Shining and GIM

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based on:

1) GIM:
hep-ph 0709:1714 with G. Cacciapaglia, C. Csaki, J. Galloway, G. Marandella, and J. Terning

2) Shining: in progress with C. Csaki, Y. Grossman, G. Perez, and Z. Surujon

1) Flavor problem and RS GIM

2) 5D GIM mechanism and 4D MFV

3) Shining Flavor and 5D MFV

The quark flavour problem

$$\mathcal{L}_{EFT} = \Lambda^2\phi^2 + \frac{\mathcal{L}^{(5)}}{\Lambda} + \frac{\mathcal{L}^{(6)}}{\Lambda^2}$$

natural stabilization of the Higgs mass

e.g. $O^{(6)} \sim \frac{(\bar{s}d)^2}{\Lambda^2}$

$\Lambda \sim$ TeV

e.g. $K - \bar{K}$ mixing $\Lambda_{\text{Flavor}} \gg$ 1 TeV

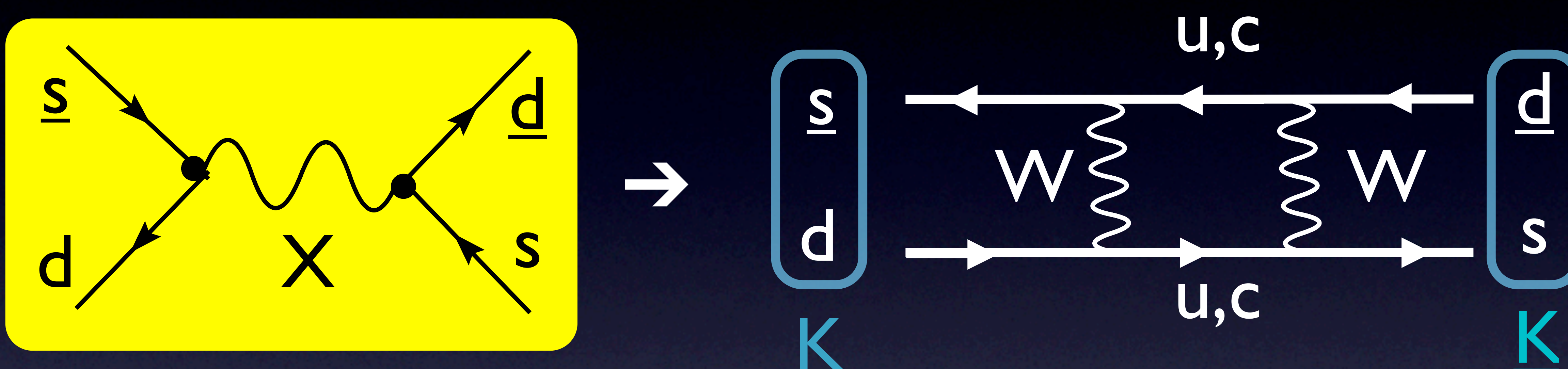
bound on Λ_{Flavor} depends on chirality (matrix element and running)

LL $(sd)_L (sd)_L$
RR $(sd)_R (sd)_R$
LR $(sd)_L (sd)_R$

UTfit ’07 flavor violation bound $(sd)^2$

	Parameter	95% allowed range	Lower limit on Λ (TeV)	
LL	$\mathrm{Re}C_K^1$	$[-9.6, 9.6] \cdot 10^{-13}$	$1.0 \cdot 10^3$	
	$\mathrm{Re}C_K^2$	$[-1.8, 1.9] \cdot 10^{-14}$	$7.3 \cdot 10^3$	
	$\mathrm{Re}C_K^3$	$[-6.0, 5.6] \cdot 10^{-14}$	$4.1 \cdot 10^3$	
LR	$\mathrm{Re}C_K^4$	$[-3.6, 3.6] \cdot 10^{-15}$	$17 \cdot 10^3$	
	$\mathrm{Re}C_K^5$	$[-1.0, 1.0] \cdot 10^{-14}$	$10 \cdot 10^3$	
LL	$\mathrm{Im}C_K^1$	$[-4.4, 2.8] \cdot 10^{-15}$	$1.5 \cdot 10^4$	
	$\mathrm{Im}C_K^2$	$[-5.1, 9.3] \cdot 10^{-17}$	$10 \cdot 10^4$	
~~CP~~	$\mathrm{Im}C_K^3$	$[-3.1, 1.7] \cdot 10^{-16}$	$5.7 \cdot 10^4$	
LR	$\mathrm{Im}C_K^4$	$[-1.8, 0.9] \cdot 10^{-17}$	$24 \cdot 10^4$	← !
	$\mathrm{Im}C_K^5$	$[-5.2, 2.8] \cdot 10^{-17}$	$14 \cdot 10^4$	

SM GIM mechanism



Loop suppression ~ $g^2/(4\ \mathrm{Pi})$ ~ 1/20

GIM: $\sin^2\theta_C \frac{g^4}{16\pi^2}\frac{m_c^2 - m_u^2}{m_W^4}$ + only **LL**.

EWSB in RS type models (dual)

1) RS1 with Higgs on TeV brane (composite Higgs)

Gherghetta, Pomarol; Agashe, Delgado, May, Sundrum, ...

2) Gauge-Higgs unification (PGB composite Higgs with naturally small mass)

Agashe, Contino, Pomarol, ...

3) Higgsless ($v \rightarrow \infty$, technicolor)

Csaki, Grojean, Pilo, Murayama, Terning, ...

