The Composite Twin Higgs and Anarchic Flavor

Michael Geller

Technion

M.G. and O. Telem, Phys.Rev.Lett. 114 (2015) 191801

C. Csaki, M.G., O. Telem and A. Weiler, to appear in 2015

Motivation

Neutral naturalness → ***Can naturalness hide @ LHC?***

The first neutrally natural model – Twin Higgs

Twin Higgs needs a UV completion – ***composite/warped***

Composite Twin Higgs ***- Is RS GIM/partial compositness enough to suppress flavor and cp?***

The Twin Higgs Model

Z. Chacko, H. S. Goh and R. Harnik, Phys. Rev. Lett. 96 (2006) 231802
Bottom-up approach: N. Craig, A. Katz, M. Strassler, R. Sundrum ,arXiv:1501.05310

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:

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

($SU(2)^A$ → v, $SU(2)^B$ → f)

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

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!

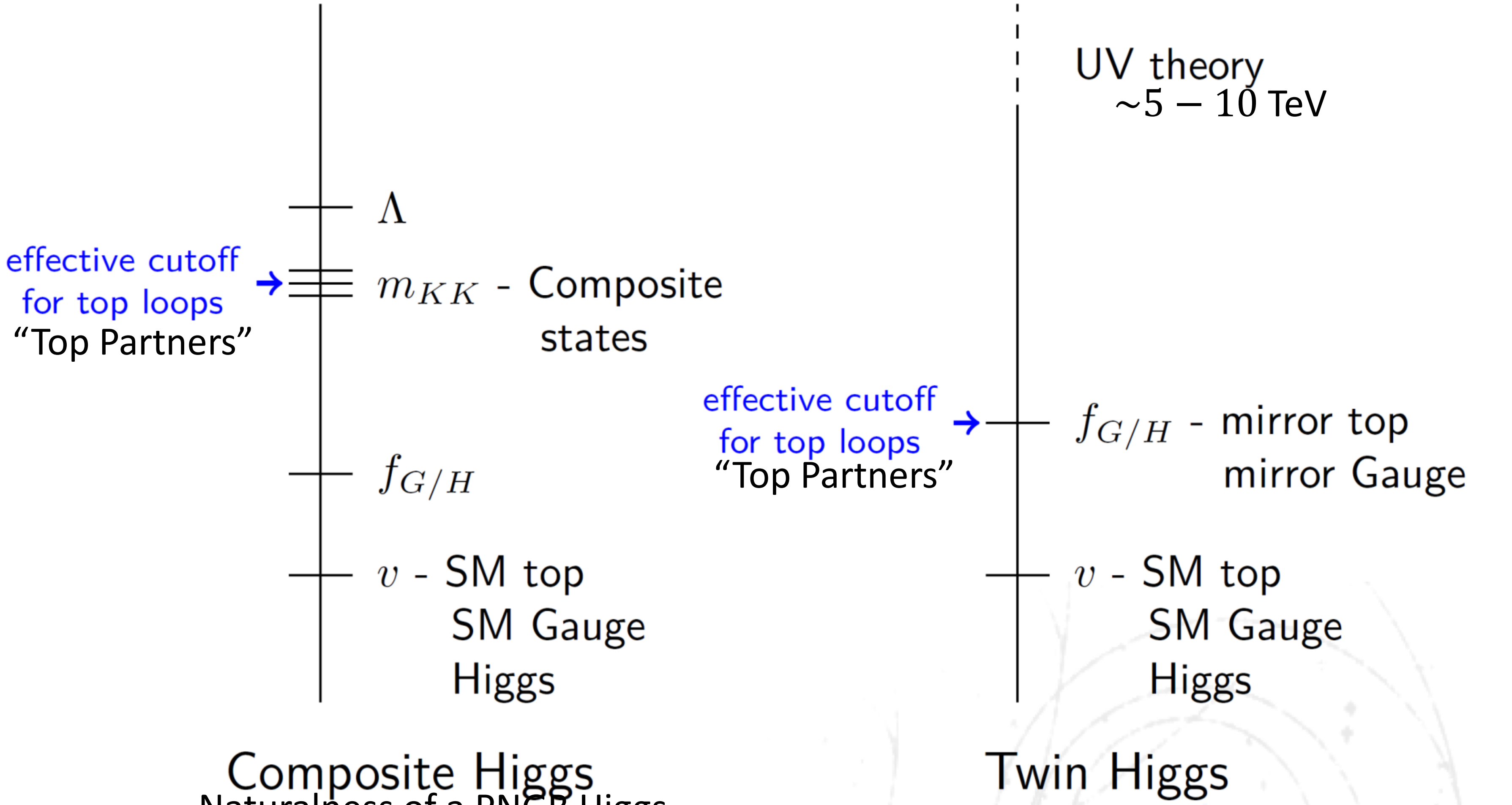
To have the same effect for the top loop: ***double the SM symmetry***

$$\underbrace{\left(SU(3) \times SU(2) \times U(1)\right)^A}_{\text{SM}} \times \underbrace{\left(SU(3) \times SU(2) \times U(1)\right)^B}_{\text{"Mirror" SM}} \qquad H = \begin{pmatrix} 0 \\ v \\ 0 \\ f \end{pmatrix}$$

Top partners are SM singlets – "Mirror Partners"!

