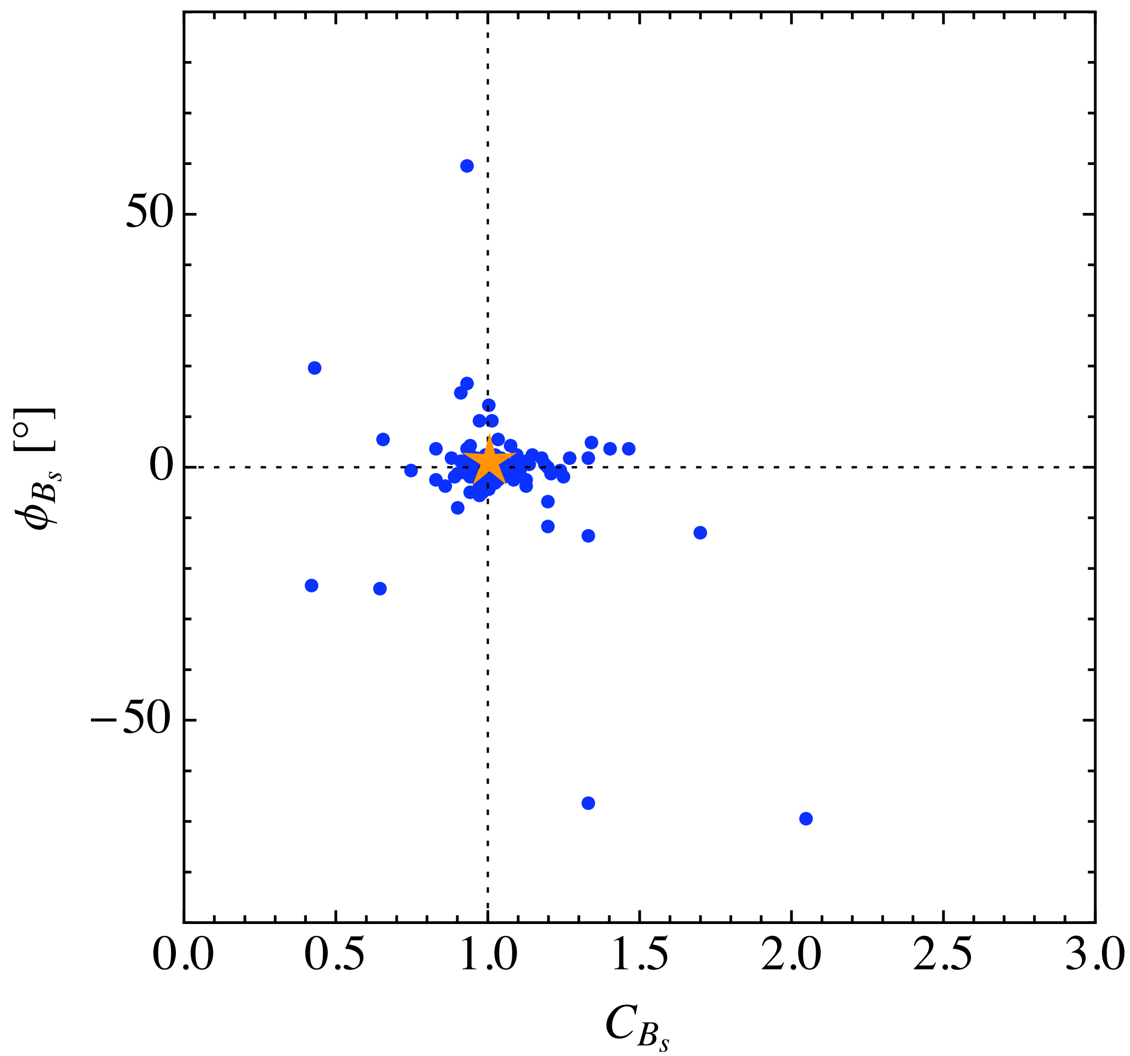


$$C_{B_s}\, e^{2i\phi_{B_s}} = \frac{\langle B_s|\mathcal{H}^{\Delta B=2}_{\text{eff,full}}|\bar{B}_s\rangle}{\langle B_s|\mathcal{H}^{\Delta B=2}_{\text{eff,SM}}|\bar{B}_s\rangle}$$

