Flavor models in warped extra dimensions

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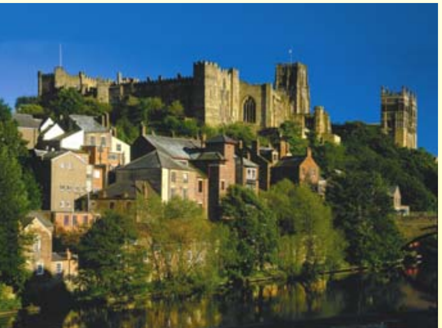

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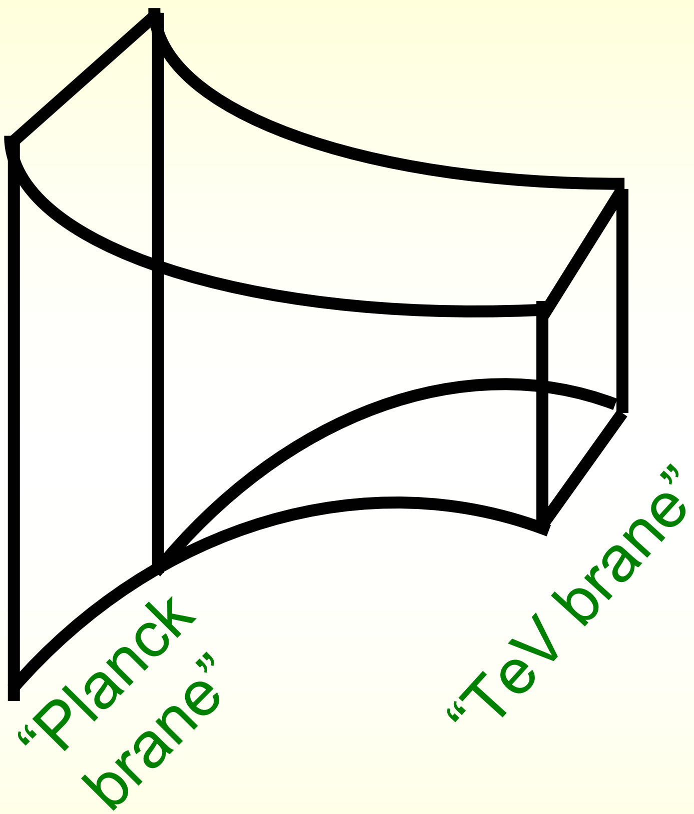
Outline

- Warped extra dimensions
- Reminder of basics of flavor
- Flavor from warped extra dimensions
- Flavor constr’s on the simplest anarchic model
- The minimal composite PGB Higgs & FCNC’s
- A GIM mechanism – but no flavor hierarchy
- Partial flavor symmetries to avoid FCNC’s
- Lepton sector
- Summary

1. Warped extra dimensions

(Randall,Sundrum; Maldacena;…)



- Metric exponentially falling

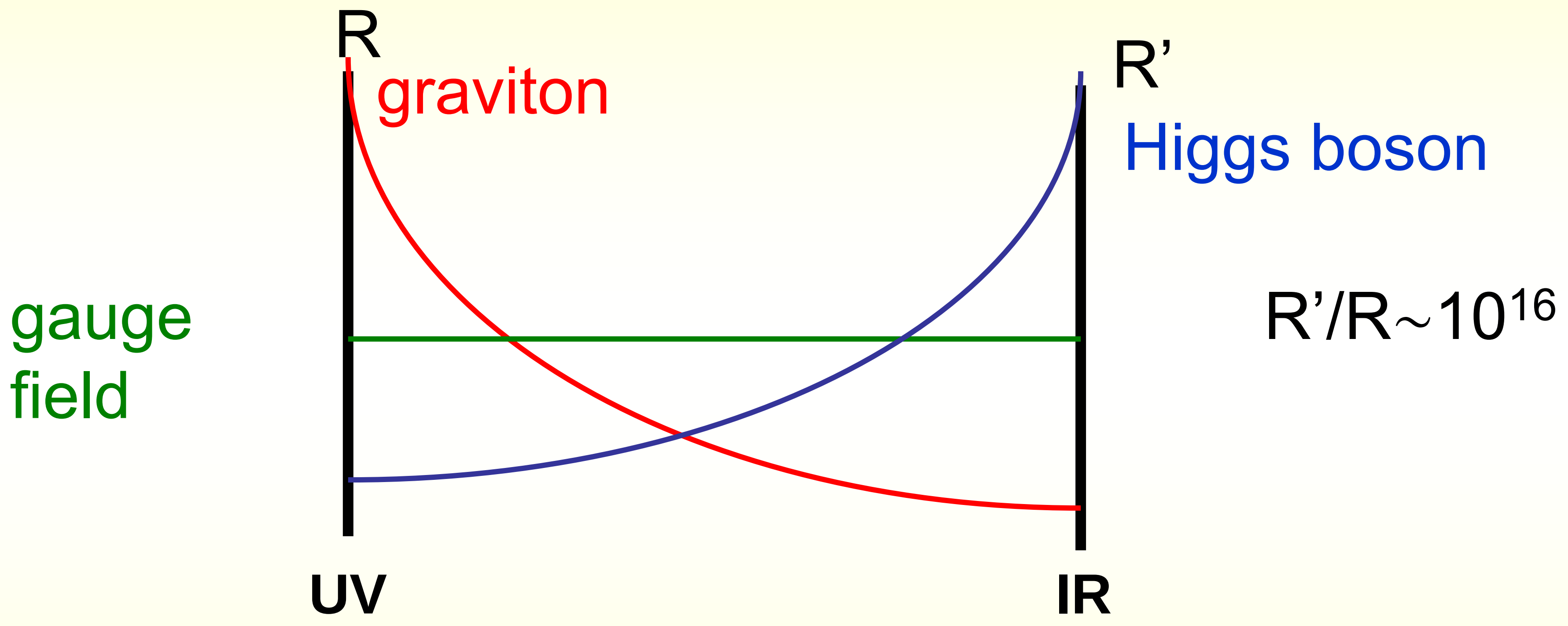
$$ds^2 = \left(\frac{R}{z}\right)^2 (dx^2 - dz^2)$$

- Mass scales very different at endpoints

- Graviton peaked at Planck

- Gauge field flat

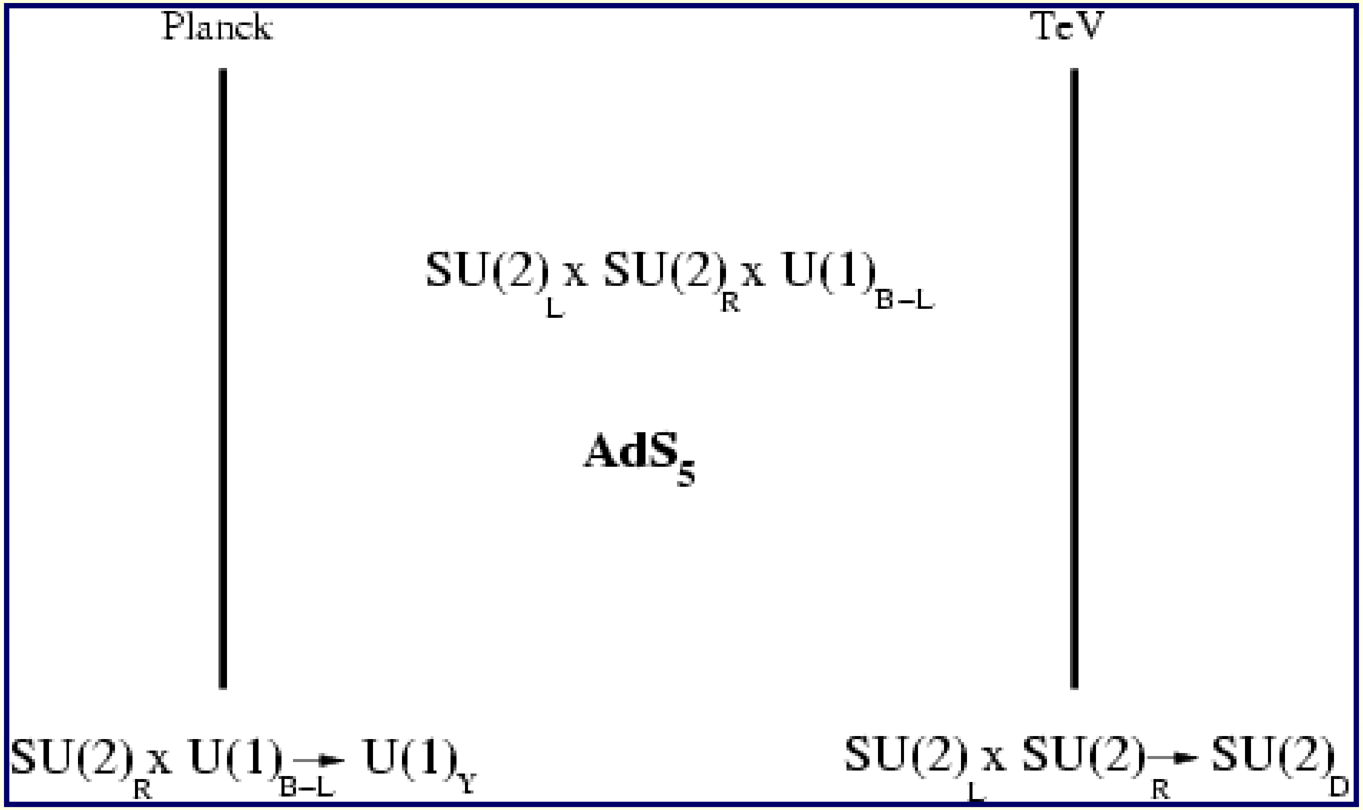
- Higgs peaked at TeV


R
graviton
R'
Higgs boson
gauge
field
$R'/R \sim 10^{16}$
UV
IR

The AdS/CFT interpretation

Bulk of AdS	CFT
z (coord. in AdS)	Energy in CFT
UV brane	UV cutoff of CFT
IR brane	Spontaneous conformal sym br.
KK modes on IR	Composites of CFT
Modes on UV	Elementary fields
Gauge field in bulk	CFT has global sym.
Gauge sym. broken UV	Global sym. not gauged
Gauge sym. unbroken	Global sym weakly gauged
Higgs on IR brane	CFT produces comp. Higgs

The realistic RS model



via BC's

via localized Higgs or BC ("higgsless")

How to get fermion masses?