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

Twin Higgs and Composite Higgs

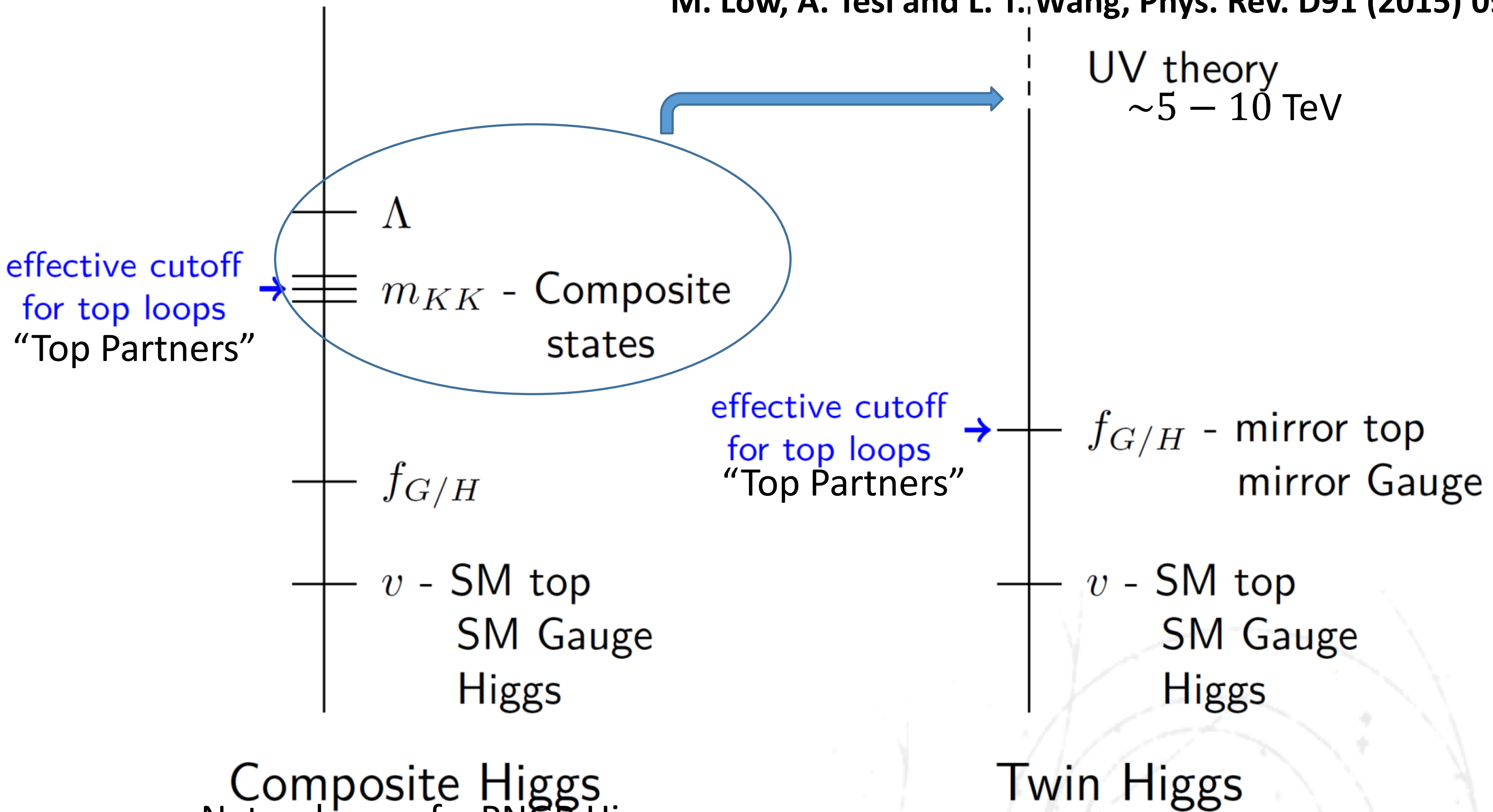


Naturalness of a PNGB Higgs
Requires light Composite states –
charged/colored naturalness

Solution to the little hierarchy
problem. “Neutral Naturalness”

Twin Higgs and Composite Higgs

R. Barbieri, D. Greco, R. Rattazzi and A. Wulzer, JHEP 1508, (2015) 161
M. Low, A. Tesi and L. T. Wang, Phys. Rev. D91 (2015) 095012



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R. Barbieri, D. Greco, R. Rattazzi and A. Wulzer, JHEP 1508 (2015) 161

M. Low, A. T

SUSY:

N. Craig and K. Howe JHEP 1403 (2014) 140

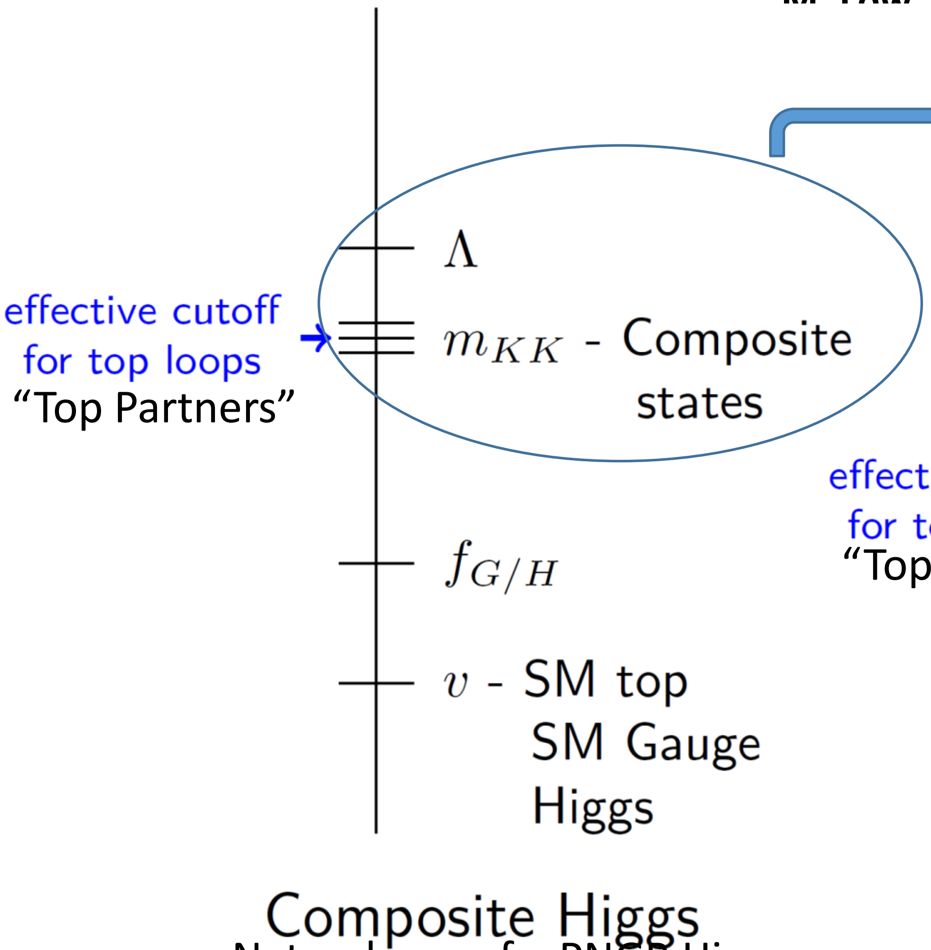
A. Falkowski, S. Pokorski, M. Schmaltz, Phys.Rev. D74(2006) 035003;

S. Chang , L. J. Hall, N.Weiner Phys.Rev. D75 (2007) 035009

Orbifold:

N. Craig, S. Knapen, P. Longhi, JHEP 1503 (2015) 106

N. Craig, S. Knapen, P. Longhi , Phys.Rev.Lett. 114 (2015) 6, 061803



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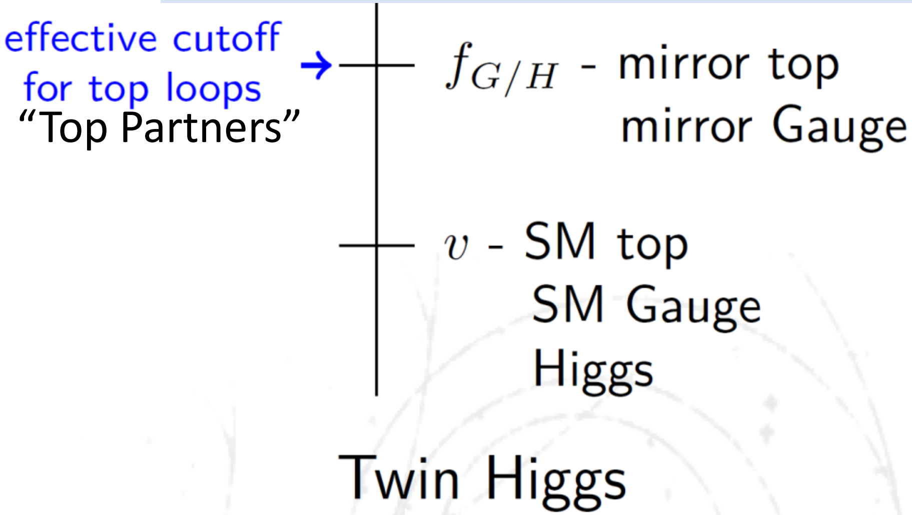
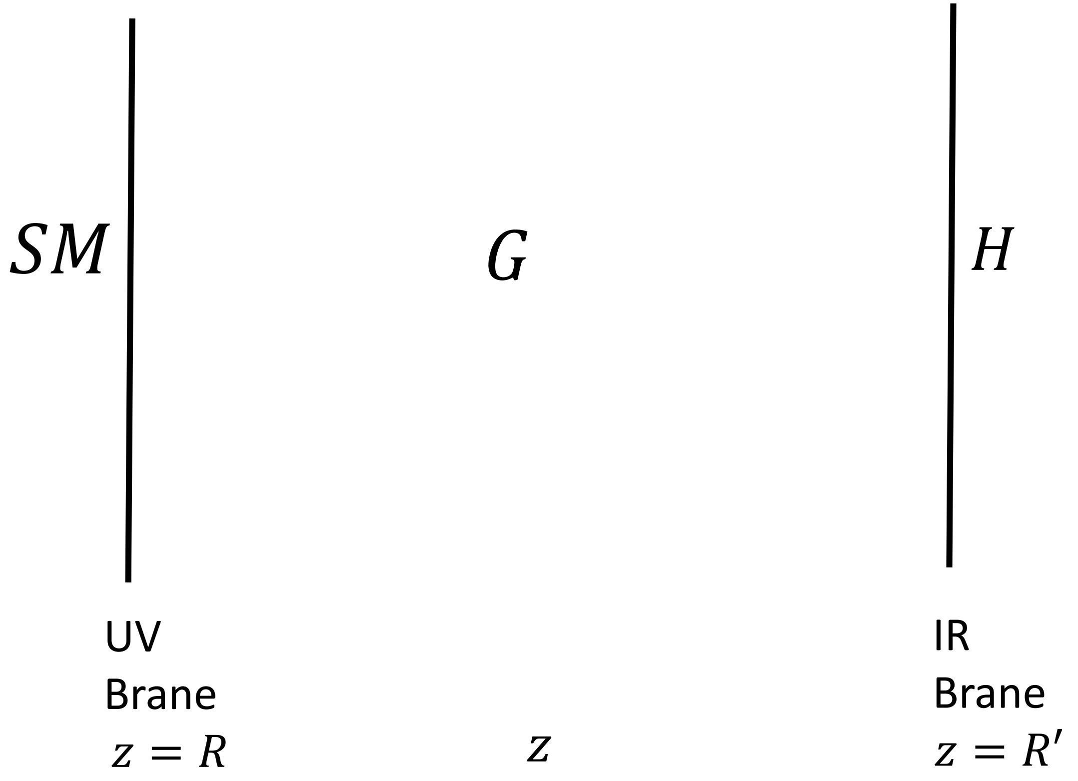


