The Flavor of the Composite Twin Higgs

Michael Geller (Technion)
NPKI 2016
Seoul 14.6.16

M.G. and O. Telem, Phys.Rev.Lett. 114 (2015) 191801
C. Csaki, M.G., O. Telem and A. Weiler, arXiv:1512.03427

Motivation

How do we probe naturalness in all sensible forms – neutral naturalness.

Need to construct sensible (UV-sensible) models.

To study implications on flavor observables – need to go into the UV.

Composite Twin Higgs – UV sensible model with inherent flavor structure.

The Twin Higgs Model

Z. Chacko, H. S. Goh and R. Harnik, Phys. Rev. Lett. 96 (2006) 231802

A global SU(4) symmetry broken by ***H*** in the fundamental: $SU(4)/SU(3)$

$$H = \begin{pmatrix} 0 \\ 0 \\ 0 \\ f \end{pmatrix}$$

Gauge the group: $\underset{\text{SM}}{SU(2)^A} \times \underset{\text{Mirror}}{SU(2)^B}$

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix}$$

7 Goldstones: 6 Eaten and 1 Higgs (Pseudo-Goldstone)

Impose a Z_2 symmetry SM ↔ Mirror.

The Twin Higgs Model: Higgs Potential

Gauging the $SU(2)\times SU(2)$ breaks the $SU(4)$

$$\Delta V = \frac{9g_A^2\Lambda^2}{64\pi^2}H_A^\dagger H_A + \frac{9g_B^2\Lambda^2}{64\pi^2}H_B^\dagger H_B \xrightarrow{Z_2} \frac{9g^2\Lambda^2}{64\pi^2}H^\dagger H$$

SU(4) symmetric

does not produce a Goldstone mass.

Quadratically divergent terms cancel!

To have the same effect for the top loop: ***double the SM symmetry***

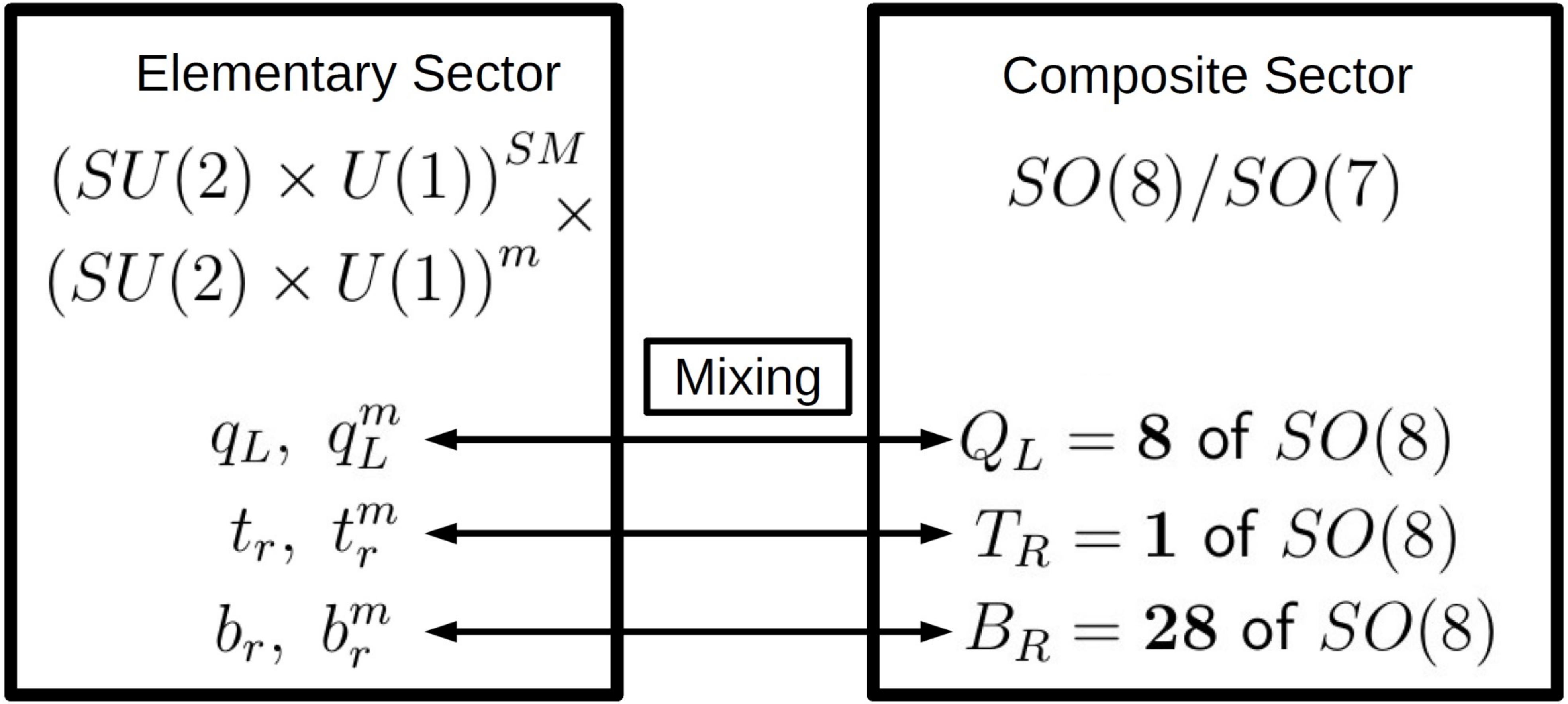
$$\underbrace{\left(SU(3)\times SU(2)\times U(1)\right)^A}_{\text{SM}} \times \underbrace{\left(SU(3)\times SU(2)\times U(1)\right)^B}_{\text{“Mirror” SM}}$$

$$H = \begin{pmatrix} 0 \\ v \\ 0 \\ f \end{pmatrix}$$

Top partners are SM singlets – “Mirror Partners”!

