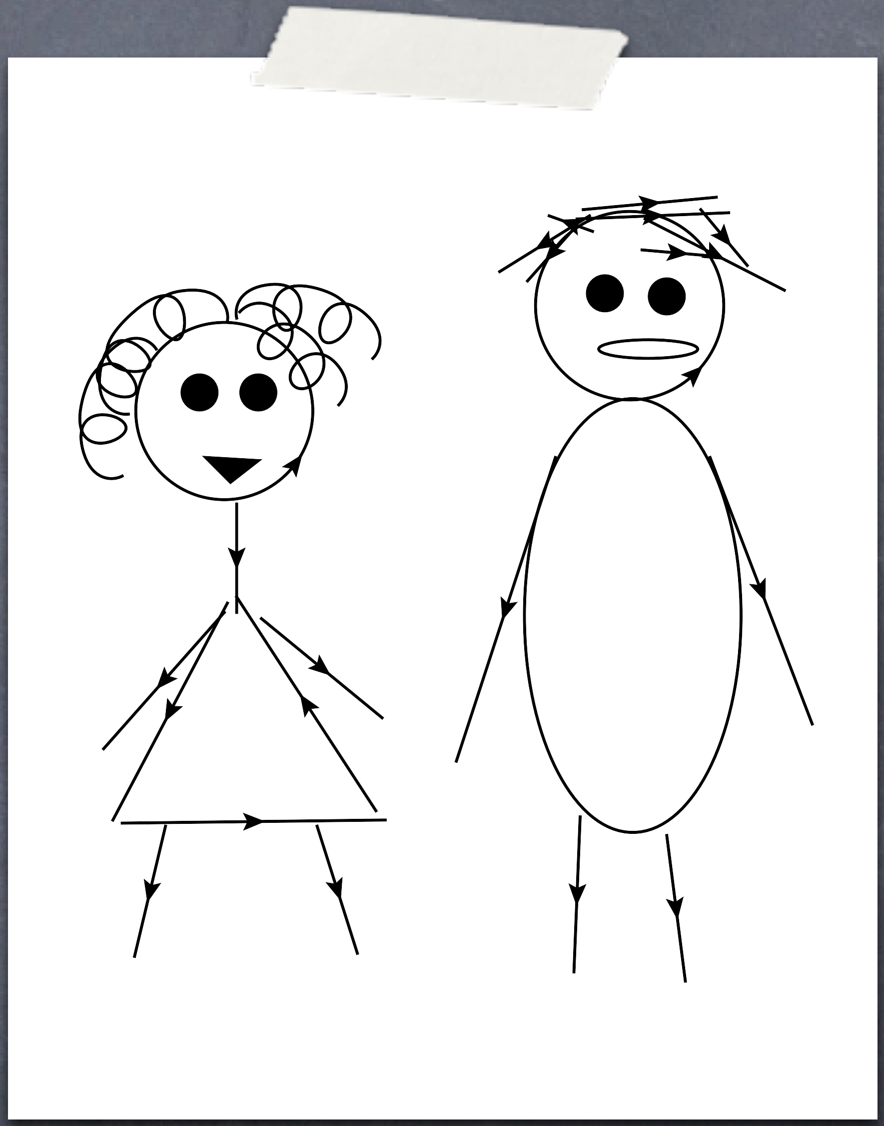
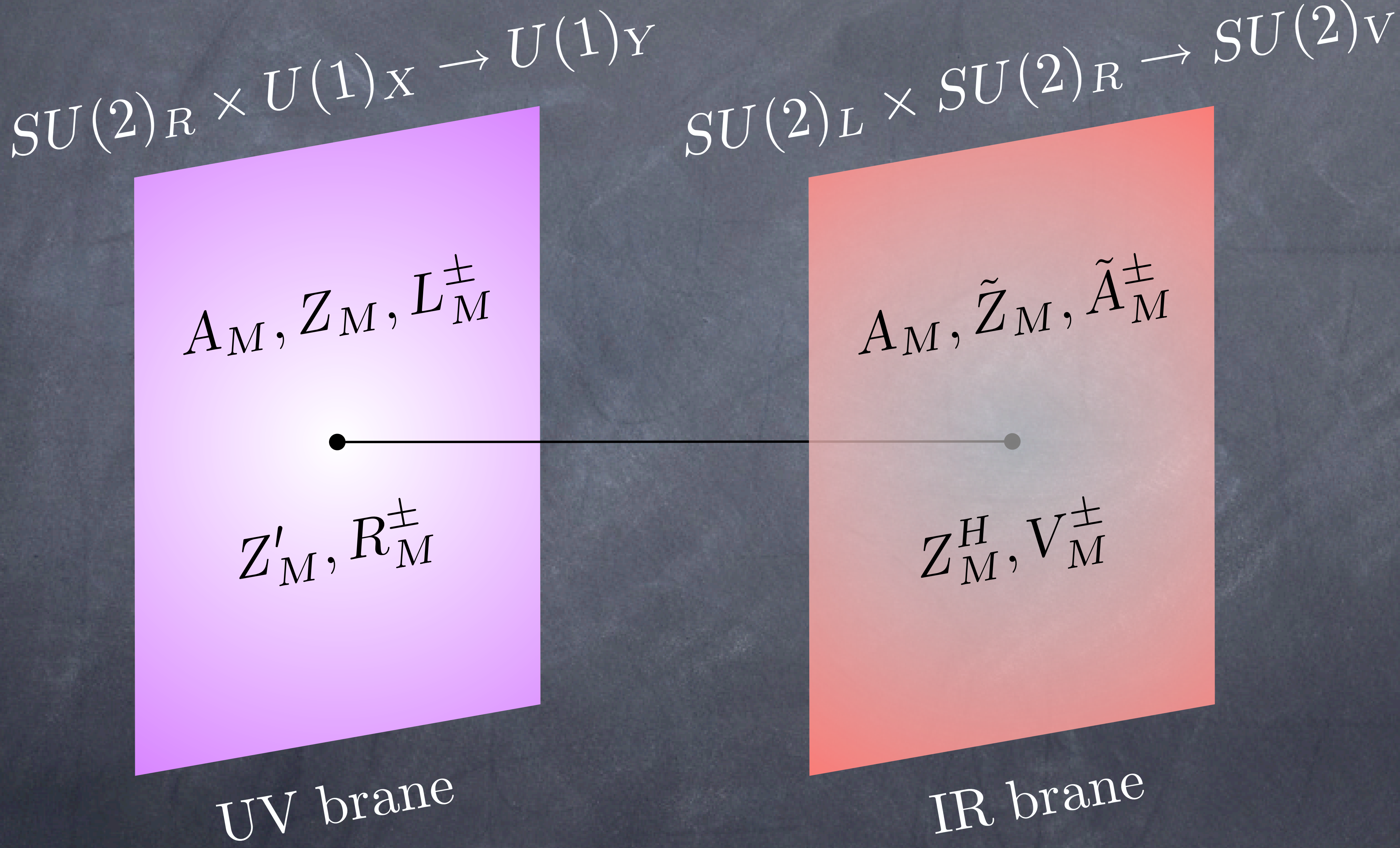
Little Randall-Sundrum (RS) Models

or

Tale of Logarithms & Exponentials



Custodial RS: Gauge Sector



Custodial RS: Quark Sector

$$(\mathbf{2},\mathbf{2})_{2/3} \ni Q_L \equiv \begin{pmatrix} u_L^{(++)}{}_{2/3} & \lambda_L^{(-+)}{}_{5/3} \\ d_L^{(++)}{}_{-1/3} & u_L'^{(-+)}{}_{2/3} \end{pmatrix}_{2/3},$$

$$(\mathbf{1},\mathbf{1})_{2/3} \ni u_R^c \equiv \begin{pmatrix} u_R^{c\,(++)}{}_{2/3} \end{pmatrix}_{2/3},$$

$$(\mathbf{3},\mathbf{1})_{2/3} \otimes (\mathbf{1},\mathbf{3})_{2/3} \ni \mathcal{T}_R \equiv \begin{pmatrix} \Lambda_R'^{(-+)}{}_{5/3} \\ U_R'^{(-+)}{}_{2/3} \\ D_R'^{(-+)}{}_{-1/3} \end{pmatrix}_{2/3} \otimes \begin{pmatrix} D_R^{(++)}{}_{-1/3} \\ U_R^{(-+)}{}_{2/3} \\ \Lambda_R^{(-+)}{}_{5/3} \end{pmatrix}^T_{2/3}$$

Question

- Gauge & in particular structure of quark sector needed to protect T & $Z \to b\underline{b}$ in custodial RS (RSc) model baroque

- Is there another, possibly more simple way to tame corrections to both oblique corrections (T) & $Zb_L\underline{b}_L$ (g_L^b)?

- To answer question, first have to understand problem better

Prelude

- In RS model there is only one moderately large parameter, namely

$$L = \ln \frac{\Lambda_{\rm UV}}{\Lambda_{\rm IR}}$$

where $\Lambda_{\rm UV}$ ($\Lambda_{\rm IR}$) is cutoff scale on UV (IR) brane

- Solving gauge-hierarchy problem between weak M_W & Planck scale M_{Pl}, requires

$$L_{\rm RS} \approx \ln \left(10^{16}\right) \approx 37$$

Problem

- Unfortunately, in $SU(2)_L \times U(1)_Y$ RS variant many observables are L-enhanced:

$$T = \frac{4\pi}{e^2 c_w^2 M_Z^2} \left[\Pi_{WW}(0) - c_w^2 \Pi_{ZZ}(0)\right]$$
$$\approx \frac{\pi v^2}{2 c_w^2 M_{\mathrm{KK}}^2} \, L \,,$$

$$\Delta g_L^b \approx \left(\frac{1}{2} - \frac{s_w^2}{3}\right) \left(\frac{M_Z^2}{2 M_{\mathrm{KK}}^2} \, \frac{F^2(c_{Q_3})}{3 + 2 c_{Q_3}} \, L\right)$$

Solution!

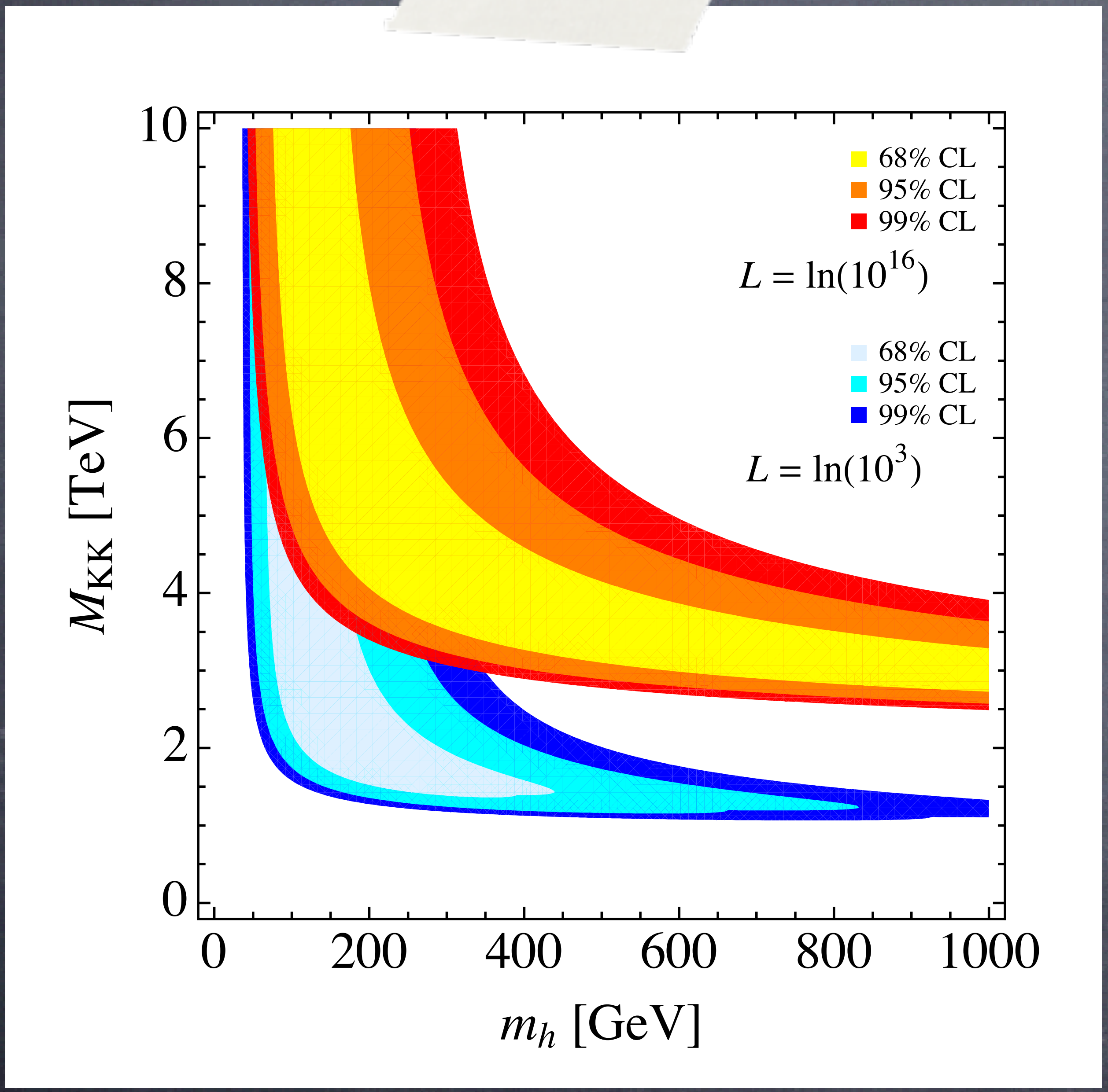
- Let's curb our ambitions & address hierarchy problem only up to $\Lambda_{UV} = 10^3$ TeV, which means

$$L_{\rm LRS} \approx \ln\left(10^3\right) \approx 7$$

- It is readily seen, that in such a little RS (LRS) model, one has:

$$T_{\rm LRS} \approx \frac{L_{\rm LRS}}{L_{\rm RS}}\, T_{\rm RS} \approx \frac{1}{5}\, T_{\rm RS}$$

Solution! cont'd



- Relative to usual RS model constraint from T relaxed by factor of > 2 in LRS setup:

$$M_{\rm KK} \gtrsim 1.5\,\text{TeV}\,,$$

$$M_{Z^{(1)},W^{(1)}} \approx 2.5\,M_{\rm KK} \gtrsim 4\,\text{TeV}$$

Solution! Really?

- In RS model, flavor non-universal observables, like $Z \to b\underline{b}$, feature both logarithms, i.e., terms enhanced by volume of extra dimension (XD), & exponentials, i.e., wave functions that describe localization of fermions in XD

- Simple rescaling of effects by factor

$$\frac{L_{\rm LRS}}{L_{\rm RS}}$$

as done in case of T, might thus be incorrect if one considers $Z \to b\underline{b}$, ε_K, ...

