Flavor Models in Warped Extra Dimensions

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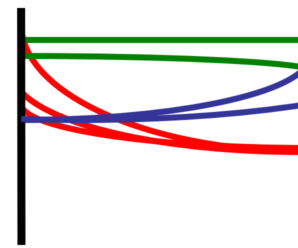
2008 Aspen Winter Conference



GIM: hep-ph 0709:1714 with G. Cacciapaglia, J.Galloway, G. Marandella, J. Terning, A. Weiler

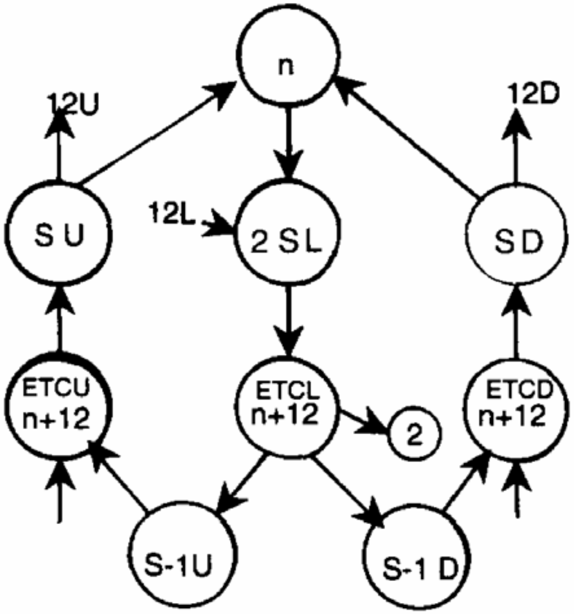
Shining: in progress with Y. Grossman, G. Perez, Z. Surujon and A. Weiler

1. GIM Mechanism in Extra Dimension

G.Cacciapaglia, J.Galloway,
G.Marandella, J.Terning, A.Weiler, C.C.

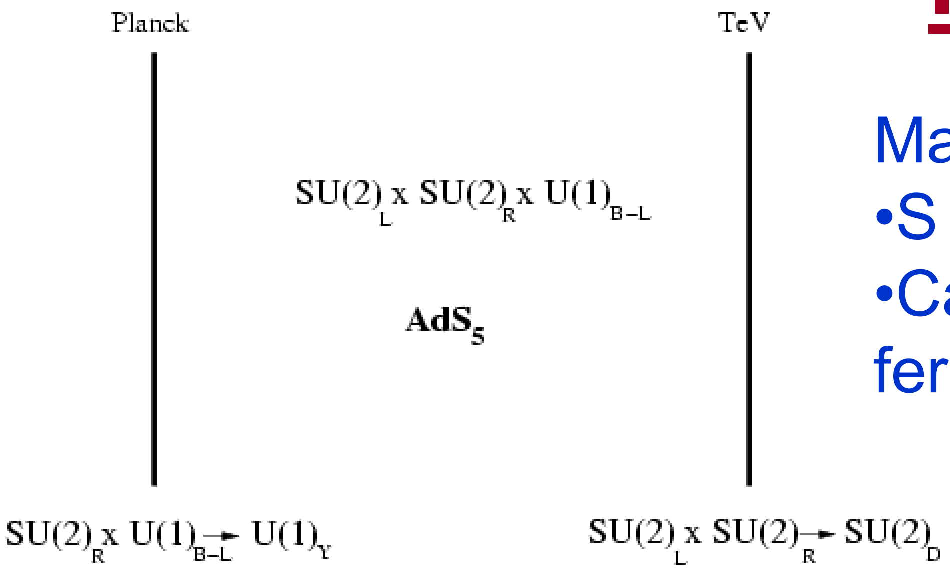
Motivation:

- Technicolor dual to extra dimensional setup
- Very difficult to protect from FCNC
- Best known model:



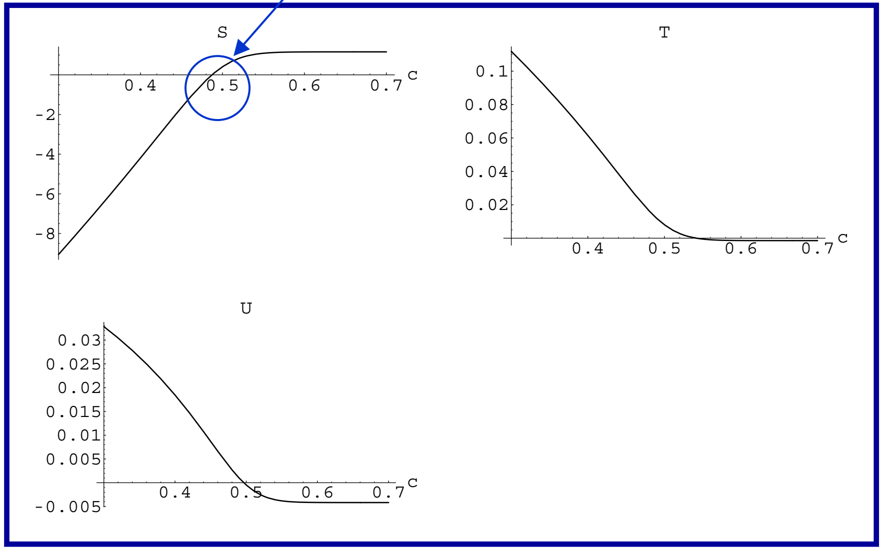
(L.Randall 1993)

Extra dimensional TC model: Higgsless EWSB



Main issue:

- S parameter large
- Can tune S away by making fermions flat in extra dim.



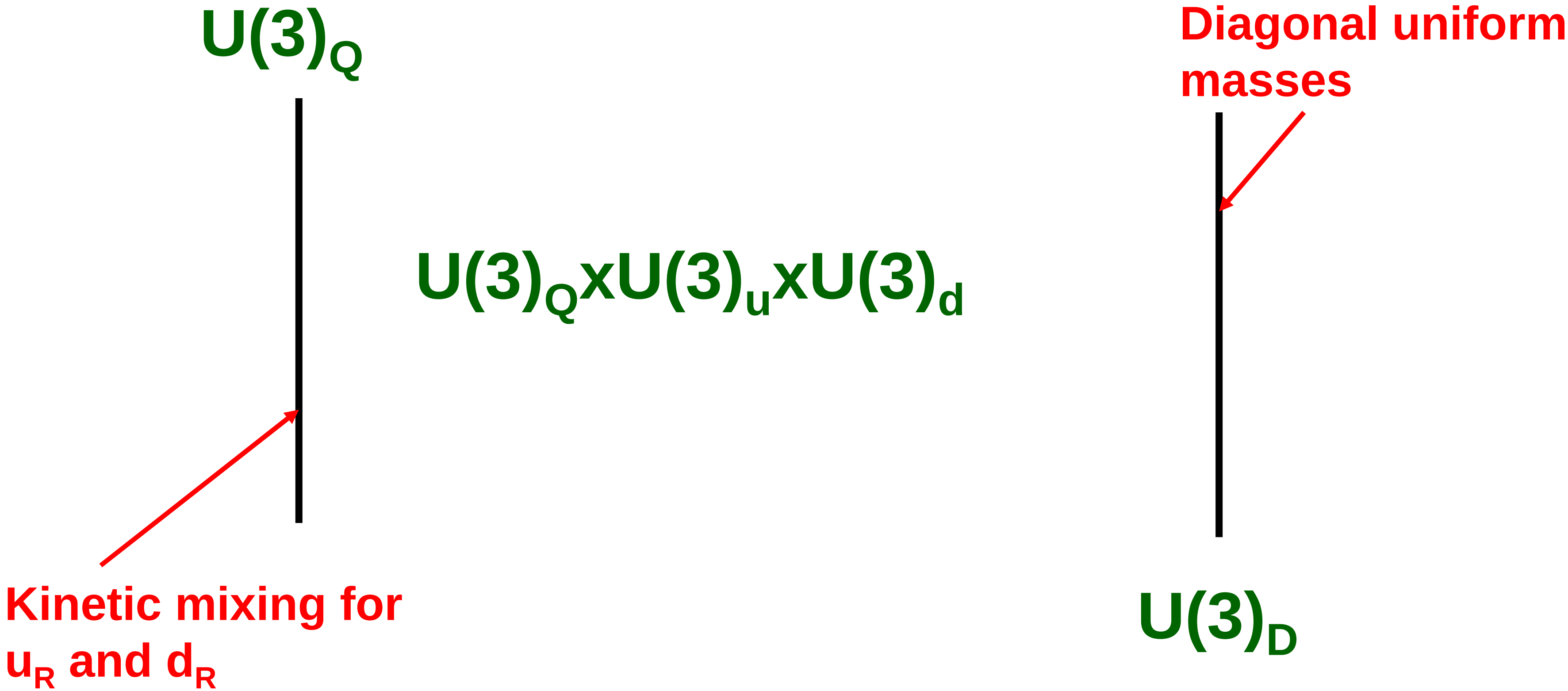
For flat fermions:

- no natural protection from FCNC
- need GIM mechanism

GIM mechanism in extra dimension

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

Wave fn's flavor universal!



In neutral current sector:

- **In bulk: $U(3)_L^u x U(3)_L^d x U(3)_R^u x U(3)_R^d$ symmetry**

- **On TeV brane $U(3)_D^u x U(3)_D^d$ due to masses**

- **Can use SU(3) matrix in u and d sector to diagonalize kinetic mixing on Planck brane**

- **Diagonal but non-uniform kinetic terms: $U(1)^u x U(1)^d x U(1)^c x U(1)^s x U(1)^t x U(1)^b$ global symmetry**

- **Symmetry protects from FCNC, <u>even due</u> to Z', g', etc**

In charged current sector:

- Separate U(1) symmetries broken: CKM mixing generated

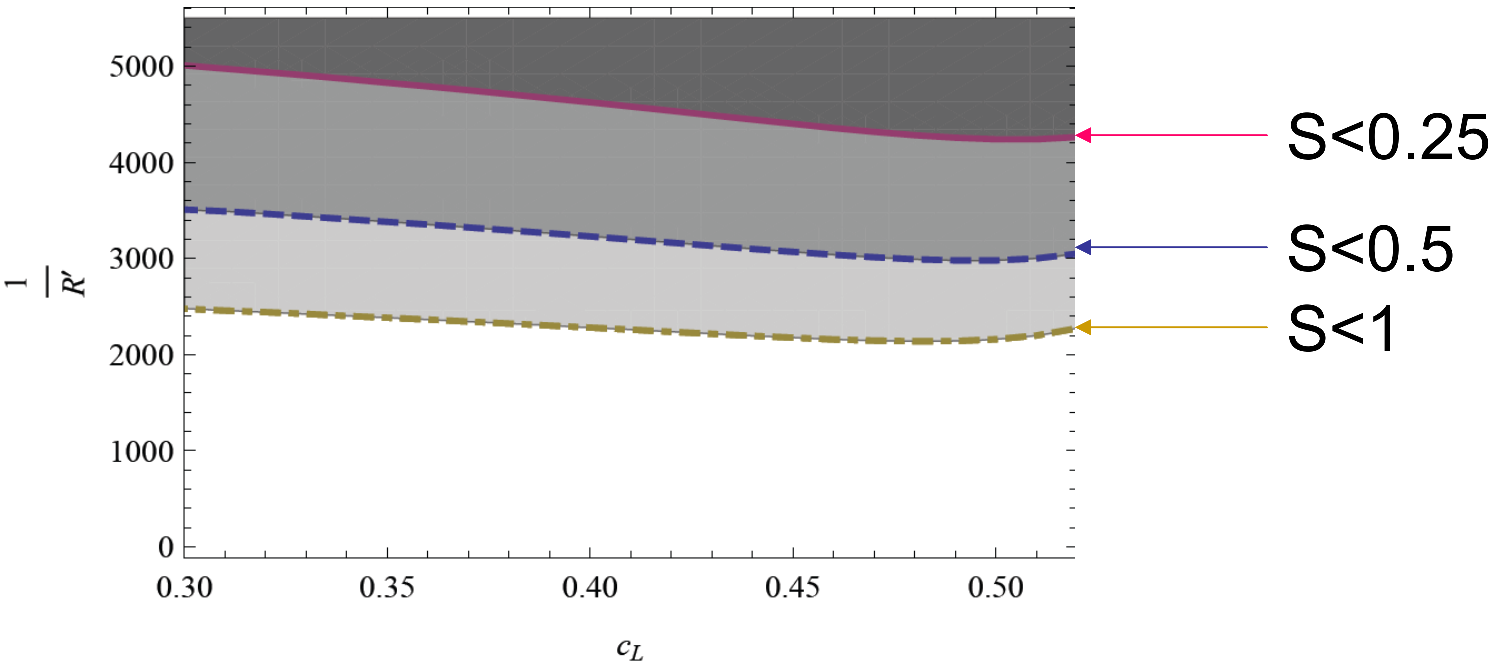
- Parameter count for N generations:

- 2 hermitian kinetic matrices: $2N^2 = N(N+1)$ real+ $N(N-1)$ phases
- Remove parameters of SU(N) matrix: $N^2-1 = N(N-1)/2$ real+ $(N-1)(N+2)/2$ pha.
- Remaining: $2N + N(N-1)/2$ real $(N-1)(N-2)/2$ phase

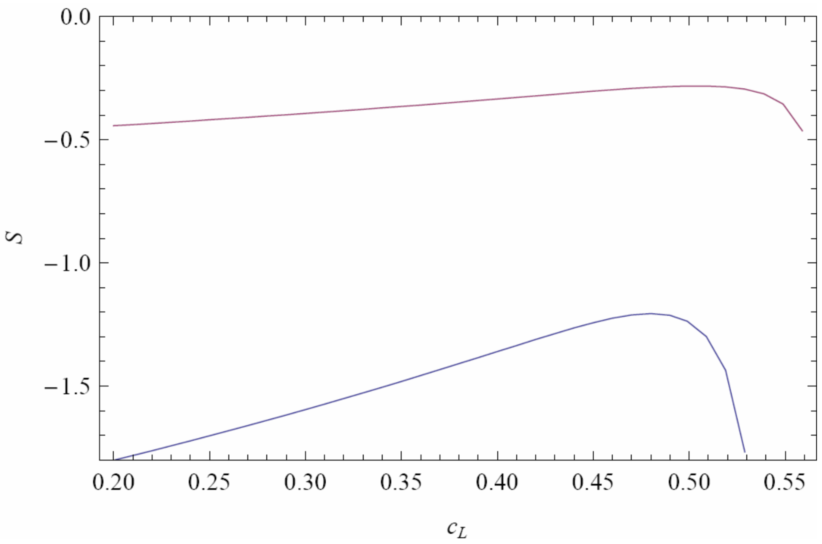
Just like ordinary CKM mechanism!

Application to models

- For 1st and 2nd generation: wave function corrections $\propto (m_c R')^2$ tiny corrections
- For 3rd generation $(m_t R')^2$ large, even R'~ TeV will give ~ 1% corrections to couplings, or S~1



S does not vanish for any c_L



- For Higgsless: S is tuned anyway via c_L.
- Just add an IR brane localized kinetic term

$$\boxed{F^L_{\mu\nu} F^R_{\mu\nu}}$$

- Still just one total tuning…
- But for RS1, MCH don't want tuning.

- Need to decouple 3rd generation mass
- Nice solution proposed by Agashe, Contino, daRold Pomarol: use different reps under $SU(2)_L x SU(2)_R$

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

Model 1

- Use new reps for all three generations

- Break $U(3)_u$ in bulk, different c_R's for u_R

- Mass terms on IR brane:

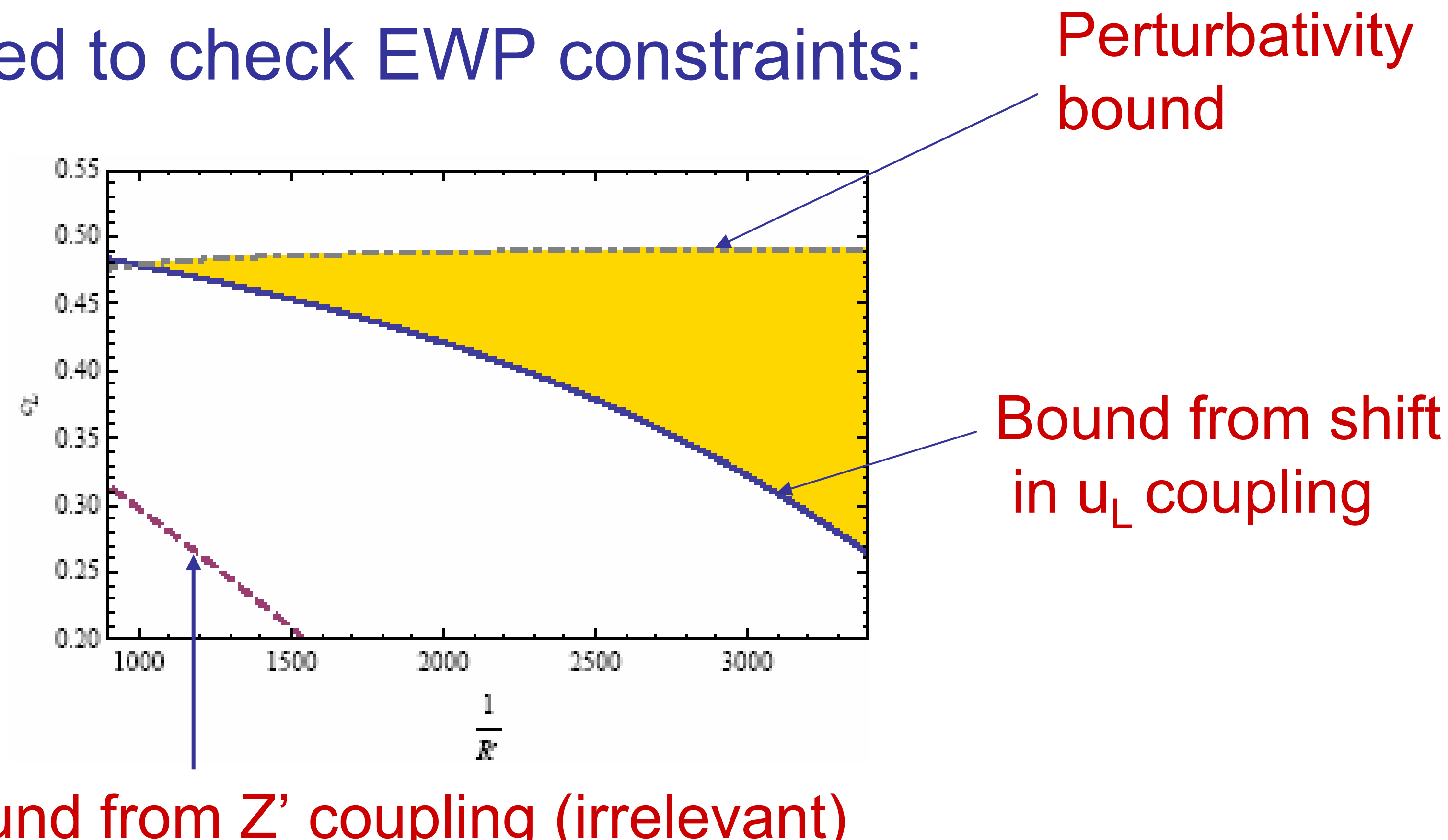
$$\boxed{Q_L^s \begin{pmatrix} m_u & & \\ & m_c & \\ & & m_t \end{pmatrix} t_R + m_b\, Q_L^t \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix} b_R}$$

KEY: large flavor breaking in up sector $U(3) \rightarrow U(1)^3$ does not get communicated to down sector since t_R mass is a singlet now

•$U(3)_d$ unbroken in IR

•If assume flavor from down-type kinetic mixing: no FCNC at all (GIM mechanism)

•Still need to check EWP constraints:



A sample point

u d	$\gamma_L^u = -3.1$ $\gamma_L^d = 1.4$	$\omega_L = -0.48$	$\gamma_R^u = 0.76$ $\gamma_R^d = -0.012$	$\omega_R < 10^{-7}$
c s	$\gamma_L^c = -3.1$ $\gamma_L^s = 1.4$	$\omega_L = -0.48$	$\gamma_R^c = 0.76$ $\gamma_R^s = -0.016$	$\omega_R < 10^{-3}$
t b	$\gamma_L^t = -3.9$ $\gamma_L^b = 1.4$	$\omega_L = -0.85$	$\gamma_R^t = 20$ $\gamma_R^b = -7.1$	$\omega_R = -2.2$

$1/R' = 1.5$ TeV, $c_L = 0.47$, $c_R = -0.51$, $c_{tR} = +1$

γ,ω are per mille deviations from SM couplings:

$$\boxed{\begin{aligned} g^Z_{f_L} &= (1+\gamma^f_L)\frac{g}{\cos\theta_W}(T_3 - \sin^2\theta_W\, Q) \\ g^W_{f_L} &= (1+\omega^f_L)g \end{aligned}}$$

Model 2

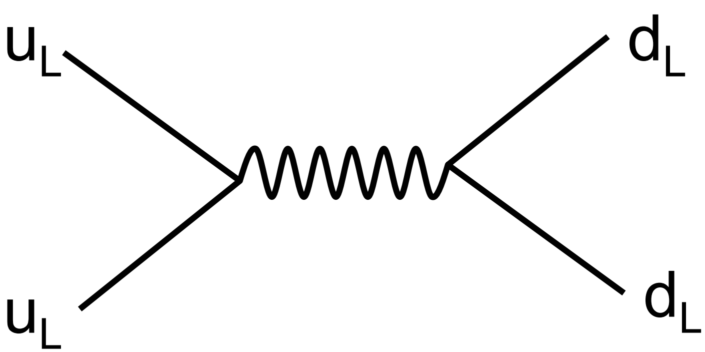
- Use new reps only for 3rd generation
- Clearly no problem with EWPO, Zbb vertex
- But now FCNC is generated since bulk no longer symmetric. We still have SU(2) symmetry for 1-2 gen.
- In up sector: kinetic mixing affects only 1-2 gen: no FCNC
- In down sector: b_R on UV brane, mixing: FCNC
- Structure of FCNC's:

$$\boxed{\begin{aligned} g_{Zds} &\sim V_{td}V_{ts}\delta \\ g_{Zdb} &\sim V_{td}\delta \\ g_{Zsb} &\sim V_{ts}\delta \end{aligned}}$$

- Z', g' OK for $M_{Z'}$=3 TeV

Flavor gauge bosons

- Expect bulk symmetries to be gauged
- $U(3)_R$ broken in UV – no light state (only KK)
- $U(3)_Q$ remains till IR – light mode ~ $1/(R'^2 \log R'/R)$
- Does it induce FCNC's?



Not really FCNC, but like CC…

$$\boxed{-\frac{g_Q^2}{2M_{W_Q}^2}\left[V_{in}\bar{u}_\ell^i\gamma_\mu d_\ell^n\right]\left[V^\dagger_{kj}\bar{d}_\ell^k\gamma_\mu u_\ell^j\right]}$$

Shining of flavor with solution to flavor puzzle

(in progress with Grossman, Perez, Surujon, Weiler)

