Beyond Minimal Flavor Violation with Minimal Flavor Violation

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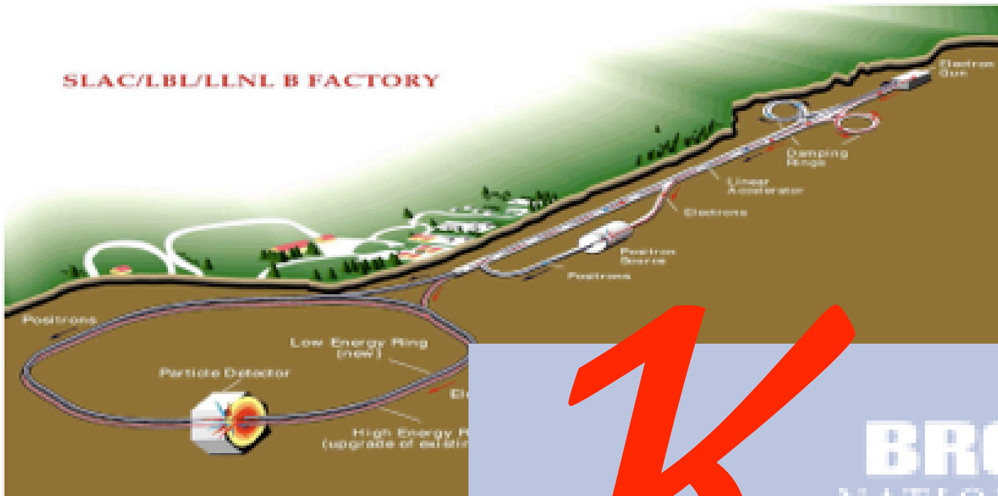
C. Csaki, Y. Grossman, GP, Z. Surujon & A. Weiler;
L. Fitzpatrick, GP & L. Randall (07);

Outline

- Precision flavor, where are we?
- RS1 flavor & CP problem.
- Solution- 5D anarchic minimal flavor violation (MFV).
- Surprises w/ MFV's "phase-diagram" (RH currents) & EFT for MFV.
- Conclusions ?

Constraints - current status $(\Delta F = 2)$



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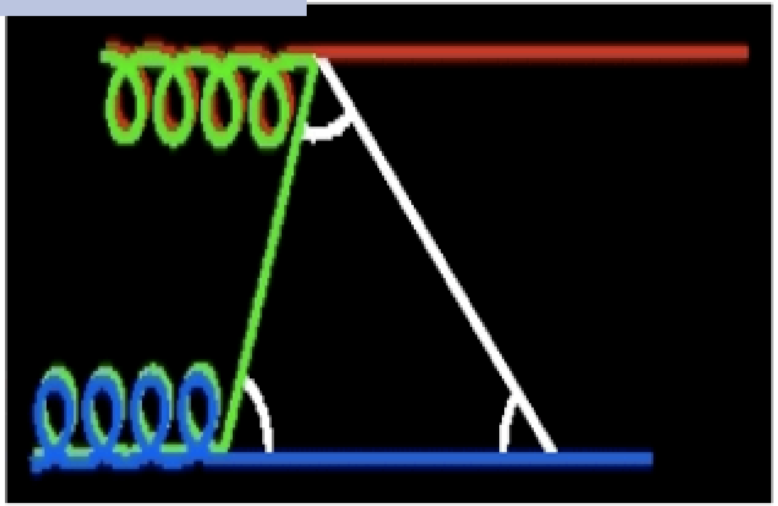


Constraints from FCNC, $\Delta F = 2$

- Expect: $\left(\frac{\bar{d}^i d^j}{\text{2-3TeV}}\right)^2$ from NP ($\Delta F = 2$).

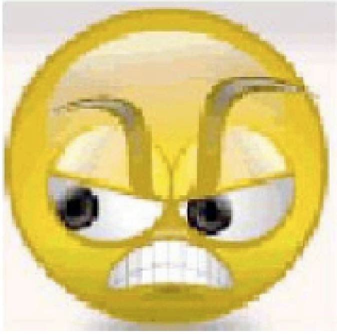
The SM scale

- Define:

$$M_{12}^{K,d,s} = M_{12}^{K,d,s}\Big|_{\mathrm{SM}} \left(1 + h_{K,d,s} e^{2i\sigma_{K,d,s}}\right).$$

Summary of constraints $h_{K,d,s}$

- Gen': $h_{K,d,s} \sim \mathcal{O}(10^5, 10^3, 10^2)\,.$



Far from gen' !!

