THE COMPOSITE TWIN HIGGS

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The Composite Higgs

- Naturalness of the weak scale requires BSM at the TeV scale
- Discovery of Higgs but no new physics $\rightarrow$
  Higgs lighter than states that restore naturalness

- In QCD:
  Λ_{QCD} is natural and pions are lighter than other states
  (PNGBs of chiral symmetry breaking)

- In Composite Higgs:
  $\Lambda \sim$ Tev is natural, Higgs lighter than other states
  (PNGB of some G/H breaking)

PNGB = Pseudo Nambu Goldstone Boson

The Composite Higgs

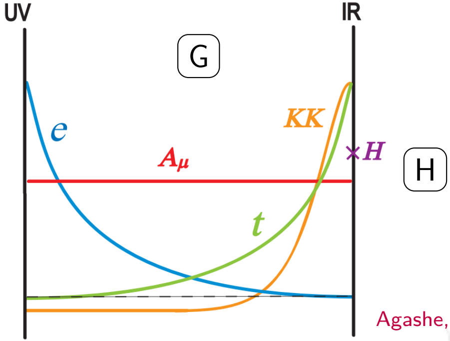
- Two sectors:
  - Elementary with SM content and gauge group
  - Strong with some gauge symmetry that confines at Λ, has a global G broken to H at this scale (the Higgs is a PNGB)

- Partial Compositeness:
  - The elementary fermions and gauge bosons mix with some of the composite fermions and mesons
  - The SM states are the light d.o.f.

- Higgs potential:
  - The mixing with the elementary sector breaks both G and H and generates a Coleman-Weinberg potential for the PNGB Higgs

The 5D Picture

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



Agashe, Contino, Pomarol 05'

- 4D low energy Largrangian of composite Higgs dictated by symmetries (CCWZ)
- The 5D picture gives the same low energy Lagrangian (composite states come at m_{KK})
- Gauge Higgs Unification - the Higgs is the broken A_5

A Little Hierarchy

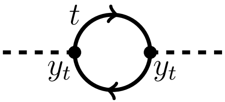
- The PNGB Higgs potential gets quadrtic corrections from top and gauge loops
- The loops are cut-off at the compositeness scale m_{KK}
- LHC non-discovery $\to$ m_{KK} pushed up $\to$ significant tuning

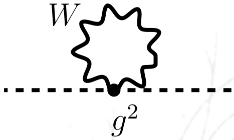
- Twin Higgs: cut-off loops with SM singlet top and gauge partners   Chacko, Harnik, Goh 05'

The Twin Higgs

- Starting point: PNGB Higgs (not necessarily composite)
- The dominant quadraticly divergent corrections to the PNGB Higgs potential are the top and gauge loops:

$$\mathcal{L} \ni y_t Q_L t_R f sin(h/f) + \frac{1}{4} P^{\mu\nu}{}_T g^2 f^2 sin^2(h/f) W_\mu^+ W_\nu^- +$$

$\delta m_h^2 =$ 

$+$ 

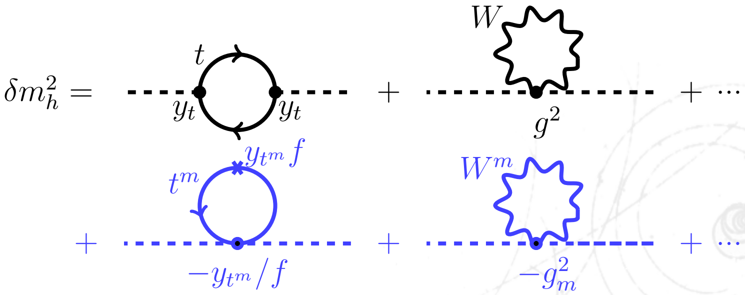
$+ \cdots$

The Twin Higgs

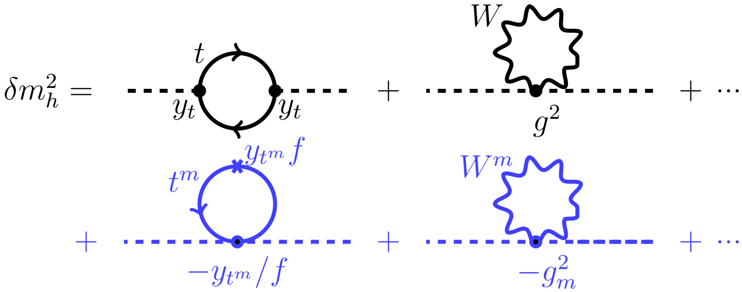
- The Twin Higgs idea is that these loops can be cancelled by new states that are SM singlets

$$\mathcal{L} \ni y_t Q_L t_R f sin(h/f) + \frac{1}{4} P^{\mu\nu}{}_T g^2 f^2 sin^2(h/f) W_\mu^+ W_\nu^- +$$

$$y_{t^m} Q_L^m t_R^m f cos(h/f) + \frac{1}{4} P^{\mu\nu}{}_T g_m^2 f^2 cos^2(h/f) W_\mu^{m+} W_\nu^{m-} + \ldots$$