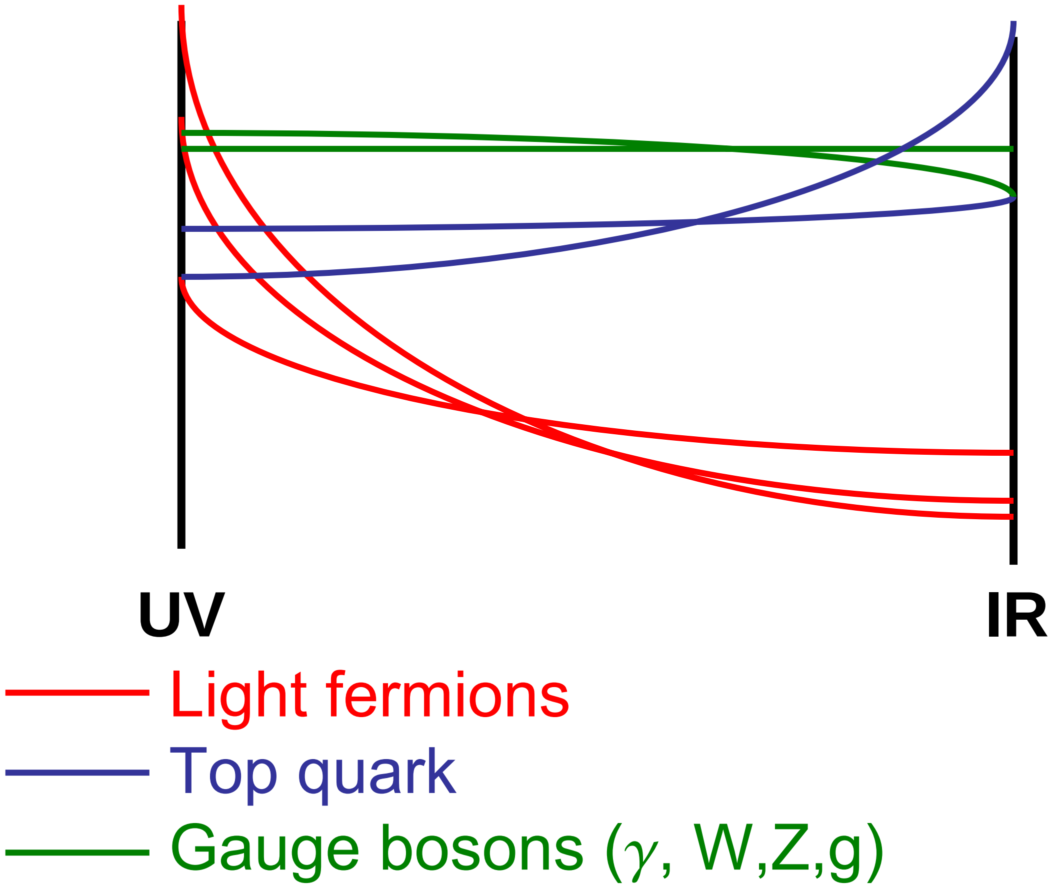
- Till now: avoided FCNC's but did not explain flavor

- Try to find a 5D model of flavor w/o large FCNC's

Flavor from 5D RS models:

Usually via wavefunction overlap

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



Gives usual RS flavor models:

Fermion masses suppressed by

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

$$m_{ij}^{(u)} = Y_{uij}\frac{v}{\sqrt{2}}f_{Q_i}f_{u_j}$$

$$m_{ij}^{(d)} = Y_{dij}\frac{v}{\sqrt{2}}f_{Q_i}f_{d_j}$$

Brane Yukawas

Relations between masses and angles automatic

Flavor	f_Q^{-1}	f_u^{-1}	f_d^{-1}
I	$\frac{\lambda^3}{f_{Q^3}} \sim 0.4 \times 10^{-2}$	$\frac{m_u}{m_t}\frac{f_{u^3}^{-1}}{\lambda^3} \sim 10^{-3}$	$\frac{m_d}{m_b}\frac{f_{d^3}^{-1}}{\lambda^3} \sim 10^{-3}$
II	$\frac{\lambda^2}{f_{Q^3}} \sim 2 \times 10^{-2}$	$\frac{m_c}{m_t}\frac{f_{u^3}^{-1}}{\lambda^2} \sim 10^{-1}$	$\frac{m_s}{m_b}\frac{f_{d^3}^{-1}}{\lambda^2} \sim 0.3 \times 10^{-2}$
III	$\frac{f_{u^3}m_t}{v\lambda_{5D}k} \sim \frac{1}{3}$	$\mathbf{O}\left(\frac{5}{6}\right)$	$\frac{m_b}{m_t}f_{u^3}^{-1} \sim 0.6 \times 10^{-2}$

FCNC's also automatically suppressed (RS-GIM), but may not be enough:

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

Bounds from Δm_K

Bound $2 \cdot 10^5$ TeV!