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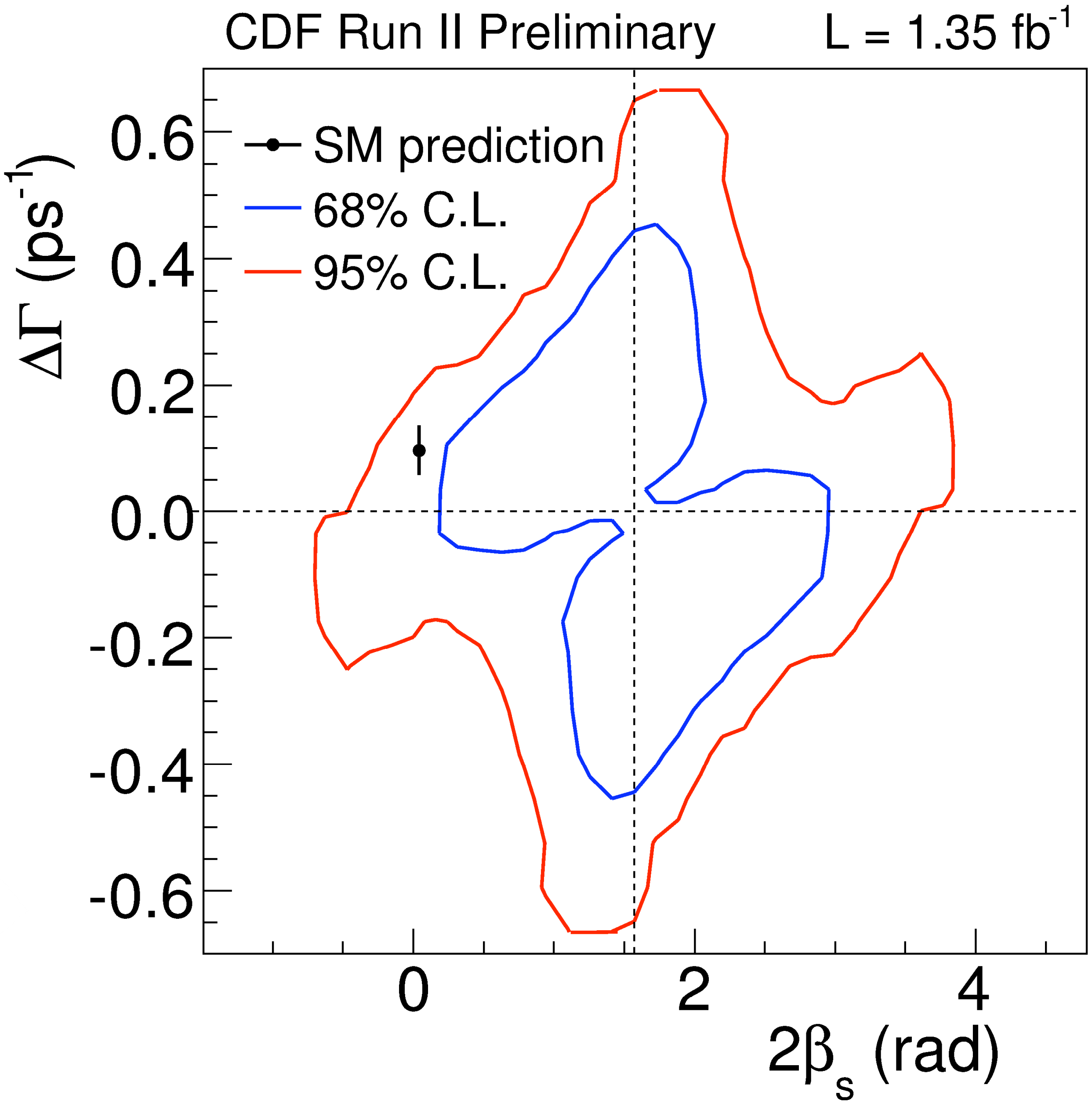

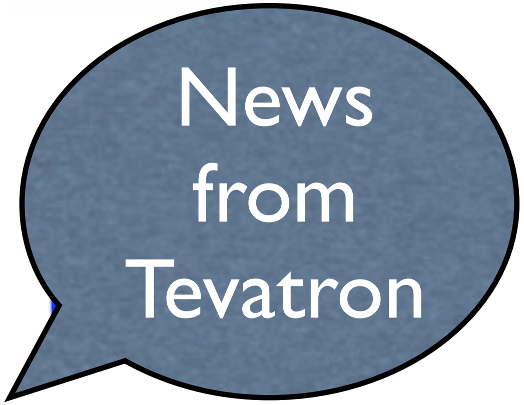

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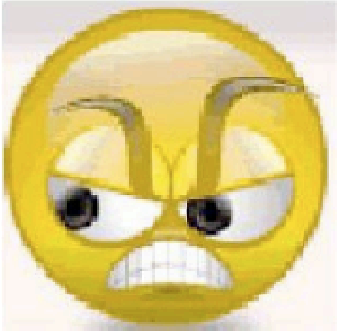

