Flavor physics in a model with a warped extra dimension*

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*in collaboration with

M. Bauer, F. Goertz, L. Gründer, U. Haisch, M. Neubert, and T. Pfoh,

arXiv: 0807.4537 and papers in preparation

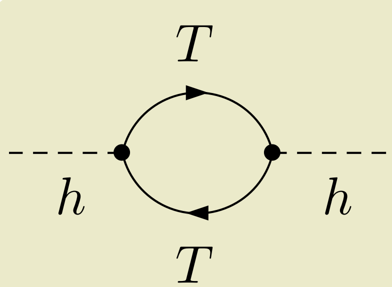
About hierachy vs. flavour

$$\mathcal{L}_{\text{EFT}} = \underbrace{\Lambda_{\text{UV}}^2 \Phi^\dagger \Phi - \lambda(\Phi^\dagger \Phi)^2}_{\text{electroweak symmetry breaking (EWSB)}} + \mathcal{L}_{\text{SM}}^{\text{gauge}} + \mathcal{L}_{\text{SM}}^{\text{Yukawa}} + \underbrace{\frac{\mathcal{L}^{(5)}}{\Lambda_{\text{UV}}} + \frac{\mathcal{L}^{(6)}}{\Lambda_{\text{UV}}^2}}_{\text{generic flavor structure}} + \ldots$$

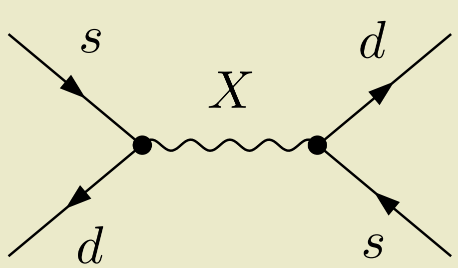
electroweak symmetry breaking (EWSB) $\Downarrow$ Higgs mass

$\Downarrow$ generic flavor structure

large FCNCs



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



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

no fine-tuning $\Downarrow$

bounds on flavor mixing $\Downarrow$

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

and indeed there is a problem of flavor ...

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

no fine-tuning $\Downarrow$ bounds on flavor mixing $\Downarrow$

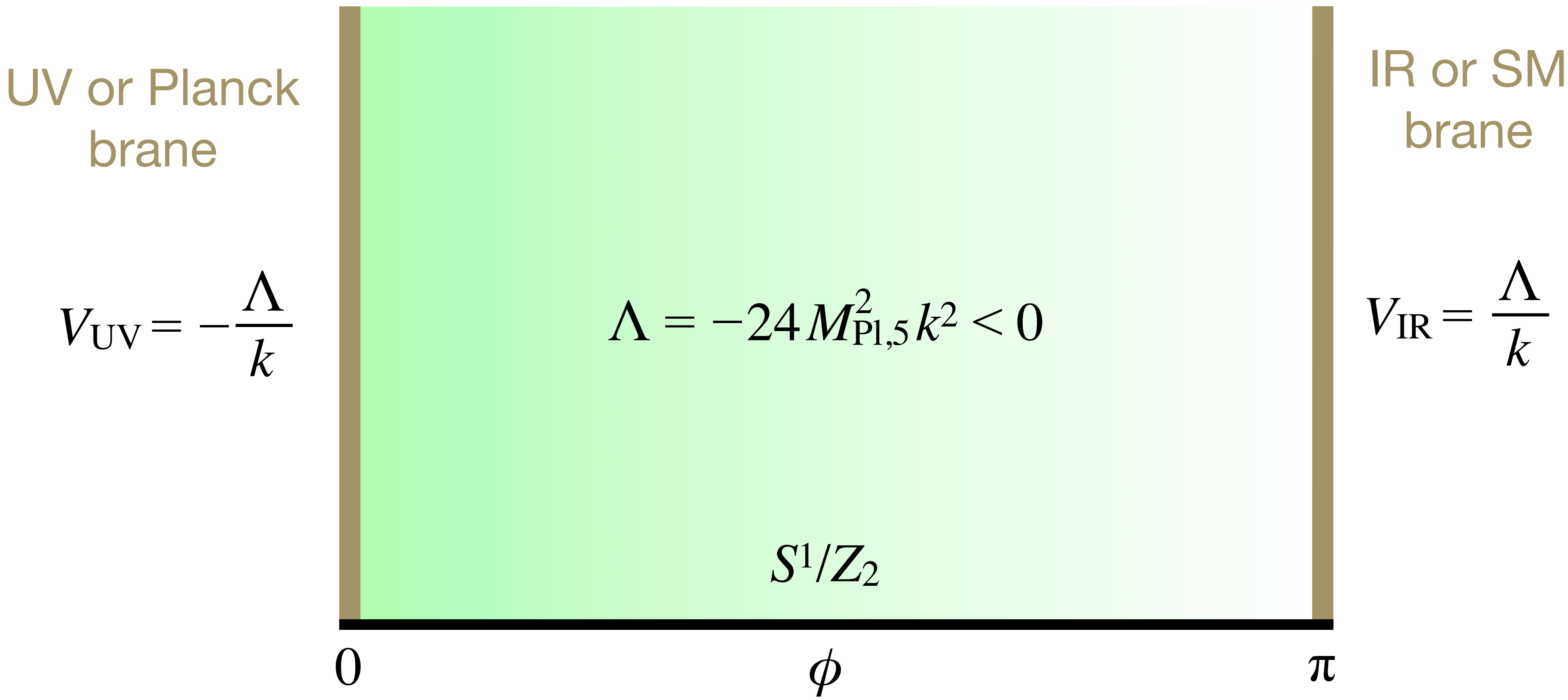
$\Lambda_{\mathrm{Higgs}} \lesssim 1$ TeV $\longrightarrow$ increasing energy scale $\longrightarrow$ $\Lambda_{\mathrm{flavor}} \gtrsim 10^3$ TeV

- Solution to flavor problem and explanation for $\Lambda_{\mathrm{Higgs}} << \Lambda_{\mathrm{flavor}}$:

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

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

RS model: Geometry

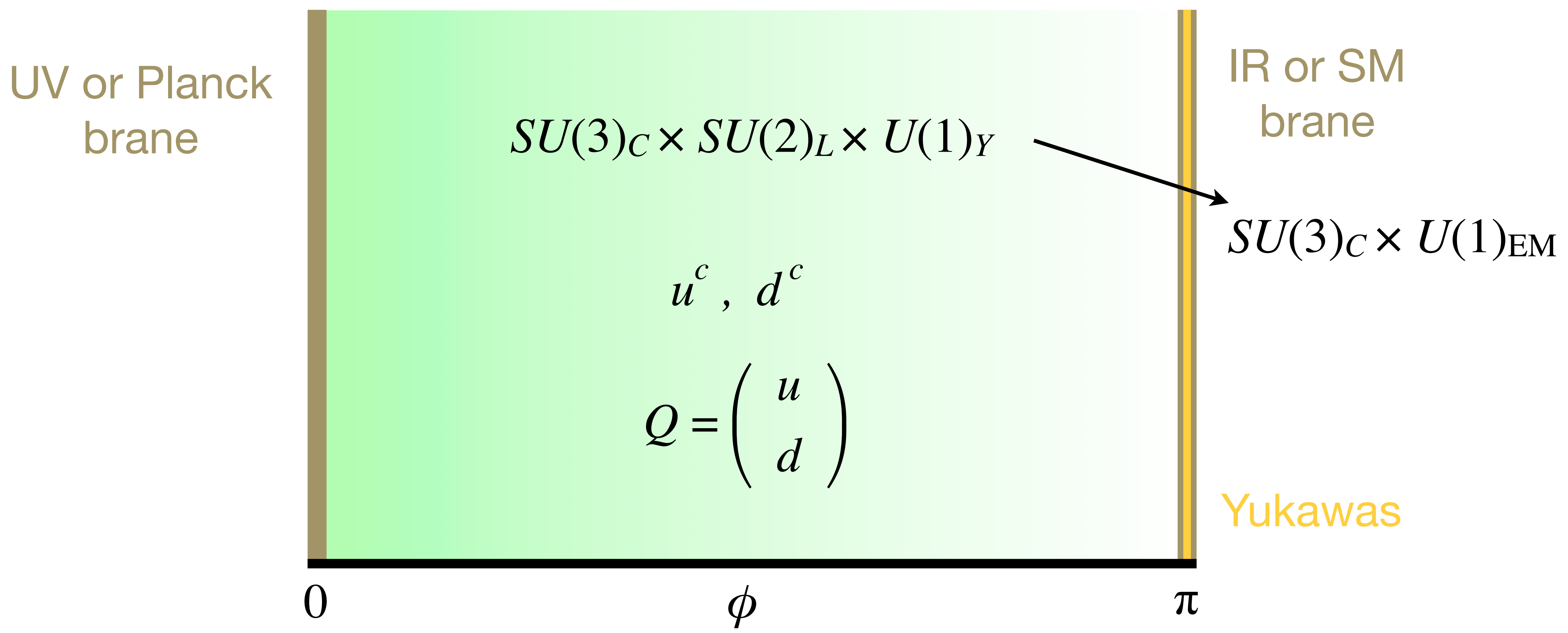


<u>Slice of AdS$_5$ with curvature k:</u>

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

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

RS model: Particle content

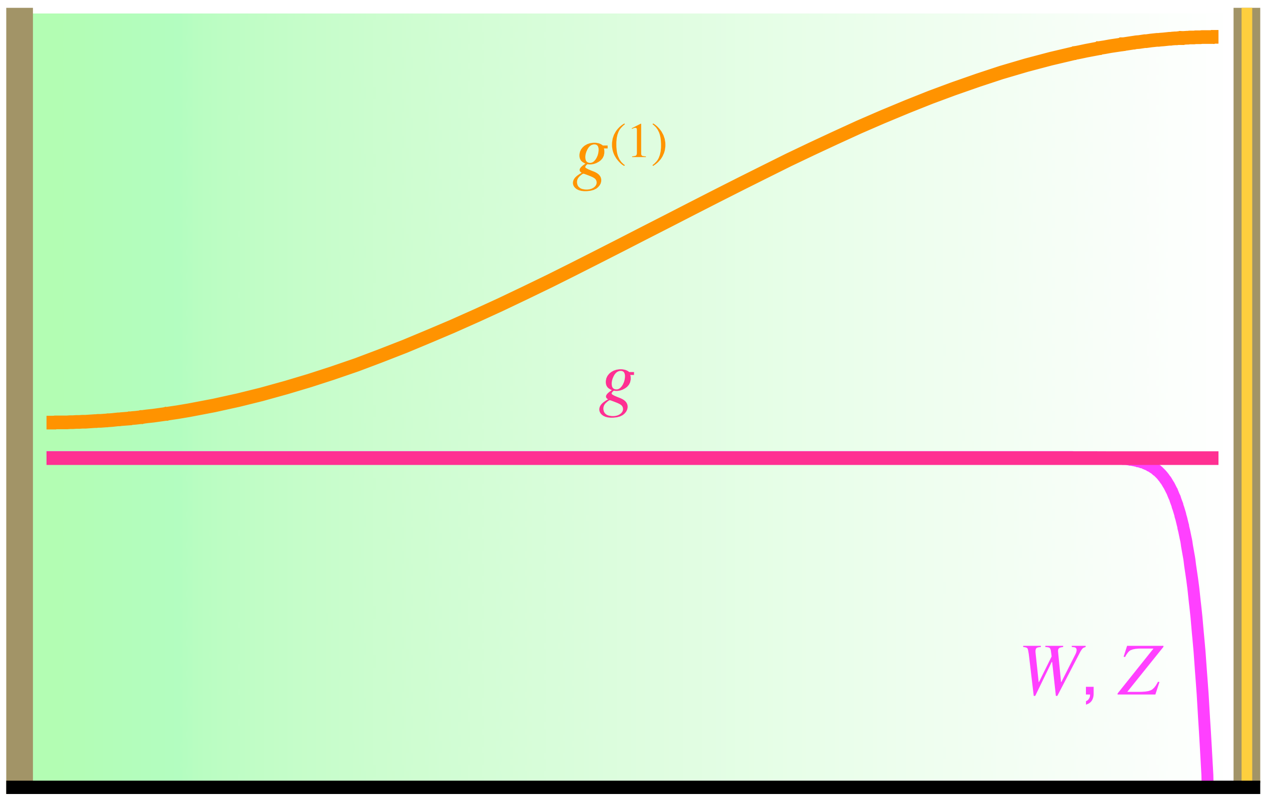


Bulk fermions and brane-localized Yukawas:

$$\mathcal{L}_{\text{ferm}} = e^{-3\sigma}\,\text{sgn}(\phi)\left(\bar{Q}\boldsymbol{M}_Q Q + \bar{q}^c \boldsymbol{M}_q q^c\right) + \frac{\sqrt{2}v\,e^{-5\sigma}}{kr}\,\delta(|\phi|-\pi)\left[\bar{q}_L \boldsymbol{Y}_q q_R^c + \text{h.c.}\right] + \ldots$$

Parameters $c_{Q,q} = \pm M_{Q,q}/k$ control localization of fermion profiles in 5th dimension

RS model: Gauge boson profiles*



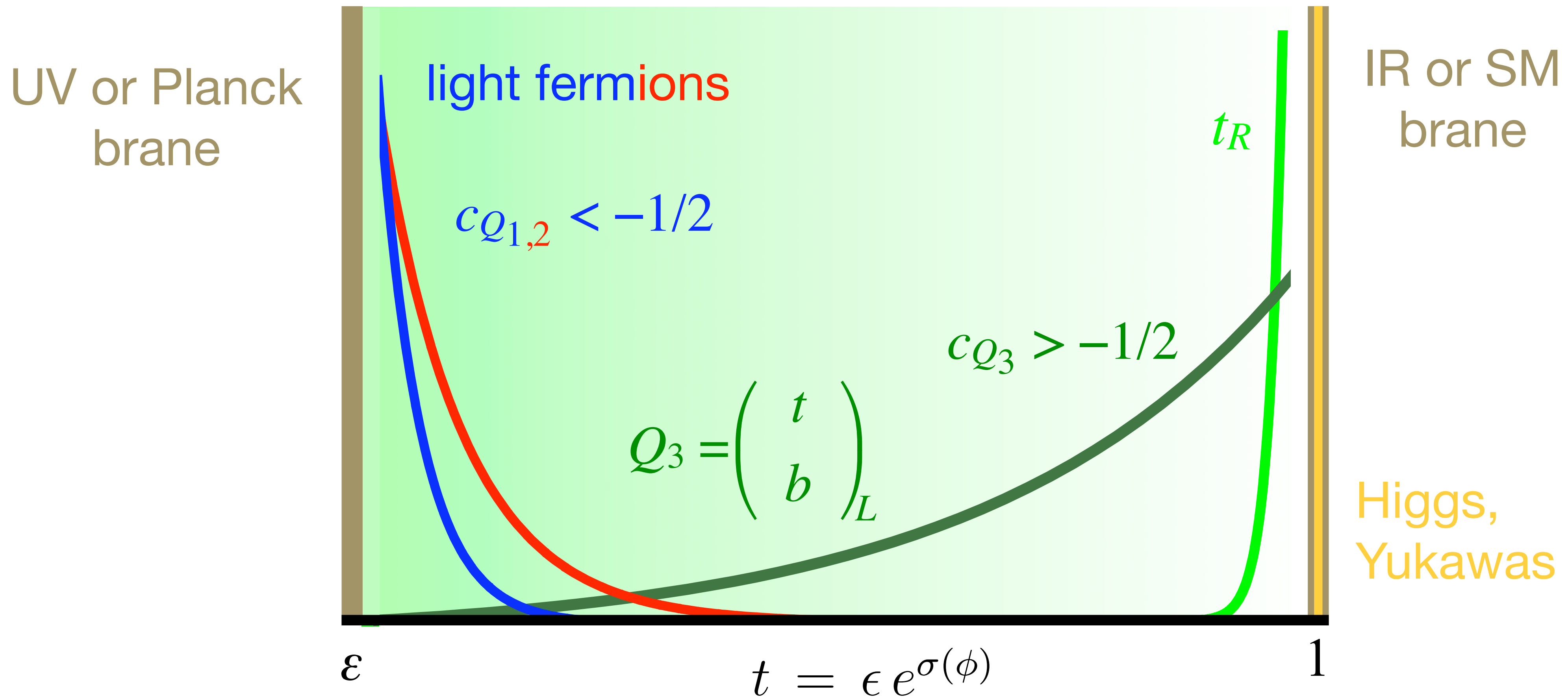
Profiles of gauge fields:

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

Wave functions of heavy gauge bosons and KK excitations peaked at IR brane

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

RS model: Fermion profiles*



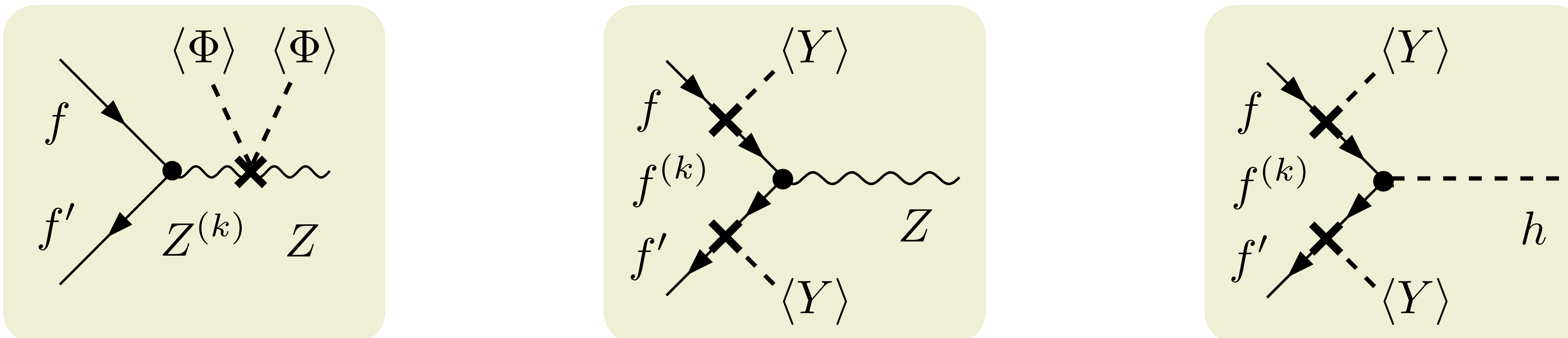
Profiles of fermion fields:

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

Top quark lives in IR to generate its large mass, while light fermions live in UV

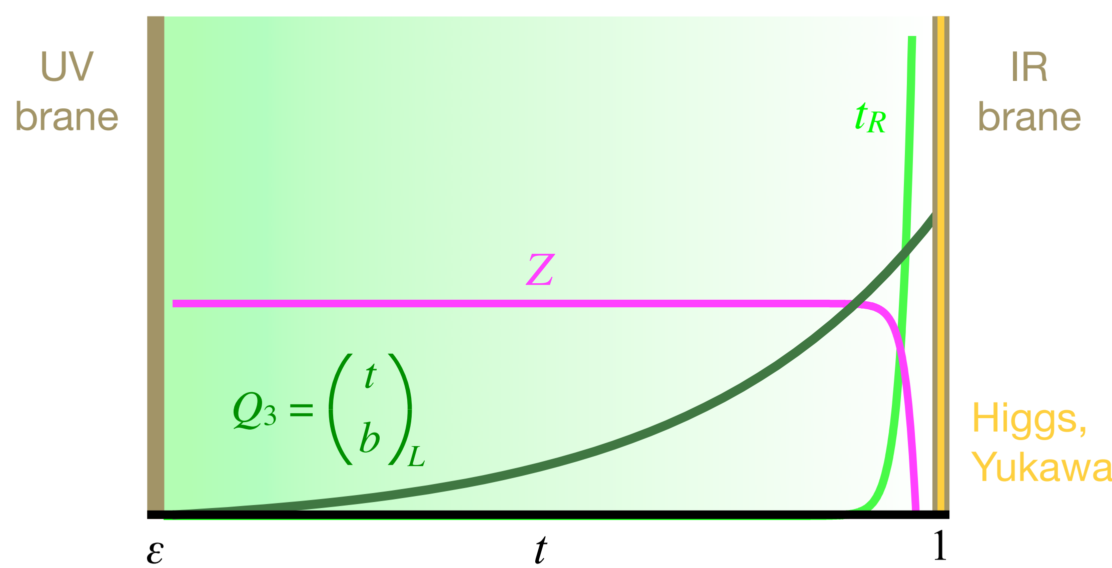
*Grossman and Neubert, hep-ph/9912408; Ghergetta and Pomarol, hep-ph/0003129, Casagrande *et al.*, arXiv:0807.4537

Sources of flavor violation: Light weak bosons



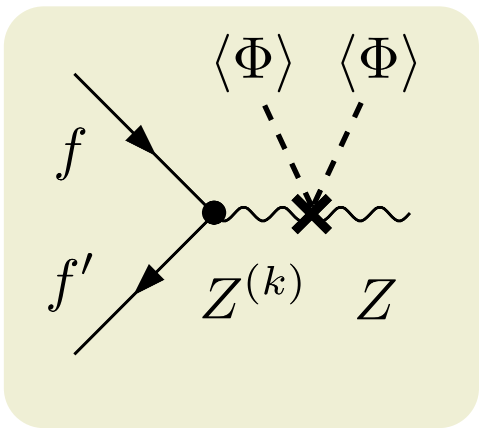
<u>Couplings of light weak bosons:</u>

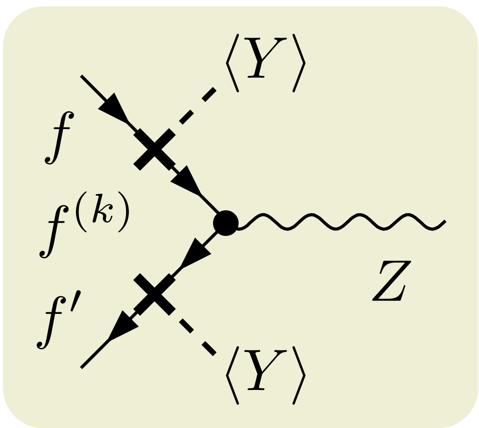
- flavor violation from modification of W, Z boson profiles due to EWSB on IR brane*
- flavor violation from non-orthonormality of fermion profiles interpreted as mixing of $SU(2)_L$ singlet and doublets