EWSB in RS type models

$y = R_{uv}$ $y = R_{ir}$

Planck brane

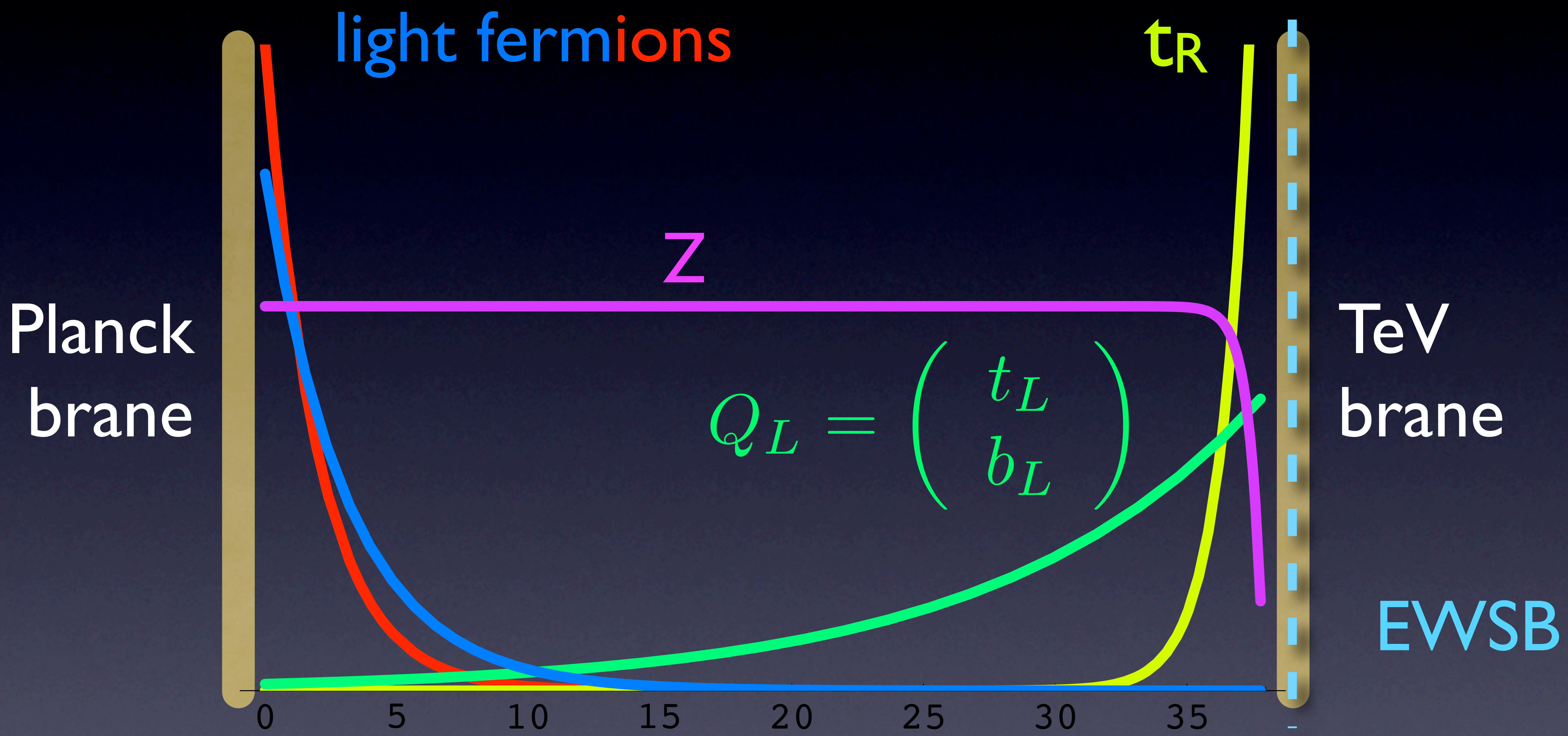
AdS_5

$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

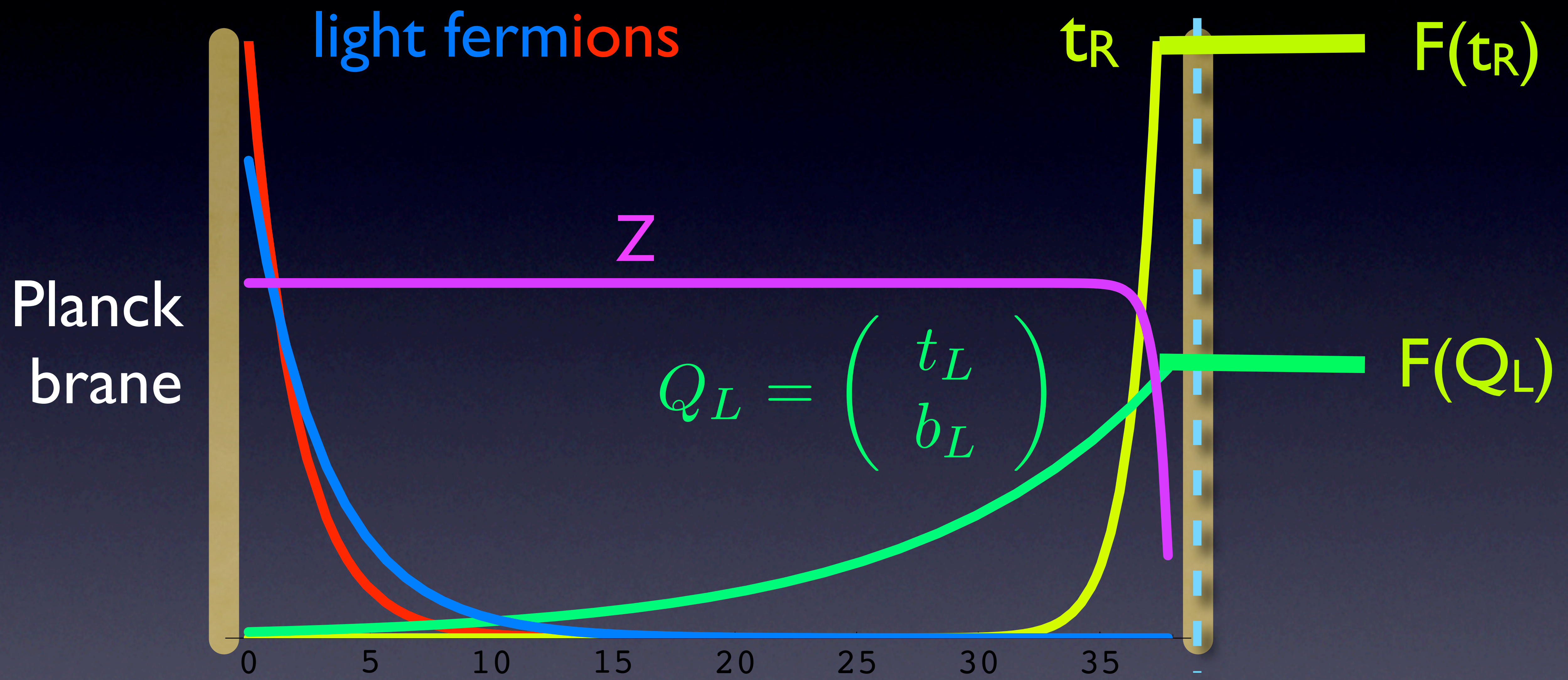
TeV brane

$SU(2)_R \times U(1)_{B-L} \rightarrow U(1)_Y$ $SU(2)_L \times SU(2)_R \rightarrow SU(2)_D$