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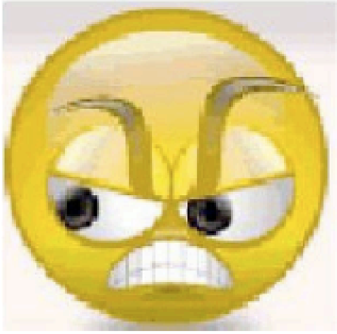


Far from gen' !!

	h_d	h_s	h_K^{LL}, h_K^{LR}
No phases	<1.5	<3	<5, <0.1
Generic	$\boxed{<0.3}$	<1.5	$\boxed{<0.6, <0.008}$

Two options stand out

◇ Minimal flavor violation (MFV) $\longrightarrow$ high Λ_F.

Flavor violation $\leftrightarrow$ SM, NP: $(\bar{d}^i Y_u^2 d^j/\Lambda_t)^2$

(D'Ambrosio, Giudice, Isidori & Strumia (02))

◇ Next to MFV (NMFV) $\longrightarrow$ low $\Lambda_F \sim \Lambda_t$.

Violation $\sim$ SM, only 3rd gen', NP: $(\bar{d}^i D_{3i} D_{3j}^* \bar{d}^j/\Lambda_t)^2$

($D \sim V_{\rm CKM}$, new sources of flavor & CP violation)

(Agashe, Papucci, GP & Pirjol (05))

$\downarrow\downarrow$

Not enough due to ϵ_K & marginal given B sys'!

UTfit (07)

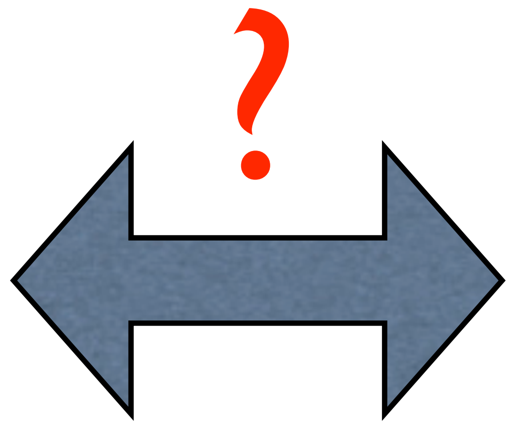
Could be enough if:

- Flavor violation is only in the up sector !

Fascinating: there's a hope for the LHC to probe dynamics of flavor through top precision!