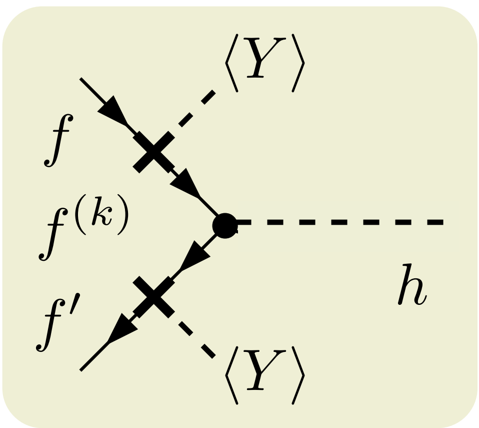


*Csaki *et al.*, hep-ph/0203034

Sources of flavor violation: Light weak bosons







<u>Couplings of light weak bosons:</u>

- flavor violation from modification of W, Z boson profiles due to EWSB on IR brane

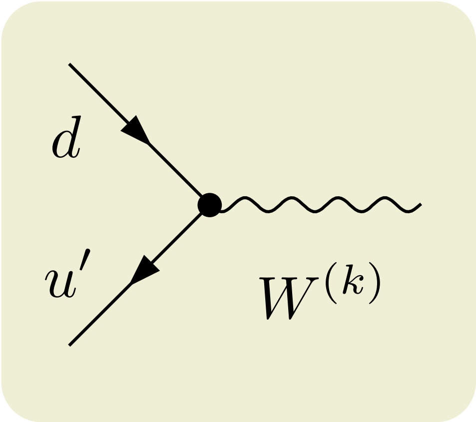
$$\int_{-\pi}^{\pi} d\phi\, e^{\sigma}\, C_m^{(A)}\, C_n^{(A)} = \delta_{mn} + \Delta C_{mn}^{(A)}\,,$$

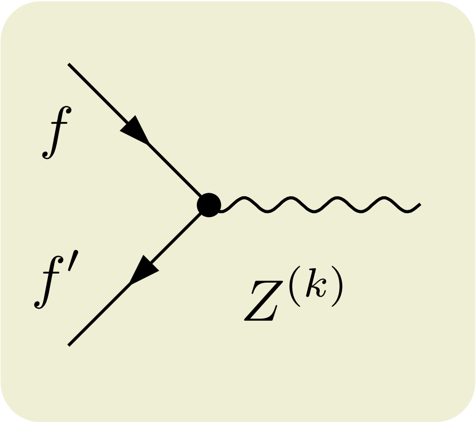
- flavor violation from non-orthonormality of fermion profiles interpreted as mixing of $SU(2)_L$ singlet and doublets*

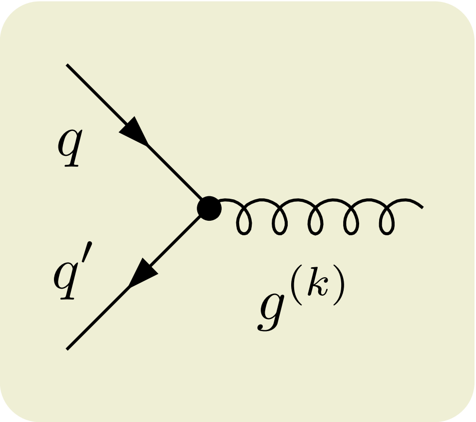
$$\int_{-\pi}^{\pi} d\phi\, e^{\sigma}\, S_m^{(A)}\, S_n^{(A)} = \delta_{mn} + \Delta S_{mn}^{(A)}$$

*Casagrande *et al.*, arXiv:0807.4537

Sources of flavor violation: KK gauge bosons

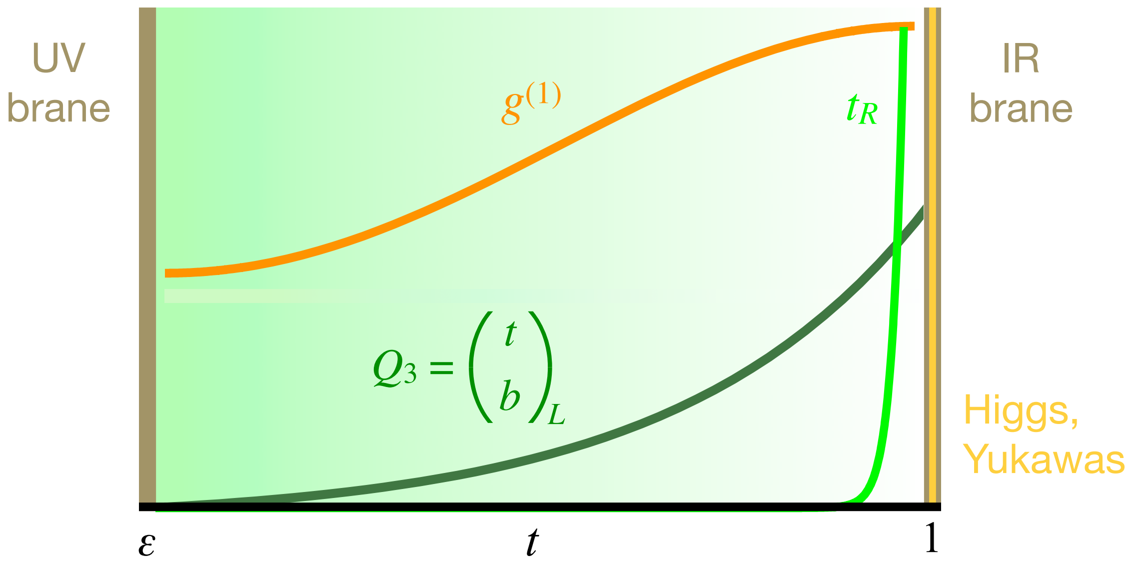






Couplings of KK gauge bosons*:

- flavor violation from non-trivial overlap integrals of KK gauge-boson profiles with SM fermion wave functions
- dominant corrections arise typically from vertices involving KK gluons



*Burdman, hep-ph/0310144; Agashe *et al*., hep-ph/0406101, hep-ph/0408134

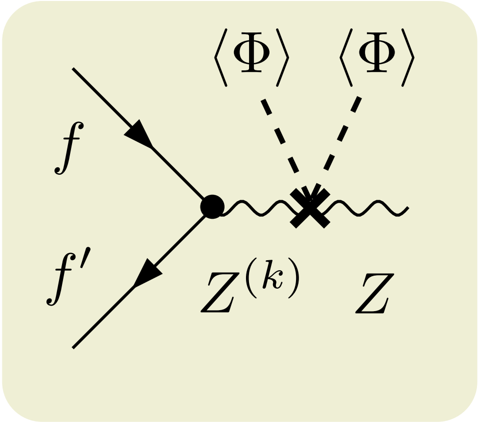
Mixing matrices: Scaling relations

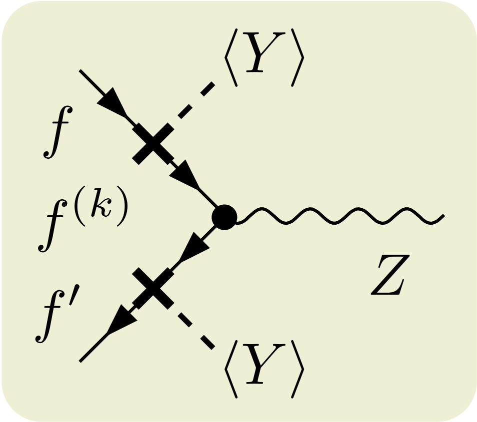
$$(\Delta_Q^{(\prime)})_{ij} \sim F_{c_{Q_i}} F_{c_{Q_j}} \,, \qquad (\delta_Q)_{ij} \sim \frac{m_{q_i} m_{q_j}}{M_{\rm KK}^2} \frac{1}{F_{c_{q_i}} F_{c_{q_j}}} \sim \frac{v^2 Y_q^2}{M_{\rm KK}^2} F_{c_{q_i}} F_{c_{q_j}} \,,$$

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

<u>Implications of scaling relations:</u>

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

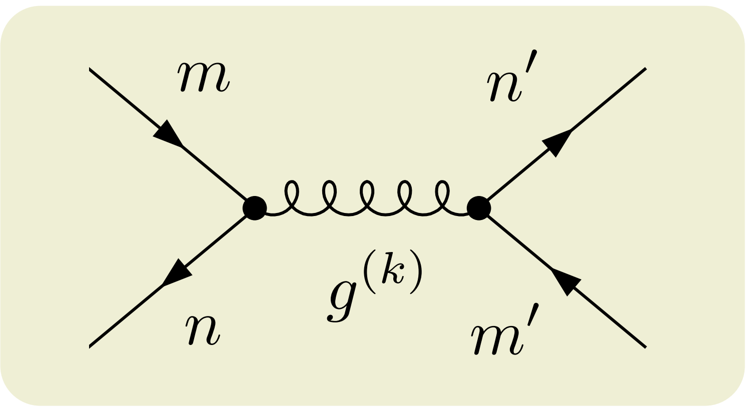


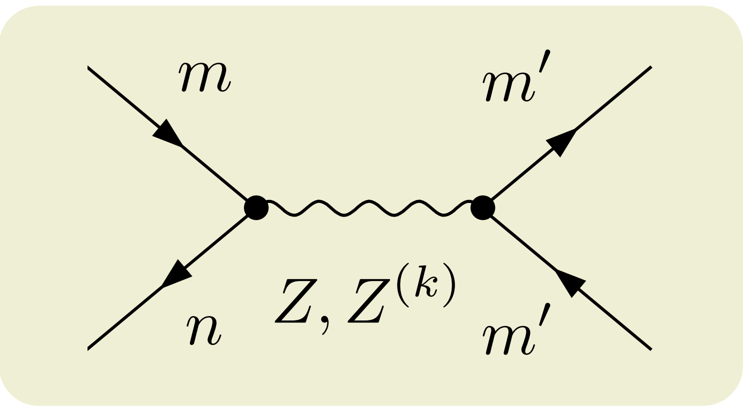


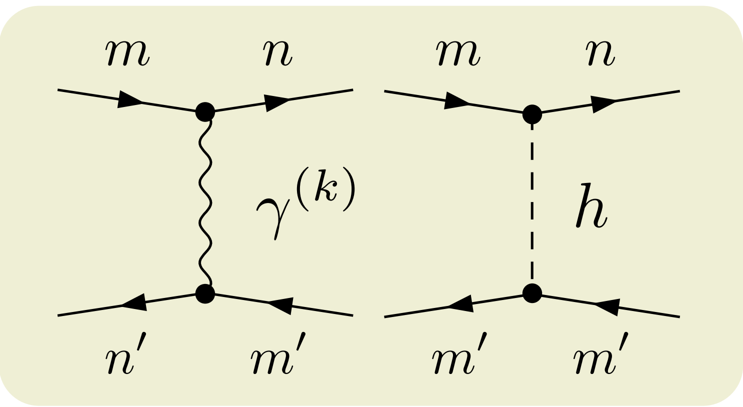
*Agashe *et al.*, hep-ph/0406101, hep-ph/0408134

Anatomy of tree-level FCNC processes

- Three types of generic contributions to dimension six operators:







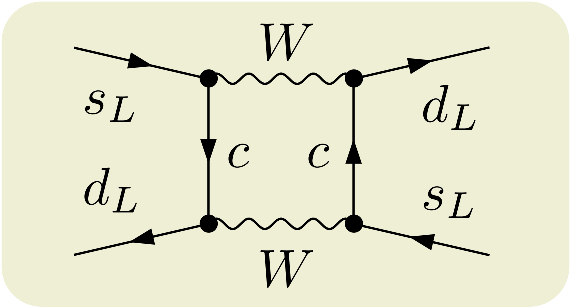
dominant contribution to $\Delta F = 2$ processes	dominant contribution to $\Delta F = 1$ processes	small contributions to $\Delta F = 1, 2$ processes

- 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

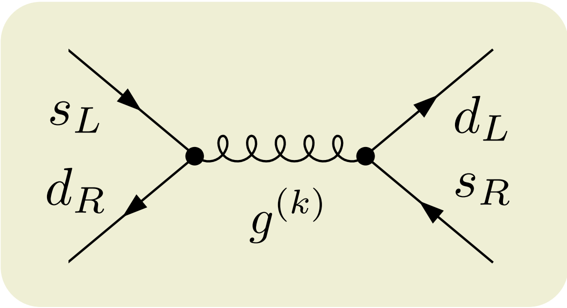
Meson mixing: Effective Hamiltonian

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

SM



RS



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

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

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

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

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

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

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

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

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

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

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

*Bauer *et al.*, arXiv:08xx.xxxx

Meson mixing: Neutral kaons*

- Presence of tree-level FCNCs mediated by vector bosons generically leads to disastrous effects. Bounds on $\Delta F = 2$ Wilson coefficients allow for sanity check in any BSM model.
- In RS scenario model-independent limit on $\mathrm{Im}\, C_4$ following from ε_K imply that KK gluon mass has to be generically larger than $20\ \mathrm{TeV}$
- Reason for stringent limit is enhancement of matrix element of Q_4 by renormalization group evolution and chiral factor $(m_K/m_s)^2$

$$|\Delta\epsilon_K|_{\mathrm{RS}} \propto \mathrm{Im}\left[C_1 + \widetilde{C}_1 + 115\left(C_4 + \frac{C_5}{3}\right)\right]$$

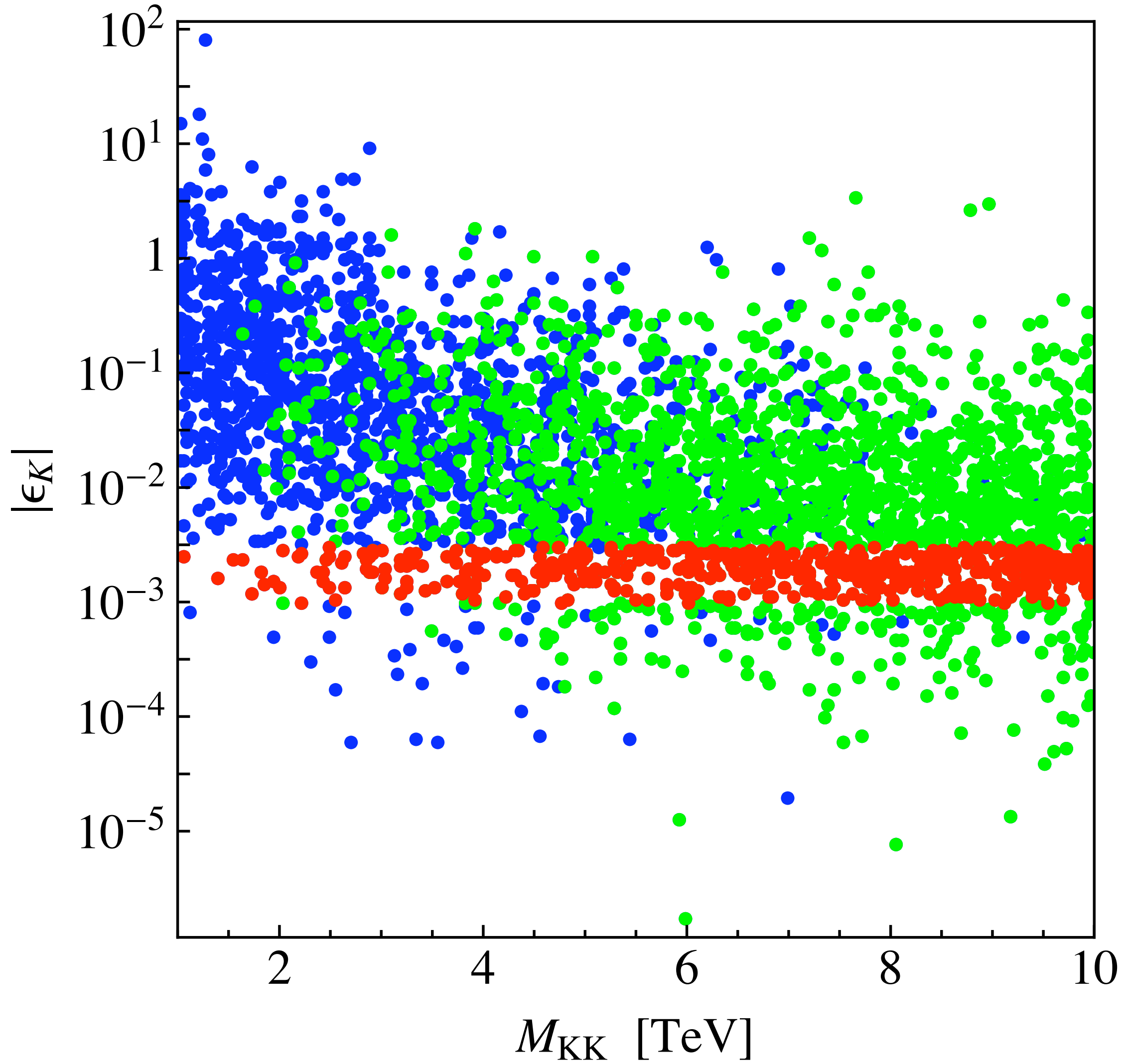
<u>In RS model:</u>

$$\mathrm{Re}\,(\epsilon_K)_{\mathrm{RS}} \approx -\frac{3.8 \cdot 10^{-3}\, \mathrm{Im}\big[(\Delta_D)_{12}(\Delta_d)_{12} - 1.4 \cdot 10^{-3}\,\big((\Delta_D)_{12}^2 + (\Delta_d)_{12}^2\big)\big]}{10^{-12} M_{\mathrm{KK}}^2\, \mathrm{TeV}^{-2}}$$

*Bona *et al*. [UTfit Collaboration], arXiv:0707.0636; Csaki *et al*., arXiv:0804.1954

Meson mixing: Neutral kaons*

- Generically $|\varepsilon_K| \approx 100\,|\varepsilon_K|_{\rm exp}$ 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 with moderate fine-tuning



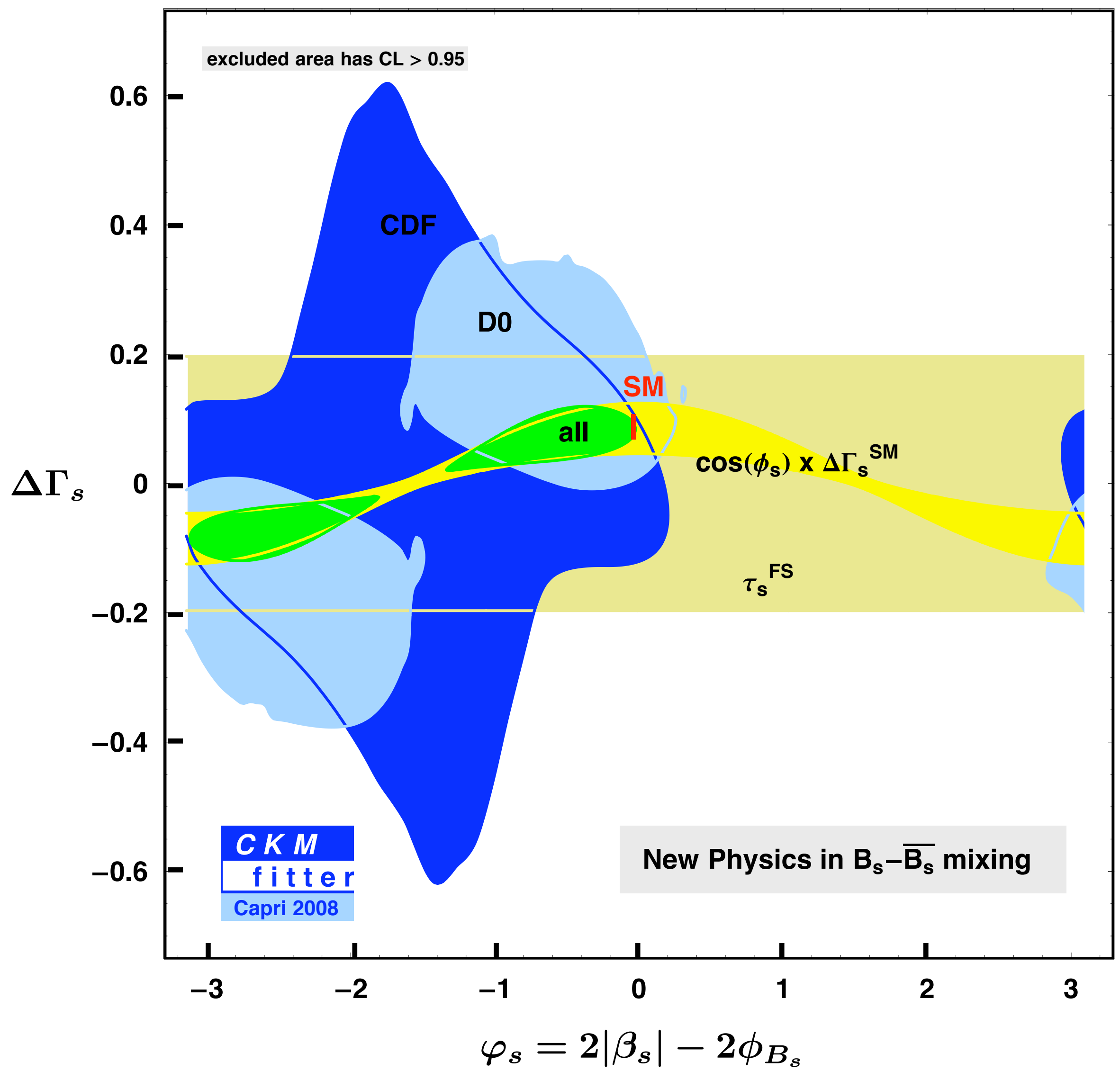
3000 randomly chosen RS points with $|Y_q| < 3$ reproducing quark masses and CKM parameters with $\chi^2/{\rm dof} < 11.5/10$ corresponding to 68% CL