RS GIM and split fermions



RS GIM and split fermions



F = wave function overlap @ IR

RS GIM and split fermions

Arkani-Hamed, Schmaltz; Grossman, Neubert (00
Burdman (02); Agashe, Perez, Soni (04)

Exponential localization of chiral zero modes.

Fermion mass hierarchy generated by exponentially small overlaps of fermion modes with IR localized Higgs field.

Light quarks have small FCNCs. Small enough?

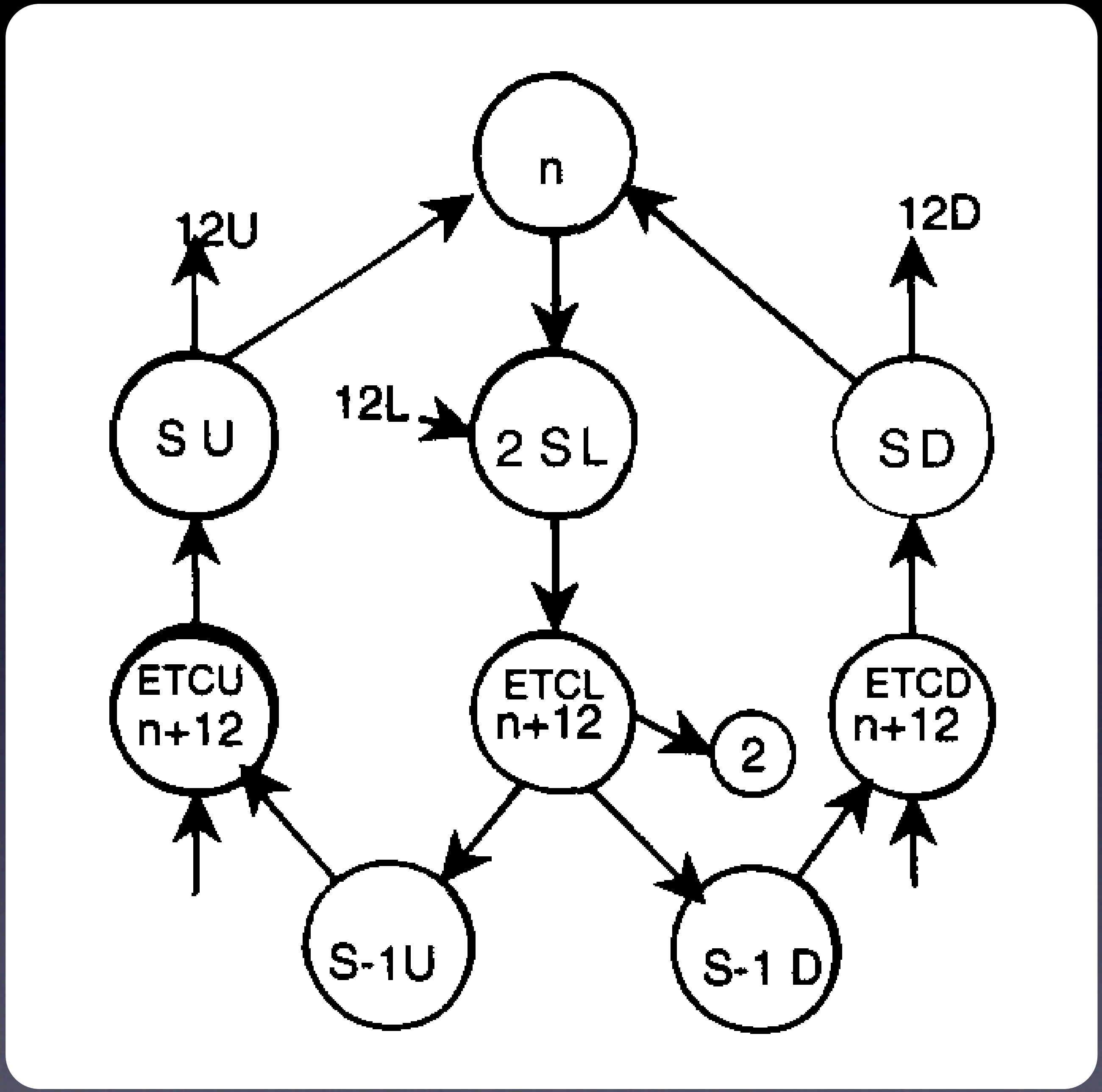
Gluon KK exchange generically leads to

$(\varepsilon_K)_{LR} \Rightarrow \Lambda_{NP} > 2 \cdot 10^5$ TeV => $m_{KK} > 9$ TeV !

Can we avoid excessively large FCNCs
by devising a **GIM** mechanism?

Technicolor with a GIM mechanism

Chivukula, Georgi '87; Chivukula, Georgi,Randall '87; Randall '93; Georgi '94



Randall '93

"[...] the model is cumbersome."

