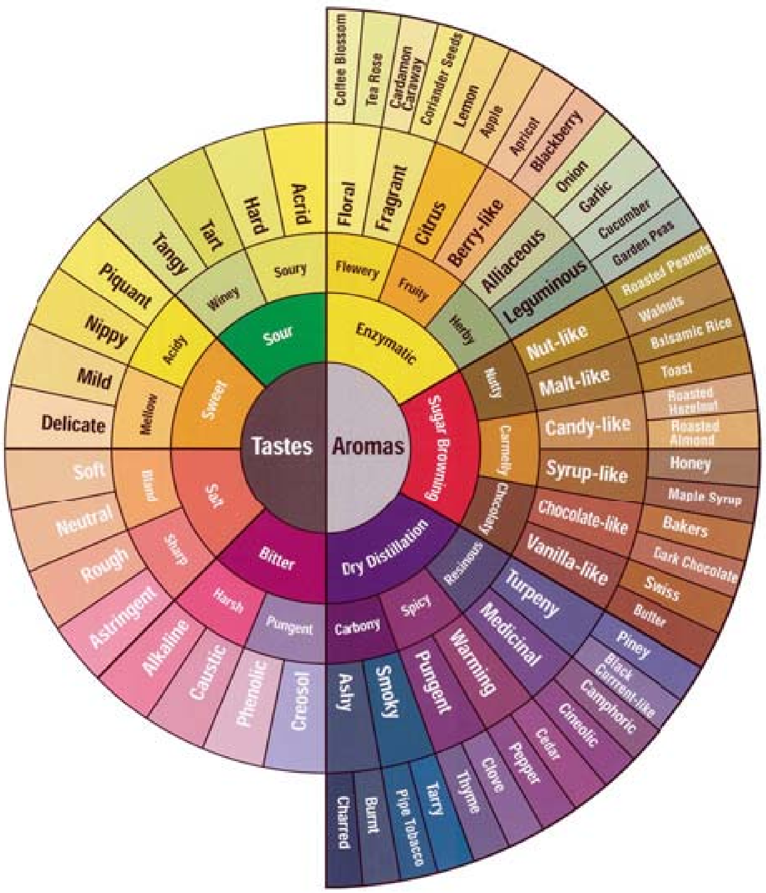
Flavor and CP Solutions via~GIM in Bulk RS



LR with Liam Fitzpatrick, Gilad Perez
-w/ Liam Fitzpatrick, Clifford Cheung

Introduction

- Lots of attention devoted to weak scale
- Flavor and CP remain outstanding issues
  - Even more difficult to solve and test?
- Yet almost any theory of weak scale physics has implications for flavor and CP
- Usually bad!
  - Almost any model with new physics involves lower scale; other interactions likely
- Worth seeking solutions in context of models, field theory
  - Geometry, string theory as well
- Problems that won't have anthropic solutions!

