Effects of warped extra dimensions on B decays

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Based on recent work by:

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

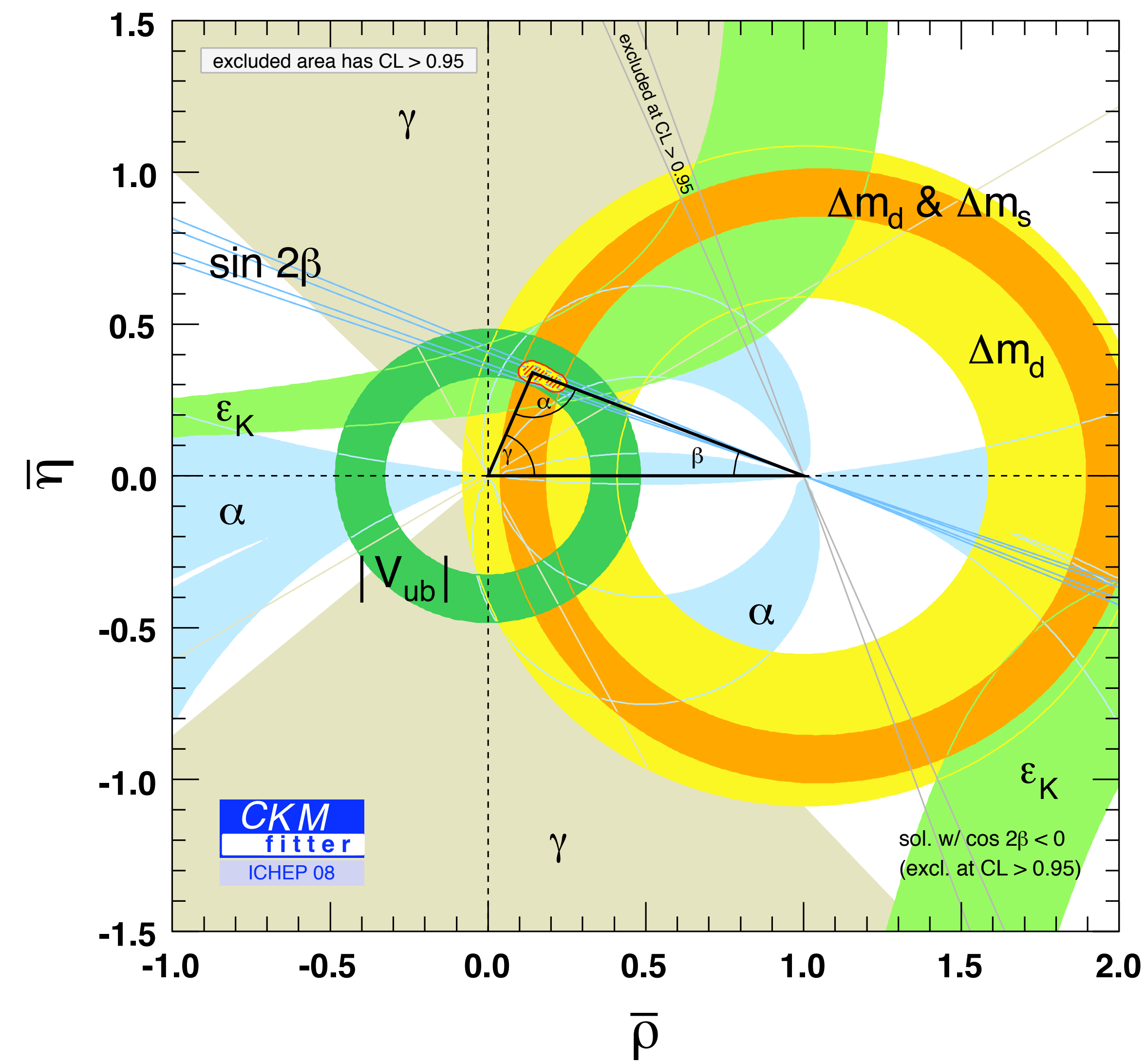
Also lots of previous important work, in particular:

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

Main lesson from quark flavor physics

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

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



Main lesson from quark flavor physics

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

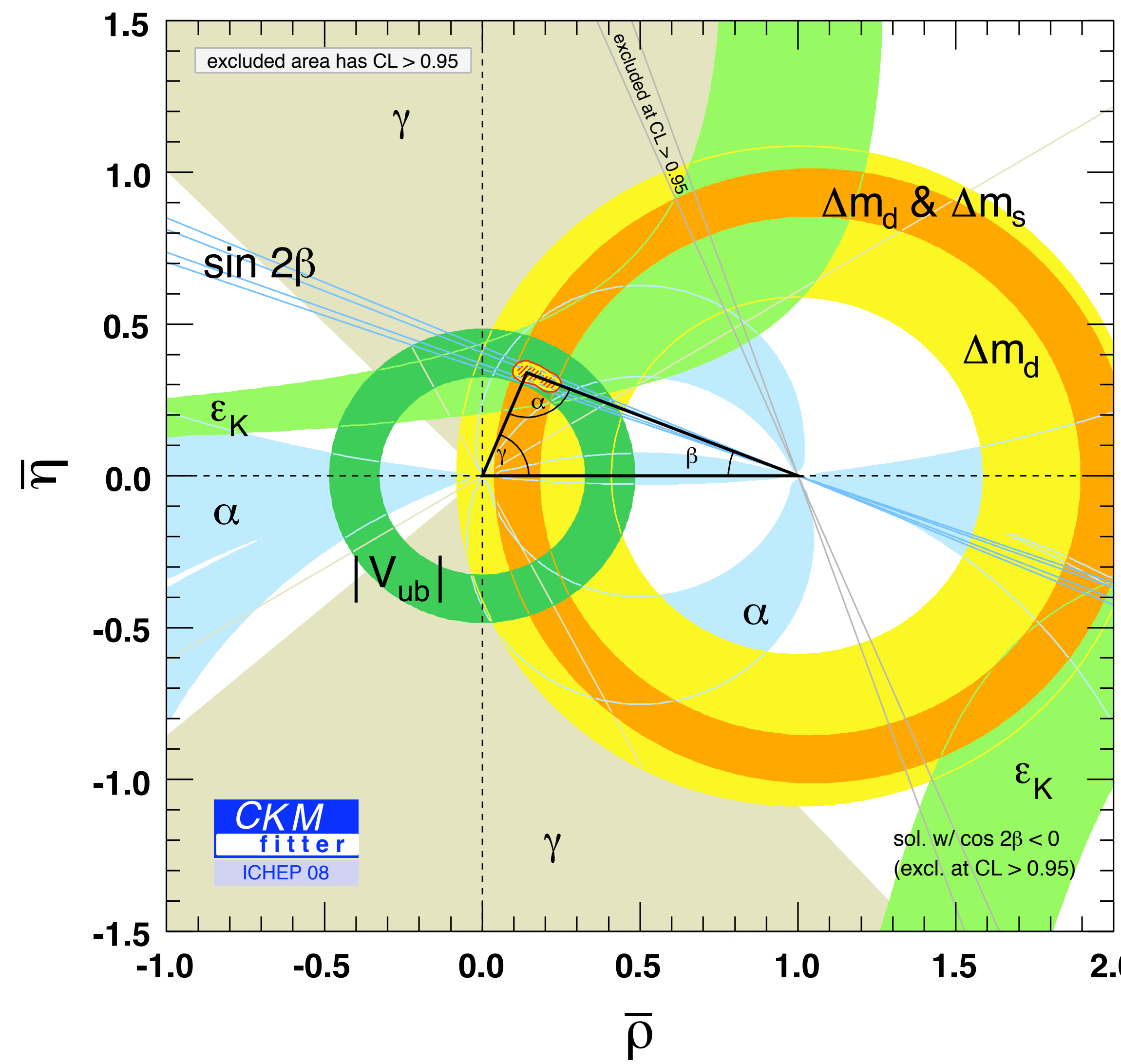

N. Cabibbo


M. Kobayashi


T. Maskawa

Nobel Prize in Physics 2008 awarded to Kobayashi and Maskawa:

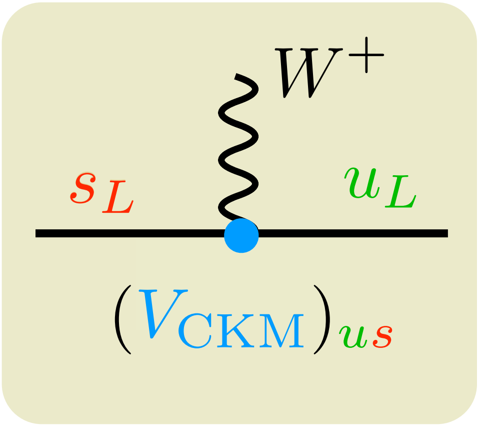
"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"



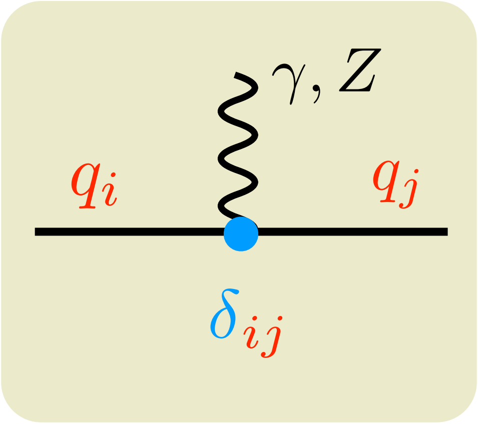
Main lesson from quark flavor physics

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

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



$V_{\rm CKM}$ = CKM matrix



δ = diagonal matrix

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

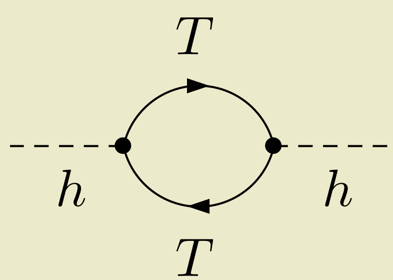
But the SM does not **explain** the hierarchies in flavor physics!

Beyond SM there is another problem of flavor ...

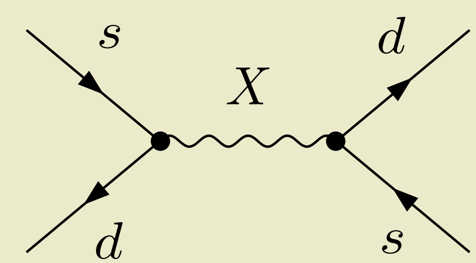
$$\mathcal{L}_{\mathrm{EFT}} = \Lambda_{\mathrm{UV}}^2 \Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2 + \mathcal{L}_{\mathrm{SM}}^{\mathrm{gauge}} + \mathcal{L}_{\mathrm{SM}}^{\mathrm{Yukawa}} + \frac{\mathcal{L}^{(5)}}{\Lambda_{\mathrm{UV}}} + \frac{\mathcal{L}^{(6)}}{\Lambda_{\mathrm{UV}}^2} + \dots$$

electroweak symmetry breaking ⇓ Higgs mass

large FCNCs ⇓ generic flavor structure



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



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

no fine-tuning ⇓

bounds on flavor mixing ⇓

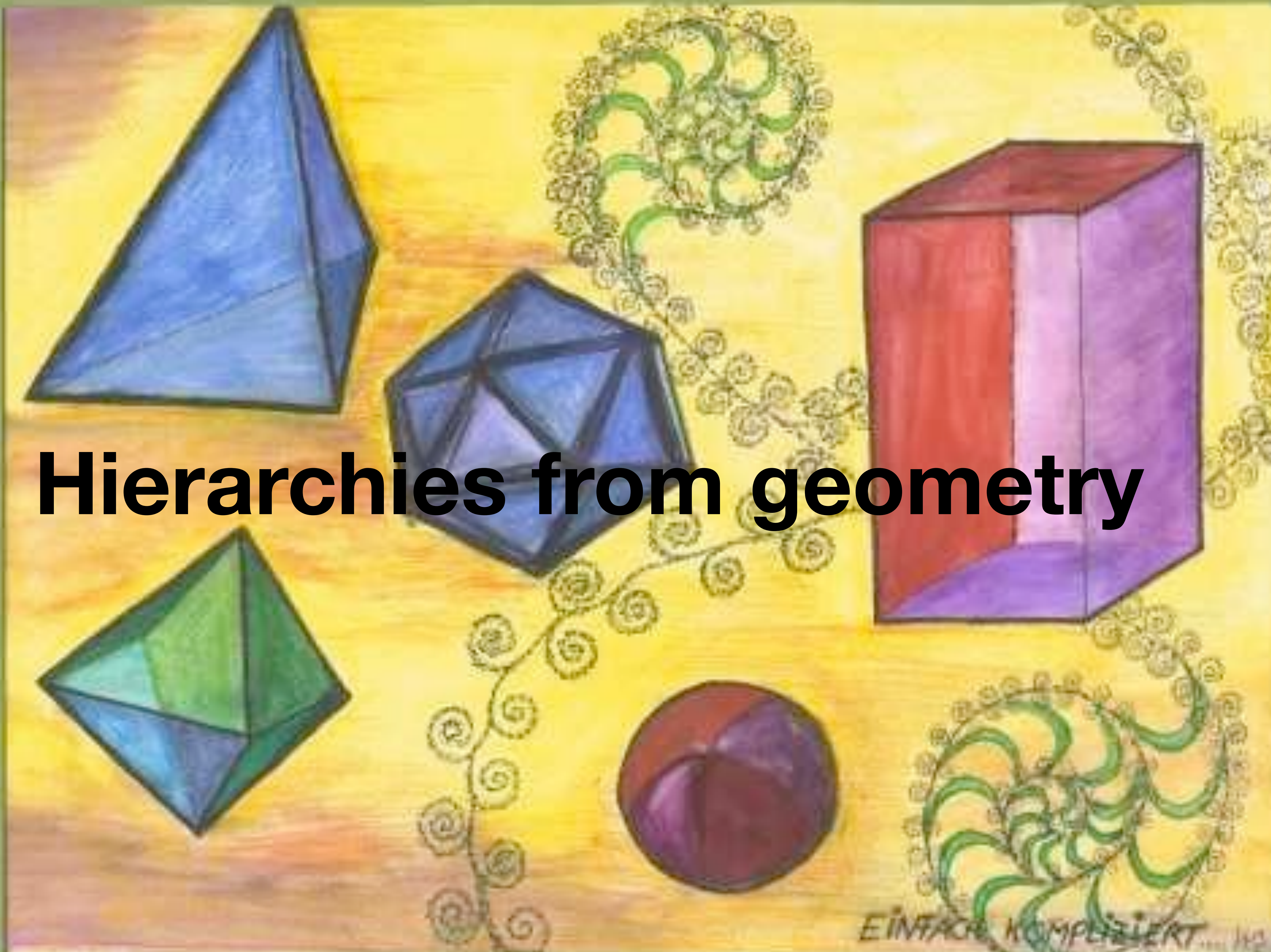
$\Lambda_{\mathrm{Higgs}} \lesssim 1\ \mathrm{TeV}$ $\longrightarrow$ increasing energy scale $\longrightarrow$ $\Lambda_{\mathrm{flavor}} \gtrsim 10^3\ \mathrm{TeV}$