Quark Localization

- Instead of usual bulk mass parameters

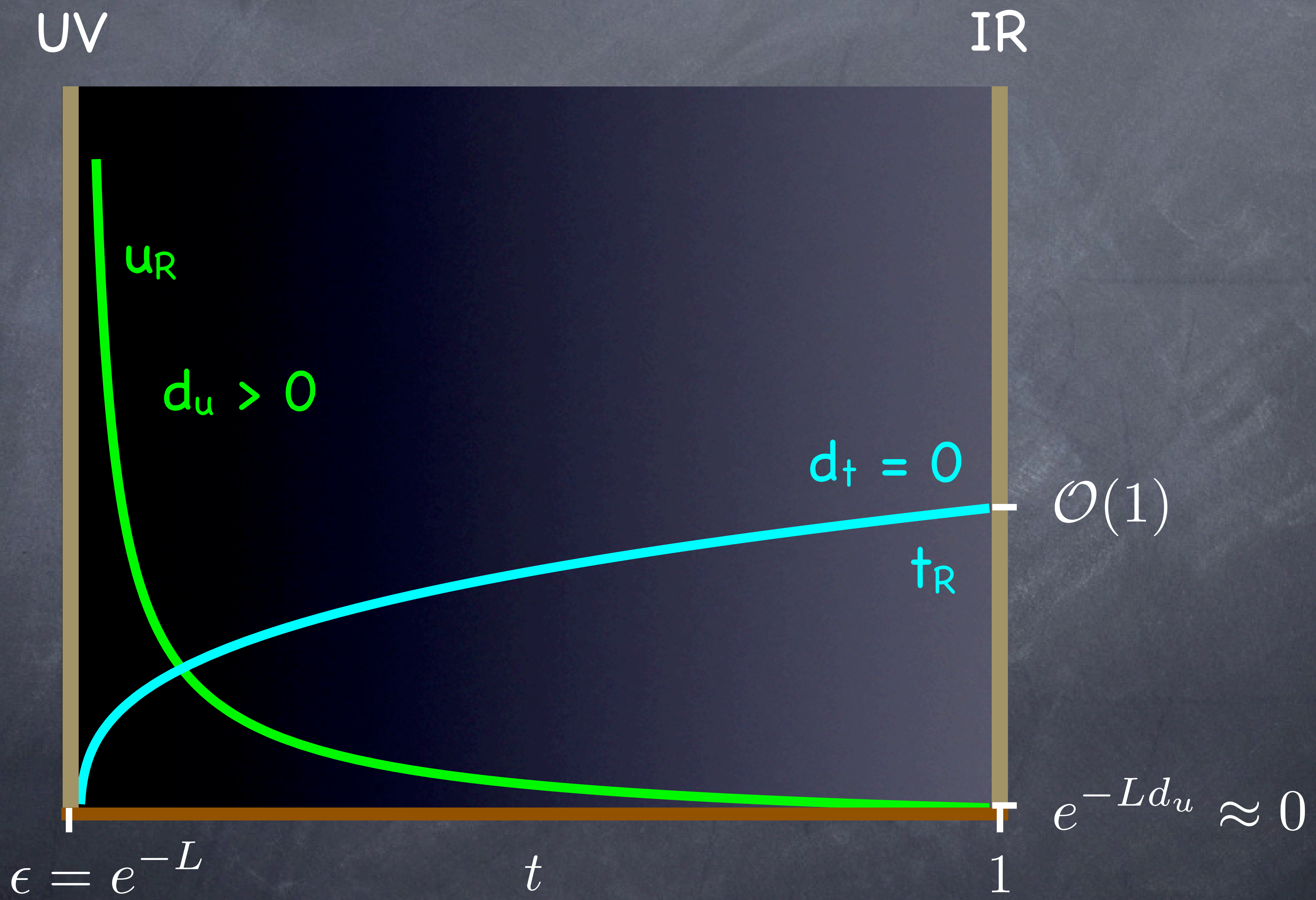
$$c_{Q_i} = \frac{M_{Q_i}}{k}\,, \qquad c_{q_i} = -\frac{M_{q_i}}{k}$$

where M_{A_i} denotes 5D masses & k curvature, it turns out to be more useful to work with

$$d_{A_i} = \max\left(-c_{A_i} - 1/2, 0\right)\,, \quad A = Q, q$$

which parametrize distance from critical point c_{A_i} = -1/2 where $F(c_{A_i})$ switch from exponential to square root behavior

Quark Localization cont'd



Froggatt-Nielsen

- Quark masses & mixings are related to d_{Ai} via

$$\frac{\sqrt{2}\, m_{q_i}}{v} \sim |Y|\, e^{-L(d_{Q_i} + d_{q_i})}\,,$$

$$\lambda \sim e^{-L(d_{Q_1} - d_{Q_2})}\,,$$

$$A \sim e^{-L(3d_{Q_2} - 2d_{Q_1} - d_{Q_3})}$$

where |Y| = O(1) Yukawa couplings. Wolfenstein parameters $\underline{\rho}$, $\underline{\eta}$ = O(1), but exact amount of $\not{C}\not{P}$ not explained

Froggatt-Nielsen cont'd

- To satisfy constraints due to masses & mixing of quarks for different L, d_{Ai} obviously have to scale like

$$d_{A_i}^{\mathrm{LRS}} = \frac{L_{\mathrm{RS}}}{L_{\mathrm{LRS}}}\, d_{A_i}^{\mathrm{RS}}$$

which implies that d_{Ai} are larger in LRS model than in native RS setup, resulting in stronger IR localization of light quark wave functions

Aside: d_{Ai} Parameters

- Assuming that $d_t = 0$, needed to explain large top-quark mass with $|Y| = O(1)$, it is easy to show that in right-handed (RH) down sector

$$L\,d_d \sim \ln\left(A\lambda^3\,\frac{m_t}{m_d}\right) \approx 6.1\,,$$

$$L\,d_s \sim \ln\left(A\lambda^2\,\frac{m_t}{m_s}\right) \approx 4.8\,,$$

$$L\,d_b \sim \ln\left(\frac{m_t}{m_b}\right) \approx 4.2$$

Aside: d_{Ai} Parameters cont'd

- In case of left-handed (LH) quark bulk mass parameters one obtains instead

$$L\, d_{Q_1} \sim \ln\left(\frac{1}{A\lambda^3}\frac{|Y|v}{\sqrt{2}m_t}\right) \approx 4.9\,,$$

$$L\, d_{Q_2} \sim \ln\left(\frac{1}{A\lambda^2}\frac{|Y|v}{\sqrt{2}m_t}\right) \approx 3.4\,,$$

$$L\, d_{Q_3} \sim \ln\left(\frac{|Y|v}{\sqrt{2}m_t}\right) \approx 0.2$$

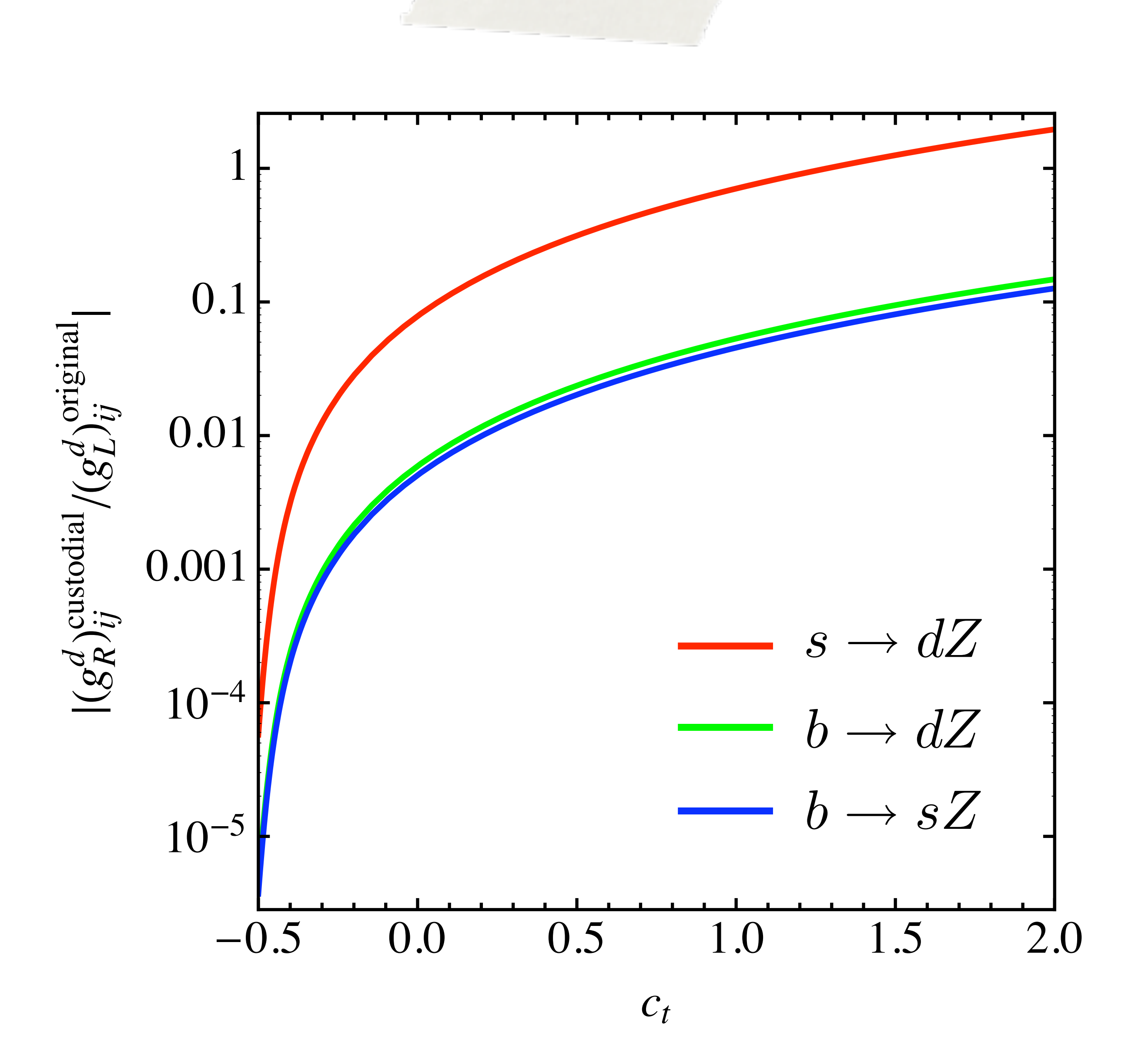
Aside: RH vs. LH FCNCs

- Latter relations imply that for $c_t \gtrsim -1/2$, RH couplings are in general strongly suppressed relative to LH counterparts:

$$\frac{|(g_R^d)_{ij}|}{|(g_L^d)_{ij}|} \approx \frac{F(c_{d_i})\,F(c_{d_j})}{F(c_{Q_i})\,F(c_{Q_j})} \approx e^{L\left(d_{d_i}+d_{d_j}-d_{Q_i}-d_{Q_j}\right)}$$

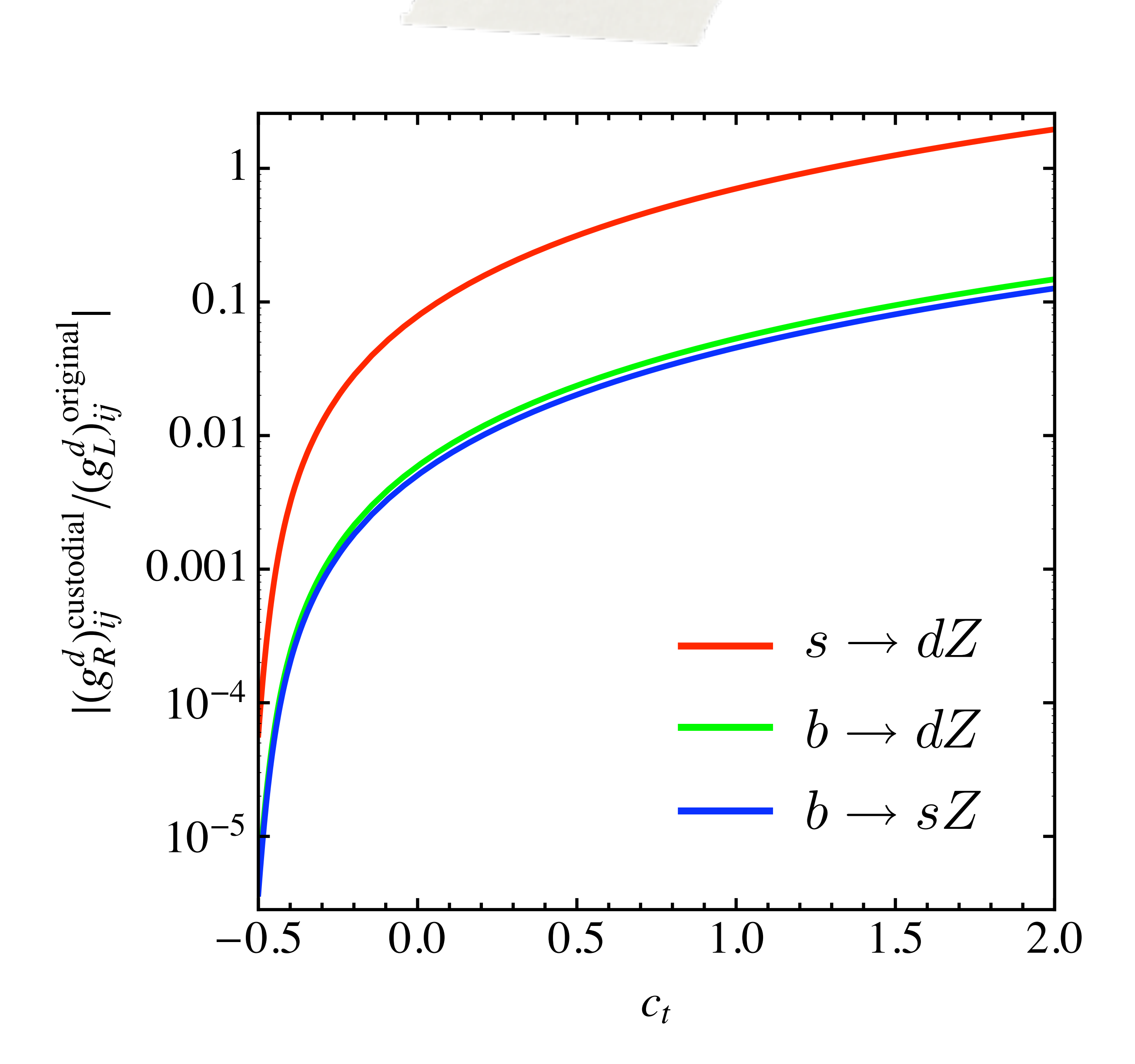
$$\approx \begin{cases} 7 \cdot 10^{-2}\,, & s \to dZ \\ 6 \cdot 10^{-3}\,, & b \to dZ \\ 5 \cdot 10^{-3}\,, & b \to sZ \end{cases}$$

Aside: RH vs. LH FCNCs cont'd



- In consequence, to obtain RH FCNCs in RSc model comparable in magnitude to LH ones in $SU(2)_L \times U(1)_Y$ variant requires bulk mass c_t for RH top of O(1) or larger

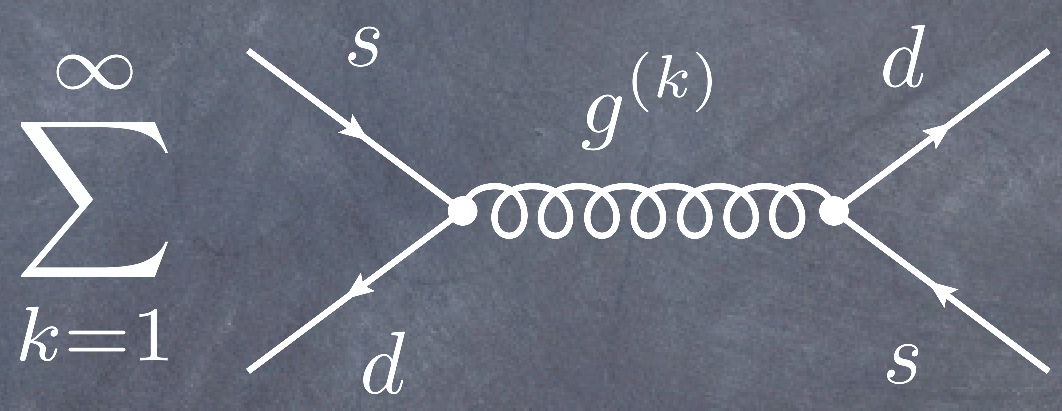
Aside: RH vs. LH FCNCs cont'd



- Notice that $c_t > 1$ means $M_t > k$, which raises question why RH top quark should be treated as brane-localized & not bulk fermion

K–$\bar{K}$ Mixing

- In RS model, leading contributions to ΔS = 2 interactions arise from Kaluza-Klein (KK) gluon exchange



& can be described by effective Lagrangian

$$\mathcal{L}_{\Delta S=2} \ni \frac{8\pi\alpha_s L}{M_{\rm KK}^2}(\tilde{\Delta}_D)_{12} \otimes (\tilde{\Delta}_d)_{12}\,(\bar{d}_R s_L)(\bar{d}_L s_R)$$

Mixing Matrices

- In terms of LH & RH rotations U_d & W_d, mixing matrices entering $\Delta S = 2$ interactions can be written as

$$(\tilde{\Delta}_D)_{12} \otimes (\tilde{\Delta}_d)_{12}$$
$$\approx (U_d^\dagger)_{1i}\,(U_d)_{i2}\,(\tilde{\Delta}_{Dd})_{ij}\,(W_d^\dagger)_{1j}\,(W_d)_{j2}$$

with

$$(\tilde{\Delta}_{Dd})_{ij} = \frac{1}{2}\,F^2(c_{Q_i})\,F^2(c_{q_j}) \times \int_\epsilon^1 dt \int_\epsilon^1 dt'\,\min\left(t^2, t'^2\right) t^{2c_{Q_i}}\,(t')^{2c_{q_j}}$$

