A Holographic/Composite Twin Higgs

Michael Geller

Technion

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

C. Csaki, M.G., O. Telem and A. Weiler, in progress

Motivation

Neutral naturalness → ***Natural theories with no BSM @ LHC***

The first neutrally natural model – Twin Higgs

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

Naturalness $\leftrightarrow$ Colored BSM

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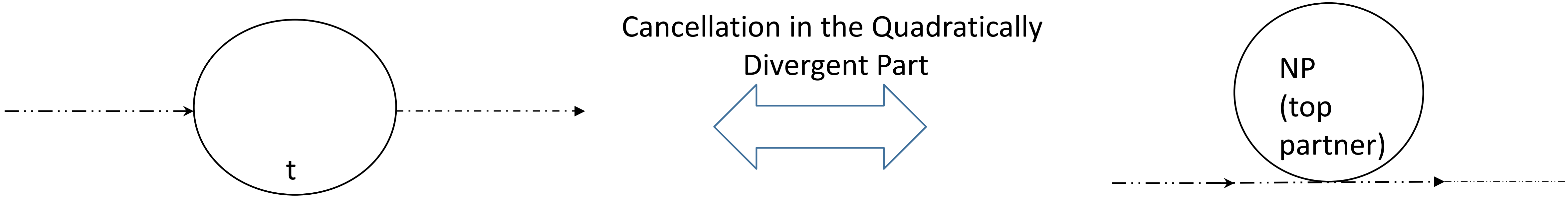
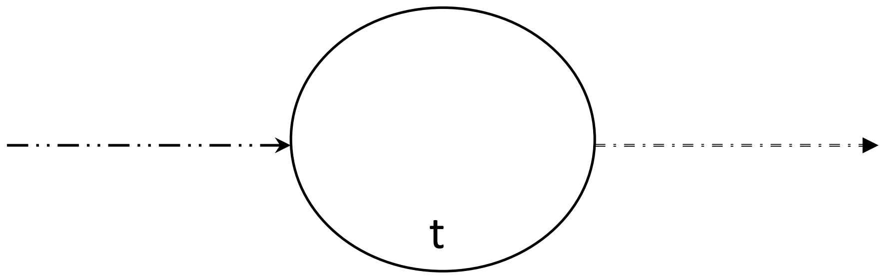
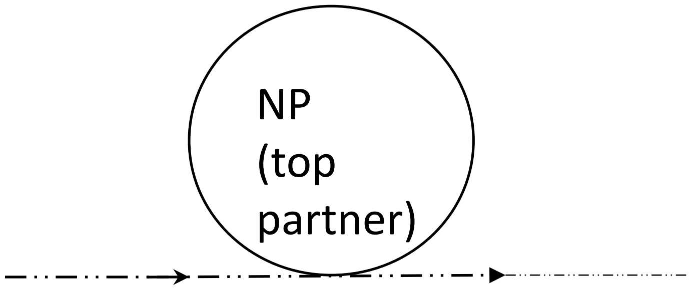


Naturalness ↔ Colored BSM

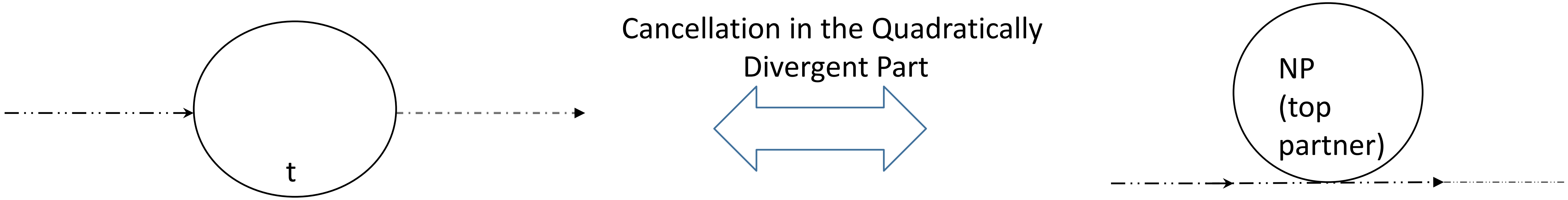


Cancellation in the Quadratically Divergent Part



The argument:

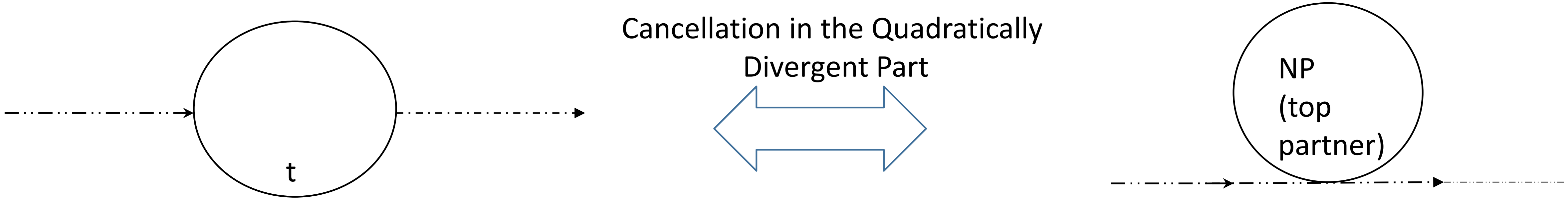
Naturalness ↔ Colored BSM



The argument:

- A symmetry is required connecting top ↔ top partners

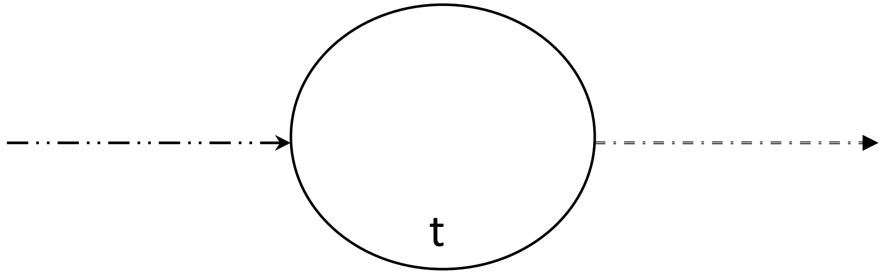
Naturalness ↔ Colored BSM



The argument:

- A symmetry is required connecting top ↔ top partners
- Naturalness requires top partners @ 1 TeV

Naturalness ↔ Colored BSM



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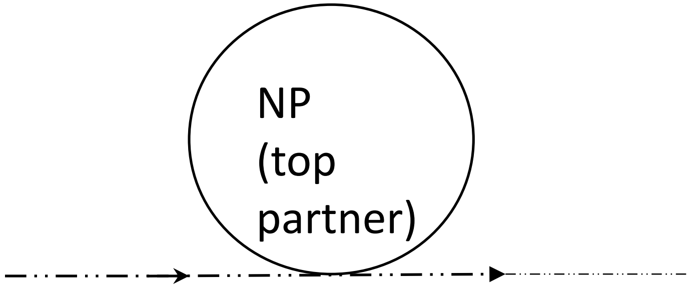
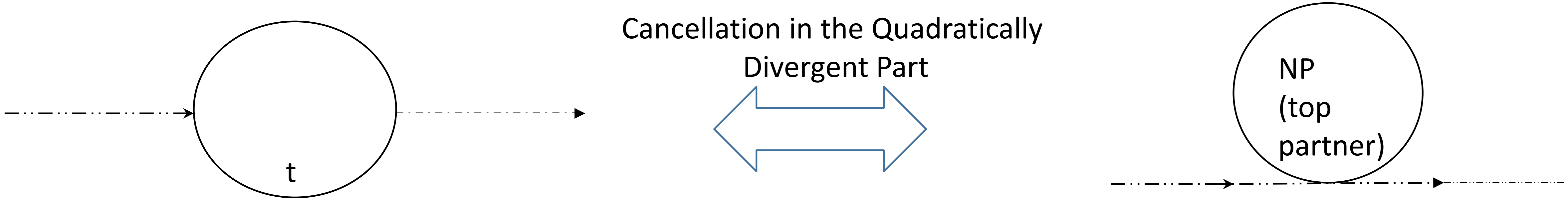


The argument:

- A symmetry is required connecting top ↔ top partners
- Naturalness requires top partners @ 1 TeV
- Colored BSM @ ~1 TeV

“Loophole”



top partners don’t have to be colored! ***Just need the N_c=3 factor.***

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:

$$\underbrace{SU(2)^A}_{\text{SM}}\xrightarrow{} v \times \underbrace{SU(2)^B}_{\text{Mirror}} \xrightarrow{} f$$

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

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

<u>*Impose a Z_2 symmetry SM ↔ Mirror*</u>.

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

<u>does not produce a Goldstone mass.</u>

Quadratically divergent terms cancel!