★ SM: $C_{B_s} = 1,\ \phi_{B_s} = 0^\circ$

● 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.*, arXiv:09xx.xxxx

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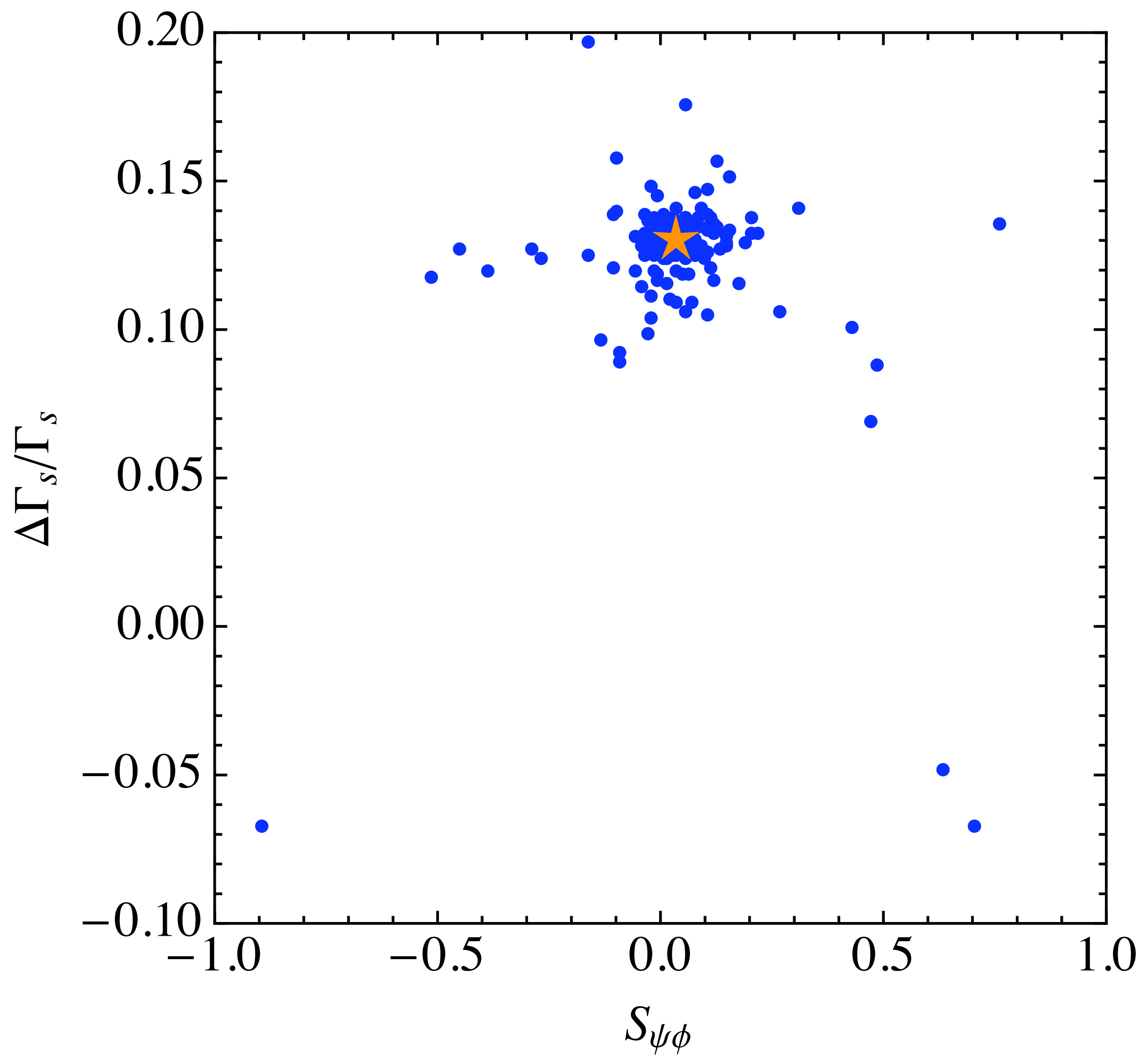



$$\Delta\Gamma_s = \Gamma_L^s - \Gamma_S^s$$
$$= 2\,|\Gamma_{12}^s|\cos(2|\beta_s| - 2\phi_{B_s})$$