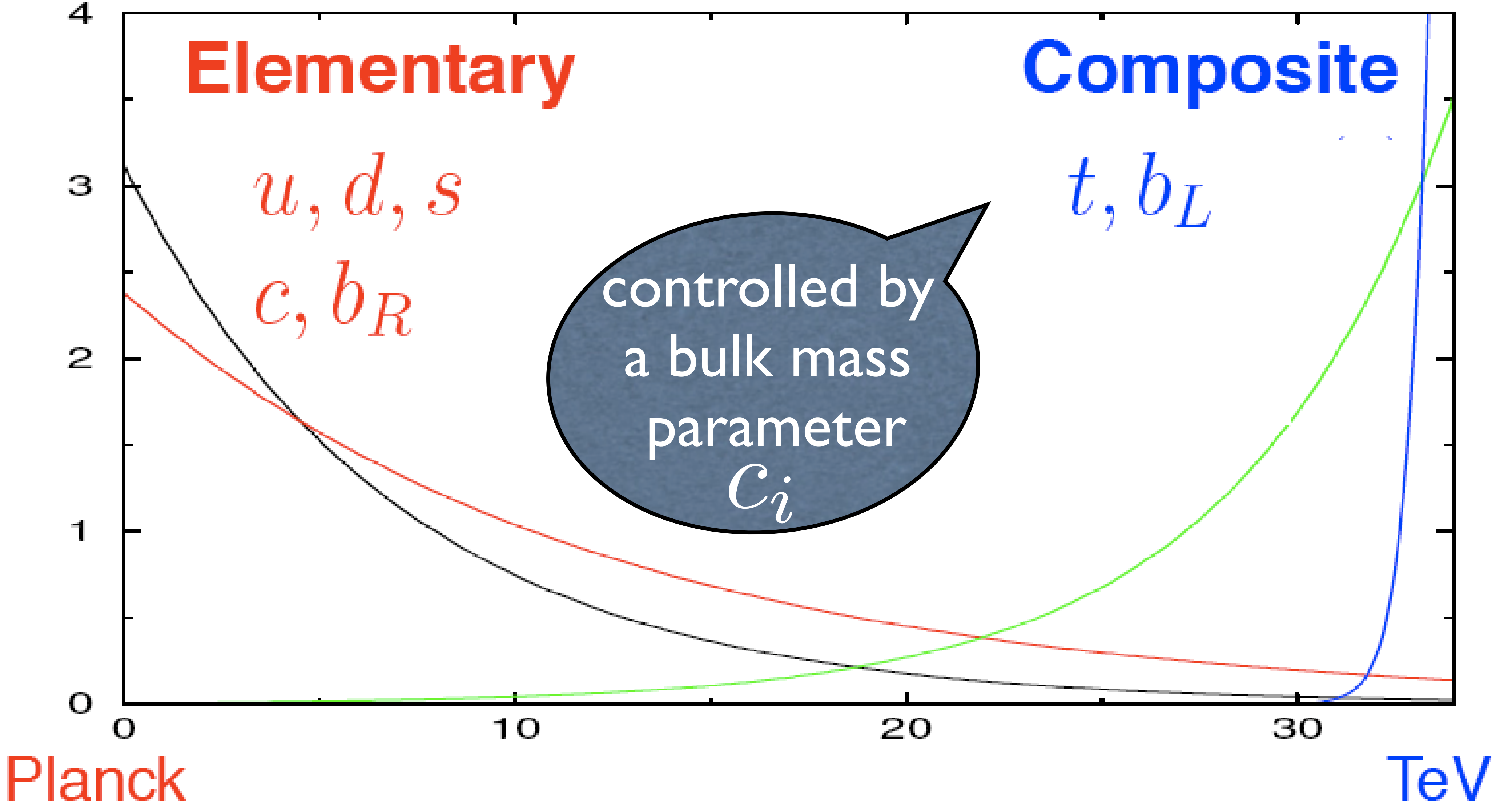
Bulk Randall Sundrum1(RS1)

RS1 flavor structure & flavor problem



Looks roughly like NMFV

- Anomalous couplings => SM heavy particles.



Determining the flavor parameters

Flavor structure determined by f

Anarchic $Y^{5D}_{u,d} \Rightarrow m^i_{u,d} \propto f_{Q^i} f_{u^i,d^i}$,

$$\Downarrow$$

$$V_{\mathrm{CKM}} \sim f_{Q^i} / f_{Q^j}$$

Determining the flavor parameters

Flavor structure determined by f

$f \rightarrow$ function of bulk mass:

$$f(c)^2 = (1/2 - c)/(1 - \epsilon^{1-2c})$$

$\epsilon = \mathrm{TeV}/M_{\mathrm{Pl}}$

Determining the flavor parameters

Flavor structure determined by f

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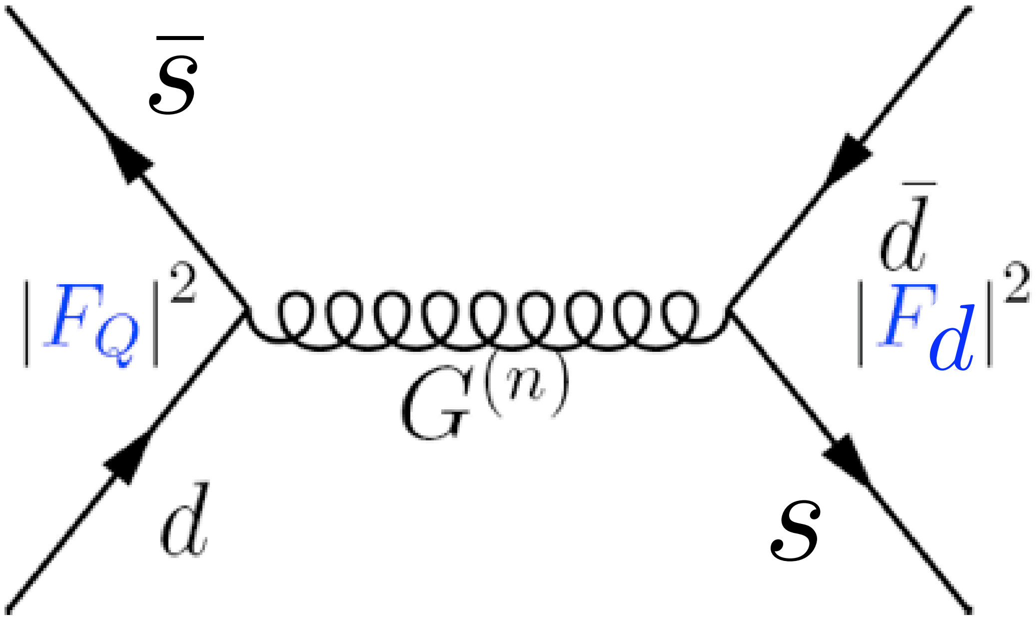
Flavor violation - KK Gluon ($\tilde{G}$)