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

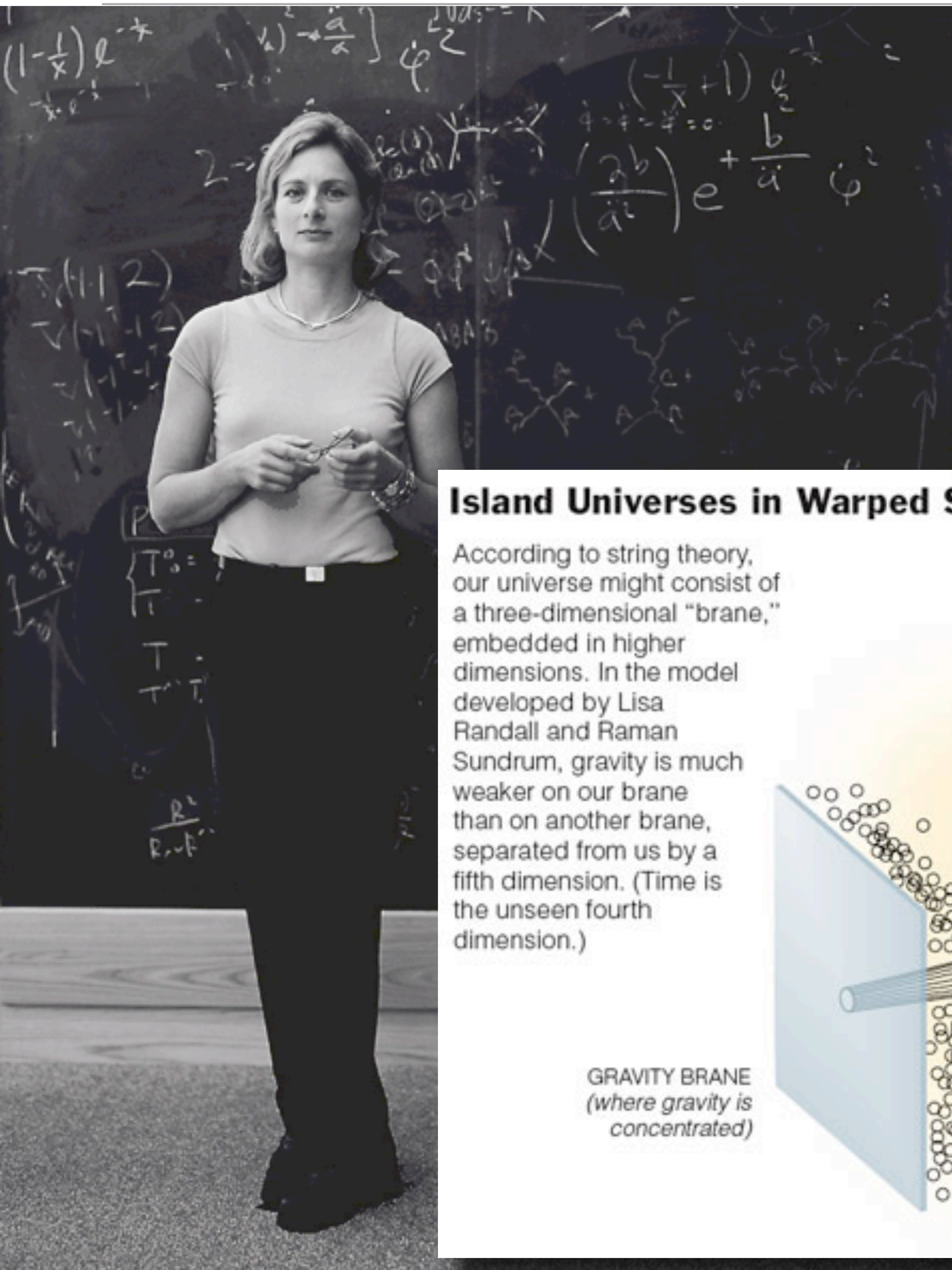
  (i) $\Lambda_{\mathrm{UV}} >> 1\ \mathrm{TeV}$: new particles too heavy to be discovered at LHC

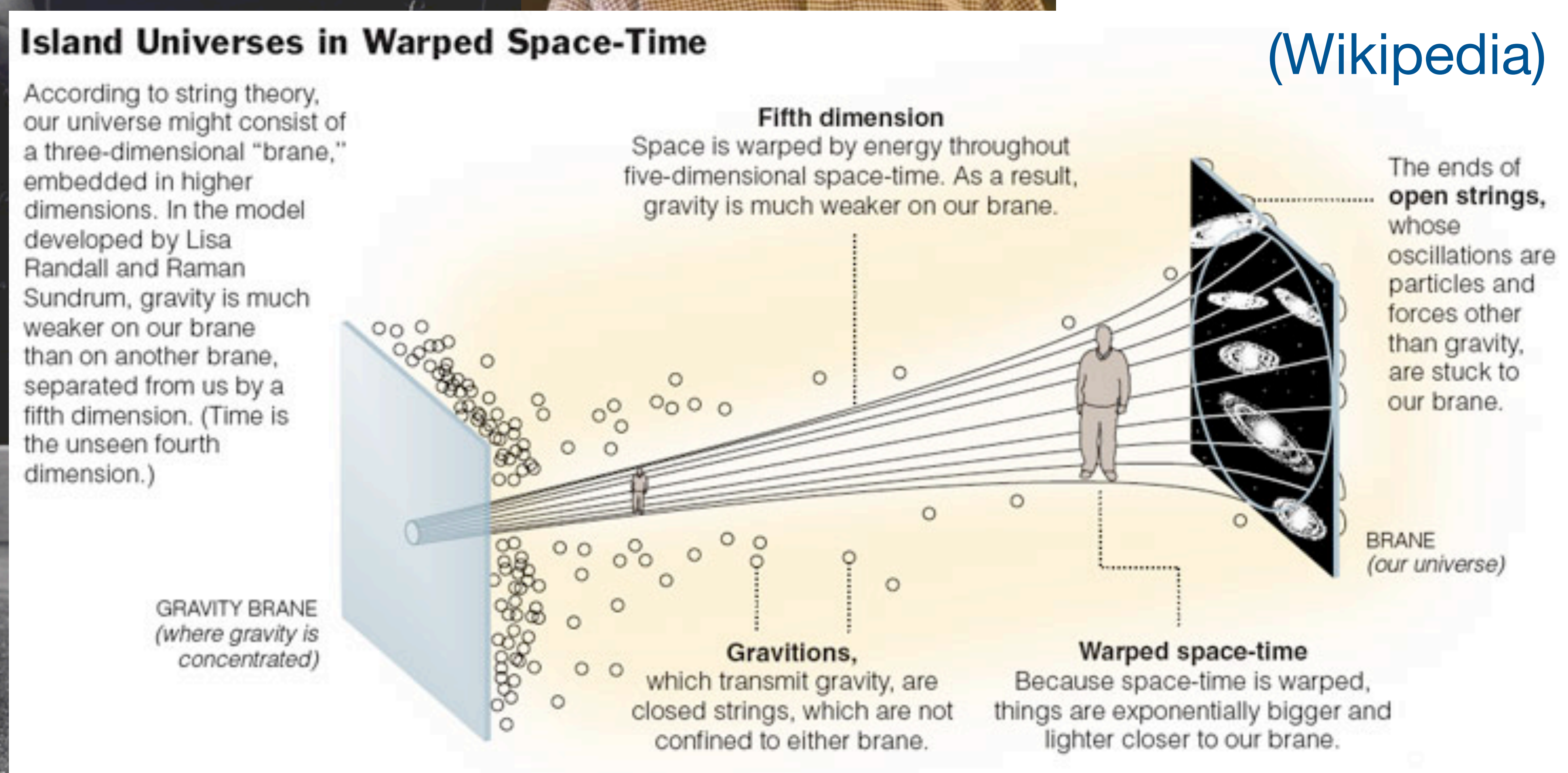
  (ii) $\Lambda_{\mathrm{UV}} \approx 1\ \mathrm{TeV}$: quark flavor mixing protected by flavor symmetry

Hierarchies from geometry



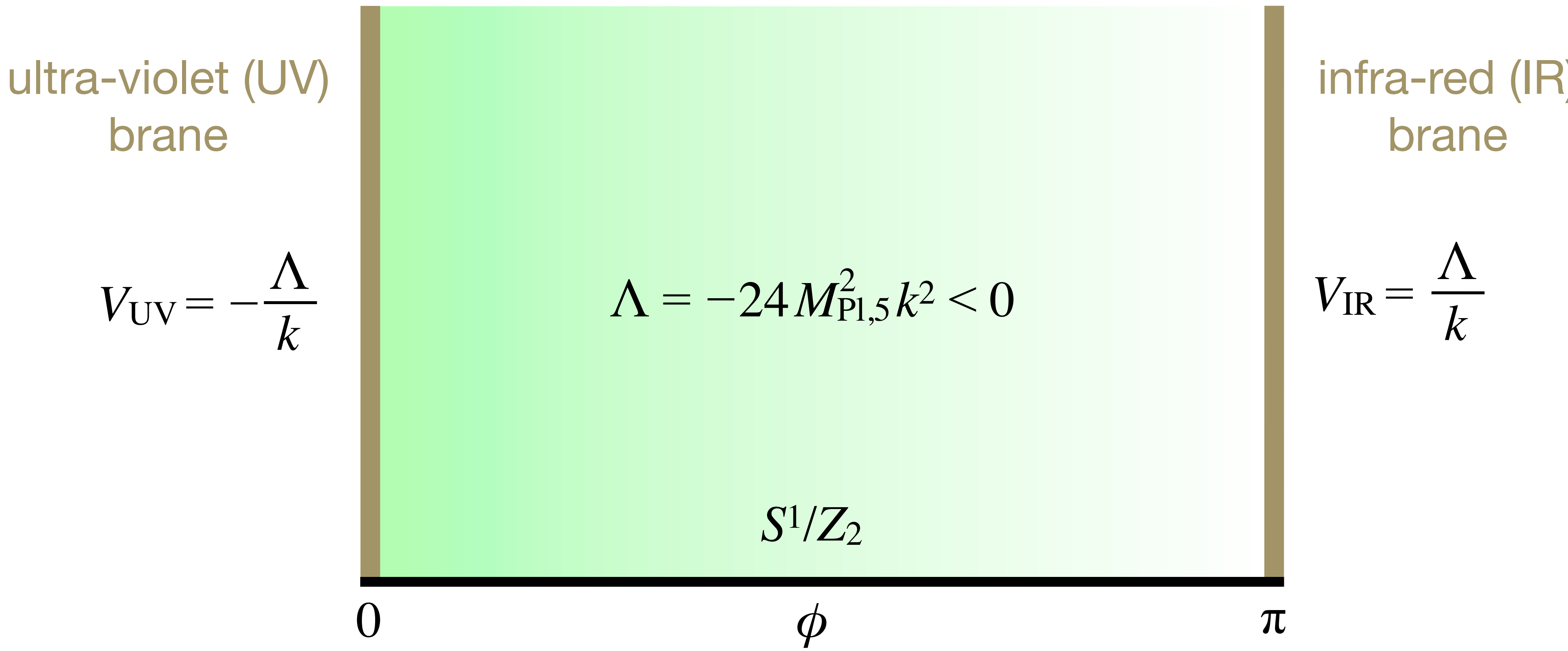
The Randall-Sundrum (RS) idea





(Wikipedia)

Hierarchies from geometry: RS model*



Slice of AdS$_5$ with curvature k:

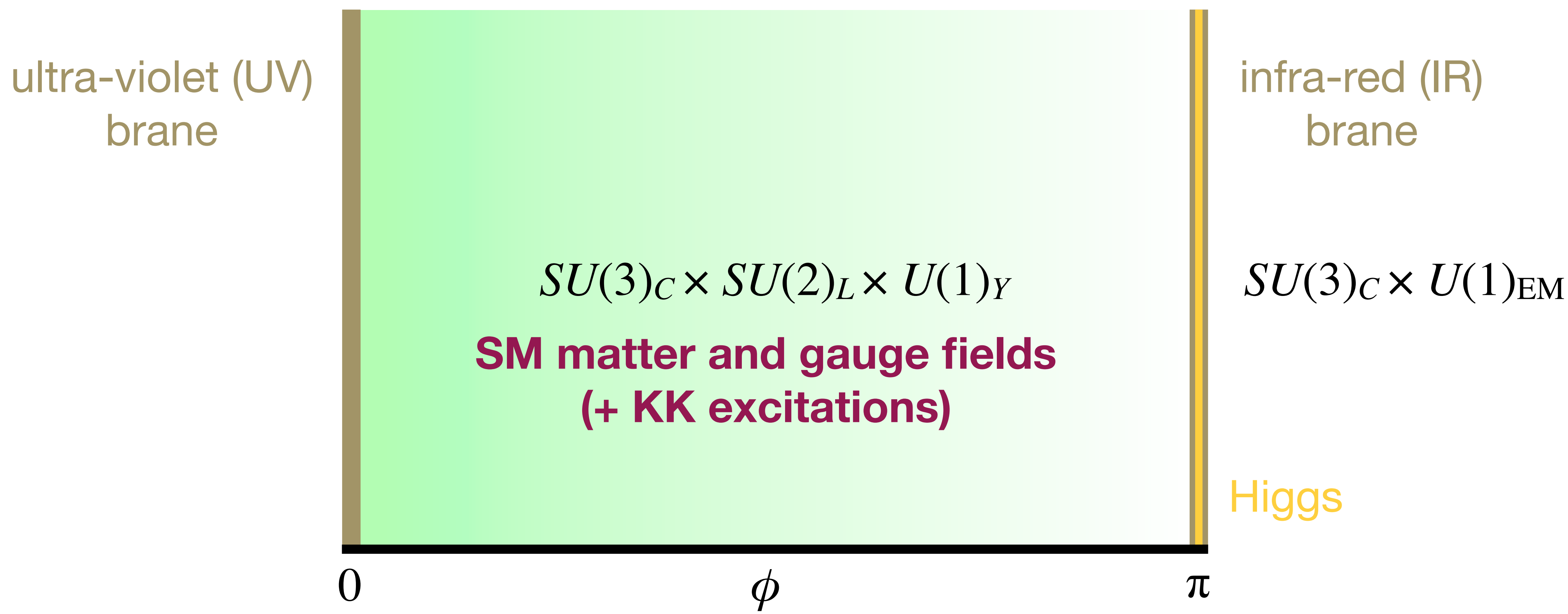
warp factor
(solution to Einstein's equations)