Mixing Matrices cont'd

- Evaluating double integral, one finds

$$(\tilde{\Delta}_D)_{12} \otimes (\tilde{\Delta}_d)_{12}$$

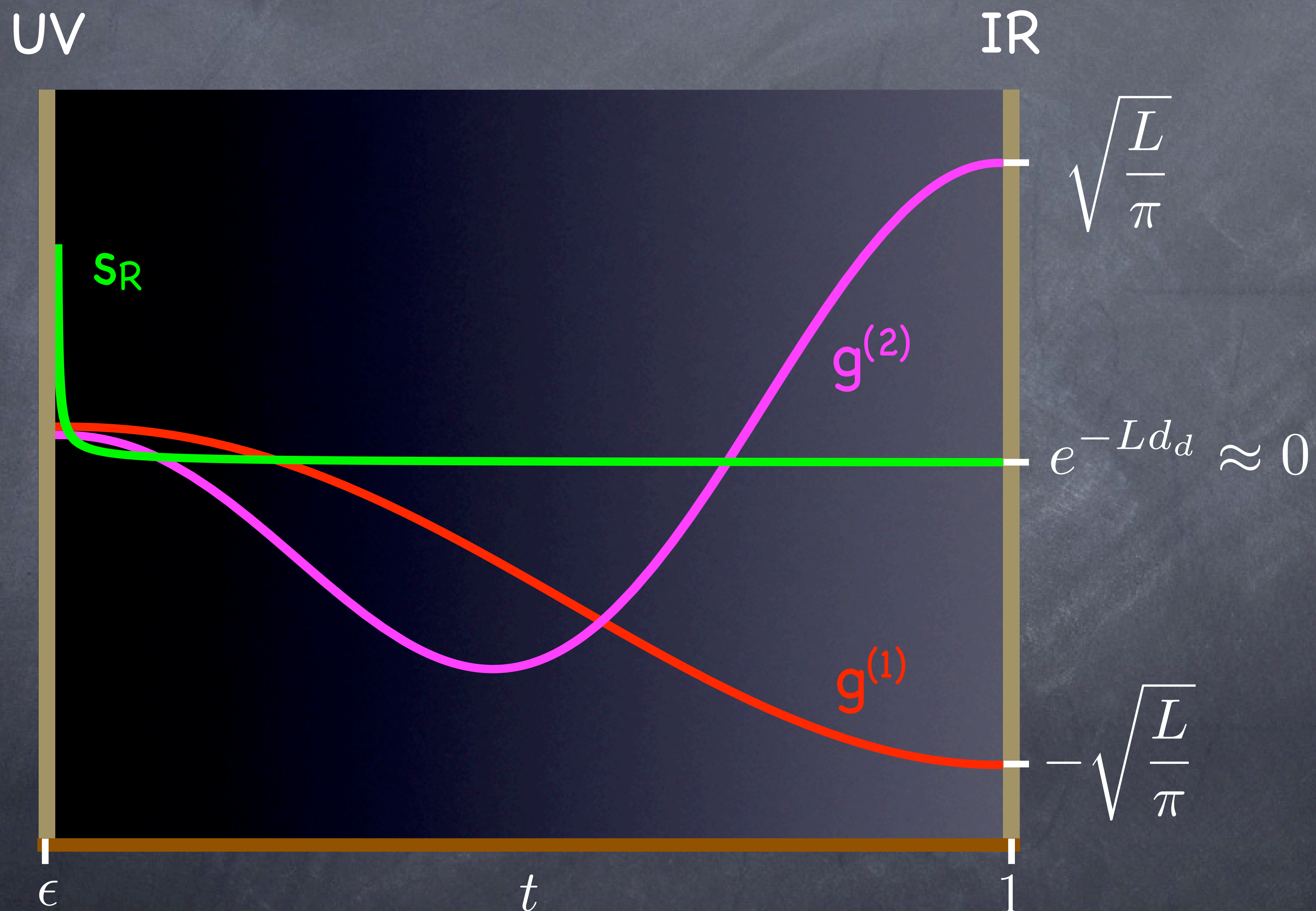
$$\sim \begin{cases} F(c_{Q_1})\, F(c_{Q_2})\, F(c_d)\, F(c_s)\,, & c_{Q_2} + c_s > -2 \\ \epsilon^2 / \left(F^2(c_{Q_2})\, F^2(c_s)\right)\,, & c_{Q_2} + c_s < -2 \end{cases}$$

which implies that in 2nd case, $\Delta S = 2$ FCNCs are enhanced by

$$e^{2L|2+c_{Q_2}+c_s|} \gg 1$$

with respect to usual RS-GIM result

UV Dominance



UV Dominance cont'd

UV

- If $c_{Q2} + c_s < -2$ weight factor $\min(t^2, t'^2)$ in overlap integral does not fall off sufficiently fast near UV brane to compensate for strong increase of quark profiles

Values of c_{Ai}: RS vs. LRS

	RS model (L = 37)	LRS model (L = 7)
c_{Q1}	-0.63 ± 0.03	-1.34 ± 0.16
c_{Q2}	-0.57 ± 0.05	-1.04 ± 0.18
c_{Q3}	-0.34 ± 0.32	-0.49 ± 0.34
c_u	-0.68 ± 0.04	-1.58 ± 0.18
c_c	-0.51 ± 0.12	-0.79 ± 0.26
c_t	$]-1/2, 2]$	$]-1/2, 5/2]$
c_d	-0.65 ± 0.03	-1.44 ± 0.17
c_s	-0.62 ± 0.03	-1.28 ± 0.17
c_b	-0.58 ± 0.03	-1.05 ± 0.13

Bounds on UV Cutoff

- To avoid UV dominance in $\Delta S = 2$ processes, one must require that $d_{Q2} + d_s < 1$, which translates into bound

$$L_{\rm LRS} = 8.2 \quad \Rightarrow \quad \frac{\Lambda_{\rm UV}}{\Lambda_{\rm IR}} > 3600\,, \quad (\Delta S = 2)$$

- For $\Delta S = 1$ FCNCs it turns out that weaker condition $d_s < 1$ is enough to avoid enhancement:

$$L_{\rm LRS} = 4.8 \quad \Rightarrow \quad \frac{\Lambda_{\rm UV}}{\Lambda_{\rm IR}} > 120\,, \quad (\Delta S = 1)$$

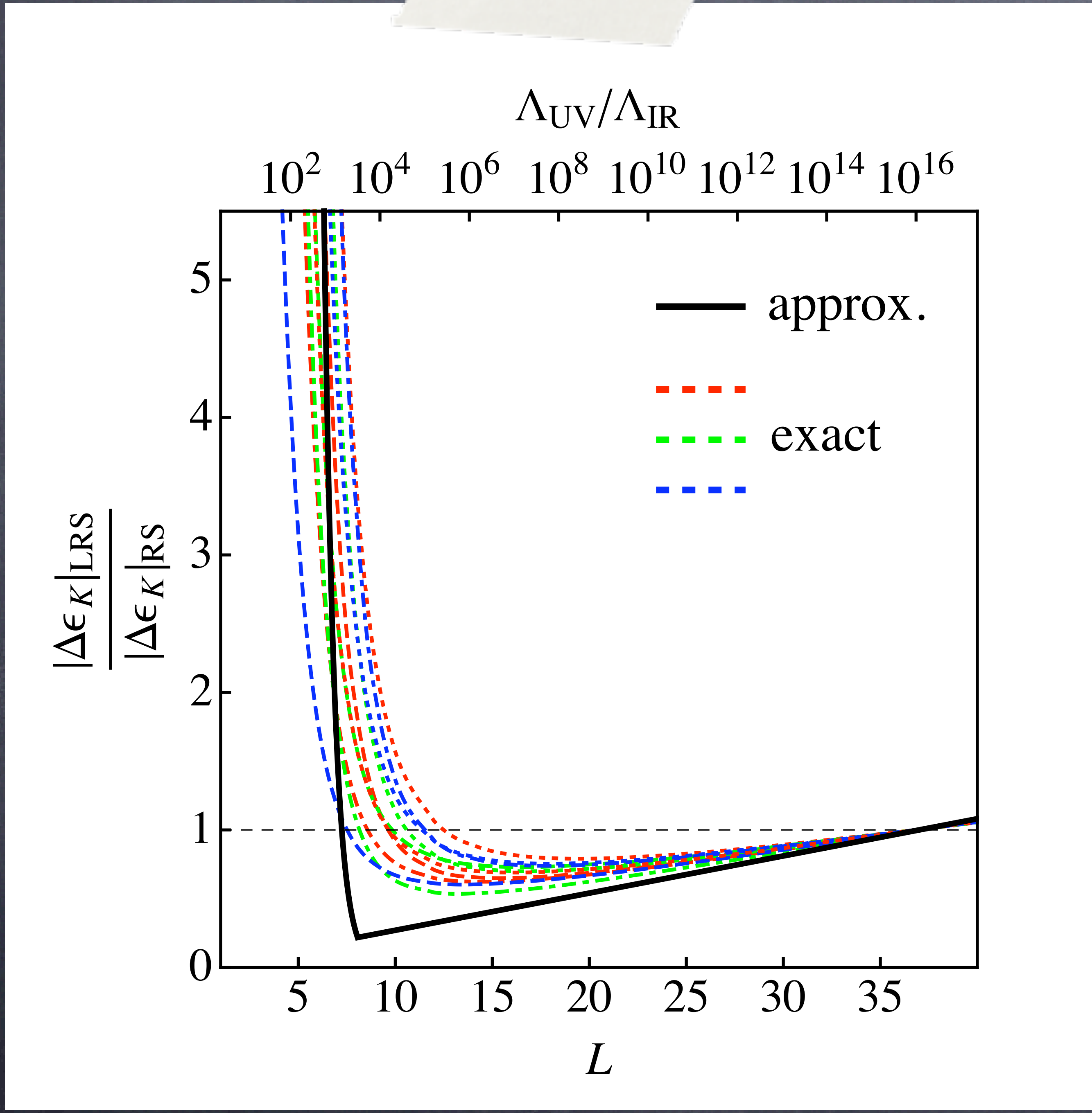
ε_K: LRS vs. RS

- Under assumption that mixed-chirality operator dominates $\Delta S = 2$ transition, it is easy to derive that ratio of new-physics contribution to ε_K in RS & LRS scenario is given by

$$\frac{|\Delta\epsilon_K|_{\rm LRS}}{|\Delta\epsilon_K|_{\rm RS}} \approx \frac{L_{\rm LRS}}{L_{\rm RS}} \max\left[1, e^{-2L_{\rm LRS}}\left(\frac{|Y|v}{\sqrt{2}m_s}\right)^2\right]$$

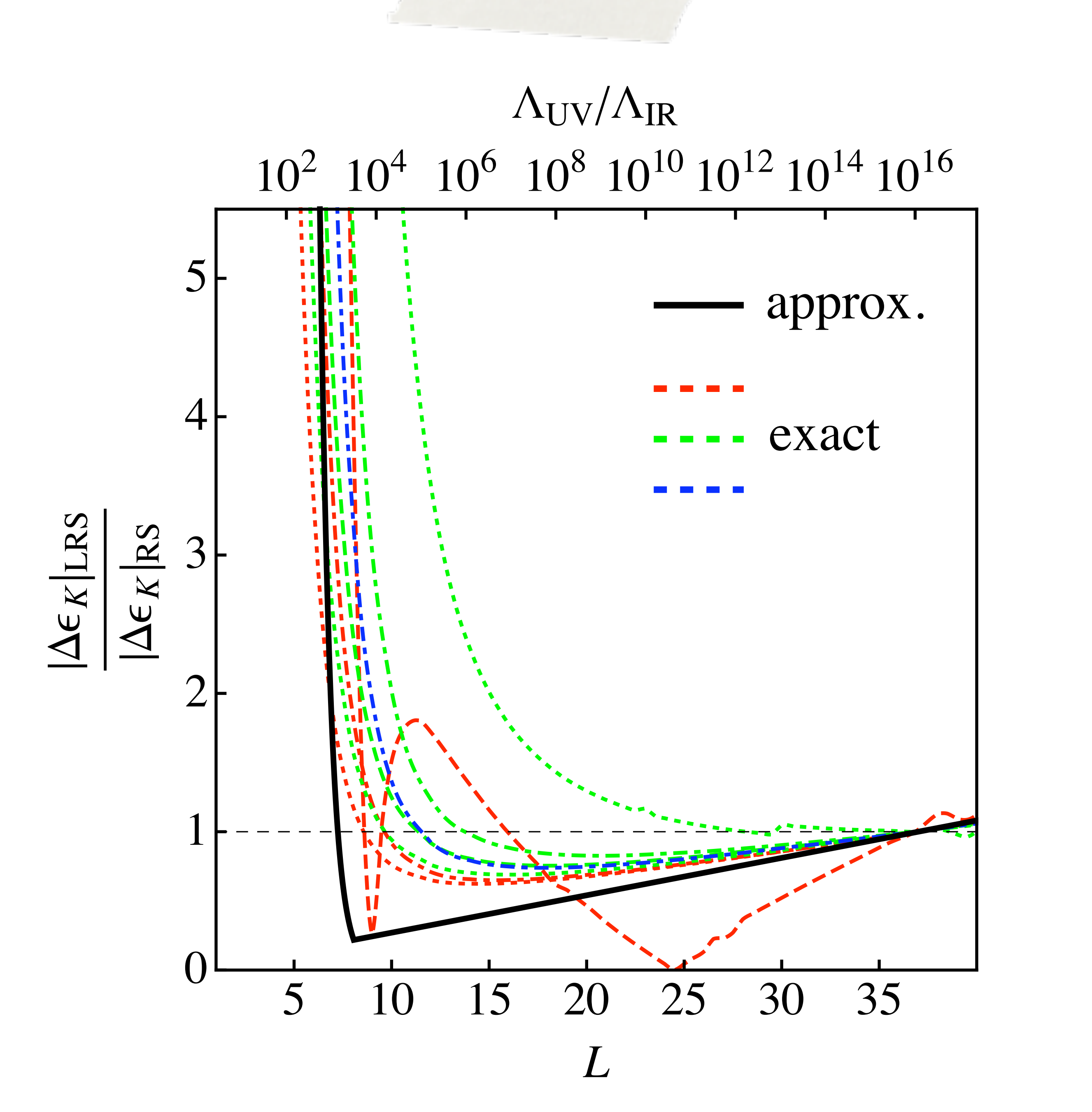
$$\approx \frac{L_{\rm LRS}}{37} \max\left[1, e^{2(8.2-L_{\rm LRS})}\right]$$

ε_K: LRS vs. RS cont'd



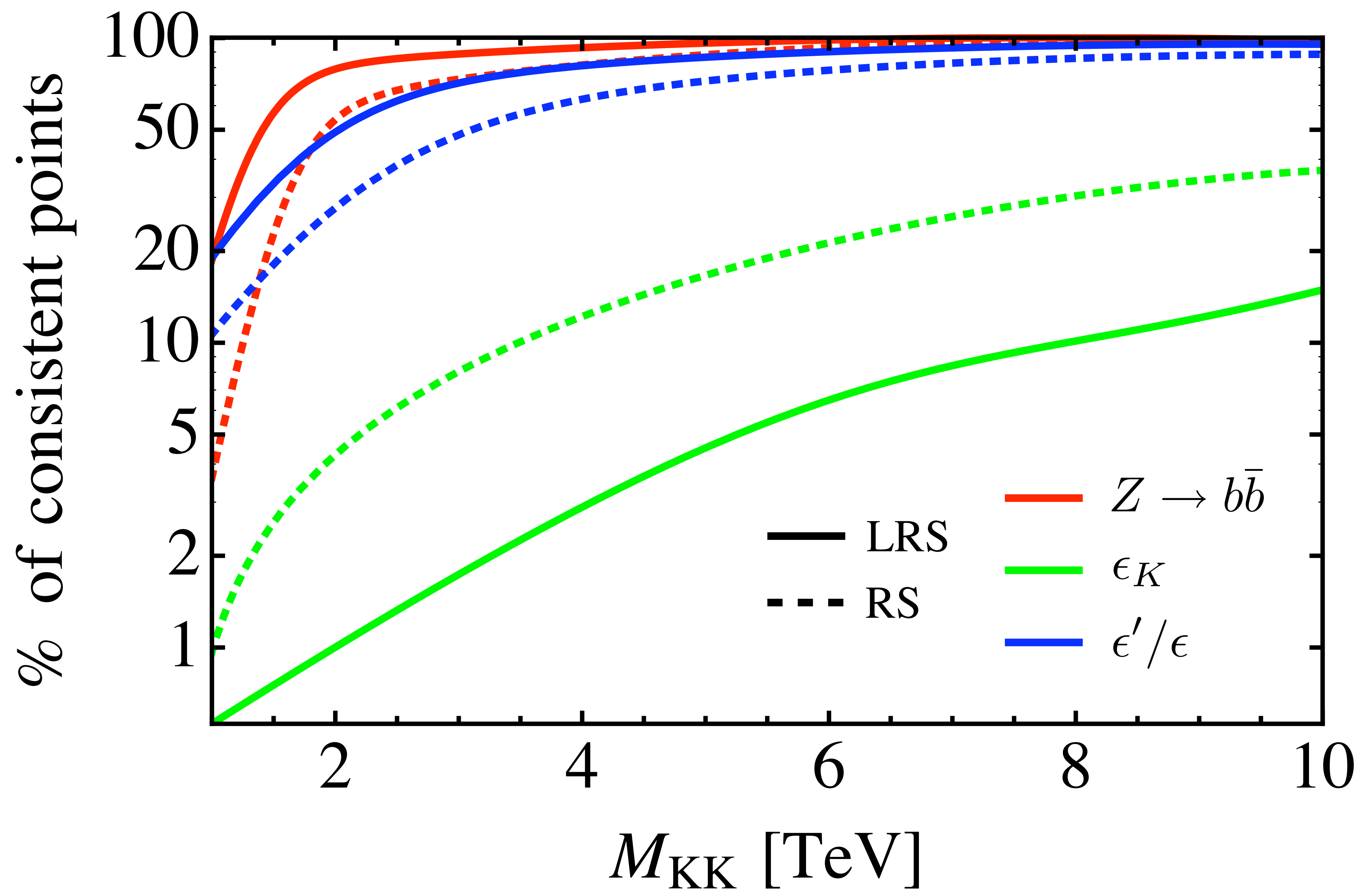
- For generic RS parameter points, featuring values of ε_K of O(100) larger than SM prediction, L dependence of exact results nicely follows approximate formula