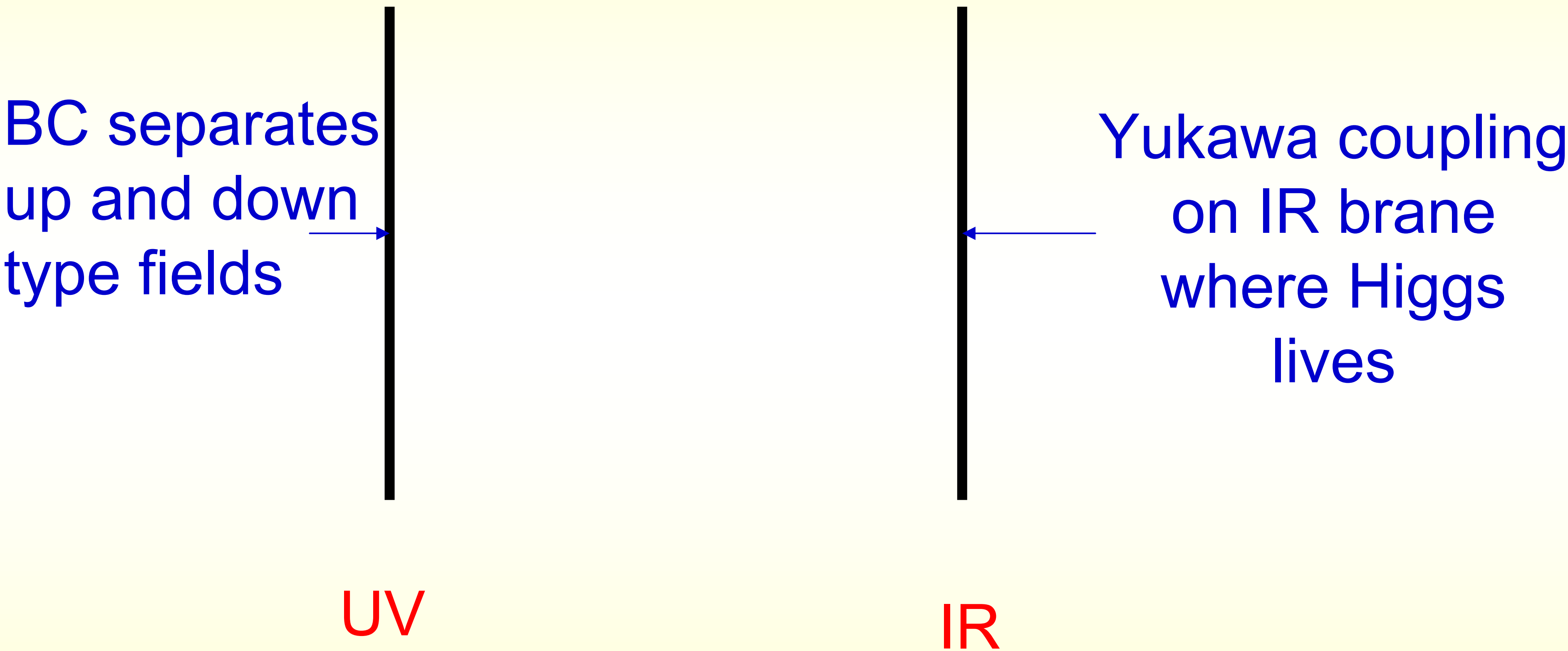
- 5D bulk fermions (Dirac fermions)

	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$
$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$\square$	1	1/6
$\begin{pmatrix} u \\ d \end{pmatrix}_R$	1	$\square$	1/6
$\begin{pmatrix} \nu \\ e \end{pmatrix}_L$	$\square$	1	$-1/2$
$\begin{pmatrix} \nu \\ e \end{pmatrix}_R$	1	$\square$	$-1/2$

- Boundary conditions to get zero modes:

$$\begin{pmatrix} \chi_{u_L} \\ \bar{\psi}_{u_L} \\ \chi_{d_L} \\ \bar{\psi}_{d_L} \end{pmatrix} \begin{matrix} + & + \\ - & - \\ + & + \\ - & - \end{matrix} \qquad \begin{pmatrix} \chi_{u_R} \\ \bar{\psi}_{u_R} \\ \chi_{d_R} \\ \bar{\psi}_{d_R} \end{pmatrix} \begin{matrix} - & - \\ + & + \\ - & - \\ + & + \end{matrix}$$

- To get massive SM fermions



To break up-down degeneracy, usually:

$$\Psi_Q \to \begin{pmatrix} \chi_{u_L} \\ \bar{\psi}_{u_L} \\ \chi_{d_L} \\ \bar{\psi}_{d_L} \end{pmatrix} \begin{matrix} + & + \\ - & - \\ + & + \\ - & - \end{matrix} \qquad \Psi_u \to \begin{pmatrix} \chi_{u_R} \\ \bar{\psi}_{u_R} \\ \chi'_{d_R} \\ \bar{\psi}'_{d_R} \end{pmatrix} \begin{matrix} - & - \\ + & + \\ + & - \\ - & + \end{matrix} \qquad \Psi_d \to \begin{pmatrix} \chi'_{u_R} \\ \bar{\psi}'_{u_R} \\ \chi_{d_R} \\ \bar{\psi}_{d_R} \end{pmatrix} \begin{matrix} + & - \\ - & + \\ - & - \\ + & + \end{matrix}$$

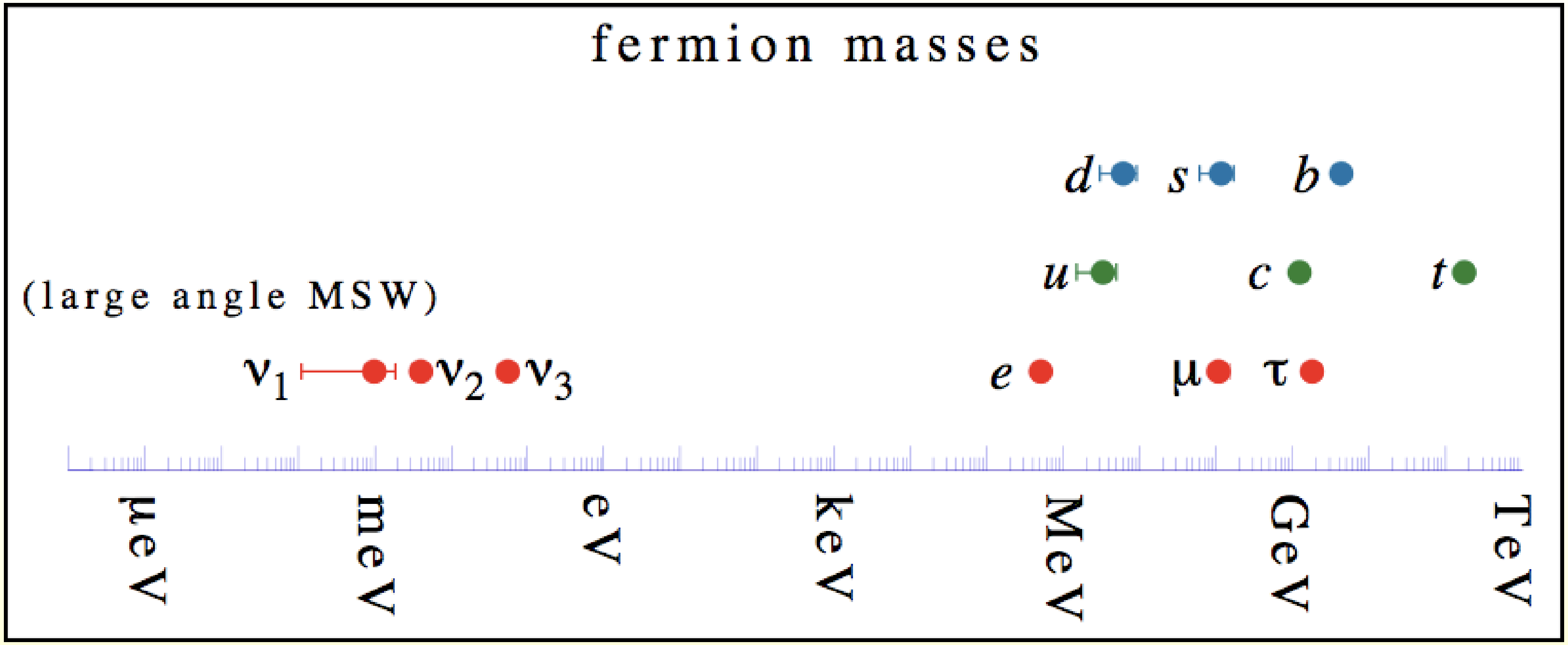
- A separate bulk field for every SM fermion.
- Fermion bulk masses are allowed:

$$\left(\frac{R}{z}\right)^4 \left(\frac{c_Q}{z}\bar{\Psi}_Q\Psi_Q + \frac{c_L}{z}\bar{\Psi}_u\Psi_u + \frac{c_d}{z}\bar{\Psi}_d\Psi_d\right)$$

- The $c_{Q,u,d}$ does not influence EXISTENCE of zero modes, but it determines the SHAPE of them
- Use c's to generate fermion mass hierarchy!

2. The Flavor Puzzle

- Fermion masses in the SM:



- In the SM: just two sources of $SU(3)^3$ flavor symmetry breaking, the Yukawa matrices

$$Y_D = (m_d, m_s, m_b)/v$$

$$Y_U = V_{CKM}^\dagger (m_u, m_c, m_t)/v$$

$$Y_D \sim (10^{-5}, 0.0005, 0.026)$$

$$Y_U \sim \begin{pmatrix} 10^{-5} & -0.002 & 0.007 + 0.004i \\ 10^{-6} & 0.007 & -0.04 + 0.0008i \\ 10^{-8} + 10^{-7}i & 0.0003 & 0.96 \end{pmatrix}$$

- This structure well confirmed
- Does not lead to much FCNC's – GIM protection

- In the SM: just two sources of $SU(3)^3$ flavor symmetry breaking, the Yukawa matrices

$$Y_D = (m_d, m_s, m_b)/v$$

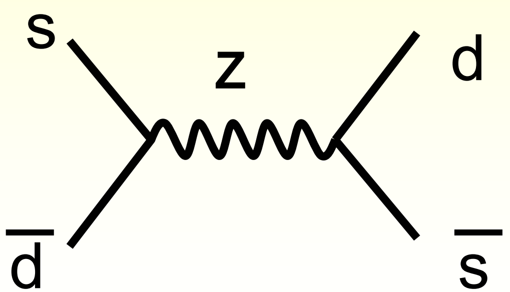
$$Y_U = V^\dagger_{CKM}(m_u, m_c, m_t)/v$$

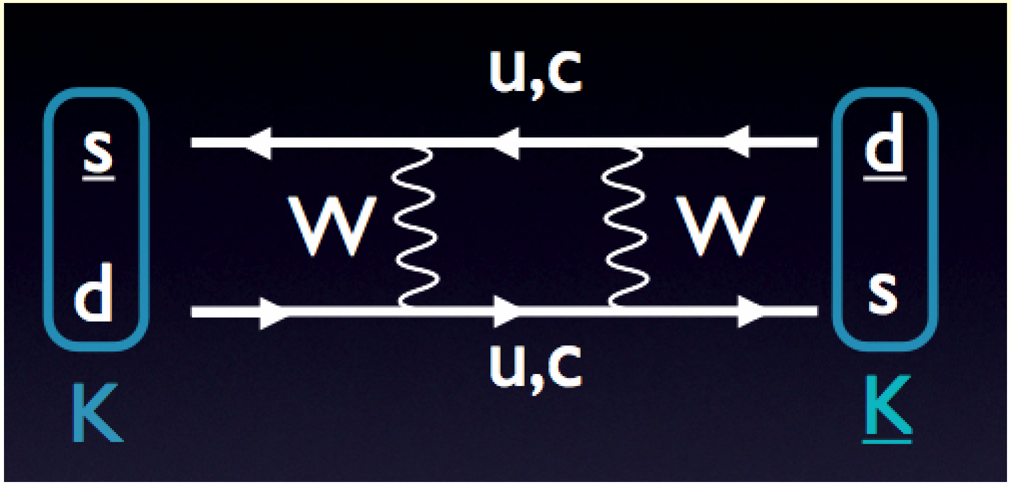
$$V_{CKM} \simeq \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & \lambda^3 \\ \lambda & 1-\frac{\lambda^2}{2} & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$\lambda = \sin\theta_C \sim 0.2$

- This structure well confirmed
- Does not lead to much FCNC's – GIM protection

The GIM mechanism





Tree-level FCNC~ $g^2/M_Z{}^2$ ~1/(100 GeV)^2 way too big!