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

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

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

Hierarchies from geometry: RS model

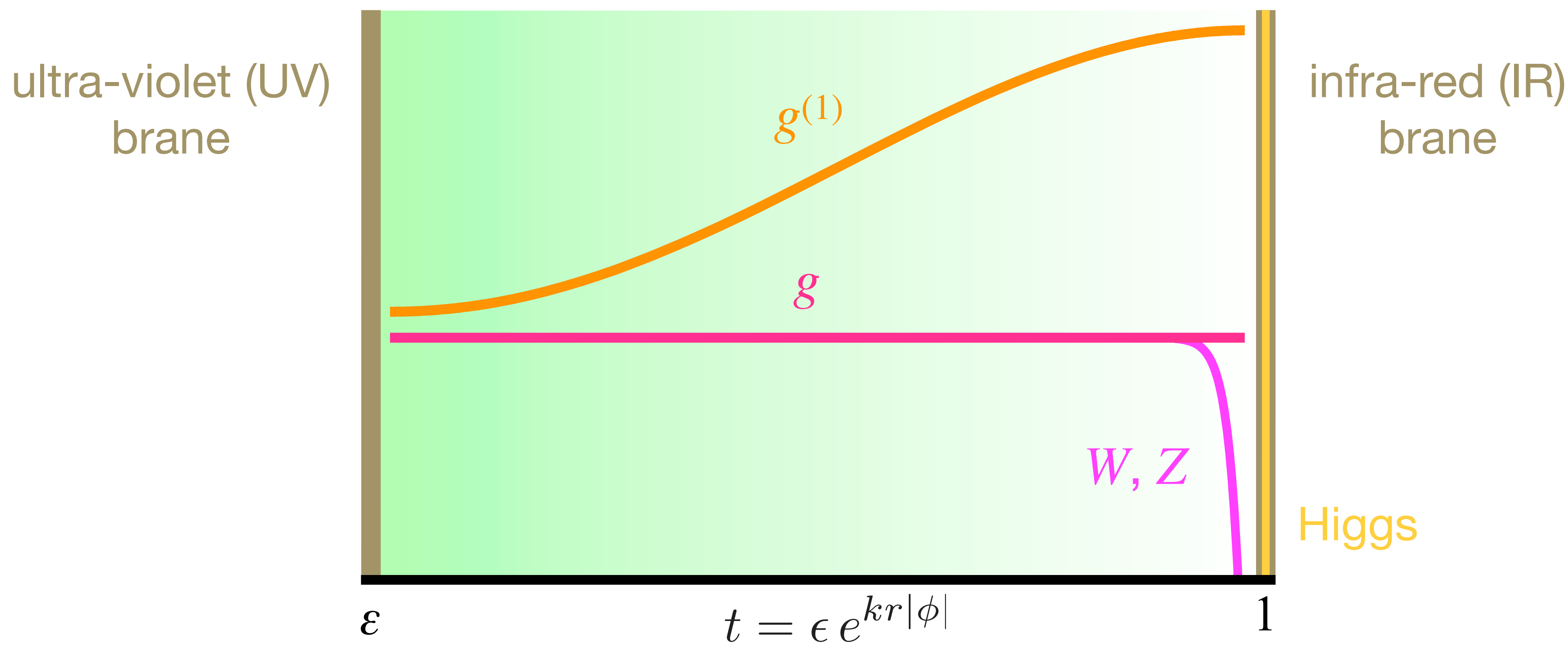


Pattern of gauge-symmetry breaking:

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

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

RS model: Gauge boson profiles*



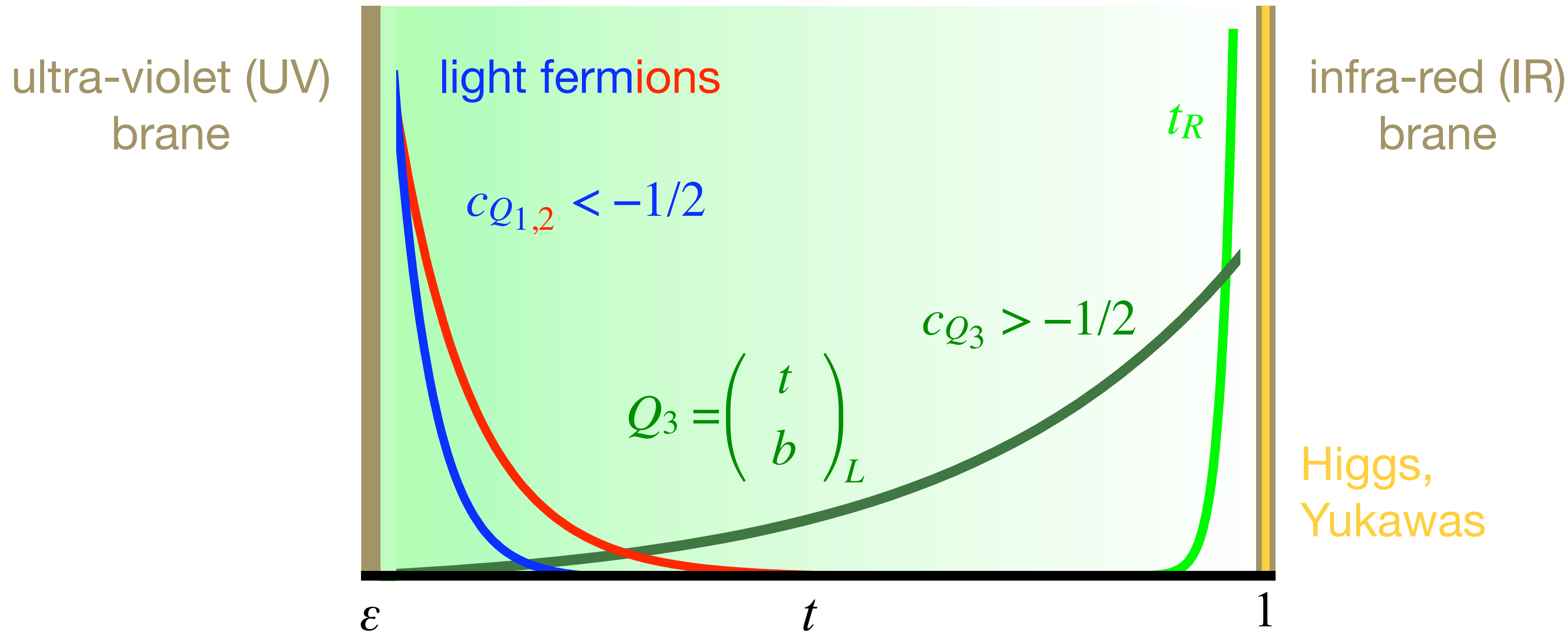
<u>Profiles of gauge fields:</u>

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

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

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

RS model: Fermion profiles*

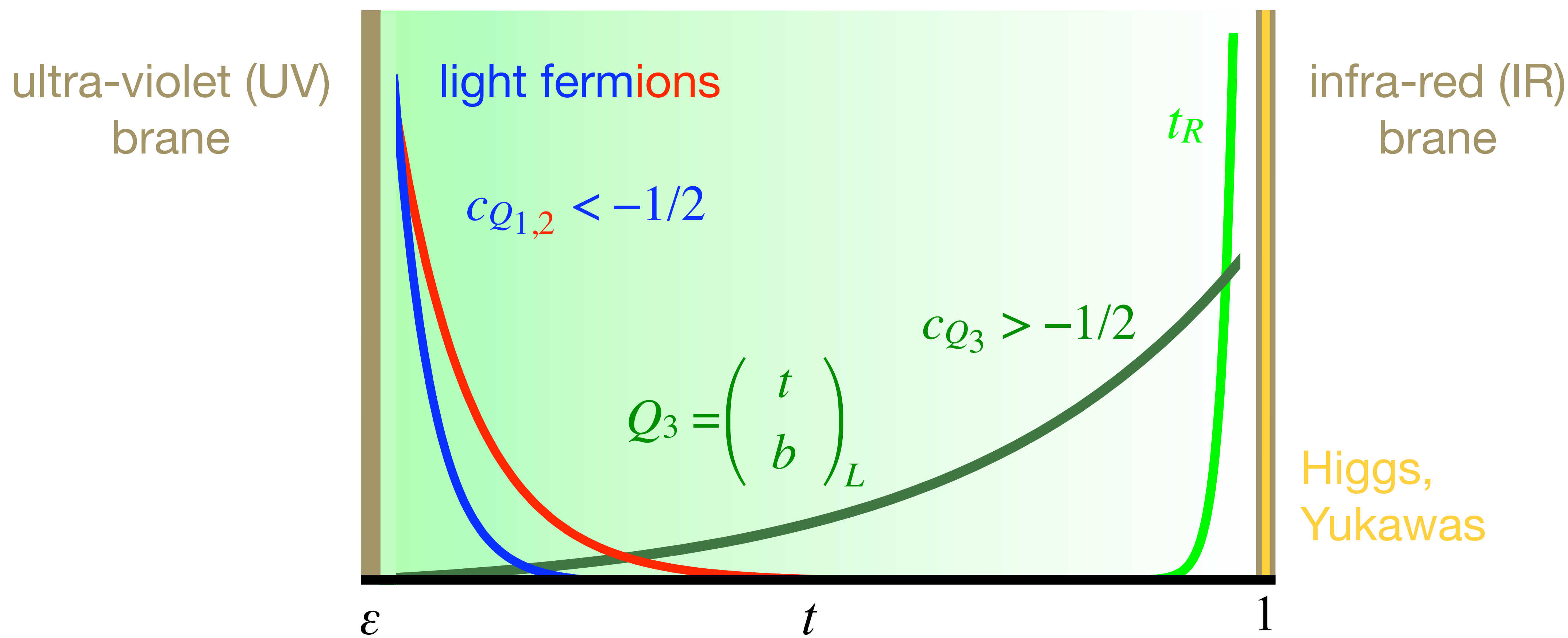


<u>Profiles of fermion fields:</u>

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

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

RS model: Fermion profiles*



Profiles of fermion fields:

$$C_0^{(A)}(\phi) \approx \sqrt{\frac{L\epsilon}{\pi}}\, F_{c_A}\, t^{c_A}$$

power law

$$F_{c_A} = \sqrt{\frac{1+2c}{1-\epsilon^{1+2c}}} \sim \epsilon^{-\frac{1}{2}-c} \quad (c < -\frac{1}{2})$$

wave function on IR brane
$(\epsilon = e^{-kr\pi} \approx 10^{-16})$

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

Quark masses and mixings in RS model*

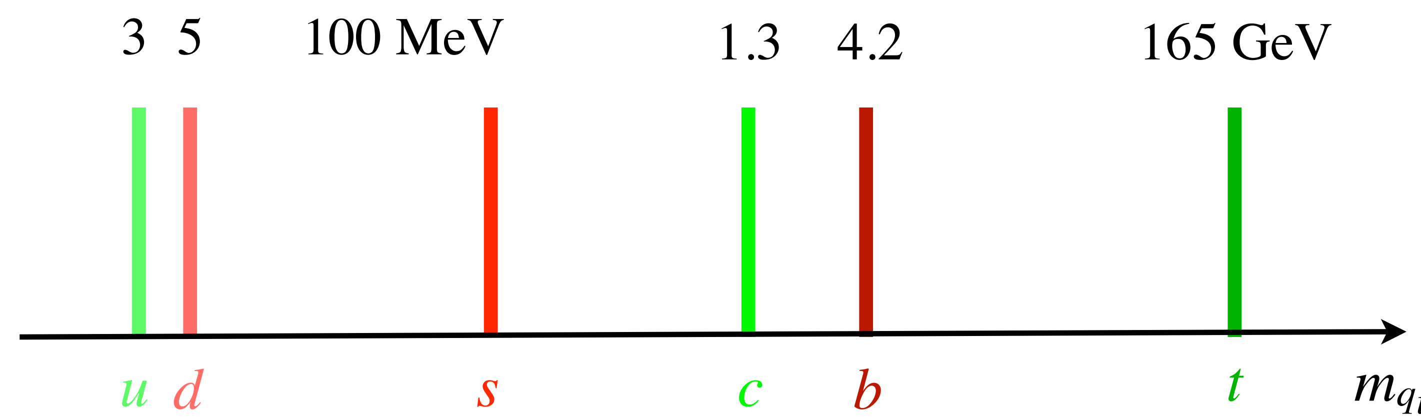
Scaling laws:

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

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

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

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



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

(+ anarchic Yukawa matrices)

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

*Huber, hep-ph/0303183

Warped-space Froggatt-Nielsen mechanism*

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

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

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

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

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

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

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

RS is a **theory** of flavor!

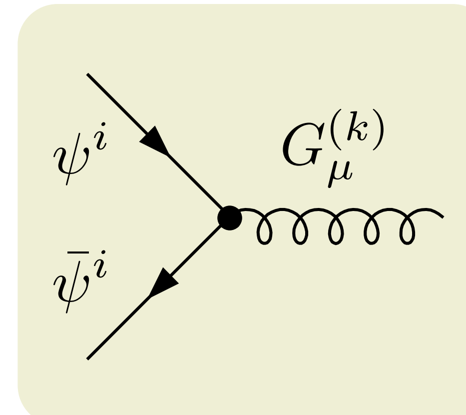
(to a good extent)

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

RS-GIM mechanism*

- Quark-quark-gluon vertex in flavor eigenbasis:

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



- Quark-quark-gluon vertex in mass eigenbasis:

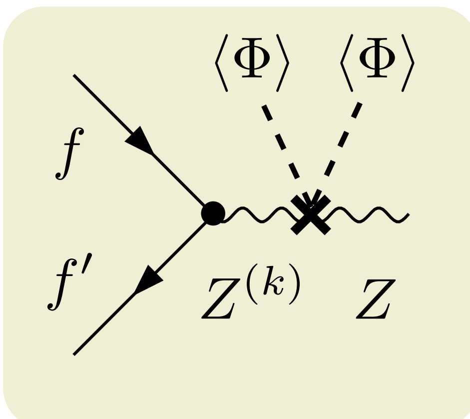
$$\bar{q}_L^i \, G_\mu^{(k)} \, q_L^j \sim -i g_s^{4\mathrm{D}} \gamma_\mu \sqrt{L} \, F_{c_{Q_i}} F_{c_{Q_j}} \,, \quad \bar{q}_R^i \, G_\mu^{(k)} \, q_R^j \sim -i g_s^{4\mathrm{D}} \gamma_\mu \sqrt{L} \, F_{c_{q_i}} F_{c_{q_j}}$$

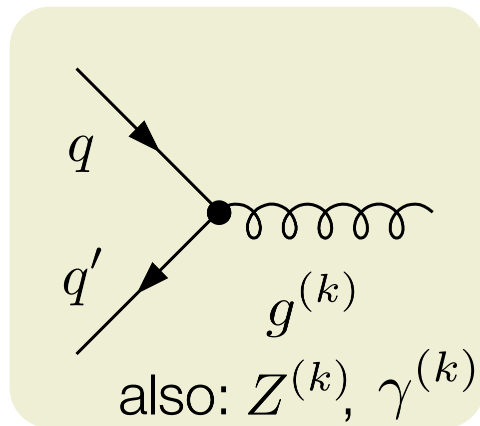
Important features:

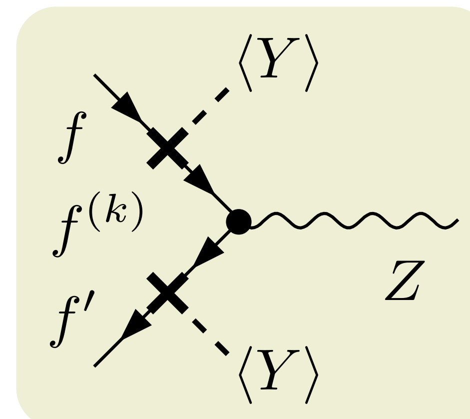
- in flavor eigenbasis KK gluon couples to quarks flavor diagonally but non-universally, so that after rotation to mass eigenstates tree-level FCNCs arise
- since FCNCs are proportional to $F_{c_{A_i}} F_{c_{A_j}}$, exponential suppression of fermion profiles $F_{c_{A_i}}$ at IR brane guarantees **flavor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

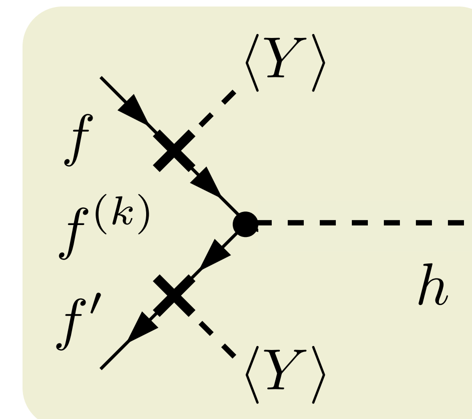
*Agashe *et al.*, hep-ph/0406101, hep-ph/0408134

Sources of flavor violation*









Flavor violation arises from:

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

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

Mixing matrices: Scaling relations

- In all cases one finds:

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

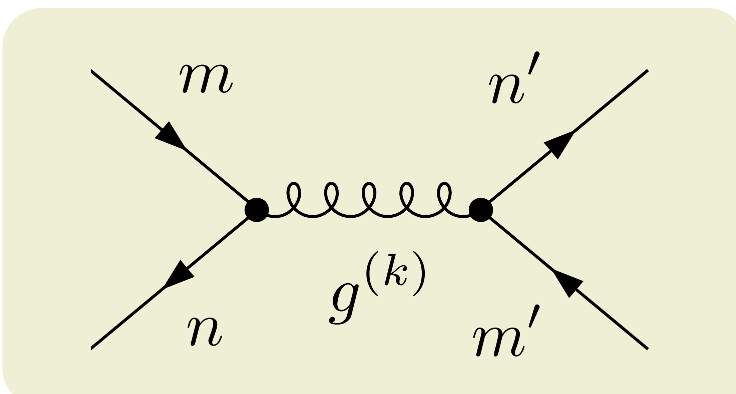
$$(\Delta_q^{(\prime)})_{ij} \sim F_{c_{q_i}} F_{c_{q_j}} \,, \qquad (\delta_q)_{ij} \sim \frac{m_{q_i} m_{q_j}}{M_{\rm KK}^2} \frac{1}{F_{c_{Q_i}} F_{c_{Q_j}}} \sim \frac{v^2 Y_q^2}{M_{\rm KK}^2} F_{c_{Q_i}} F_{c_{Q_j}}$$

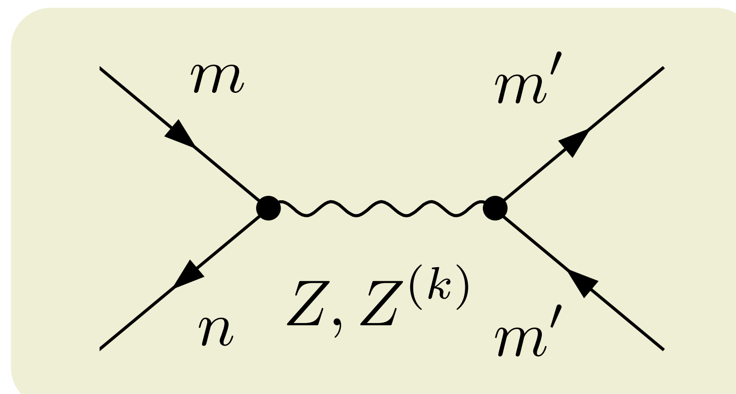
Implications of scaling relations:

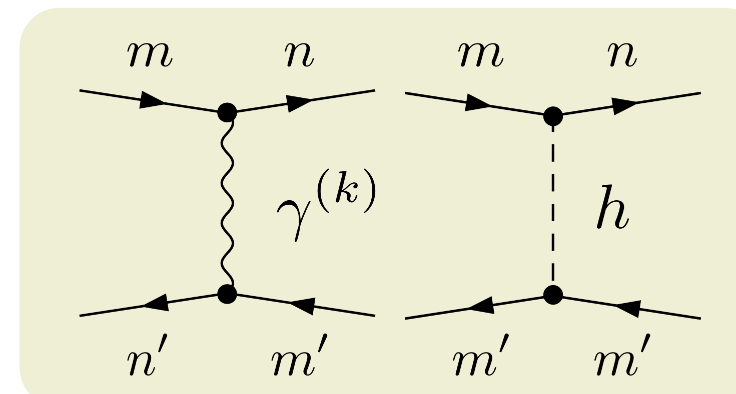
- all effects are proportional to $F_{c_{A_i}} F_{c_{A_j}}$, so that all flavor-violating vertices involving light, UV-localized fermions are suppressed
- this suppression of dangerous FCNCs involving light quarks reflects the RS-GIM mechanism

Anatomy of tree-level FCNC processes

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







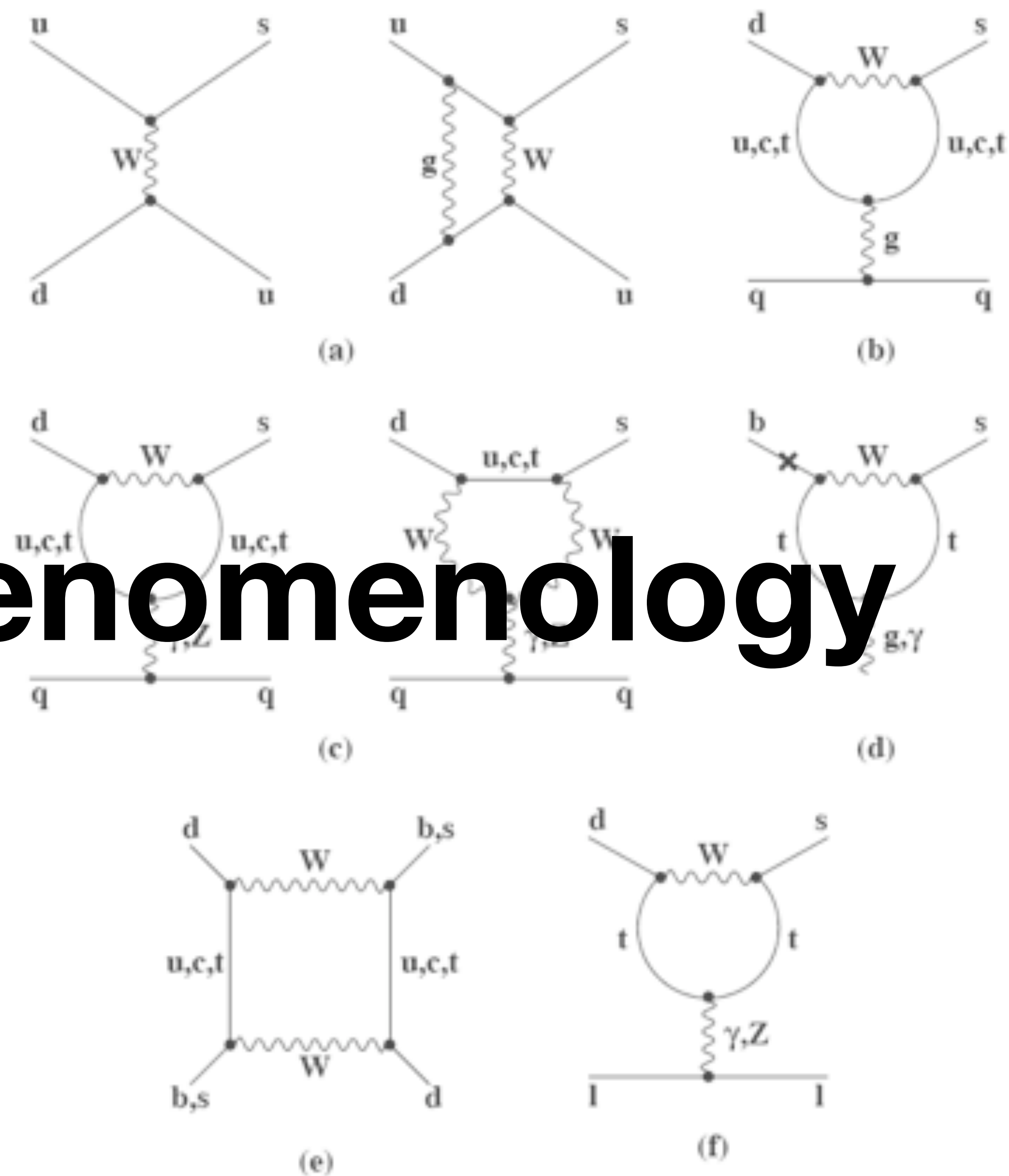
dominant contribution to $\Delta F = 2$ processes

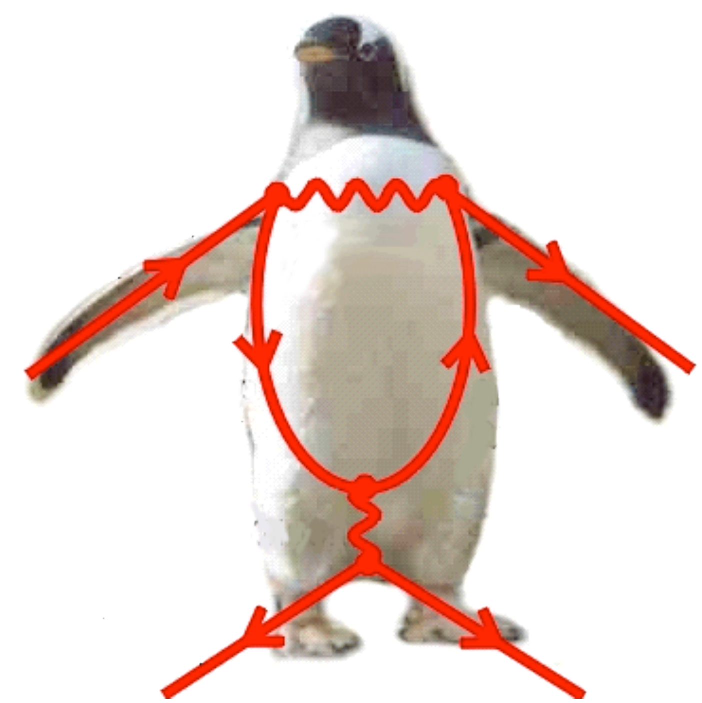
dominant contribution to $\Delta F = 1$ processes

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

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

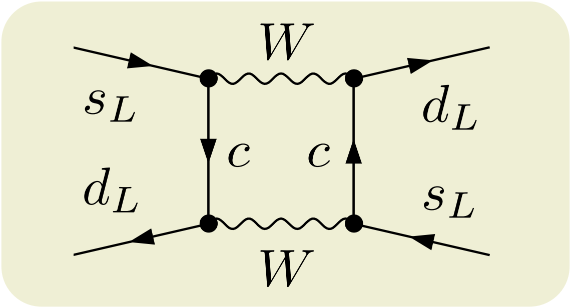
Phenomenology



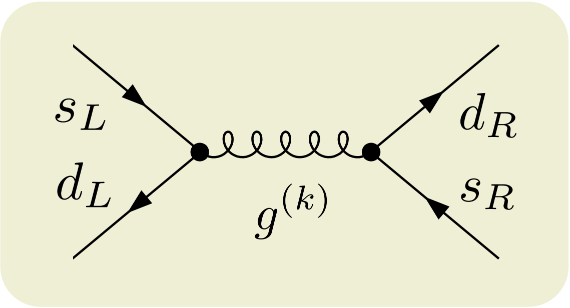


Meson mixing: Effective Hamiltonian*

SM



RS



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

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

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

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

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

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

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

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

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

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

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

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

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

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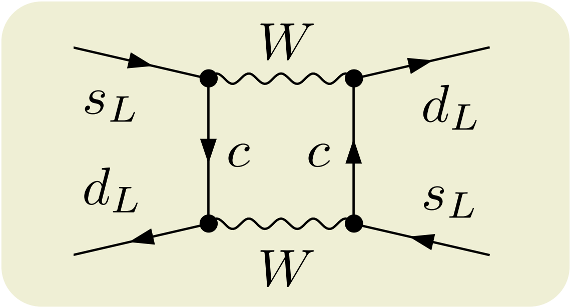
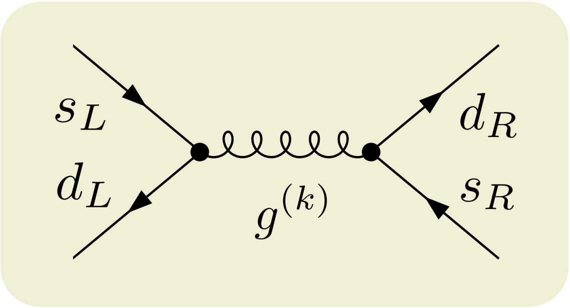
SM