Proposal in 5D dual theory:

I. 5D GIM mechanism

(with C. Csaki, J.Galloway, G. Marandella, and J. Terning)

Flavor symmetries: RS GIM

Cacciapaglia, Csaki, Galloway, Marandella, Terning, AW

- kinetic mixings for $\mathbf{u_R}$ and $\mathbf{d_R}$ on Planck brane
- degenerate Dirac mass on TeV brane

$U(3)_Q$

$U(3)^3 \rightarrow U(3)_D$

Planck brane

bulk flavor symmetry

$U(3)_Q \times U(3)_u \times U(3)_d$

$$\sim c_L \bar{\Psi}^i_L \Psi^i_L + c_R \bar{\Psi}^i_R \Psi^i_R$$

TeV brane

$$R \; i\xi^{\alpha}_R \, \bar{\sigma}_\mu D^\mu \, \mathcal{K}^{\alpha\beta} \bar{\xi}^{\beta}_R \Big|_{z=R}$$

$$M_D R_{\rm ir} \left(\chi^i_{uL}\xi^i_{uR} + \chi^i_{dL}\xi^i_{dR}\right)\Big|_{z=R_{ir}}$$

for u_R and d_r

5D picture

$$\Psi_L = \begin{pmatrix} \chi_L \subset Q \\ \xi_L \end{pmatrix} \qquad \Psi_R = \begin{pmatrix} \chi_R \\ \xi_R \subset u, d \end{pmatrix}$$

EOMs flavor independent

$$\begin{aligned} \chi_L^\alpha &= A^\alpha f_L(m,z) & \chi_R^\alpha &= A^\alpha f_R(m,z) \\ \xi_L^\alpha &= A^\alpha g_L(m,z) & \xi_R^\alpha &= A^\alpha g_R(m,z) \end{aligned}$$

A^α determined by UV brane kinetic terms

$$R\, i\xi_R^\alpha \bar{\sigma}_\mu D^\mu \mathcal{K}^{\alpha\beta} \bar{\xi}_R^\beta \Big|_{z=R} \rightarrow \chi_R(R) = mR\, \mathcal{K}_R \xi_R(R)$$

Quark masses set eigenvalues $\mathcal{K}_R A = \frac{f_R(m,R)}{mR\, g_R(m,R)} A$

Charged currents

Parameter counting for hermitian brane kinetic mixing exactly as for **CKM** (use $U(3)_D$ below $1/R_{uv}$): reproduces CKM mixing (3 angles, 1CP),

Compare to split fermion RS flavour:
10 CP phases and 21 physical mixing angles
=>coincidence and CP problem: EDMs and ε_K.

Neutral currents

No flavor violation in tree coupling to Z, $Z^{(n)}$, $g^{(n)}$, $\gamma^{(n)}$!

Degenerate IR brane Dirac mass has to be large because of top:

→ large mixing of SM zero modes with "wrong quantum number" KK modes.

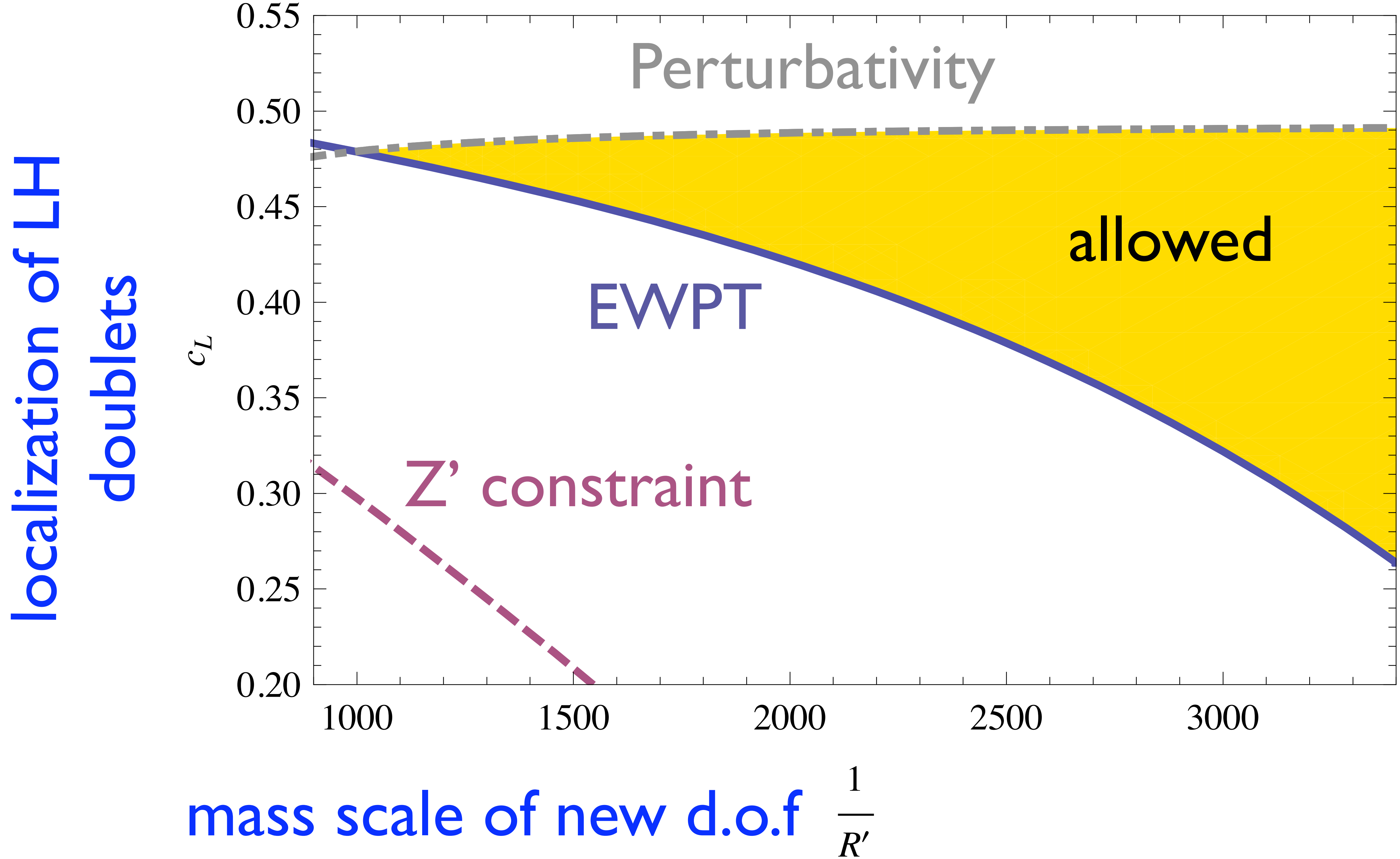
→ Large vertex correction (S, Zbb).