1-loop: $(\underline{s}d)(\underline{s}d) \sim g^4/(4\pi)^2\, 1/m_W{}^2 \sim 1/(3\ \text{TeV})^2$

GIM: **GIM:** $(\underline{s}d)(\underline{s}d) \sim \sin^2\theta_C \dfrac{g^4}{16\pi^2}\dfrac{m_c^2 - m_u^2}{m_W^4} \sim 1/(10^3\ \text{TeV})^2$

Flavor hierarchy from horizontal symmetries

(Froggatt, Nielsen)

- Horizontal $U(1)_F$, flavon field Φ with $m_\Phi \sim \Lambda$, $\langle\Phi\rangle = F \ll \Lambda$
- Assume $q_\Phi = -1$
- Yukawas generated:

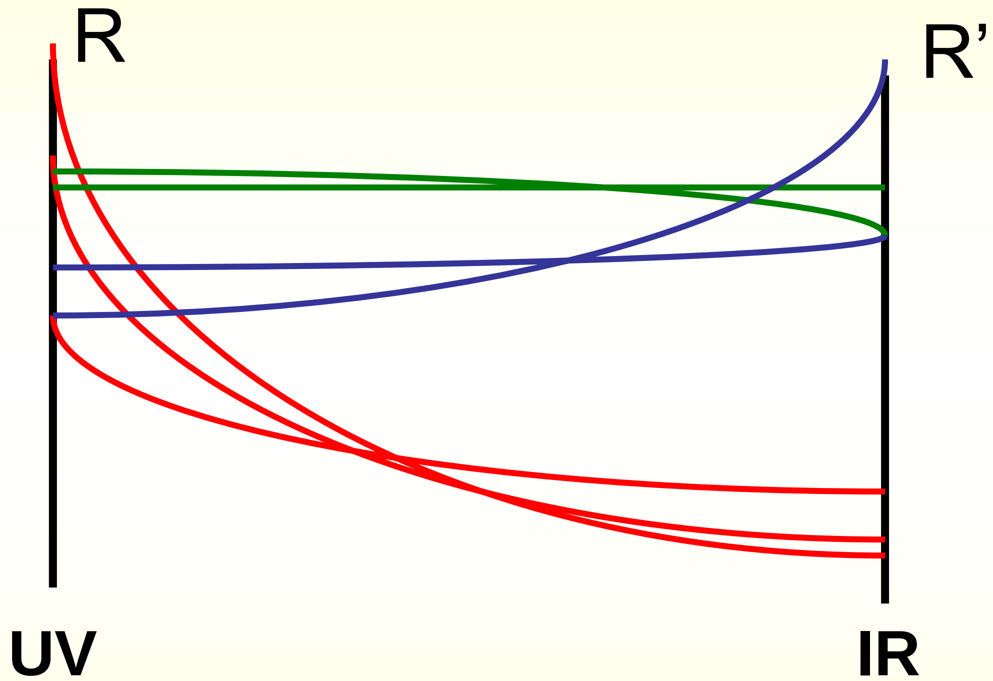
$$Y_D^{ij} \left(\frac{F}{\Lambda}\right)^{-q_i+d_j} \bar{Q}_i H d_j$$

- Effective Yukawa:

$$Y_{D,eff}^{ij} = Y_D^{ij} \left(\frac{F}{\Lambda}\right)^{-q_i+d_j}$$

3. Flavor from warped extra dim's (Hierarchies w/o symmetries)

Wavefunction overlap generates hierarchies



R'/R $\sim 10^{16}$

Light fermions
Top quark
Gauge bosons (γ, W,Z,g)

$$ds^2 = \left(\frac{R}{z}\right)^2 (dx^2 - dz^2)$$

(Arkani-Hamed, Schmaltz; Grossman, Neubert; Gherghetta, Pomarol)

- For c>1/2: fermions localized exponentially on Planck brane
- For c<1/2 fermions localized on TeV brane

- Light fermions: on UV brane, $\mathcal{O}(1)$ differences in c result in hierarchies

- Top right should be on IR brane to ensure heavy top mass

•Fermion wave function on TeV brane:

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

~ √(1-2c) for c<1/2

~√(2c-1) (R/R')$^{c-1/2}$

•Structure of Yukawa matrix on TeV brane:

$$m_u^{SM} = \frac{v}{\sqrt{2}} f_q \tilde{Y}_u f_{-u},$$
$$m_d^{SM} = \frac{v}{\sqrt{2}} f_q \tilde{Y}_d f_{-d}$$

Anarchic flavor model:

- Assume all 5D Yukawa couplings $\mathcal{O}(1)$ in natural units

- The flavor hierarchies in the masses and mixing angles all arise from the c's

- Hierarchical eigenvalues

$$(m_{u,d})_{ii} \sim \frac{v}{\sqrt{2}} Y_* f_{q_i} f_{-u_i,d_i}$$

- AND hierarchical mixing angles (Huber)

$$|U_{L\ ij}| \sim \frac{f_{q_i}}{f_{q_j}}, \quad |U_{R\ ij}| \sim \frac{f_{-u,d_i}}{f_{-u,d_j}}, \quad i \leq j$$

- Have 9 unknown c's: can exactly fit 6 masses and 3 mixing angles. Predicts hierarchical masses and mixings, but no specific relation, except that $V_{13}/V_{23} \sim V_{12}$ perfect!

- To fit V_{CKM} of the form

$$V_{CKM} \sim \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & \lambda^3 \\ \lambda & 1-\frac{\lambda^2}{2} & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

- We need for mixing angles

$$f_{q_2}/f_{q_3} \sim \lambda^2, \qquad f_{q_1}/f_{q_3} \sim \lambda^3$$

- Remaining c's fixed by mass eigenvalues

$$f_{-d_3} \sim \frac{m_b}{m_t}, \quad f_{-u_2} \sim \frac{m_c}{m_t}\frac{1}{\lambda^2}, \quad f_{-d_2} \sim \frac{m_s}{m_t}\frac{1}{\lambda^2}, \quad f_{-u_1} \sim \frac{m_u}{m_t}\frac{1}{\lambda^3}, \quad f_{-d_1} \sim \frac{m_d}{m_t}\frac{1}{\lambda^3}$$

- Good theory of flavor, but we want more: also (or mostly) want to explain hierarchy problem, scale TeV

A numerical example

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	$0.46,\ \ 0.2$	- $0.06, 0.8$	$0.58, 0.02$

4. Constraints on RS flavor from FCNC's

(Falkowski, Weiler, C.C.)

- Coupling to heavy gauge bosons in gauge basis diagonal but flavor dependent. Eg. KK gluon:

$$g_x \approx g_{s*}\left(-\frac{1}{\log R'/R} + f_x^2\,\gamma(c_x)\right)$$

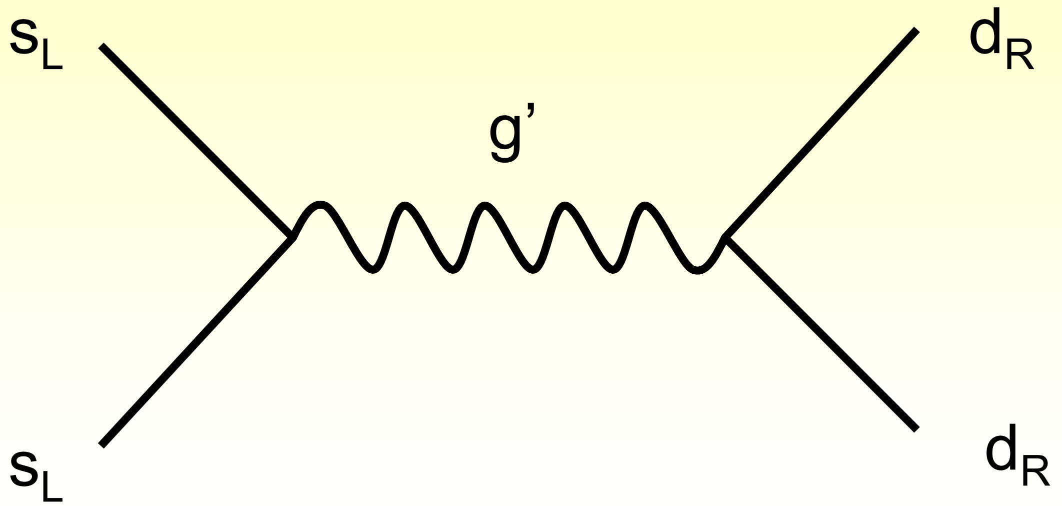
- Structure of coupling after flavor rotations

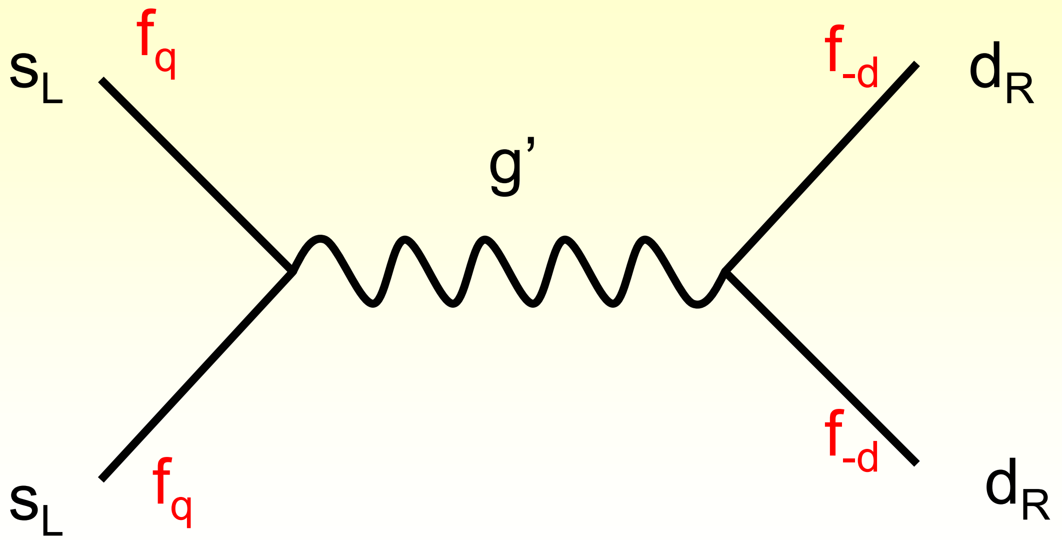
$$g^{ij}_{L,u}\bar{u}^i_L\gamma_\mu G^{\mu(1)}u^j_L + g^{ij}_{L,d}\bar{d}^i_L\gamma_\mu G^{\mu(1)}d^j_L + (L\to R)$$