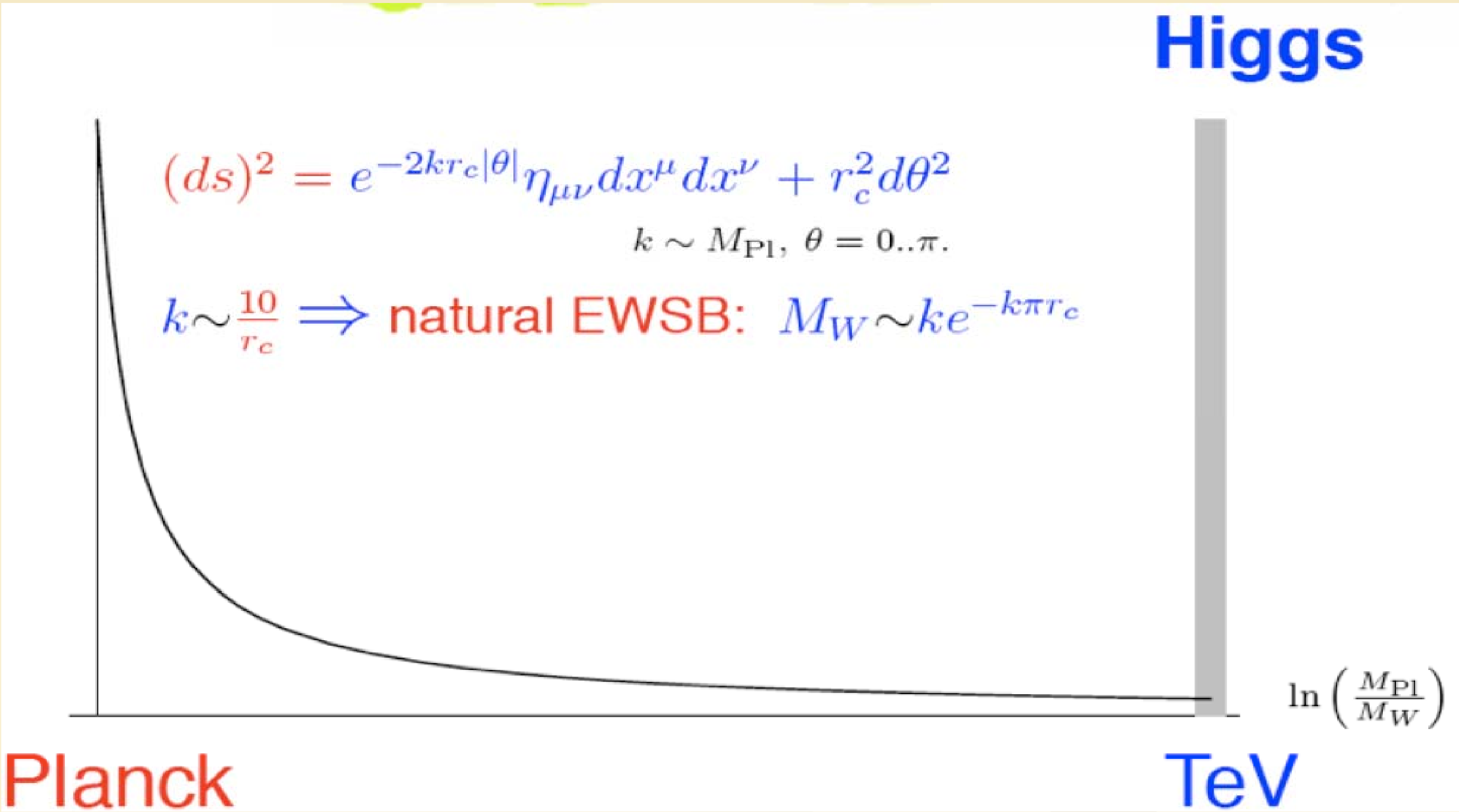
Geometry and Flavor

- Extra-dimensional geometry promising for explaining hierarchies
  - Warped geometry in particular provides multiple mass scales
  - Exponential hierarchies natural in extra dimensions
- Extra-d geometry might also explain flavor
  - Bulk fields with nontrivial profiles
    - Exponential dependence on bulk mass parameters so no very large parameters necessary
    - Angles connected to masses in suggestive way

Outline

- Elaborate on Flavor
- Describe potential flavor and strong CP issues
- Show how to solve them
- How well can we do?
- New model to solve strong CP problem

RS1


Higgs
$(ds)^2 = e^{-2kr_c|\theta|}\eta_{\mu\nu}dx^\mu dx^\nu + r_c^2 d\theta^2$
$k \sim M_{\rm Pl},\ \theta = 0..\pi.$
$k \sim \frac{10}{r_c} \Rightarrow$ natural EWSB: $M_W \sim k e^{-k\pi r_c}$
$\ln\left(\frac{M_{\rm Pl}}{M_W}\right)$
Planck
TeV

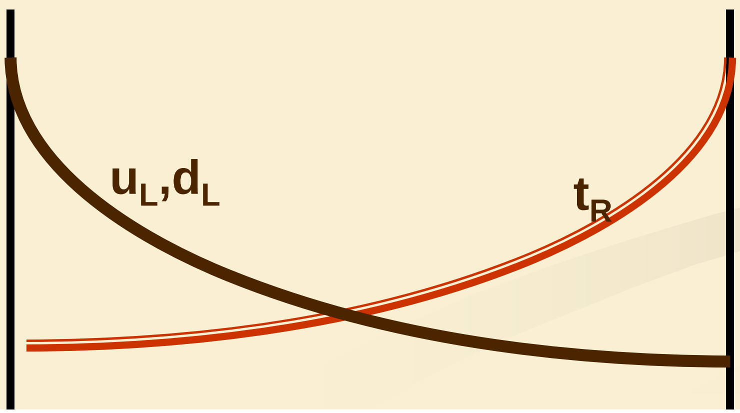
Where are fermions?

- Only Higgs needs to be on brane to satisfy hierarchy
- If light fermions on the brane, can satisfy observations with MFV like in SM
  - However UV sensitive; not calculable
    - Expect higher-dimension operators
  - No explanations for small size of coefficient
- With bulk fermions, possible explanation of flavor
- However can no longer hide flavor violation and not MFV
- Nonetheless get NMFV (flavor violation primarily via 3rd generation)
  - Almost good enough

Worth investigating possibilities

Flavor from Bulk Wave Functions

- When fermions in bulk, expect nontrivial fermion wave function profiles
- Fermion masses depend on overlap with Higgs
  - Expect light fermions localized near Planck/Gravity brane
  - (Heavy) top near TeV brane



Flavor hierarchies

- $d_z f=(M/k+1/2)\ f$
- $f \sim z^{\nu}$
- $z \sim e^{kr\phi}$
- $f \sim e^{\ kr\phi(M/k+1/2)}$
- $M/k=\nu<-1/2$: light quarks
- $\nu>-1/2$: top quark
- Natural hierarchies from small deviations in M/k

Angles Natural as Well!