ε_K: LRS vs. RS cont'd



- L dependence of curves corresponding to points consistent with measured value of ε_K, can look more complicated, but characteristic feature of UV dominance stays intact

Big Picture: LRS vs. RS



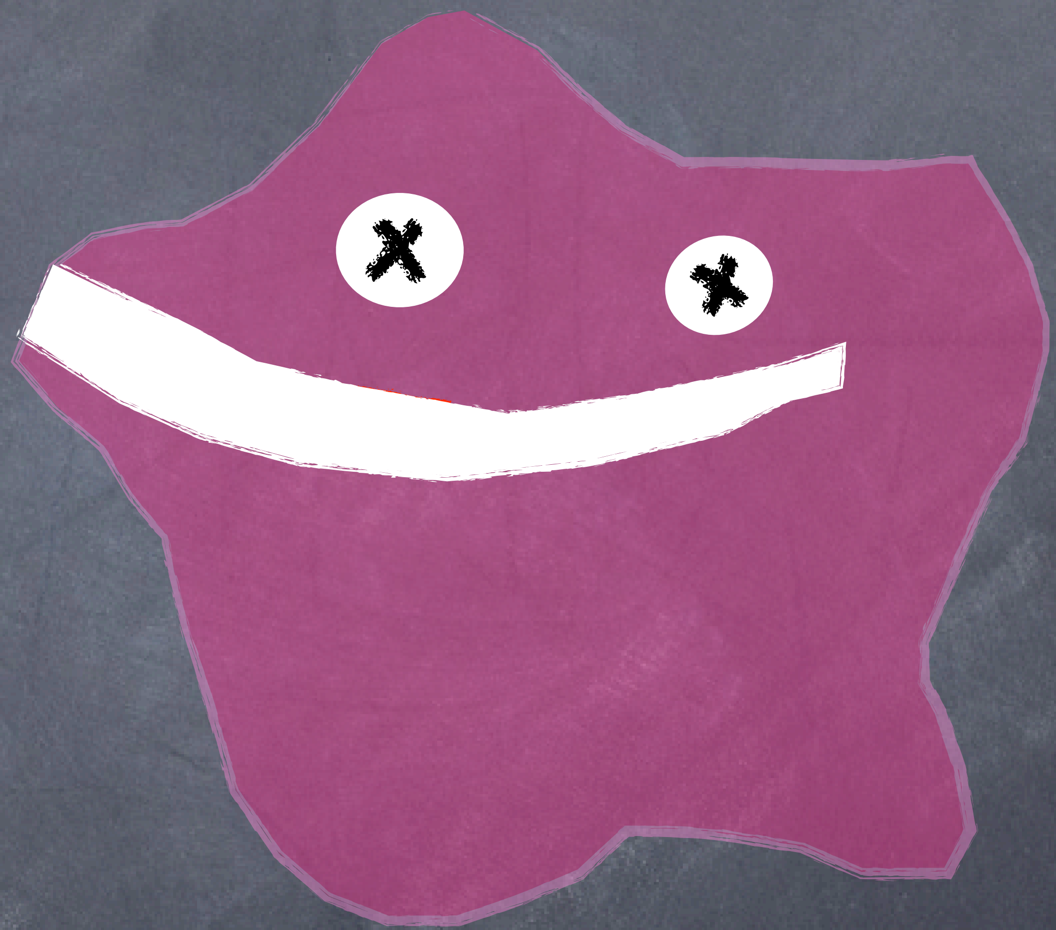
Summary

- Considering volume-truncated versions of RS setup with UV cutoff $\Lambda_{UV} \ll M_{Pl}$ allows to mitigate constraints from both T & $Z \to b\underline{b}$
- ε_K provides bound on Λ_{UV} of few 10^3 TeV. Even if bound is satisfied no improvement in ε_K can be achieved in LRS compared to native RS model
- Effect arises since for $c_{Q2} + c_s < -2$, overlap integrals of 5D gluon propagator with profiles of 1st & 2nd generation quarks are dominated by region near UV brane, which partially evades RS-GIM mechanism

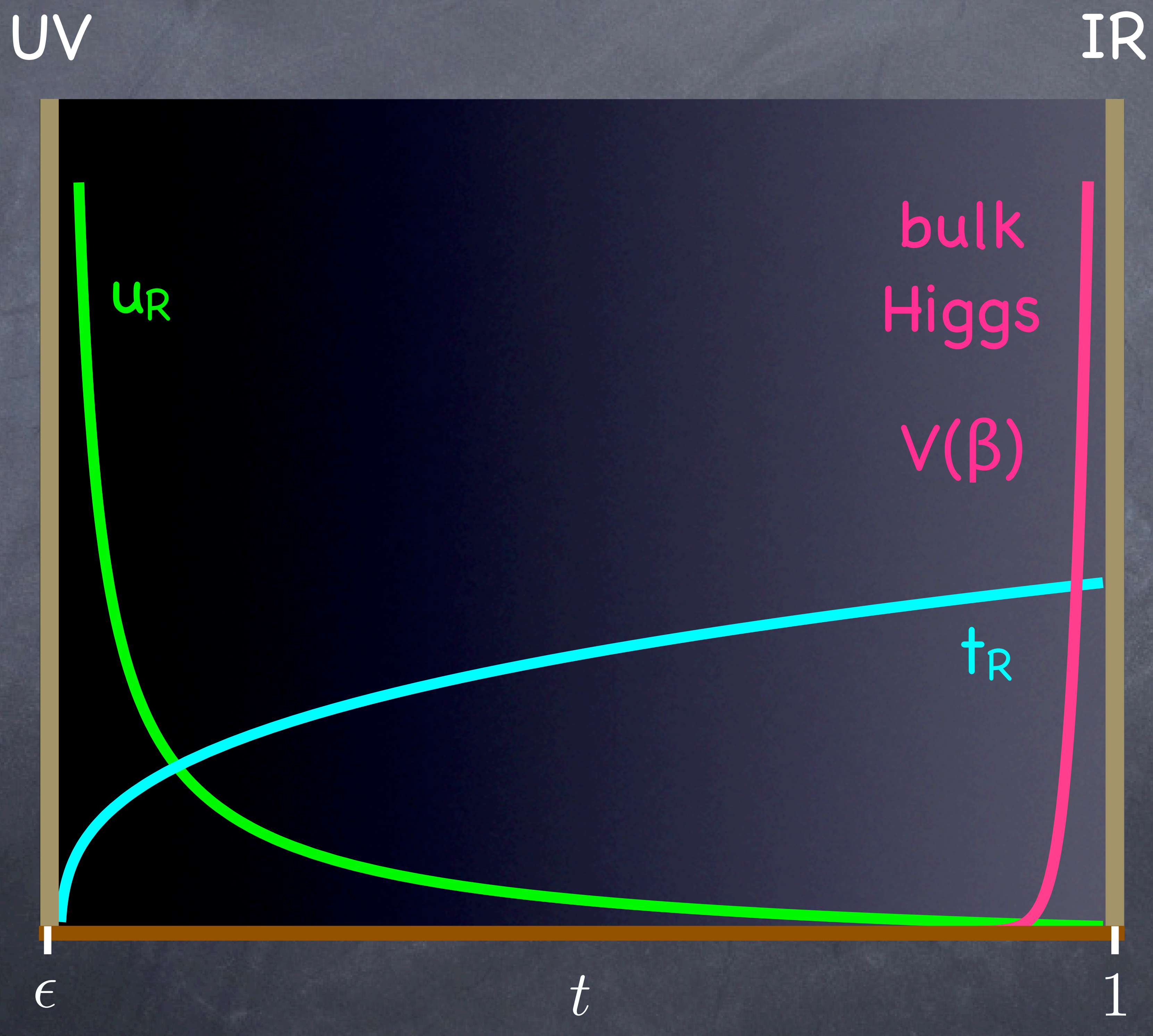
Higgs-Boson
FCNCs

or

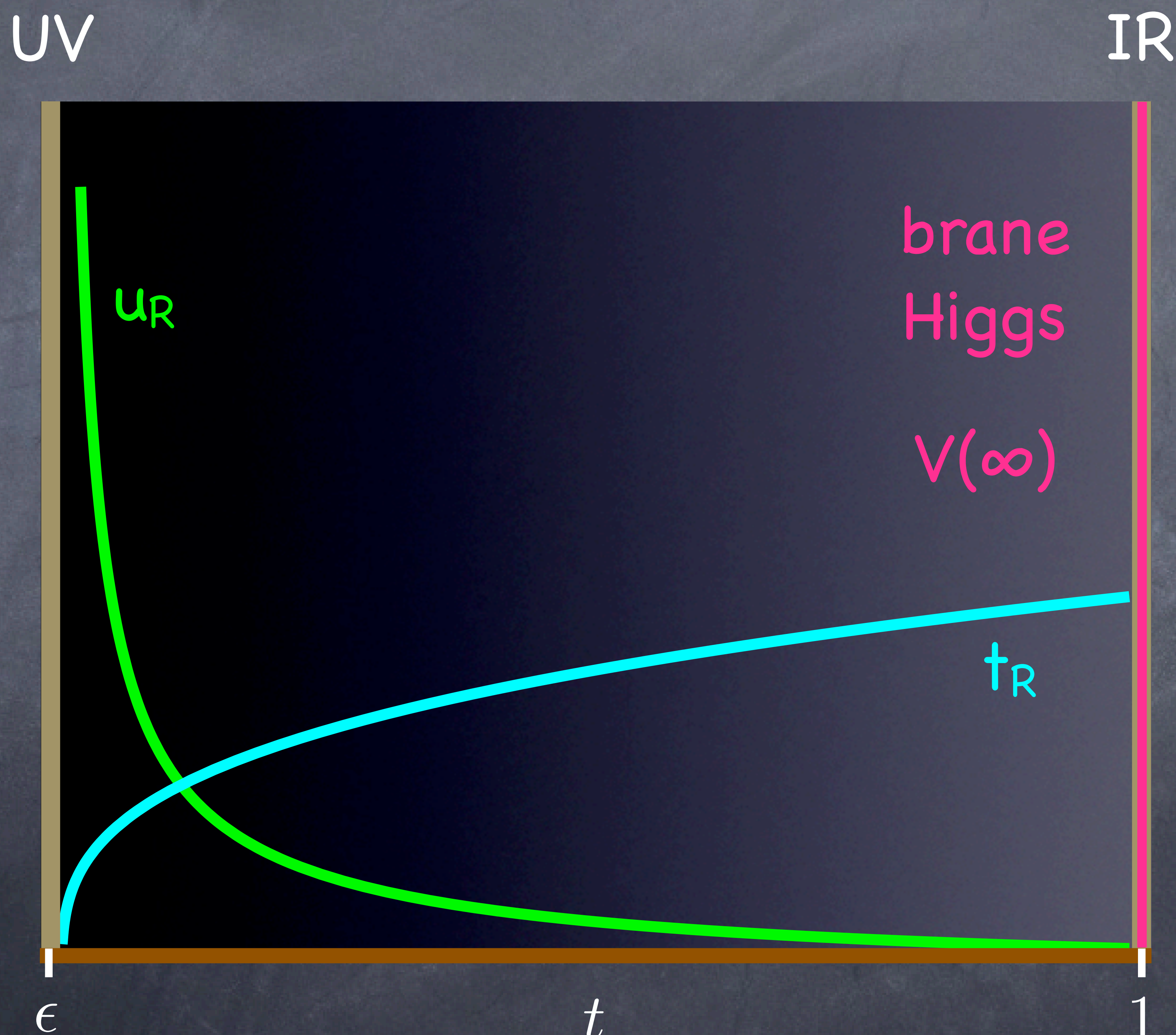
Fun with δ & $\underline{\Theta}$ distributions



Higgs Localization



Higgs Localization cont'd



Yukawa Sector

- In following let's focus on brane-Higgs case where one can find analytic, all order solution. Action describing Yukawa interactions given by

$$\mathcal{S} \propto -\int d^4x \int_\epsilon^1 dt\, \delta(t-1) \left[\bar{Q}_L Y_q^C q_R + \bar{Q}_R Y_q^S q_L \right]$$

where Y_q^C & Y_q^S are Yukawa couplings that can in principle be different & q = u, d. Notice that in bulk case $Y_q^C = Y_q^S$ due to 5D general covariance

Decomposition of 5D Fields

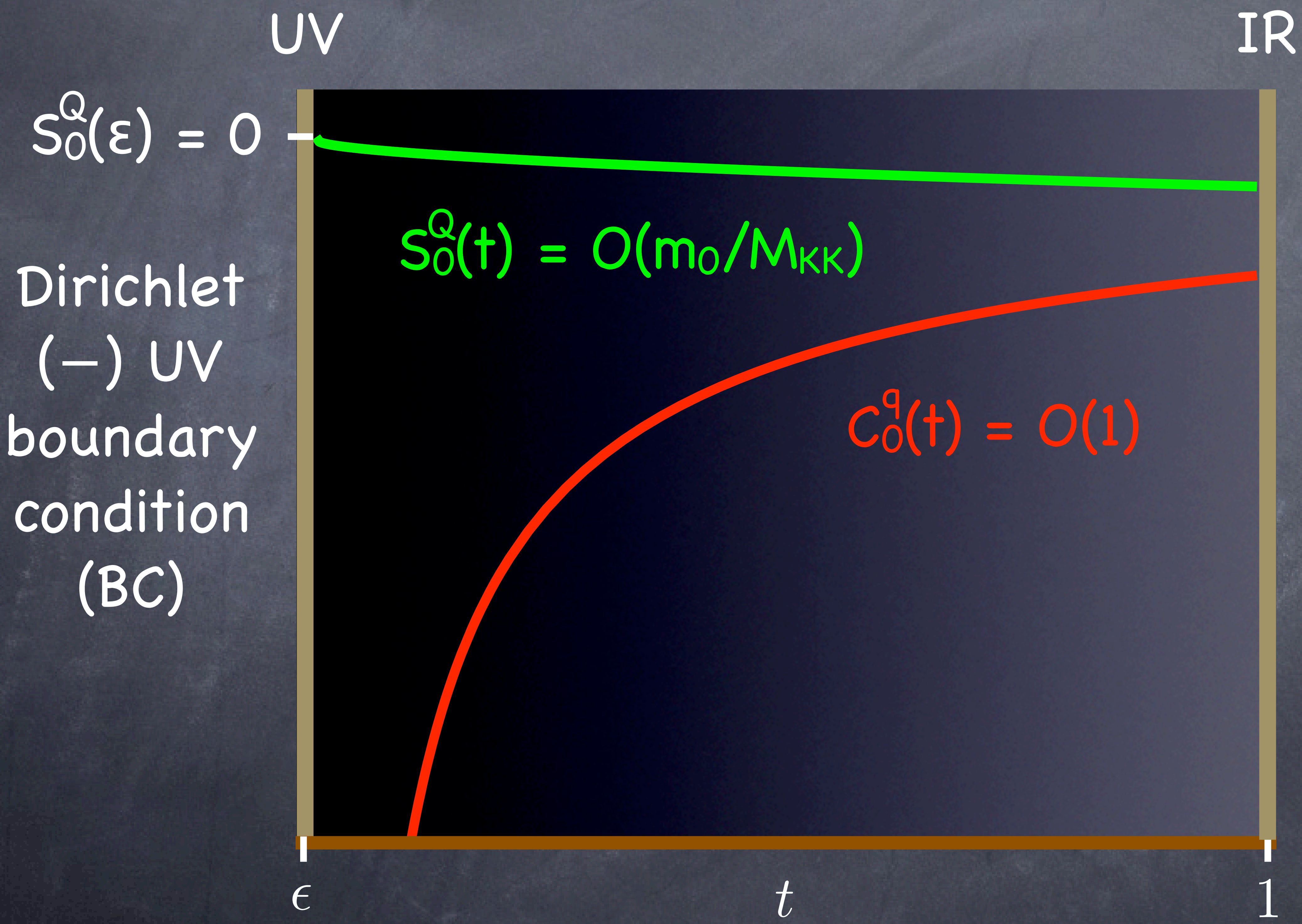
- In order to derive equations of motions (EOMs) for quark profiles in XD, we decompose 5D into left- & right-chiral 4D fields as follows

$$Q_L \propto \sum_k C_k^Q(t)\, q_L^{(k)}(x)\,, \quad Q_R \propto \sum_k S_k^Q(t)\, q_R^{(k)}(x)\,,$$

$$q_L \propto \sum_k S_k^q(t)\, q_L^{(k)}(x)\,, \qquad q_R \propto \sum_k C_k^q(t)\, q_L^{(k)}(x)$$