Where

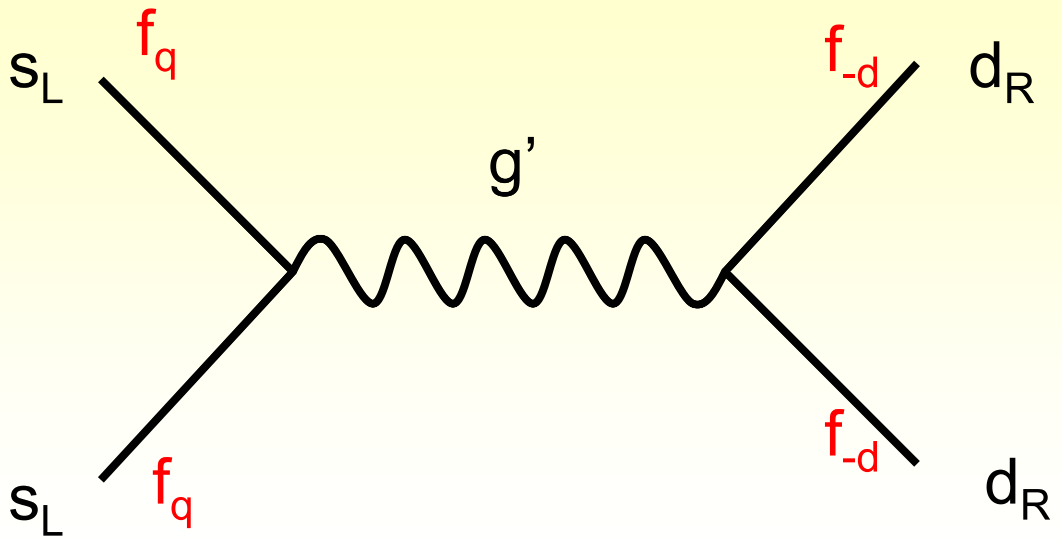
$$(g_{L,q})_{ij} \sim g_{s*} f_{q_i} f_{q_j} \quad (g_{R,u})_{ij} \sim g_{s*} f_{-u_i} f_{-u_j} \quad (g_{R,d})_{ij} \sim g_{s*} f_{-d_i} f_{-d_j}$$

- RS GIM! FCNC's suppressed by f's as well! But is enough?


s_L
s_L
g'
d_R
d_R



after rotation at every leg gets
f(c) factor suppressing operator

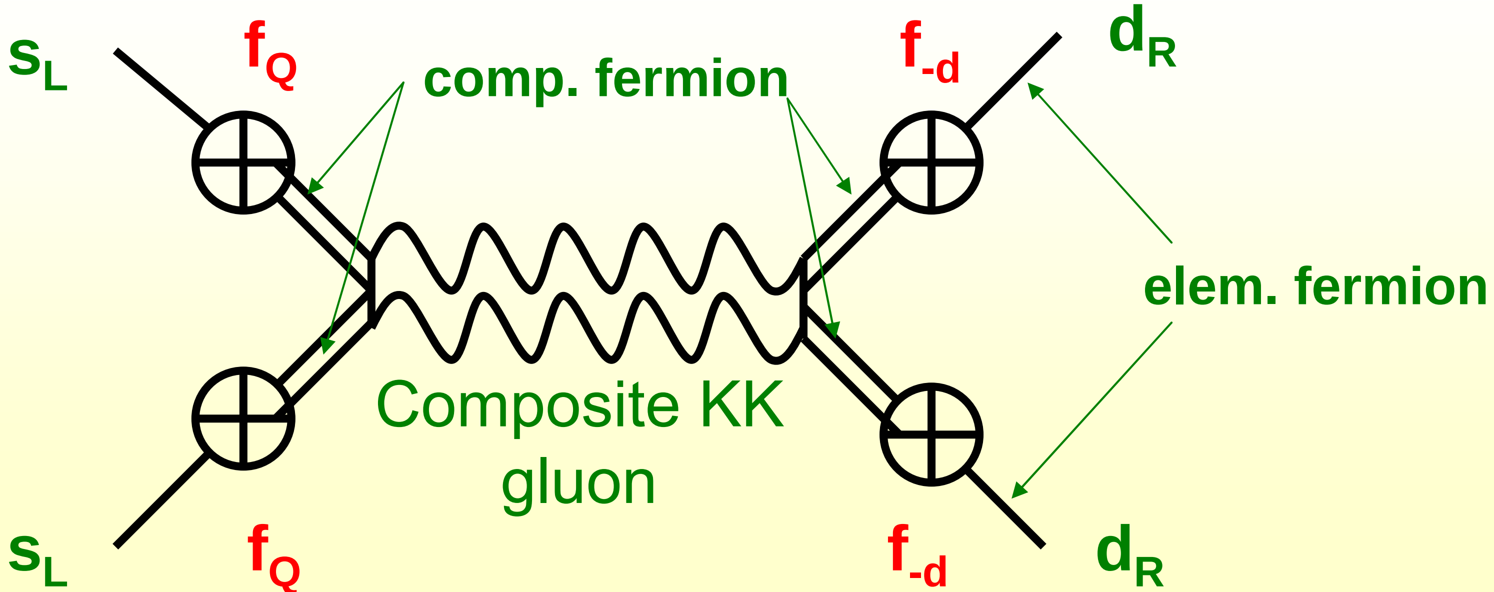


RS GIM: after rotation at every leg gets f(c) factor suppressing operator

(Ghergehtta, Pomarol; Agashe, Perez, Soni)

The holographic interpretation of RS-GIM

- Fermion on UV brane: “elementary fermion”
- Fermion on IR brane: “composite fermion”
- Light fermion: mostly elementary, f_c gives admixture
- Gluon: mixture of elementary and composite (this is how it can be flat)
- KK gluon: small elementary, large composite part



- RS-GIM makes it possible for scale to be quite low, M_{KK}~few 10 TeV
- Generic expressions for FCNC 4-Fermi op's:

$$\frac{g_{s*}^2}{M_G^2} f_{q_1} f_{q_2} f_{-d_1} f_{-d_2} \sim \frac{1}{M_G^2} \frac{g_{s*}^2}{Y_*^2} \frac{2 m_d m_s}{v^2}$$

- Since $m_d = Y_* v f_Q f_{-d}/\sqrt{2}$
- RS-GIM greatly reduces FCNC's
- But: is it enough to make it a viable model of flavor AND of the hierarchy problem at the SAME time?

•Effective 4-fermi operators generated:

$$\begin{aligned}\mathcal{H} &= \frac{1}{M_G^2}\left[\frac{1}{6}g_L^{ij}g_L^{kl}(\bar{q}_L^{i\alpha}\gamma_\mu q_{L\alpha}^j)\,(\bar{q}_L^{k\beta}\gamma^\mu q_{L\beta}^l) - g_R^{ij}g_L^{kl}\left((\bar{q}_R^{i\alpha}q_{L\alpha}^k)\,(\bar{q}_L^{l\beta}q_{R\beta}^j) - \frac{1}{3}(\bar{q}_R^{i\alpha}q_{L\beta}^l)\,(\bar{q}_L^{k\beta}q_{R\alpha}^j)\right)\right] \\ &= C^1(M_G)(\bar{q}_L^{i\alpha}\gamma_\mu q_{L\alpha}^j)\,(\bar{q}_L^{k\beta}\gamma^\mu q_{L\beta}^l) + C^4(M_G)(\bar{q}_R^{i\alpha}q_{L\alpha}^k)\,(\bar{q}_L^{l\beta}q_{R\beta}^j) + C^5(M_G)(\bar{q}_R^{i\alpha}q_{L\beta}^l)\,(\bar{q}_L^{k\beta}q_{R\alpha}^j)\end{aligned}$$

•In particular we get estimate for $C^4{}_K$:

$$C_{4K}^{RS} \sim \frac{g_{s*}^2}{M_G^2} f_{q_1} f_{q_2} f_{-d_1} f_{-d_2} \sim \frac{1}{M_G^2}\frac{g_{s*}^2}{Y_*^2}\frac{2m_d m_s}{v^2}$$

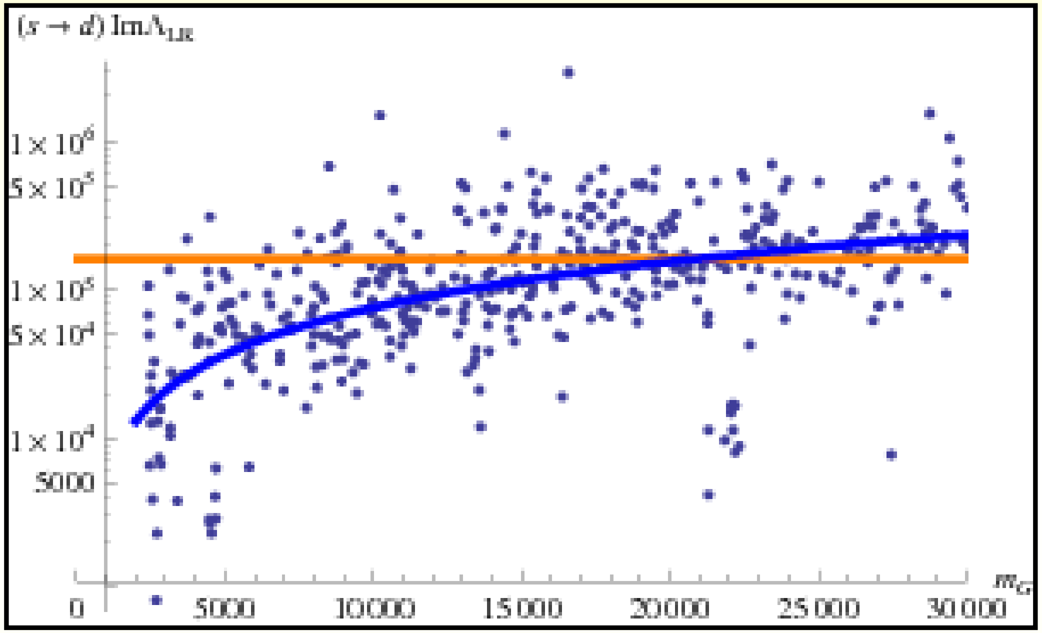
•This will have both real AND O(1) imaginary parts,
Many new physical phases will appear