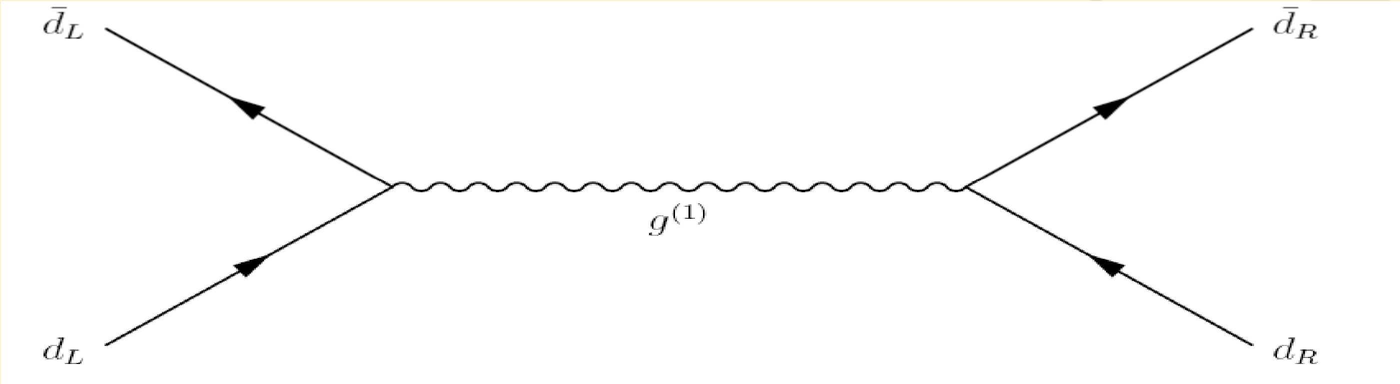
- No flavor symmetry necessary
- Mixing matrices can be anarchic
- Mixing angles from wave function hierarchies
- $Y_u = F_Q V_u Fu$
- $Yu\, Yu^+ = F_Q (V_u F_u F_u^+ V_u^+) F_Q^+$
- When bulk mass diagonal, F_Q diagonalized with eigenvalues f_{Qi}
- $K^u_{ij} \sim f_{Qi}/f_{Qj}$
- Naturally scales as square root of masses
- Angles align with mass structure

Flavor from Bulk

- ✓ Masses
- ✓ Angles
- What about flavor violation?
- Seems very dangerous
  - Functions violating flavor
  - KK mode interactions violate flavor
- ☝ Surprisingly not nearly so bad as you'd expect

New sources of flavor, CP violation

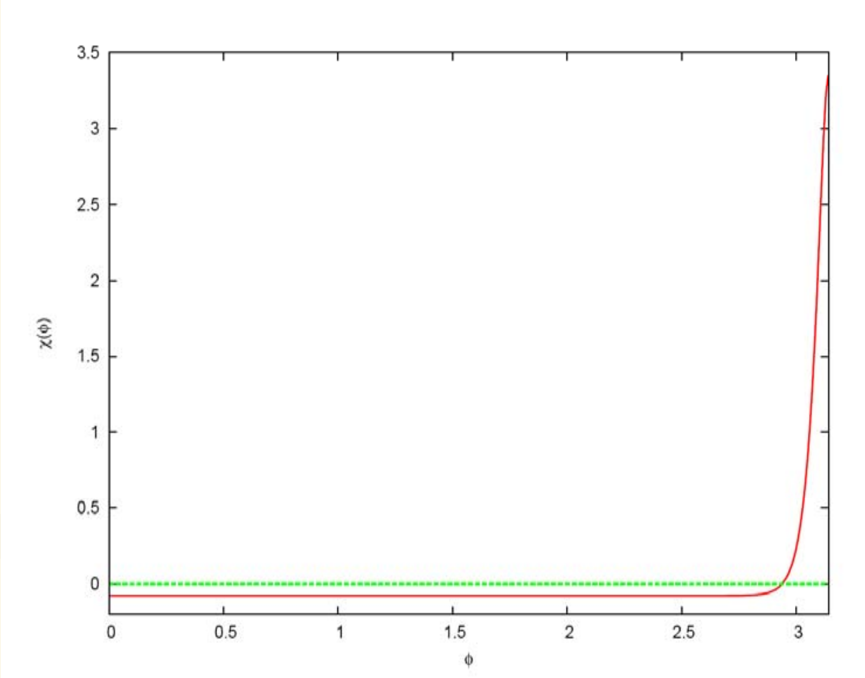
- KK modes of gauge bosons don't have universal couplings
- Different profiles for different generations
- Different overlap with TeV-localized KK gluons
- Left and right handed fermions in bulk means (e.g.)
  - Large contributions to K Kbar mixing



Better than you might think

- KK modes of gauge bosons don't have universal couplings
  - Less severe in RS
  - Light fields localized in UV
  - KK gluons flat in UV