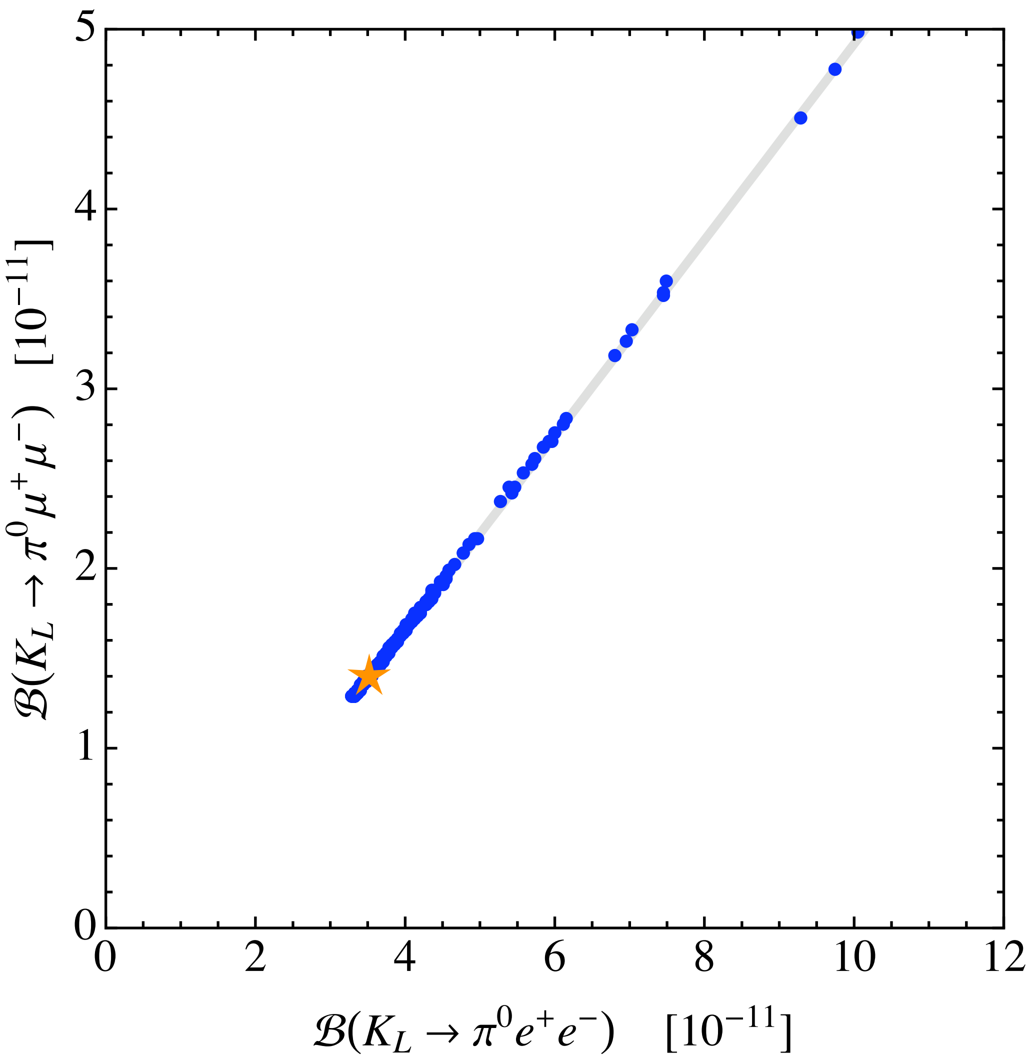
★ SM: $\Delta\Gamma_s/\Gamma_s \approx 0.13$, $S_{\psi\phi} \approx 0.04$

● 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.*, arXiv:09xx.xxxx

# Rare $K$ decays: Silver modes*

- Order one enhancements possible in $K_L \longrightarrow \pi^0 l^+ l^-$ modes. Effects in $e^+e^-$ and $\mu^+\mu^-$ channel are strongly correlated due to axial-vector dominance