Bounds vs. RS GIM suppression scales

Parameter	Limit on Λ_F (TeV)	Suppression in RS (TeV)
$\mathrm{Re}C_K^1$	$1.0 \cdot 10^3$	$\sim r/(\sqrt{6}\,\lvert V_{td}V_{ts}\rvert f_{q3}^2) = 23 \cdot 10^3$
$\mathrm{Re}C_K^4$	$12 \cdot 10^3$	$\sim r(vY_*)/(\sqrt{2\,m_d m_s}) = 22 \cdot 10^3$
$\mathrm{Re}C_K^5$	$10 \cdot 10^3$	$\sim r(vY_*)/(\sqrt{6\,m_d m_s}) = 38 \cdot 10^3$
$\mathrm{Im}C_K^1$	$15 \cdot 10^3$	$\sim r/(\sqrt{6}\,\lvert V_{td}V_{ts}\rvert f_{q3}^2) = 23 \cdot 10^3$
$\mathrm{Im}C_K^4$	$160 \cdot 10^3$	$\sim r(vY_*)/(\sqrt{2\,m_d m_s}) = 22 \cdot 10^3$
$\mathrm{Im}C_K^5$	$140 \cdot 10^3$	$\sim r(vY_*)/(\sqrt{6\,m_d m_s}) = 38 \cdot 10^3$
$\lvert C_D^1\rvert$	$1.2 \cdot 10^3$	$\sim r/(\sqrt{6}\,\lvert V_{ub}V_{cb}\rvert f_{q3}^2) = 25 \cdot 10^3$
$\lvert C_D^4\rvert$	$3.5 \cdot 10^3$	$\sim r(vY_*)/(\sqrt{2\,m_u m_c}) = 12 \cdot 10^3$
$\lvert C_D^5\rvert$	$1.4 \cdot 10^3$	$\sim r(vY_*)/(\sqrt{6\,m_u m_c}) = 21 \cdot 10^3$
$\lvert C_{B_d}^1\rvert$	$0.21 \cdot 10^3$	$\sim r/(\sqrt{6}\,\lvert V_{tb}V_{td}\rvert f_{q3}^2) = 1.2 \cdot 10^3$
$\lvert C_{B_d}^4\rvert$	$1.7 \cdot 10^3$	$\sim r(vY_*)/(\sqrt{2\,m_b m_d}) = 3.1 \cdot 10^3$
$\lvert C_{B_d}^5\rvert$	$1.3 \cdot 10^3$	$\sim r(vY_*)/(\sqrt{6\,m_b m_d}) = 5.4 \cdot 10^3$
$\lvert C_{B_s}^1\rvert$	30	$\sim r/(\sqrt{6}\,\lvert V_{tb}V_{ts}\rvert f_{q3}^2) = 270$
$\lvert C_{B_s}^4\rvert$	230	$\sim r(vY_*)/(\sqrt{2\,m_b m_s}) = 780$
$\lvert C_{B_s}^5\rvert$	150	$\sim r(vY_*)/(\sqrt{6\,m_b m_s}) = 1400$

$r = M_g/g_{s*}$

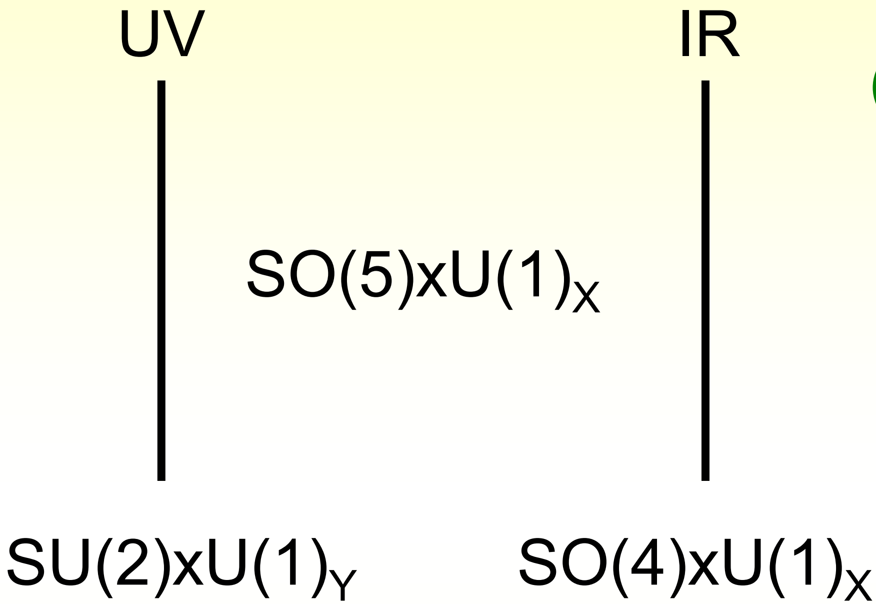
Scan over parameter space for Im C_4^K



Generically need m_G>21 TeV to satisfy constraint in ϵ_K

BUT: some points do satisfy constraint, any rationale to live at those points? ("Coincidence problem")

5. The 5D pGB Higgs model & FCNCs



(Agashe, Contino, Pomarol)

Simplest model with:

- Custodial symmetry
- A_5 zero mode with Higgs quantum #
- small correction to EWPO's
- solves little hierarchy problem

- Many possible choices for fermion matter content
- Our choice: 2x5+10 for every generation (Zbb)

$$\Psi_q = \begin{pmatrix} q_q[+,+] & \tilde{q}_q[-,+] \\ & u_q^c[-,+] \end{pmatrix} \qquad \Psi_u = \begin{pmatrix} q_u[+,-] & \tilde{q}_u[+,-] \\ & u_u^c[-,-] \end{pmatrix}$$

$$\Psi_d = \begin{pmatrix} l[+,-] & r = \begin{pmatrix} X_r[+,-] \\ u_r[+,-] \\ d_r[-,-] \end{pmatrix} \\ q_d[+,-] & \tilde{q}_d[+,-] \end{pmatrix}$$

- Plus boundary terms to generate Yukawas:

$$\mathcal{L}_{IR} = -\left(\frac{R}{R'}\right)^4 \left[\tilde{m}_u(\chi_{q_q}\psi_{q_u} + \chi_{\tilde{q}_q}\psi_{\tilde{q}_u}) + \tilde{M}_u\chi_{u_q^c}\psi_{u_u^c} + \tilde{m}_d(\chi_{q_q}\psi_{q_d} + \chi_{\tilde{q}_q}\psi_{\tilde{q}_d})\right]$$

- New effect: zero modes have kinetic mixing
- For example LH doublet lives in 3 reps

$$\chi_{q_q}(z) = \frac{1}{\sqrt{R'}}\left(\frac{z}{R}\right)^2\left(\frac{z}{R'}\right)^{-c_q} f_q$$
$$\chi_{q_u}(z) = \frac{1}{\sqrt{R'}}\left(\frac{z}{R}\right)^2\left(\frac{z}{R'}\right)^{-c_u} \tilde{m}_u^\dagger f_q$$
$$\chi_{q_d}(z) = \frac{1}{\sqrt{R'}}\left(\frac{z}{R}\right)^2\left(\frac{z}{R'}\right)^{-c_d} \tilde{m}_d^\dagger f_q$$

- Resulting kinetic mixings:

$$K_q = 1 + f_q \tilde{m}_u f_u^{-2} \tilde{m}_u^\dagger f_q + f_q \tilde{m}_d f_d^{-2} \tilde{m}_d^\dagger f_q,$$
$$K_u = 1 + f_{-u} \tilde{M}_u^\dagger f_{-q}^{-2} \tilde{M}_u f_{-u},$$
$$K_d = 1,$$

- The mass matrices now:

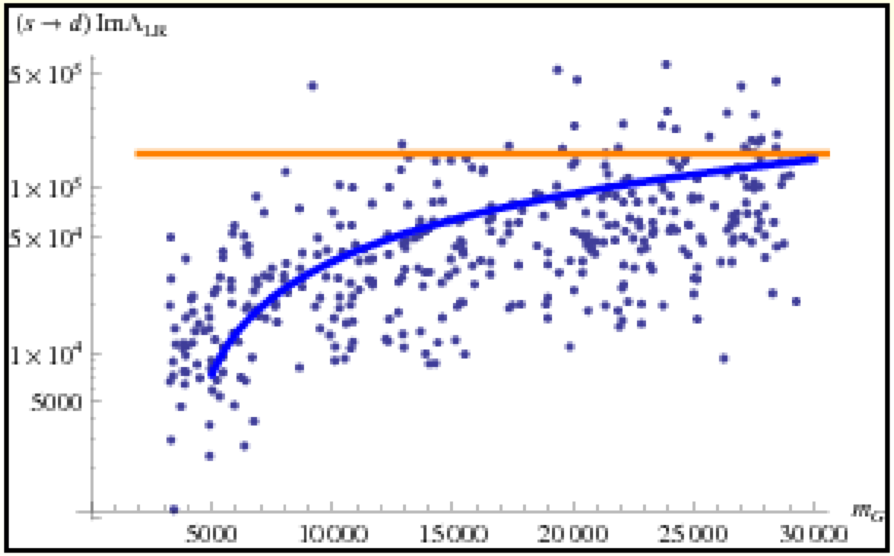
$$m_u = \frac{g_* v}{2\sqrt{2}} f_q (\tilde{m}_u - \tilde{M}_u) f_{-u}$$
$$m_d = \frac{g_* v}{2\sqrt{2}} f_q \tilde{m}_d f_{-d}$$

- But you also need to diagonalize K.
- Final estimate of strongest constraint:

$$C_K^4 \sim \frac{1}{M_G^2} \frac{g_{s*}^2}{g_*^2} \frac{8 m_d m_s}{v^2} \frac{1+\tilde{m}^2}{\tilde{m}_d^2}$$

- Y_*/g_* enhancement
- Extra factor $(1+\tilde{m}^2)/\tilde{m}_d^2$

Scan of parameter space for C_4^K



M_G>30 TeV to bring ϵ_K within bounds

Bound stronger than in generic RS

Possible ways out:

- Throw away solution to flavor, to lower KK scale make theory fully flavor invariant, GIM mechanism

- Try to keep as much of flavor explanation as possible, with some partial flavor symmetries

- Try to tweak model parameters to the limit and hope that a small region of parameters works

Is there a way of modifying the model slightly w/o running into constraints?