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

*Blanke *et al.*, arXiv:0809.1073; Bauer *et al.*, arXiv:08xx.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:

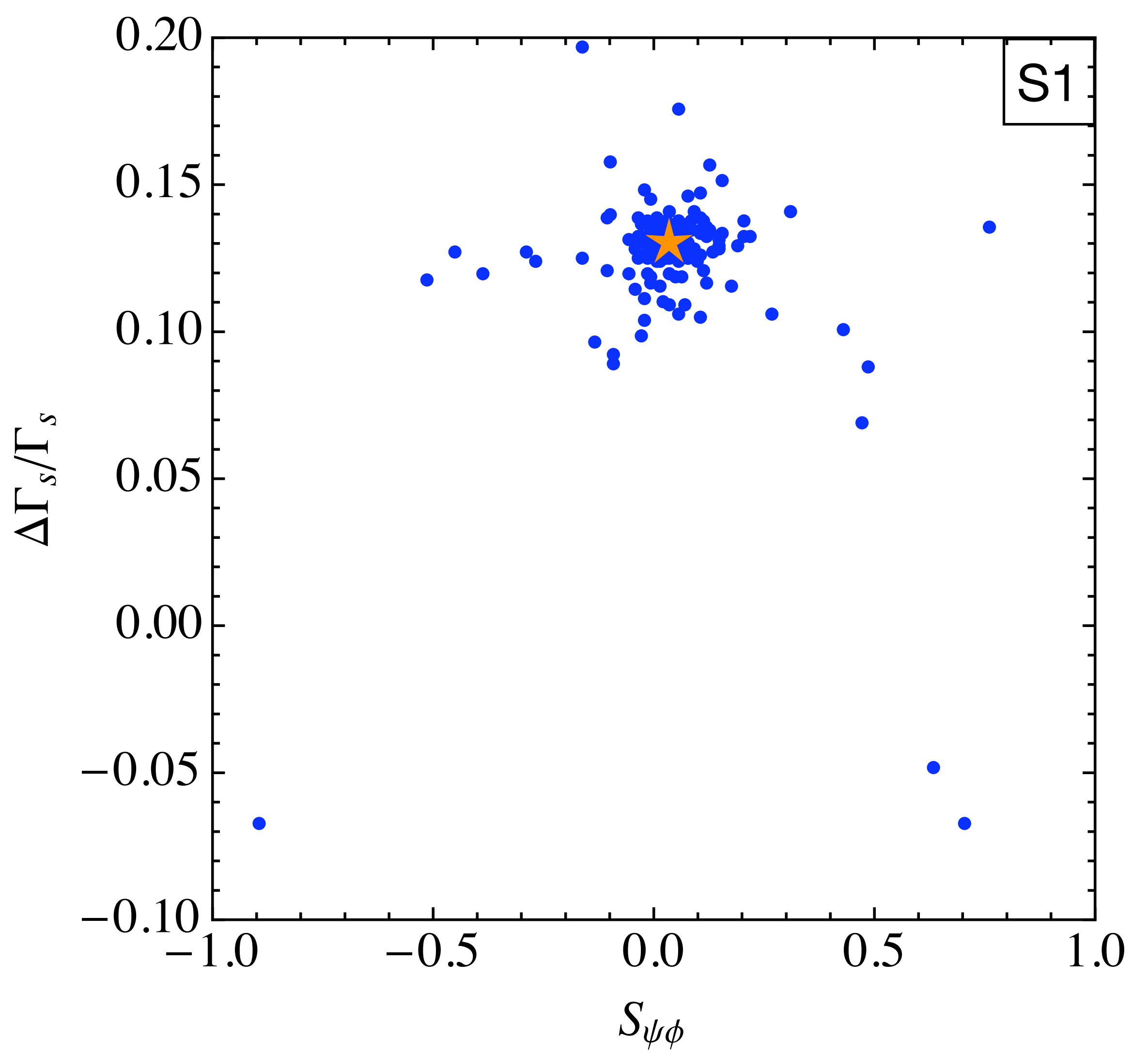
- CDF data only 2.1σ
- DØ data only 1.9σ
- CDF and DØ data 2.7σ
- full BSM physics fit 2.5σ

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 order one effects in width difference $\Delta\Gamma_s/\Gamma_s$ of B_s system



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

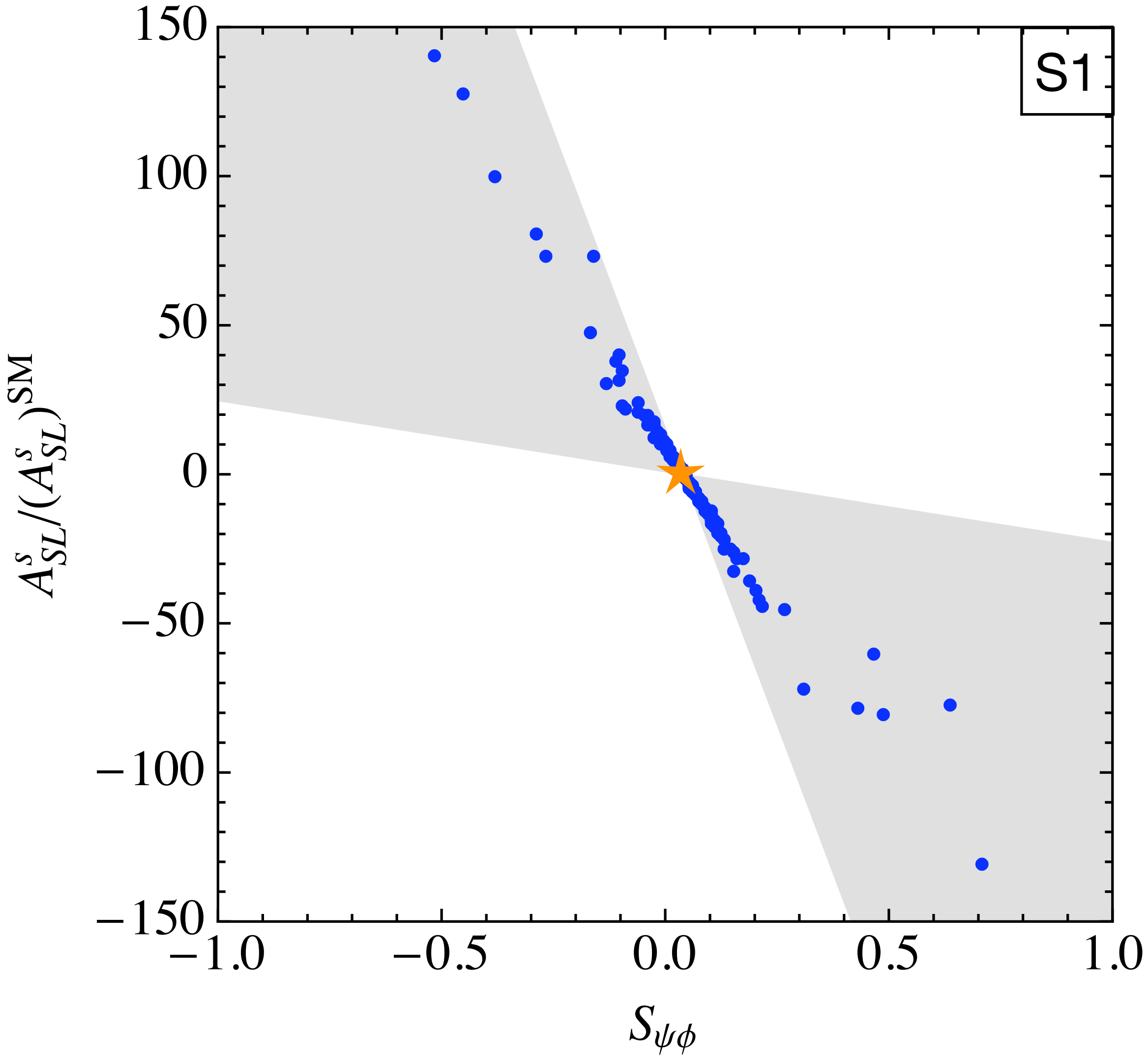
★ SM: $\Delta\Gamma_s/\Gamma_s \approx 0.13$, $S_{\psi\phi} \approx 0.04$

● 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.*, arXiv:08xx.xxxx

Meson mixing: Neutral B_s mesons*

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



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

$$= \text{Im}\left(\frac{\Gamma^s_{12}}{M^s_{12}}\right)$$

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

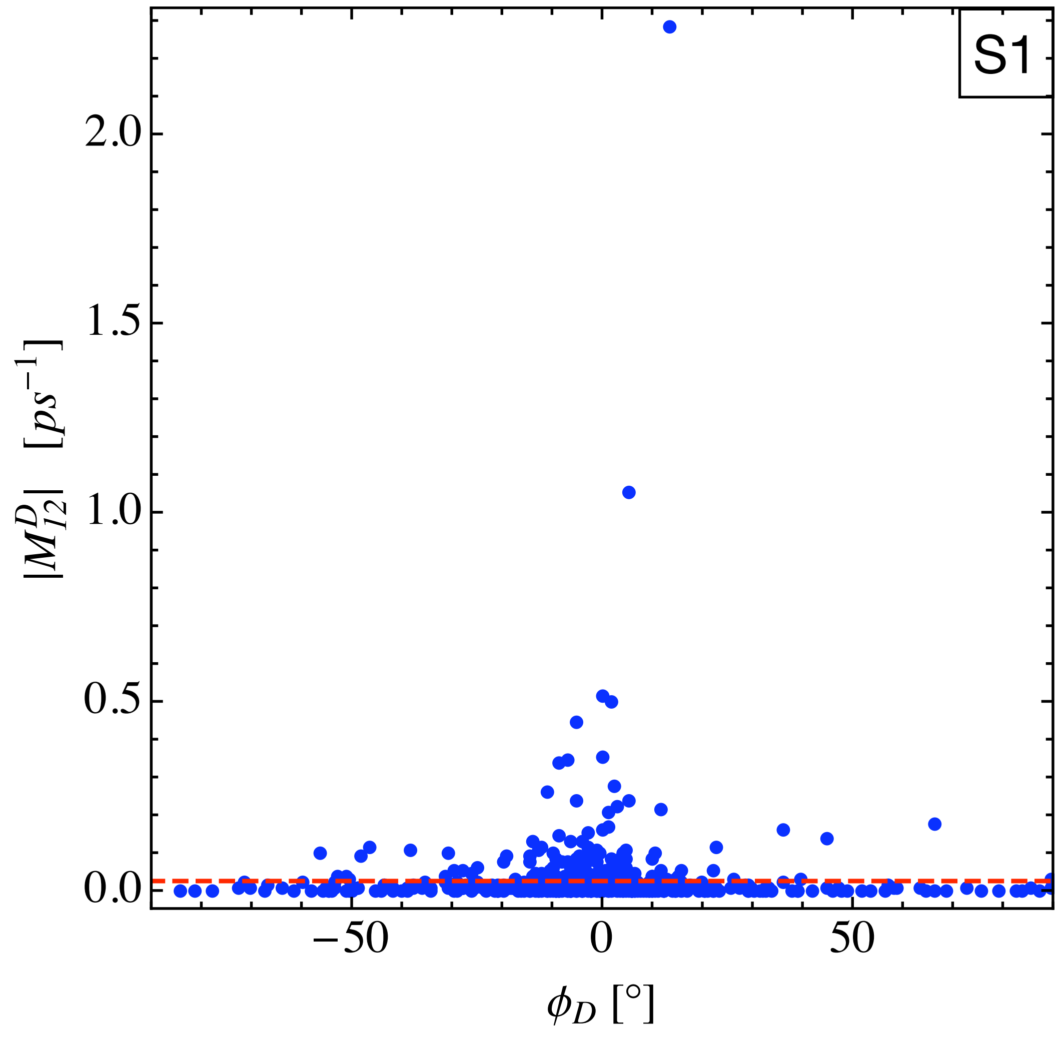
model-independent prediction

● 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:08xx.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



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

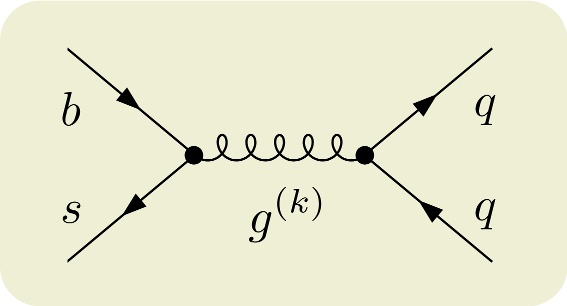
- - maximal allowed SM effect with no significant CP phase

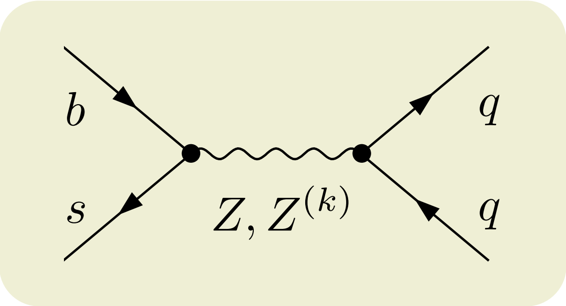
● consistent with quark masses, CKM parameters, and 95% CL limit $|\varepsilon_K| \in [1.3, 3.3] \cdot 10^{-3}$

*Bauer *et al*., arXiv:08xx.xxxx

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 $Q_{3\text{–}6}$. Electroweak penguins $Q_{7\text{–}10}$ arise almost entirely from exchange of Z and its KK modes

*Bauer *et al.*, arXiv:08xx.xxxx

Rare decays: Effective Hamiltonian*

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

Only four couplings:

- $\boldsymbol{\Delta}_Q$, $\boldsymbol{\Delta}_q$ 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

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

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

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

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

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

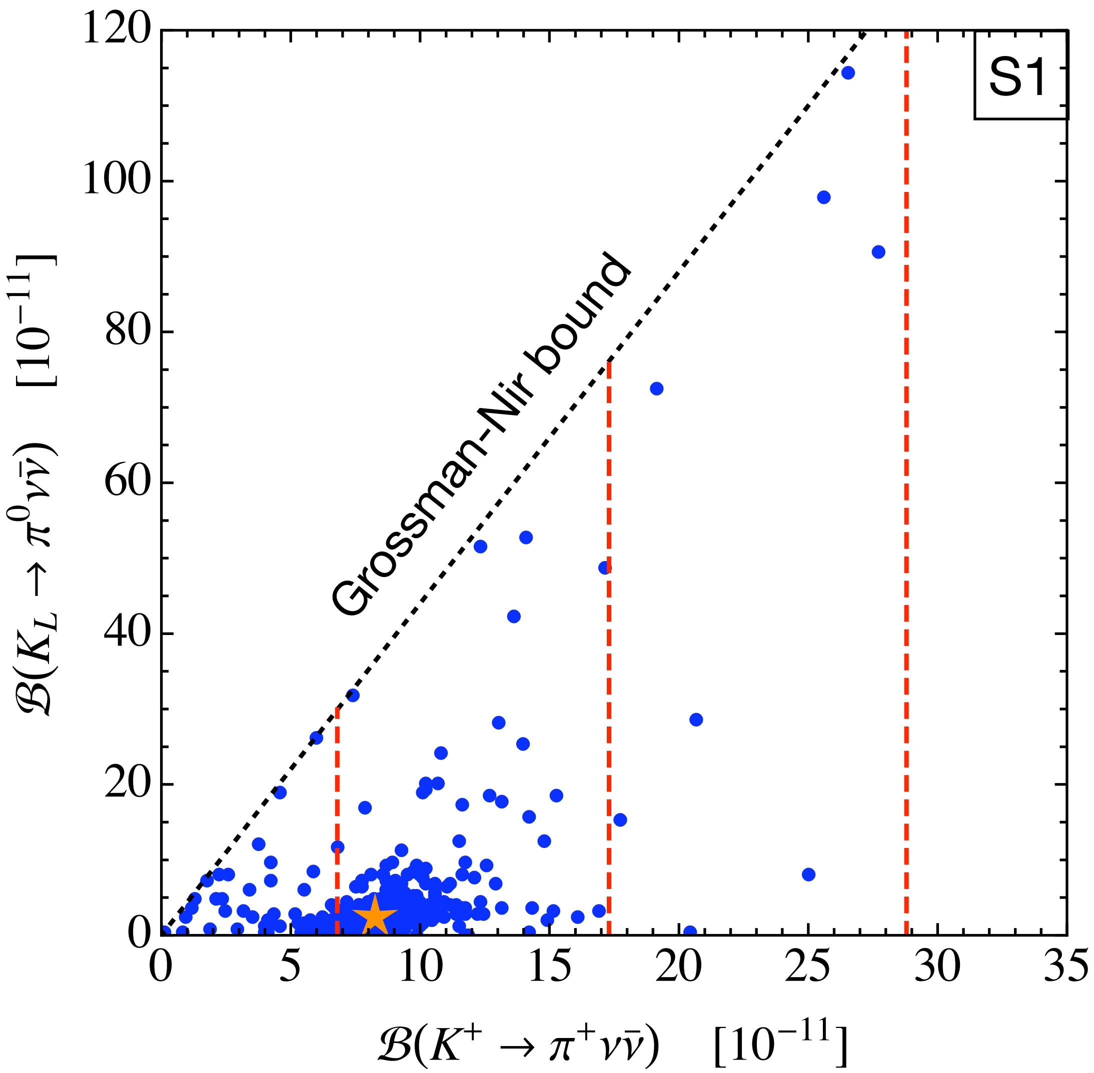
$$C_9^{\rm RS} = \frac{2\pi\alpha}{9M_{\rm KK}^2}\,(\Delta_D)_{23} + \frac{2\pi\alpha}{3s_w^2\,M_{\rm KK}^2}\,,$$

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

*Bauer *et al.*, arXiv:08xx.xxxx

Rare K decays: Golden modes*

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



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

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

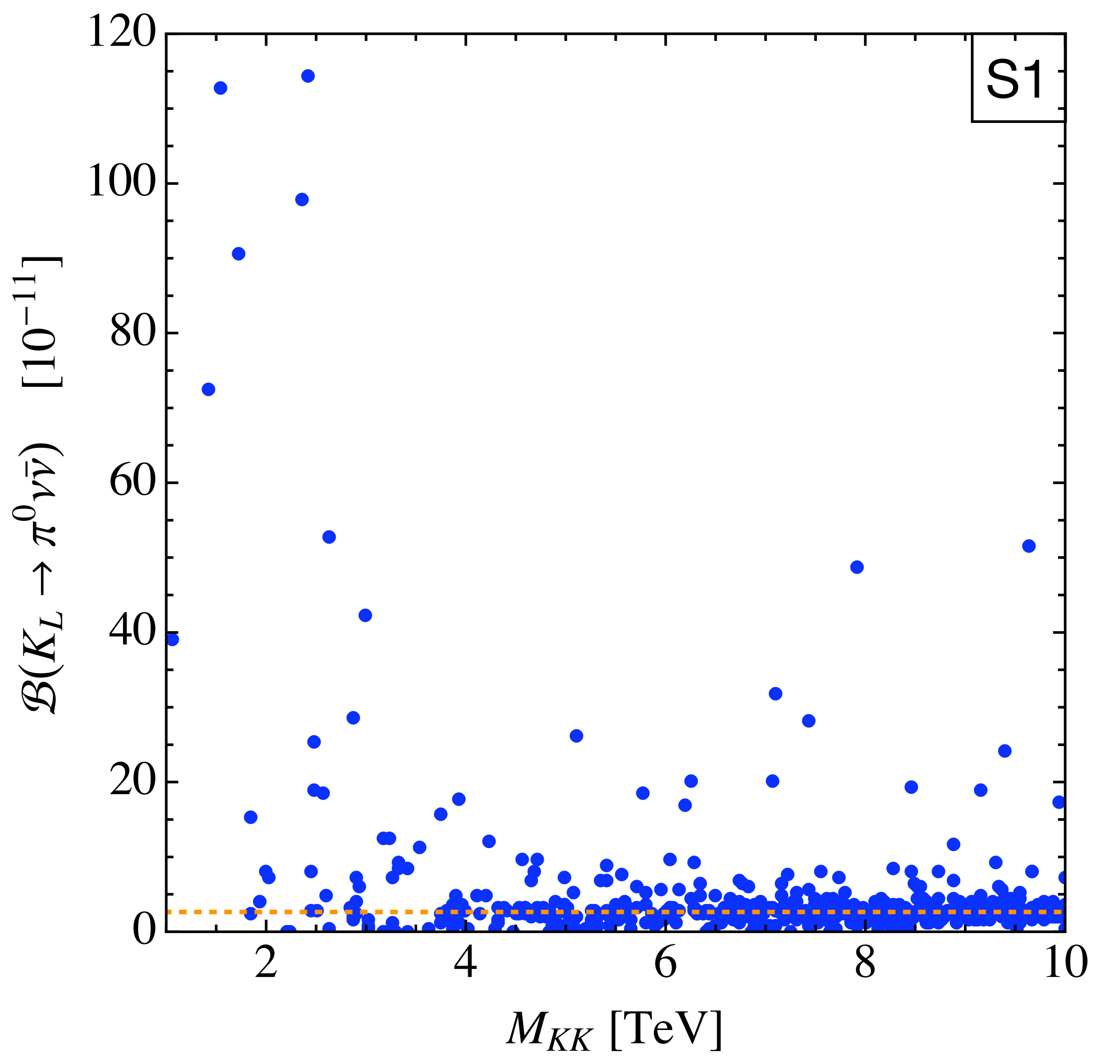
- - central value and 68% CL limit $\mathrm{B}(K^+ \to \pi^+\nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \cdot 10^{-11}$ from E949

● 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; Artamonov *et al*. [E949 Collaboration], arXiv:0808.2459; Bauer *et al*., arXiv:08xx.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