Nice solution proposed by Agashe, Contino, daRold, Pomarol:

Non-minimal $SU(2)_R$ representations

	$SU(2)_L$	$SU(2)_R$	$U(1)_X$
Q_L	$\square$	$\square$	$\frac{2}{3}$
t_R	1	1	$\frac{2}{3}$
b_R	1	$\square\square$	$\frac{2}{3}$

Constraints



Summary of part I

We have presented a GIM realization using flavor symmetries in realistic warped space models such as RS1 or MCHM.

We have shown how Minimal Flavor Violation (MFV) and next-to-MFV (NMFV) can be implemented.

Cacciapaglia, Csaki, Galloway, Marandella, Terning, AW, arXiv:0709.1714 [hep-ph]

II. Let the flavor shine!

with C. Csaki, Y. Grossman, G. Perez, Z. Surujon

Let the flavor shine!

GIM construction avoided excessive FCNCs but did not explain mass and mixing hierarchies.

Promote Y_u and Y_d to dynamical fields (as suggested by Fitzpatrick, Perez, Randall) which give contributions to bulk masses

"**5D MFV model**"

How can we get a full model? CFT interpretation? FCNCs?

Basic Idea: gauged flavor symmetry only broken in UV. Breaking shines into bulk and on IR only via almost marginal fields $Y_{u,d}$.

The shining

UV brane

IR brane

“**Shining of flavor in RS**”: Rattazzi, Zaffaroni ‘00

Flavor symmetry broken

$Y_u\, \underline{Q}Hu + Y_d\, \underline{Q}Hd$

flavor gauge symmetry
$U(3)_Q \times U(3)_u \times U(3)_d$

Planck brane

TeV brane

$\Phi_u : (3,3^*,1), \quad <\Phi_u> = Y_u\, (z/R)^{-\varepsilon}$

$\Phi_d : (3,1,3^*), \quad <\Phi_d> = Y_d\, (z/R)^{-\varepsilon}$

Assume: only breaking of flavor symmetry by $\Phi_{u,d.}$

$\Phi_{u,d}$ are close to marginal, other breaking irrelevant.

Main new ingredient:
higher dimensional bulk operators break bulk flavor symmetry

$$\int d^5x \left(\frac{R}{z}\right)^5 M\psi\chi \to \int d^5x \left(\frac{R}{z}\right)^5 \psi\chi \left(M + \alpha\frac{\phi^\dagger\phi}{\Lambda^2} + \ldots\right)$$

$$\to \int d^5x \left(\frac{R}{z}\right)^5 \psi\chi \left(M + \alpha\frac{Y^\dagger Y}{\Lambda^2}\left(\frac{R}{z}\right)^{2\epsilon} + \ldots\right)$$

=> small breaking effect exponentiates

$m_{4D} \sim F_q\, Y\, F_u$ with $F \sim (\mathrm{TeV}/\mathrm{Planck})^{2c-1}$

$Y_{u,d}$ give **both** IR brane Yukawa and splitting of bulk masses!

RS flavor analysis

bulk masses

$$
\begin{aligned}
c_Q &= \alpha_Q \cdot 1 + \beta_Q Y_u^\dagger Y_u + \gamma_Q Y_d^\dagger Y_d \\
c_u &= \alpha_u \cdot 1 + \beta_u Y_u Y_u^\dagger \\
c_d &= \alpha_d \cdot 1 + \gamma_d Y_d Y_d^\dagger
\end{aligned}
$$

wave-function IR brane

$$f^2 = \frac{\frac{1}{2} - c}{1 - \left(\frac{R}{R'}\right)^{1-2c}}$$

effective mass terms

$$m_{ij}^{(u)} = (Y_u)_{ij} \frac{v}{\sqrt{2}} f_{Q\,i} f_{u\,j} \qquad m_{ij}^{(d)} = (Y_d)_{ij} \frac{v}{\sqrt{2}} f_{Q\,i} f_{d\,j}$$

Assume $Y_{U,D}$ anarchic, $|Y_{U,D}|$ ~ O(1)

SM hierarchies both in masses and mixings fix
F_Q, F_u, F_d

CKM (2): $F_{Q2}/F_{Q3} \sim \theta_{23} \sim \lambda^2$,
$F_{Q1}/F_{Q3} \sim \theta_{13} \sim \lambda^3$

masses (6): $F_{u2} = m_c / (v F_{Q2})$, $F_{d1} = m_d / (v F_{Q1})$, ...