Solution to the little hierarchy problem. “Neutral Naturalness”

Composite Higgs (Gauge-Higgs Unification)

- The holographic dual of composite Higgs:



The Higgs is the fifth component of the G/H gauge fields:

$$A_5(z) = \sqrt{\frac{2}{R}\frac{z}{R'}}T^a_{G/H}h^a$$

The A_5 is a zero mode at tree level, and gets potential due to (mostly) top and SM gauge loops.

Gauge Higgs Unification

- To find the Higgs potential we need to find the masses of the KK modes.

(+) b.c.

q_L $\qquad \Psi_q\ (rep. of\ G)$ $\qquad$ (+) b.c. $\Psi^1_{qL}, \Psi^2_{qL} \ldots (rep. of\ H)$

t_R $\qquad \Psi_u\ (rep. of\ G)$ $\qquad \Psi^1_{uR}, \Psi^2_{uR} \ldots (rep. of\ H)$

IR mass terms: $m\Psi^1_{qL}\Psi^1_{uR}\ \ldots$

UV Brane $z = R$ $\qquad z \qquad$ IR Brane $z = R'$

Gauge Higgs Unification

The Gauge-Higgs vev enters the fermion EOMs:

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

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

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

$$\Omega = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \cos(\frac{v}{f}) & 0 & 0 & 0 & \sin(\frac{v}{f}) \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -\sin(\frac{v}{f}) & 0 & 0 & 0 & \cos(\frac{v}{f}) \end{pmatrix}$$

The Higgs Potential

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

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

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

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

The Holographic Twin Higgs

$$SM \times mirror \times Z_2$$

$$G: SO(8) \times SU(3)_c \times U(1)_X \times SU(3)_c^m \times U(1)_X^m \times Z_2$$

$$H: SO(7) \times SU(3)_c \times U(1)_X \times SU(3)_c^m \times U(1)_X^m \times Z_2$$

$$SO(8) \to SU(2)_L \times SU(2)_R \times SU(2)_L^m \times SU(2)_R^m \qquad Y = T_R^3 + X \qquad Y^m = T_R^{3m} + X^m$$

Possibly: $SU(3)_c \times U(1)_x \times SU(3)_c^m \times U(1)_x^m \times Z_2 \in SU(7)$

The Top Quark

	SO(8)	$SU(3)_c$	$U(1)_X$
Ψ_q	8	3	2/3
Ψ_t	1	3	2/3

$\longleftrightarrow$ $bulk\ Z_2$, 7 of SU(7)

	SO(8)	$SU(3)_c^{\mathrm{m}}$	$U(1)_X^{\mathrm{m}}$
Ψ_q^m	8	3	2/3
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UV b.c. (+):

	$SU(2)_L$	$SU(3)_c$	$U(1)_Y$
Q_L	**2**	**3**	1/6
t_R	**1**	**3**	2/3

$UV\ Z_2$ ⟷

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IR b.c. (+):

	SO(7)	$SU(3)_c$	$U(1)_X$
Ψ_{qL}^7, Ψ_{qL}^1	7,1	3	2/3
Ψ_{tR}	1	3	2/3

$IR\ Z_2$, 7 of SU(7) ⟷

	SO(7)	$SU(3)_c^{\mathrm{m}}$	$U(1)_X^{\mathrm{m}}$
$\Psi_{qL}^{7m}, \Psi_{qL}^{1m}$	7,1	3	2/3
Ψ_{tR}^m	1	3	2/3

IR masses: $m_t^1 \Psi_{qL}^1 \Psi_{tR}$

IR masses: $m_t^1 \Psi_{qL}^{1m} \Psi_{tR}^m$

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 top mass

- At low energies

$$\rho_t(p) \approx 1 - m_t^2/p^2 \qquad \rho_{tm}(p) \approx 1 - m_{tm}^2/p^2$$

- The top mass can be calculated

$$m_t = \frac{\frac{g_* v}{2\sqrt{2}} \tilde{m}_t f_q f_{-u}}{\sqrt{1 + f_{-u}^2 f_{-q}^{-2}\, \tilde{m}_t^2}} \qquad f_c = \sqrt{\frac{1-2c}{1-\left(\frac{R'}{R}\right)^{2c-1}}}$$

- Using the known $m_t(3\ TeV)$ we can find $g_*(c_q, c_u, \tilde{m}_t\ )$

The Higgs Potential

The Higgs potential:

$$V(h) \approx \underbrace{-\alpha_2 \sin^2 \frac{h}{f} + \frac{\alpha}{2} \sin^4 \frac{h}{f}}_{\text{Top+Gauge}} \underbrace{- \alpha_2\, cos^2 \frac{h}{f} + \frac{\alpha}{2} \cos^4 \frac{h}{f}}_{\text{Mirror top+gauge}} = \alpha \sin^2 \frac{h}{f} \cos^2 \frac{h}{f} + const$$

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

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

The Higgs Potential

Suppose we have added a term:

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

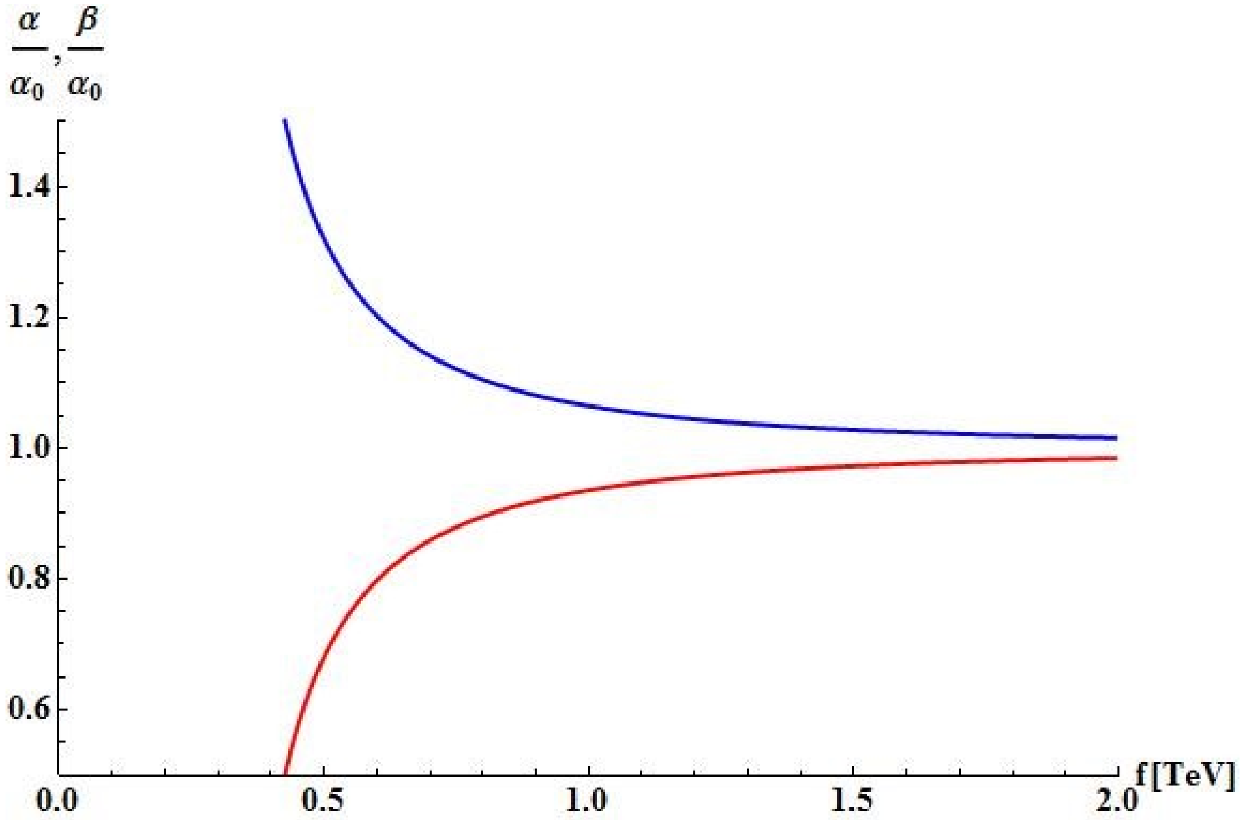
Higgs mass and vev

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

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

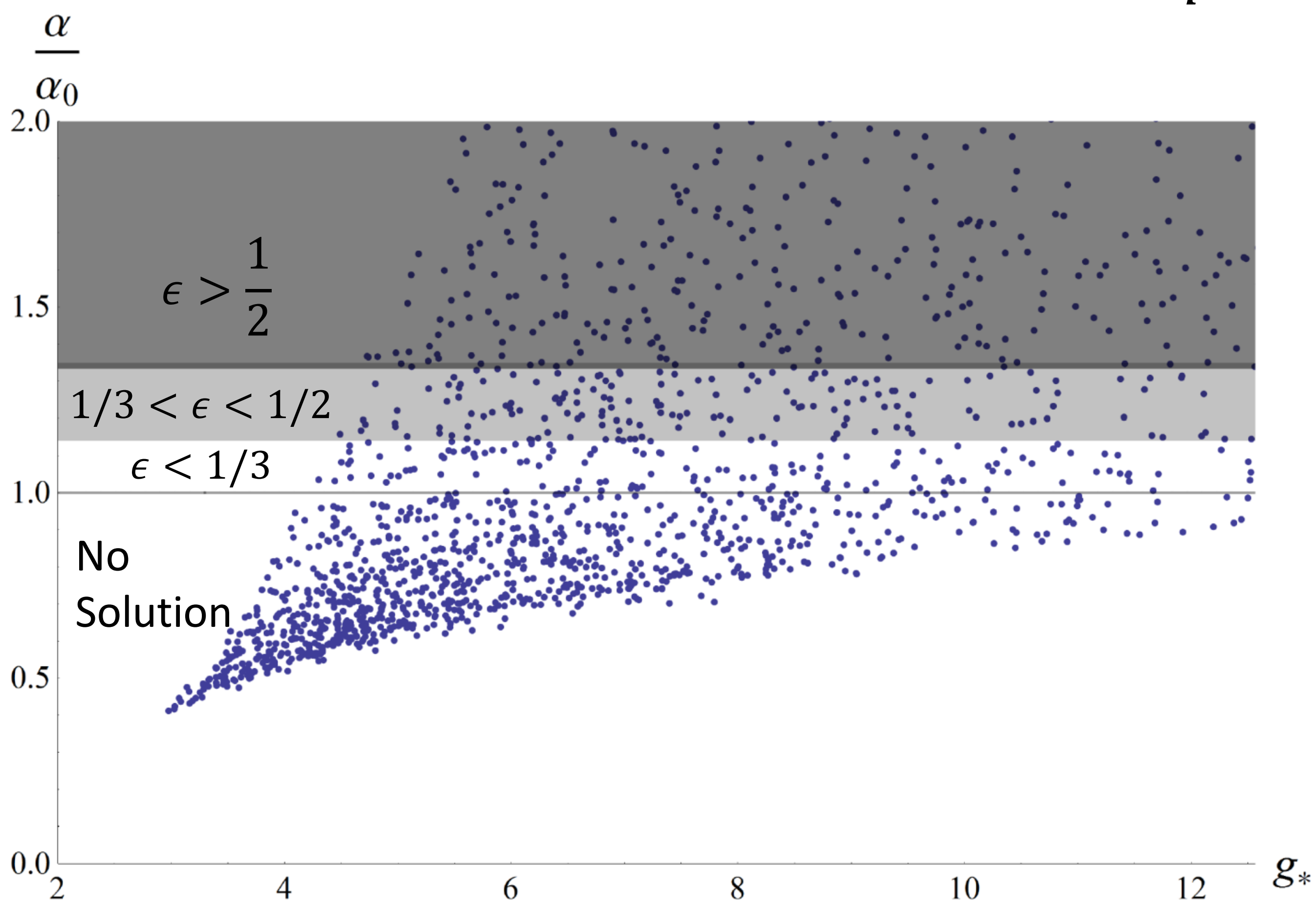
- The tuning is:

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



The Higgs Potential

- The Z_2 conserving contribution - $\alpha(c_q, c_u, m)$



$$\Delta \sim \frac{f^2}{v^2}$$

Holographic Twin Higgs

Naturalness without KK – tops

- The KK tops don't enter the tuning.
- The tuning scales as f^2/v^2 – Higgs data.
- M_{KK} can be arbitrarily high, but unitarity requires $M_{KK} < 4\pi f$

Need Z_2 breaking

- Higgs potential – $\beta \sin^2 \frac{h}{f}$
- Dark radiation – Mirror neutrinos and Mirror photon.

Anarchic Flavor in Warped/Composite Higgs

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In CH anarchic flavor is in tension with naturalness:

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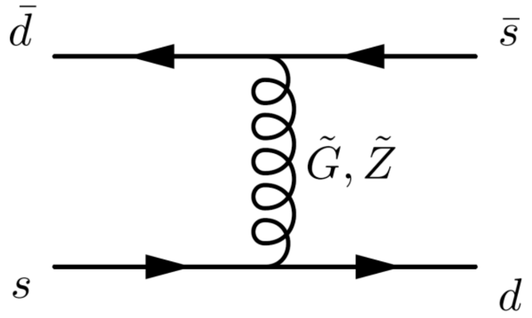
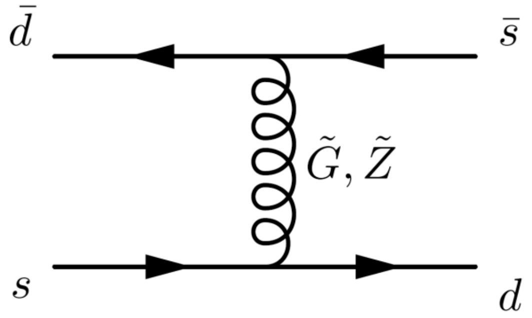


$$C_K^4 \sim \frac{1}{(1.6 \times 10^5\ \text{TeV})^2} \left(\frac{100\ \text{TeV}}{g_*^2 f \tilde{m}_d} \right)^2 \qquad g_*^2 f \tilde{m}_d > 100\ \text{TeV}\ ,\ \ g_* < 6.7$$

$$C_K^5 \sim \frac{1}{(1.4 \times 10^5\ \text{TeV})^2} \left(\frac{100\ \text{TeV}}{g_*^2 f \tilde{m}_d} \right)^2 \frac{1}{4} \left[\left(\frac{g_*}{3} \right)^2 - 1 \right] \qquad g_* f \tilde{m}_d > 17.7\ \text{TeV}\ ,\ \ g_* > 6.7$$