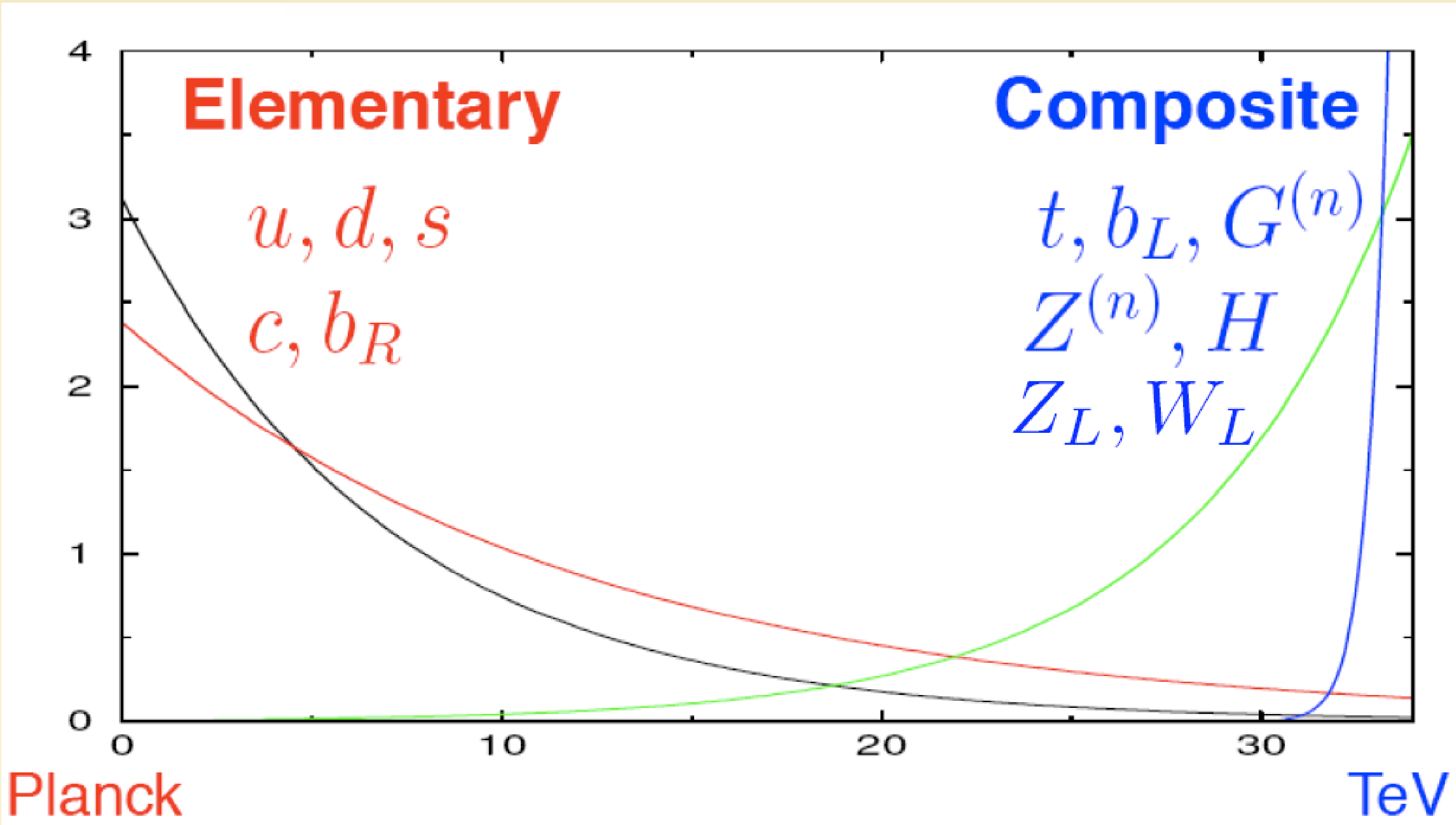
$$\chi_A^{(n)} = \frac{e^\sigma}{N_n^A}\left[J_1(z_n^A) + \alpha_n^A\, Y_1(z_n^A)\right] ,$$



IR contribution

- No flavor violations from UV
- However also IR KK gluon-f f contributions
  - However hierarchy of fermion wavefunctions in IR
  - Light masses implies small wavefunctions
- Dominant contributions through mixing to top sector (NMFV)
- Gluon vertex: L_u diag(0 0 1) L_u^+
- ($V_{CKM}=L_u L_d^+$)

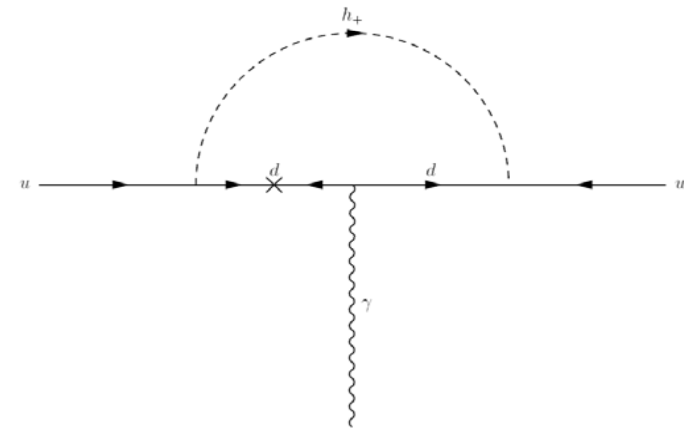
~NMFV



- Still: LR contribution (to ε_K) constrains KK scale to be ~8 TeV

Strong CP Violation

- Another potential problem "Little CP Problem"
- New sources of EDM when bulk fermions
- KK modes of fermions
- Both L and R KK modes ->large contributions
- ~10-15 TeV KK modes
- (Assuming strong CP problem solved)



This talk

- Two different models addressing different issues
  - GIM-like mechanism with anarchic flavor matrices
    - Additional flavor assumption
    - Lowers KK scale to 2 TeV
  - Sequestering C and P violation to solve strong CP
    - Effectively superGIM-like at low energies
    - Solves strong CP

w/Fitzpatrick, Perez

How to do better than generic case?

- What is generic case?
- Flavor Violating Parameters:
  - Y_u, Y_d (Yukawas to Higgs)
  - $C_{u/d}$
  - C_Q
- (note notation M->C)
- Five flavor matrices when bulk flavor
- Vs. two in Standard Model
  - Standard GIM says either ups or downs can be diagonalized
  - Only flavor violation when both are present
    - Can be virtual

Our Model: Bulk GIM Assumption

- Assume Y_u, Y_d (Yukawas to bulk Higgs) *only* flavor violating parameters
- Anarchic flavor violation
- Assume bulk mass: $C_{u/d}=Y_{u/d}^{+}Y_{u/d}$
- Assume bulk mass: $C_Q=rY_u Y_u^{+} + Y_d Y_d^{+}$
- (higher order terms, order one coeff not explicit)

Why this is a good thing:

- Despite anarchic Yukawa, theory flows to hierarchical theory (as before)
- Even with fewer parameters, we can get mixing angles (and flavor violation through mixing with the third generation)

☺ In the r->0 limit, no flavor violation in down sector--solely in up quark sector

☺ Has added advantage that might be probed with precision top quark measurements

Value of r?