Largest contr' are from KK gluon exchange which generates

(V-A)(V+A) currents $\propto (F_Q^2)_{12}(F_d^2)_{12} \simeq f_{Q^1} f_{Q^2} f_{d^1} f_{d^2}$

F_X: corresponds to a general flavor basis.



=> ϵ_K

RS1 flavor problem

$$\epsilon_K \Rightarrow M_{\rm KK}^G \gtrsim 8\,\mathrm{TeV}!$$

Solution - 5D anarchic MFV

Fitzpatrick, GP & Randall (07)

(or give up on solving the flavor puzzle, Rattazzi & Zaffaroni (00), Cacciapaglia, Csaki, Galloway, Marandella, Terning & Weiler (07))

- $Y_{u,d}$ => anarchic & the only source of flavor breaking.

  (unlike UED models)

- The 5D CKM is also anarchic, big mixing angles.

- Also, bulk masses are functions of same spurions:

$$C_{u,d} = Y_{u,d}^\dagger Y_{u,d} + \ldots , \; C_Q = r Y_u Y_u^\dagger + Y_d Y_d^\dagger + \ldots ,$$

Structure of anarchic 5D MFV

- The 4D theory is hierarchical, flavor puzzle is solved.

$$Y^{4D}_{u,d} \quad \propto \quad F_Q \, Y_{u,d} \, F_{u,d} \sim e^{-C_Q} \, Y_{u,d} \, e^{-C_{u,d}}$$

$$\sim \quad e^{-(rY_u Y_u^\dagger + Y_d Y_d^\dagger)} \, Y_{u,d} \, e^{-Y^\dagger_{u,d} Y_{u,d}}$$

- Still flows to NMFV with multiple flavor and CPV sources:

KK gluon couplings (both RH & LH currents):

$$g_5^{KKG} \propto F_Q^2 \sim e^{-2C_Q} \sim e^{-2(rY_u Y_u^\dagger + Y_d Y_d^\dagger)}$$

What about the flavor problem?

- Sharp limit: no down type flavor violation when $r \to 0$.

$$Y_d^{4D} \sim e^{-Y_d Y_d^\dagger}\, Y_d\, e^{-Y_d^\dagger Y_d}$$

$$g_5^{KKG} \sim e^{-2(Y_d Y_d^\dagger, Y_d^\dagger Y_d)}$$

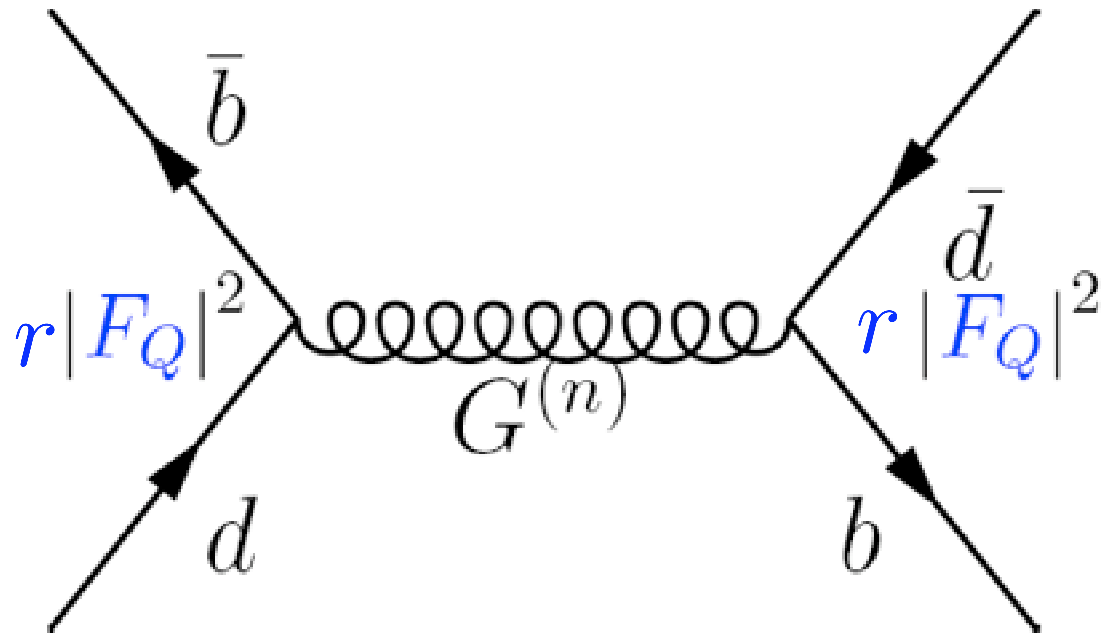
- Up type sector: still generates the CKM matrix & additional