Here $C_k^A(t)$ & $S_k^A(t)$ with $A = Q, q$ are Z_2-even & -odd profiles on orbifold

Zero-Mode Profiles



Regularization

- To derive correct behavior of Z_2-even & -odd profiles close to IR brane, one has to regularize δ-function properly. Let's use

$$\lim_{\eta \to 0^+} \delta^\eta(x) = \delta(x)$$

with compact support on $x \in [-\eta, 0]$. This limit is understood in weak sense

$$\lim_{\eta \to 0^+} \int_{-\infty}^{+\infty} dx\, \delta^\eta(x)\, f(x) = f(0)$$

for all test functions f(x)

EOMs for $t \in [1-\eta, 1]$

- Using 5D variational principle leads to following EOMs in infinitesimal interval $t \in [1-\eta, 1]$, i.e., in vicinity of IR brane:

$$-\partial_t S_k^Q(t) = \delta^\eta(t-1)\,\frac{v}{\sqrt{2}M_{\mathrm{KK}}}\,Y_q^C\,C_k^q(t)\,,$$

$$-\partial_t C_k^q(t) = \delta^\eta(t-1)\,\frac{v}{\sqrt{2}M_{\mathrm{KK}}}\,Y_q^{S*}\,S_k^Q(t)$$

Equations for remaining 2 quark profiles are obtained by replacements $Q \leftrightarrow q$ & "-" → "+"

EOMs for $t \in [1-\eta, 1]$ cont'd

- Integrating latter equations from $t \leq 1-\eta$ to 1 & using that $S_k^A(1) = 0$, one obtains

$$S_k^Q(t) = \frac{v}{\sqrt{2}\,M_{\rm KK}}\,Y_q^C \int_t^1 dt'\,\delta^\eta(t'-1)\,C_k^q(t')\,,$$

$$C_k^q(t) = C_k^q(1) + \frac{v}{\sqrt{2}\,M_{\rm KK}}\,Y_q^{S\,*} \int_t^1 dt'\,\delta^\eta(t'-1)\,S_k^Q(t')$$

& similar relations in remaining cases. How do solutions to these equations look like?

Solution!

- In order to find solution to integral equations, we introduce regularized Heaviside function

$$\bar{\theta}^{\eta}(x) = 1 - \int_{-\infty}^{x} dy\, \delta^{\eta}(y)$$

which obeys

$$\bar{\theta}^{\eta}(0) = 0\,, \quad \bar{\theta}^{\eta}(-\eta) = 1\,, \quad \partial_x \bar{\theta}^{\eta}(x) = -\delta^{\eta}(x)$$

- Using latter properties it is readily shown that

$$\int_t^1 dt'\, \delta^{\eta}(t'-1)\left[\bar{\theta}^{\eta}(t'-1)\right]^n = \frac{1}{n+1}\left[\bar{\theta}^{\eta}(t-1)\right]^{n+1}$$

Solution! cont'd

- As notation suggests, solutions to integral EOMs thus take form

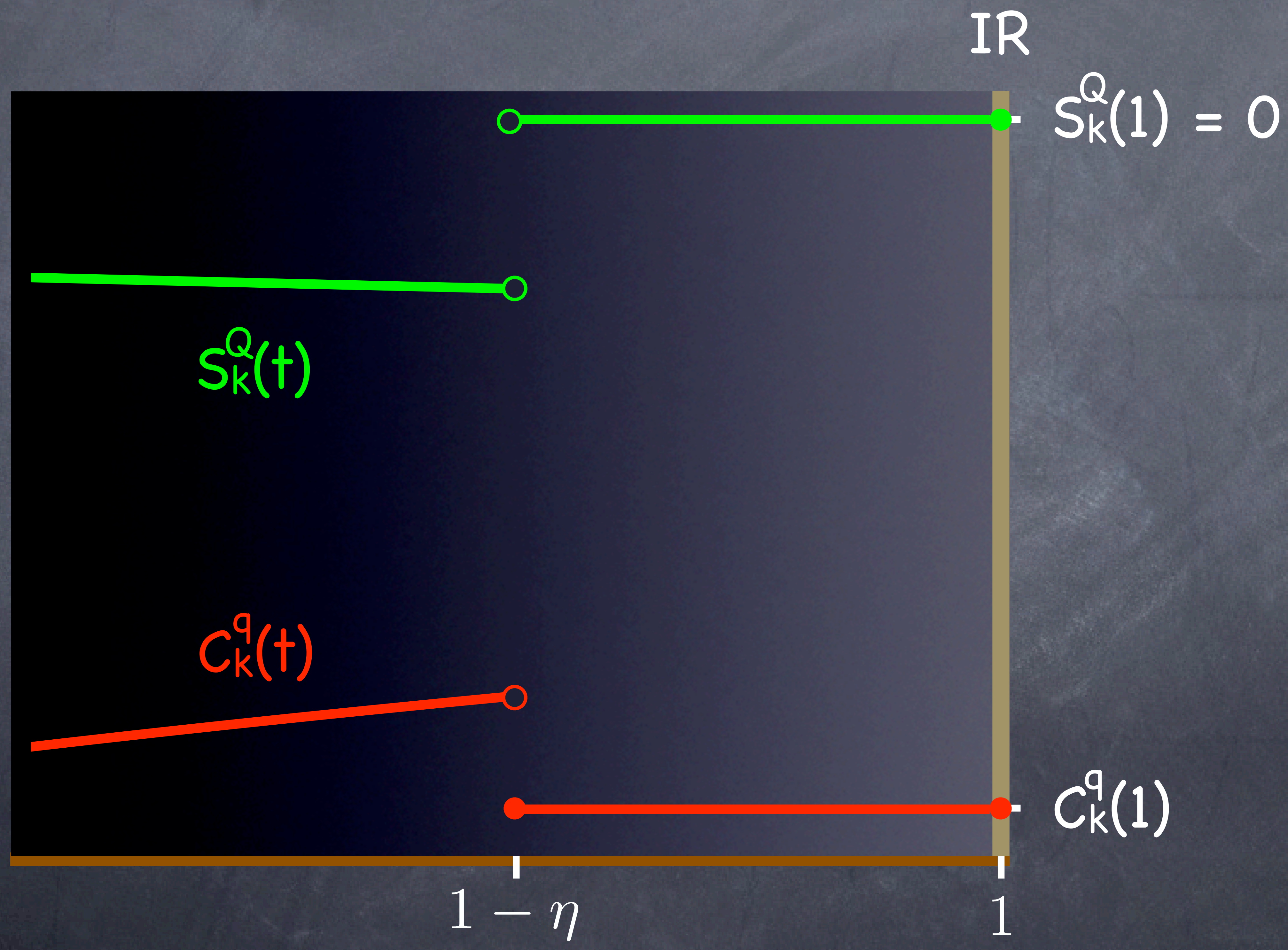
$$S_k^Q(t) = Y_q^C \left(\sqrt{Y_q^{S*} Y_q^C}\right)^{-1}$$

$$\times \sinh\left(\frac{v}{\sqrt{2}M_{\mathrm{KK}}}\,\bar{\theta}^\eta(t-1)\,\sqrt{Y_q^{S*}Y_q^C}\right) C_k^q(1)\,,$$

$$C_k^q(t) = \cosh\left(\frac{v}{\sqrt{2}M_{\mathrm{KK}}}\,\bar{\theta}^\eta(t-1)\,\sqrt{Y_q^{S*}Y_q^C}\right) C_k^q(1)$$

& similarly in remaining cases

Solution! cont'd



IR BCs

- Since t-integration has been performed, we can now take limit $\eta \to 0^+$ & trade on-brane profiles for bulk wave functions. This leads to

$$S_k^Q(1^-) = \frac{v}{\sqrt{2}M_{\rm KK}} \overline{Y}_q \, C_k^q(1^-) \, ,$$

$$-S_k^q(1^-) = \frac{v}{\sqrt{2}M_{\rm KK}} \overline{Y}_q^* \, C_k^Q(1^-)$$

where

$$\overline{Y}_q = f\left(\frac{v}{\sqrt{2}M_{\rm KK}} Y_q^C \, Y_q^{S\,*}\right) Y_q^C \, , \quad f(A) = \tanh\left(A\right) A^{-1}$$

IR BCs cont'd

- There are 2 important things to notice. 1st, new Yukawa matrices $\underline{Y}_q$ have following expansion in v/M_{KK}

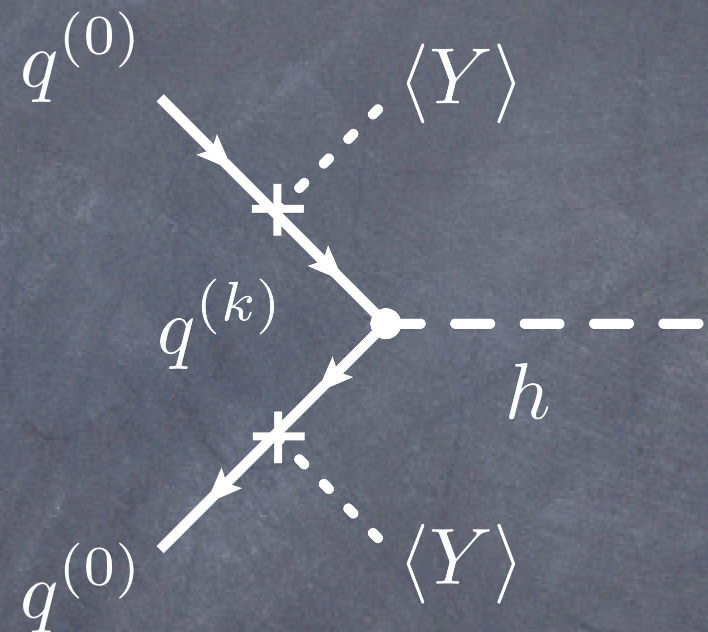
$$\overline{Y}_q = Y_q^C + \mathcal{O}(v^2/M_{\mathrm{KK}}^2)$$

  which implies that Z_2-odd couplings Y_q^S could be set to 0 without spoiling quark-mass generation

- 2nd, since Y_q^C, Y_q^S & c_{Ai} are chosen such that zero-mode masses & mixings match experimental data, rescaling has no observable effect on spectrum

Higgs-Boson FCNCs

- Mixing of quark zero-modes with KK excitations leads to Higgs-boson FCNCs:



- There are 2 types of misalignments. 1st one is chirally suppressed & also appears in Z-boson FCNCs, 2nd one is not & thus renders dominant correction for 1st & 2nd generation quarks

Higgs-Boson FCNCs cont'd

- To see where these 2 types of effects come from we have to look at Higgs-boson couplings to quarks. In unitary gauge they are given by

$$\mathcal{L} \ni -\sum_{q,k,l} (g_h^q)_{kl}\, h\, \bar{q}_L^{(k)}\, q_R^{(l)} + \text{h.c.}$$

where

$$(g_h^q)_{kl} = \frac{\sqrt{2}\pi}{L\epsilon} \int_\epsilon^1 dt\, \delta(t-1) \Big[C_k^Q(t) Y_q^C\, C_l^q(t) + S_k^q(t) Y_q^{S*}\, S_l^Q(t) \Big]$$

Higgs-Boson FCNCs cont'd

- Term bi-linear in Z_2-even wave functions can be rewritten by making use of canonical normalization of kinetic terms. We employ

$$m_k\,\delta_{kl} = \frac{\pi}{L\epsilon}\int_\epsilon^1 dt\,\Big\{ m_l\,S_k^q\,S_l^q + S_k^Q\,S_l^Q\,m_k + \sqrt{2}v\,\delta(t-1)\left[C_k^Q\,Y_q^C\,C_l^q - S_k^q\,Y_q^{S\,*}\,S_l^Q\right]\Big\}$$

which follows from EOMs

Higgs-Boson FCNCs cont'd

- Defining misalignment $(\Delta g_h^q)_{kl}$ via

$$(g_h^q)_{kl} = \delta_{kl}\,\frac{m_{q_k}}{v} - (\Delta g_h^q)_{kl}$$

one finds

$$(\Delta g_h^q)_{kl} = \frac{m_{q_k}}{v}\,(\Phi_q)_{kl} + (\Phi_Q)_{kl}\,\frac{m_{q_l}}{v} + (\Delta\tilde{g}_h^q)_{kl}$$

with

$$(\Phi_A)_{kl} = \frac{2\pi}{L\epsilon}\int_\epsilon^1 dt\, S_k^A(t)\, S_l^A(t)\,, \quad A = Q, q$$

$$(\Delta\tilde{g}_h)_{kl} = -\sqrt{2}\,\frac{2\pi}{L\epsilon}\int_\epsilon^1 dt\,\delta(t-1)\, S_k^q(t)\, Y_q^{S*} S_l^Q(t)$$

Higgs-Boson FCNCs cont'd

- Corrections suppressed by small quark masses, i.e., $(\phi_A)_{kl}$ terms also affect Z-boson couplings. Including corrections to 2nd order in v/M_{KK} they scale as

$$(\Phi_Q)_{kl} \sim \frac{v^2 \left(Y_q^C\right)^2}{M_{\rm KK}^2} \, F(c_{Q_k}) \, F(c_{Q_l}) \, ,$$

$$(\Phi_q)_{kl} \sim \frac{v^2 \left(Y_q^C\right)^2}{M_{\rm KK}^2} \, F(c_{q_k}) \, F(c_{q_l})$$

Higgs-Boson FCNCs cont'd

- To calculate chirally unsuppressed correction one again has to regularize δ-function. Final result can be cast into form

$$(\Delta\tilde{g}_h^q)_{kl} = \frac{1}{\sqrt{2}}\,\frac{2\pi}{L\epsilon}\,\frac{v^2}{3M_{\rm KK}^2}\,C_k^Q(1^-)\,\overline{Y}_q\,\widetilde{Y}_q^*\,\overline{Y}_q\,C_l^q(1^-)$$

where

$$\widetilde{Y}_q^* = Y_q^{S*}\;g\left(\frac{v}{\sqrt{2}M_{\rm KK}}\sqrt{Y_q^C Y_q^{S*}}\right),$$

$$g(A) = \frac{3}{2}\left[\sinh\left(2A\right)\left(2A\right)^{-1} - 1\right]\left(\sinh\left(A\right)\right)^{-2}$$

Higgs-Boson FCNCs cont'd

- Since rescaled Yukawa couplings entering latter expression coincide to leading order in v/M_{KK} with original ones, i.e.,

$$\overline{Y}_q = Y_q^C + \mathcal{O}(v^2/M_{\rm KK}^2)\,, \quad \widetilde{Y}_q = Y_q^S + \mathcal{O}(v^2/M_{\rm KK}^2)$$