$$m_t^m = \frac{f}{v}m_t$$

The Composite Twin Higgs



Elementary Sector

$$(SU(2)\times U(1))^{SM}\times(SU(2)\times U(1))^{m}$$

Composite Sector

$$SO(8)/SO(7)$$

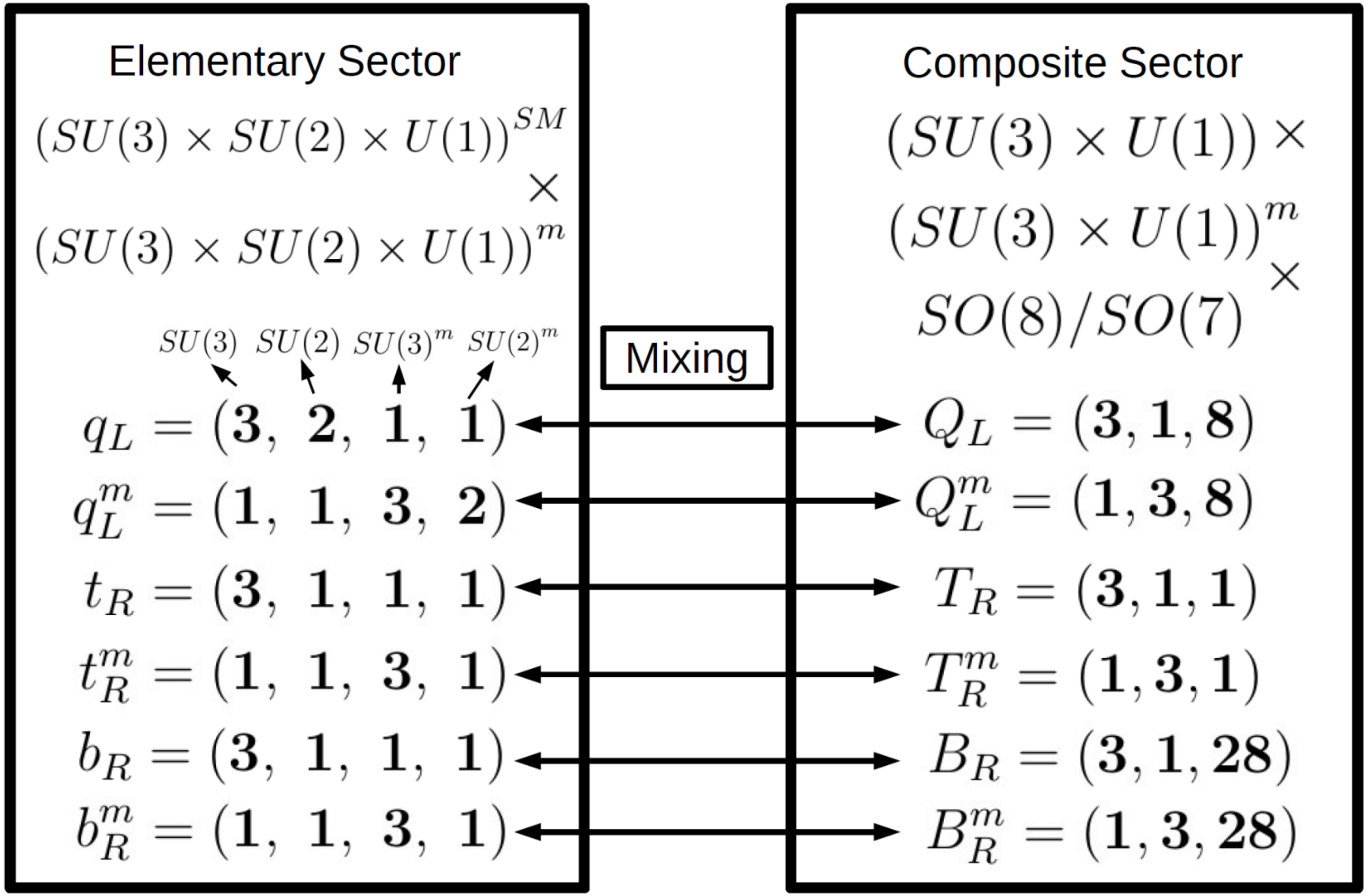
Mixing

$q_L,\ q_L^m$ ⟷ $Q_L = \mathbf{8}$ of $SO(8)$

$t_r,\ t_r^m$ ⟷ $T_R = \mathbf{1}$ of $SO(8)$

$b_r,\ b_r^m$ ⟷ $B_R = \mathbf{28}$ of $SO(8)$

The Composite Twin Higgs – with color



Elementary Sector

$$(SU(3)\times SU(2)\times U(1))^{SM} \times (SU(3)\times SU(2)\times U(1))^{m}$$

$$\begin{array}{rccccc}
 & SU(3) & SU(2) & SU(3)^m & SU(2)^m & \\
q_L = & (\mathbf{3}, & \mathbf{2}, & \mathbf{1}, & \mathbf{1}) & \\
q_L^m = & (\mathbf{1}, & \mathbf{1}, & \mathbf{3}, & \mathbf{2}) & \\
t_R = & (\mathbf{3}, & \mathbf{1}, & \mathbf{1}, & \mathbf{1}) & \\
t_R^m = & (\mathbf{1}, & \mathbf{1}, & \mathbf{3}, & \mathbf{1}) & \\
b_R = & (\mathbf{3}, & \mathbf{1}, & \mathbf{1}, & \mathbf{1}) & \\
b_R^m = & (\mathbf{1}, & \mathbf{1}, & \mathbf{3}, & \mathbf{1}) &
\end{array}$$

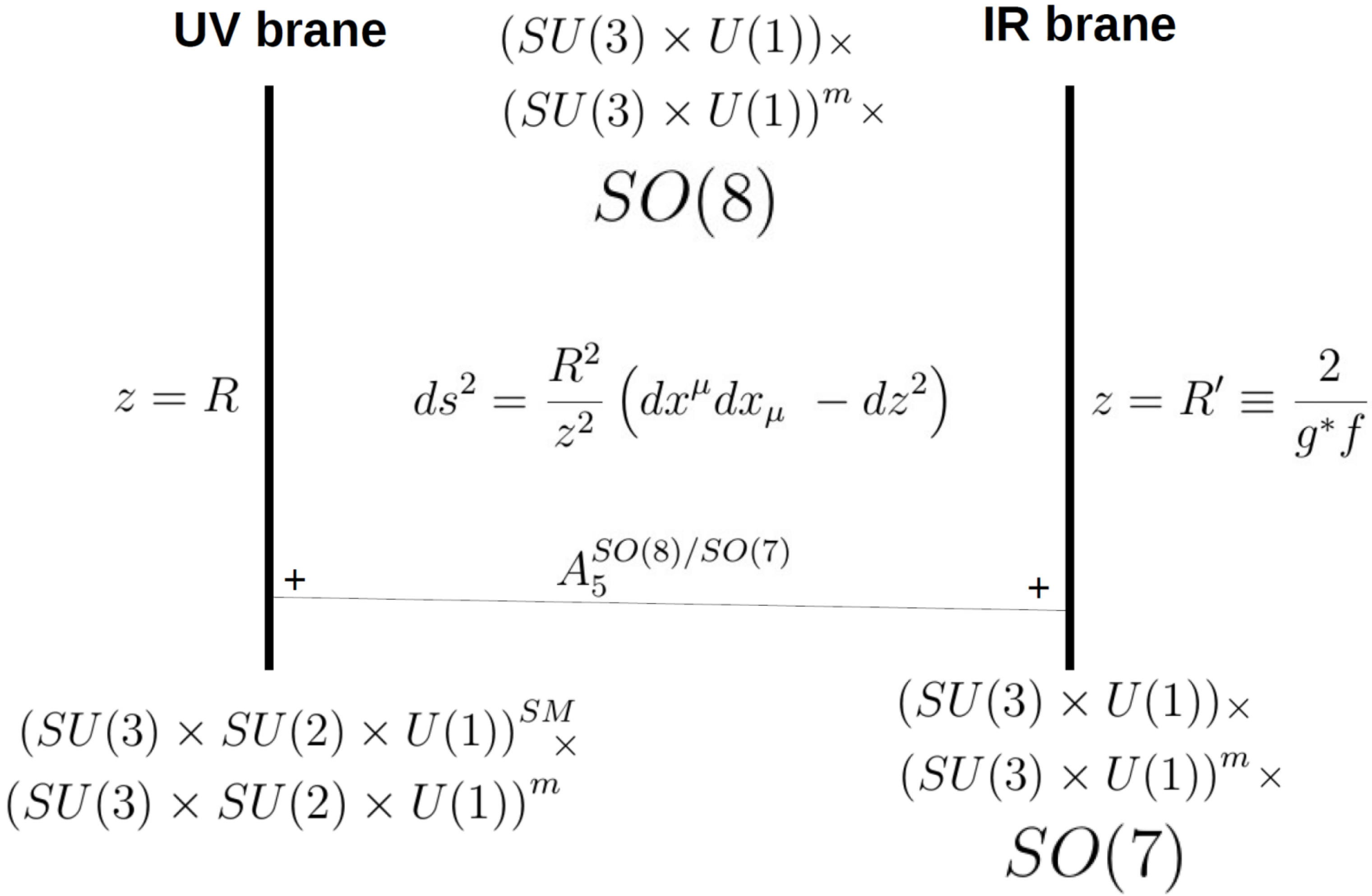
Mixing

Composite Sector

$$(SU(3)\times U(1))\times (SU(3)\times U(1))^{m} \times SO(8)/SO(7)$$

$$Q_L = (\mathbf{3},\mathbf{1},\mathbf{8})$$
$$Q_L^m = (\mathbf{1},\mathbf{3},\mathbf{8})$$
$$T_R = (\mathbf{3},\mathbf{1},\mathbf{1})$$
$$T_R^m = (\mathbf{1},\mathbf{3},\mathbf{1})$$
$$B_R = (\mathbf{3},\mathbf{1},\mathbf{28})$$
$$B_R^m = (\mathbf{1},\mathbf{3},\mathbf{28})$$