flavor violation:

$$Y_u^{4D} \sim e^{-Y_d Y_d^\dagger}\, \boxed{Y_u}\, e^{-Y_u^\dagger Y_u}$$

$$g_5^{KKG} \sim e^{-2(Y_d Y_d^\dagger, Y_u^\dagger Y_u)}$$

Parametric suppression of down type flavor violation



$$\Rightarrow r^2 \epsilon_K$$

- When the H is in the bulk (A5) we can raise the overall scale of the 5D Yukawa by 3/2 which yield a (2/3)^2 suppression.

RS1 flavor problem is eliminated

$$\epsilon_K \Rightarrow M_{\rm KK}^G \gtrsim 2\,{\rm TeV!}$$

RS1 flavor problem is eliminated

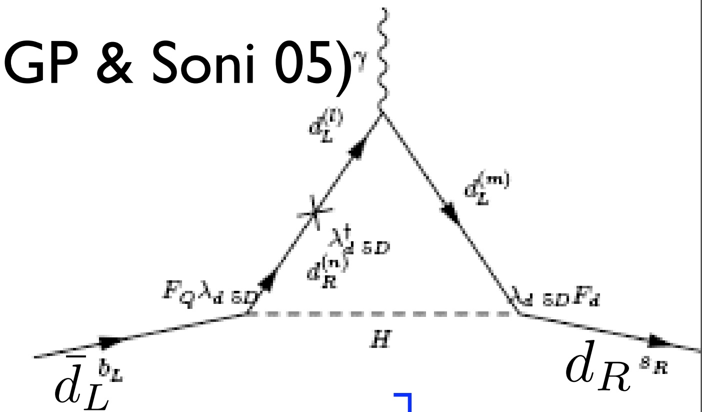
$$\epsilon_K \Longrightarrow M_{\rm KK}^G \gtrsim 2\,{\rm TeV}!$$

Gravity theory don't respect global currents.
New gauge field should be there, accessible to the LHC !

C. Csaki, Y. Grossman, GP, Z. Surujon & A. Weiler.

RS1 CP problem is also solved

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

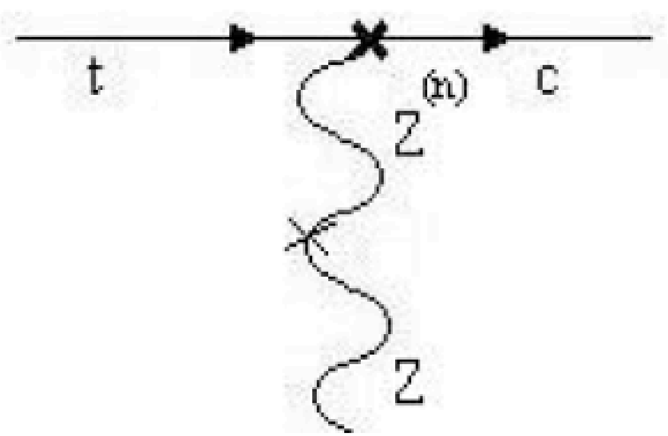


$$
\begin{aligned}
d_N &\equiv Im\left[F_Q(Y_u Y_u^\dagger + Y_d Y_d^\dagger)Y_d F_d\right]_{11} \\
&= Im\left[F_Q(C_Q)(C_Q/ar + Y_d Y_d^\dagger(1-1/r))Y_d F_d\right]_{11}
\end{aligned}
$$

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

Huge $t_R \to c_R Z$ still there!

- EWSB: Z mixes with the KKs.
- t_R mostly composite $\rightarrow$ non-univ. couplings .
- $BR(t \to c_R Z) \propto |U_R|_{23} \times \delta g_Z \sim 10^{-5}$.



Agashe, GP & Soni (06)

$r = 0, \infty$: 5D MFV => 4D MFV

C. Csaki, Y. Grossman, GP, Z. Surujon & A. Weiler

- Down type int' are diagonal when $r \to 0$.

- Up type: flavor violation controlled by CKM matrix.