- r not a free parameter
- --Determined by quark masses
- C_{Q3} much smaller than other Cs implies through consistency relation
- $diag(C_Q)=adiag[r(V^5{}_{KM}{}^+C_uV^5{}_{KM}+C_d]$
- r turns out to be small (between 0.1 and 0.4)

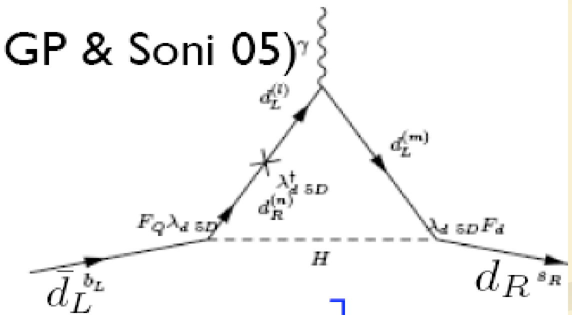
FCNC and EDM?

- FCNC suppressed by r^2
- Enough to lower KK scale to 2 TeV
- Furthermore EDMs also suppressed because like in SM
- Only a single phase

EDM only at two loops

- RS1: EDM is generated at one loop, only 2 gen' are needed. (Agashe, GP & Soni 05)

$$
\begin{aligned}
d_N &\equiv Im\left[F_Q(Y_uY_u^\dagger + Y_dY_d^\dagger)Y_dF_d\right]_{11} \\
&= Im\left[F_Q(C_Q)(C_Q/ar + Y_dY_d^\dagger(1-1/r))Y_dF_d\right]_{11}
\end{aligned}
$$



- 5D MFV: Secretly only one phase, requires 3 gen' => 2 loops!

Possible Signatures

- Low energy:
- Small down type flavor violation
- DDbar CPV at about 10%
- Penguins vs tree level in delta F=1 processes?

- High energy:
- Top FCNC: t->cZ few 10^{-6}
-
- High energy flavor preserving
  KK gluon decaying into tops
- Maybe KK graviton or other KK modes

So far…

- Minimal Flavor Violation in UV
- Sort of GIM
- Small r reduces severity of flavor changing constraints
- Can have KK scale as low as a few TeV
- Worth finding explicit realizations

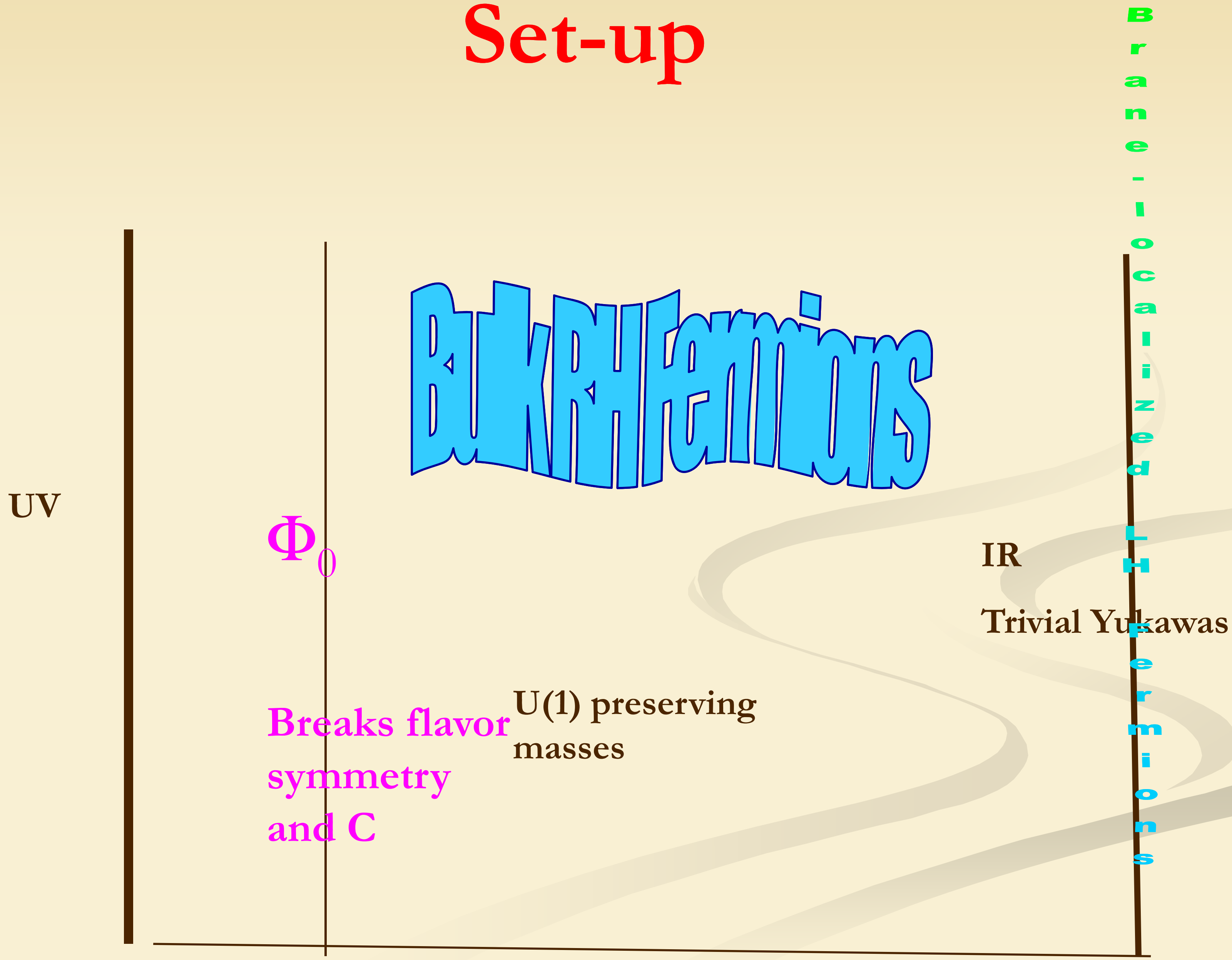
Can we do better?