Anarchic Flavor in Warped/Composite Higgs

In CH anarchic flavor is in tension with naturalness:



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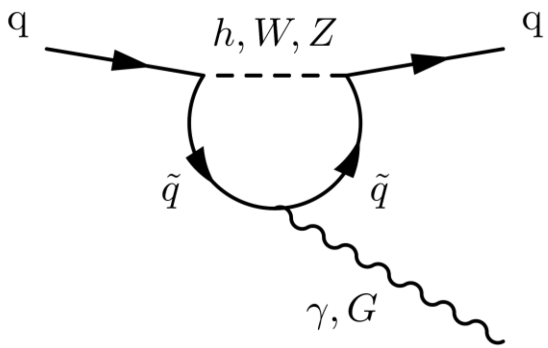

$$\frac{c}{8\pi^2 f^2} m_d \bar{d}_L \sigma^{\mu\nu} e F_{\mu\nu} d_R$$

$$c \sim \frac{1}{g_*^2 m_d}\frac{v}{\sqrt{2}}\left[f_Q (Y_d Y_d^\dagger + Y_u Y_u^\dagger) Y_d f_{-d}\right] \sim \frac{1}{g_*^2}(Y^2) = \frac{\tilde{m}_d^2}{2}$$

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

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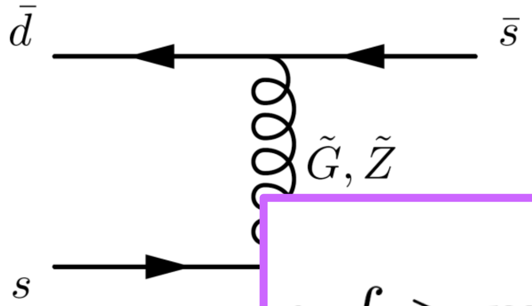


$$C_K^4 \sim \frac{1}{(1.6\times 10^5\ \text{TeV})^2}\left(\frac{100\ \text{TeV}}{g_*^2 f \tilde{m}_d}\right)^2$$

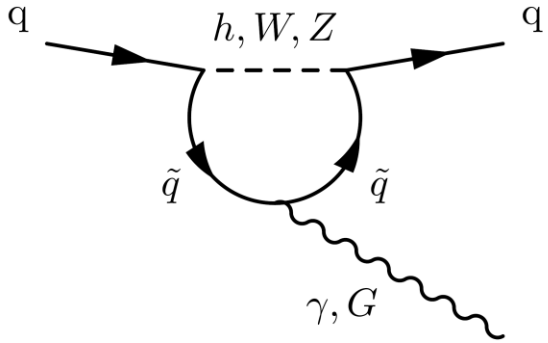
$$C_K^5 \sim \frac{1}{\ldots}\left(\frac{100\ \text{TeV}}{\ldots}\right)^2 \frac{1}{4}\left[\left(\frac{g_*}{3}\right)^2 - 1\right]$$

$$g_*^2 f \tilde{m}_d > 100\ \text{TeV}\ ,\ \ g_* < 6.7$$

$$g_* f \tilde{m}_d > 17.7\ \text{TeV}\ ,\ \ g_* > 6.7$$

$$g_* f > \max\left(1, \sqrt{\frac{g_*}{6.7}}\right) 17\ \text{TeV}$$

→ ***< 0.1% tuning***



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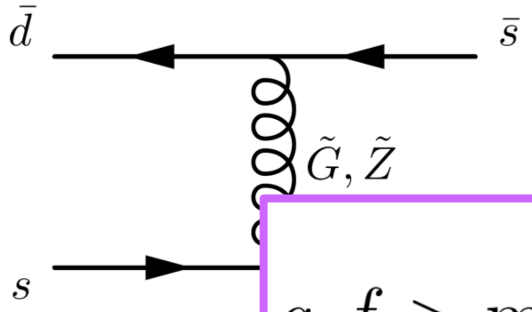


$$C_K^4 \sim \frac{1}{(1.6 \times 10^5\ \text{TeV})^2}\left(\frac{100\ \text{TeV}}{g_*^2 f \tilde{m}_d}\right)^2$$

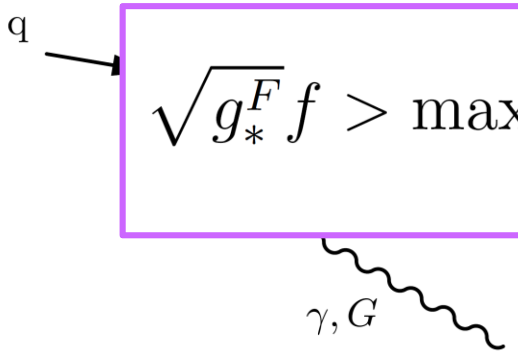
$$C_K^5 \sim \frac{1}{\cdots}\left(\frac{100\ \text{TeV}}{\cdots}\right)^2 \frac{1}{4}\left[\left(\frac{g_*}{3}\right)^2 - 1\right]$$

$g_*^2 f \tilde{m}_d > 100\ \text{TeV}\ ,\ g_* < 6.7$

$g_* f \tilde{m}_d > 17.7\ \text{TeV}\ ,\ g_* > 6.7$

$$g_* f > \max\left(1, \sqrt{\frac{g_*}{6.7}}\right) 17\ \text{TeV}$$

→ **_< 0.1% tuning_**



$$\sqrt{g_*^F} f > \max\left(\sqrt{\frac{1}{g_*^V}}, \sqrt{\frac{1}{6.7}}\right) 17\ \text{TeV}$$

→ **_~ 0.3% tuning_**

$$\cdots Y_u^\dagger) Y_d f_{-d}\right] \sim \frac{1}{g_*^2}(Y^2) = \frac{\tilde{m}_d^2}{2}$$

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

Anarchic Flavor in Composite Twin Higgs

The bounds are similar

$$g_* f > \max\left(1, \sqrt{\frac{g_*}{6.7}}\right) 17 \text{ TeV}$$

The tuning scales as $\frac{v^2}{f^2}$***,*** g_* ***is essentially a free parameter.***

For $g_* \to 4\pi$ ***,*** $f \sim 1.85\ TeV$ ***and the tuning is*** $\sim 2\%$

More realistically, $g_* \sim 2\pi$ ***leads to 1% tuning.***

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 relevant bounds – Kaon mixing

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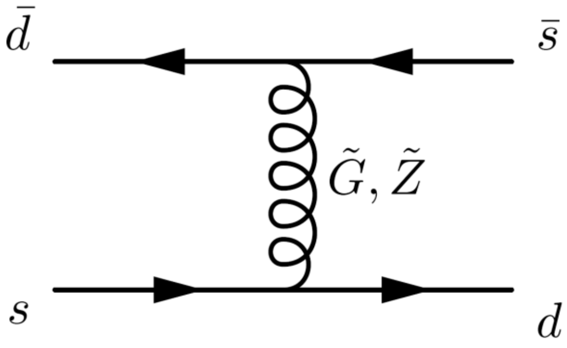