RS



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

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

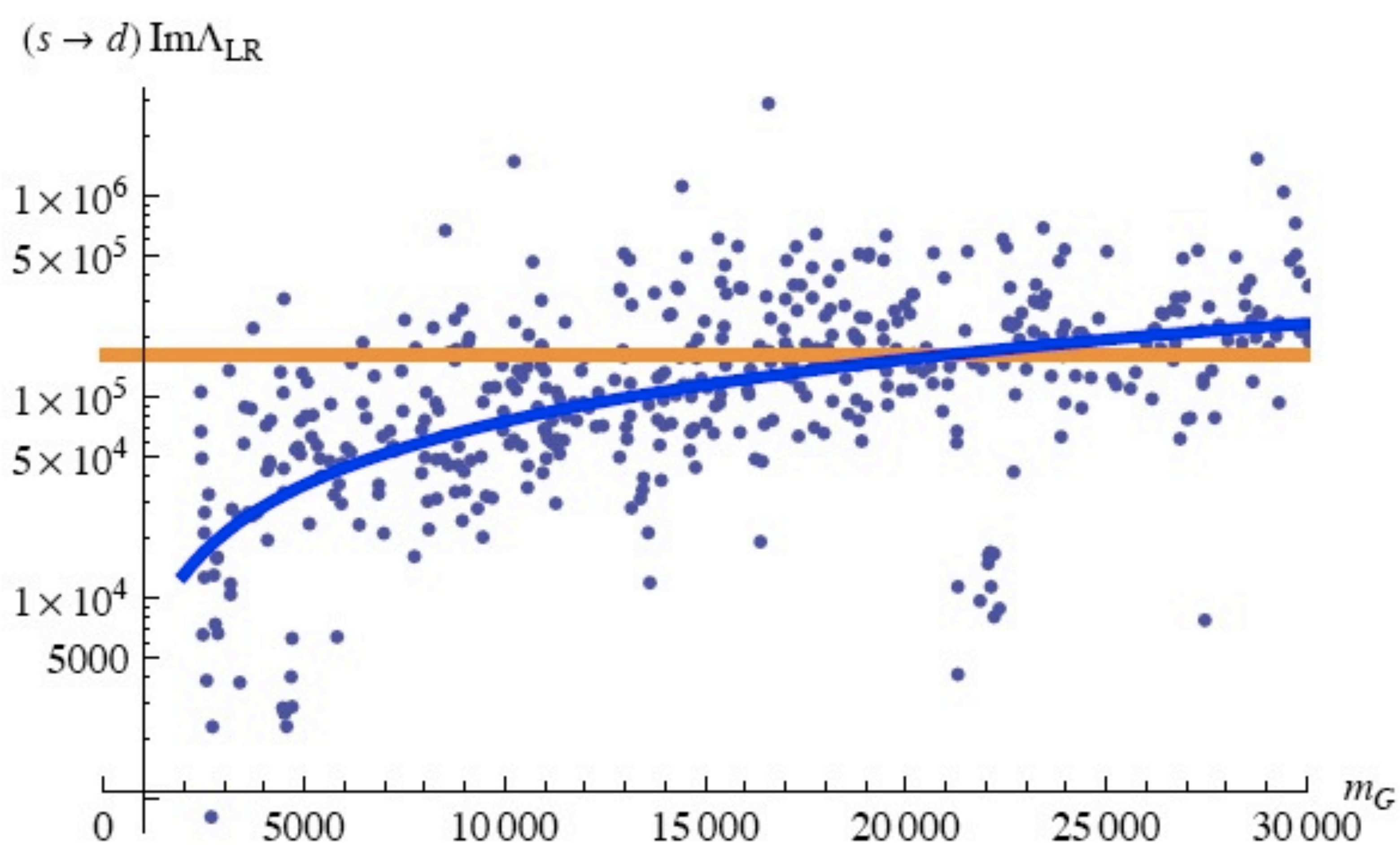
- Contribution from Wilson coefficient of Q_4 to CP-violating quantity ε_K strongly enhanced through renormalization-group evolution and chiral factor $(m_K/m_s)^2$ in matrix element:

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

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

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

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



Csaki, Falskowski, Weiler: arXiv:0804.1954

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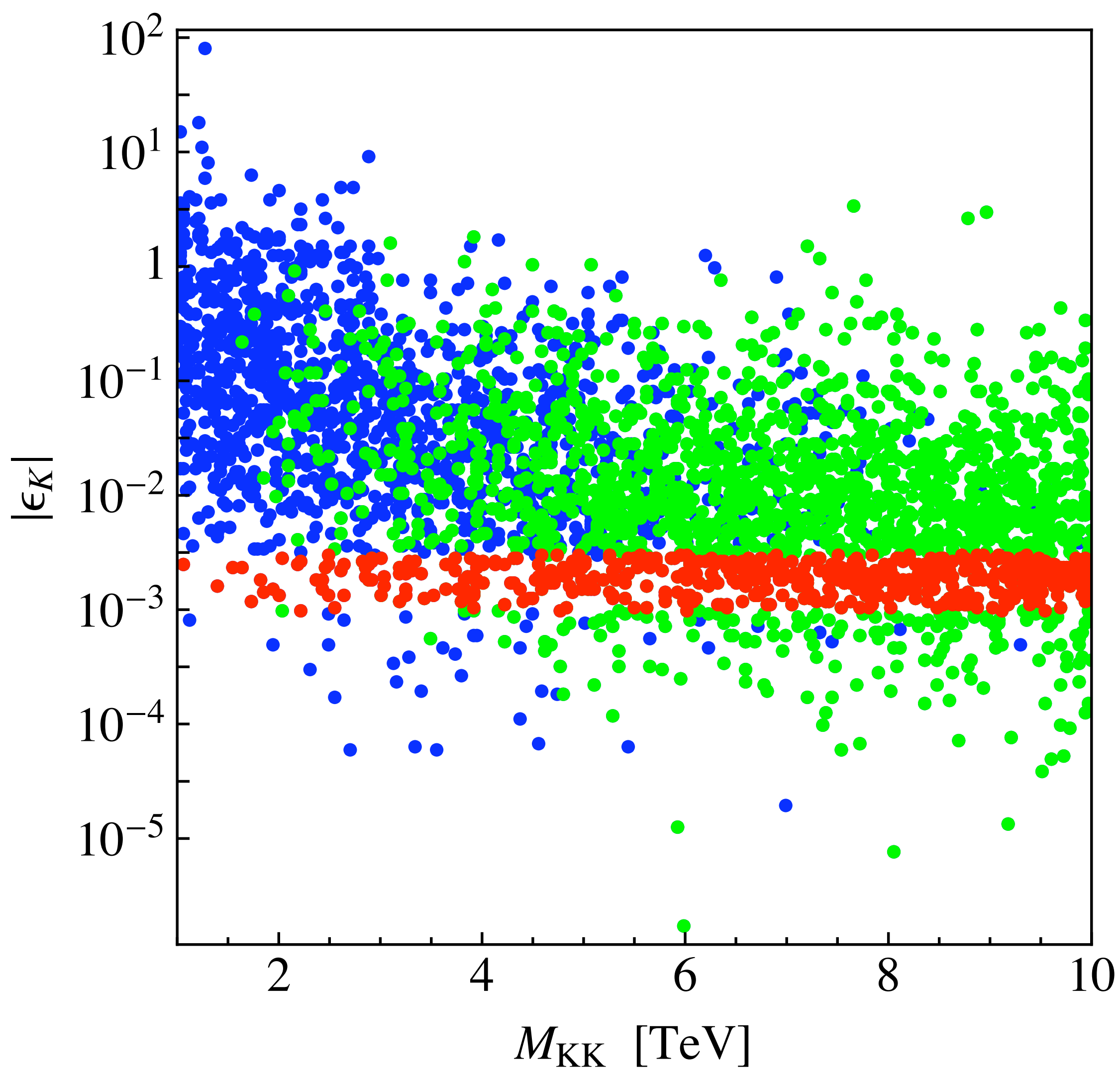


3000 randomly chosen RS points with $|Y_q| < 3$ reproducing quark masses and CKM parameters with $\chi^2/\text{dof} < 11.5/10$ (corresponding to 68% CL)

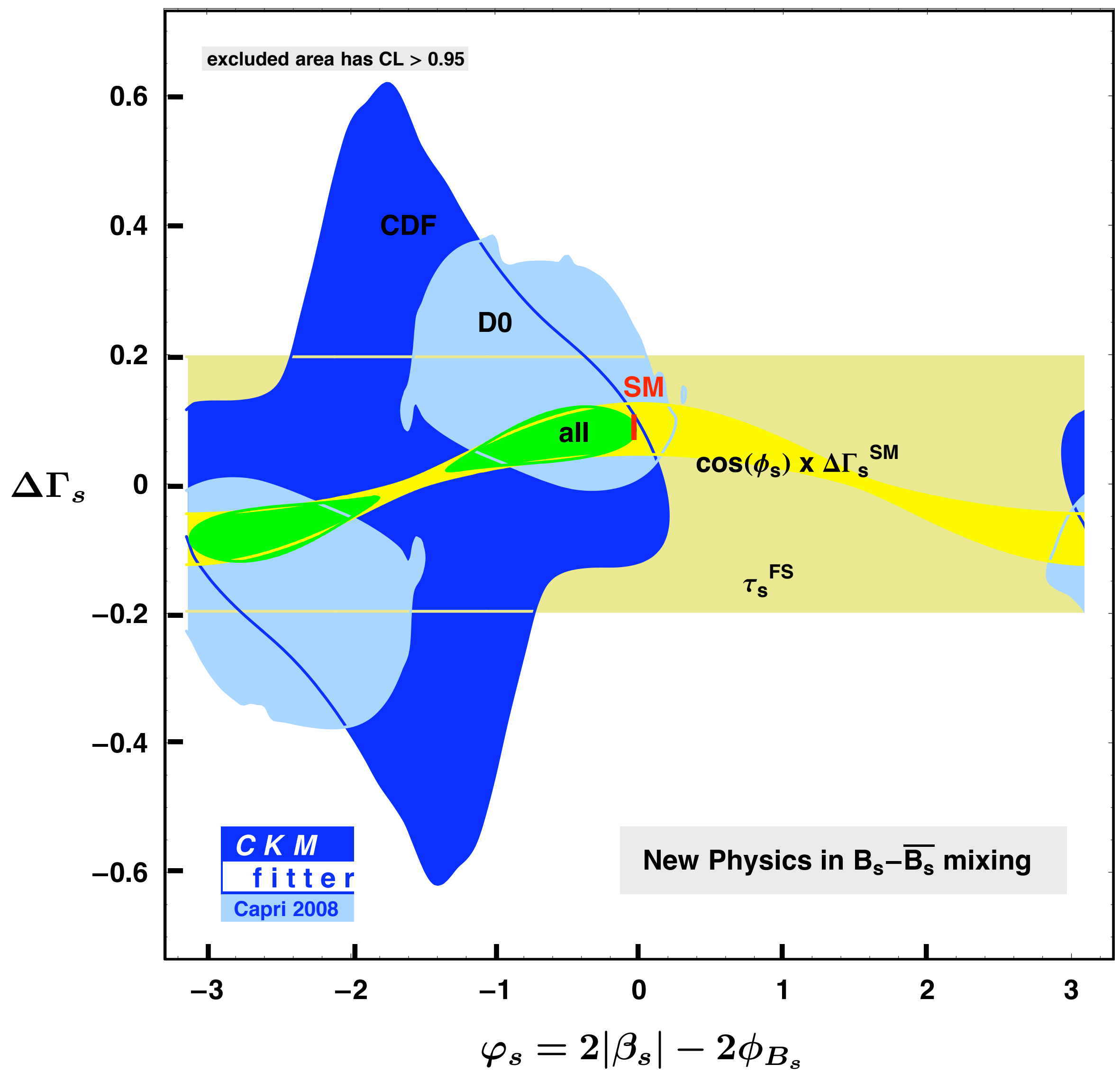
- satisfying 95% CL limit $|\varepsilon_K| \in [1.3, 3.3] \cdot 10^{-3}$
- without $Z \to b\bar{b}$ constraint
- with $Z \to b\bar{b}$ constraint at 95% CL

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

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

BSM physics in B_s mixing*

- Tantalizing hints for new physics phase in $B_s - \bar{B}_s$ mixing from flavor-tagged analysis of mixing-induced CP violation in $B_s \to J/\psi\phi$ by CDF and DØ



<u>CKMfitter combination:</u>

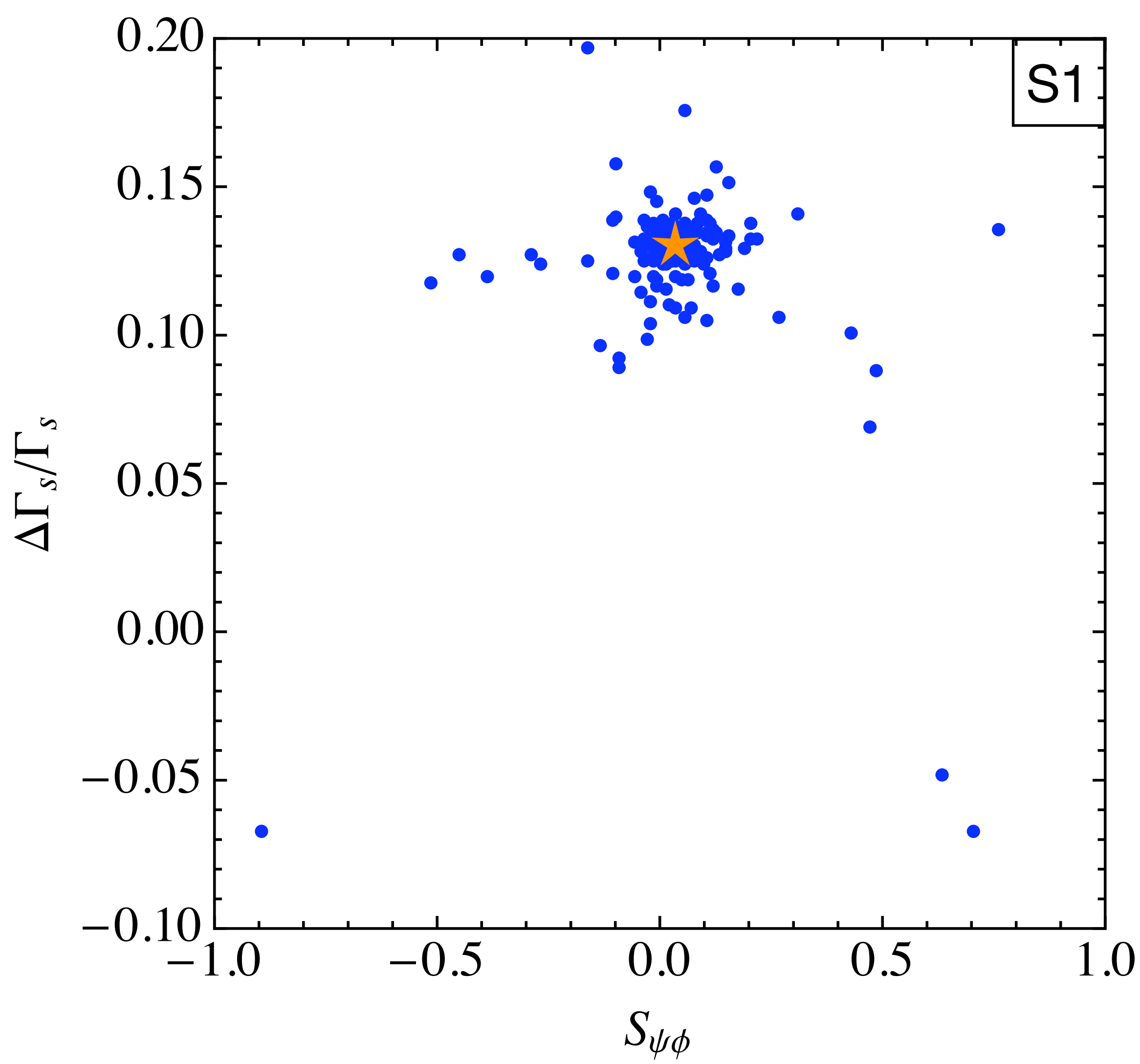
- CDF data only 2.1σ
- DØ data only 1.9σ
- CDF and DØ data 2.7σ
- full BSM physics fit 2.5σ