The RS picture



UV brane

$(SU(3) \times U(1)) \times$
$(SU(3) \times U(1))^m \times$
$SO(8)$

IR brane

$z = R$

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

$z = R' \equiv \frac{2}{g^* f}$

$A_5^{SO(8)/SO(7)}$

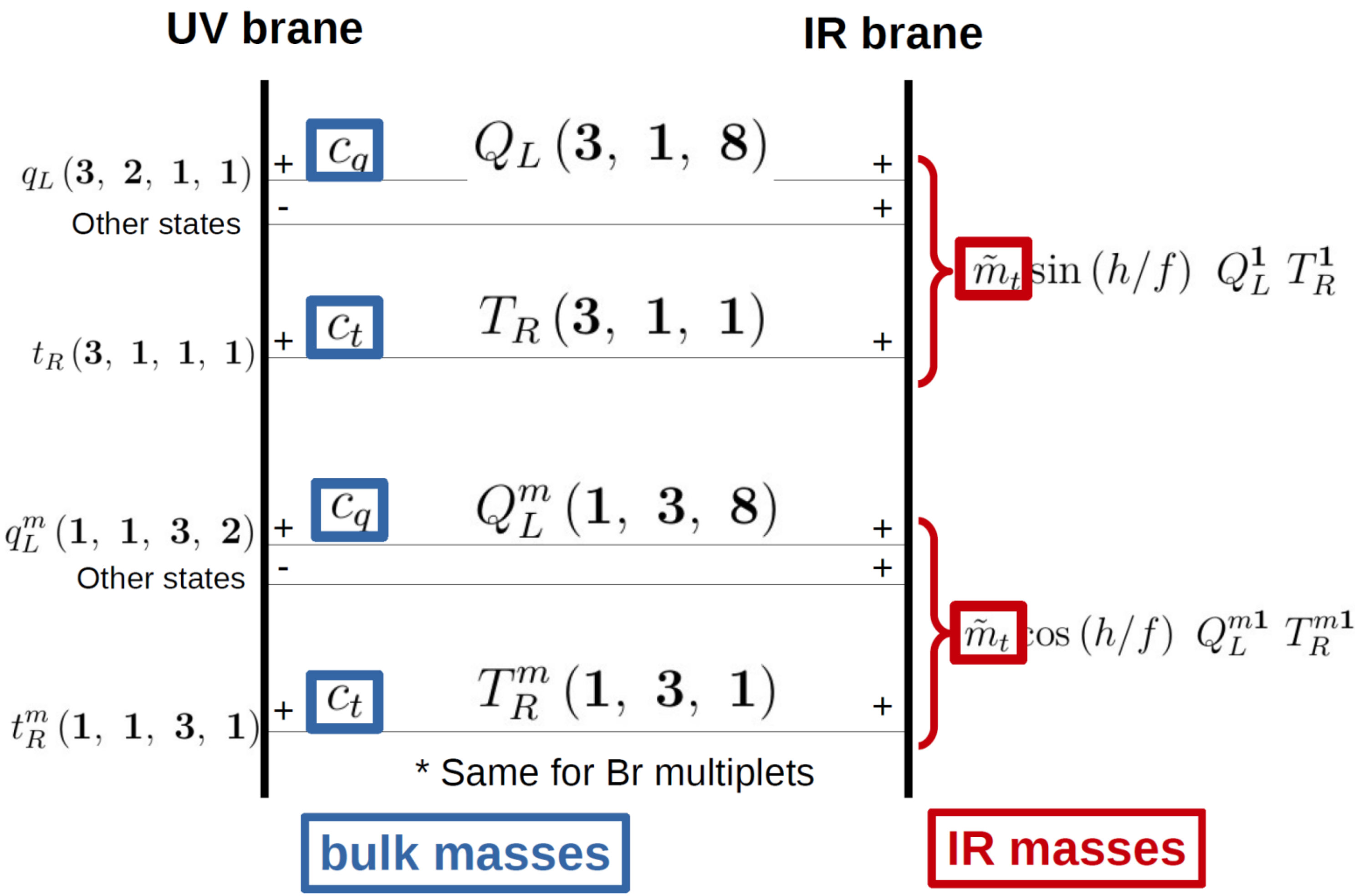
+

+

$(SU(3) \times SU(2) \times U(1))^{SM}_{\times}$
$(SU(3) \times SU(2) \times U(1))^m$

$(SU(3) \times U(1)) \times$
$(SU(3) \times U(1))^m \times$
$SO(7)$

Bulk Fermions



UV brane

IR brane

$q_L\,(\mathbf{3},\ \mathbf{2},\ \mathbf{1},\ \mathbf{1})$ + $\boxed{c_q}$ $Q_L\,(\mathbf{3},\ \mathbf{1},\ \mathbf{8})$ +

Other states - +

$t_R\,(\mathbf{3},\ \mathbf{1},\ \mathbf{1},\ \mathbf{1})$ + $\boxed{c_t}$ $T_R\,(\mathbf{3},\ \mathbf{1},\ \mathbf{1})$ +

$\boxed{\tilde{m}_t}\sin(h/f)\ \ Q_L^{\mathbf{1}}\ T_R^{\mathbf{1}}$

$q_L^m\,(\mathbf{1},\ \mathbf{1},\ \mathbf{3},\ \mathbf{2})$ + $\boxed{c_q}$ $Q_L^m\,(\mathbf{1},\ \mathbf{3},\ \mathbf{8})$ +

Other states - +

$t_R^m\,(\mathbf{1},\ \mathbf{1},\ \mathbf{3},\ \mathbf{1})$ + $\boxed{c_t}$ $T_R^m\,(\mathbf{1},\ \mathbf{3},\ \mathbf{1})$ +

$\boxed{\tilde{m}_t}\cos(h/f)\ \ Q_L^{m\mathbf{1}}\ T_R^{m\mathbf{1}}$

* Same for Br multiplets

bulk masses

IR masses

Gauge Higgs Unification

The Gauge-Higgs vev enters the fermion EOMs:

$$\Psi_q(z,v) = \Omega(z,v)\Psi_q(z)$$ $$\Omega(\mathrm{z}) = e^{ig_5 \int A_5(z)}$$ - The Wilson line

With some definitions: $g_* \triangleq \frac{g_5}{\sqrt{R}}$ $f \triangleq \frac{2}{g_* R'}$ $M_{KK} \triangleq \frac{2}{R'} = g_* f$

$\Omega(\mathrm{R}') = e^{\frac{iT^a h^a}{f}\sqrt{2}}$ - The Goldstone matrix

The Higgs Potential

The Coleman-Weinberg potential for the Higgs is calculated using:

$$V(h) = \frac{N}{(4\pi)^2} \int dpp^3 \log(\rho[-p^2])$$

$\rho(p^2)$ is the spectral function –

$\rho(m_n^2) = 0$ for any KK state in the presence of the EW vacuum.

The spectral function of Composite-Twin Higgs

- The spectral functions of the top and mirror top:

$$\rho_t(p^2) = 1 + f_t(p^2)\ \sin^2\left(\frac{h}{f}\right)$$

$$\rho_{tm}(p^2) = 1 + f_t(p^2)\ \cos^2\left(\frac{h}{f}\right)$$

- The Higgs potential

$$V_{eff}(h) = \frac{-4N_c}{(4\pi)^2}\int_0^\infty dpp^3\log(\rho_t[-p^2]\rho_{tm}[-p^2])$$

The Higgs Potential

The Higgs potential can be expanded as:

$$V_{eff}(h) = -\alpha_2 \sin^2\frac{h}{f} - \alpha_4 \sin^4\frac{h}{f} - n_t \sin^4\frac{h}{f} \log\frac{2m_{t0}^2 \sin^2\frac{h}{f}}{\Lambda^2} + (\sin \to \cos)$$

Approximated by

$$V_{eff}(h) \approx \underbrace{-\alpha_2 \sin^2\frac{h}{f} - \frac{\alpha}{2}\sin^4\frac{h}{f}}_{\text{SM contr.}} \underbrace{- \alpha_2 \cos^2\frac{h}{f} - \frac{\alpha}{2}\cos^4\frac{h}{f}}_{\text{Mirror contr.}}$$

$$\to \sin\frac{v}{f} = \cos\frac{v}{f}$$

$$\to v = 0 \ or \ f$$

NDA:

$$\alpha_2 \sim \cancel{\frac{3}{32\pi^2} y_t^2 f^2 m_{KK}^2}$$

$$\alpha \sim \frac{3}{64\pi^2} y_t^4 f^4 \log\frac{2M_{KK}^2}{y_t^2 f^2}$$

The Higgs Potential

Suppose we add a term:

$$V(h) = -\alpha \sin^2\frac{h}{f}\, cos^2\frac{h}{f} + \ \beta \sin^2\frac{h}{f}$$