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

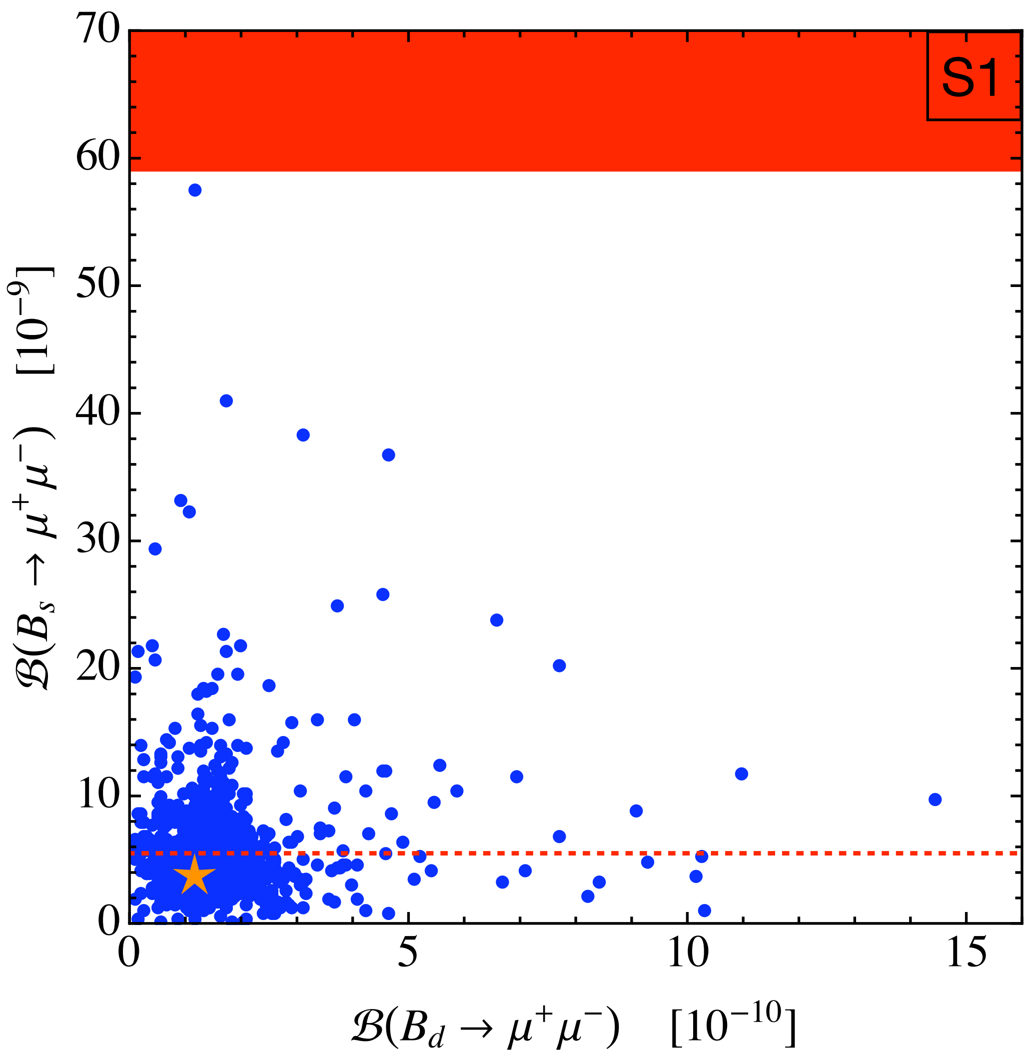
SM: $\mathrm{B}(K_L \to \pi^0 \nu\bar{\nu}) \approx 2.7 \cdot 10^{-11}$

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

*Bauer *et al.*, arXiv:08xx.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: $\mathrm{B}(B_d \to \mu^+\mu^-) \approx 1.2 \cdot 10^{-10}$, $\mathrm{B}(B_s \to \mu^+\mu^-) \approx 3.9 \cdot 10^{-9}$

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

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

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

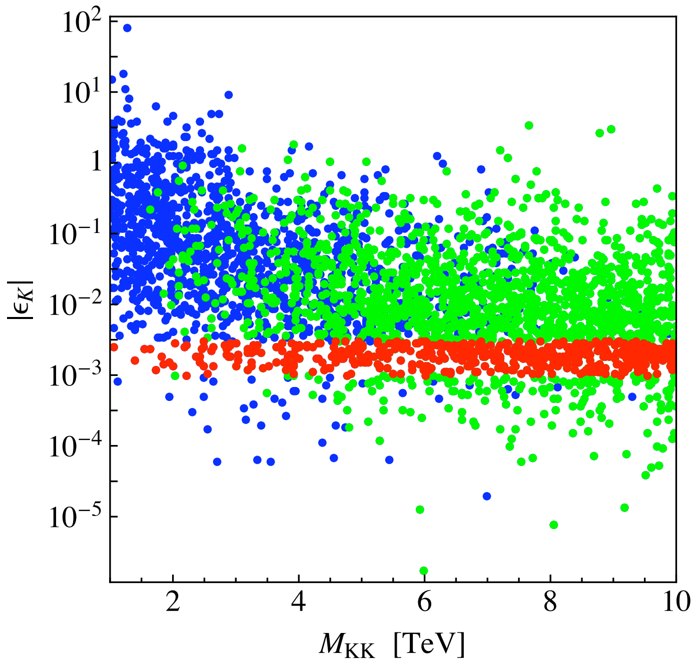
*Aaltonen *et al*. [CDF Collaboration], arXiv:0712.1708; Bauer *et al*., arXiv:08xx.xxxx

Conclusions

- Models with warped extra dimension offer elegant solution to both gauge and fermion hierarchy problem
- Rich structure of flavor-violating interactions in gauge couplings to quarks generically not of CKM-type
- Mixing amplitudes dominated by KK gluon exchange, while rare decays receive largest contribution from diagrams involving Z
- Effects naturally of order one or larger in modes where deviations from SM are allowed or indicated by data, while small in other modes
- Flavor-changing transitions of K and B_s mesons particularly interesting in RS framework

Additional Slides

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

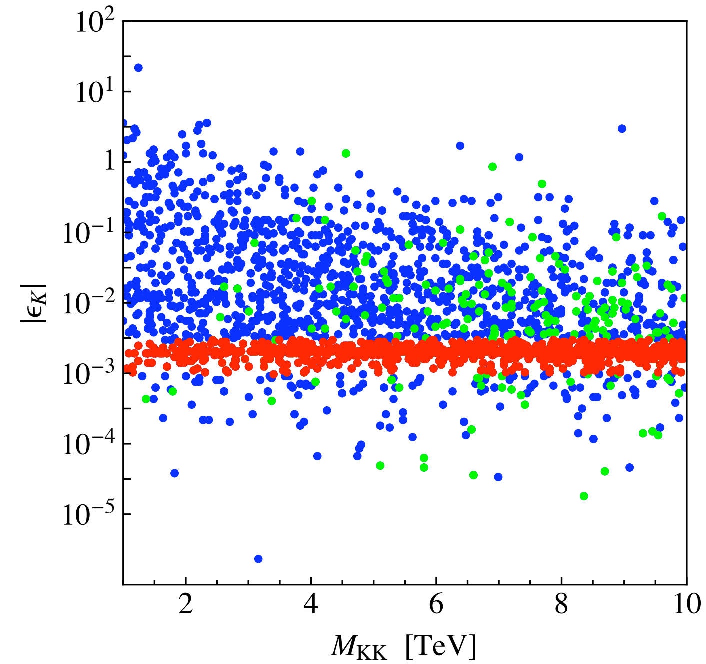


<u>S1: Standard</u>

$|Y_q| < 3$

- 16%
- 59%

13% pass

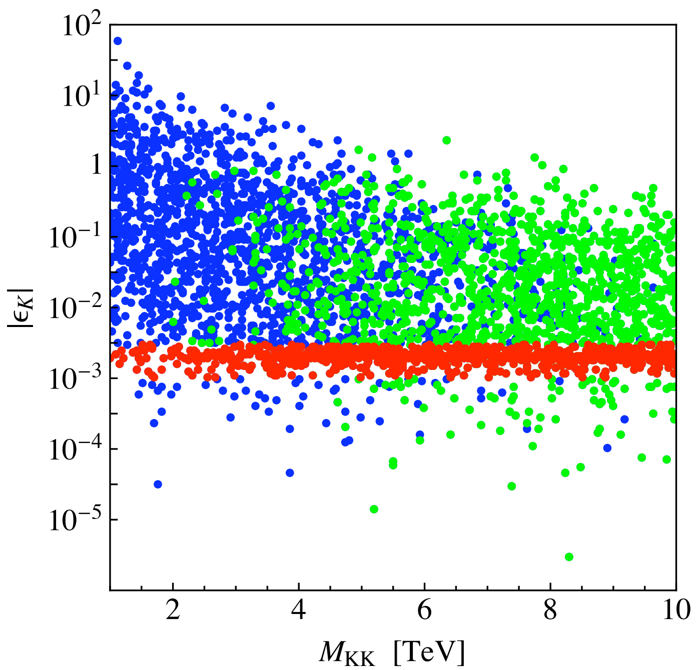


<u>S2: Big Yukawas</u>

$|Y_q| < 12$

- 44%
- 26%

19% pass

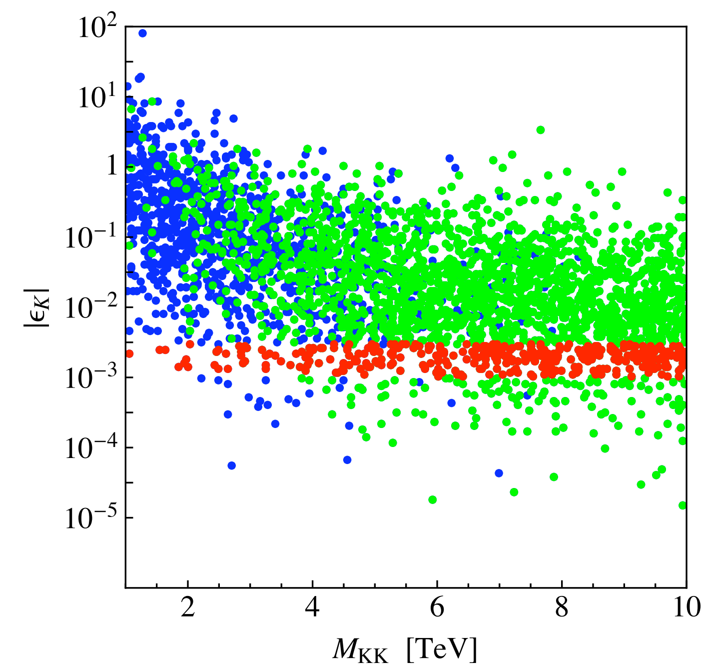


<u>S3: Alignement</u>

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

- 48%
- 24%

16% pass



<u>S4: Little RS</u>

$L = 7$

- 11%
- 68%

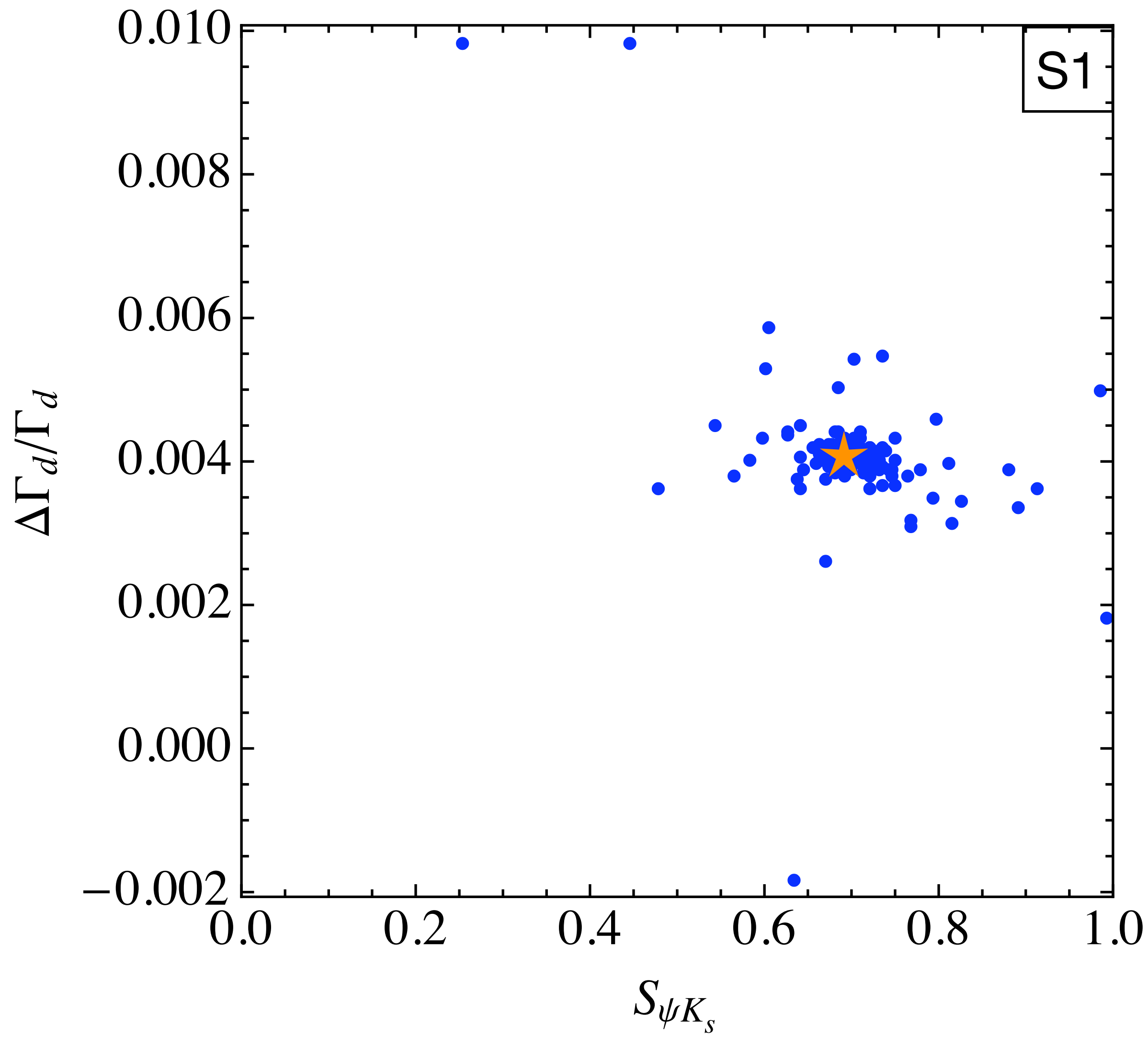
9% pass

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

*Davoudiasl *et al.*, arXiv:0802.0203; Santiago, arXiv:0806.1230; Bauer *et al.*, arXiv:08xx.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



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

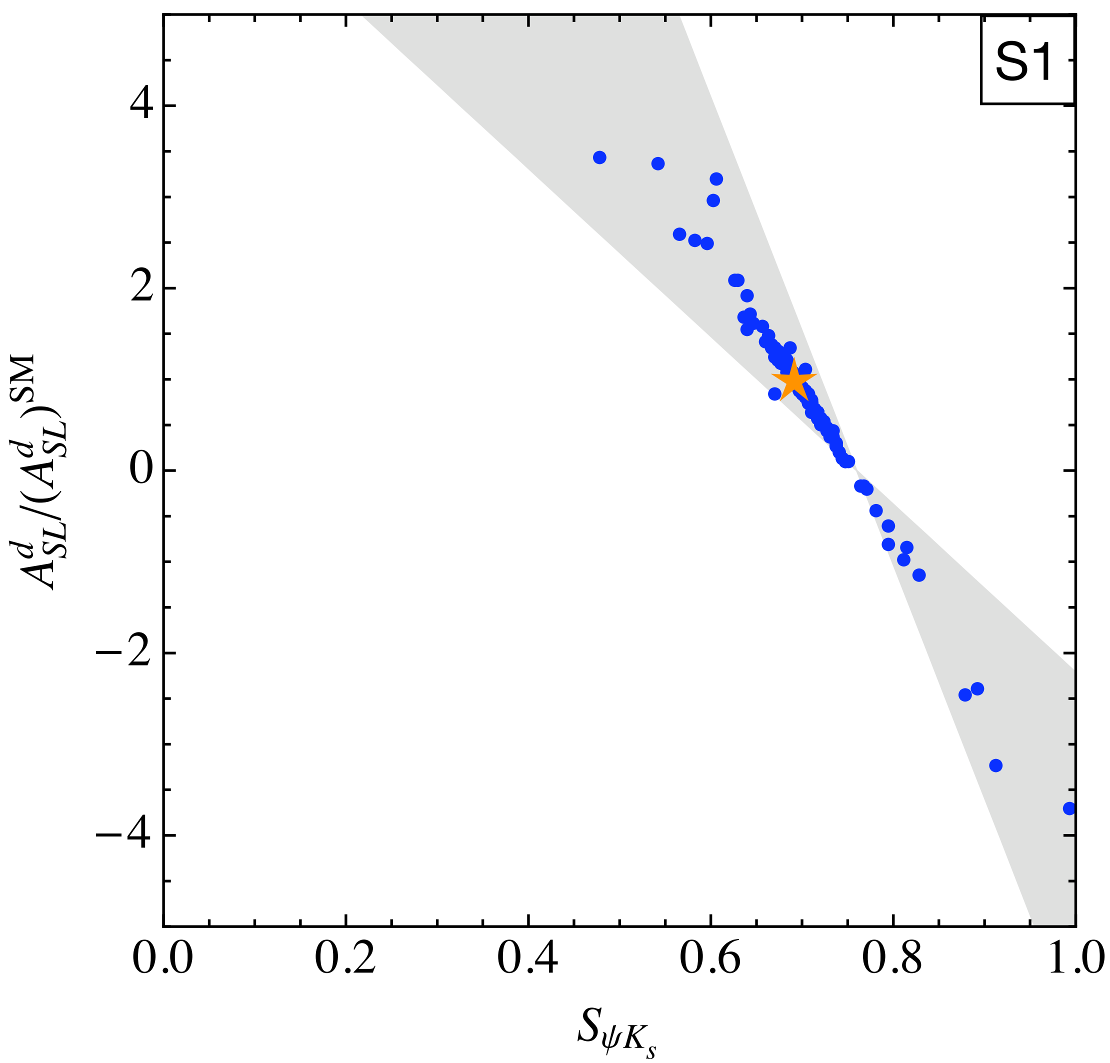
★ SM: $\Delta\Gamma_d/\Gamma_d \approx 0.004$, $S_{\psi K_s} \approx 0.69$

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

*Bauer *et al.*, arXiv:08xx.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: $A_{SL}^d \approx -5 \cdot 10^{-4}$, $S_{\psi K_s} \approx 0.69$