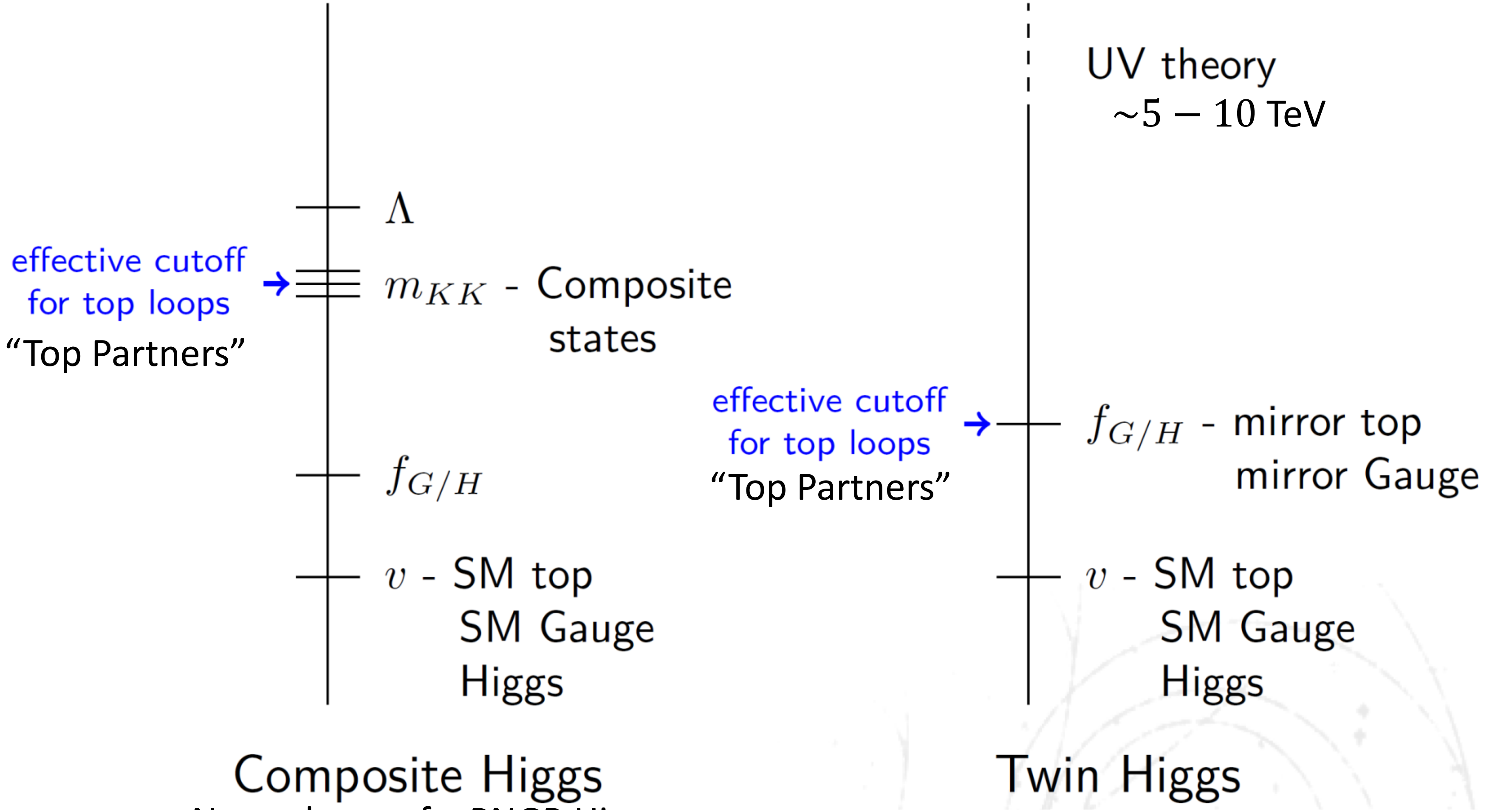
To have the same effect for the top loop: ***double the SM symmetry***