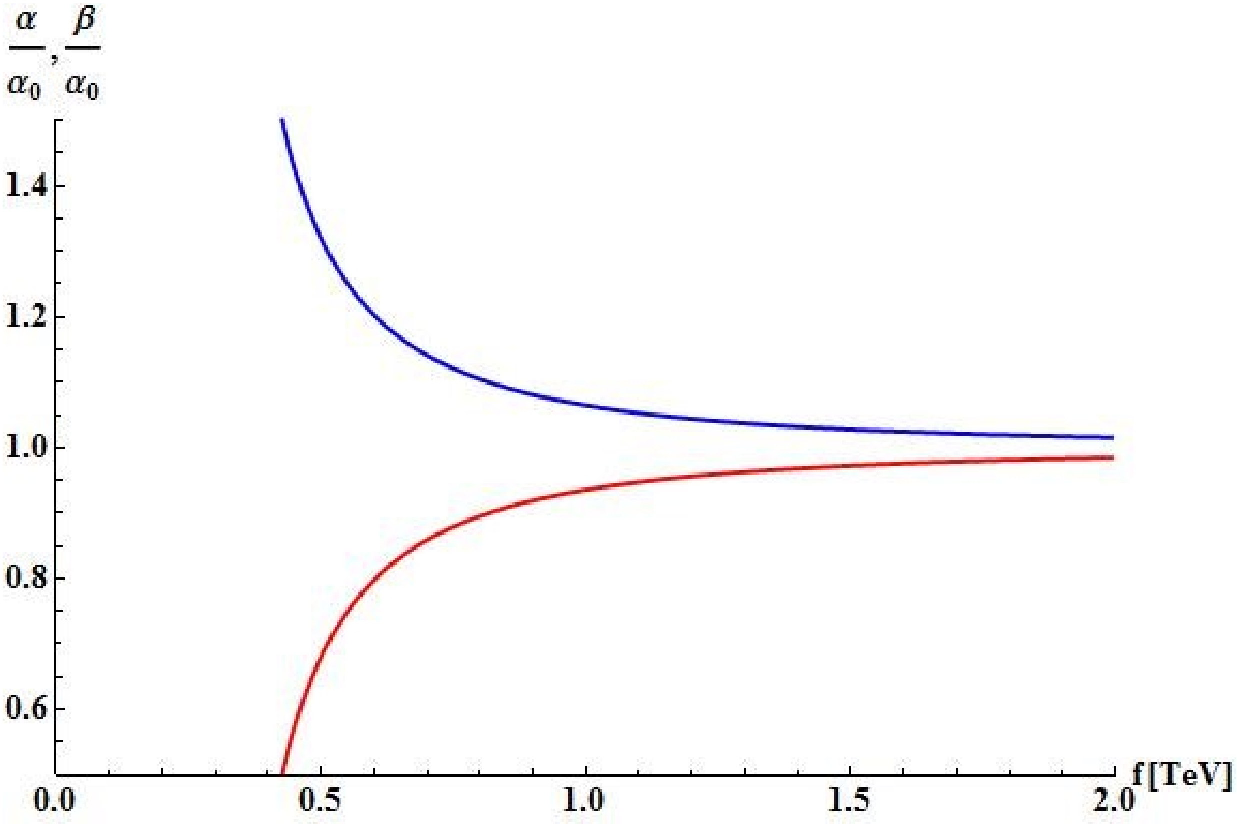
Higgs mass and vev

$$\frac{\alpha}{\alpha_0} = \frac{1}{1-\epsilon^2} \qquad \frac{\beta}{\alpha_0} = \frac{1-2\epsilon^2}{1-\epsilon^2}$$

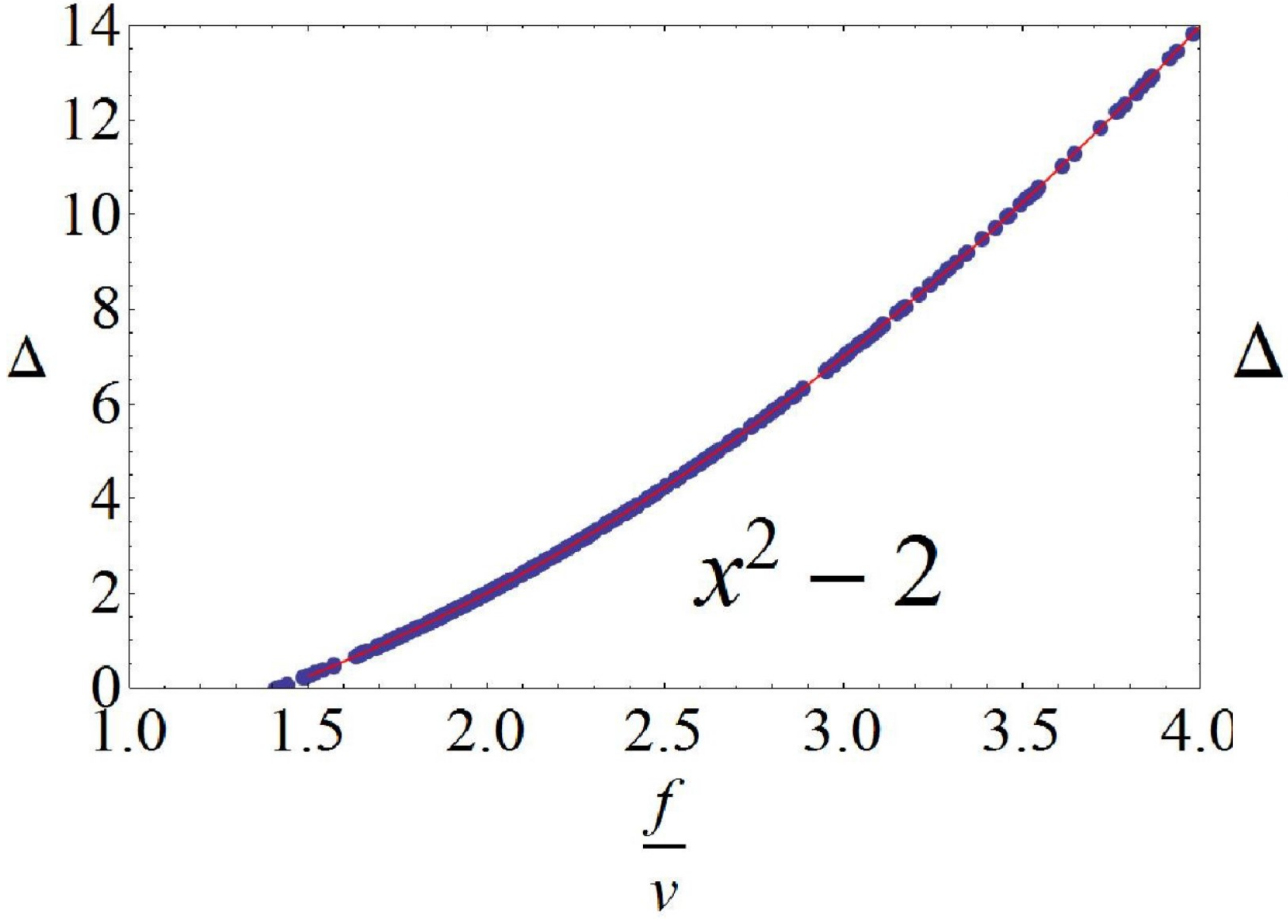
$$\alpha_0 = \frac{f^4 m_h^2}{8v^2} \qquad \epsilon = v/f$$

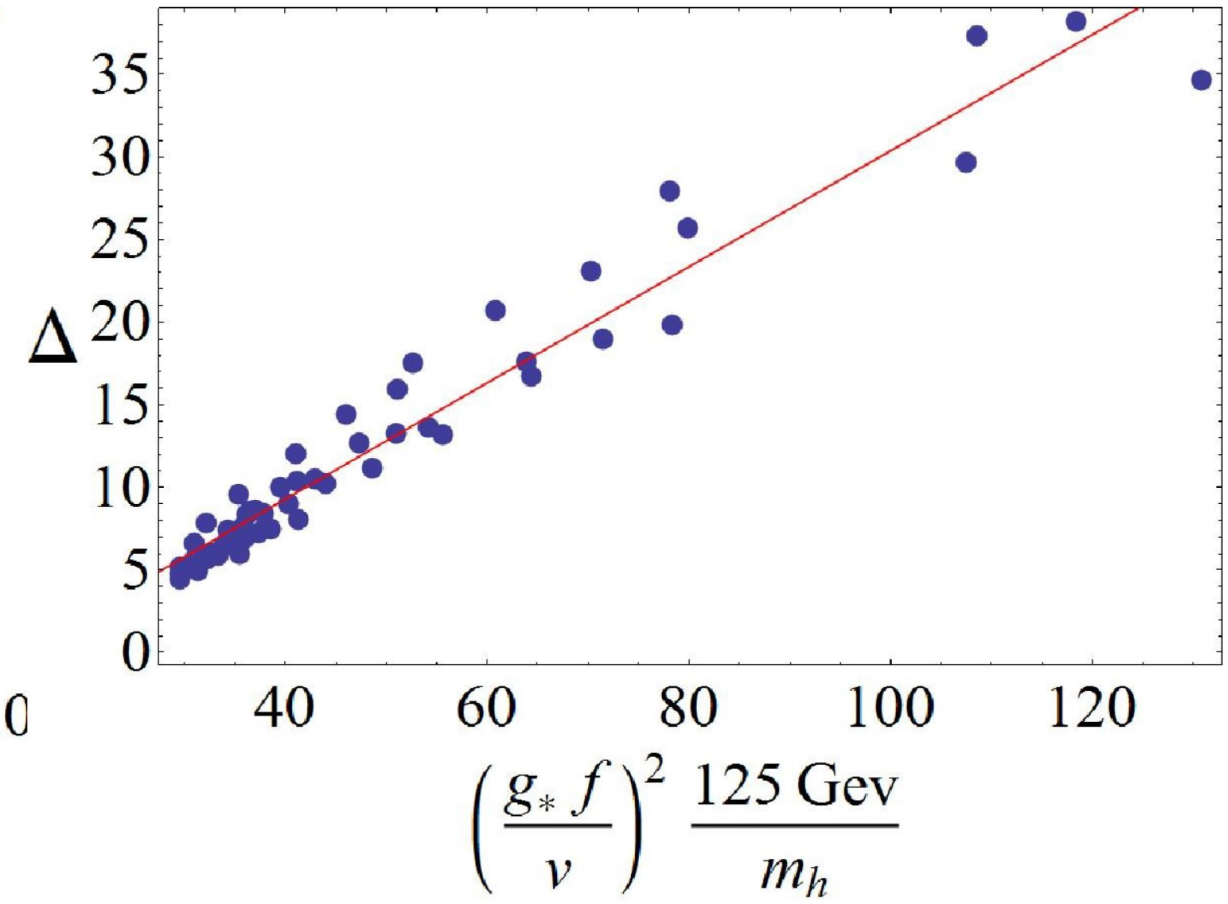
- The tuning is:

$$\Delta = \max\left|\frac{d\log v}{d\log p_i}\right| = \frac{1}{2}\left(\frac{f^2}{2v^2}-1\right)\max\left|\frac{d\log\alpha,\beta}{d\log p_i}\right|$$



Tuning





Tuning in CTH

Tuning in ordinary CH*

SO(5) with an adjoint and 2 fundamentals

The Flavor Story

No new flavor violating processes. Flavor violation scales as in CH.

Allowed parameter space is entirely different:

CH: high g_* is inconsistent with light Higgs. **Need light KK modes.**

CTH: The Higgs potential is (almost) independent of g_*. **KK modes can be heavy**

The main parameters

f	sigma model scale
g_*	coupling among composites.
$\widetilde{m}$	IR mixings
c	bulk masses

$M_{KK} = g_* f$	scale of excitations
$Y = \frac{g_* \widetilde{m}}{2}$	effective 5d Yukawa
f_c	fermion profile on IR

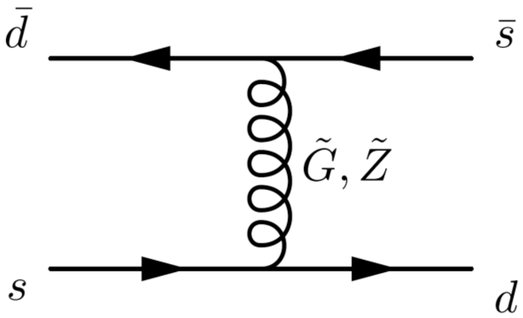
The flavor parameters

$$m_q \sim \frac{v}{\sqrt{2}} Y f_{q_L} f_{-q_R}$$

$$U_{L\,ij} \sim \frac{f_{q_{iL}}}{f_{q_{jL}}}, \; U_{R\,ij} \sim \frac{f_{-q_{iR}}}{f_{-q_{jR}}}$$

The Flavor Story

In Composite Higgs the main bound is the $\Delta F = 2$ in the Kaon system:



$$\sim g_{s*}^2 \frac{f_d f_s f_d f_s}{M_{KK}^2}$$

The bound is $\boldsymbol{M_{KK} > O(20\, TeV)}$.

Taken at face value, implies a sub-permille level tuning.

In CTH, the tuning is (almost) independent of $\boldsymbol{M_{KK}}$

Simple Estimates

The main bounds in the Kaon system are on the C_K^4, C_K^5 operators:

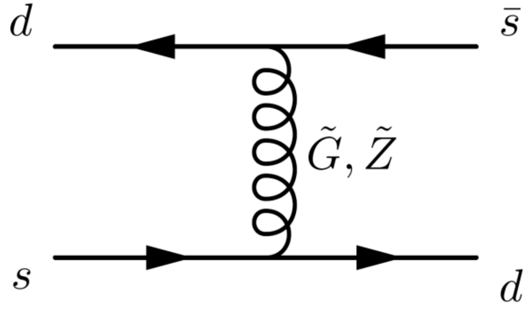
$$\mathrm{Im}(C_K^4)(\bar{s}_L^\alpha d_R^\alpha)(\bar{s}_R^\beta d_L^\beta)\ ,\ \Lambda_F > 1.6 \times 10^5\ \mathrm{TeV}$$

$$\mathrm{Im}(C_K^5)(\bar{s}_L^\alpha d_R^\beta)(\bar{s}_R^\beta d_L^\alpha)\ ,\ \Lambda_F > 1.4 \times 10^5\ \mathrm{TeV}$$

New bounds – 2 times better
Ligeti, Sala arXiv:1602.08494

We can estimate:

$$C_K^4 \sim \frac{1}{M_{KK}^2}\frac{g_{s*}^2}{g_*^2}\frac{8m_d m_s}{v^2}\frac{1+\tilde{m}_d^2}{\tilde{m}_d^2}$$
$$C_K^5 \sim \frac{1}{3}\left(4\frac{g_*^2}{g_{s*}^2} - 1\right) C_K^4,$$



Simple Estimates

Dipole moments:

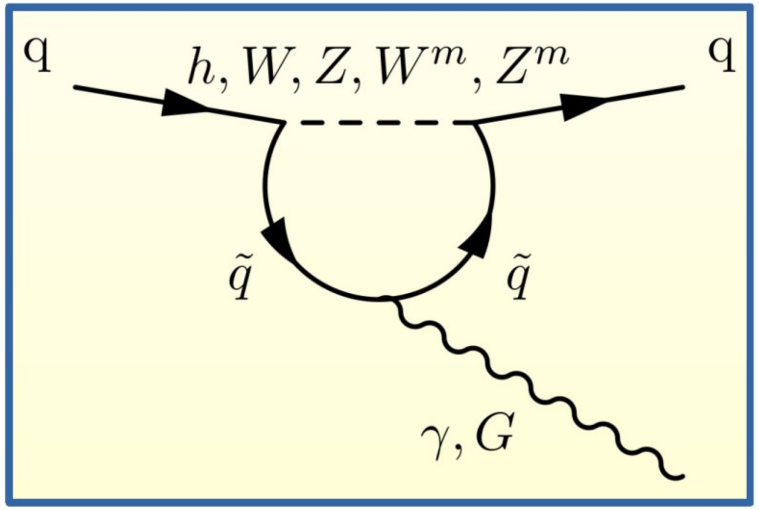
$$\frac{c}{8\pi^2 f^2} m_d \bar{d}_L \sigma^{\mu\nu} e F_{\mu\nu} d_R + \frac{\tilde{c}}{8\pi^2 f^2} m_d \bar{d}_L \sigma^{\mu\nu} g_s G_{\mu\nu} d_R$$

$$\frac{f}{\sqrt{c}} > 3.11 \text{ TeV} \ , \ \ \frac{f}{\sqrt{\tilde{c}}} > 3.79 \text{ TeV}.$$