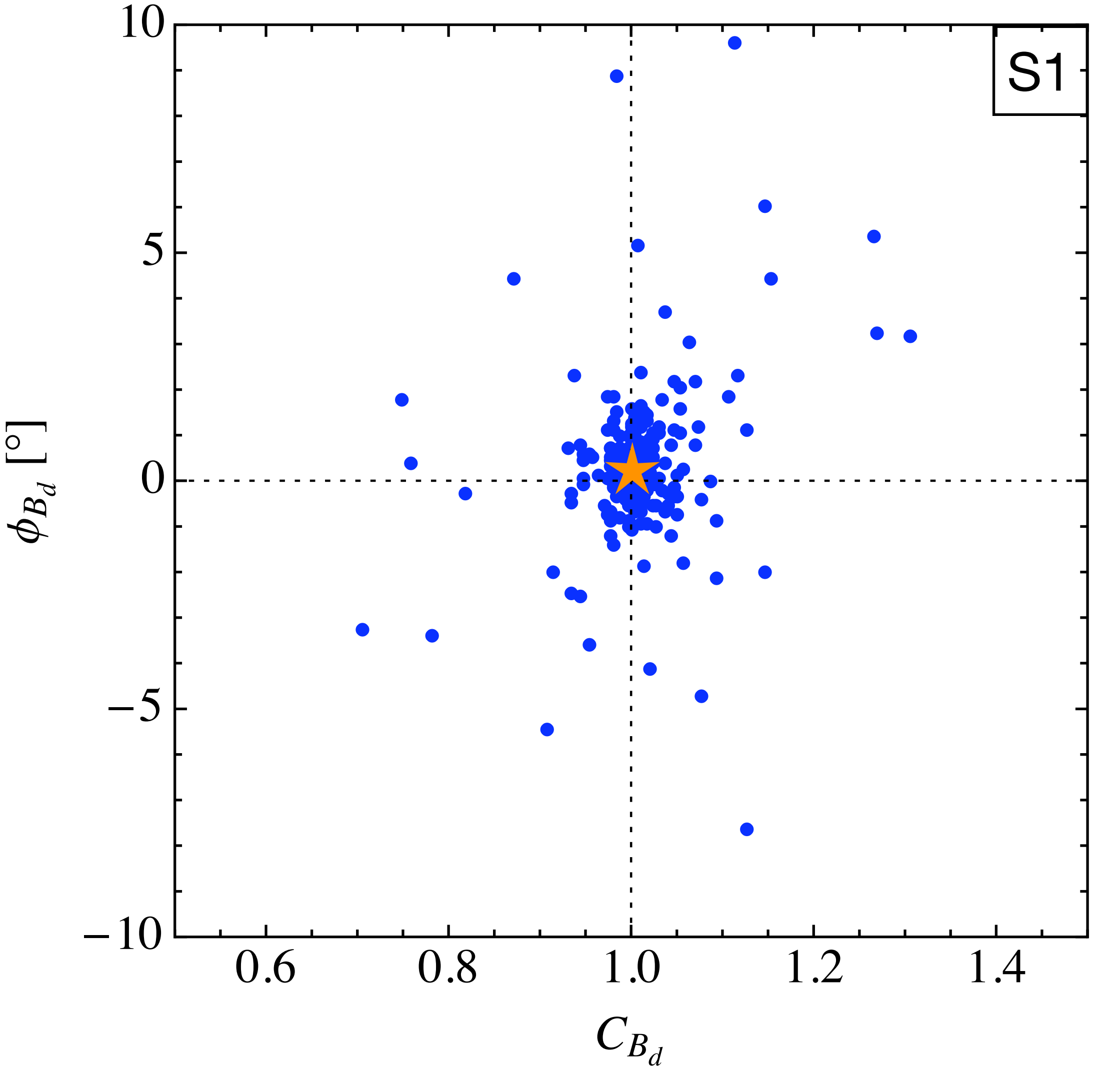
■ model-independent prediction

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

*Bauer *et al.*, arXiv:08xx.xxxx

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



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

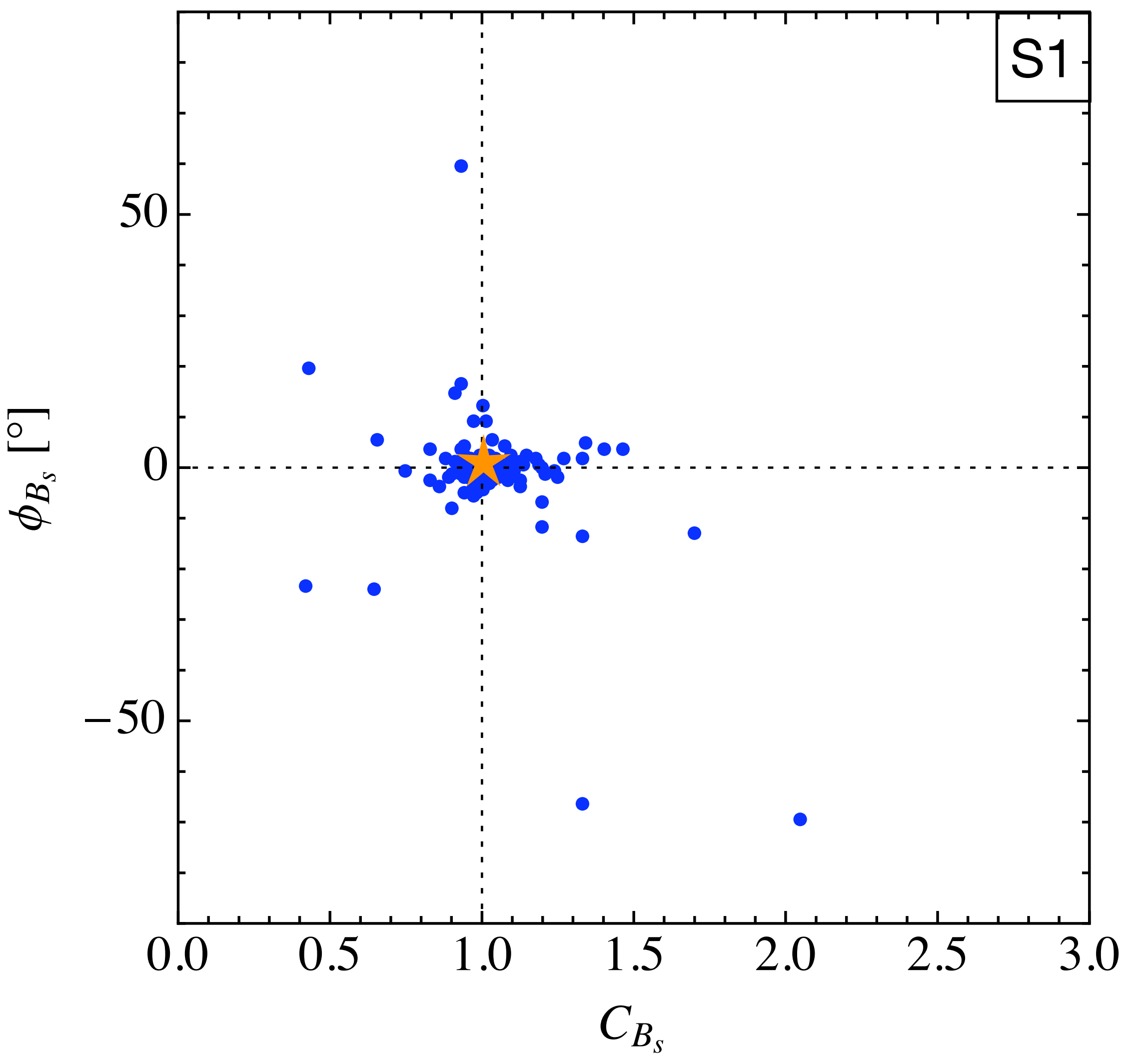
★ SM: $C_{B_d} = 1$, $\phi_{B_d} = 0^\circ$

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

*Bauer *et al.*, arXiv:08xx.xxxx

Meson mixing: Neutral B_s mesons*

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



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

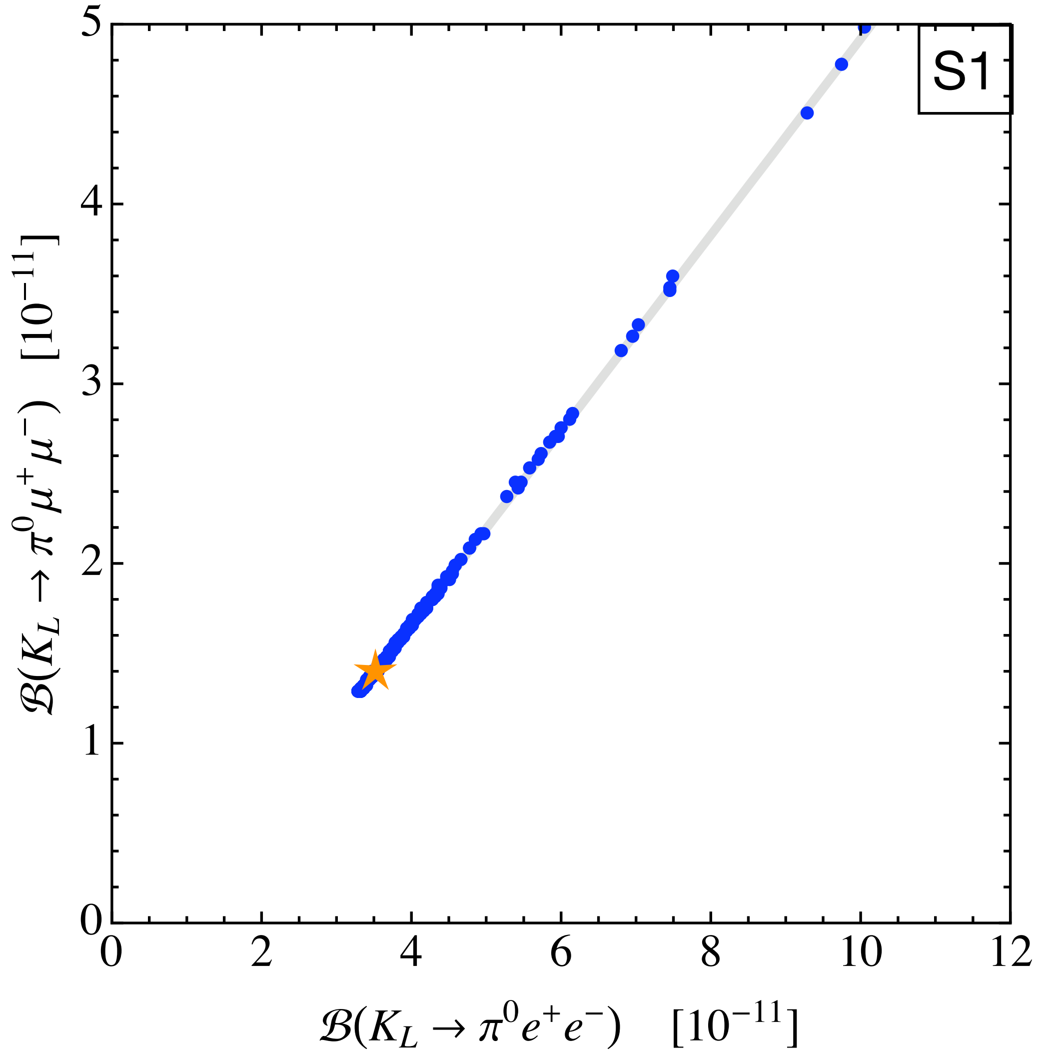
★ SM: $C_{B_s} = 1,\ \phi_{B_s} = 0^\circ$

● 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:08xx.xxxx

Rare K decays: Silver modes*

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



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

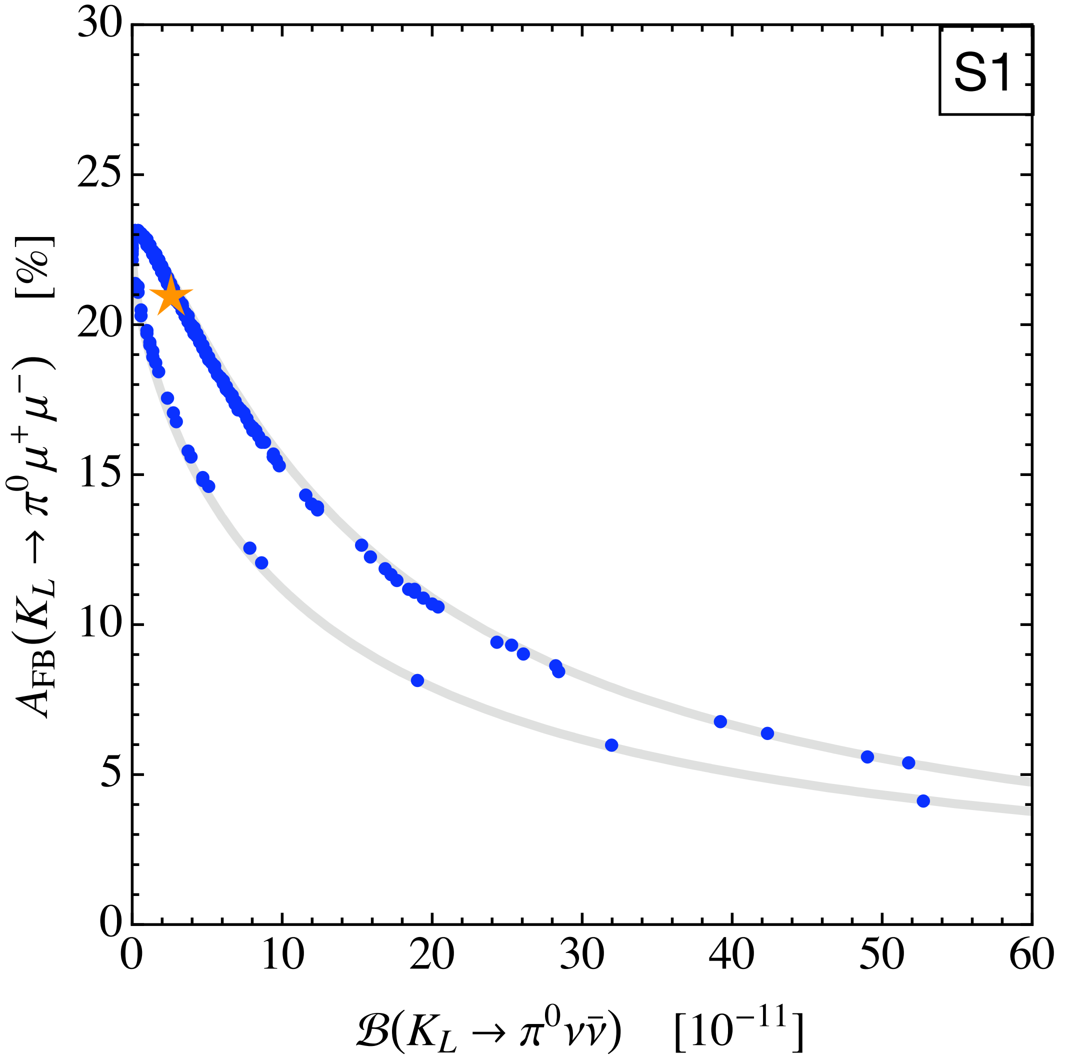
— model-independent prediction

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

*Bauer *et al.*, arXiv:08xx.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: $\mathrm{B}(K_L \longrightarrow \pi^0 \nu\bar{\nu}) \approx 2.7 \cdot 10^{-11}$,
$A_{\mathrm{FB}}(K_L \longrightarrow \pi^0 \mu^+\mu^-) \approx 21\%$
for constructive interference

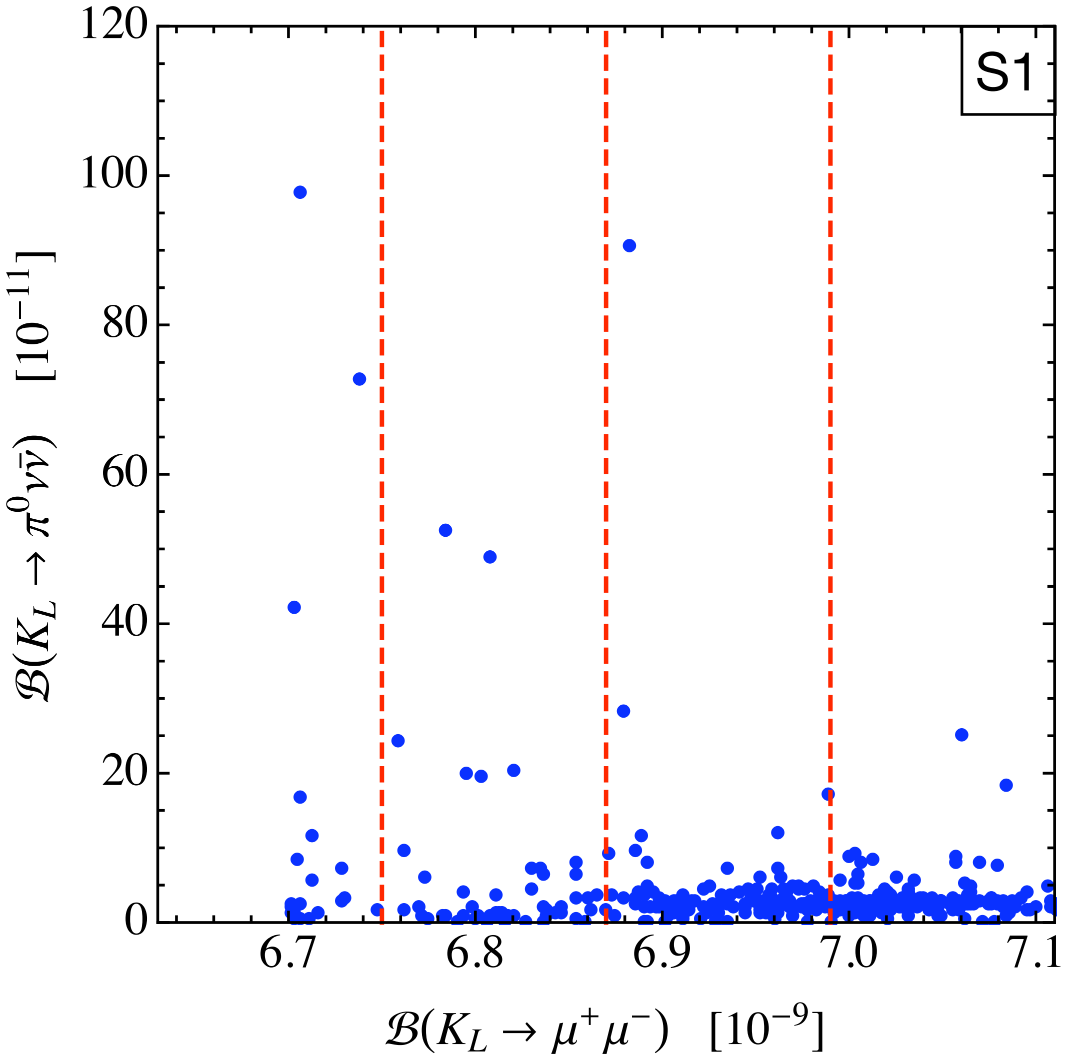
— model-independent prediction

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

*Bauer *et al.*, arXiv:08xx.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 $K_L \to \pi^0 \nu\bar{\nu}$



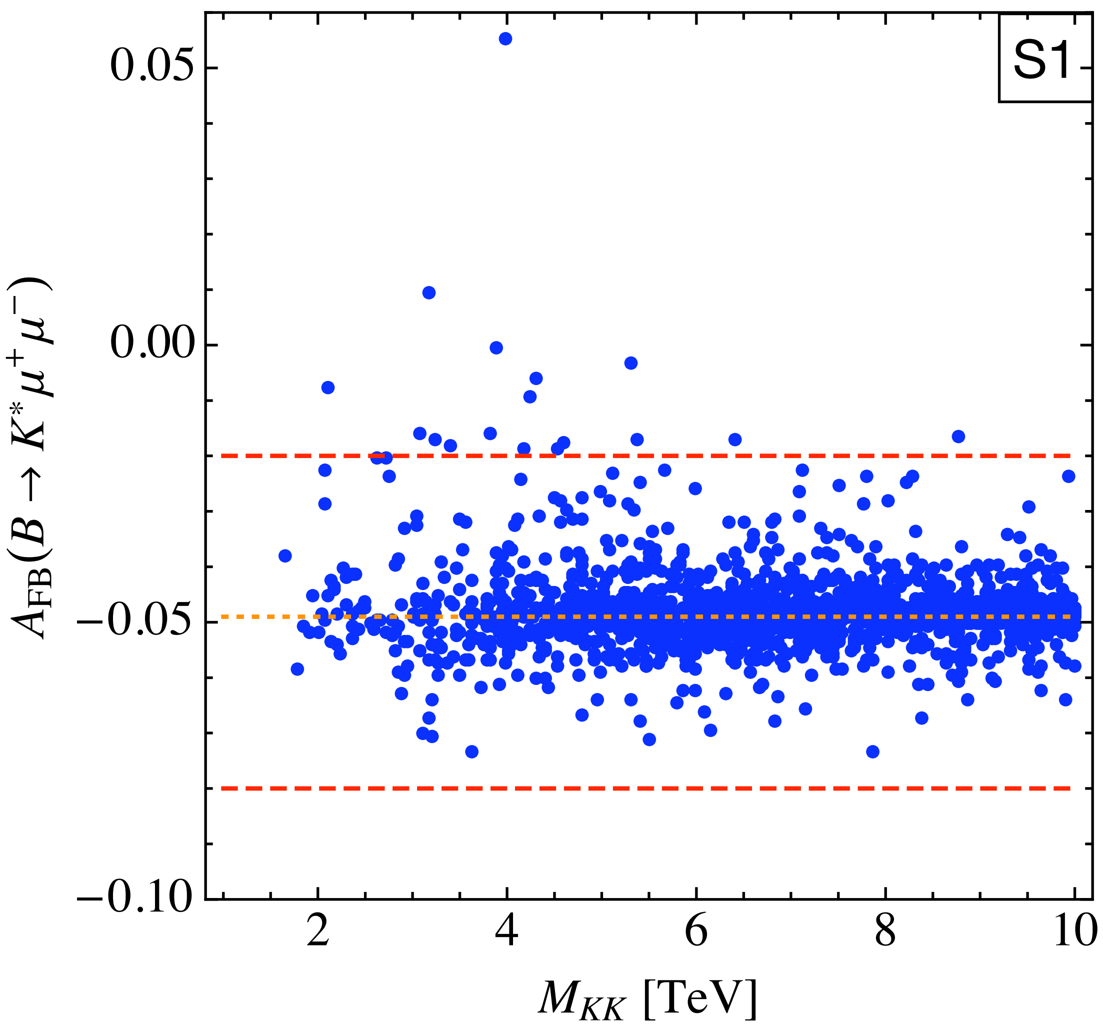
- - PDG central value and 3σ range
$\mathrm{B}(K_L \to \mu^+\mu^-) = (6.87 \pm 0.12) \cdot 10^{-9}$

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

*Bauer *et al*., arXiv:08xx.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

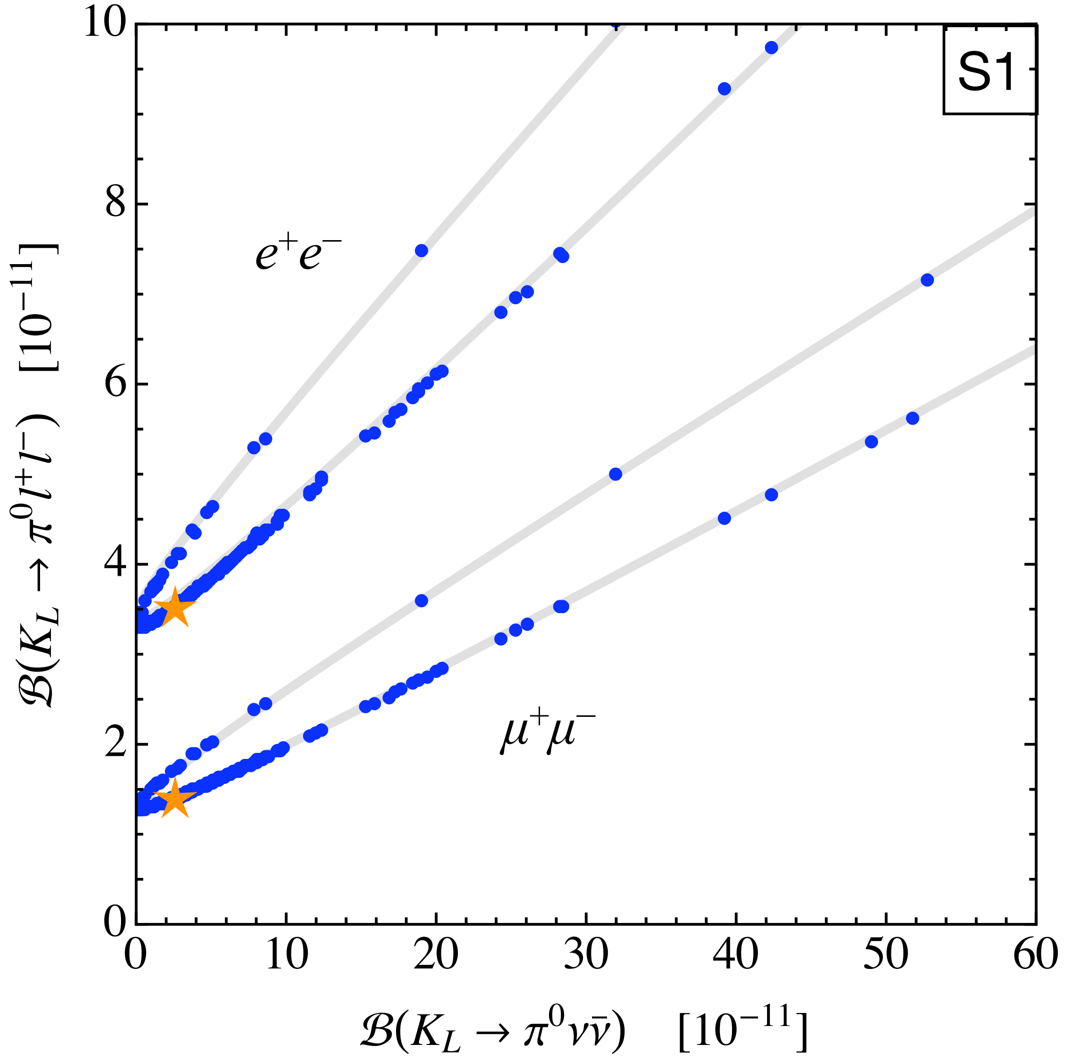
expected sensitivity of LHCb, 2 fb^{-1}

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

*Bauer *et al.*, arXiv:08xx.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: $\mathrm{B}(K_L \to \pi^0 \nu\bar{\nu}) \approx 2.7 \cdot 10^{-11}$,
$\mathrm{B}(K_L \to \pi^0 e^+ e^-) \approx 3.6 \cdot 10^{-11}$,
$\mathrm{B}(K_L \to \pi^0 \mu^+ \mu^-) \approx 1.4 \cdot 10^{-11}$
for constructive interference