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

<u>Top partners are SM singlets – "Mirror Partners"!</u>

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

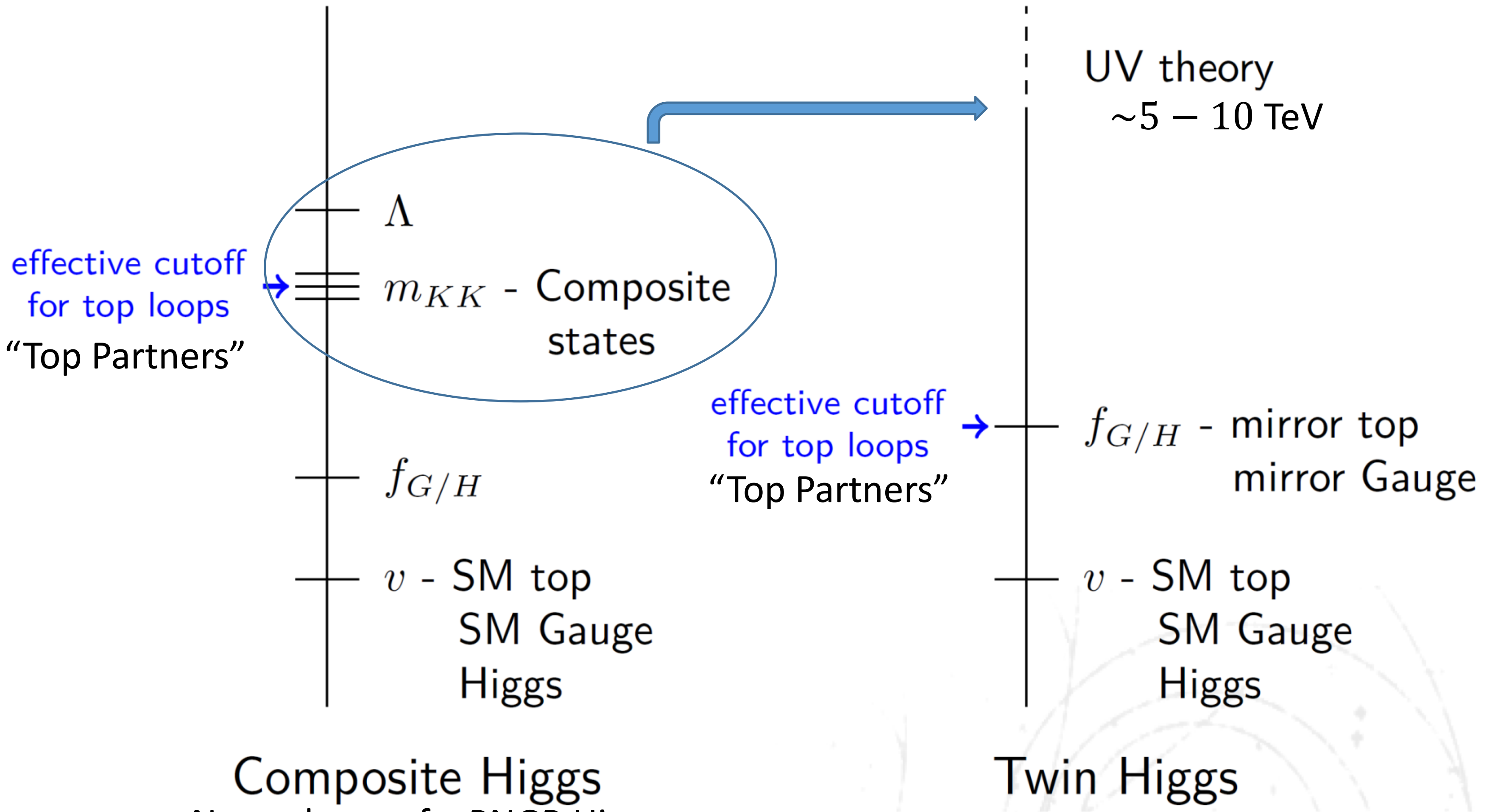
Twin Higgs and Composite Higgs



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



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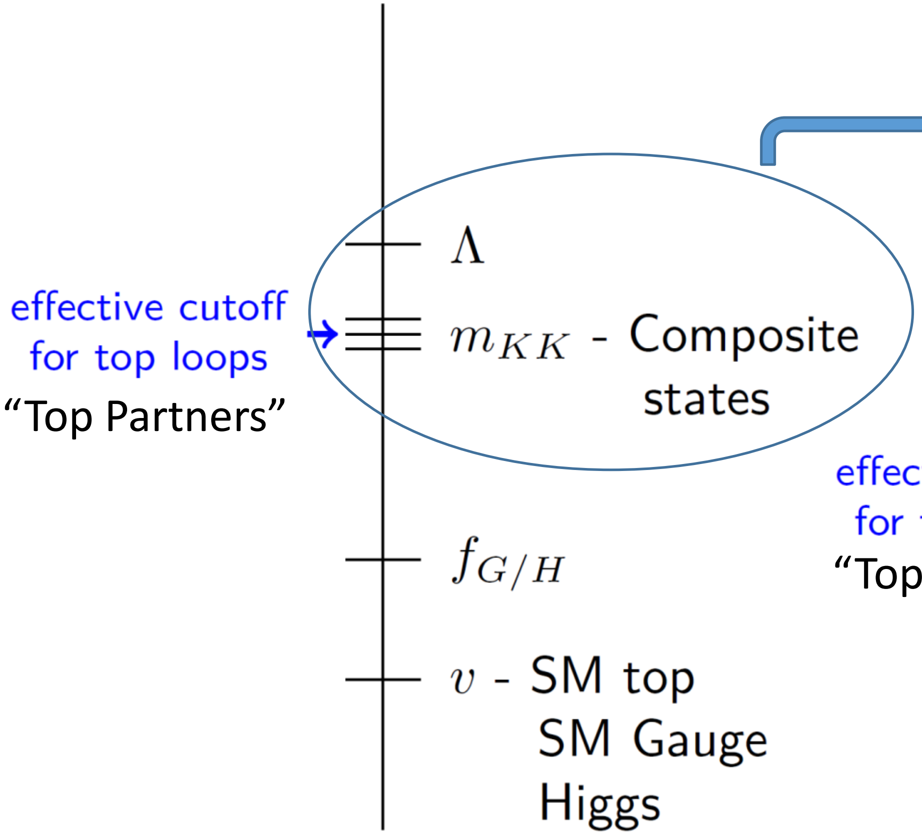

Composite Higgs

Naturalness of a PNGB Higgs
Requires light Composite states –
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SUSY:

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

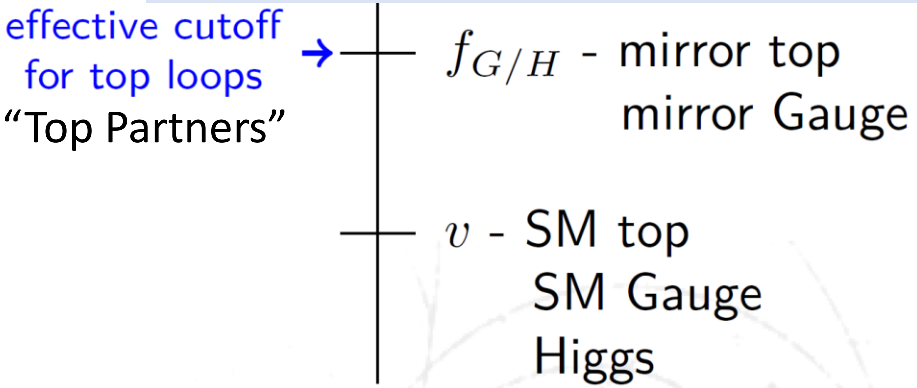
A. Falkowski, S. Pokorski, M. Schmaltz, Phys.Rev. D74(2006) 035003;