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

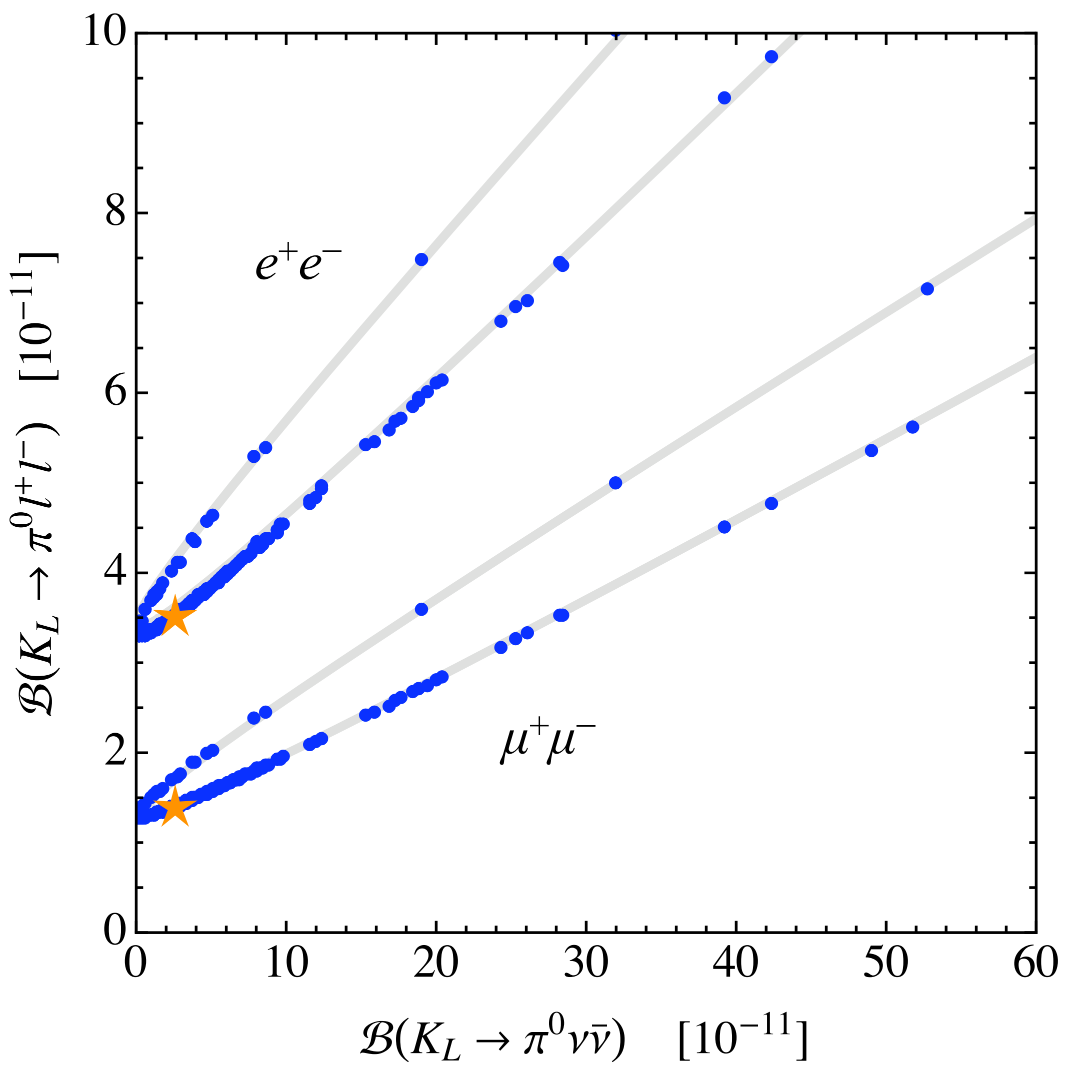
— model-independent prediction

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

*Bauer *et al*., arXiv:09xx.xxxx

# 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




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

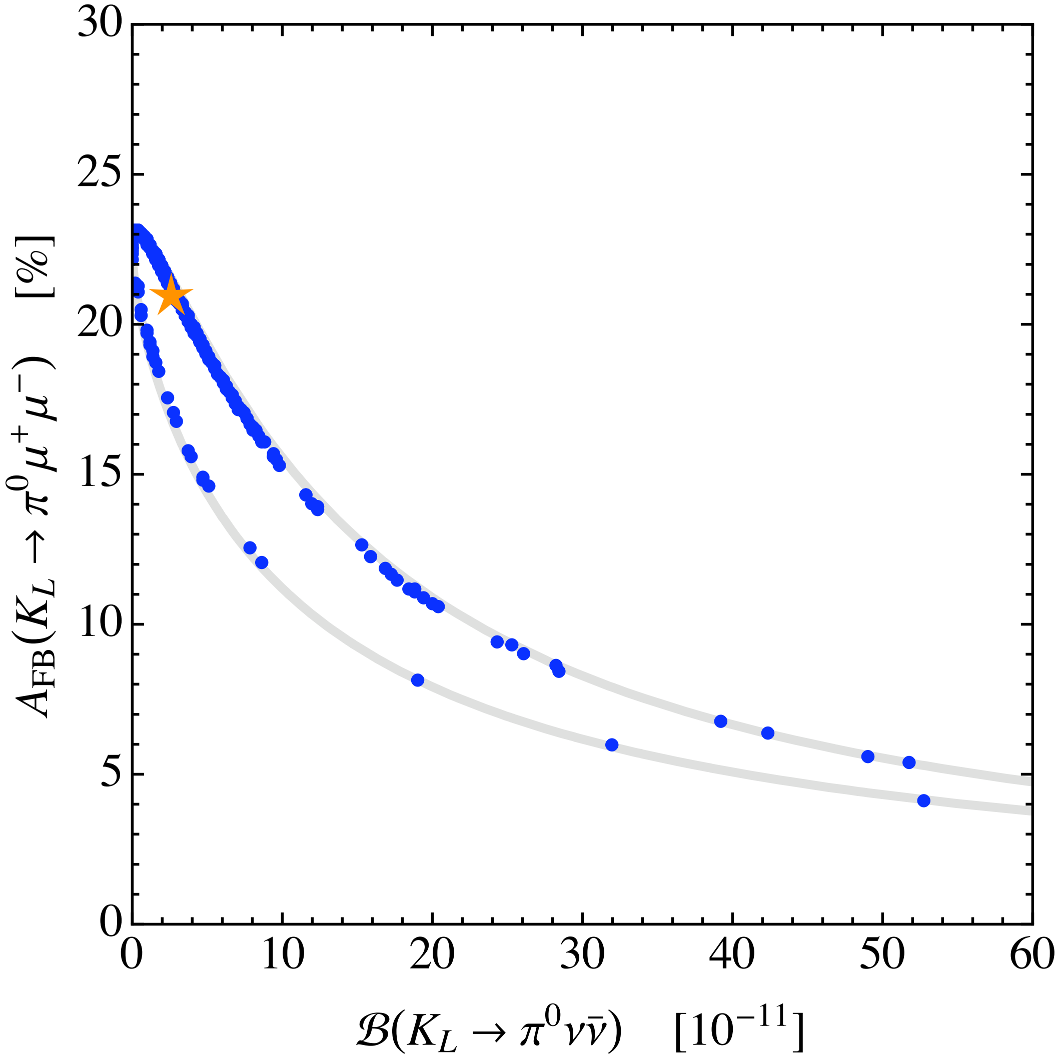
— model-independent prediction

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

*Bauer *et al.*, arXiv:09xx.xxxx

# 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: $\mathcal{B}(K_L \longrightarrow \pi^0 \nu\bar{\nu}) \approx 2.7 \cdot 10^{-11}$,
$A_{\rm FB}(K_L \longrightarrow \pi^0 \mu^+\mu^-) \approx 21\%$
for constructive interference