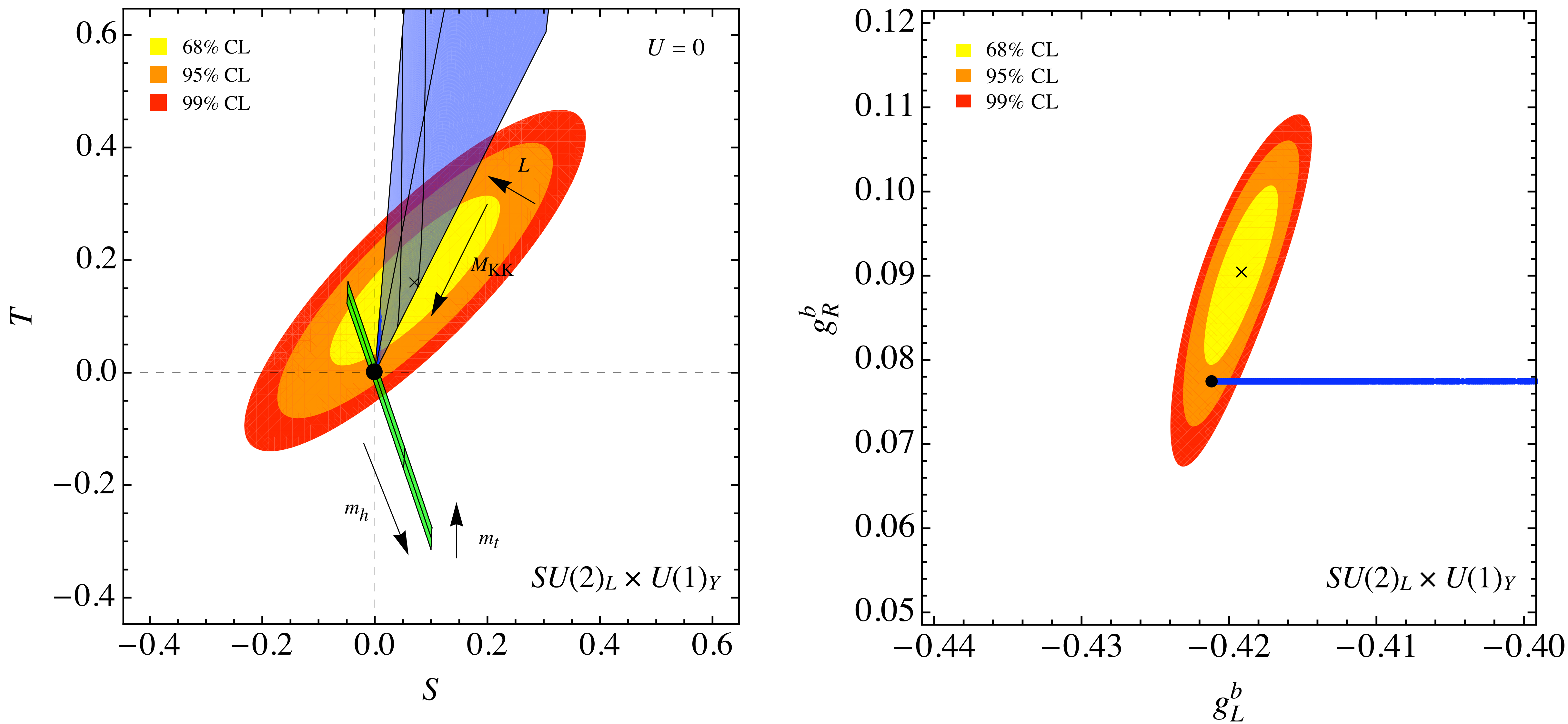
  it is easy to read off scaling of dominant Higgs FCNC correction. One obtains

$$(\Delta\tilde{g}_h^q)_{kl} \sim \frac{v^2}{M_{\rm KK}^2}\, F(c_{Q_k})\, Y_q^C\, Y_q^{S\,*}\, Y_q^C\, F(c_{q_l})$$

Conclusions & Outlook

- Correct implementation of both Z_2-even & -odd Yukawa couplings non-trivial, but offers quite a bit of fun with δ & $\underline{\theta}$ distributions
- Phenomenological impact of 1^{st} & 2^{nd} generation Higgs FCNCs is limited. Most pronounced effect occurs in ε_K, but even here it is typically smaller than corrections due to KK gluon exchange
- Large effects can however occur naturally in observables that involve couplings to composite sector, e.g., $t \to ch$, $gg \to h$, $h \to \gamma\gamma$, ...

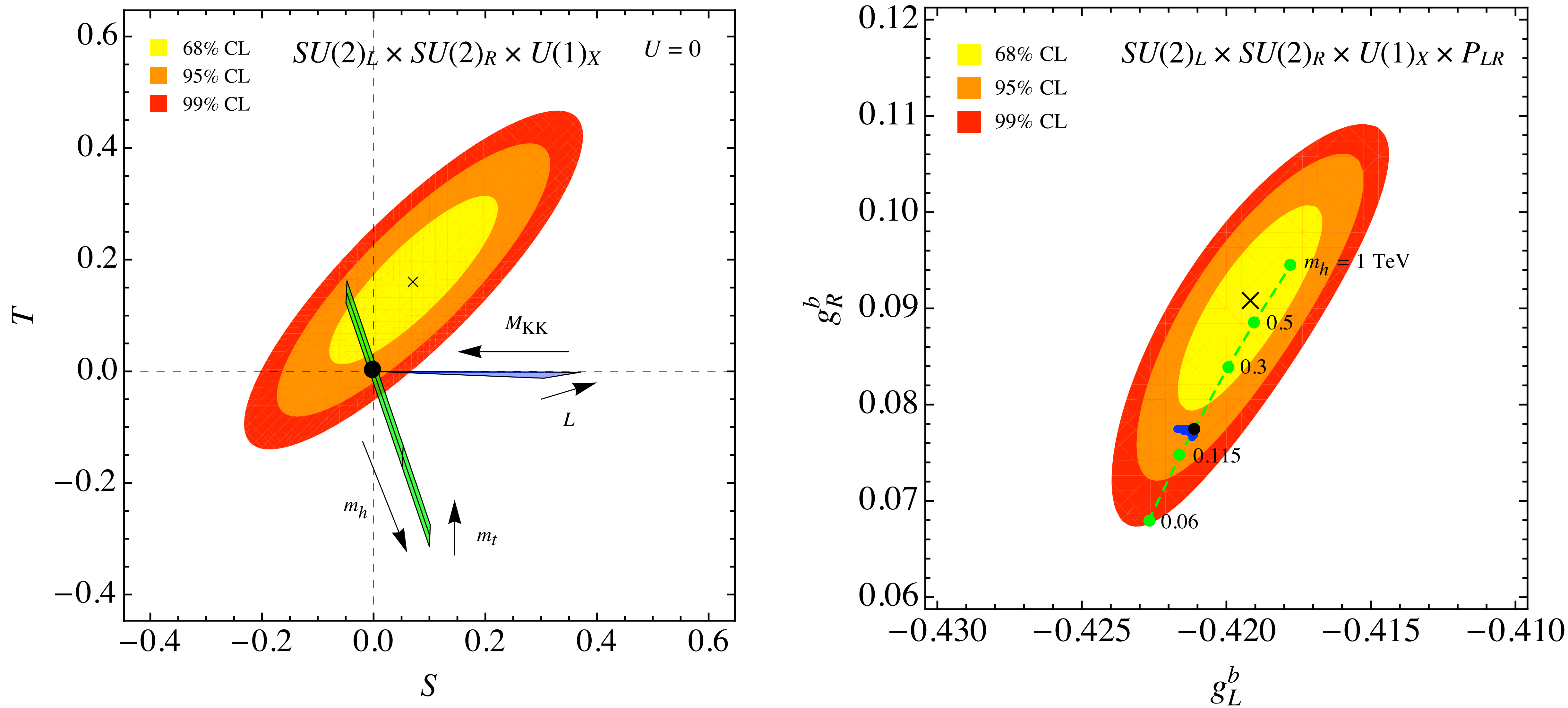
Precision observables in original RS model*



- Both T parameter and $Zb_L\bar{b}_L$ coupling are L-enhanced in $SU(2)_L \times U(1)_Y$ model. To avoid these constraints one needs KK gauge-boson masses above 6.5 TeV

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

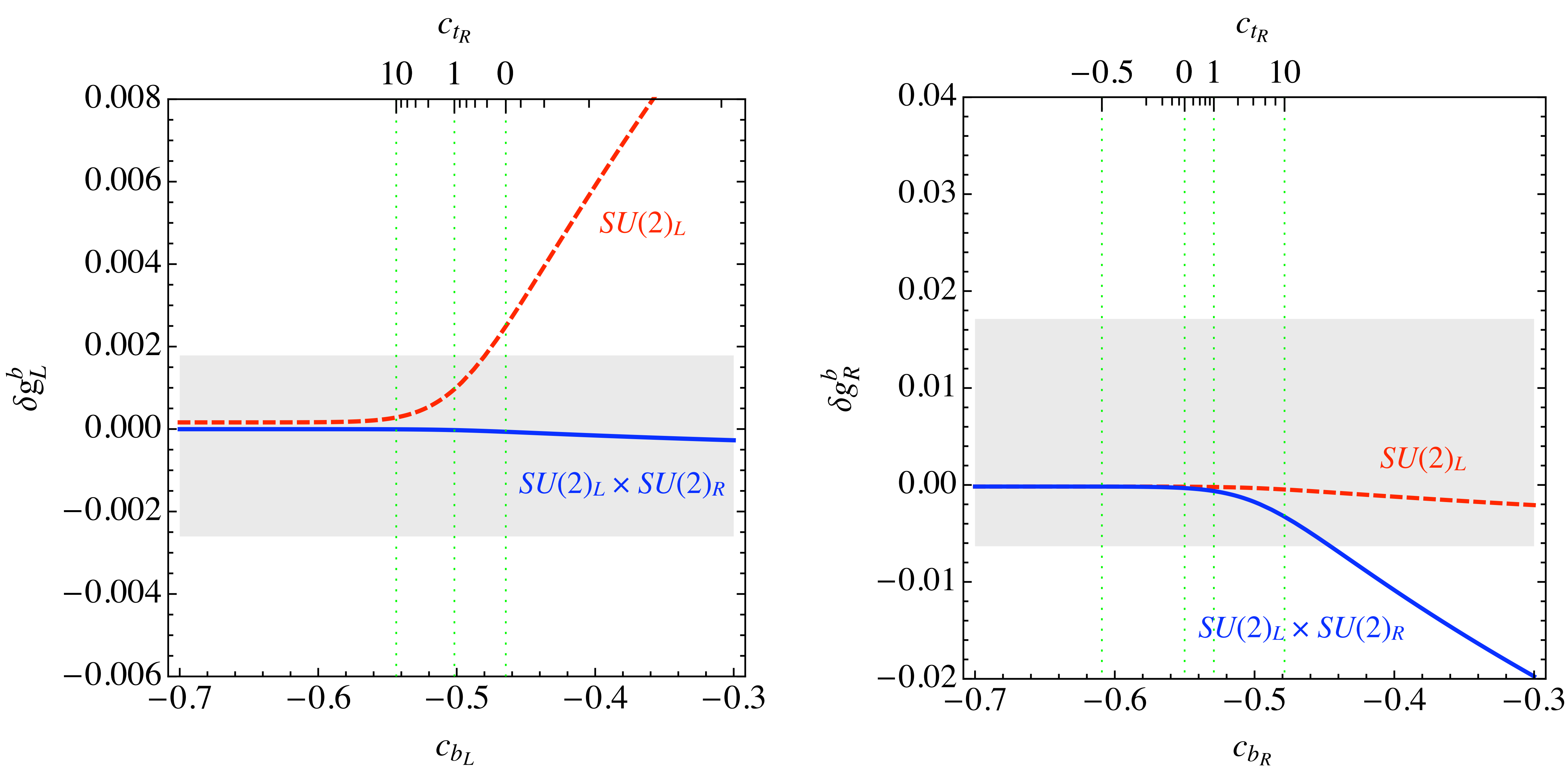
Precision observables in extended RS model*



- While $Zb\bar{b}$ couplings pose no strong constraint in $SU(2)_L \times SU(2)_R \times U(1)_X \times P_{LR}$ model, T and S parameter can be problematic for heavy Higgs boson

*Agashe *et al*., hep-ph/0308036; Carena *et al*., hep-ph/0607106; Casagrande *et al*., arXiv:0807.4537, arxiv:1001.xxxx

Remarks on $Zb_L\bar{b}_L$ and $Zb_R\bar{b}_R$ couplings*

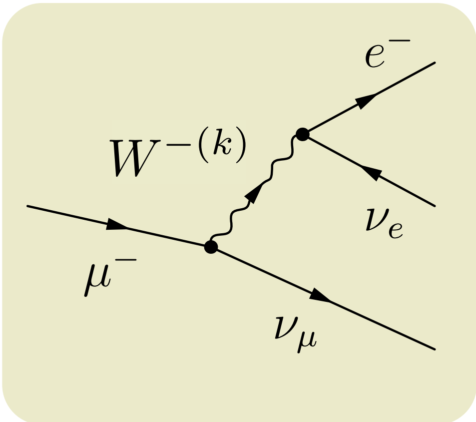


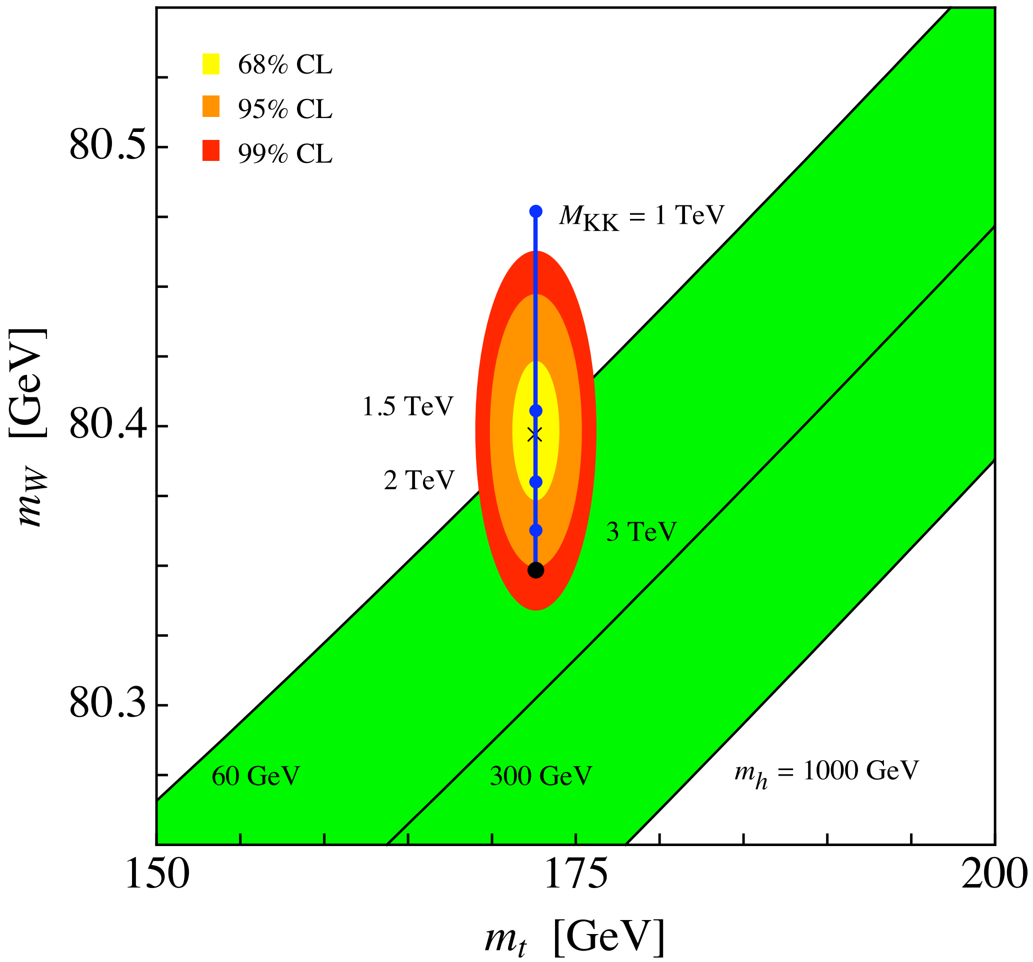
- Corrections to $Zb_R\bar{b}_R$ coupling that would cure 3σ anomaly in bottom-quark forward-backward asymmetry not possible if b_L and t_L sit in same multiplet

*Carena *et al.*, hep-ph/0607106; Casagrande *et al.*, arXiv:0807.4537, arxiv:1001.xxxx