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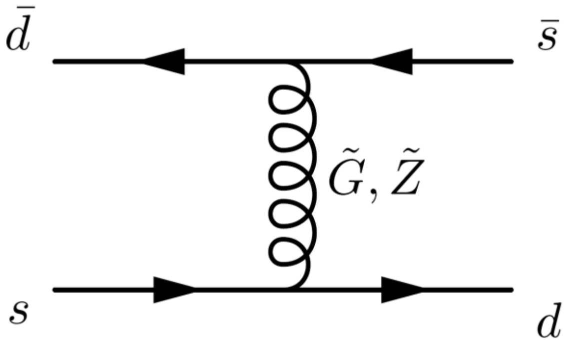


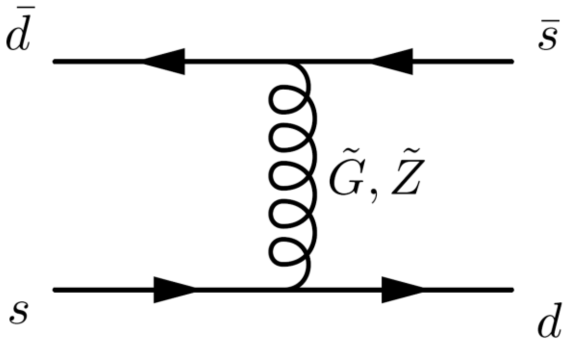
$$g_L^d = D_L^\dagger H_q \left(g_8^{dL}(G) + F_q \tilde{M}_d F_d^{-2} g_{28}^{dL}(G) \tilde{M}_d^\dagger F_q \right) H_q D_L$$

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

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

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

The relevant bounds – Kaon mixing



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

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

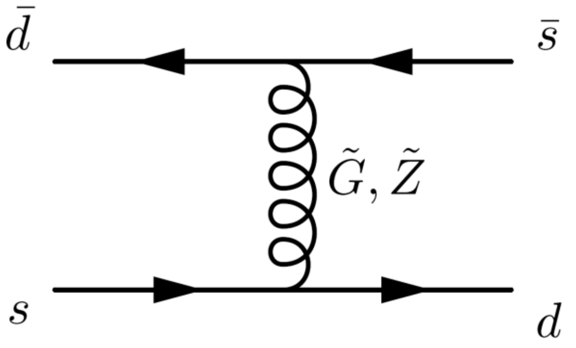
KK gluon

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

KK Z

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

The relevant bounds – Kaon mixing



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

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

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

The relevant bounds – Neutron EDM

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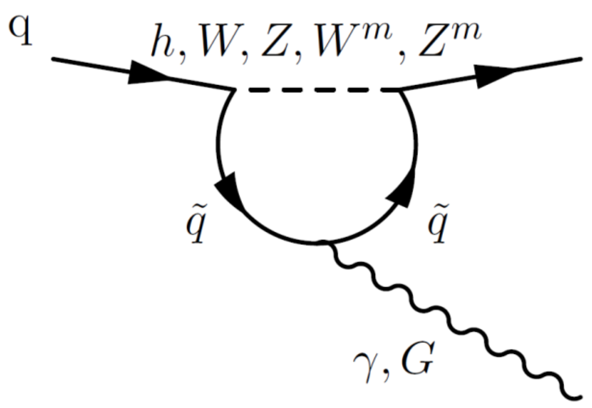
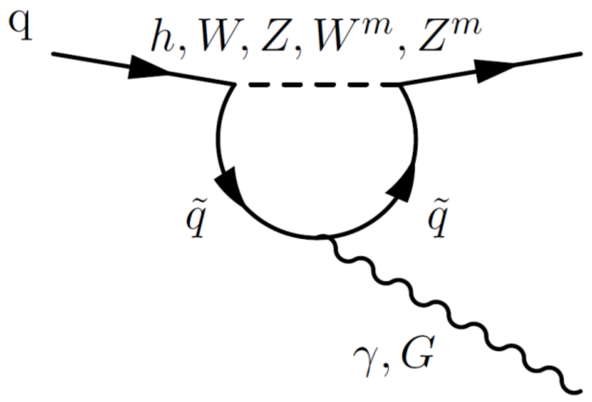


$$\frac{c}{8\pi^2 f^2} m_d \bar{d}_L \sigma^{\mu\nu} e F_{\mu\nu} d_R + \frac{\tilde{c}}{8\pi^2 f^2} m_d \bar{d}_L \sigma^{\mu\nu} g_s G_{\mu\nu} d_R$$

The relevant bounds – 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

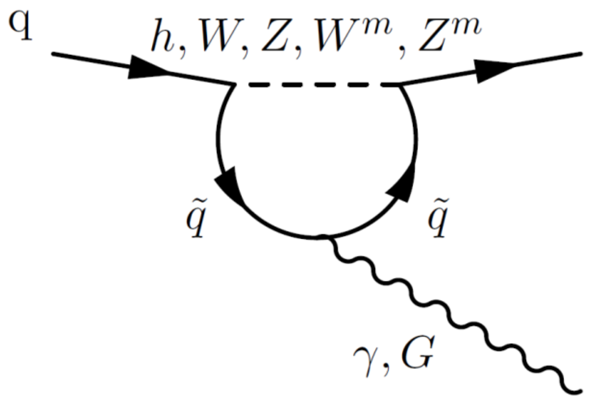
$$c = \sum_{\Psi, X} \frac{m_\Psi}{m_d m_X^2} V_{XR}^{d\Psi} V_{XL}^{d\Psi *} L_X^\Psi \ , \ \tilde{c} = \sum_{\Psi, X} \frac{m_\Psi}{m_d m_X^2} V_{XR}^{d\Psi} V_{XL}^{d\Psi *} \tilde{L}_X^\Psi$$

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

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

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

The relevant bounds – Neutron EDM



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

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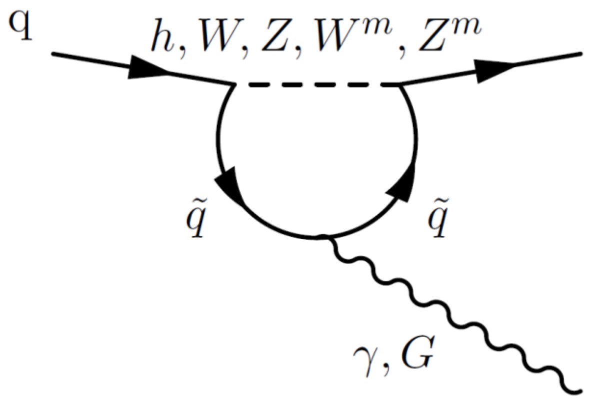
$$Y_d = \frac{g_*}{2} \tilde{m}_d$$

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

The relevant bounds – Neutron EDM



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

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

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

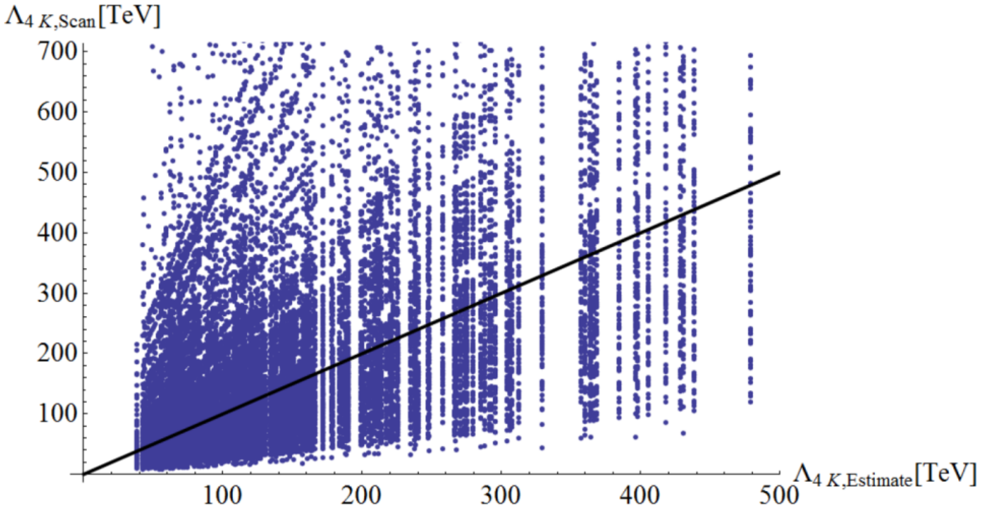
$$\frac{f}{\tilde{m_d}} > 2.85 \text{ TeV}$$