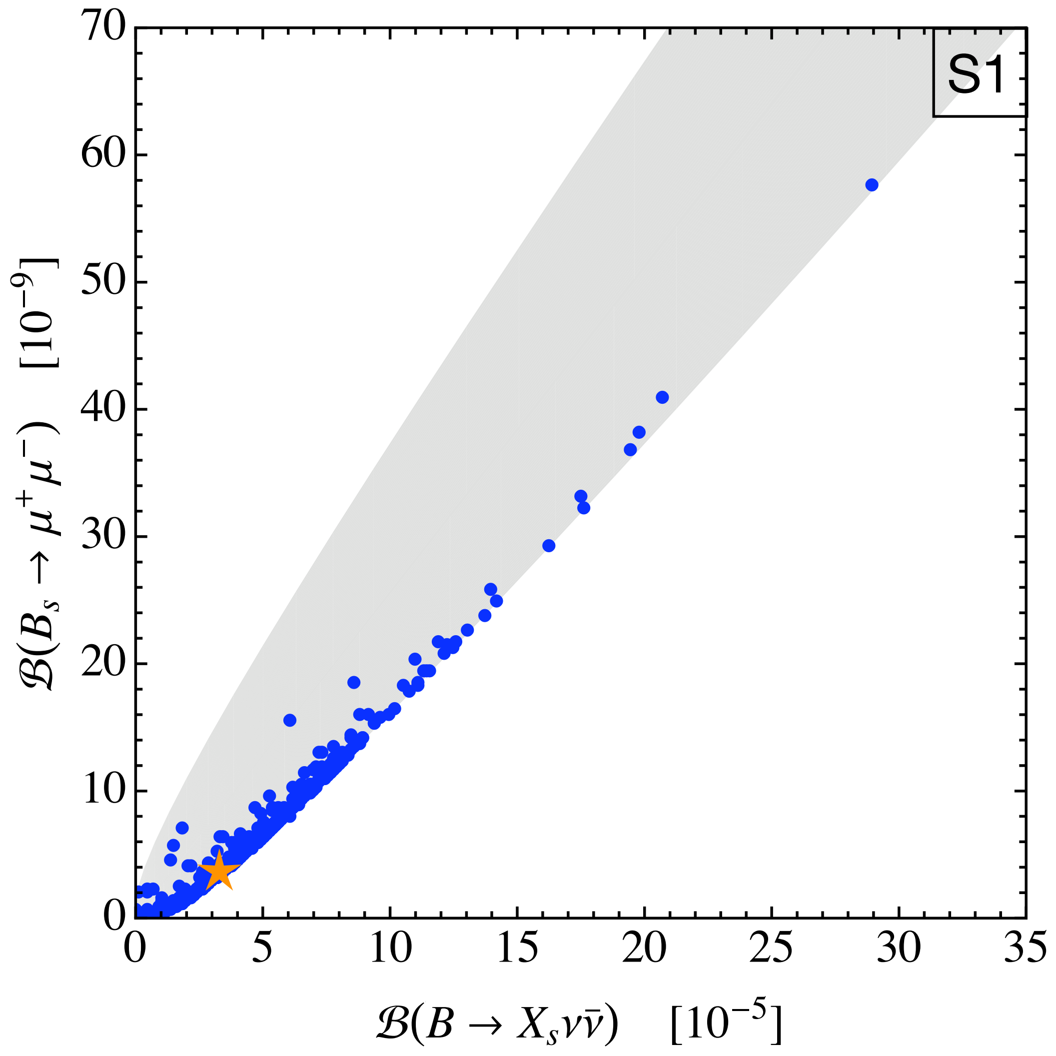
— model-independent prediction

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

*Bauer *et al.*, arXiv:08xx.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



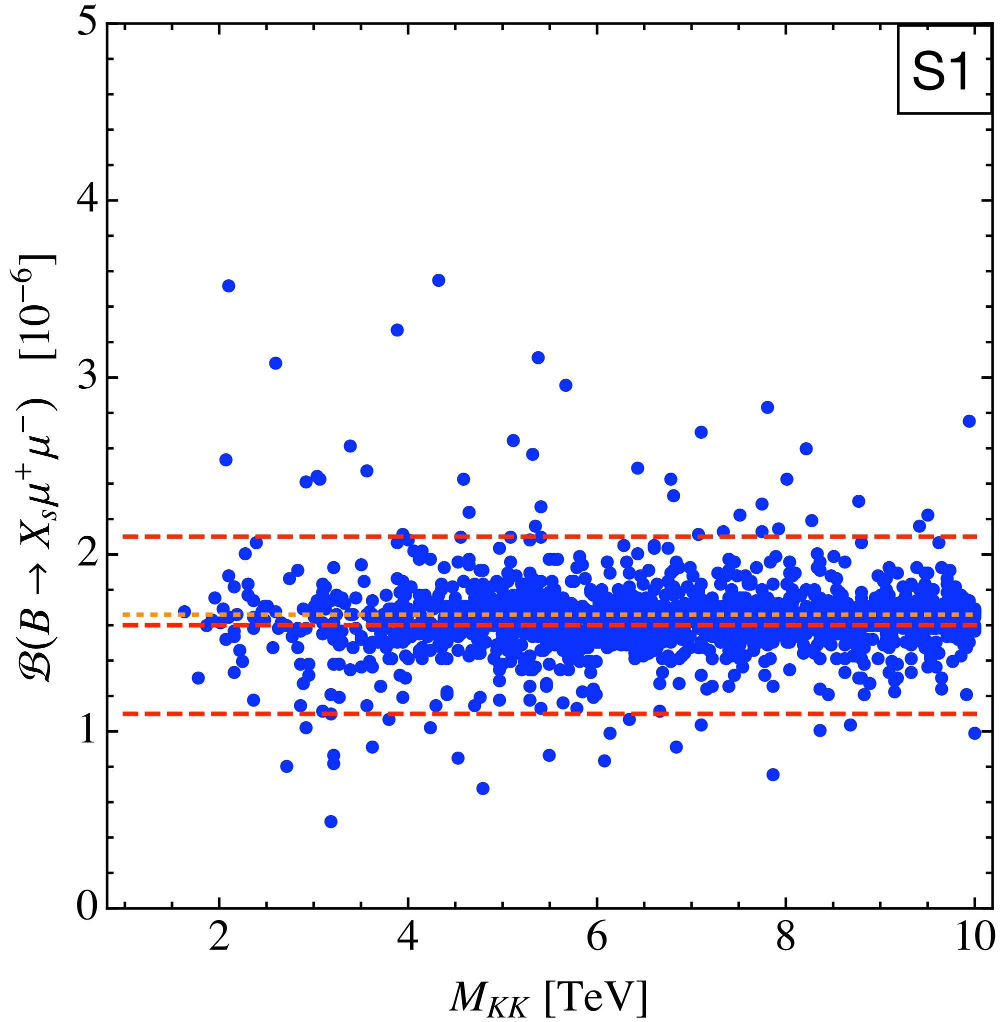
★ SM: $\mathrm{B}(B_s \to \mu^+\mu^-) \approx 3.9 \cdot 10^{-9}$,
$\mathrm{B}(B \to X_s\nu\bar{\nu}) \approx 3.5 \cdot 10^{-5}$

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

*Bauer *et al.*, arXiv:08xx.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: $\mathrm{B}(B \to X_s \mu^+\mu^-) \approx 1.7 \cdot 10^{-6}$ for $q^2 \in [1, 6]$ GeV^2

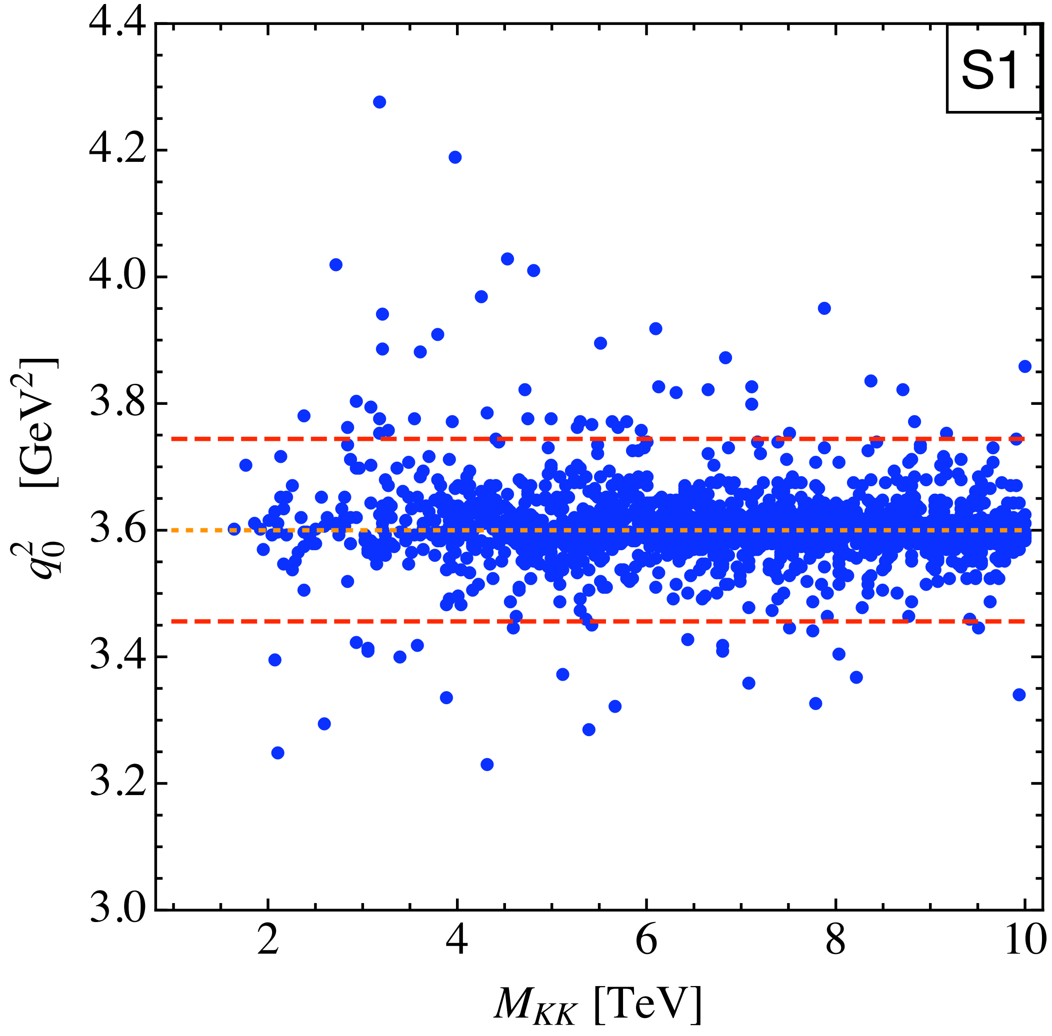
central value and 68% CL limit $\mathrm{B}(B \to X_s \mu^+\mu^-) = (1.6 \pm 0.5) \cdot 10^{-6}$ from BaBar and Belle

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

*Aubert *et al*. [BaBar Collaboration], hep-ex/0404006; Abe *et al*. [Belle Collaboration], hep-ex/0408119; Bauer *et al*., arXiv:08xx.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: $q_0^2 \approx 3.6\,\mathrm{GeV}^2$

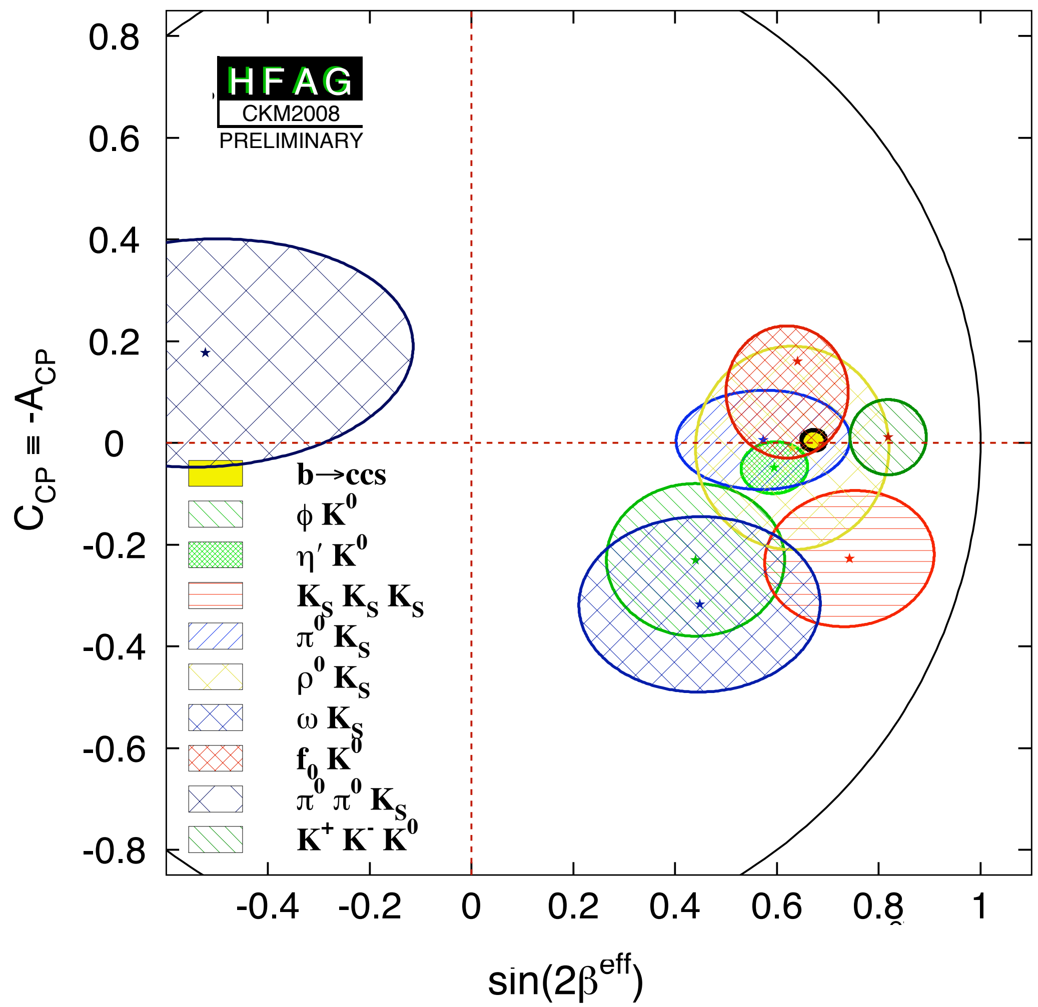
expected sensitivity at SuperB factory, $75\ \mathrm{ab}^{-1}$

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

*Bauer *et al.*, arXiv:08xx.xxxx

Non-leptonic B and K decays*

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



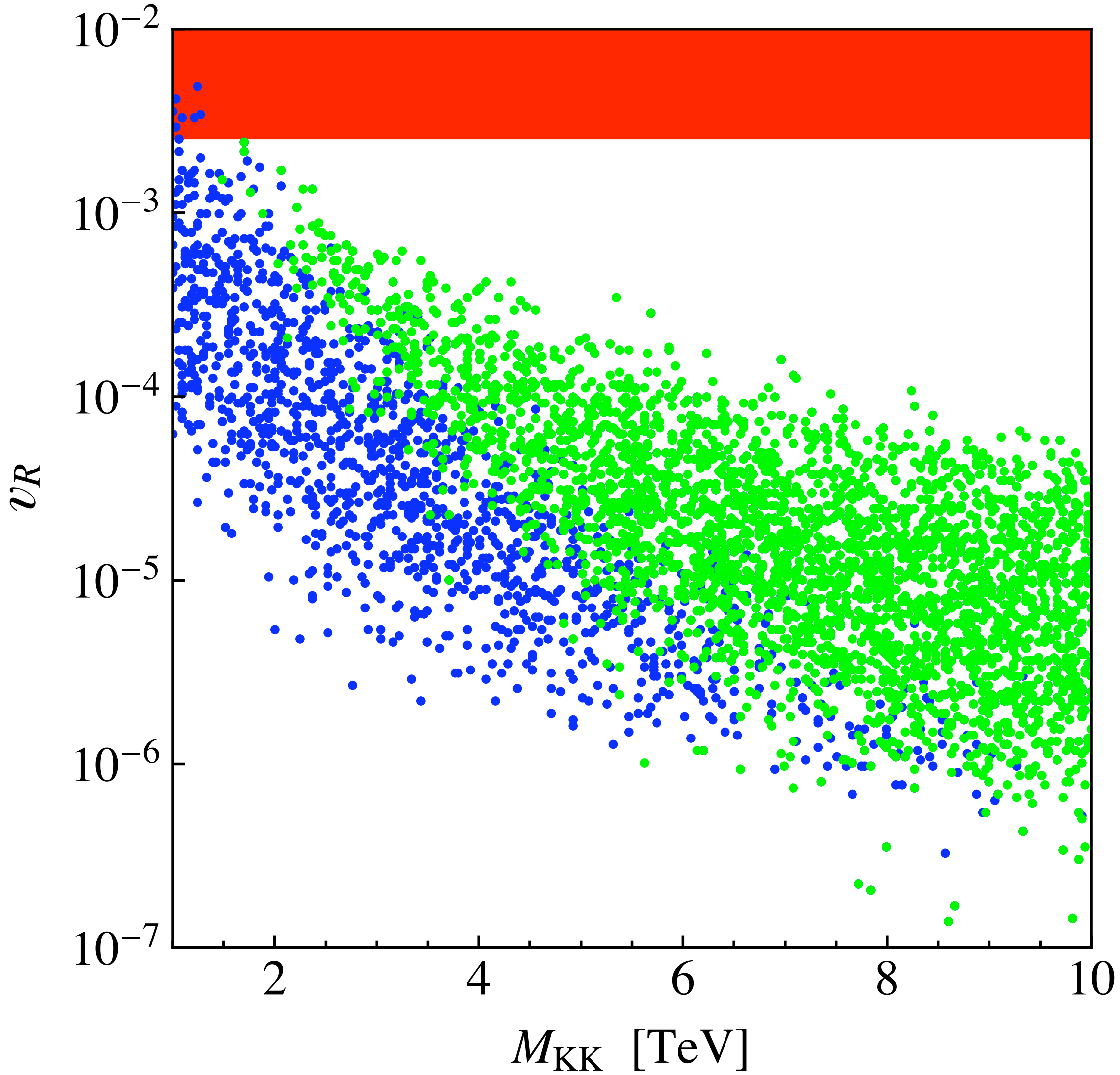
Potentially relevant for:

- 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:08xx.xxxx

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



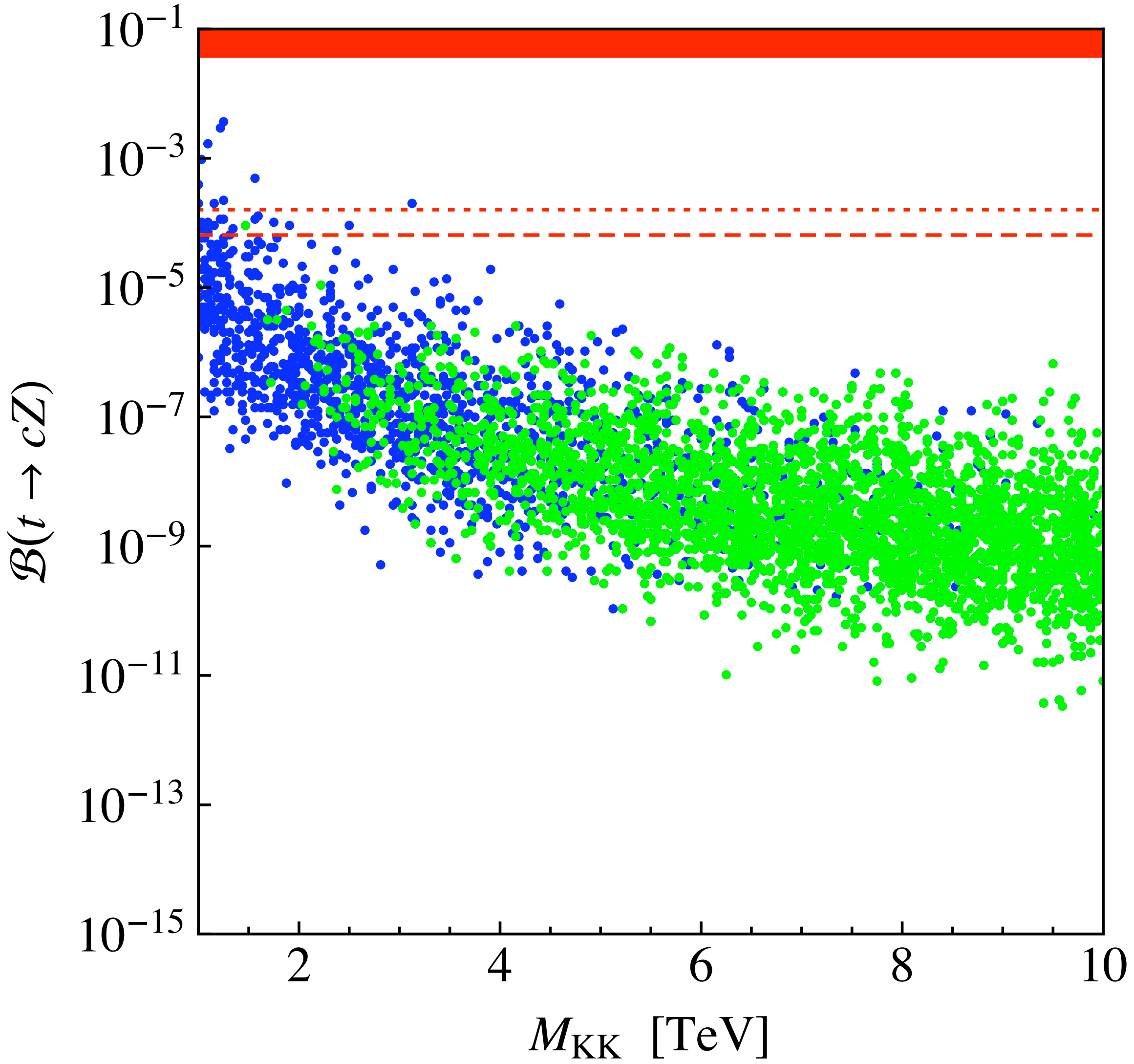
3000 randomly chosen RS points with $|Y_q| < 3$ reproducing quark masses and CKM parameters with $\chi^2/\mathrm{dof} < 11.5/10$ corresponding to 68% CL