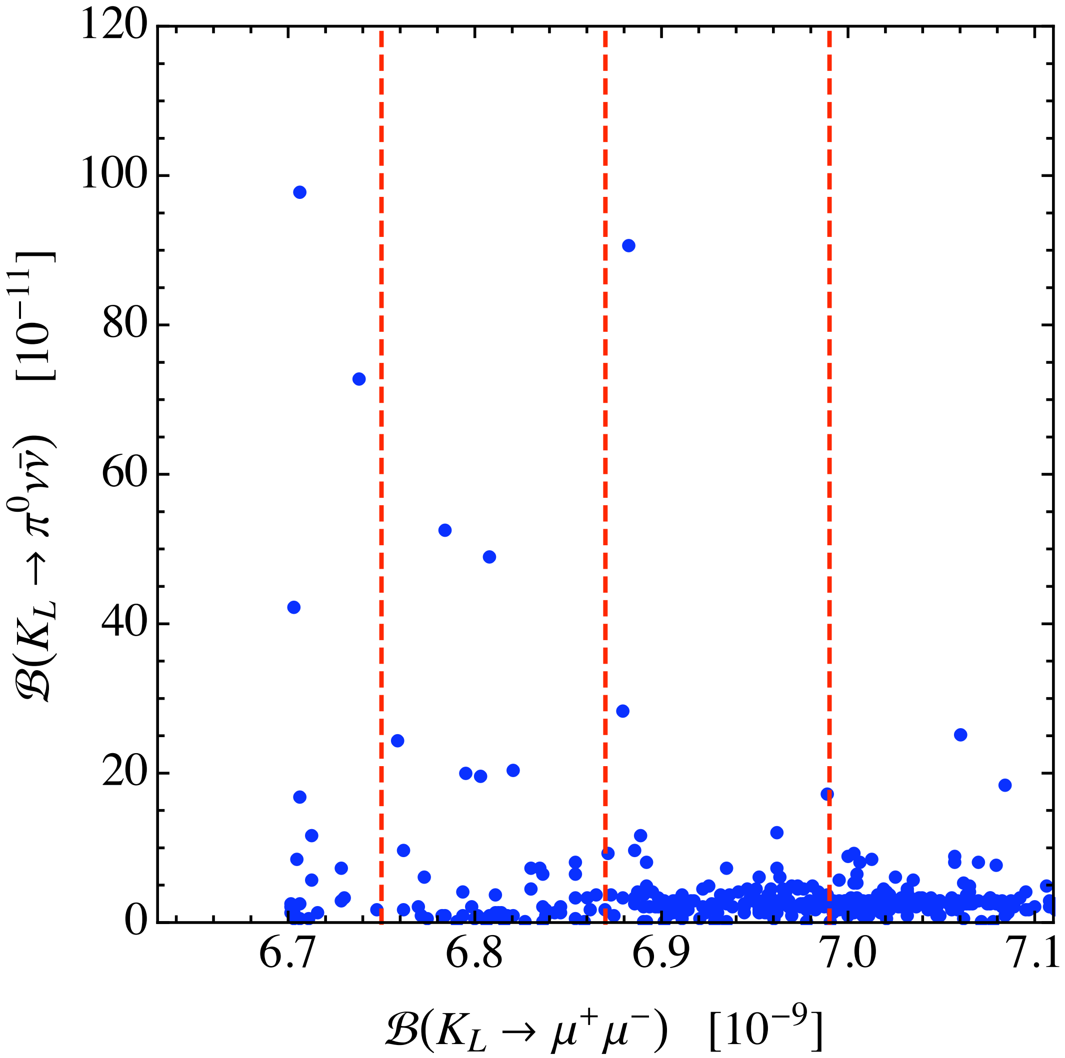
— model-independent prediction

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

*Bauer *et al.*, arXiv:09xx.xxxx

# Rare $K$ decays: Bronze mode*

- Better theoretical understanding of precisely measured $K_L \to \mu^+\mu^-$ mode could allow to constrain possible enhancement of $K_L \to \pi^0 \nu\bar{\nu}$