(Agashe, Azatov, Zhu)

- Include localized kinetic term for gluons on UV brane: g_* can be reduced (OR increased) by a factor of 2
- Using bulk Higgs peaked on IR brane instead of IR brane localized Higgs
- Using bulk Higgs there is another factor of 2 in expression of matching to Yukawa (and NDA different)
- Pushing all these to limit m_{KK} might be as low as 5 TeV
- However now loop factors only ~1/2 to 1/3
- Brane localized loop effects might be comparable

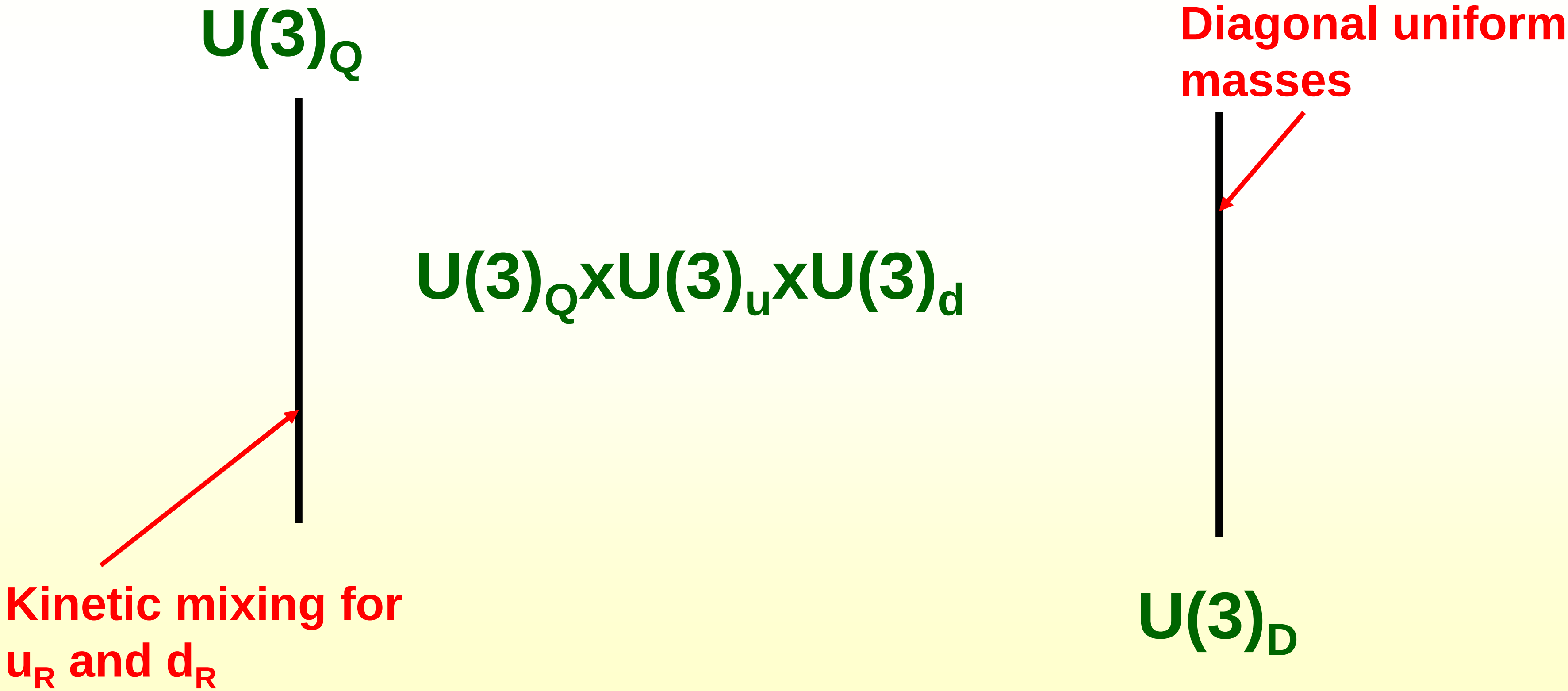
6. Models with GIM mechanism

- Give up on explanation for flavor, just try to eliminate FCNC's
- Probably too extreme for generic RS, pGBH
- Probably necessary for higgsless models

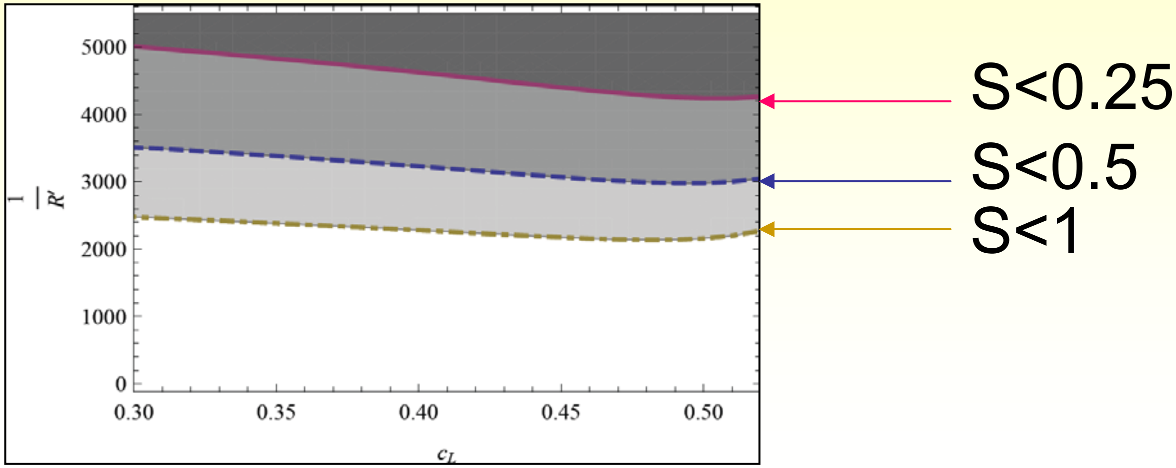
GIM mechanism in extra dimension

(Cacciapaglia, Galloway, Marandella, Terning, Weiler, CC)

- Flavor symmetry in bulk
- TeV brane masses universal
- Flavor violation only on Planck brane



•If exact GIM mechanism, S-parameter too large:



•Break flavor in u_R sector in bulk and IR, and generate mixing only in d_R sector: still no FCNC

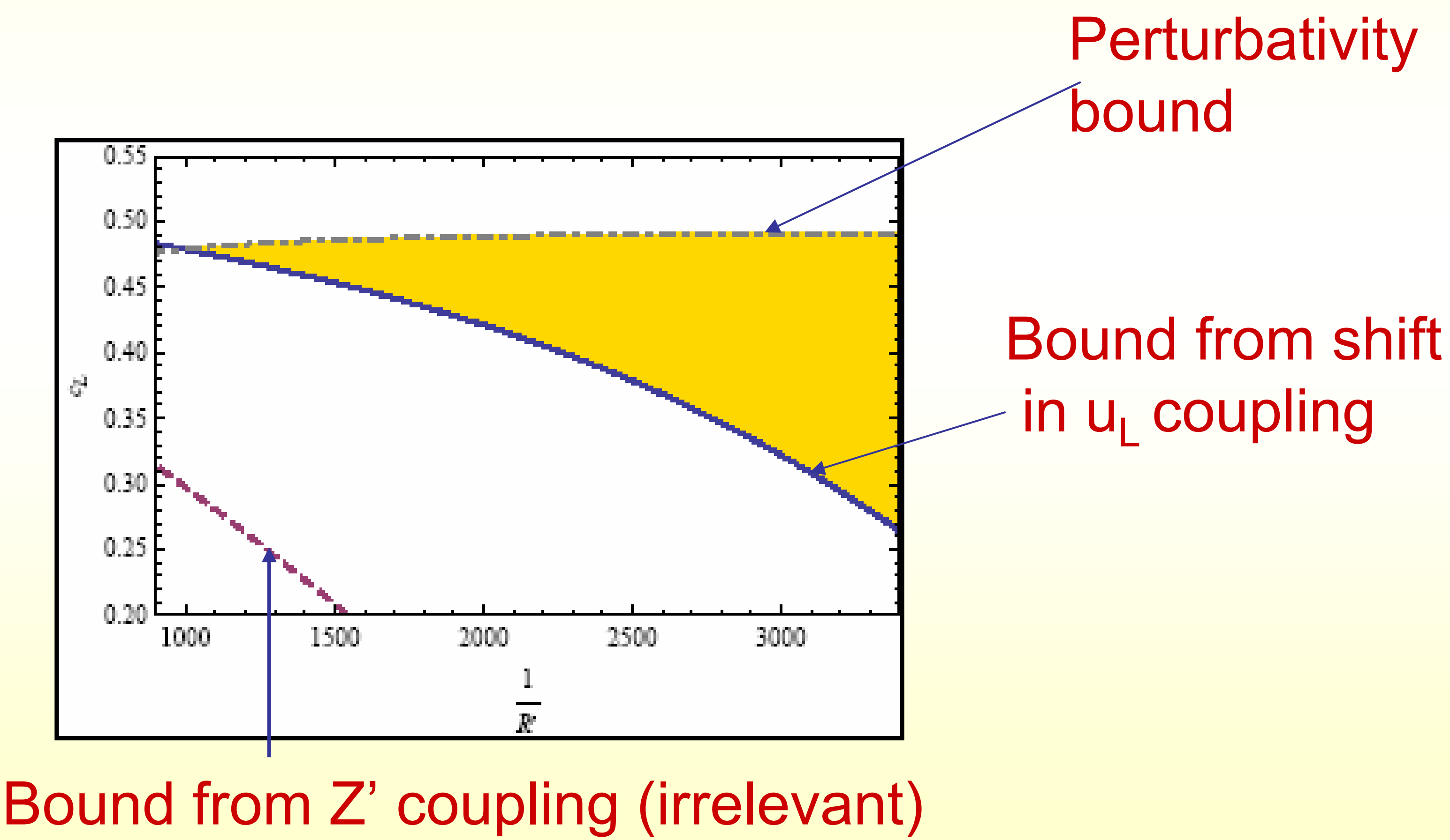
	$SU(2)_L$	$SU(2)_R$	$U(1)_X$
Q_L	$\square$	$\square$	$\frac{2}{3}$
t_R	1	1	$\frac{2}{3}$
b_R	1	$\square\square$	$\frac{2}{3}$

Reps to separate u_R from d_R

IR brane mass

$$Q_L^s \begin{pmatrix} m_u & & \\ & m_c & \\ & & m_t \end{pmatrix} t_R + m_b\, Q_L^t \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix} b_R$$

- Universal c_Q, c_d
- There will be still EWP constraints:



7. Partial flavor symmetries to avoid FCNC constraints

- Previous approach with exact GIM overkill
- Can we just avoid the strongest constraints and keep an explanation of the hierarchy?

U(1) flavor symmetries

(Falkowski, Weiler, C.C.)