- Next model I present really has a close approximation to IR GIM
- ☹ KK scale higher (precision electroweak and unitarity of CKM)
- But much smaller flavor violation
- ☺ New solution to strong CP

Spontaneously Broken CP

- **Address strong CP**
- Why?
  - Not many solutions
  - Axion models: need to eliminate higher order terms breaking PQ symmetry
  - Advantageous for EDM: “little CP" problem
    - Occurs in most models addressing hierarchy
  - Exploit a possible natural connection between flavor and CP
- No anthropic solution

Set-up



Bulk RH Fermions
Brane-localized LH Fermions
UV
Φ_0
Breaks flavor symmetry and C
U(1) preserving masses
IR
Trivial Yukawas

Alert!

- Worst part of model is LH fermions on IR brane
- Necessary to avoid 1-loop CP violation
  - In model where we also explain flavor
- Constraints from precision electroweak
- Precision measurements of fermion couplings

Precision Electroweak

- We will see that vanishing theta at tree level requires LH fermions on IR brane
- Strong precision electroweak constraints
- KK mass 15-20 TeV;
- We accept and move on to solve strong CP

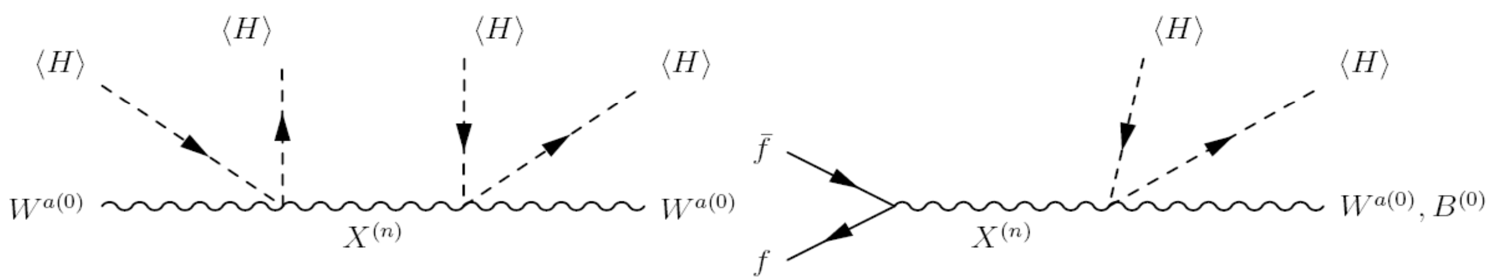


Figure 3: Diagrams that give contributions to electroweak observables at tree-level. The left diagram contributes to T and the right contributes to fermion-Higgs operators. $X^{(n)}$ indicates KK modes of bulk gauge fields.

Model

$$S = S_{\rm bulk} + S_{\rm brane},$$

$$S_{\rm bulk} = \int d^5x\sqrt{G}\left\{-\bar{U}'_L(M_u + g_u\Phi\delta(\phi-\phi_0))U_R - \bar{D}'_L(M_d + g_d\Phi\delta(\phi-\phi_0))D_R + {\rm h.c.}\right\},$$

$$S_{\rm brane} = \int d^4x\sqrt{-g}\left\{\bar{Q}_L\tilde{H}\lambda_u U_R + \bar{Q}_L H\lambda_d D_R + {\rm h.c.}\right\},$$

Only Hermitian part of Φ couples to fermions

Futhermore Φ is CP odd so antisymmetric couplng

$$\mathcal{L} \supset (\Phi_{[ij]} + \Phi^\dagger_{[ij]})(\bar{\Psi}_{Li}\Psi_{Rj} + \bar{\Psi}_{Ri}\Psi_{Lj})$$

Ingredients

- Exploit existing AdS spacetime isometry $\Phi(\bar{\Psi}_{Li} \Psi_{Rj} + \bar{\Psi}_{Ri} \Psi_{Lj})$
  - Guarantees vanishing tree level Θ
- Spont break CP with field sequestered field Φ
  - Hides C violation and flavor violation from IR
- Flavor Symmetry
  - U(3)Q x U(3)U x U(3) D ->U(3) by Yukawas
  - ->U(1)3 by bulk fermion masses
  - ->nothing by Φ couplings
- LH fields on IR brane giving ~GIM when Φ in UV and K K heavy