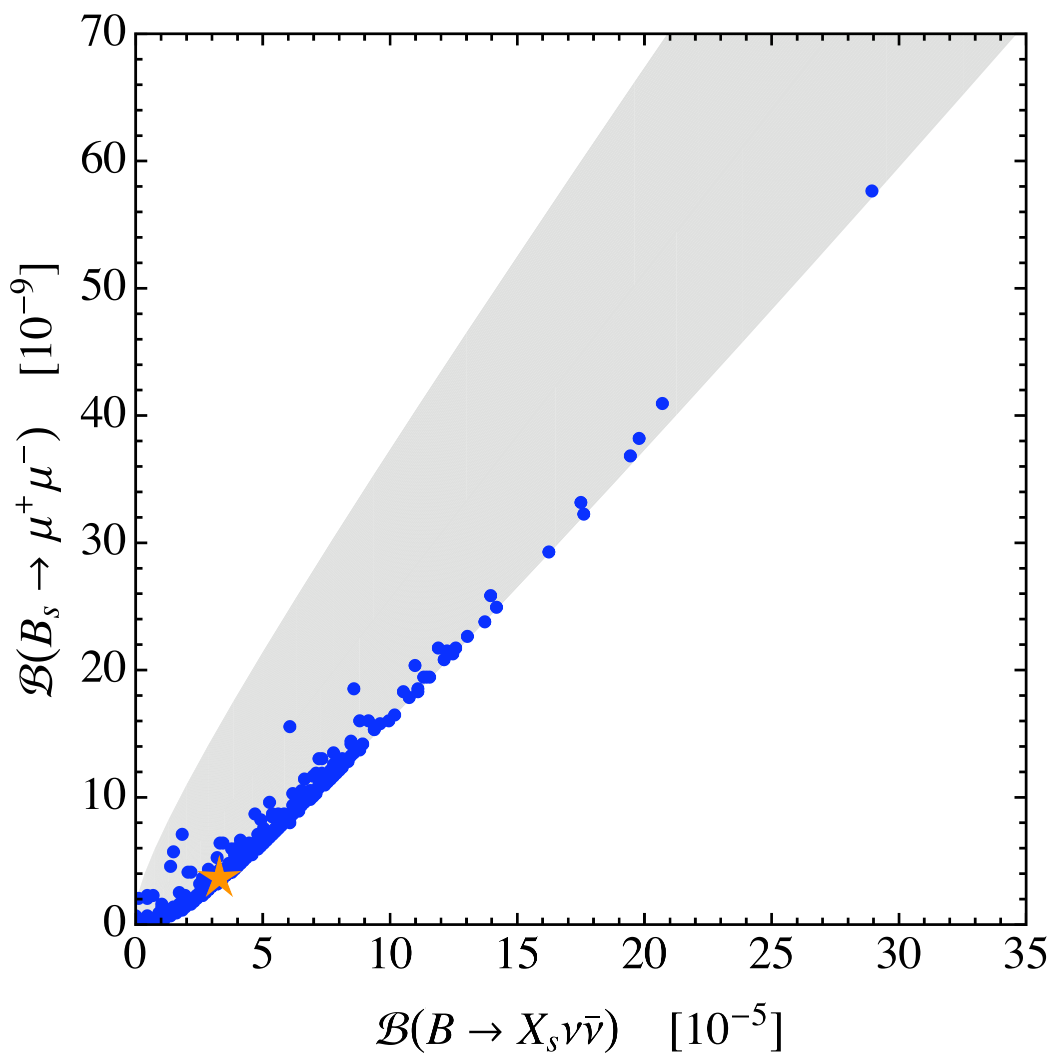

PDG central value and $3\sigma$ range
$\mathcal{B}(K_L \to \mu^+\mu^-) = (6.87 \pm 0.12) \cdot 10^{-9}$

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

*Bauer *et al.*, arXiv:09xx.xxxx

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

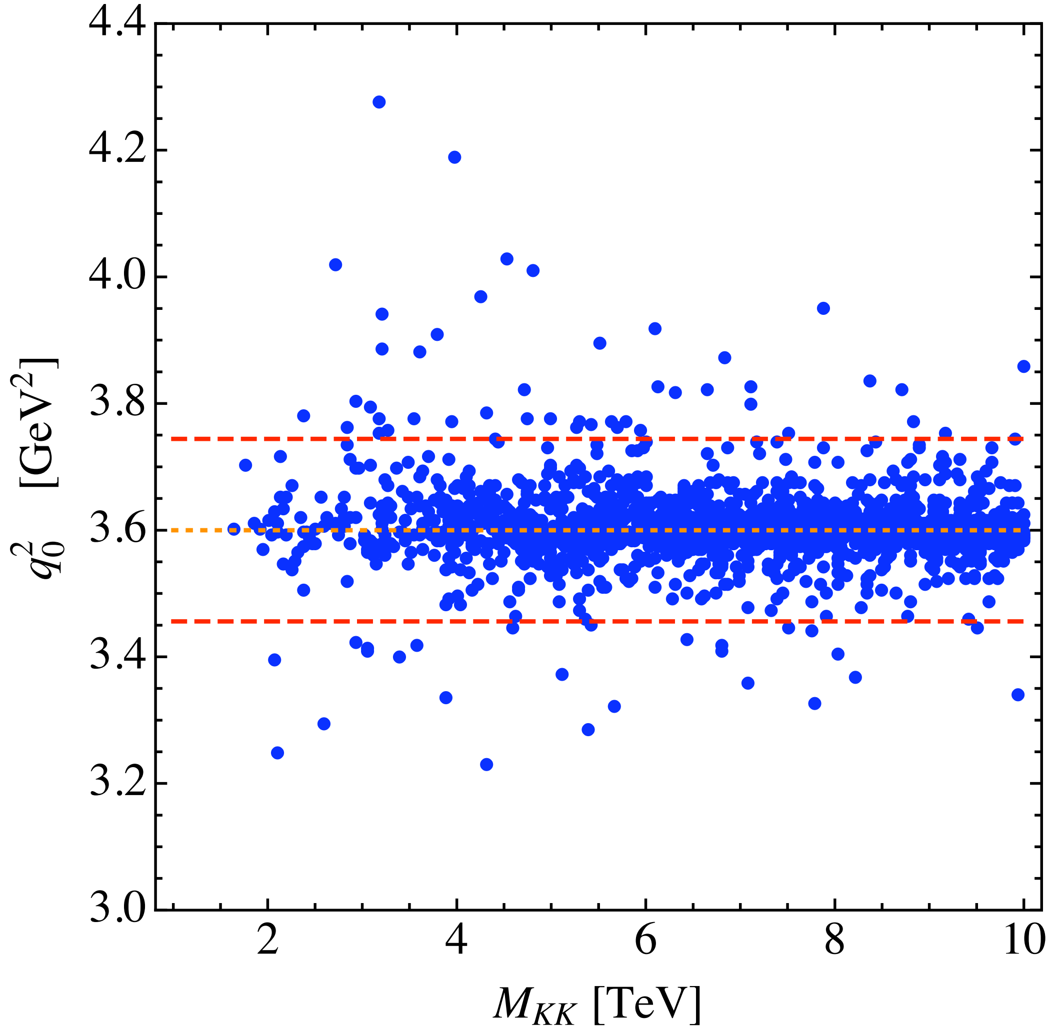
model-independent prediction

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

*Bauer *et al.*, arXiv:09xx.xxxx

# Rare $B$ decays: Inclusive semileptonic modes*

- Deviations of zero of 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: $q_0^2 \approx 3.6\,\text{GeV}^2$