  Can express flavor parameters, $F_{Q,u,d}, Y_{u,d}$, as a function of $M^{4D}_{u,d}$

- Looks exactly like MFV!

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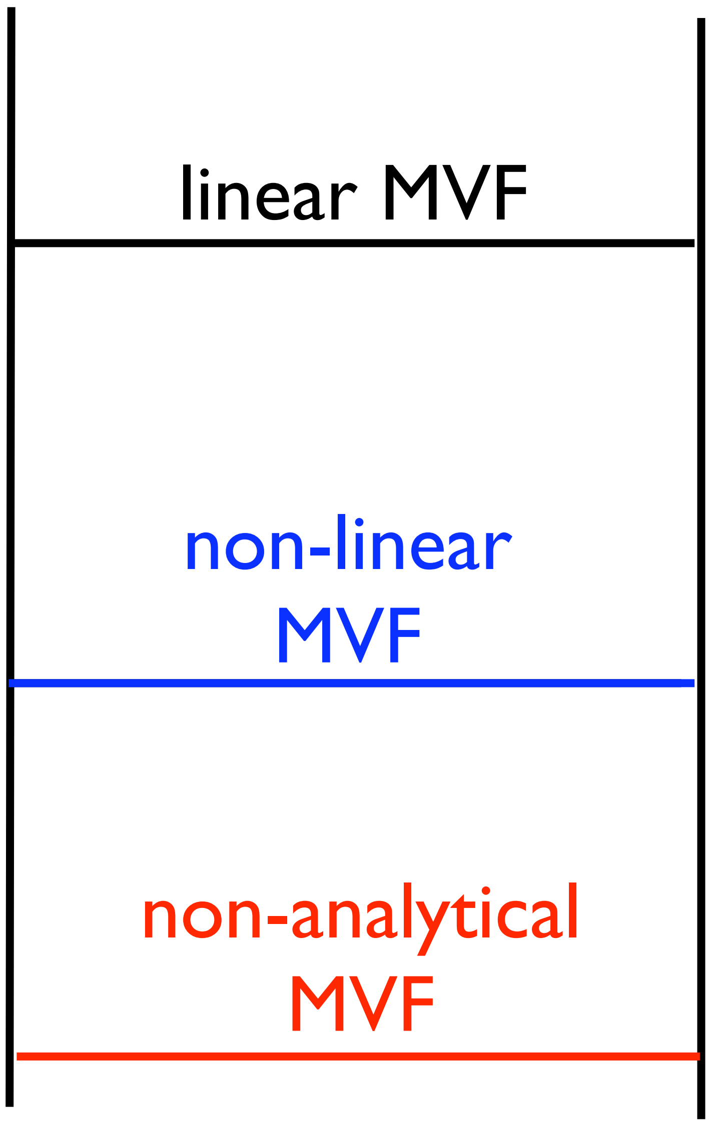
Where did huge RH current $(t_R \to c_R Z)$ come from??

“Fake” EFT for MFV

N. Arkani-Hamed, A. Kagan, GP & T. Volansky

The MFV ladder



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The MFV ladder

1-2 & 2-3 transition,
correlated

linear MVF

non-linear
MVF

non-analytical
MVF

Truncated polynom of $Y_{u,d}$

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Truncated polynom of $Y_{u,d}$

1-2 & 2-3 transition,
uncorrelated;
SUSY w/ large logs,
RS1 w/ shining

non-linear MVF

EFT below Λ_T scale,

$$e^{iT^a\chi_u^a/\Lambda_t}\begin{pmatrix}\Phi_u/\Lambda_t & 0\\ 0 & y_t\end{pmatrix}e^{-iT^a\rho_u^a/\Lambda_t}$$

non-analytical MVF

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Interpolates between 2 MFV def’s: Ali, Buras & D’Ambrosio et. al.

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“Fake” EFT for MFV

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The MFV ladder

1-2 & 2-3 transition, correlated

linear MVF

1-2 & 2-3 transition, uncorrelated;
SUSY w/ large logs,
RS1 w/ shining

non-linear MVF

large “tan β” enhanced
RH currents appear

non-analytical MVF

Truncated polynom of $Y_{u,d}$

Interpolates between 2 MFV def’s: Ali, Buras & D’Ambrosio et. al.