- Want: eliminate FCNC in down sector
- Keep explanation of hierarchies in CKM and mass

- Want: c_Q, c_d, Y_d diagonal in same basis
- Key ingredient: two separate reps (q_u,q_d) for Q_L
- Naturally there in version of pGBH model (Zbb)

BC on UV:

$$\theta q_u - q_d = 0$$

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$$\theta q_u - q_d = 0$$

IR masses:

$$\frac{v}{\sqrt{2}} f_{q_u} Y_u f_{-u}$$

$$\frac{v}{\sqrt{2}} f_{q_d} Y_d f_{-d}$$

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BC on UV:

$$\boxed{\theta q_u - q_d = 0}$$

Forces θ to be diagonal

	$U(1)_d$ $(-,+)$	$U(1)_q$ $(+,-)$
q_u	0	$\begin{pmatrix} q_1 \\ q_2 \\ q_3 \end{pmatrix}$
u	0	0
q_d	$\begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \\ \tilde{q}_3 \end{pmatrix}$	$\begin{pmatrix} q_1 \\ q_2 \\ q_3 \end{pmatrix}$
d	$\begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \\ \tilde{q}_3 \end{pmatrix}$	0

- Want: c_Q, c_d, Y_d diagonal in same basis
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IR masses:

$$\frac{v}{\sqrt{2}} f_{q_u} Y_u f_{-u}$$

$$\frac{v}{\sqrt{2}} f_{q_d} Y_d f_{-d}$$

Y_d diagonal

	$U(1)_d$ $(-,+)$	$U(1)_q$ $(+,-)$
q_u	0	$\begin{pmatrix} q_1 \\ q_2 \\ q_3 \end{pmatrix}$
u	0	0
q_d	$\begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \\ \tilde{q}_3 \end{pmatrix}$	$\begin{pmatrix} q_1 \\ q_2 \\ q_3 \end{pmatrix}$
d	$\begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \\ \tilde{q}_3 \end{pmatrix}$	0

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- U(1) charges imply c_{qu}, c_{qd}, c_d all diagonal

- All flavor violation happens in up sector via Y_u (and c_u)

	$U(1)_d$ $(-,+)$	$U(1)_q$ $(+,-)$
q_u	0	$\begin{pmatrix} q_1 \\ q_2 \\ q_3 \end{pmatrix}$
u	0	0
q_d	$\begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \\ \tilde{q}_3 \end{pmatrix}$	$\begin{pmatrix} q_1 \\ q_2 \\ q_3 \end{pmatrix}$
d	$\begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \\ \tilde{q}_3 \end{pmatrix}$	0

- Flavor bound from charm (D-$\bar{D}$ mixing) much Weaker
- Bound from KK gluon exchange $m_G > 1$ TeV from C_4^D
- But get additional contribution from exchange of U(1) gauge bosons if they are gauged: $g_5^d < 1/300\ g_5^{QCD}$, almost like a global symmetry…

The leading constraints from D-physics

Parameter	Suppression	$f_{q_u^3} = 0.3$	$f_{q_u^3} = 1$	Bound (TeV)
$\lvert C_D^1 \rvert$	$\frac{\sqrt{6}}{g_{s*}\lambda^5 f_{q_u^3}^2} M_G$	$7.8 \cdot 10^3 M_G$	$0.7 \cdot 10^3 M_G$	$1.2 \cdot 10^3$
$\lvert \tilde{C}_D^1 \rvert$	$\frac{\sqrt{3} Y_*^2 v^2 \lambda^5 f_{q_u^3}^2}{\sqrt{2} g_{s*} m_u m_c} M_G$	$1.2 \cdot 10^3 M_G$	$1.3 \cdot 10^5 M_G$	$1.2 \cdot 10^3$
$\lvert C_D^4 \rvert$	$\frac{v Y_*}{g_{s*}\sqrt{2}\, m_u m_c} M_G$	$1.2 \cdot 10^3 M_G$	$1.2 \cdot 10^3 M_G$	$3.5 \cdot 10^3$
$\lvert C_K^1 \rvert$	$\frac{\sqrt{6}}{g_{s*}\lambda^5 f_{q_u^3}^2 \delta} M_G$	$3.0 \cdot 10^6 M_G$	$2.7 \cdot 10^5 M_G$	$1.5 \cdot 10^4$
$\lvert \tilde{C}_K^1 \rvert$	$\frac{\sqrt{3} Y_*^2 v^2}{\sqrt{2} g_{s*} m_d m_s \lambda \delta} M_G$	$1.5 \cdot 10^{10} M_G$	$1.5 \cdot 10^{10} M_G$	$1.5 \cdot 10^4$
$\lvert C_K^4 \rvert$	$\frac{Y_* v}{g_{s*}\sqrt{2 m_d m_s}\lambda^3 f_{q_u^3} \delta} M_G$	$2.8 \cdot 10^7 M_G$	$8.5 \cdot 10^6 M_G$	$1.6 \cdot 10^5$

g_*=6 and boundary kinetic mixing of NDA size assumed

Alignment via shining

(Grossman, Perez, Surujon, Weiler, C.C. in progress)

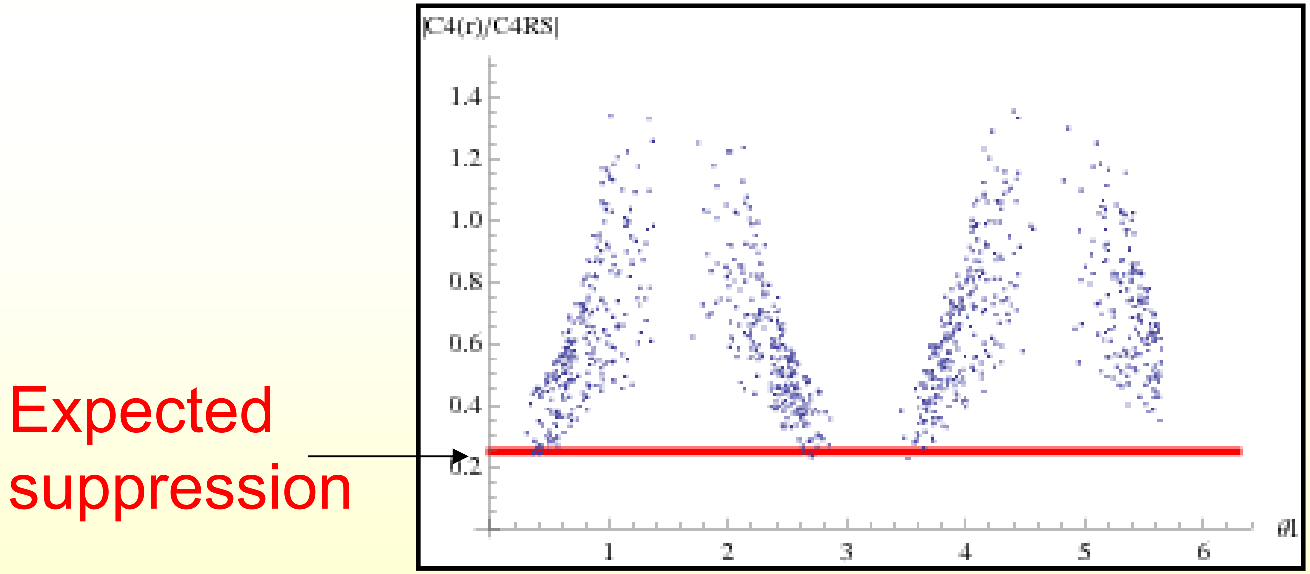
- Would like c_Q, c_d, Y_d to be aligned (like before)
- Assume hiearchy in c's and brane Yukawa have same origin: scalar fields Y_u, Y_d shining UV brane flavor violation

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

- To remove constraint would need $\beta_Q \to 0$

(Fitzpatrick, Perez, Randall)

- However, $r=\beta_Q/\gamma_Q$ ~0.3 not enough to suppress FCNC
- Real suppression is by misalignment of direction In flavor space
- Scan over 5D mixing angles keeping r=0.25 fixed:



- Need r=0 solution. Actually possible!

• Possible alignments that suppress LR FCNC in down sector

1. $c_Q \sim Y_d^\dagger Y_d$
   $c_d \sim Y_d^\dagger Y_d$

•Possible alignments that suppress LR FCNC in down sector

1. $c_Q \sim Y_d^{\dagger} Y_d$ $\quad c_Q = (0.62, 0.58, 0.43) = 0.428 + 0.02\, Y_d^{\dagger} Y_d$

   $c_d \sim Y_d^{\dagger} Y_d$ $\quad c_d = (0.66, 0.62, 0.51) = 0.51 + 0.015\, Y_d Y_d^{\dagger}$

   $Y_d = \mathrm{diag}(3.2, 2.8, 0.27)$

•Possible alignments that suppress LR FCNC in down sector

1. $c_Q \sim Y_d^\dagger Y_d$ $\quad c_Q=(0.62,0.58,0.43)=0.428+0.02\, Y_d^\dagger Y_d$

$c_d \sim Y_d^\dagger Y_d$ $\quad c_d=(0.66,0.62,0.51)=0.51+0.015\, Y_d Y_d^\dagger$

$Y_d=\mathrm{diag}(3.2,2.8,0.27)$

•Bulk $SU(3)_Q x SU(3)_d$ symmetry, Y_d in bulk Y_u on IR brane. No d_R FCNC at all

•Conceptually clear, reasonable numerical solution with small tuning

•Possible alignments that suppress LR FCNC in down sector

2. $c_Q \sim Y_d$
   $c_d \sim Y_d$ or ~ 1

$c_Q = (0.62, 0.58, 0.43)$
$c_d = 0.56$
$Y_d = \mathrm{diag}(0.22, 0.39, 0.95)$

- Possible alignments that suppress LR FCNC in down sector

2. $c_Q \sim Y_d$
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$c_Q=(0.62,0.58,0.43)$
$c_d=0.56$
$Y_d=\mathrm{diag}(0.22,0.39,0.95)$

- $SU(3)_{Q+d}$ in bulk, with bulk adjoint $Y_d \sim 8$
- No symmetry for u_R in bulk. Y_u on IR brane
- Numerically works very well, but why does $Y_u^\dagger Y_u$ feed into d_R kinetic term?

8. The lepton sector

(Delaunay, Grojean, Grossman, C.C.)

- Anarchy: hierarchical masses AND mixing angles
- Neutrino mixing angles LARGE, not hierarchical
- Suggests need flavor symmetry to protect angles
- This symmetry will also protect from LFV's
- Use most popular A_4 flavor symmetry for getting tri-bimaximal neutrino mixing

$SU(2)_L x SU(2)_R x U(1)_{B-L} x$
$x\ A_4\ x\ Z_2$

$A_4 \rightarrow Z_2$ $A_4 \rightarrow Z_3$

$$\Psi_L = \begin{pmatrix} L & [+,+] \end{pmatrix} \quad \Psi_{e,\mu,\tau} = \begin{pmatrix} \tilde{\nu}_{e,\mu,\tau} & [+,-] \\ e,\mu,\tau & [-,-] \end{pmatrix} \quad \Psi_\nu = \begin{pmatrix} \nu & [-,-] \\ \tilde{l} & [+,-] \end{pmatrix}$$

Matter content

	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$	$A4$	Z_2
Ψ_L	$\square$	1	-1	3	$-$
$\Psi_{e,\mu,\tau}$	1	$\square$	-1	$1, 1', 1''$	$+$
Ψ_ν	1	$\square$	-1	3	$-$
$H \ (IR)$	$\square$	$\square$	0	1	$+$
$\phi' \ (IR)$	1	1	0	3	$-$
$\phi \ (UV)$	1	1	0	3	$+$

Equal c's!