Estimate:

$$c \sim \tilde{c} \sim \frac{1}{g_*^2 m_d} \frac{v}{\sqrt{2}} f_Q Y_d Y_d^\dagger Y_d f_{-d}$$

$$\sim \frac{1}{g_*^2}(Y^2) = \frac{\tilde{m}_d^2}{4}$$



Estimated Combined Bounds

Kaon $\Delta F = 2$:

$$g^{*2} f \tilde{m}_d > 106 \text{ TeV}$$

$$g^{*} f \tilde{m}_d > 17.7 \text{ TeV}$$

Dipoles:

$$\frac{f}{\tilde{m}_d} > 2.85 \text{ TeV}$$

Combination:

$$\boxed{g_* f > \max\left(1, \sqrt{\frac{g_*}{6.7}}\right) 17.3 \text{ TeV}}$$

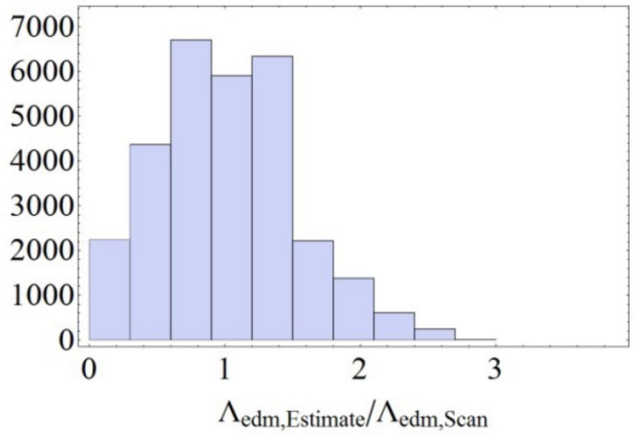
$$g_* = 4\pi \longrightarrow f > 1.9 \text{ TeV}$$

$$g_* = 2\pi \longrightarrow f > 2.7 \text{ TeV}$$

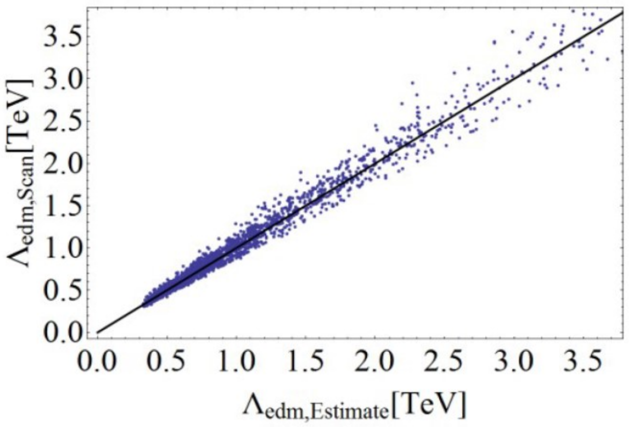
<u>Tuning:</u> $\frac{v^2}{f^2}$ **_O(1%) tuning_**

Verification in a Full Calculation

- We perform a scan with 7000 points that give correct EWSB in $g_*, f, c_{tL}, c_{tR}, \widetilde{m}_t$
- For each such point we produce 100 sets of light quark parameters that give the correct quark masses and CKM.