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

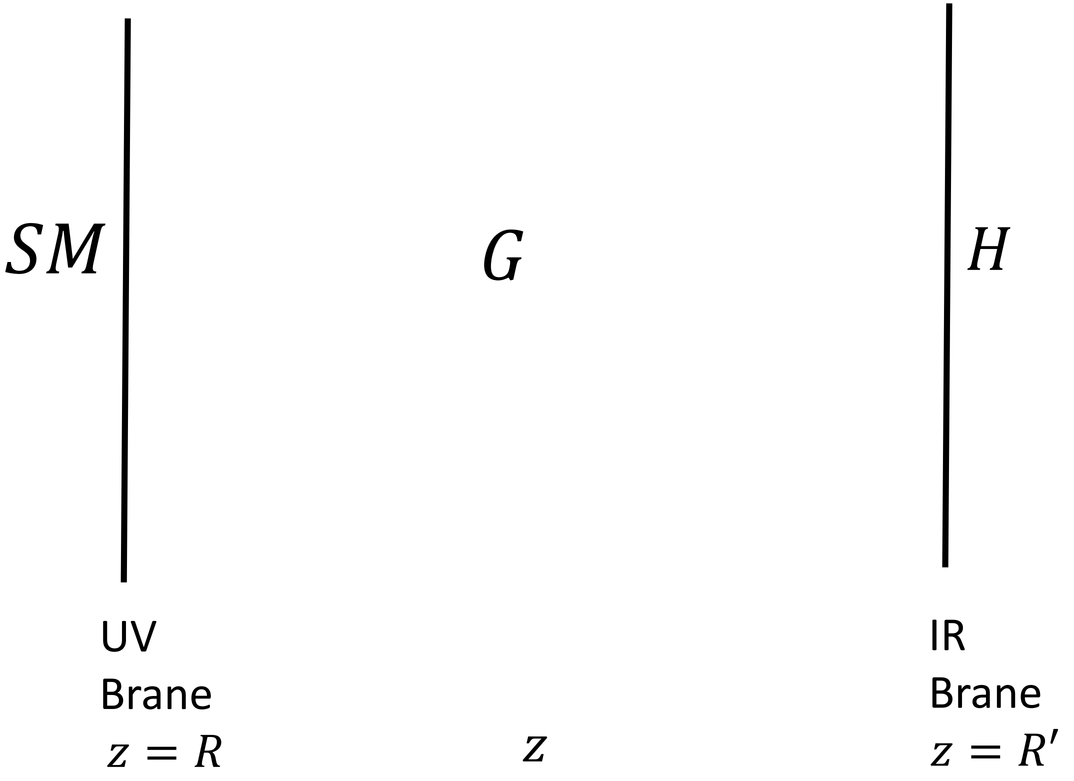


Twin Higgs

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

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

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

UV Brane $z = R$ | z | IR Brane $z = R'$

Gauge Higgs Unification

The Gauge-Higgs vev enters the fermion EOMs:

$$\Psi_q(z,v) = \Omega(z,v)\Psi_q(z)$$

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

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

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

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

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

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

$\xleftrightarrow{bulk\ Z_2,\ \text{7 of SU(7)}}$

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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

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	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

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

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

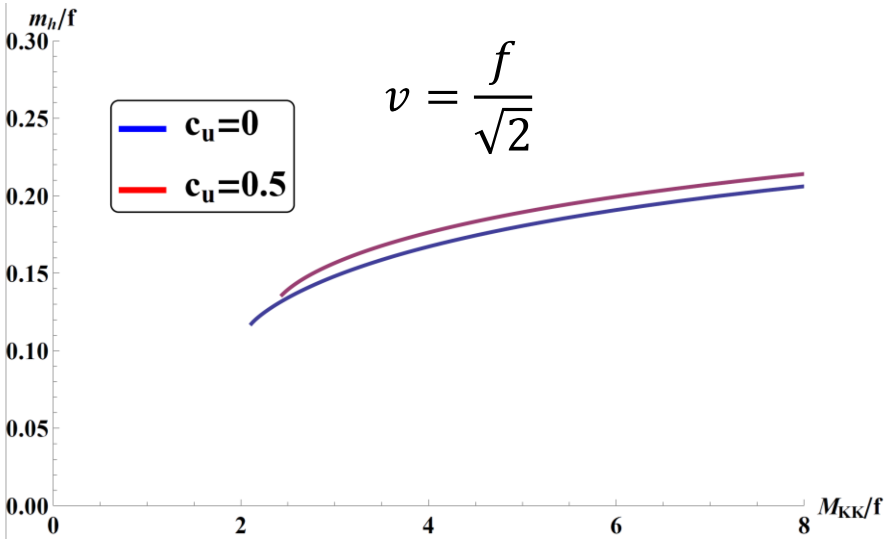
The Higgs Potential

The Higgs potential:

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

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

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



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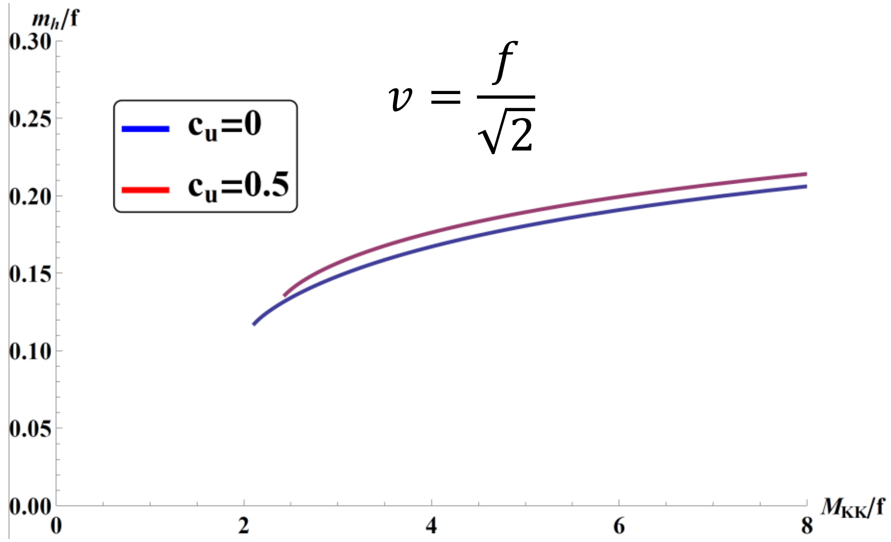