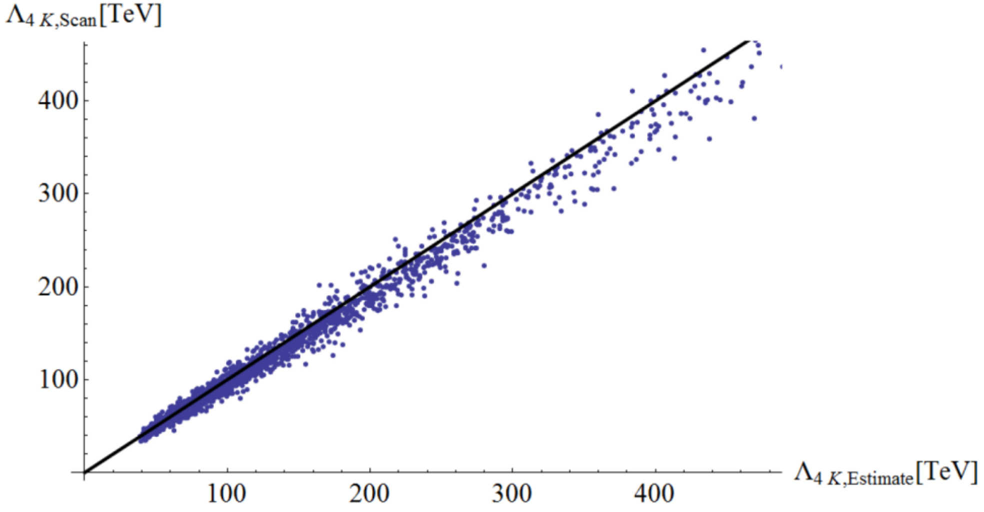
Numerical Scan

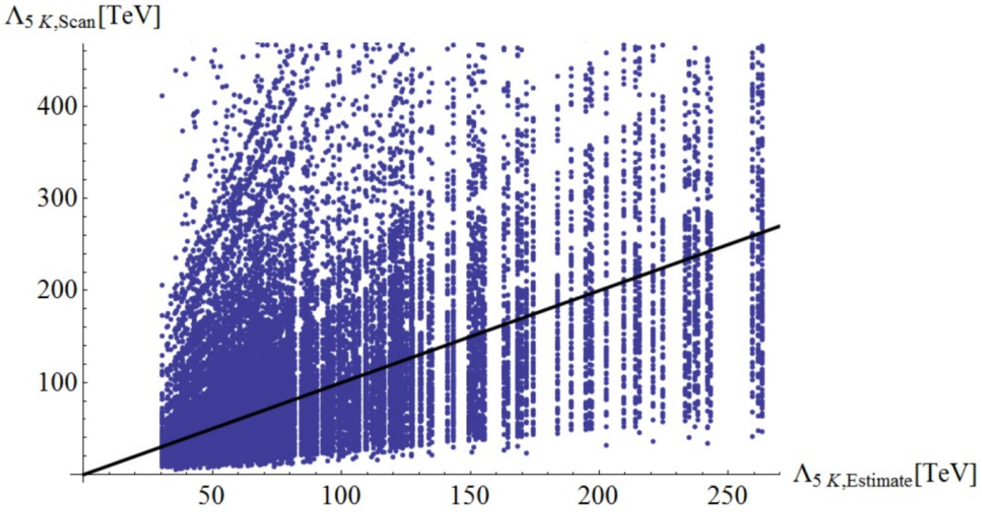
To check our estimates:

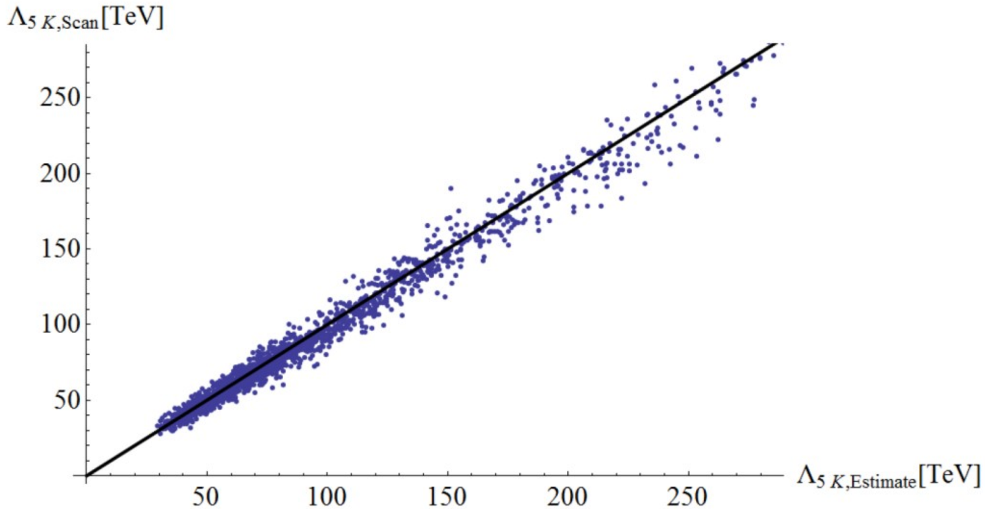
- **Generate random anarchic matrices: $\tilde{m}_d^{ij}, \tilde{m}_u^{ij}$. The eigenvalues are distributed with mean - $\tilde{m}$ + Random unitary rotation.**
- **The top sector parameters are set by the Higgs potential.**
- **Impose quark masses, CKM, Jarlskogg invariant.**
- **Calculate the bounds and compare with the estimates.**