A_4 breaking VEV's

$$\langle \phi' \rangle = (v', v', v'),$$

$$\langle \phi \rangle = (v, 0, 0),$$

Yukawa terms on the branes:

- On UV: universal+A_4 breaking Majorana mass

$$\mathcal{L}_{UV} = -\frac{M}{2\Lambda}\psi_\nu\psi_\nu - x_\nu\frac{\phi}{2\Lambda}\psi_\nu\psi_\nu + \text{h.c.} + \cdots$$

- On IR brane: A_4 sym. neutrino mass+A_4 breaking charged lepton masses

$$\begin{aligned}\mathcal{L}_{IR} \;=\; & -\frac{y_\nu}{\Lambda'}\overline{\Psi}_L H\Psi_\nu - \frac{y_e}{\Lambda'^2}\left(\overline{\Psi}_L\phi'\right)H\Psi_e \\ & -\frac{y_\mu}{\Lambda'^2}\left(\overline{\Psi}_L\phi'\right)'H\Psi_\mu - \frac{y_\tau}{\Lambda'^2}\left(\overline{\Psi}_L\phi'\right)''H\Psi_\tau + \text{h.c.} + \cdots,\end{aligned}$$

Charged lepton mass matrix

$$\mathcal{M}_{\mathrm{D}}^{\mathrm{e}} = f_L \frac{v_H v'}{\sqrt{2} R' \Lambda'^2} \begin{pmatrix} y_e f_{-e} & y_\mu f_{-\mu} & y_\tau f_{-\tau} \\ y_e f_{-e} & \omega y_\mu f_{-\mu} & \omega^2 y_\tau f_{-\tau} \\ y_e f_{-e} & \omega^2 y_\mu f_{-\mu} & \omega y_\tau f_{-\tau} \end{pmatrix}$$

Neutrino Dirac mass

$$\mathcal{M}_{\mathrm{D}}^{\nu} = y_\nu f_L f_{-\nu} \frac{v_H}{\sqrt{2} R' \Lambda'} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Neutrino Majorana mass matrix

$$\mathcal{M}_{\mathrm{M}}^{\nu} = F_{-\nu}^2 R^{-1} \begin{pmatrix} \epsilon_s & 0 & 0 \\ 0 & \epsilon_s & \epsilon_t \\ 0 & \epsilon_t & \epsilon_s \end{pmatrix}$$

$\epsilon_s = M/\Lambda$, $\epsilon_t = x_\nu v/\Lambda$

See-saw mass after integrating out heavy RHν's:

$$\begin{aligned} \tilde{\mathcal{M}}^{\nu}_{\mathbf{M}} &\equiv -\mathcal{M}^{\nu}_{\mathbf{D}} \cdot \left(\mathcal{M}^{\nu}_{\mathbf{M}}\right)^{-1} \cdot \left(\mathcal{M}^{\nu}_{\mathbf{D}}\right)^{T} \\ &= -y_{\nu}^{2} \frac{v_H^2 R}{2\Lambda'^2 R'^2} \frac{f_L^2 f_{-\nu}^2}{F_{-\nu}^2} \begin{pmatrix} 1/\epsilon_s & 0 & 0 \\ 0 & \epsilon_s/\Delta & -\epsilon_t/\Delta \\ 0 & -\epsilon_t/\Delta & \epsilon_s/\Delta \end{pmatrix} \end{aligned}$$

As usual in A_4 (the MAIN feature of these models): charged lepton matrix diagonalized from L by V

$$\mathbf{V} = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & \omega^2 & \omega \\ 1 & \omega & \omega^2 \end{pmatrix}$$

Neutrino masses diagonalized by U_{HPS}:

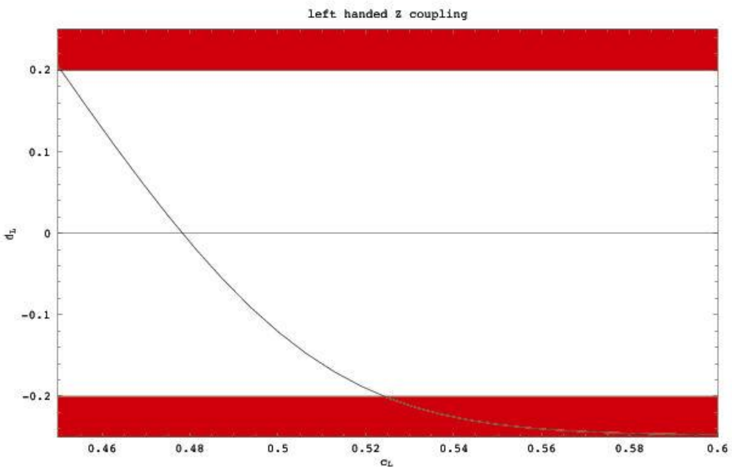
$$U_{HPS} = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

Tri-bimaximal neutrino mixing:

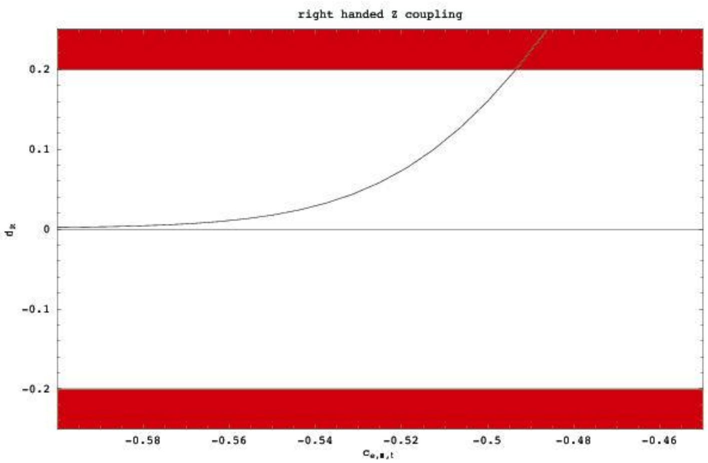
$$\theta_{13} = 0, \quad \sin^2(2\theta_{12}) = 8/9 \quad \theta_{23} = \pi/4$$

Fixing neutrino masses fixes parameters in RS

The bounds from EWPO’s

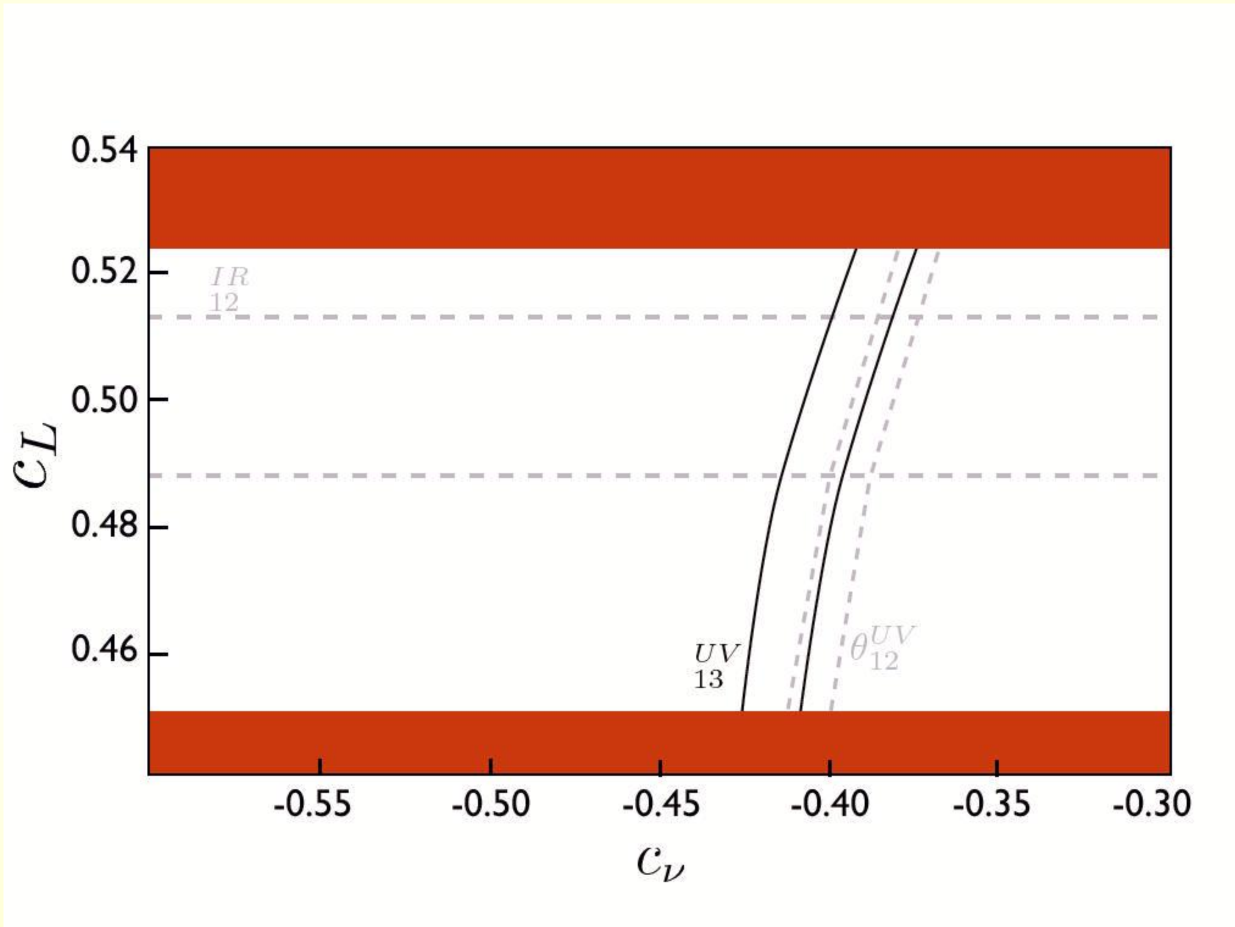


ZLL coupling



ZRR coupling

Effect of higher dimensional operators: can get away from exact tri-bimaximal mixing



dashed line: $\sin^2 2\theta_{12}$=0.9,0.95

solide line: $\sin^2 2\theta_{13}$=0.01,0.19

New ingredients RS can add to A_4 constructions

- Alignment of VEV's solved, live on separate branes

- Cutoff well defined, effects of higher dimensional ops under control

- Charged lepton hierarchy explained in the RS way

- LFV will be completely absent at tree level

Another possible approach to leptons

(Agashe, Okui, Sundrum)

- The overlap integrals with a BULK Higgs may be dominated either at IR brane (as usual) OR at UV brane if localization of fermions is very strong on UV

$$\int_0^a Y_{5D,ij}\, e^{-(M_{L_i}+M_{R_i})y+M_H(y-a)}$$

$(M_{L_i} + M_{R_j}) > M_H$ → $\tilde{Y}_{0,ij}\, e^{-M_H a}$

$(M_{L_i} + M_{R_j}) < M_H$ → $\tilde{Y}_{a,ij}\, e^{-(M_{L_i}+M_{R_j})a}$

- Integral could be dominated at UV brane
- Yukawa still exponentially suppressed, but mixings $\mathcal{O}(1)$!

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•Lepton flavor can also be addressed