$$v = \frac{f}{\sqrt{2}}$$

The Higgs Potential

Suppose we have added a term:

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

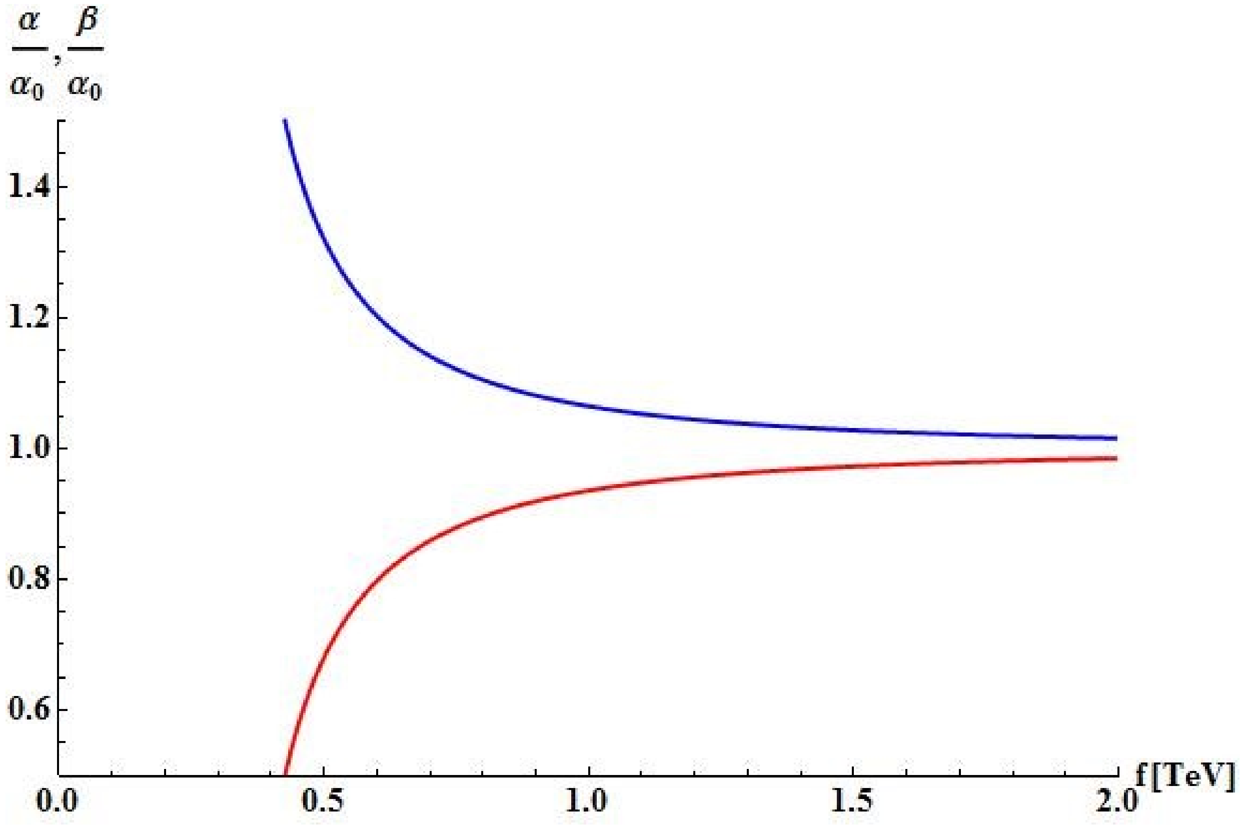
Higgs mass and vev

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

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

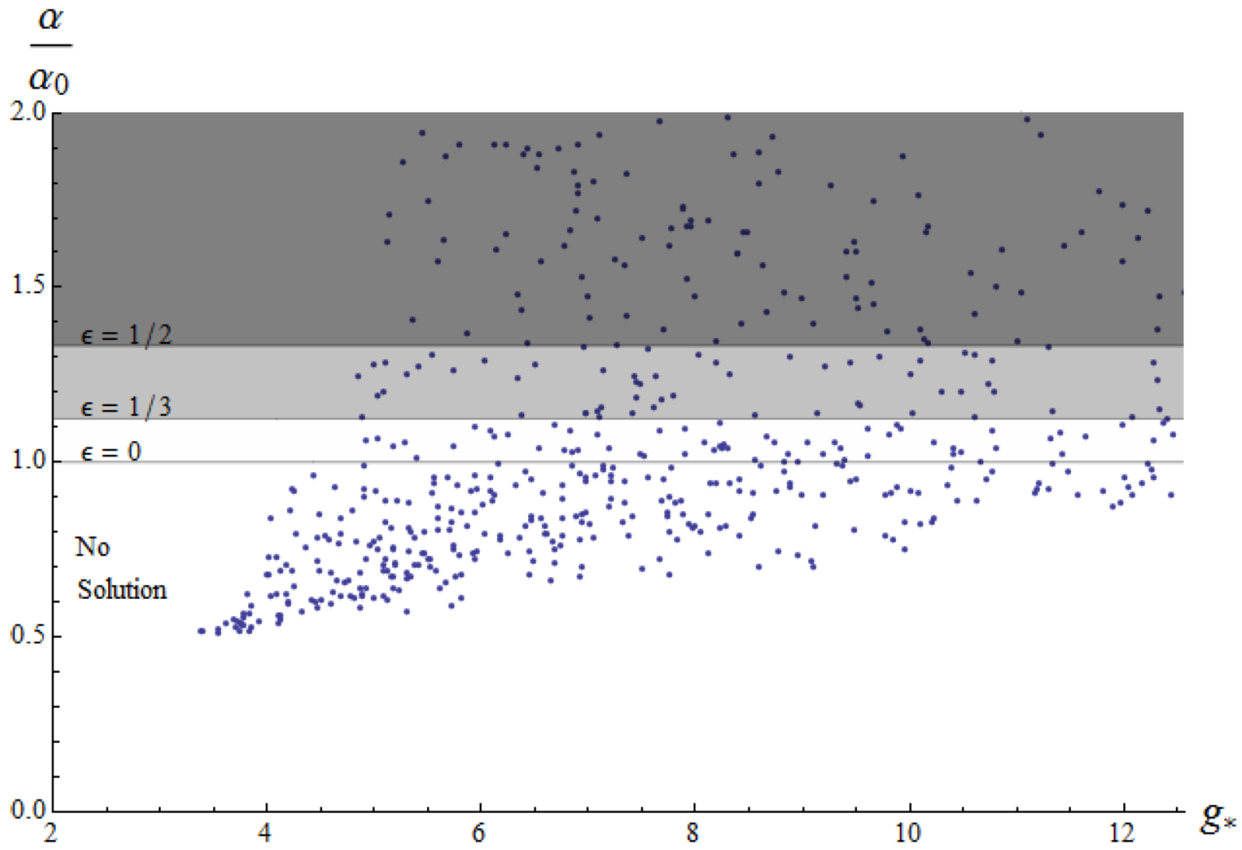
- The tuning is:

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



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.

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

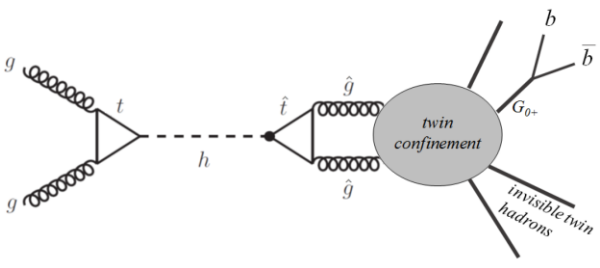
Accessible in future hadronic colliders

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



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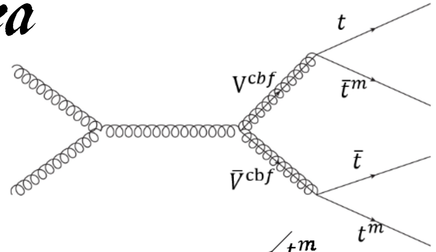