Results – Kaon Mixing

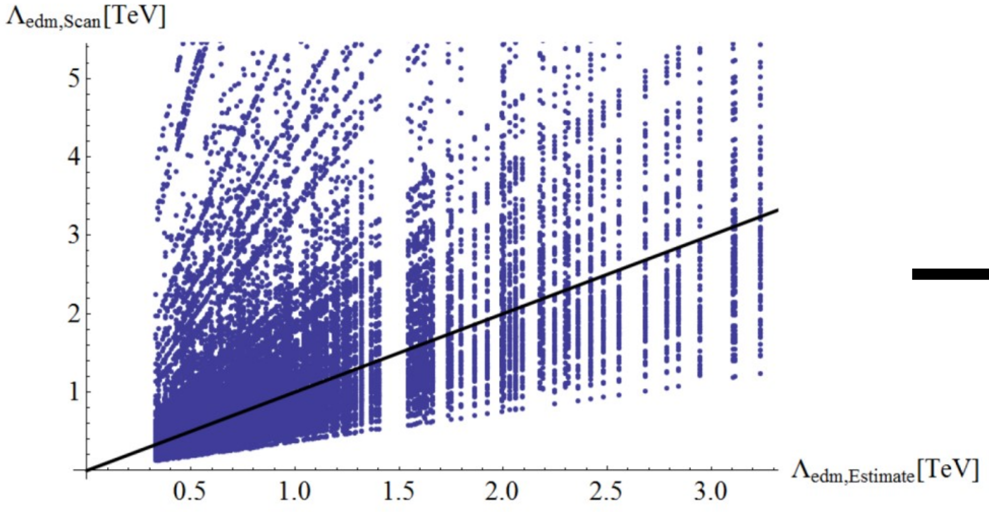


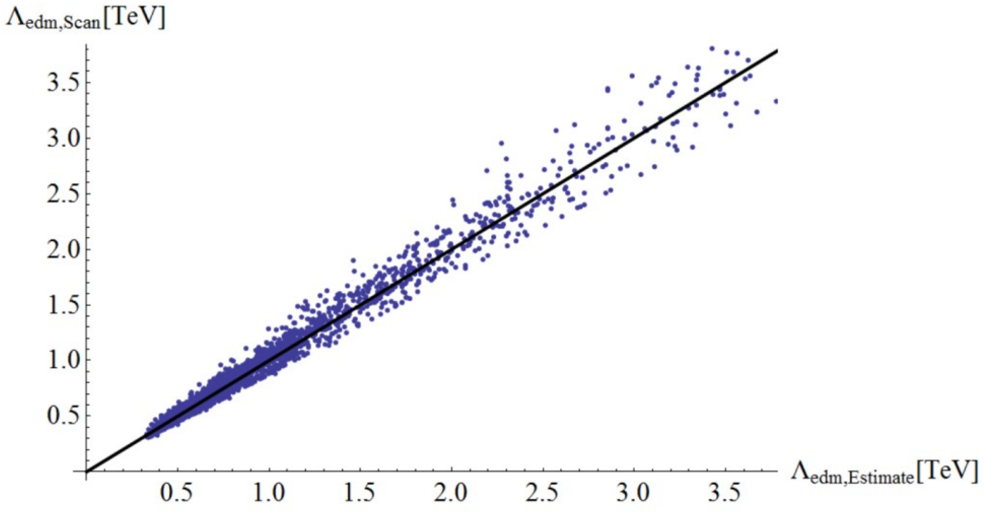






Results - EDM


$\Lambda_{edm,Scan}$[TeV]
5
4
3
2
1
0.5
1.0
1.5
2.0
2.5
3.0
$\Lambda_{edm,Estimate}$[TeV]


$\Lambda_{edm,Scan}$[TeV]
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.5
1.0
1.5
2.0
2.5
3.0
3.5
$\Lambda_{edm,Estimate}$[TeV]

Z_2 Breaking

Requirements:

- Higgs potential.
- Avoid dark radiation.
- Z_2 in the top and gauge sector

Possible ways to break Z_2:

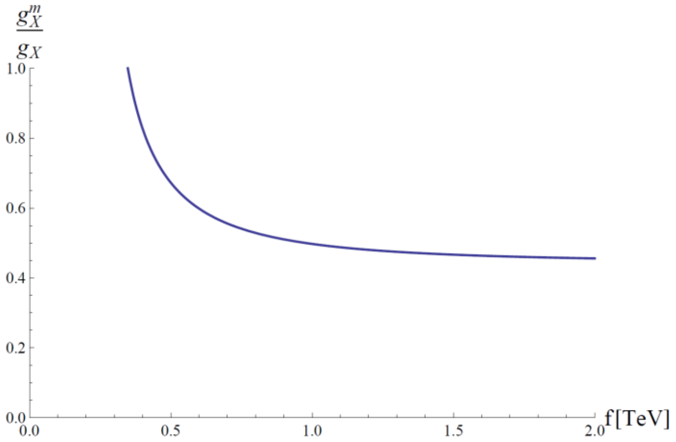
- Bulk – fermion bulk masses, gauge couplings.
- Branes – boundary conditions,IR masses, gauge kinetic terms.

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



$$g_{X*} > g_{X*}^m$$

$$\downarrow$$

$$\beta \approx \frac{3}{128\pi^2}(g'^2 - g_m'^2)g_*^2 f^4 \approx \frac{3}{128\pi^2}\frac{(g_{X*}^2 - g_{X*}^{m2})}{\log\frac{R'}{R}} g_*^2 f^4$$

- An additional loop effect on the bulk masses – same order.

Pheno

EW precision

Tree Level: $M_{KK} > 3\, TeV$

Higgs Loops: may potentially be dangerous

Vector-like Quarks/Resonances

LHC reach: 1.5 TeV for Kktops
~4 TeV for KKGlue

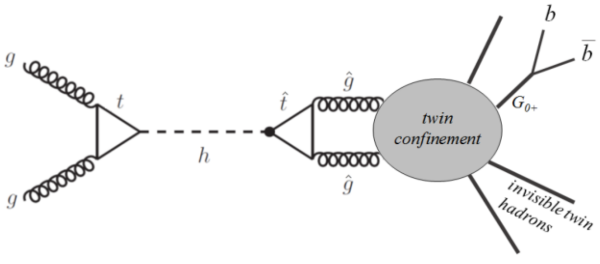
Accessible in future hadronic colliders

Higgs precision

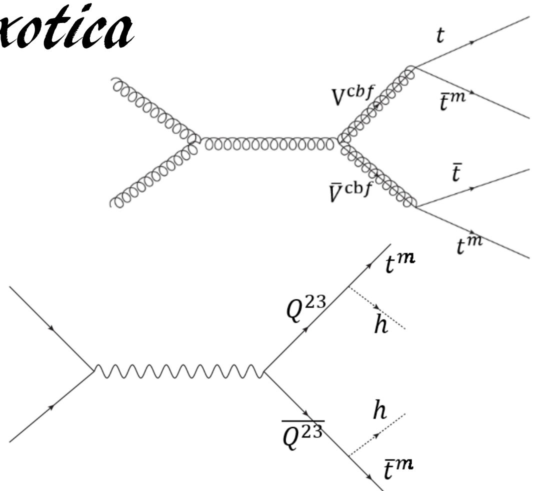
PNGB – all couplings $\left(1 - \frac{v^2}{f^2}\right)$

Invisible Decays $Br(h \to b^m b^m) \approx \frac{v^2}{f^2} Br(h \to bb)$

Exotica



N. Craig, A. Katz, M. Strassler, R. Sundrum ,arXiv:1501.05310



Summary

- Twin Higgs – SM singlet top partners.

- Needs "UV completion" - Holographic Twin Higgs:
  - Only log dependence on M_{KK} in the Higgs potential.
  - Tuning scales as $\frac{f^2}{v^2}$. $M_{KK} \lesssim 4\pi f$ by unitarity.
  - Needs Z_2 breaking.

- Quark flavor:
  - The bounds are similar to CHM , but now $g_* \rightarrow 4\pi$ is not forbidden by naturalness.
  - Leads to percent level tuning.

Thank You!

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

Z_2 breaking

Bulk $\not{Z}_2$:

Bulk masses: $c_q \neq c_q^m \rightarrow y_q \neq y_q^m$

Gauge couplings: $g_5^{SU(3)_c/U(1)_x} \neq g_5^{SU(3)_c^m/U(1)_x^m}$

IR $\not{Z}_2$:

IR masses $m_{IR} \neq m_{IR}^m \rightarrow y_q \neq y_q^m$

IR b.c.: e.g. break $U(1)_X^m$ - massive mirror photon

UV $\not{Z}_2$:

Neumann b.c.: eliminate mirror zero modes

UV Kinetic terms $\rightarrow y_q \neq y_q^m$

Z_2 breaking

Light mirror fermions:

- Eliminate using UV $\not{Z}_2$
- Arbitrary masses – e.g. MeV-GeV mirror neutrinos using bulk $\not{Z}_2$.

Massive mirror photon:

- UV brane – eliminated (= not gauged)
- IR brane – EW scale mass.

Higgs potential

Generate the right term using the hypercharge: $g' \neq g'_m$

$$\mathrm{V}(h) = \alpha_2 \sin^2 \frac{h}{f} + \alpha_2^m \cos^2 \frac{h}{f} = \beta \sin^2 \frac{h}{f} + const \qquad \beta = \alpha_2^m - \alpha_2$$

The Spectral Function in CTH

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

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