Ing I:Hermiticity of Wavefunction and Vanishing Tree Level Θ

$$\left(\partial_t - \frac{\mu}{t}\right) F_L^{(0)} \;=\; 0,$$

$$t = \epsilon e^{kr|\phi|} \in [\epsilon, 1]$$

$$F_L^{(0)} = \mathcal{P}\exp\left(\int^t \frac{\mu(t')}{t'} dt'\right)$$

μHermitian due to AdS symmetries (essentially a type of parity)

F product of infinitesimal Hermitian matrices

Wave function on IR brane has real determinant

$$Y_{u,d} = F_q^{(0)} \lambda_{u,d} F_{u,d}^{(0)}.$$

Contains phase but has real determinant--- at tree level

Ing II:Sequestering C, flavor Violation

- Guarantees CP violation enters only through wavefunctions of bulk fermions
- Prevents dangerous operators such as $\Phi_{ij}\ Q_{Li}\ H\ U_{Rj}$
- Plus our "anarchic" mixing comes from third brane in bulk
- Shields it from IR
- Keeps KK modes very diagonal--important for loop effects
  - Modes combination of regular and singular mode
  - Regular mode vanishing in UV
  - Singular mode small there
  - Turnaround to regular mode deep in UV
  - Shields from mass-dependent phase shift
  - Value on IR brane will be essentially $\sqrt{2}$

Twisting

- Also called twisting in literature
- Diagonal wave functions up to localized Yukawa
- Enters into flavor, CP through wave function
  - In fact in dual interpretation, we have flavor entering through wave function renormalization
  - But in 5d geometry model is calculable

Ing III and IV: Flavor Symmetry and Isolated L fields

- ~GIM mechanism when 3rd brane->UV
- All mass structure from R fermions and no KK modes for L fermions
- no R matrices--in mass eigenstate basis all absorbed into mass insertions

☺Flavor changing absorbed into V_{CKM} like SM

$$\begin{aligned} V_{\rm CKM} &= L_u P_0 L_d^\dagger \\ V_{uu} &= V_{\rm CKM} V_{\rm CKM}^\dagger \\ V_{dd} &= V_{\rm CKM}^\dagger V_{\rm CKM}. \end{aligned}$$

$$P_0 \equiv \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

But 0 mode wavefunctions enter through $(v/M)^2$ effects

Angles naturally connected to masses in this model too

$$
\begin{aligned}
F^{(0)}(1) &= F(1;t_0) \times \exp\left(krg\Phi\right) \times F(t_0;\epsilon) \\
F(1;t_0) &\equiv \left[\mathcal{P}\exp\left(\int_{t_0}^{1} \frac{\mu}{t'}dt'\right)\right] = t_0^{-\nu} \\
F(t_0;\epsilon) &\equiv \left[\mathcal{P}\exp\left(\int_{\epsilon}^{t_0} \frac{\mu}{t'}dt'\right)\right] = \left(\frac{\epsilon}{t_0}\right)^{-\nu}
\end{aligned}
$$

$t_0 \approx 4 \times 10^{-11}$.

Restrict to zero modes

$$
Y_{u,d}Y_{u,d}^{\dagger} = F_{u,d}(1;t_0)e^{krg\Phi}F_{u,d}(t_0;\epsilon)F_{u,d}(t_0;\epsilon)^{\dagger}e^{krg\Phi}F_{u,d}(1;t_0)^{\dagger}
$$

structure $(Y_{u,d}Y_{u,d}^{\dagger})_{ij} \approx F_{u,d}(1;t_0)_{ik}\zeta_{kk'}F_{u,d}(1;t_0)^{\dagger}_{k'j}$ with $\zeta_{kk'} \sim \mathcal{O}(1)$.

$\theta_{ij} \approx (m_i/m_j)^{-(\log t_0)/(k\pi r_c)}$ since $F(1;t_0)$ contains only a fraction $\log t_0/\log\epsilon$ of mass hierarchy

$t_o \sim 4\ 10^{-11}$

Example

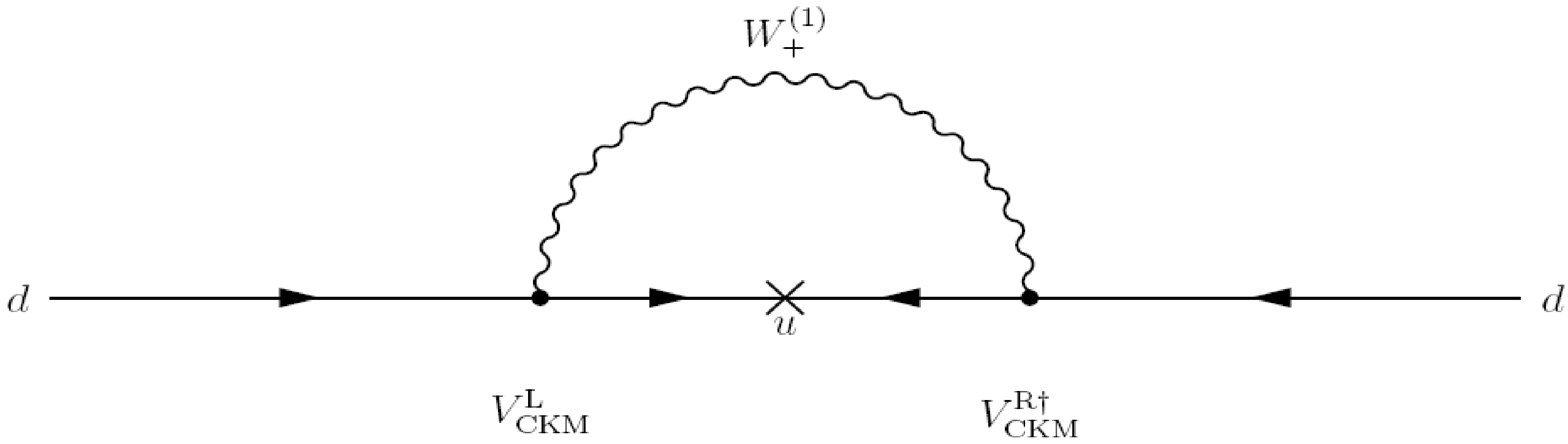
$$\begin{aligned}
\nu_U &= (-0.831, -0.665, -0.241) \\
\nu_D &= (-0.788, -0.734, -0.632) \\
\langle kr\Phi \rangle &= \begin{pmatrix} 0 & 1.039i & -1.342i \\ -1.039i & 0 & 1.481i \\ 1.342i & -1.481i & 0 \end{pmatrix} \\
g_u &= 0.3 \\
g_d &= 0.7 \\
t_0 &= 10^{-12}
\end{aligned}$$