- $v_R \in [-0.0007, 0.0025]$ 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 5σ 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 $B(t \to u(c)Z) < 3.7\%$

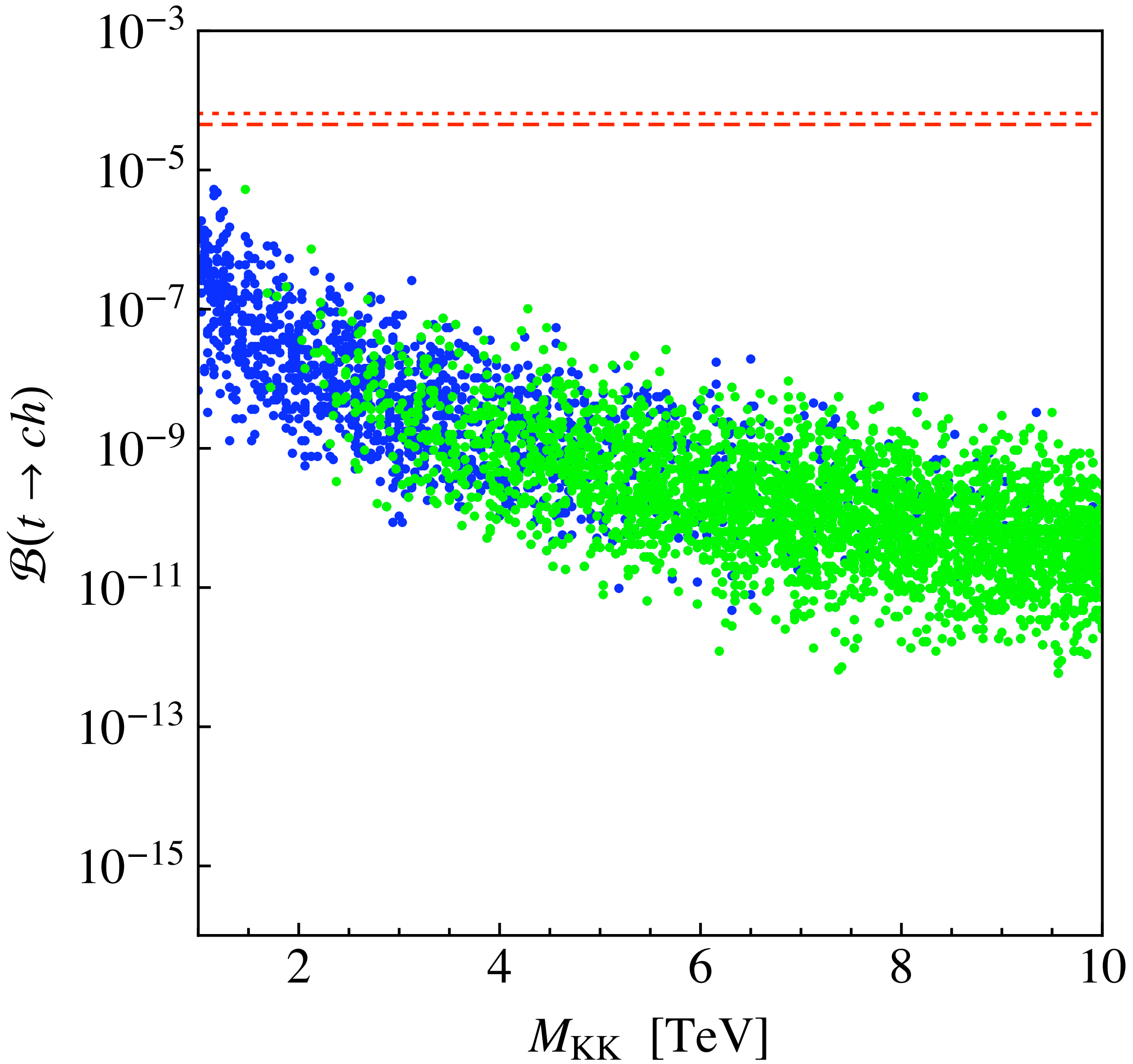
without $Z \to b\bar{b}$ constraint

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

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 $6.5 \cdot 10^{-4}$ for 3σ evidence by LHC

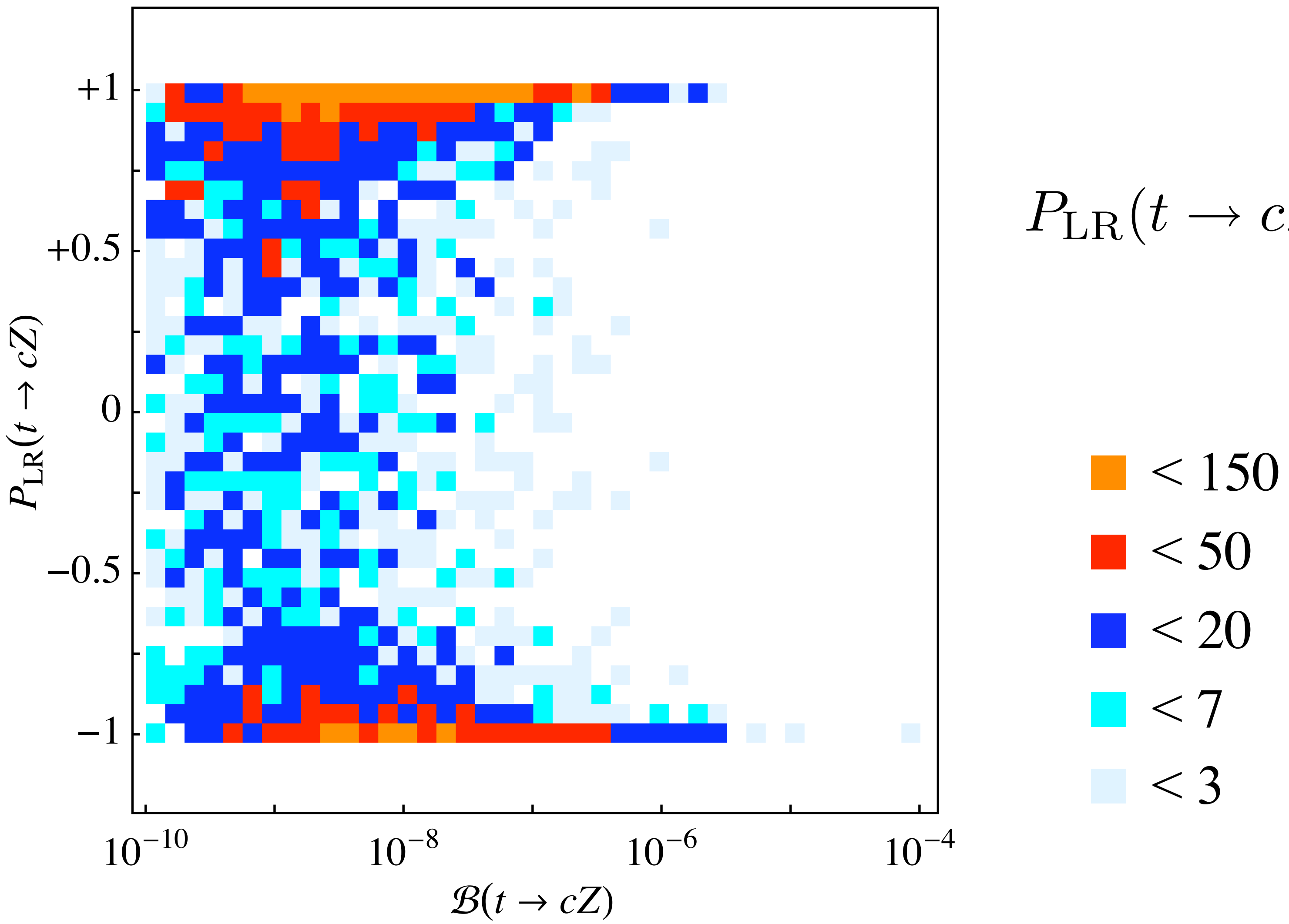
95% CL limit from LHC $B(t \to ch) < 4.5 \cdot 10^{-5}$

- 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



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

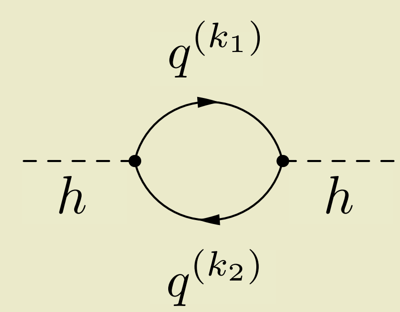
events in bin after imposing $Z \to b\bar{b}$ constraint at 95% CL

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

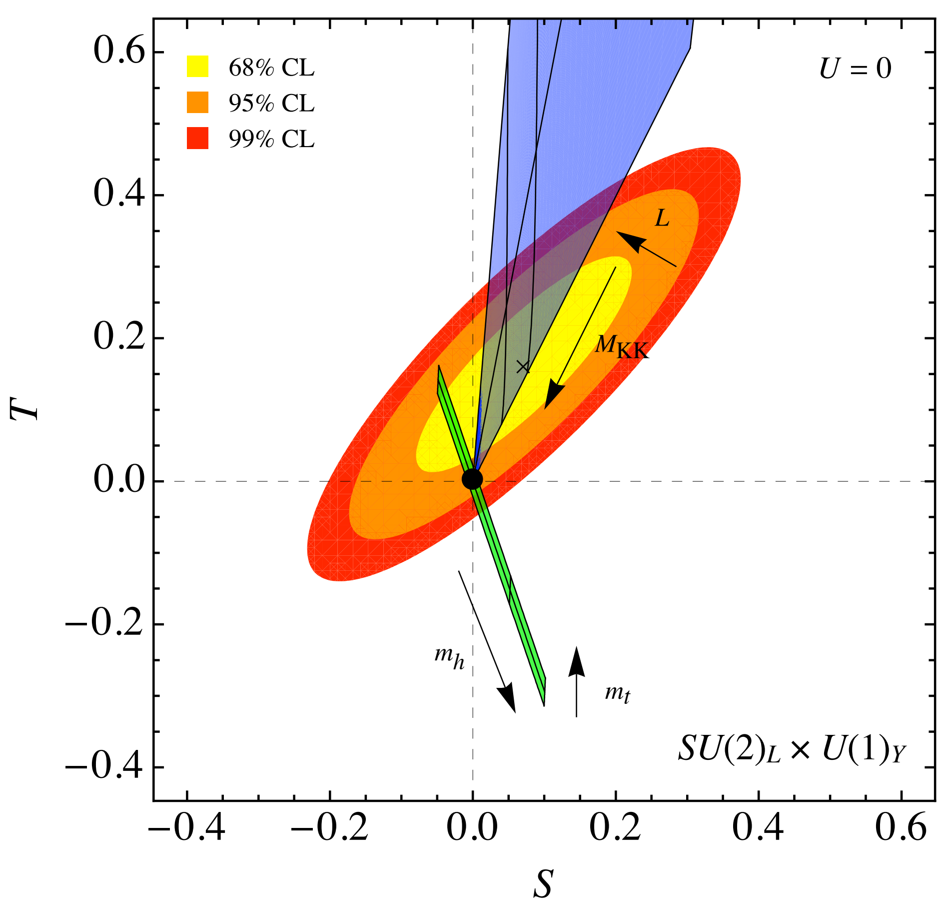
More additional Slides

S and T parameters in minimal RS model*

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



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



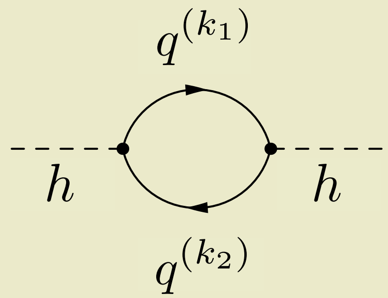
$$\Delta S = \frac{1}{6\pi} \ln \frac{m_h}{m_h^{\text{ref}}} \,, \qquad \Delta T = -\frac{3}{8\pi c_w^2} \ln \frac{m_h}{m_h^{\text{ref}}}$$

- 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

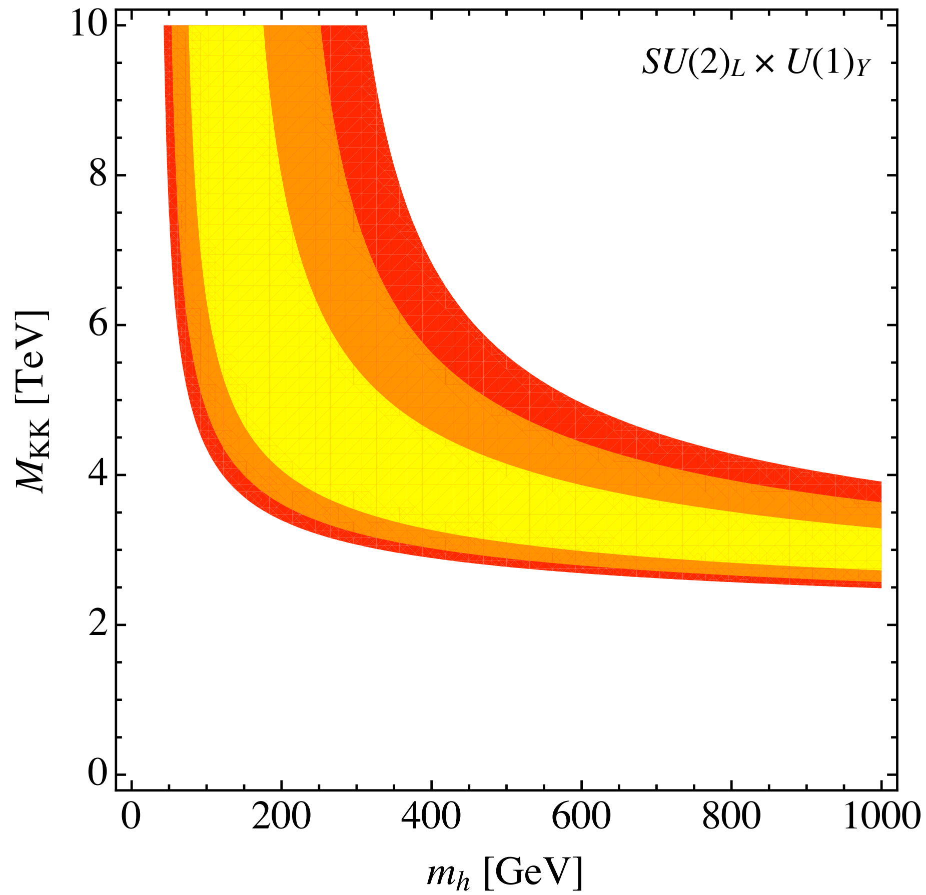
*Carena *et al.*, hep-ph/0305188; Casagrande *et al.*, arXiv:0807.4537

S and T parameters in minimal RS model*

- In warped models with brane-localized Higgs sector, m_h naturally of order M_{KK}. Heavy Higgs allows for $M_{\mathrm{KK}} > 2.6$ TeV at 95% CL consistent with S and T



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



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

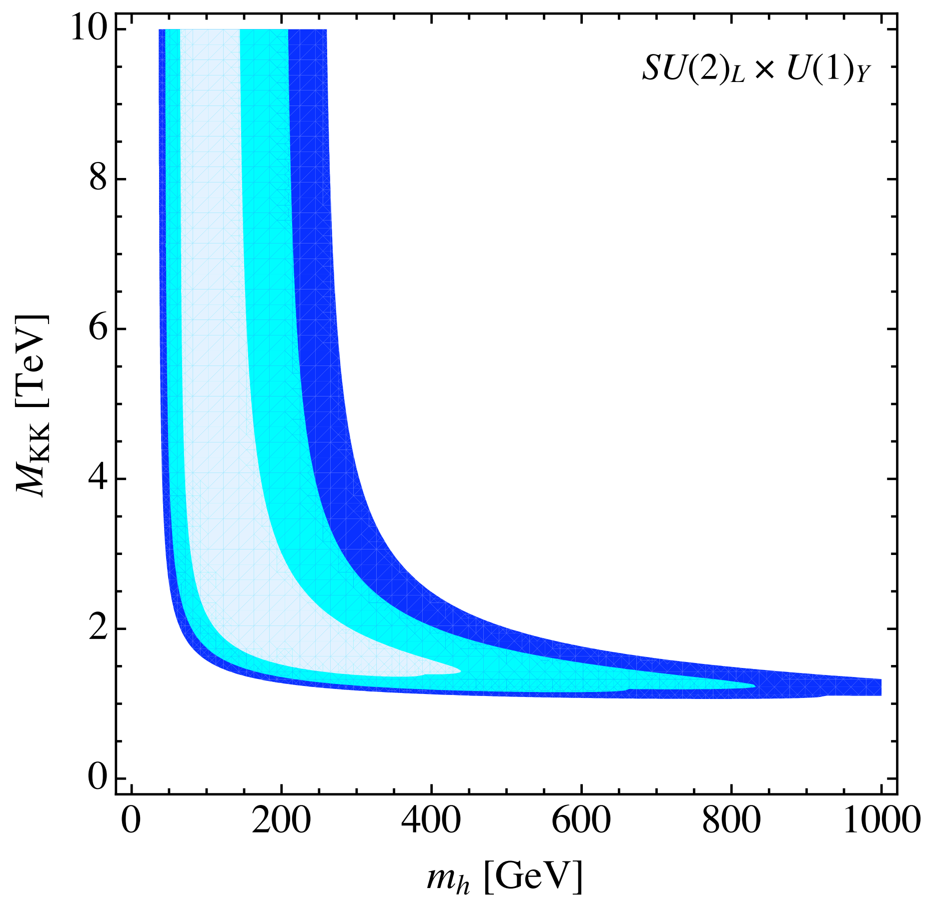
68% CL
95% CL
99% CL

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 $M_{\rm KK} > 1.5$ TeV at 99% CL for $m_h = 150$ GeV



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

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

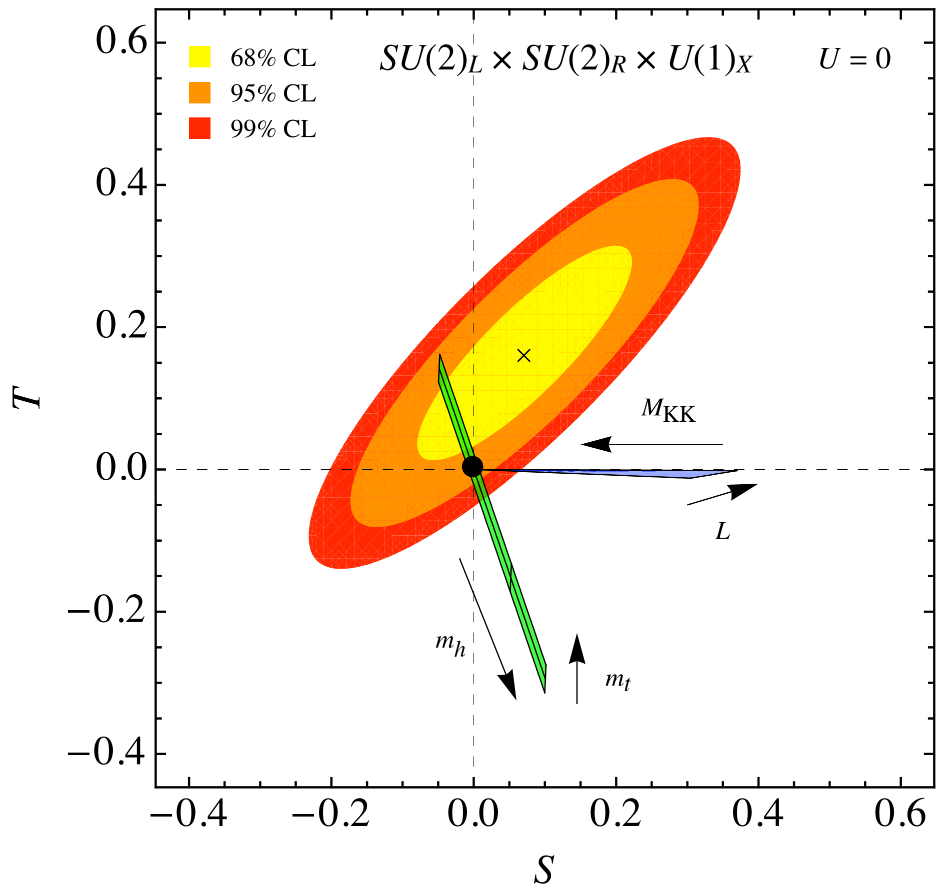
68% CL
95% CL
99% CL

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 $M_{\text{KK}} > 2.4$ TeV at 99% CL. Yet presence of heavy Higgs boson could spoil global electroweak fit