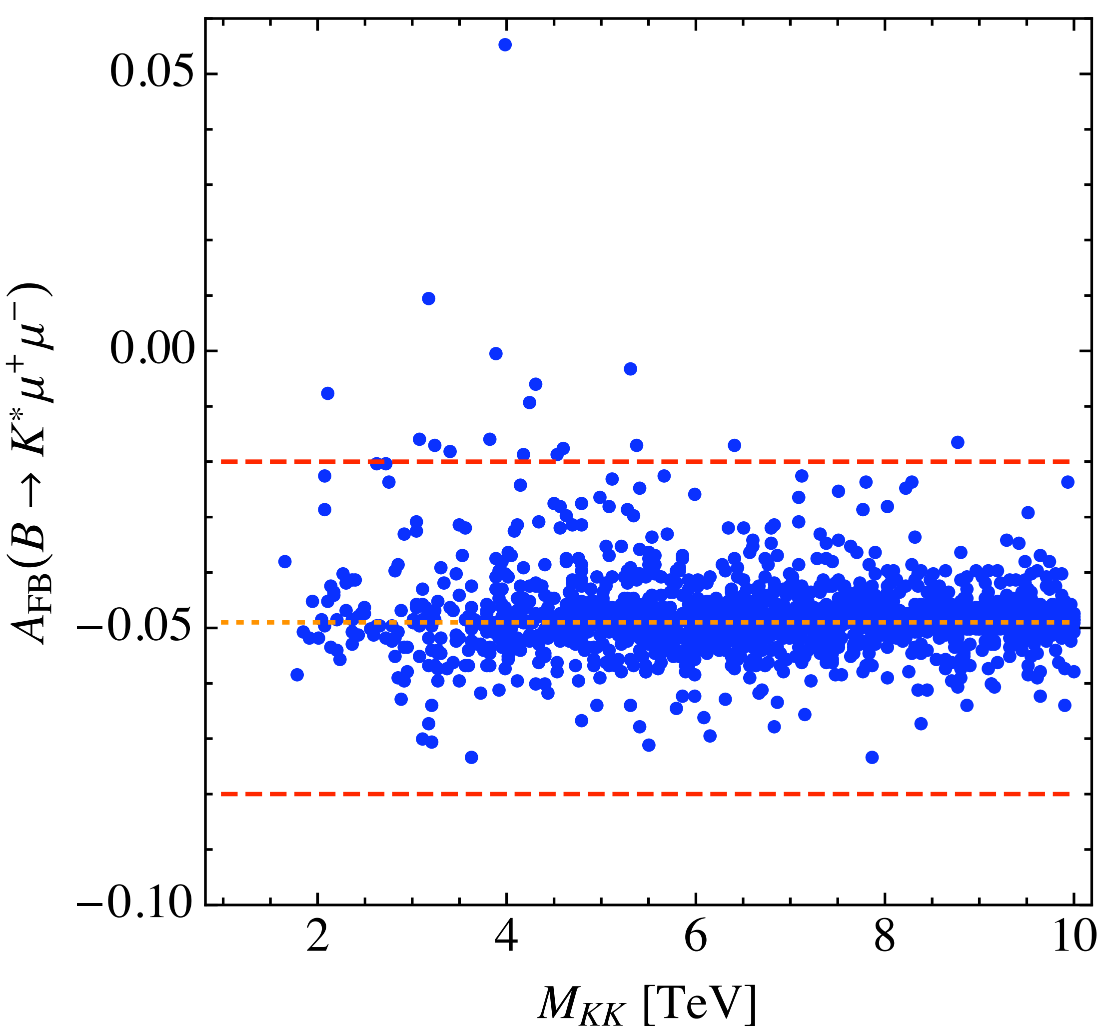
expected sensitivity at SuperB factory, 75 ab$^{-1}$

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

*Bauer *et al.*, arXiv:09xx.xxxx

# Rare $B$ decays: Exclusive semileptonic modes*

- Corrections to $A_{\mathrm{FB}}(B \to K^* \mu^+ \mu^-)$ on average below LHCb sensitivity. Other angular distributions such as $A_{\mathrm{T}}^{(3)}(B \to K^* \mu^+ \mu^-)$ might offer better prospects




SM: $A_{\mathrm{FB}}(B \to K^* \mu^+ \mu^-) \approx -0.05$ for $q^2 \in [1, 6]$ GeV$^2$

expected sensitivity of LHCb, 2 fb$^{-1}$

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

*Bauer *et al.*, arXiv:09xx.xxxx