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} = \begin{pmatrix} 0.982 & 0.185 & 0.0091 \\ 0.185 & 0.980 & 0.046 \\ 0.012 & 0.045 & 0.998 \end{pmatrix}$$

Rephasing invariant

$$\Delta^{(4)} \equiv \mathrm{Im}(V_{11} V_{12}^{\dagger} V_{22} V_{21}^{\dagger}) = 7.6 \times 10^{-5}\ \mathrm{I}$$

Θ: One loop level



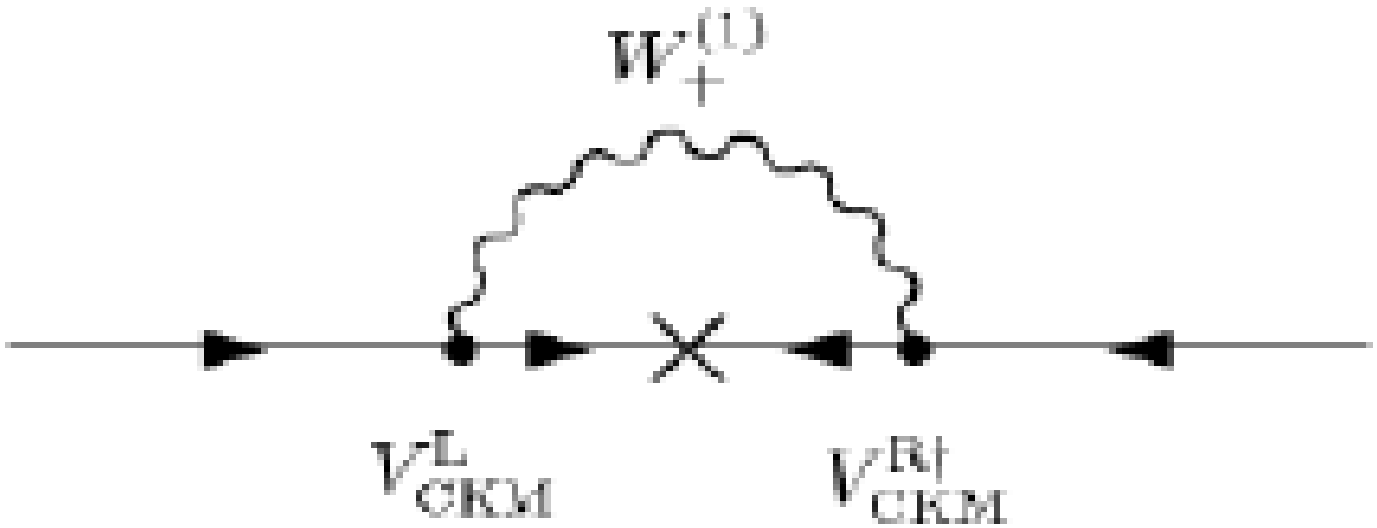
$$d_i \;\propto\; \mathrm{Im}\left(L_d(Y_u(M_u^\dagger M_u)^n M_u^\dagger + Y_d(M_d^\dagger M_d)^n M_d^\dagger)Y_d R_d^\dagger\right)_{ii}$$

$= \mathrm{Im\ Tr}\ (L_d P_0 L_u^+ L_u M_u (M_u^+ M_u)^n M_u^+ L_u^+ L_u P_0 L_d^+ L_d M_d R_d^+$

$$d_i \;\propto\; \mathrm{Im}\left(V_{\mathrm{CKM}}^\dagger \mu_u^{2n+2} V_{\mathrm{CKM}} \mu_d + V_{dd} \mu_d^{2n+2} V_{dd} \mu_d\right)_{ii}$$ **=0**

Vanishes at one loop!

Notice essential to localize R fields



Would have been one-loop contribution

Conclude

- Flavor very interesting in higher dimensions
- Worthwhile to explore how well we can do
- Many possibilities with bulk and brane fields
- Potentially richer symmetry structure

☺Can get natural exponential hierarchy

☺Natural KM angles even with anarchic mixing

☺Can use sequestering to address strong CP problem

- For the future: can you apply these ideas to other models
- Explicit geometric or string theoretic realizations?