EFT below Λ_T scale,

$$e^{iT^a \chi_u^a/\Lambda_t} \begin{pmatrix} \Phi_u/\Lambda_t & 0 \\ 0 & y_t \end{pmatrix} e^{-iT^a \rho_u^a/\Lambda_t}$$

EFT below the scale
$\langle \chi_{u,d} \rangle \approx (\lambda_C^2, \lambda_C^3)$
large RH currents $\sim m_c/\lambda_C^2$

Conclusions

- Anarchic 5D MFV, non-trivial.
  - (i) Lead to 4D hierarchy => solves the flavor puzzle.
  - (ii) Flows to NMFV, new mixings and phases.
- Sharp limit, no d-flavor violation, solves the RS1 flavor & CP problem.
- Can we derive from underlying theory ?
- Requires gauge flavor sym', implications?
- EFT for MFV => non-trivial surprises.

Top Diag' Flavor Physics @ LHC

Top Diag’ Flavor Physics @ LHC

Challenges

- Suppressed production.
- Non-trivial final states (t_R, W_L, Z_L, h).
- Heavy states => Urel' decay particles.
- Broad objects.

LHC Reach/Searches

- **KK gluon.**

  (Agashe, Belyaev, Krupovnickas, GP & Virzi; Also Lillie, Randall & Wang*)*

- **KK graviton.**

  (Agashe, Davoudiasl, GP & Soni; Also Fitzpatrick, Kaplan, Randall & Wang)

- **Top precision tests.**

  (K. Agashe, L. Almeida, T. Han, G. Sterman, J. Virzi & W. Vogelsang, in progress)

- **Ultra-relativistic tops (mostly leptonic).**

  (K. Agashe, T. Han, M. Strassler & J. Virzi ... in progress)

- **RS electroweak sector.**

  (K. Agashe, H. Davoudiasl, S. Gopalakrishna, T. Han, G. Huang, Z. Si, A. Soni, in progress)

Flavor violation, tree level gauge KK

KK's "live" on the TeV brane

- Roughly NMFV with multiple flavor and CPV sources:

KK gauge couplings: $g_5^{KKG} \propto F^2_{Q,u,d} \sim e^{-2C_{Q,u,d}}$

- The NMFV limit is realized since only 3rd eigenvalue of $F_{Q,u,d}$ is sizable & they are quasi aligned with $Y^{4D}_{u,d}$

Does the numerology work?

- We need to solve the following eq.:

$$\mathrm{diag}(C_Q) = a\,\mathrm{diag}[r\ V_5^{\mathrm{KM}\,\dagger}(\theta_{ij},\delta)C_u\,V_5^{\mathrm{KM}}(\theta_{ij},\delta) + C_d],$$

V_5^{KM} is the 5D CKM matrix θ_{ij} is a mixing angle between the ith and jth generations and δ is the 5D CKM phase.

- Remarkably due to the large top mass and the fact that only the RH top couplings were not well tested we have:

$$C_Q \sim C_d \neq C_u \quad \Longrightarrow \quad r = \mathcal{O}(0.25)$$

Flavor parameters

Flavor	f_Q	f_u	f_d
I	$\lambda^3 f_{Q^3} \sim 4\times 10^{-3}$	$\frac{m_u}{m_t}\frac{\lambda^3}{f_{u3}} \sim 10^{-3}$	$\frac{m_d}{m_b}\frac{\lambda^3}{f_{d3}} \sim 10^{-3}$
II	$\lambda^2 f_{Q^3} \sim 2\times 10^{-2}$	$\frac{m_c}{m_t}\frac{\lambda^2}{f_{u3}} \sim 5\times 10^{-1}$	$\frac{m_s}{m_b}\frac{\lambda^2}{f_{d3}} \sim 3\times 10^{-3}$
III	$\frac{m_t}{v f_{u3}} \sim \frac{1}{3}$	$\mathcal{O}\left(\frac{5}{6}\right)^*$	$\frac{m_b}{m_t f_{u3}} \sim 6\times 10^{-3}$

* Determined by m_t & EWPM, $Z \to b\bar{b}$.

Note that: $f_{1,2} \ll 1$ <=> roughly NMFV

RS1 Flavor structure

- $$\mathcal{L}_f = \sqrt{G}k \left[C_Q \bar{Q}Q + C_d \bar{d}d + C_u \bar{u}u + h\bar{Q}\left(Y_u u + Y_d d\right)\Big|_{\mathrm{TeV}} \right]$$
- Quarks: $f_\psi \propto e^{\left(\frac{1}{2}-c\right)\sigma}, \;\; \sigma \equiv k\pi r_c \theta \,.$
- Heavy [light] quarks $\Rightarrow c \gtrless \frac{1}{2}\,.$
- SM (3gen'): $c \Rightarrow$ diag$(C_{Q,u,d})$

  $f_\psi \Rightarrow$ diag$\left(F_{Q,u,d} \sim e^{-C_{Q,u,d}}\right)$