From the UTfit collaboration (M.Bona et al.)
hep-ph:0707.0636

To protect from FCNC: shining of flavor in RS

(Rattazzi, Zaffaroni 2000)

$U(3)^3$ bulk flavor sym.

Flavor broken by many op's → UV

Y_u: $(3,\bar{3},\underline{1})$
Y_d: $(3,1,\bar{3})$

Bulk fields: coupled to UV sources. Only $Y_{u,d}$ are close to marginal. Others irrel.

IR ← $Y_u \underline{\bar{Q}}\, \bar{H}\, u$ + $Y_d\, Q\, H\, d$

Brane localized Yukawa

Does not on its own explain hierarchy

Explain hierarchy and protect From FCNC via shining

Use Recent suggestion of Fitzpatrick, Perez, Randall:

Feed Y_u,Y_d spurions to feed into bulk masses "5D MFV model"

- How can you get a full model? (What is interpretation?)
- FCNC's?

•New: higher dim. bulk op’s break bulk symmetry

•Small breaking exponentiates: gives flavor hierarchy

$$\boxed{\begin{array}{l}(\alpha_Q + \beta_u^L Y_u^\dagger Y_u + \beta_d^L Y_d Y_d^\dagger)\bar{\Psi}_Q \Psi_Q \\ (\alpha_u + \beta_u^R Y_u Y_u^\dagger)\bar{\Psi}_u \Psi_u \\ (\alpha_d + \beta_d^R Y_d^\dagger Y_u)\bar{\Psi}_d \Psi_d\end{array}}$$

UV

IR

•$Y_{u,d}$ now gives **both** IR brane Yukawa and **splitting** of bulk masses

A simple well-motivated model

- Y_d is actually a brane field (gen. by CFT)

- Only Y_u is in bulk, can go to Y_u diag. basis

- Up-type wave functions aligned with Y_u, no FCNC in up sector

- d_R wave functions completely universal, no FCNC in d_R sector either, ONLY in d_L sector, LLLL type op.

- General case close to this form

- Can solve problem exactly

An explicit example

- Can literally scan over parameter space and see how large the O(1) numbers have to be

- A sample point (with smallest tuning):

$Y_t=1.98\quad Y_b=3.30$
$Y_c=1.27\quad Y_s=1.06$
$Y_u=0.95\quad Y_d=0.20$

$$U_5=\begin{pmatrix} -0.42 & -0.67 & 0.59 \\ 0.55 & 0.32 & 0.77 \\ -0.72 & 0.64 & 0.24 \end{pmatrix}$$

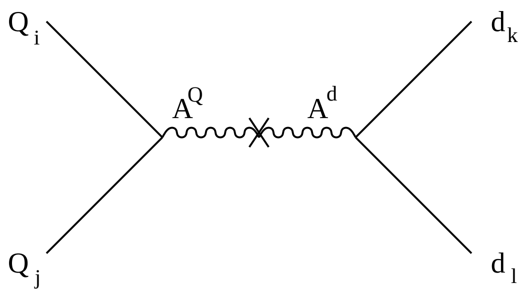
$c_{Q3}=0.38$, $c_{u3}=0.025$
$c_{dR}=0.58$, $\beta_L=-0.2$, $\beta_R=-0.08$

Little tuning still left (w/o expect $m_d/m_s= V_{us}$ …)

- Scale of FCNC from KK gluon exchange LLLL op. ~1.6 10^3 TeV, OK for LLLL…

Experimental consequences

- Flavor gauge bosons:



- Masses as KK gluons
- If Y_d brane field lighter
- Will give new FCNC
- For example with scale

$$\boxed{\Lambda^{-1} = 0.46\, a\, \epsilon_Q \epsilon_u g^2 \log(\frac{R'}{R}) R'}$$

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

- Scalars from Y_u

- Yukawas bulk scalars
- Will have own KK modes
- Coupled to SM fields with Yukawa strength, FCNC?

Summary

- Warped extra dimensions give new playground for models with DSB, composite higgs, flavor

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•Can find new way of implementing GIM into technicolor-type models (masses from kin. mixing)

•For theories with somewhat higher scales (composite Higgs) can find solution to flavor puzzle: shine Y_u and dynamically generate $Y_{d.}$ FCNC OK then.