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





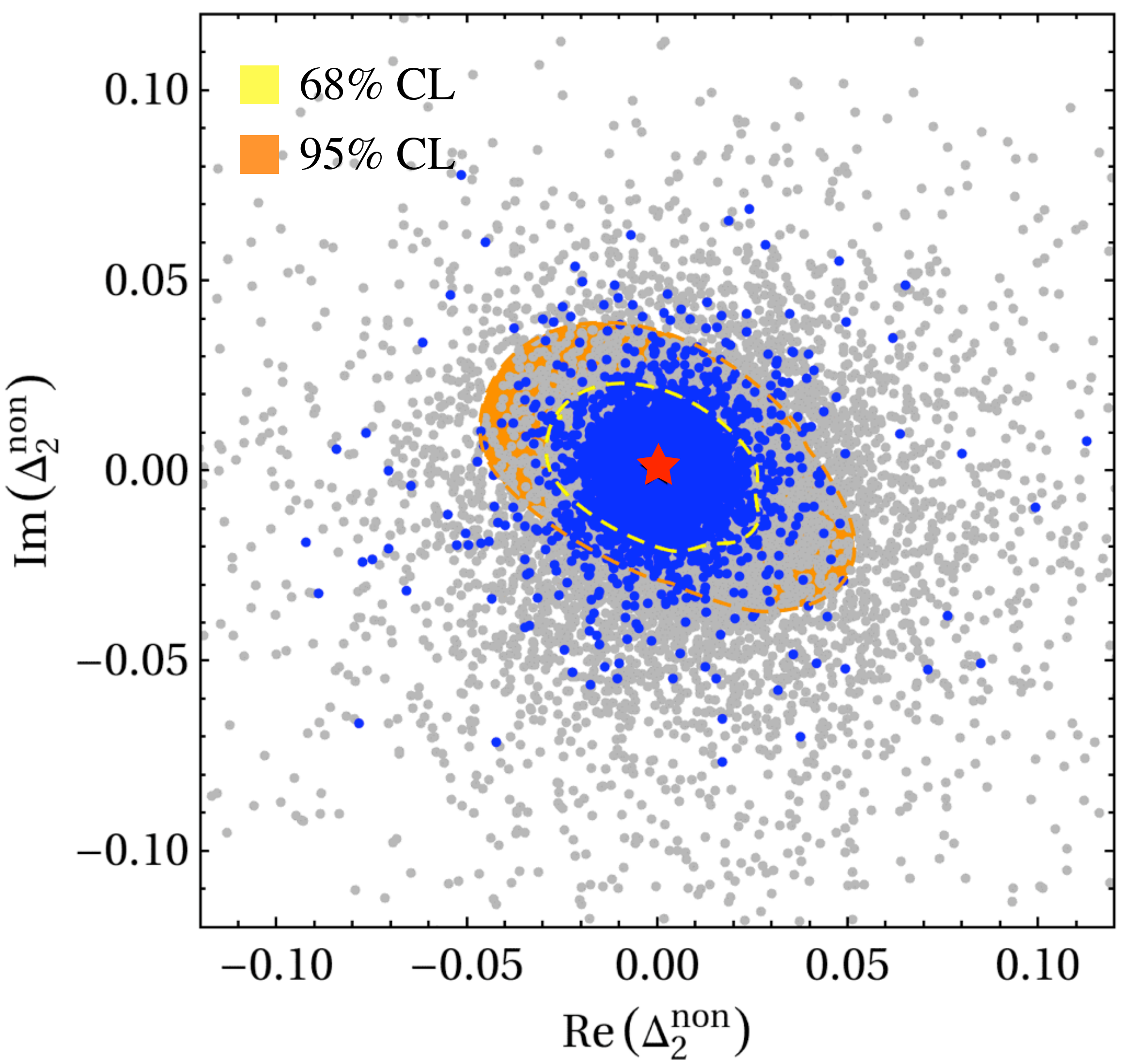
$$(m_W)_{\rm ind} \approx m_W \left[1 - \frac{m_W^2}{4M_{\rm KK}^2}\left(1 - \frac{1}{2L}\right)\right]$$

- $(m_W)_{\rm ind}$ 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

Non-unitarity of CKM matrix*

- Improvement of determination of unitarity triangle at LHC or SuperB might allow to detect non-closure of CKM triangle predicted in RS framework



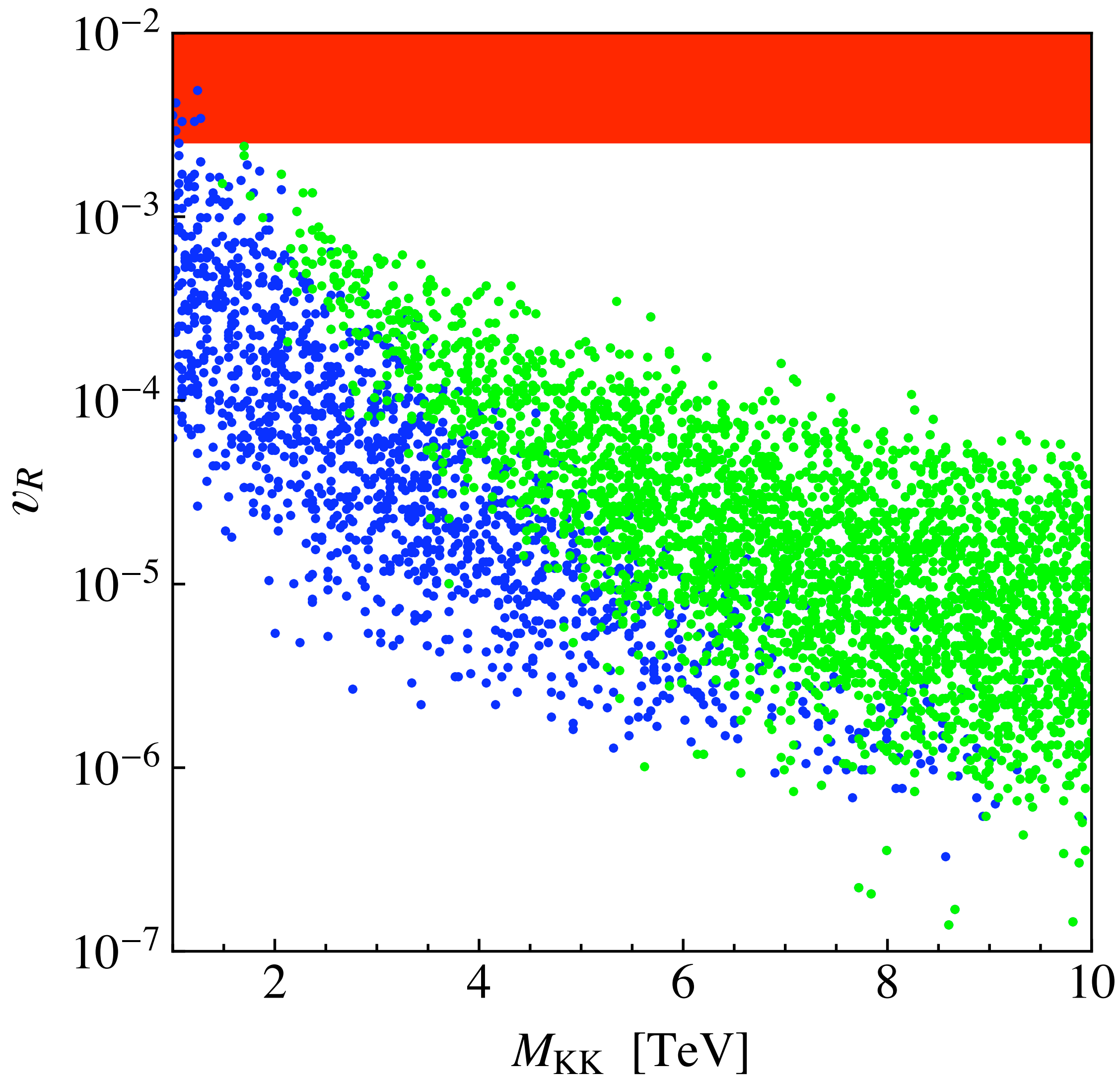
$$\Delta_2^{\mathrm{non}} \equiv 1 + \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}$$

- ★ SM
- consistent with hierarchies in quark sector and $Z \to b\bar{b}$ constraint at 95% CL
- without $Z \to b\bar{b}$ constraint

*Casagrande *et al*., arXiv:0807.4537, arXiv:0912.1625, arXiv:1010.xxxx; Buras, Duling & Gori, arXiv: 0905.2318

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

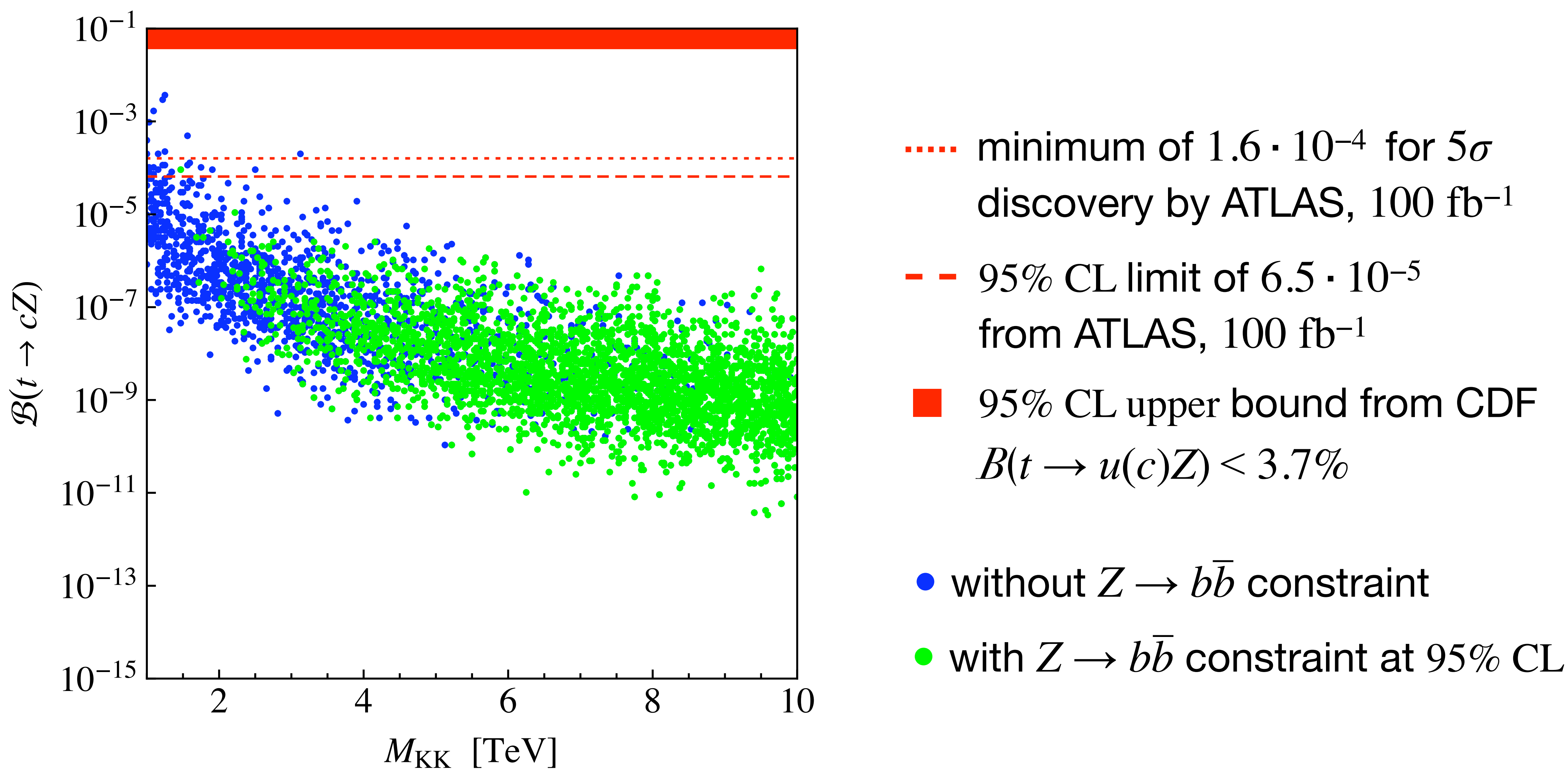
$v_R \in [-0.0007, 0.0025]$ at 95% CL exclusion bound from $B \to X_s\gamma$

- 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. Extended model offers better prospects



*Agashe *et al.*, hep-ph/0606293; Chang *et al.*, arXiv:0806.0667; Casagrande *et al.*, arXiv:0807.4537, arXiv:1001.xxxx

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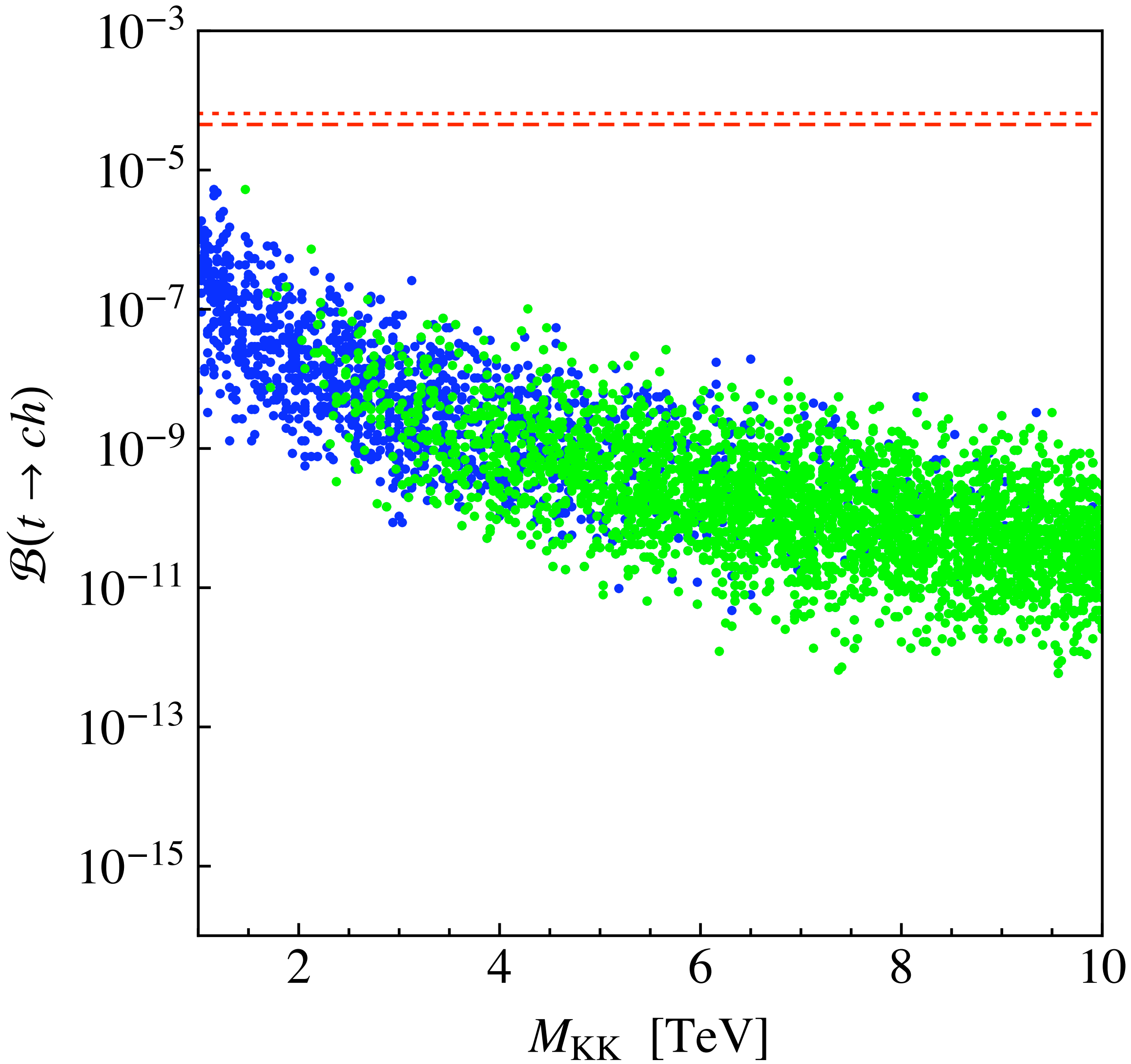


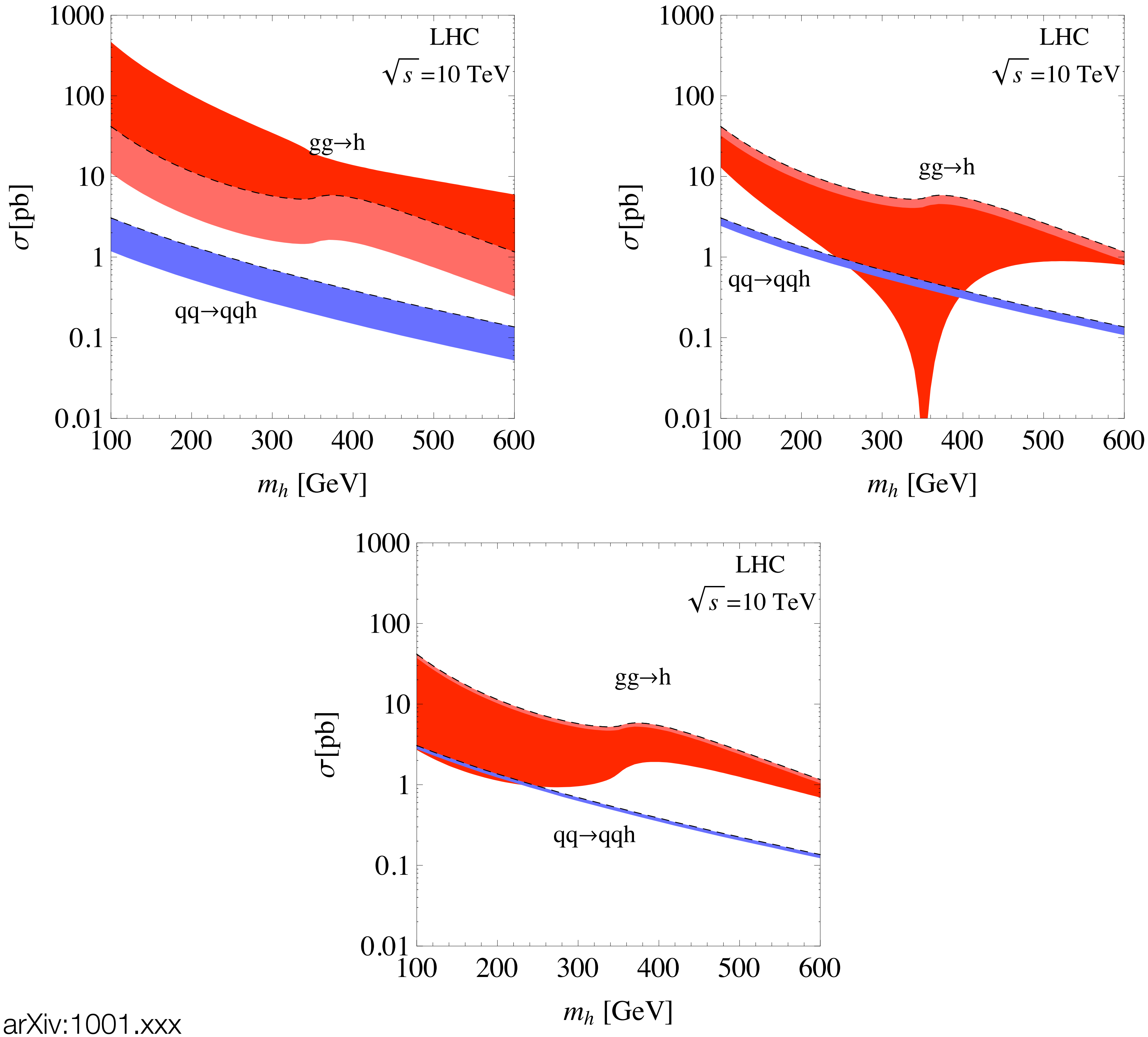
minimum of $6.5 \cdot 10^{-4}$ for 3σ evidence by LHC