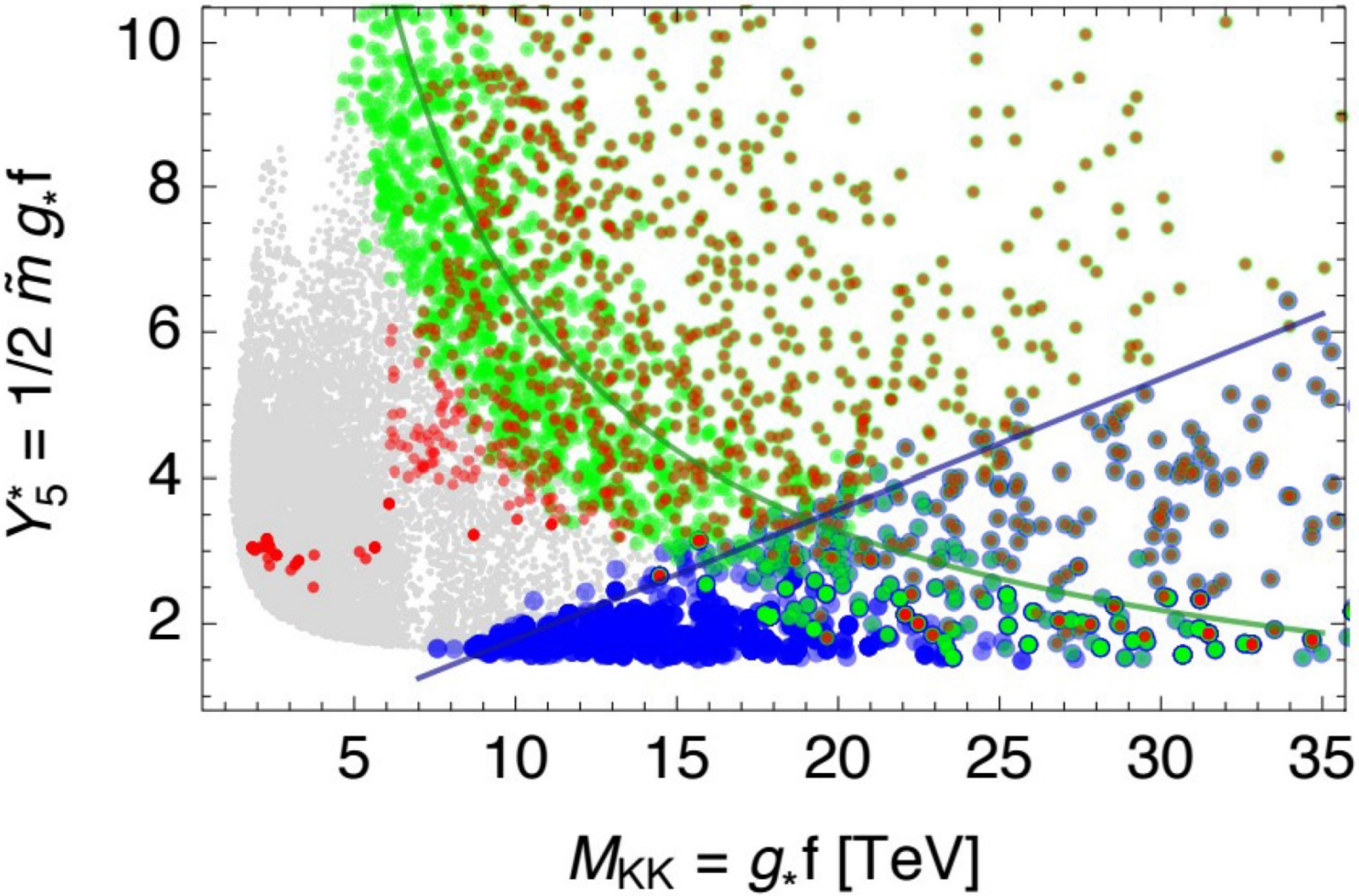


Histogram of ratio between exact results and the naïve estimate for nEDM



Exact results vs. naïve estimate for nEDM

The Full Results

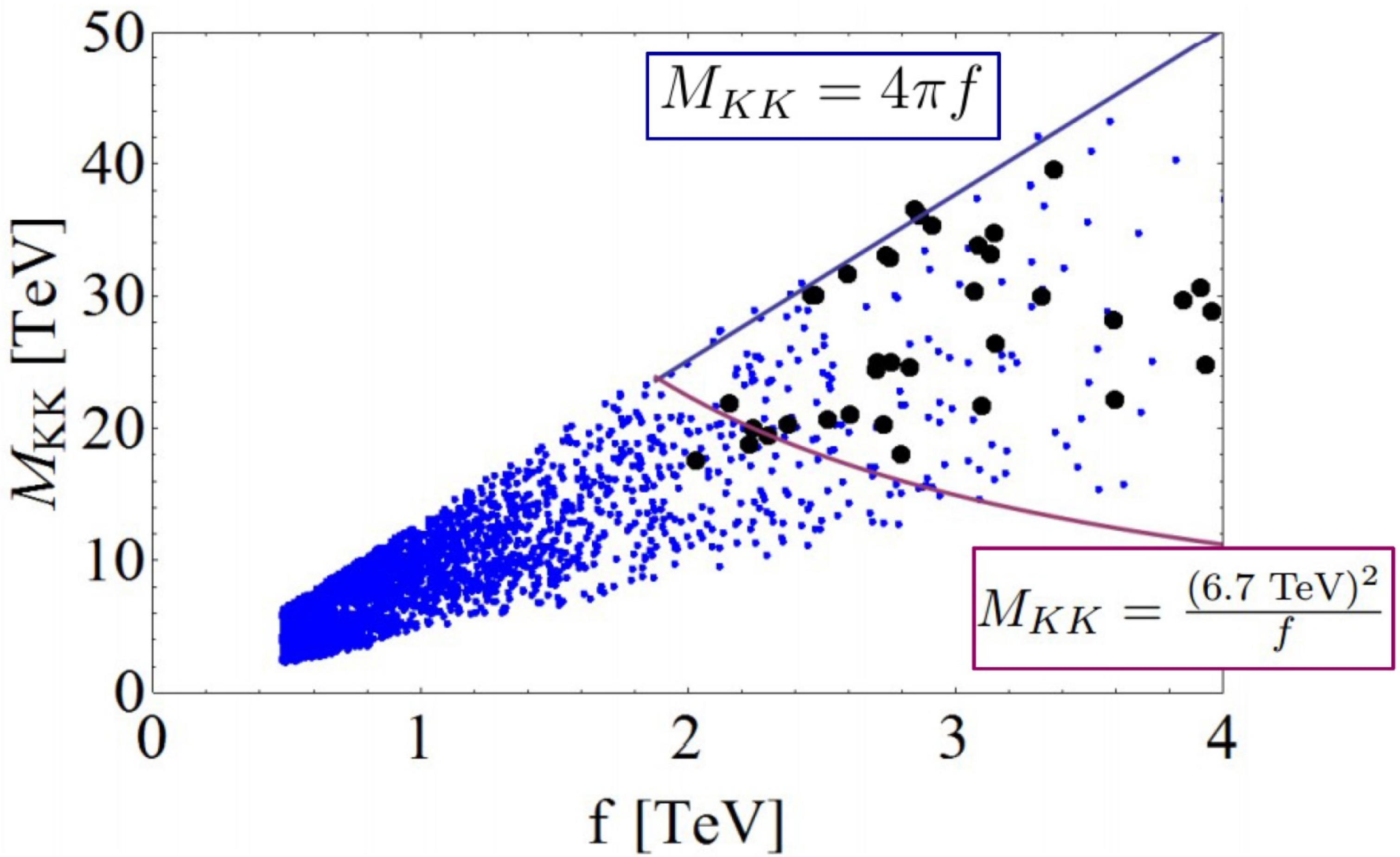


Green – pass C_K^4

Red – pass C_K^5

Blue – pass EDM

The Full Results



Summary

- To study flavor in neutral naturalness – UV theory.
- CTH is a simple UV theory with an inherent flavor structure.
- Flavor in CTH scales similarly to CH, but naturalness does not constrain the parameter space.
- An anarchic theory consistent with EWSB + Flavor at 1% tuning.

Thank You!


$M(H^0) = \pi \left(\frac{1}{137}\right)^8 \sqrt{\frac{hc}{G}}$
$3987^{12} + 4365^{12} = 4472^{12}$
$\Omega(t_0) > 1$

Fermion Masses

Mass terms

$$m_u = \frac{g_* v}{2\sqrt{2}} f_Q \tilde{m}_u f_{-u}$$

$$m_d = \frac{g_* v}{2\sqrt{2}} f_Q \tilde{m}_d f_{-d}$$

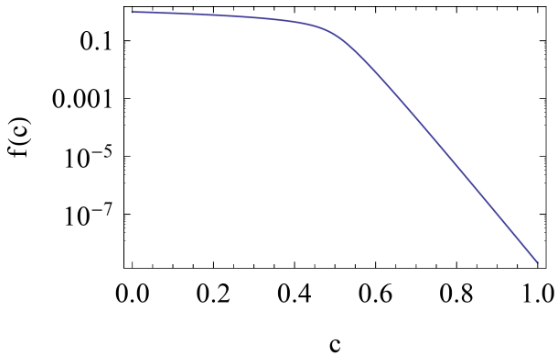
Kinetic Mixing: $\bar{\Psi} K \not{D} \Psi$

$$K_q = 1 + f_q \widetilde{m}_d f_d^{-2} \widetilde{m}_d^{\dagger} f_q$$

$$K_u = 1 + f_{-u} \widetilde{m}_u f_{-q}^{-2} \widetilde{m}_u^{\dagger} f_{-u}$$

$$K_d = 1$$

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



Physical top mass: $$m_t = \frac{\frac{g_* v}{2\sqrt{2}} \widetilde{m}_t f_q f_{-u}}{\sqrt{1+f_{-u}^2 f_{-q}^{-2}\, \widetilde{m}_t^2}}$$

Z_2 breaking – Higgs Potential

- Hypercharge -

$$\frac{1}{g'^2} = \log\frac{R'}{R}\left(\frac{1}{g_*^2} + \frac{1}{g_{X*}^2}\right) \approx \frac{1}{g_{X*}^2}\log\frac{R'}{R}$$

- Detune the $U(1)_X$ gauge coupling in the bulk

$$\beta_1 \approx \frac{3}{128\pi^2}(g'^2 - g'^2_m)g_*^2 f^4 \approx \frac{3}{128\pi^2}\frac{(g_{X*}^2 - g_{X*}^{m2})}{\log\frac{R'}{R}}g_*^2 f^4 \sim \delta_{g^2_{X*}}\alpha_0$$

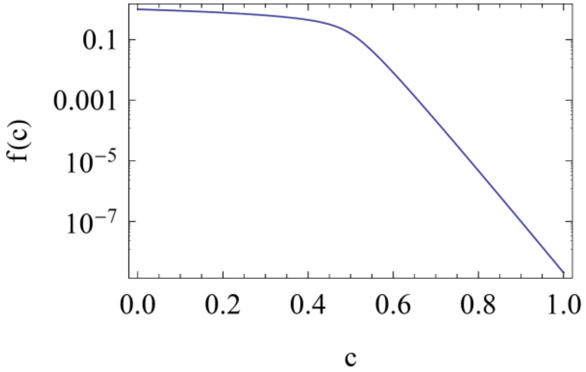
$$\beta_2 \sim 2\Delta c\,\alpha_2\frac{d\log y_t}{dc} \sim \delta_{g^2_{X*}}\alpha_0$$

$$\Rightarrow \qquad \beta \sim \delta_{g^2_{X*}}\alpha_0$$

Flavor in RS/Composite Higgs

In RS, the flavor structure of the SM is realized:

IR brane wavefunction: $$f_c = \sqrt{\frac{1-2c}{1-\left(\frac{R'}{R}\right)^{2c-1}}}$$



$$F_u = \mathrm{Diag}\left(f_u, f_c, f_t\right)\ ,\ F_d = \mathrm{Diag}\left(f_d, f_s, f_b\right)\ ,\ F_q = \mathrm{Diag}\left(f_{q_1}, f_{q_2}, f_{q_3}\right)$$

Anarchic IR Yukawas/mass parameters:

$$Y_{ij} = \begin{pmatrix} Y_{11} & Y_{12} & Y_{13} \\ Y_{21} & Y_{22} & Y_{23} \\ Y_{31} & Y_{32} & Y_{33} \end{pmatrix} \sim O(1)$$

$$m^u = \frac{v}{\sqrt{2}} Y_{ij} F_q F_u$$

$$m^d = \frac{v}{\sqrt{2}} Y_{ij} F_q F_d$$

$$V_{CKM}^{12} \sim \frac{f_{q1}}{f_{q2}} \quad V_{CKM}^{13} \sim \frac{f_{q1}}{f_{q3}} \quad V_{CKM}^{23} \sim \frac{f_{q2}}{f_{q3}}$$

Anarchic Quark Flavor: the ***8-1-28*** model

In the “bulk” basis:

Masses

$$m_u^{ij} = \left(\frac{g_* v}{2\sqrt{2}} F_Q \tilde{M}_u F_{-u} \right)^{ij}$$

$$m_d^{ij} = \left(\frac{g_* v}{2\sqrt{2}} F_Q \tilde{M}_d f_{-d} \right)^{ij}$$

Kinetic terms
(due to the IR mixing)

$$K_q^{ij} = \delta^{ij} + \left(F_q \tilde{M}_d F_d^{-2} \tilde{M}_d^\dagger F_q \right)^{ij}$$

$$K_u^{ij} = \delta^{ij} + \left(F_{-u} \tilde{M}_u F_{-q}^{-2} \tilde{M}_u^\dagger F_{-u} \right)^{ij}$$

$$K_d^{ij} = \delta^{ij}$$

In the mass basis

$$M_u = \frac{g_* v}{2\sqrt{2}} U_L^\dagger H_q F_Q \tilde{M}_u F_{-u} H_u U_R$$

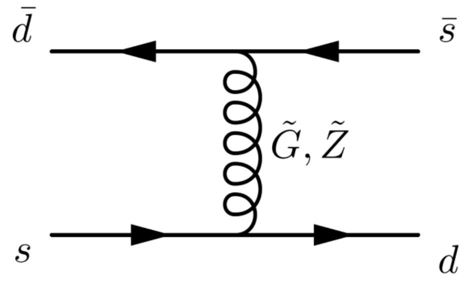
$$M_d = \frac{g_* v}{2\sqrt{2}} D_L^\dagger H_q F_Q \tilde{M}_d F_{-d} D_R$$

The main flavor and CP bounds

- **$\Delta F = 2$**: operators in the Kaon system:

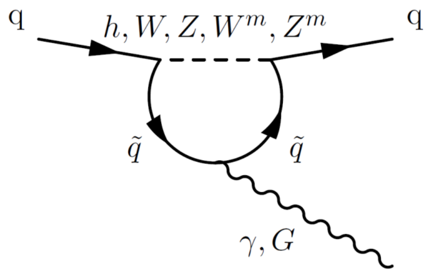
$$\mathrm{Im}(C_K^4)(\bar{s}_L^\alpha d_R^\alpha)(\bar{s}_R^\beta d_L^\beta)\ ,\ \Lambda_F > 1.6 \times 10^5\ \mathrm{TeV}$$

$$\mathrm{Im}(C_K^5)(\bar{s}_L^\alpha d_R^\beta)(\bar{s}_R^\beta d_L^\alpha)\ ,\ \Lambda_F > 1.4 \times 10^5\ \mathrm{TeV}$$

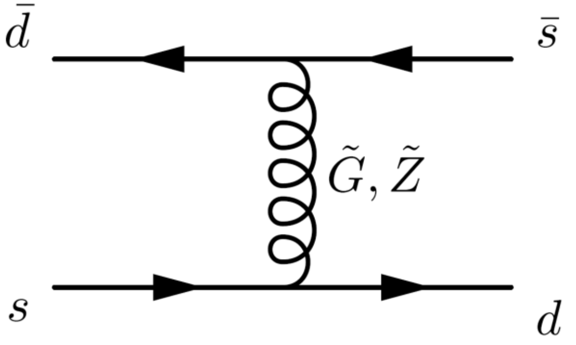


- ***Dipole operator***: Neutron EDM

$$\frac{c}{8\pi^2 f^2} m_d \bar{d}_L \sigma^{\mu\nu} e F_{\mu\nu} d_R + \frac{\tilde{c}}{8\pi^2 f^2} m_d \bar{d}_L \sigma^{\mu\nu} g_s G_{\mu\nu} d_R$$



The relevant bounds – Kaon mixing



$$g_L^d = D_L^\dagger H_q \left(g_8^{dL}(G) + F_q \tilde{M}_d F_d^{-2} g_{28}^{dL}(G) \tilde{M}_d{}^\dagger F_q \right) H_q D_L$$

$$g_L^u = U_L^\dagger H_q \left(g_8^{uL}(G) + F_q \tilde{M}_d F_d^{-2} g_{28}^{uL}(G) \tilde{M}_d{}^\dagger F_q \right) H_q U_L$$

$$g_R^d = D_R^\dagger g_{28}^{dR}(G) D_R$$

$$g_R^u = U_R^\dagger H_u \left(g_1^{uR}(G) + F_{-d} \tilde{M}_u F_{-q}^{-2} g_8^{uR}(G) \tilde{M}_u{}^\dagger F_{-d} \right) H_u U_R$$

$$\mathrm{Im}(C_K^4)(\bar{s}_L^\alpha d_R^\alpha)(\bar{s}_R^\beta d_L^\beta) \ , \ \Lambda_F > 1.6 \times 10^5 \text{ TeV}$$

$$\mathrm{Im}(C_K^5)(\bar{s}_L^\alpha d_R^\beta)(\bar{s}_R^\beta d_L^\alpha) \ , \ \Lambda_F > 1.4 \times 10^5 \text{ TeV}$$

KK gluon

$$\mathrm{Im}(C_K^4) = -\mathrm{Im}(3C_k^5) = \mathrm{Im}(g_L^{s12} g_R^{s21}) \sim \frac{1}{f^2} \frac{g_{s*}^2}{g_*^4} \frac{1}{\tilde{m}^2} \frac{8 m_d m_s}{v^2}$$

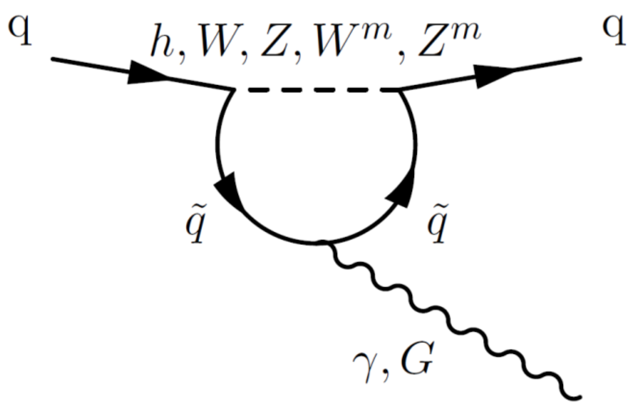
KK Z

$$C_K^4 = 0 \ , \mathrm{Im}(C_k^5) = 2\,\mathrm{Im}(g_L^{Z_H 12} g_R^{Z_H 12} + g_L^{Z' 12} g_R^{Z' 21}) \sim \frac{4}{3f^2} \frac{1}{g_*^2} \frac{1}{\tilde{m}^2} \frac{8 m_d m_s}{v^2}$$

$$C_K^4 \sim \frac{1}{(1.6 \times 10^5 \text{ TeV})^2} \left(\frac{100 \text{ TeV}}{g_*^2 f \tilde{m}_d} \right)^2$$

$$C_K^5 \sim \frac{1}{(1.4 \times 10^5 \text{ TeV})^2} \left(\frac{100 \text{ TeV}}{g_*^2 f \tilde{m}_d} \right)^2 \frac{1}{4} \left[\left(\frac{g_*}{3} \right)^2 - 1 \right]$$

The relevant bounds – Neutron EDM



$$\frac{c}{8\pi^2 f^2} m_d \bar{d}_L \sigma^{\mu\nu} e F_{\mu\nu} d_R + \frac{\tilde{c}}{8\pi^2 f^2} m_d \bar{d}_L \sigma^{\mu\nu} g_s G_{\mu\nu} d_R$$

Approximation: First KK state fermions

$$c = \sum_{\Psi,X} \frac{m_\Psi}{m_d m_X^2} V_{XR}^{d\Psi} V_{XL}^{d\Psi*} L_X^\Psi \ , \ \tilde{c} = \sum_{\Psi,X} \frac{m_\Psi}{m_d m_X^2} V_{XR}^{d\Psi} V_{XL}^{d\Psi*} \tilde{L}_X^\Psi$$

$$c = \frac{1}{4} \frac{1}{g_*^2} \frac{v}{\sqrt{2}} D_L^\dagger H_d F_Q Y_d Y_d^\dagger Y_d F_{-d} D_R$$

$$\tilde{c} = \frac{9}{4} \frac{1}{g_*^2} \frac{v}{\sqrt{2}} D_L^\dagger H_d F_Q Y_d Y_d^\dagger Y_d F_{-d} D_R$$

$$Y_d = \frac{g_*}{2} \tilde{m_d}$$

$$\frac{f}{\sqrt{c}} > 3.11 \text{ TeV} \ , \ \frac{f}{\sqrt{\tilde{c}}} > 3.79 \text{ TeV}$$

$$\boxed{\frac{f}{\tilde{m_d}} > 2.85 \text{ TeV}}$$

A comment on $\Delta F = 1$

We take the example of $t \to cZ$:

$$Br(t \to cZ) \sim 1 \times 10^{-6} \frac{(1\ \mathrm{TeV})^4}{f^4} \frac{1}{g_*^2}$$

See e.g. **A. Azatov, G. Panico, G. Perez, Y. Soreq, arXiv:1408.4525**

Well below LHC reach!

Note that $t \to cZ^m$ is not allowed by $T_L^{3m} = T_R^{3m} = 0$ in the quark sector.

The Spectral Function in CTH

$$f_t = \frac{\frac{1}{2}C_{-1}\widetilde{m}_u^2}{\left(C_{-8}S_1 + C_{-1}S_8\widetilde{m}_u^2\right)S_{-8}} \qquad C_{\pm i} \equiv C_{\pm c_i}(R',p),\ S_{\pm i} \equiv S_{\pm c_i}(R',p)$$

$$\begin{aligned}(kz)^{c+2}C_c(z,p) &= \frac{\pi p}{2k}(kz)^{\frac{5}{2}}\left[J_{c+\frac{1}{2}}\left(\frac{p}{k}\right)Y_{c-\frac{1}{2}}(zp) - Y_{c+\frac{1}{2}}\left(\frac{p}{k}\right)J_{c-\frac{1}{2}}(zp)\right]\\ (kz)^{c+2}S_c(z,p) &= \frac{\pi p}{2k}(kz)^{\frac{5}{2}}\left[J_{\frac{1}{2}-c}\left(\frac{p}{k}\right)Y_{\frac{1}{2}-c}(zp) - Y_{\frac{1}{2}-c}\left(\frac{p}{k}\right)J_{\frac{1}{2}-c}(zp)\right]\end{aligned}$$