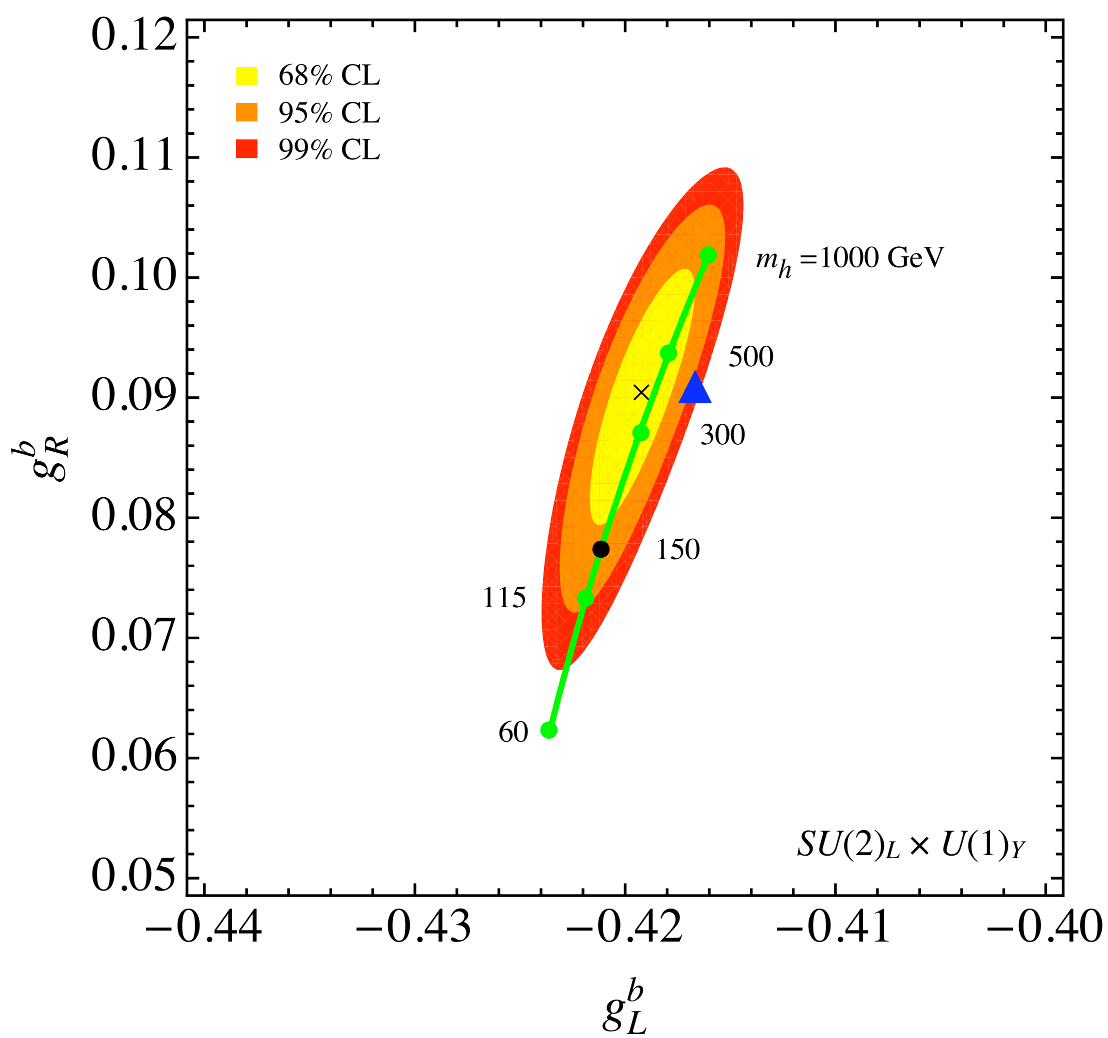
$$S = \frac{2\pi v^2}{M_{\text{KK}}^2}\left(1 - \frac{1}{L}\right), \quad T = -\frac{\pi v^2}{4c_w^2 M_{\text{KK}}^2}\frac{1}{L}$$

- prediction in extended RS model 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

*Agashe *et al*., hep-ph/0308036; 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 2.1σ anomaly in $A_{\rm FB}^{0,b}$ since in this setup Higgs-boson mass is expected to 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

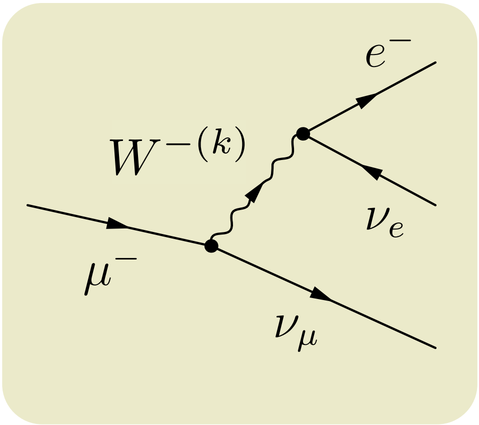
● SM prediction for $m_h \in [60, 1000]$ GeV

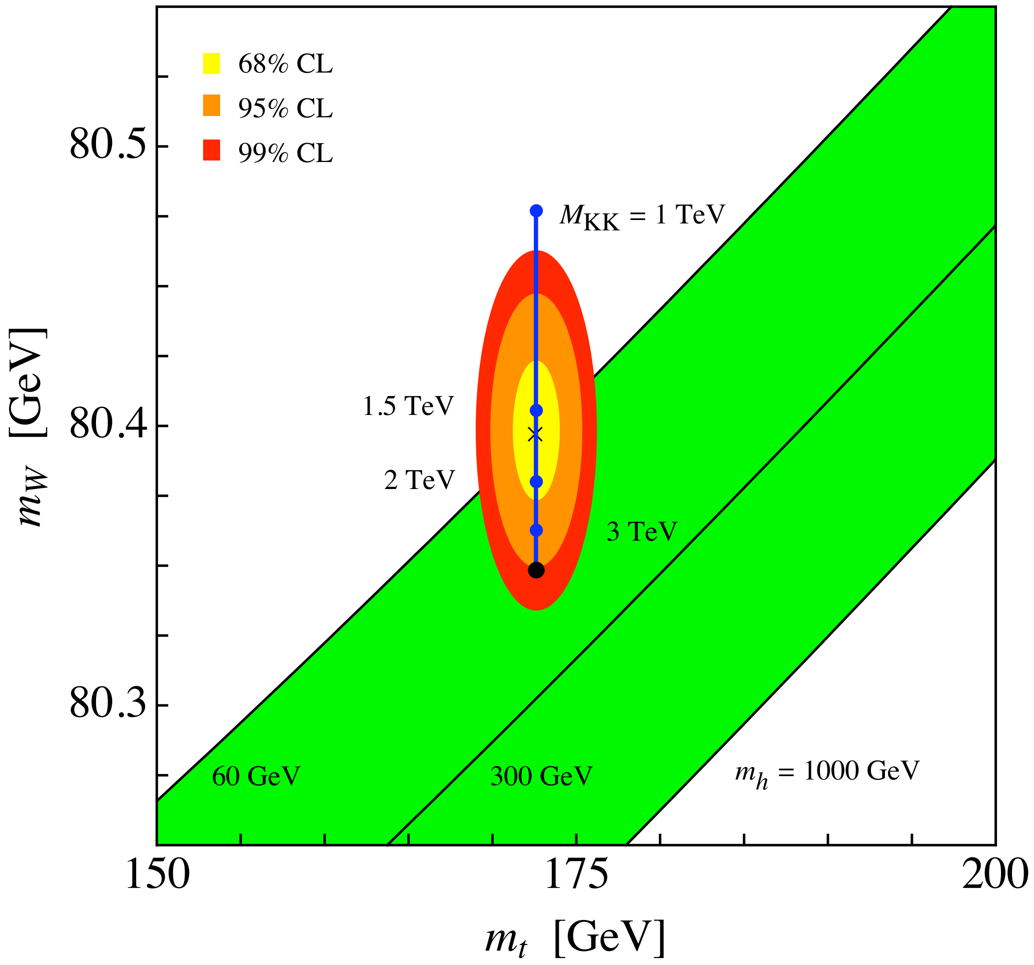
● SM prediction for $m_h = 150$ GeV

*Casagrande *et al.*, arXiv:0807.4537

Mass 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





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

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

*Casagrande *et al.*, arXiv:0807.4537

Even more additional slides

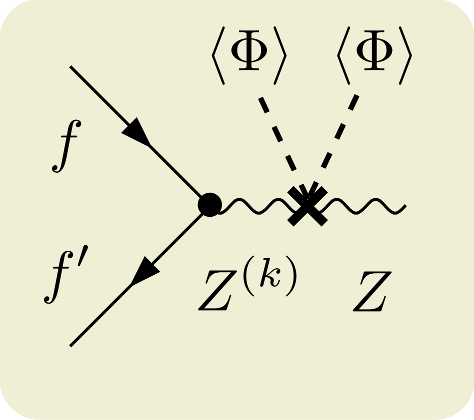
Mixing matrices: Gauge and KK boson effects

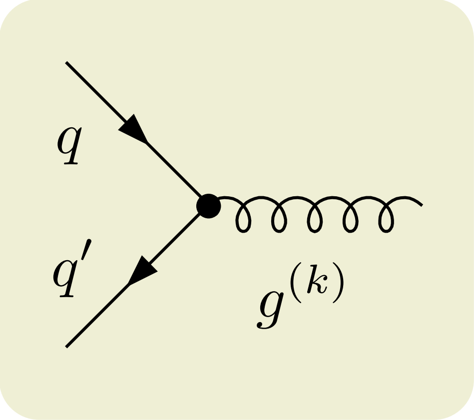
$$(\Delta_Q)_{ij} \to \left(\boldsymbol{U}_q^\dagger \, \mathrm{diag}\left[\frac{F^2_{c_{Q_i}}}{3+2c_{Q_i}} \right] \boldsymbol{U}_q \right)_{ij}, \quad (\Delta_q)_{ij},\, (\Delta'_q)_{ij} : Q_i \to q_i,\, \boldsymbol{U}_q \to \boldsymbol{W}_q\,,$$

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

Effects due to gauge-boson profiles*:

- in flavor eigenbasis couplings of gauge bosons and KK modes to fermions are flavor-diagonal but non-universal
- after transformation to mass eigenbasis via left- and right-handed rotations $\boldsymbol{U}_q$ and $\boldsymbol{W}_q$, tree-level FCNCs arise





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

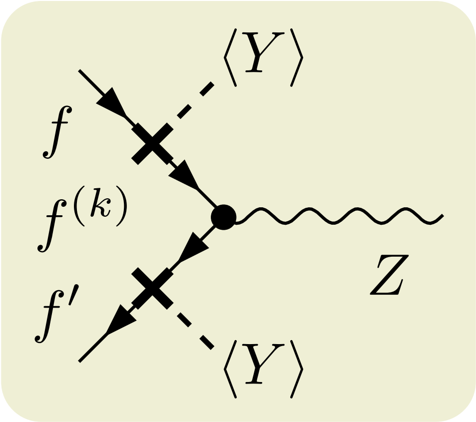
Mixing matrices: Fermion mixing

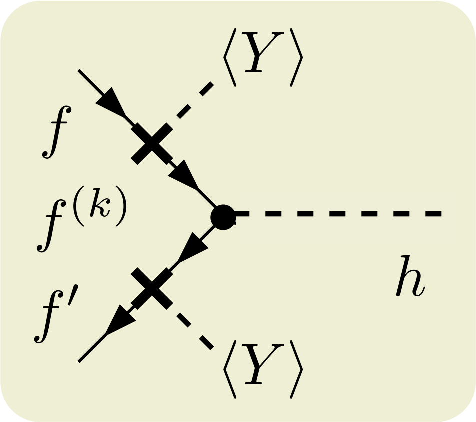
$$(\delta_Q)_{ij} \to \left(\boldsymbol{x}_q \, \boldsymbol{W}_q^\dagger \, \mathrm{diag}\left[\frac{1}{1-2c_{q_i}} \left(\frac{1}{F^2_{c_{q_i}}} - 1 + \frac{F^2_{c_{q_i}}}{3+2c_{q_i}} \right) \right] \boldsymbol{W}_q \, \boldsymbol{x}_q \right)_{ij} ,$$

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

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

- mixing matrices $\boldsymbol{\delta}_A$ are parametrically of same order as $\boldsymbol{\Delta}_A$ since 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

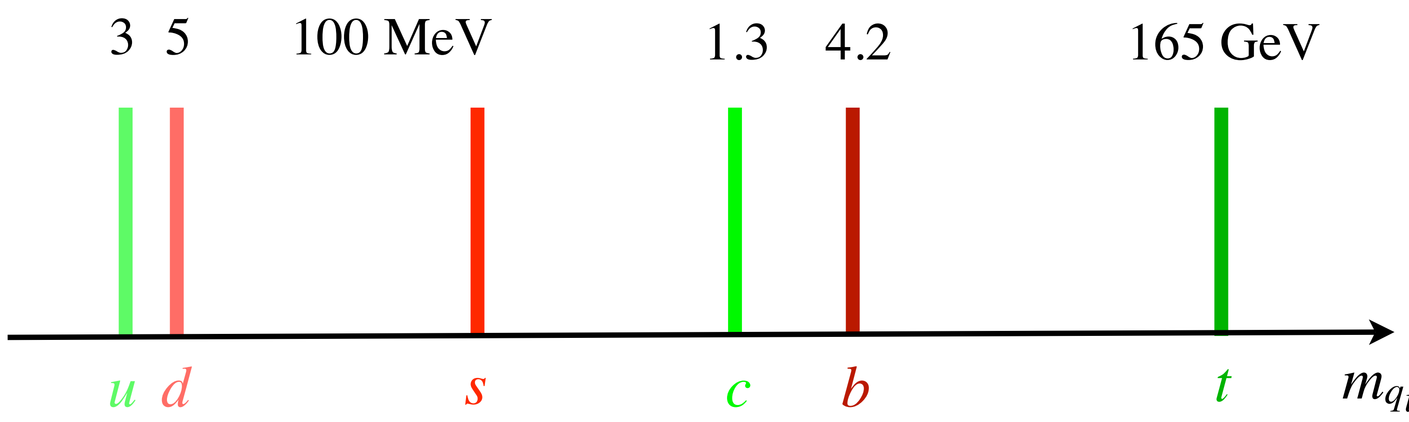




*Casagrande *et al*., arXiv:0807.4537

Quark masses and mixings in RS model*

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



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

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

$$\boldsymbol{V}_{\rm CKM} \approx \begin{pmatrix} 1 & \lambda & A\lambda^3(\bar\rho - i\bar\eta) \\ -\lambda & 1 & A\lambda^2 \\ A\lambda^3(1-\bar\rho - i\bar\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

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

$$\lambda \approx 0.23\,, \quad A \approx 0.81\,, \quad \bar\rho \approx 0.14\,, \quad \bar\eta \approx 0.34$$

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

*Huber, hep-ph/0303183

Non-unitarity of CKM matrix*

- Typical RS prediction:

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

- 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

Physical parameters in quark sector*

Flavor is violated by:

- bulk parameters c_Q, c_u, c_d — 3×6 real parameters
  - 3×3 hermitian matrices — 3×3 complex phases
- Yukawa couplings Y_u, Y_d — 2×9 real parameters
  - 3×3 complex matrices — 2×9 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

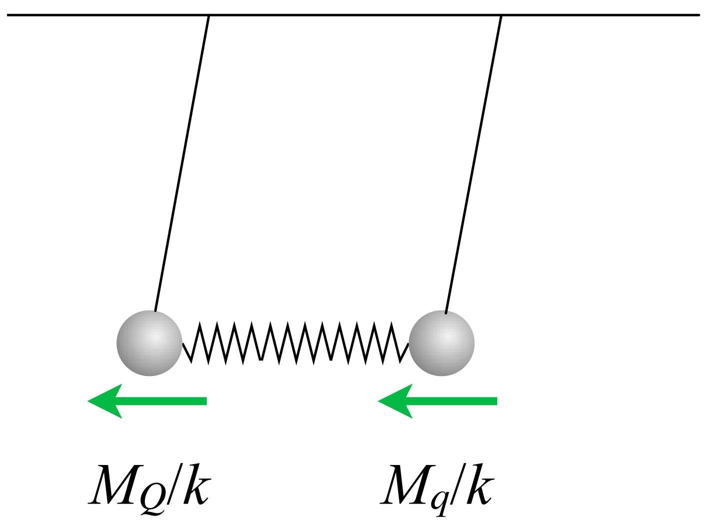
Reparametrization invariance*

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

<u>RPI-1:</u>

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

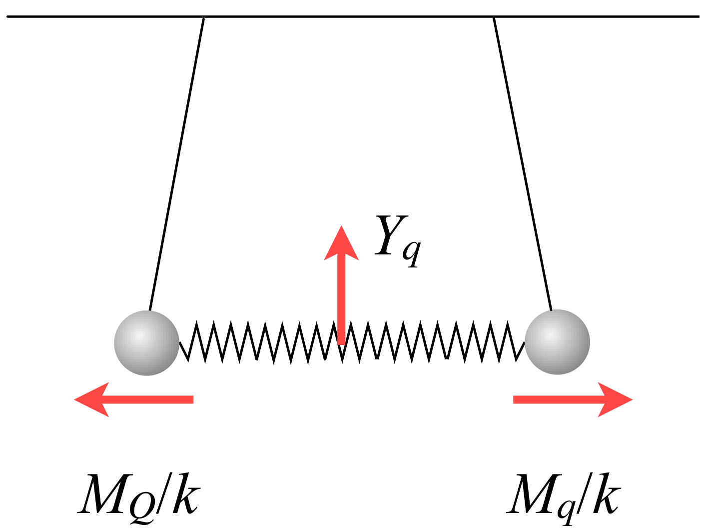
$$F_{c_q} \to e^{+\xi}\, F_{c_q}\,, \qquad \left[c_q \to c_q + \frac{\xi}{L}\right]$$



<u>RPI-2:</u>

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

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



*Casagrande *et al*., arXiv:0807.4537

Mixing matrices: Transformation properties

RPI-1:

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

RPI-2:

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

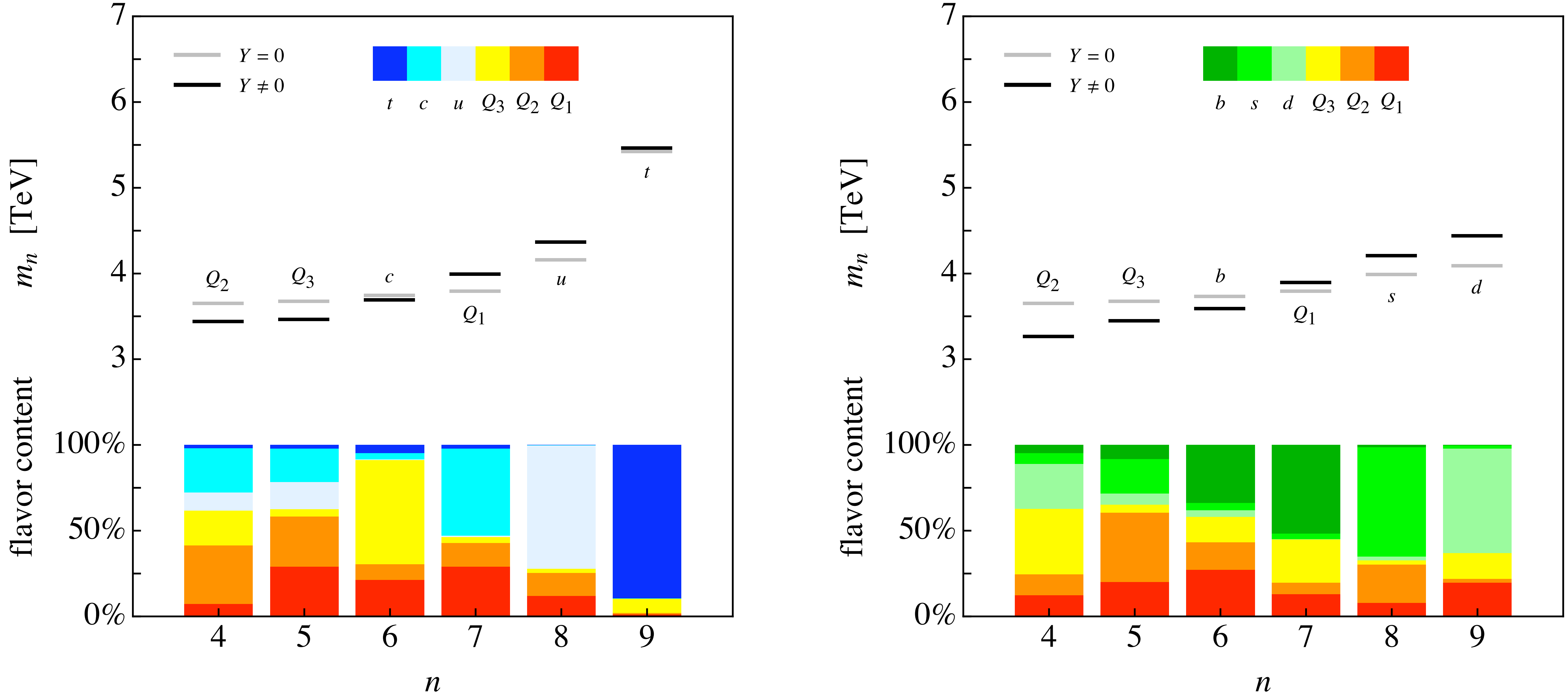
Reparametrization transformations imply*:

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

*Casagrande *et al.*, arXiv:0807.4537

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