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

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

Meson mixing: Neutral B_s mesons*

- Constraint from $|\varepsilon_K|$ does not exclude O(1) effects in width difference $\Delta\Gamma_s/\Gamma_s$ of B_s system



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

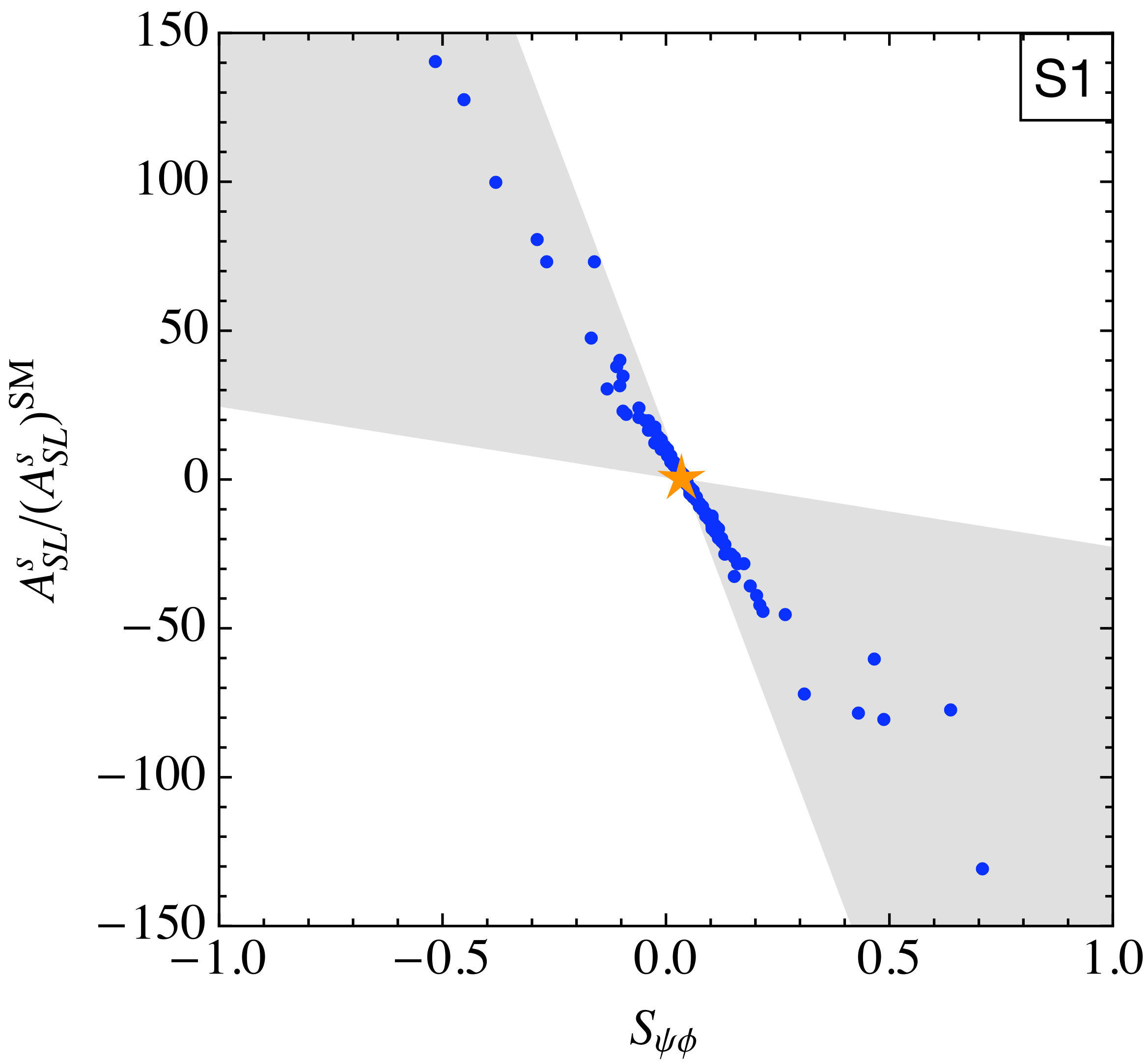
★ SM: $\Delta\Gamma_s/\Gamma_s \approx 0.13$, $S_{\psi\phi} \approx 0.04$

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

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

Meson mixing: Neutral B_s mesons*

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



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

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

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

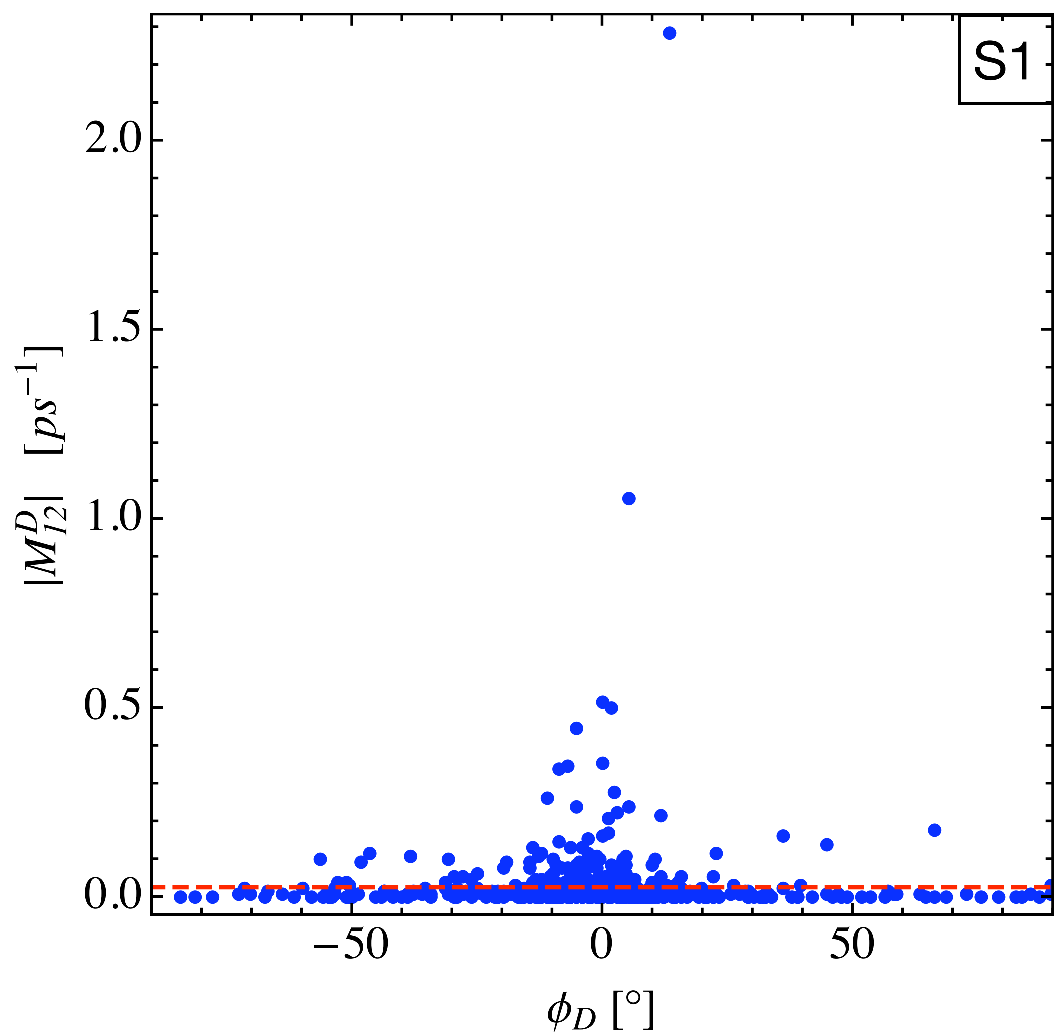
■ model-independent prediction

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

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

Meson mixing: Neutral D mesons*

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



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

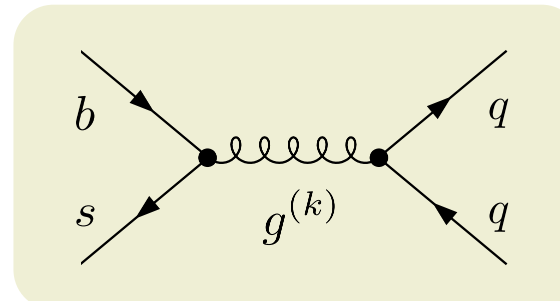
- - maximal allowed SM effect with no significant CP phase

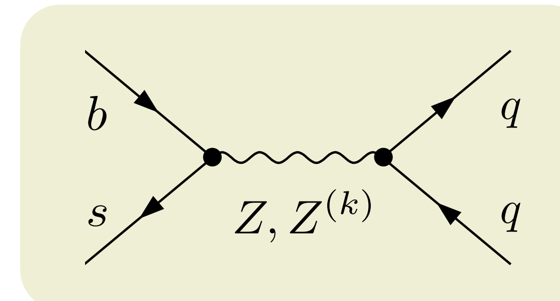
● consistent with quark masses, CKM parameters, and 95% CL limit $|\varepsilon_K| \in [1.3, 3.3] \cdot 10^{-3}$

*Bauer *et al*., paper in preparation

Rare decays: Effective Hamiltonian*

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





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

$$\vdots$$

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

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

$$\vdots$$

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

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

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

*Bauer *et al*., paper in preparation

Rare decays: Effective Hamiltonian*

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

Only four couplings:

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

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

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

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

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

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

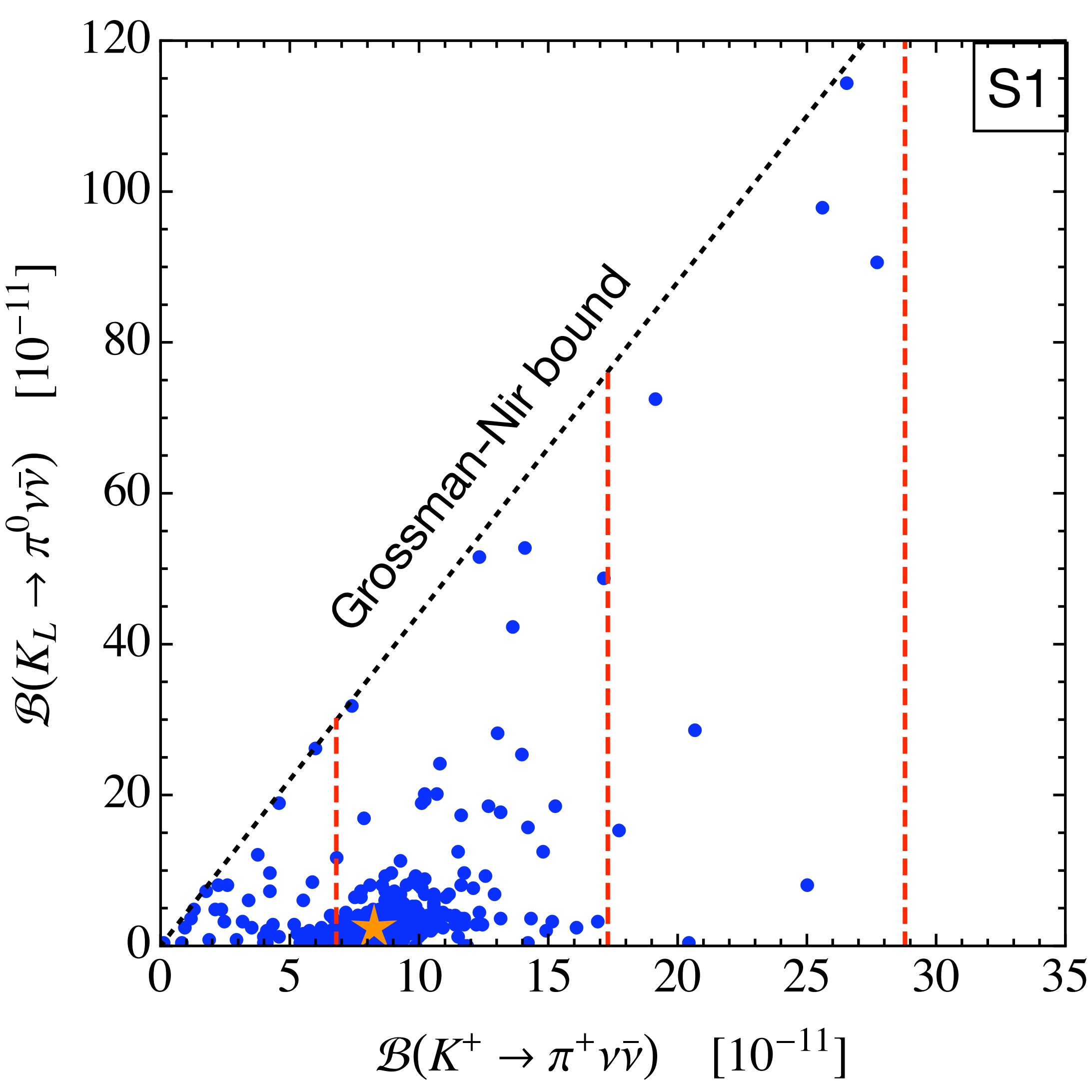
$$C_9^{\rm RS} = \frac{2\pi\alpha}{9M_{\rm KK}^2}\,(\Delta_D)_{23} + \frac{2\pi\alpha}{3s_w^2\,M_{\rm KK}^2}(\Sigma_D)_{23}\,,$$