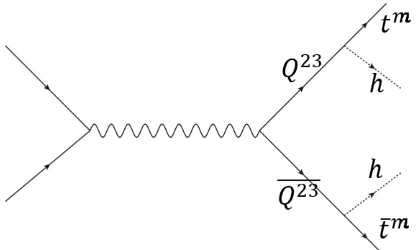




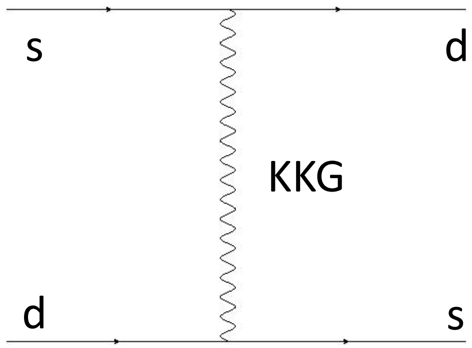
Flavor – Work in Progress

In composite Higgs flavor violation is suppressed by RS-GIM:

- Flavor violation is due to KK modes - occurs near the IR brane.
- The wavefunction of the light quarks on the IR brane is supressed:

$$f_q \sim f_{-u} \sim \sqrt{\frac{m_q}{g_* v}}$$

Anarchic flavor in composite Higgs is not enough



$\longrightarrow$ $M_{KK} > 10 - 30\ TeV$

$(\Lambda > 160 \times 10^3\ TeV)$

See e.g. **C. Csaki et. al. arXiv:0804.1954**

Flavor in Composite Twin Higgs

Contrary to CH – M_{KK} is bound only by pertubativity: $M_{KK} < 4\pi f$

Is anarchic flavor enough in the CTH? What is the limit on f?