=>

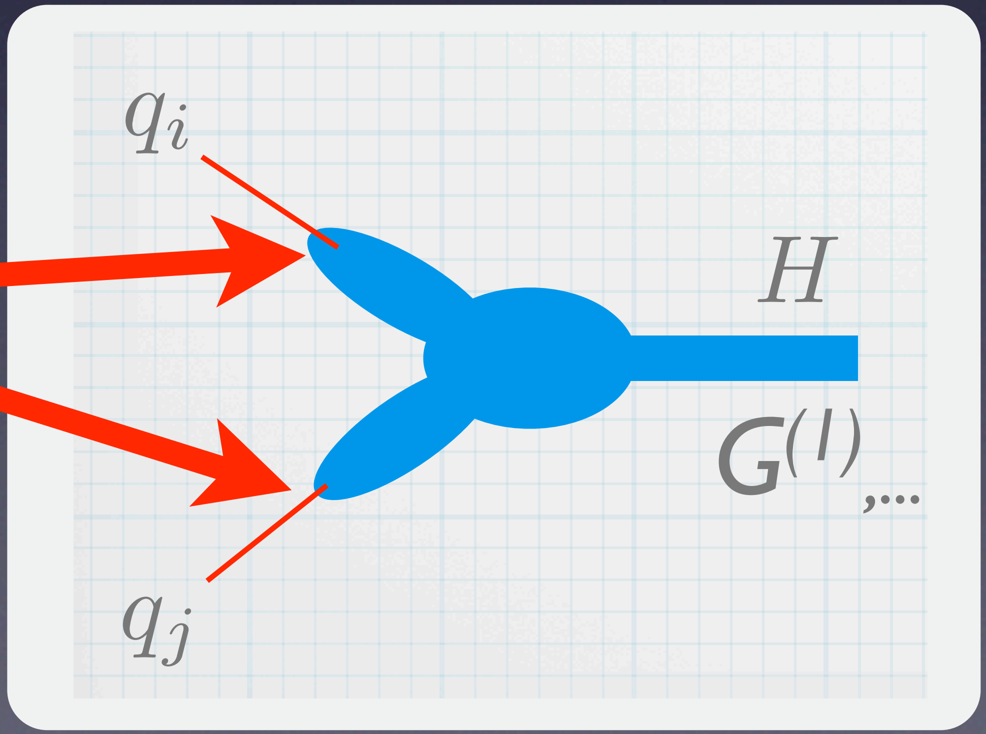
Flavor	$c_Q\,,\ f_Q$	$c_u\,,\ f_u$	$c_d\,,\ f_d$
I	$0.64, 0.002$	$0.68,\ 7\,10^{-4}$	$0.65, 2\,10^{-3}$
II	$0.59, 0.01$	$0.53, 0.06$	$0.60, 0.008$
III	$0.46,\ 0.2$	$-\ 0.06, 0.8$	$0.58, 0.02$

F_Q, F_u, $F_d \neq 1_{3x3}$ will lead to FCNCs

$$g_5 \int dz \left(\frac{R}{z}\right)^4 G^{(1)}(z) f_L(z)^2 \approx g_4 \sqrt{\log \frac{R'}{R}} \left(-\frac{1}{\log \frac{R'}{R}} + F(c)^2\right)$$

c-dependent fermion KK-gauge coupling (same F_i as in Yukawa)

in **CFT** picture
mass ~ compositeness ~ F(c)
mixing with CFT excitation



The road to the mass basis.

1) Start with 5D MFV-basis

$\mathbf{Y_U} = \mathbf{V_5}^{\mathbf{CKM}}\,\mathrm{diag}(y_u, y_c, y_t)$

$\mathbf{Y_D} = \mathrm{diag}(y_d, y_s, y_b)$

2) Diagonalize bulk masses ($\mathbf{c_Q}$, $\mathbf{c_u}$, $\mathbf{c_d}$)

$Q_L \rightarrow \mathbf{U_Q}\, Q_L$

3) Masses for down-type quarks

$$\bar{Q}_{Li} f_{Q\,i} U^{\dagger}_{Q\,ij} \mathrm{diag}(\mathrm{y_d}, \mathrm{y_s}, \mathrm{y_b})_{\mathrm{jk}} \mathrm{f_{d\,k}} \mathrm{d_{R\,k}}$$

4) rotate 4D modes into mass basis

$Q_L \rightarrow \mathbf{V_Q}\, Q_L$, $d_R \rightarrow \mathbf{V_d}\, d_R$

with

$$V_Q^{\dagger} f_Q U_Q^{\dagger} D^{(diag)} f_d V_d = \mathrm{diag}(m_d, m_s, m_b)$$

Origin of FCNCs: in the basis where the bulk masses are diagonal, the couplings to the KK gauge bosons are diagonal but **not universal**.

After rotation to the mass-basis, the coupling to the KK gluon becomes:

$$\left(\bar{Q}_L V_Q^\dagger f_Q \gamma_\mu f_Q V_Q Q_L + \bar{d}_R V_d^\dagger f_d \gamma_\mu f_d V_d d_R\right) G^{(1)\mu}$$

Dangerous 4-fermi operators are generated, especially CPV LLRR contributions.

Two limiting cases

$$c_Q = \alpha_Q \cdot 1 + r_u \beta_Q Y_u^\dagger Y_u + r_d \gamma_Q Y_d^\dagger Y_d$$

1) $r_u \to 0$, no down-quark FCNCs
(c_Q, c_d, Y_d^{eff} simultaneously diagonal)

2) $r_d \to 0$, no up-quark FCNCs
(c_Q, c_u, Y_u^{eff} simultaneously diagonal)

If $r_u \ll r_d$ then down FCNCs suppressed by r_u^2
(Fitzpatrik, Perez, Randall claim always the case)