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

*Bauer *et al*., paper in preparation

Rare K decays: Golden modes*

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



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

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

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

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

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

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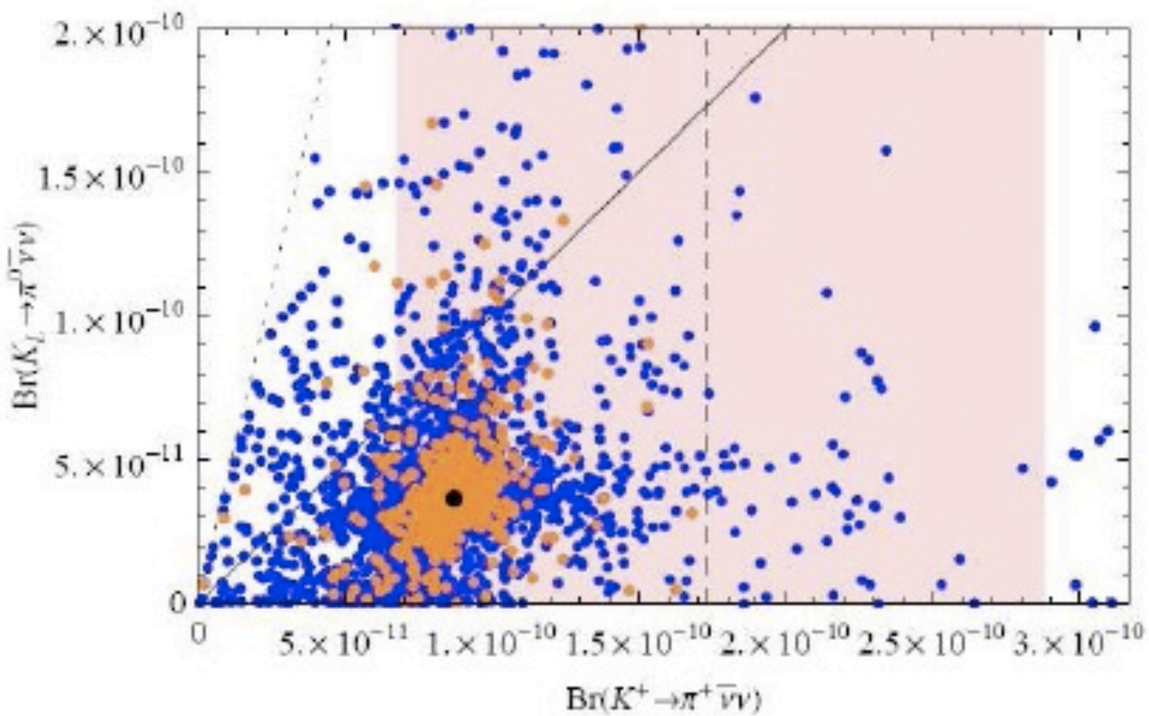
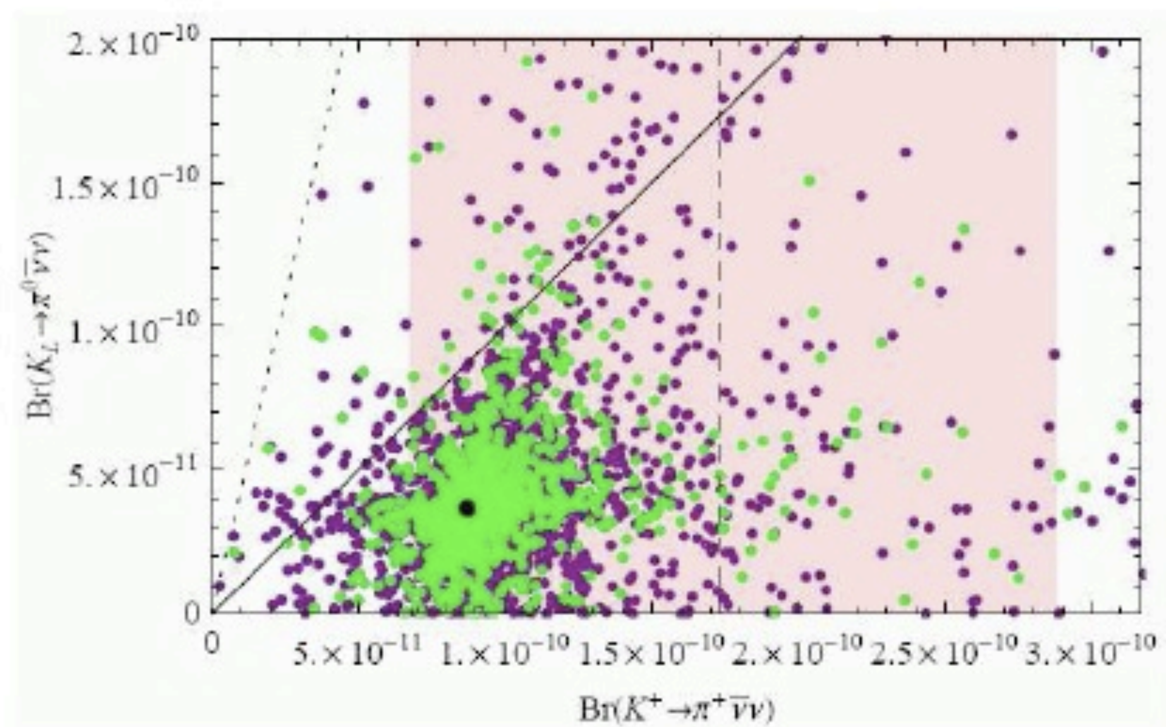


with custodial protection (extended gauge symmetry)

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



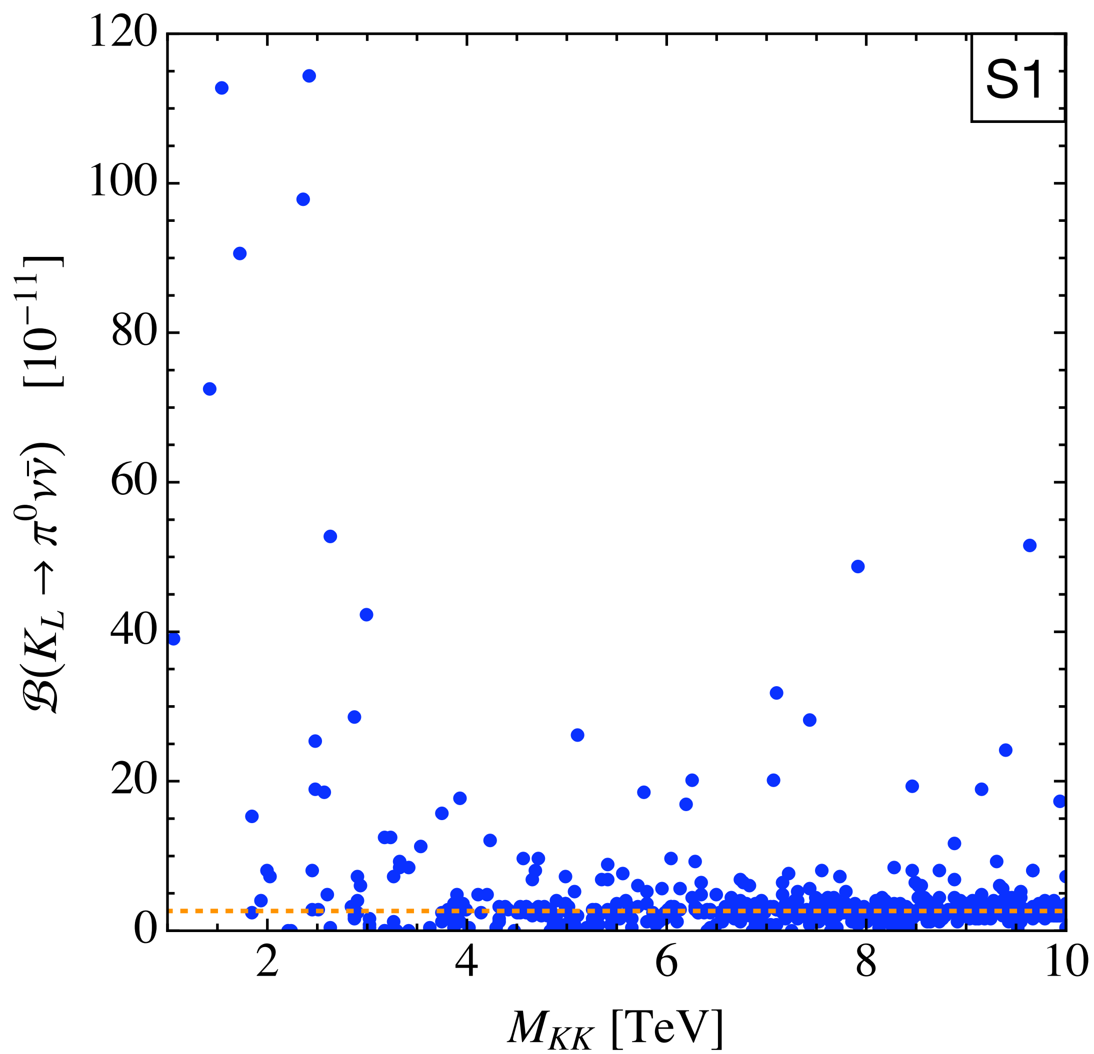
without custodial protection (minimal model)

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

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

Rare K decays: Golden modes*

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



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

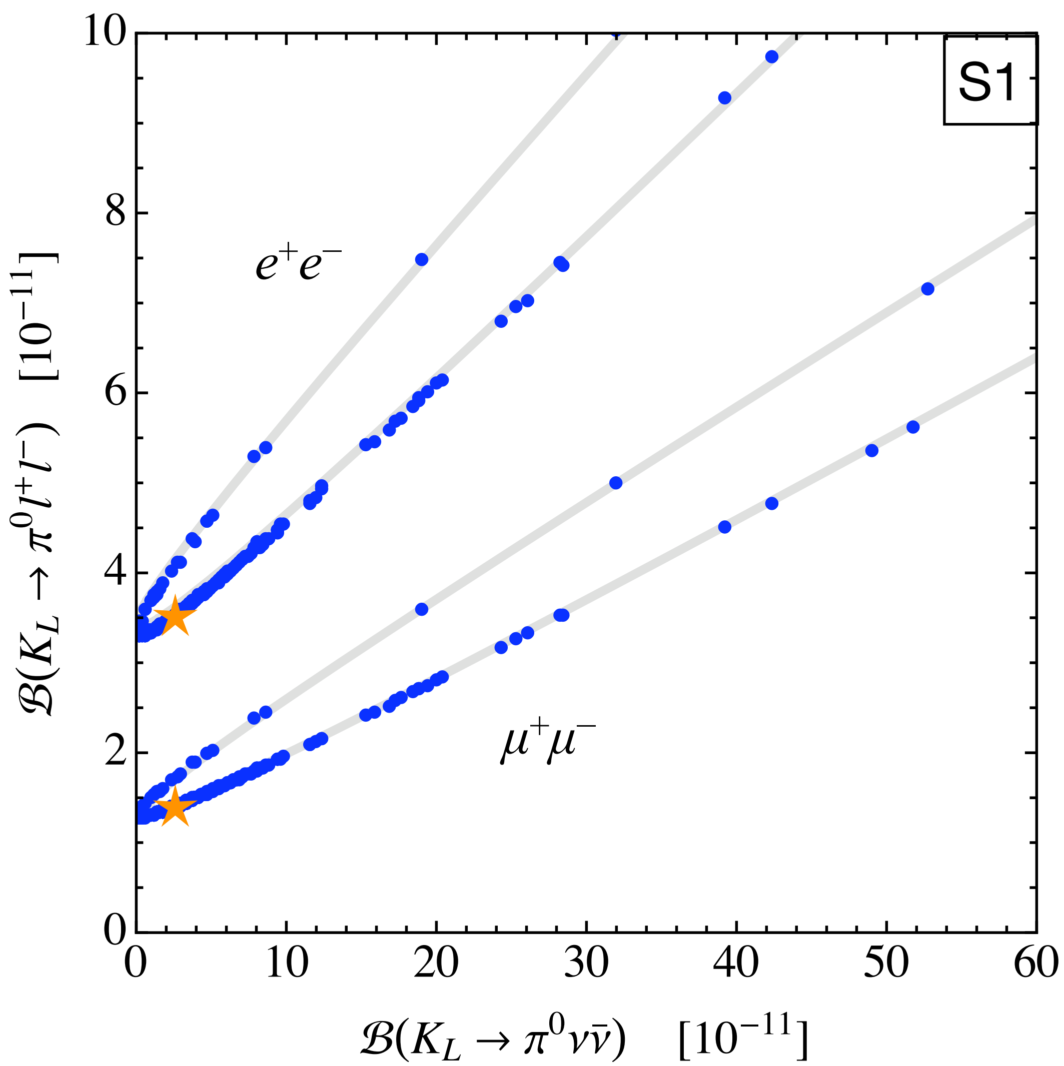
SM: $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) \approx 2.7 \cdot 10^{-11}$

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

*Bauer *et al.*, paper in preparation

Rare K decays: Silver modes*

- Deviations from SM expectations in $K_L \to \pi^0 \nu\bar{\nu}$ 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.*, paper in preparation

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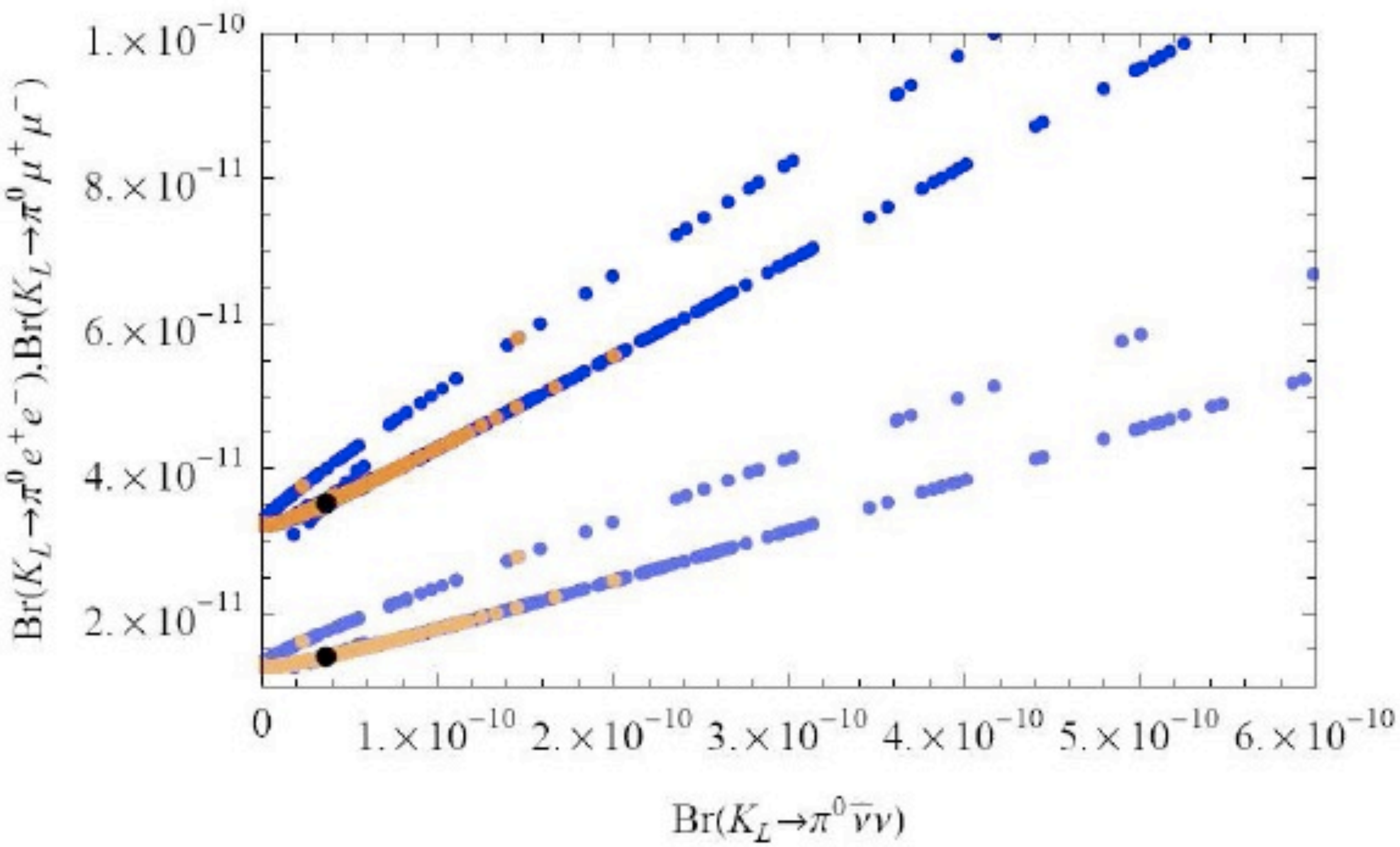