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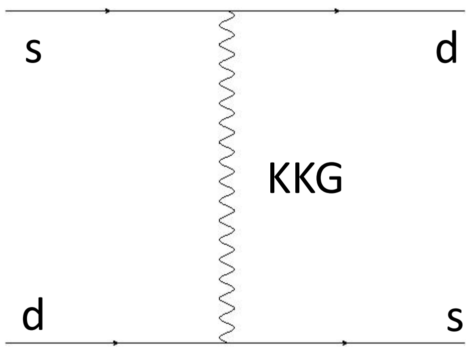

$$C_k^4 = \frac{1}{(1.6 \times 10^5 \text{ TeV})^2} \left(\frac{106 \text{ TeV}}{g_*^2 f \tilde{m}_d} \right)^2$$

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

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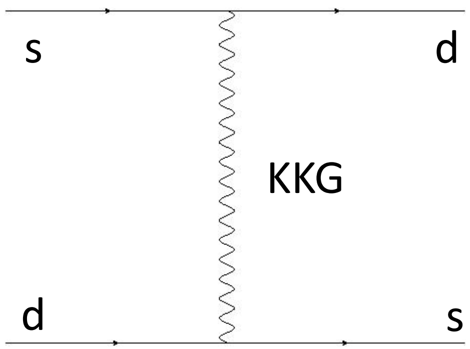

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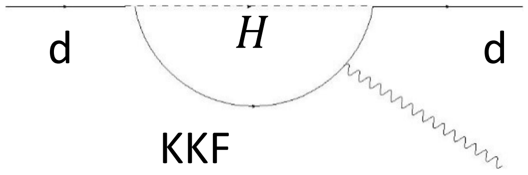

$$\frac{c}{16\pi^2 f^2} m_d \bar{d}_L \sigma^{\mu\nu} e F_{\mu\nu} d_R \quad c \sim \frac{1}{g_*^2}(Y^2) = \frac{\tilde{m}_d^2}{4}$$

$$\frac{2f}{\tilde{m}_d} > 7.29\ \mathrm{TeV}$$

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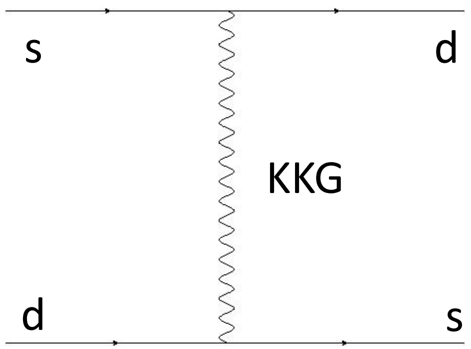

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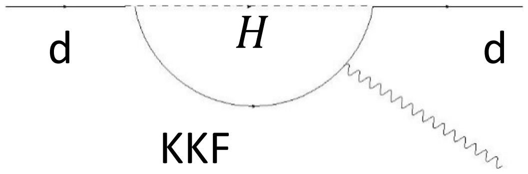

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$$\frac{2f}{\tilde{m}_d} > 7.29\ \mathrm{TeV}$$

$$g_* f > 19.6\ \mathrm{TeV}$$

Flavor in Composite Twin Higgs

In our estimations the combination of the two most stringent bounds:

$$g_* f > 19.6 \text{ TeV}$$

At the limit of perturbative control $g_* = 4\pi \rightarrow f > 1.5\, TeV$.

The tuning in the Higgs potential is at the percent level.

Z_2 breaking

Bulk $\cancel{Z_2}$:

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 $\cancel{Z_2}$:

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 $\cancel{Z_2}$:

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 $\cancel{Z_2}$
- Arbitrary masses – e.g. MeV-GeV mirror neutrinos using bulk $\cancel{Z_2}$.

Massive mirror photon:

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

Higgs potential

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

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

Z_2 breaking – Higgs Potential

- Hypercharge -

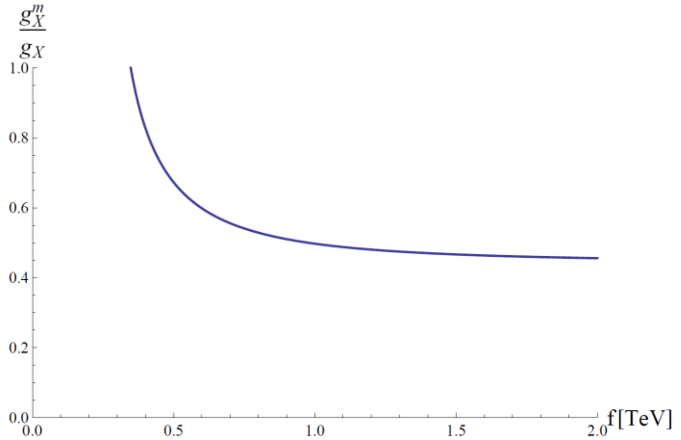
$$\frac{1}{g'^2} = \log\frac{R'}{R}\left(\frac{1}{g_*^2} + \frac{1}{g_{X*}^2}\right) \approx \frac{1}{g_{X*}^2}\log\frac{R'}{R}$$

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

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

$\downarrow$

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



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.
- Flavor:
  - Anarchic flavor requires $M_{KK} \gtrsim 20\ TeV$.
  - Leads to percent level tuning.
- Pheno:
  - Higgs couplings, Invisible width.
  - Colored states and exotics at future hadronic colliders

Thank You!

The Spectral Function in CTH

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

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

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