Remember we want to reproduce

Flavor	$c_Q,\ f_Q$	$c_u,\ f_u$	$c_d,\ f_d$
I	$0.64, 0.002$	$0.68,\ 7\,10^{-4}$	$0.65, 2\,10^{-3}$
II	$0.59, 0.01$	$0.53, 0.06$	$0.60, 0.008$
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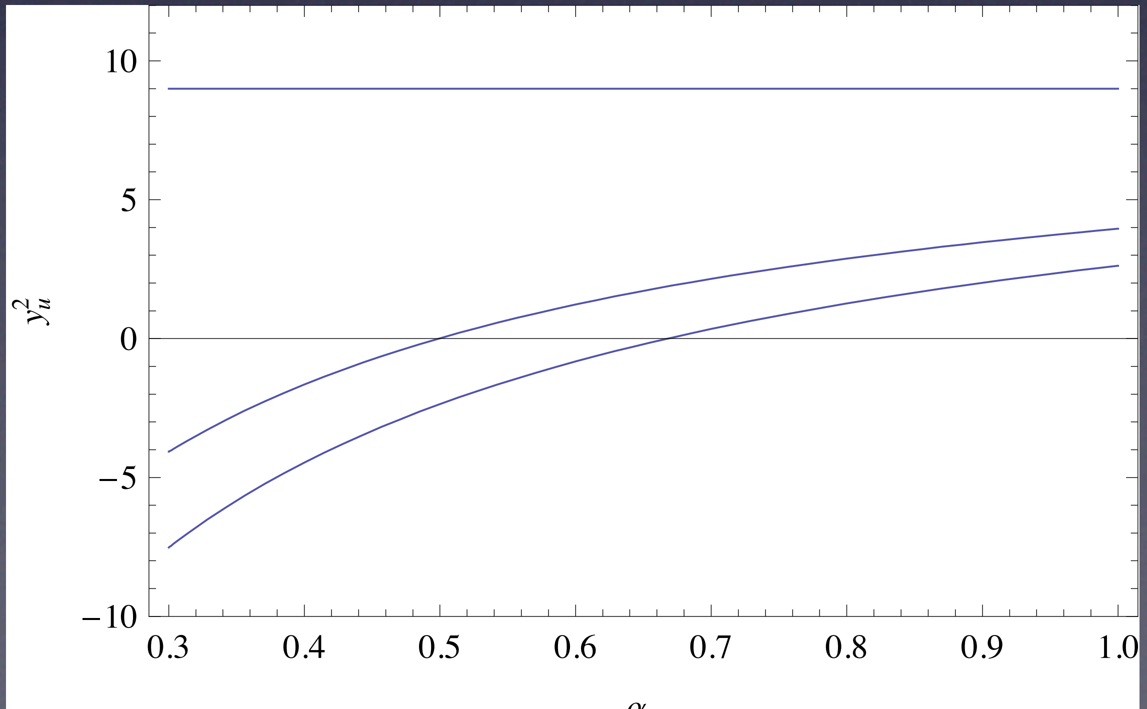
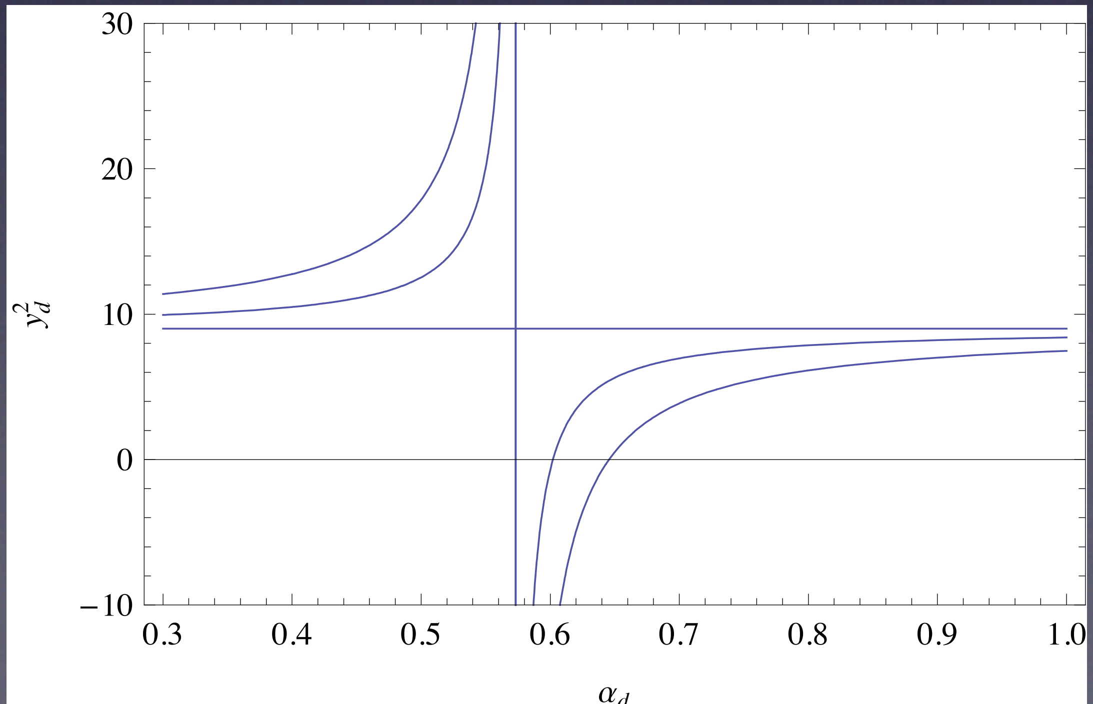
Assume perturbativity for Yukawas, we find

$\alpha_U > 0.6$, $\alpha_D > 0.7$ and $r_u > 1$ (not small)





A simple way to see $r_u > 1$

$$
\begin{aligned}
c_Q &= \alpha_Q \cdot 1 + \beta_Q Y_u^\dagger Y_u + \gamma_Q Y_d^\dagger Y_d \\
c_u &= \alpha_u \cdot 1 + \beta_u Y_u Y_u^\dagger \\
c_d &= \alpha_d \cdot 1 + \gamma_d Y_d Y_d^\dagger
\end{aligned}
$$

take trace-less part, α_i drop out

c_Q - 1/3 Tr(c_Q) = (0.11,0.06,-0.17)

c_U - 1/3 Tr(c_U) = (0.33,0.15,-0.48)

c_D - 1/3 Tr(c_D) = (0.04,-0.005,-0.033)

linear dependence

(c_Q - 1/3 Tr(c_Q)) ~ 1/3 (c_U - 1/3 Tr(c_U))

therefore find: **$r_u = \beta_Q/\gamma_Q > 1$** (contrary to F/L/R)