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

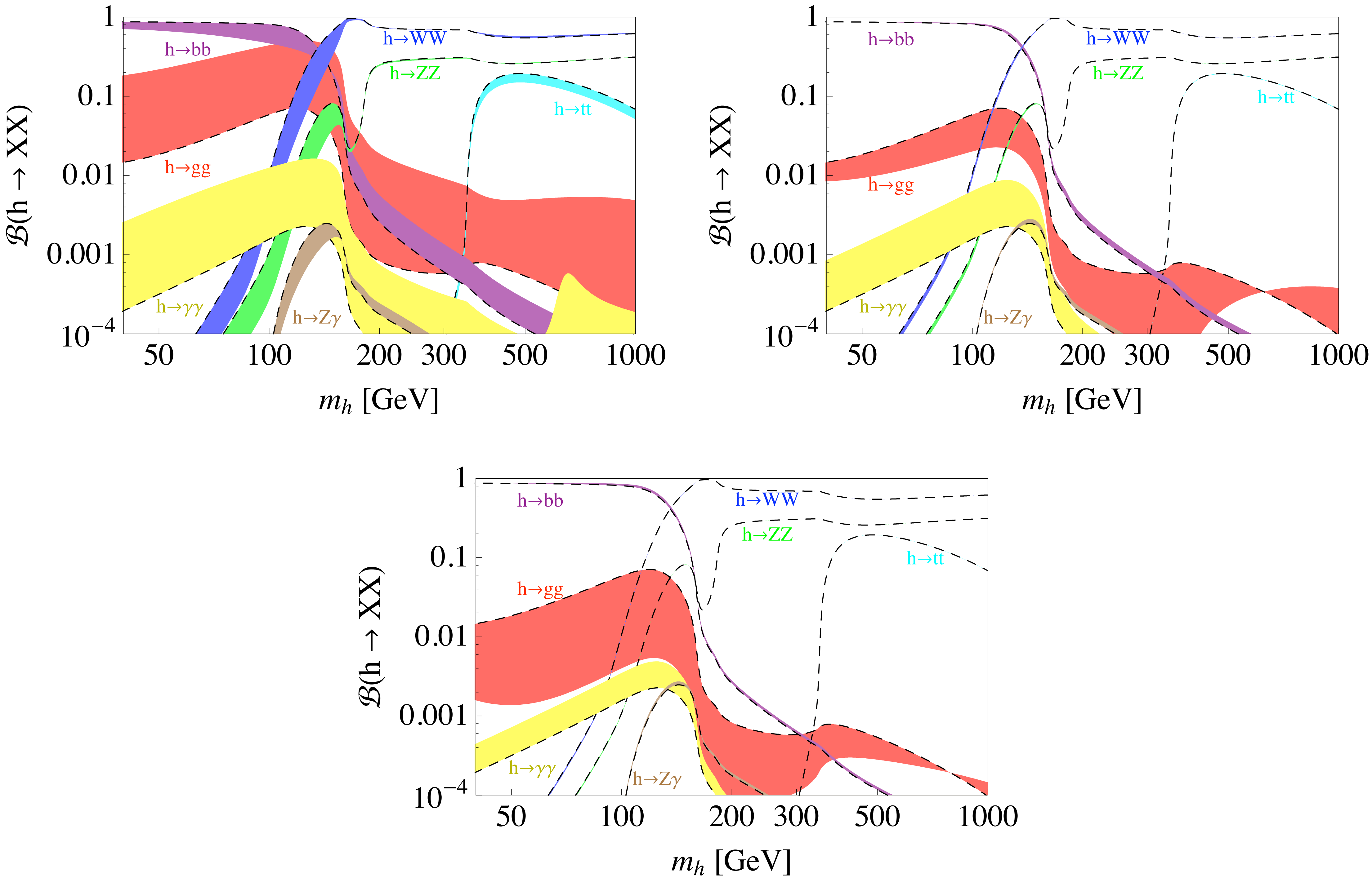
*Casagrande *et al.*, arXiv:0807.4537, arXiv:1001.xxxx; Azatov, Toharia & Zhu, arXiv:0906.1990

Higgs-boson production in RS models*



*Casagrande *et al.*, arXiv:1001.xxx

Higgs-boson decays in RS models*



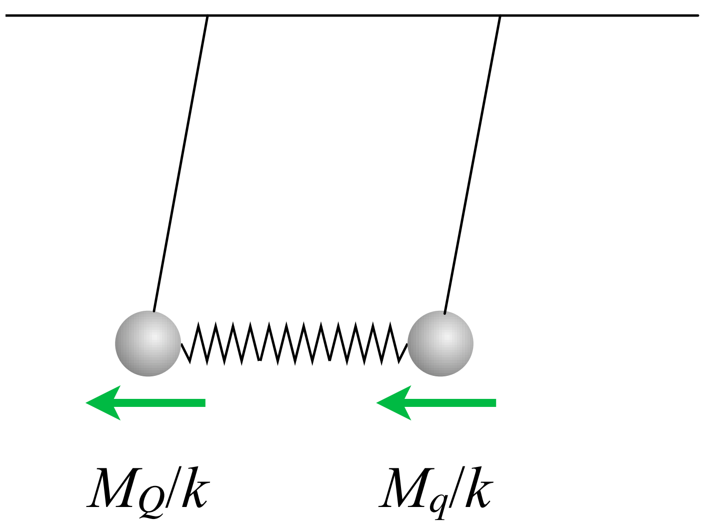
*Casagrande *et al.*, arXiv:1001.xxx

Reparametrization invariance*

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

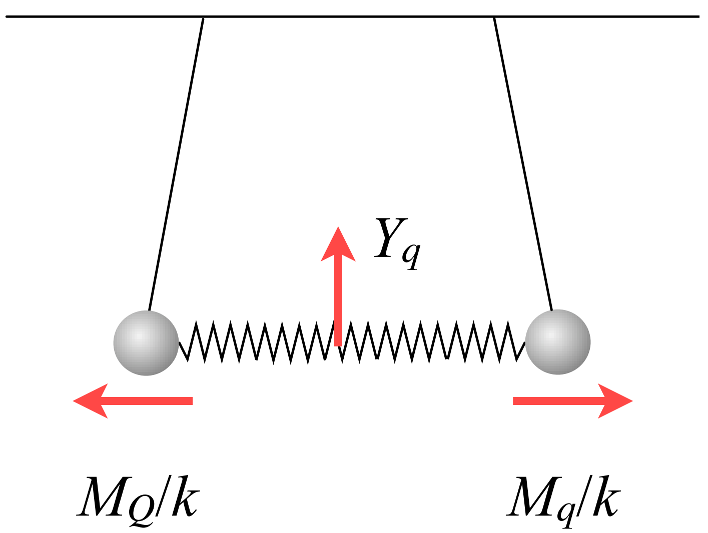
<u>RPI-1:</u>

$$\boxed{\begin{aligned} F_{c_Q} &\to e^{-\xi}\, F_{c_Q}\,, \\ F_{c_q} &\to e^{+\xi}\, F_{c_q}\,, \end{aligned}} \qquad \begin{aligned} &\left[c_Q \to c_Q - \frac{\xi}{L}\right], \\ &\left[c_q \to c_q + \frac{\xi}{L}\right] \end{aligned}$$



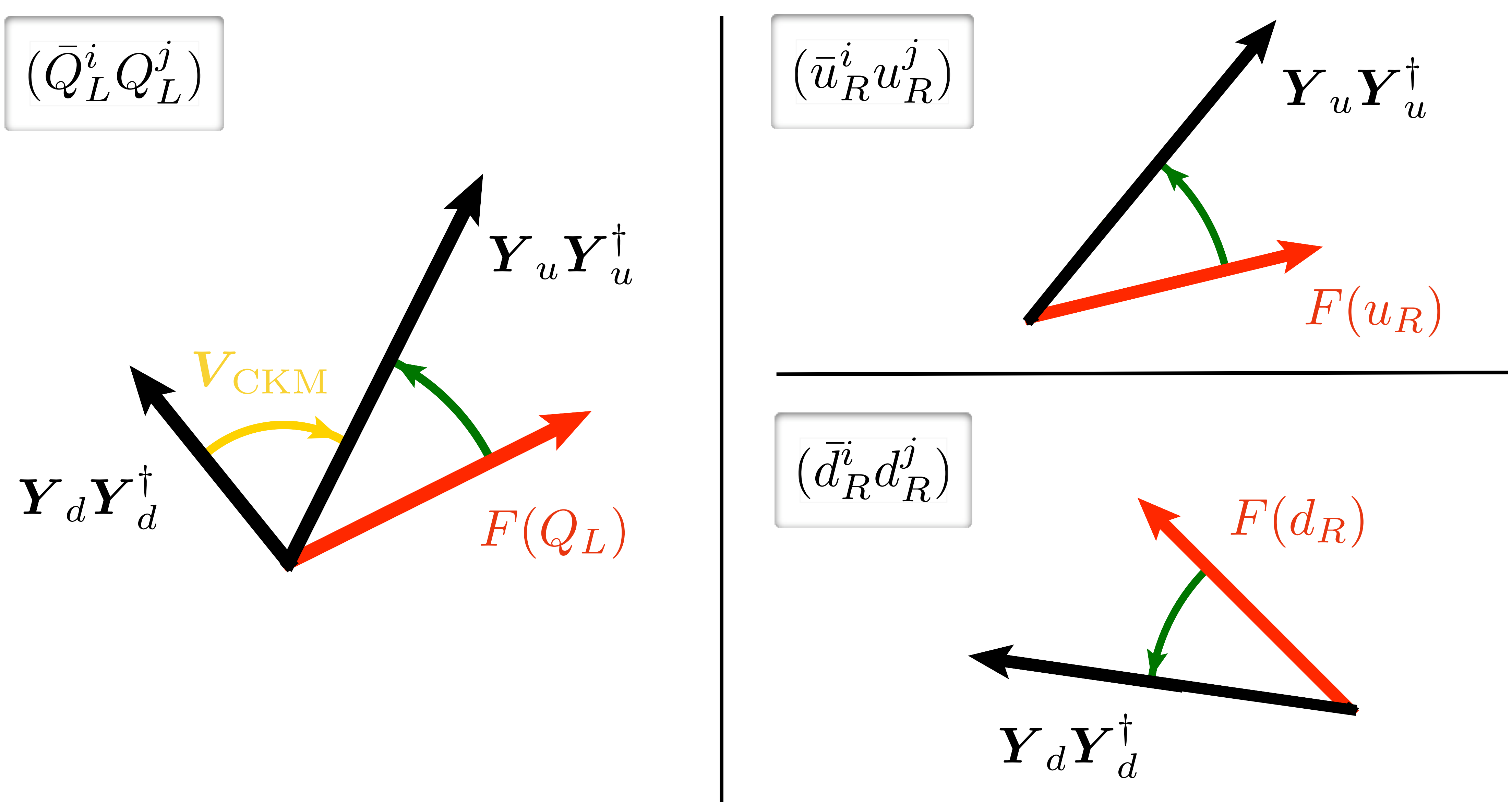
<u>RPI-2:</u>

$$\boxed{\begin{aligned} F_{c_A} &\to \zeta\, F_{c_A}\,, \\ \boldsymbol{Y}_q &\to \frac{1}{\zeta^2}\,\boldsymbol{Y}_q \end{aligned}} \qquad \left[c_A \to c_A - \frac{\ln\zeta}{L}\right],$$



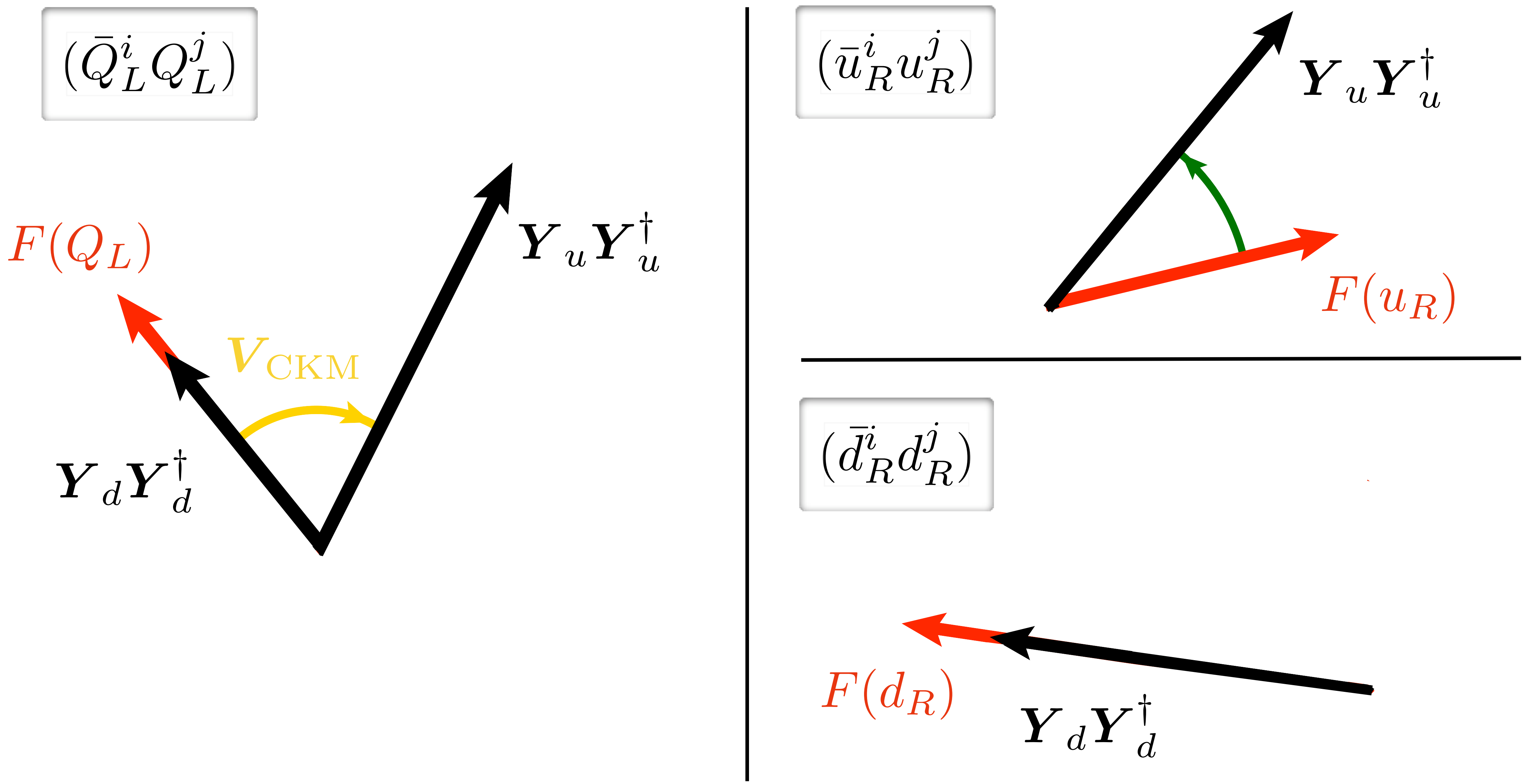
*Casagrande *et al.*, arXiv:0807.4537

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 ε_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