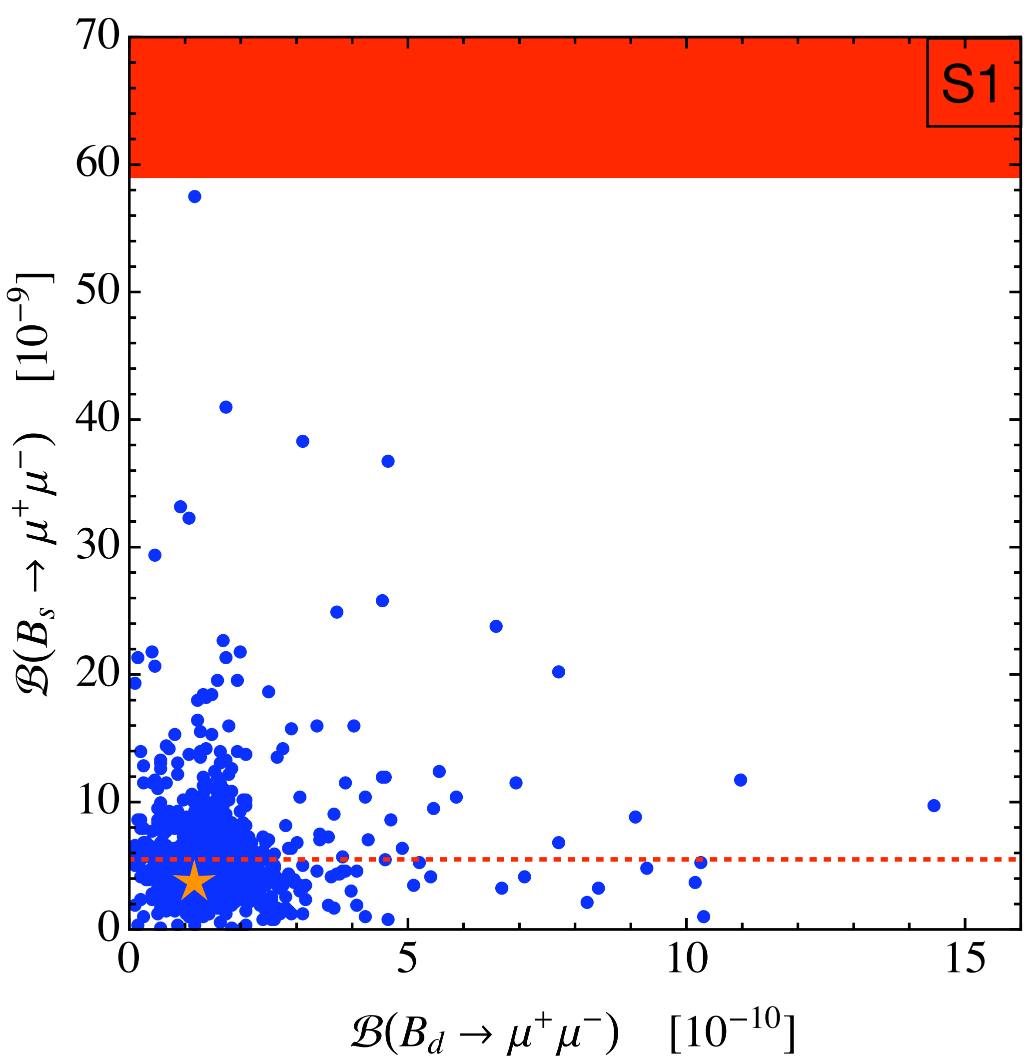
with custodial protection
(extended gauge symmetry)

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

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

Rare B decays: Purely leptonic modes*

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



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

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

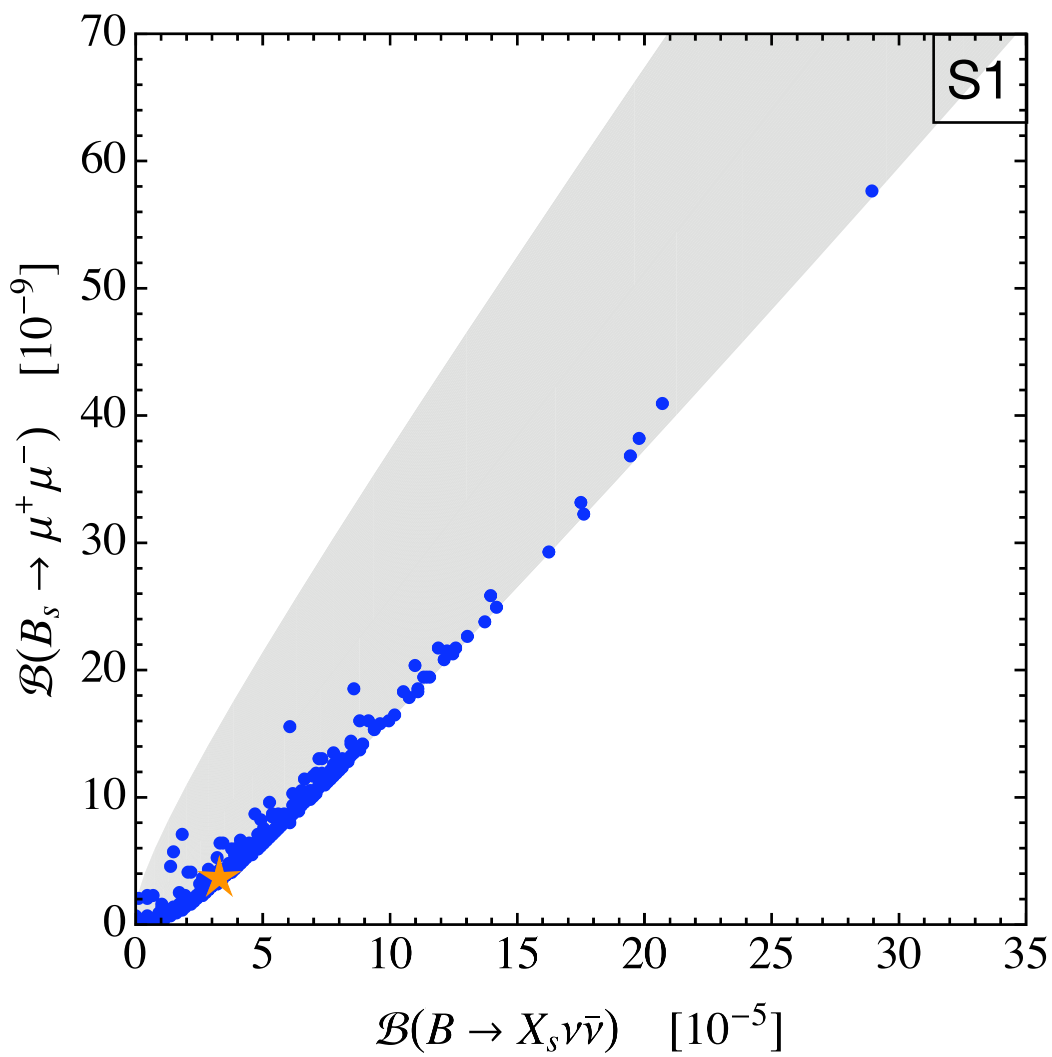
95% CL upper limit from CDF $\mathcal{B}(B_s \to \mu^+\mu^-) < 5.8 \cdot 10^{-8}$

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

*Bauer *et al.*, paper in preparation

Rare B decays: Purely leptonic modes*

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



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

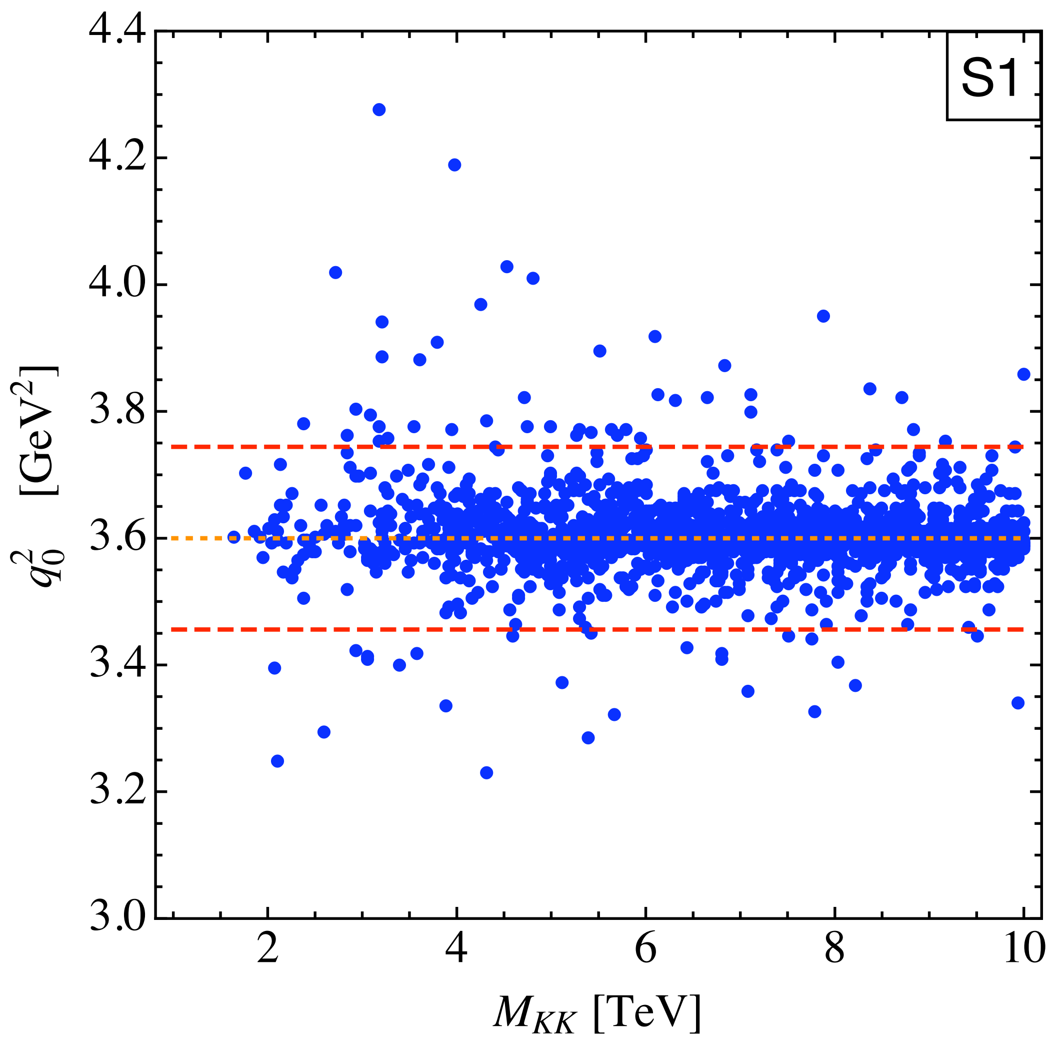
■ model-independent prediction

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

*Bauer *et al.*, paper in preparation

Rare B decays: Inclusive semileptonic modes*

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



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

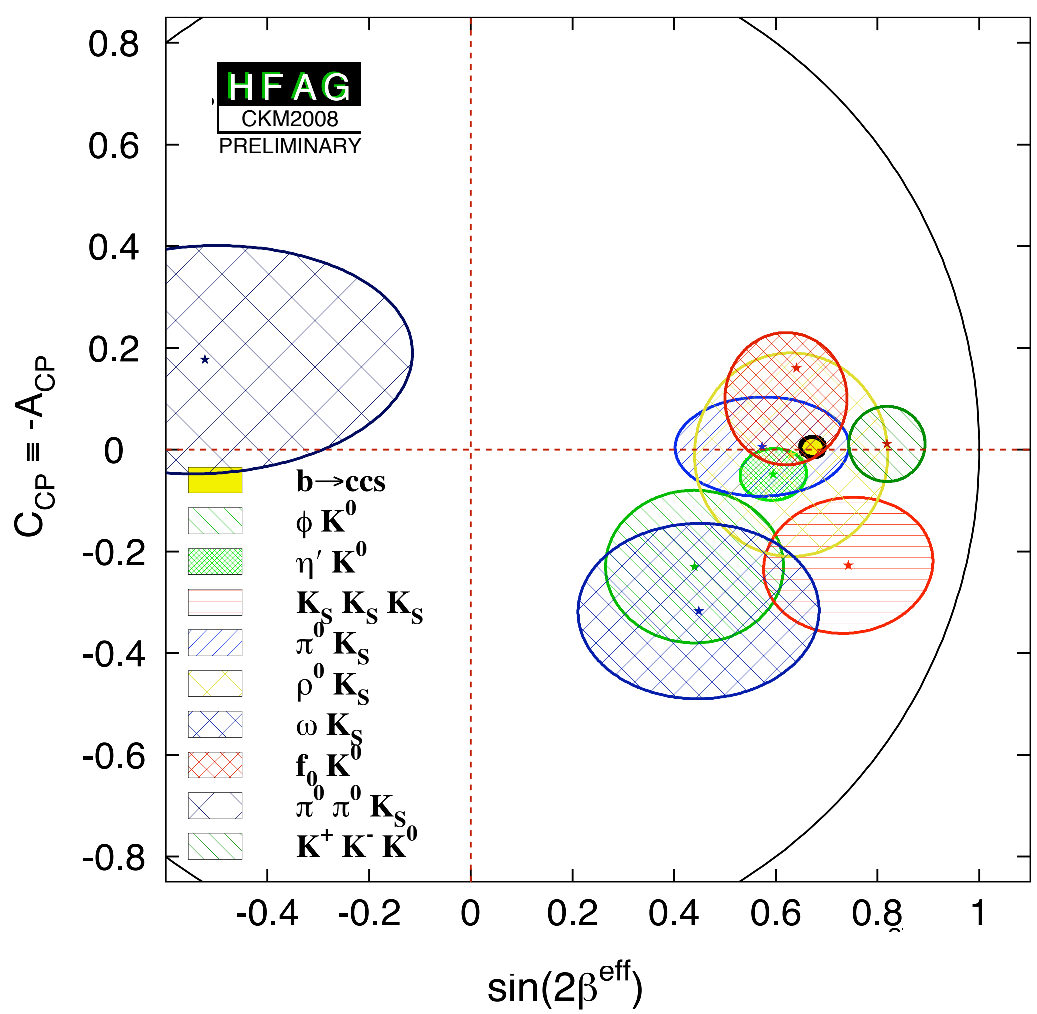
expected sensitivity at SuperB factory, 75 ab^{-1}

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

*Bauer *et al*., paper in preparation

Non-leptonic B and K decays*

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



<u>Potentially relevant for:</u>

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

*Bauer *et al.*, paper in preparation

Conclusions

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