New feature: **flavor gauge-bosons**

($-_{uv}$ $+_{ir}$) boundary conditions: m_{KK} ~ 2.4 1/R'~ TeV

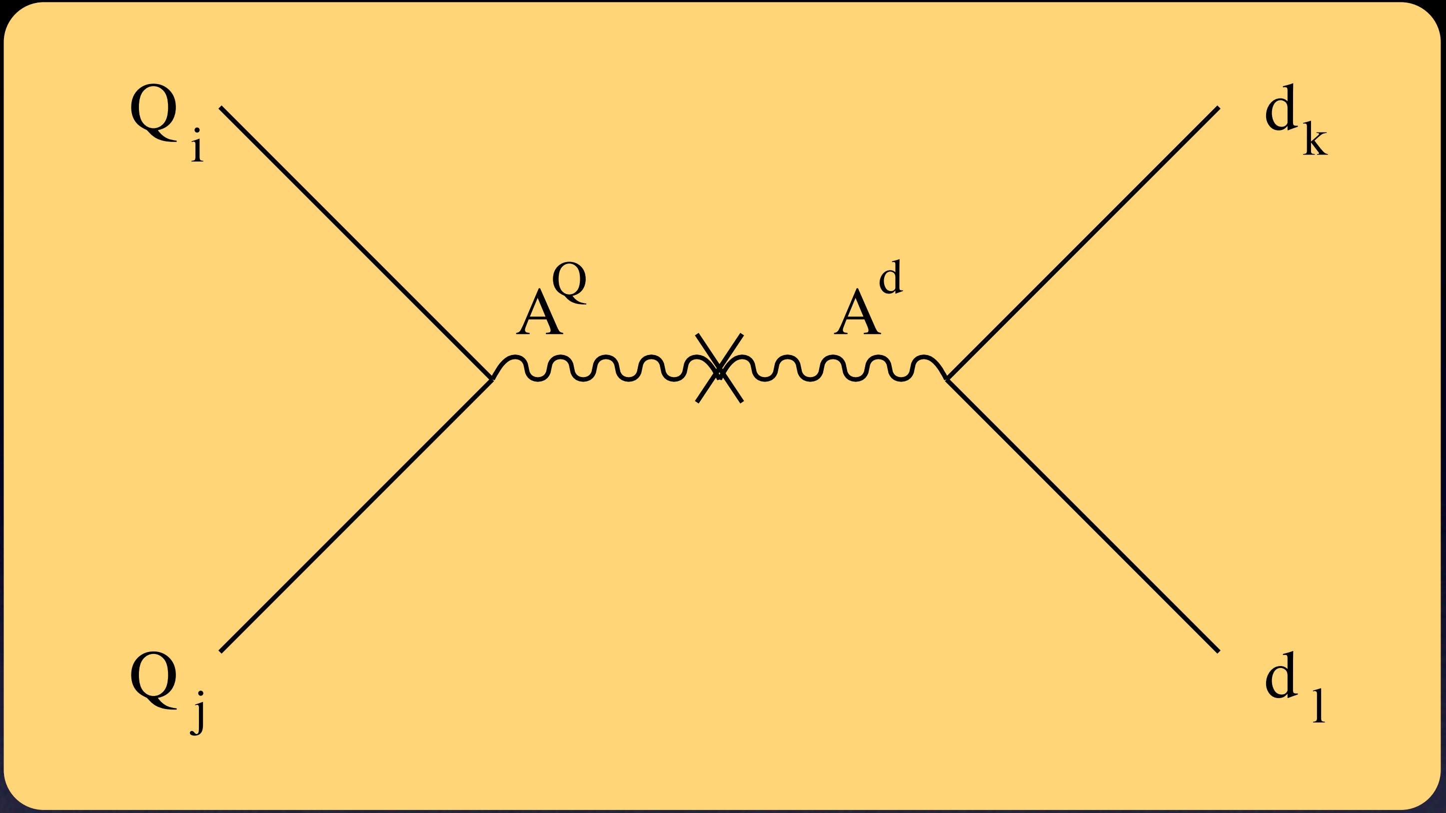
shining flavor breaking generates additional masses

$$\int dz \left(\frac{R}{z}\right)^3 \left(\mathrm{Tr}|g_5^Q A_\mu^Q y_u - g_5^u y_u A_\mu^u|^2 + \mathrm{Tr}|g_5^Q A_\mu^Q y_d - g_5^d y_d A_\mu^d|^2\right)$$

with non-diagonal mass terms

$$g_4^u g_4^Q \log\frac{R'}{R} \frac{2R^3}{R'^2 J_1(x_1)^2} \int_0^1 J_1(x_1 y)^2 \frac{dy}{y} \left[\mathrm{Tr}(T^a y_d T^b y_d^\dagger) + \mathrm{h.c.}\right] A_\mu^{a(Q)} A^{\mu b(u)}$$

FCNCs generated by U(3)^3-flavor gauge bosons



$$\sim \left[V_Q^\dagger f_Q T^a f_Q V_Q\right]_{ij} (M_Q^{-2})^{ab} \mathrm{Tr}[Y_d^\dagger T^b Y_d T^c] (M_d^{-2})^{ce} \left[V_d^\dagger f_d T^e f_d V_d\right]_{kl}$$

Fierzing the SU(3) generators reveals 3 contributions with different flavor structure but same suppression as gluon KK FCNCs.

Phenomenology: work in progress

Single CP phase leads to some correlations of CPV FCNC observables.
Flavor gauge boson contribution in FCNCs, discovery potential at LHC?

Conclusions

starting point: 5D MFV (same # parameters in Yukawas as SM, 6 masses, 3 angles, 1 CP)

strong dynamics

- o explanation of mass and mixing hierarchy
- o phenomenology very different from 4D MFV (due to exponentiation of Yukawas) resulting in a testable flavor model (1 CP phase, flavor gauge-bosons)
- o No CP problem and $(\varepsilon_K)_{LR}$ less severe
  $m_{KK} \sim$ 2-3 TeV is allowed.

THE END

FCNCs generated by U(3)^3-flavor gauge bosons II

1) [(ij) (kl)]^2

$$\frac{1}{9\Lambda^2}\left(\mathrm{Tr}(Y_d^\dagger Y_d)\right)[\bar{Q}V_Q^\dagger f_Q \gamma^\mu f_Q V_Q Q][\bar{d}V_d^\dagger f_d \gamma_\mu f_d V_d d]$$

2) [(il) (kj)]^2

$$\frac{1}{\Lambda^2 v^2}|\bar{Q} m_d^{ij} d|^2$$

3) [(il) (kj)]⊗[(ij) (kl)]

$$\frac{1}{3\Lambda^2}[\bar{Q}V_Q^\dagger f_Q \gamma^\mu f_Q V_Q Q][\bar{d}V_d^\dagger f_d Y_d^\dagger \gamma_\mu Y_d f_d V_d d] + \mathrm{h.c.}$$