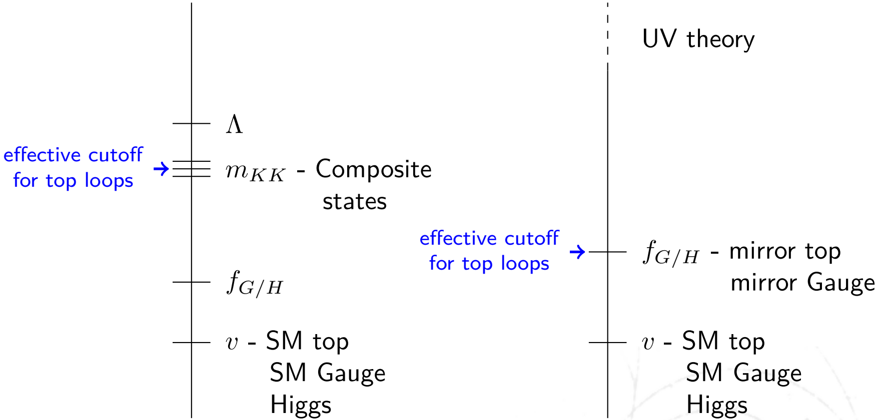


The Twin Higgs



- The quadratically divergent loops cancel provided that $y_t = y_t^m$ and $g = g^m$ (a postulated Z_2 symmetry)
- Only finite and log divergent corrections remain in the effective potential
- To calculate exactly (and for a natural m_{KK}) - need UV theory.
  In our case: composite Higgs.

A Useful Cartoon



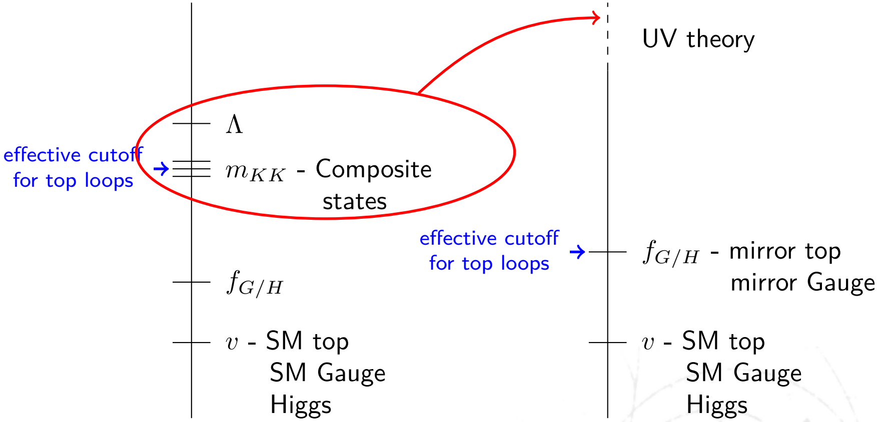
Composite Higgs

Solution to naturalness via
dimensional transmutation & PNGB Higgs.
LHC non discovery - little hierarchy

Twin Higgs

Solution to "little hierarchy-problem" for PNGB Higgs,
logarithmically sensitive
to UV theory

A Useful Cartoon



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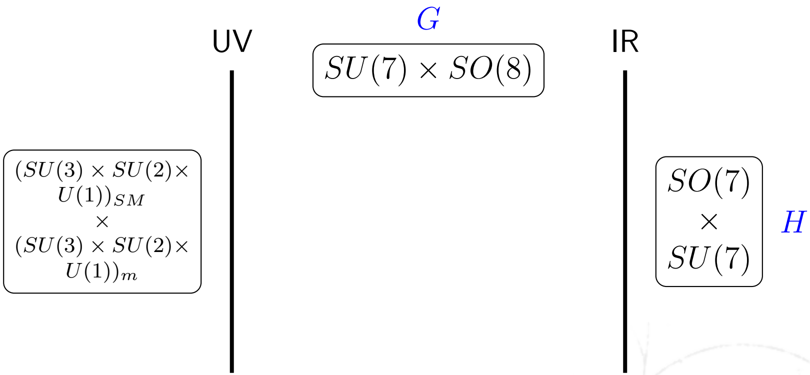
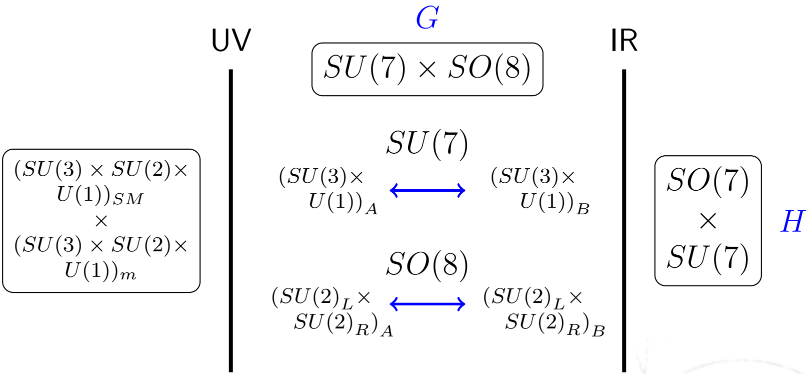
The Model



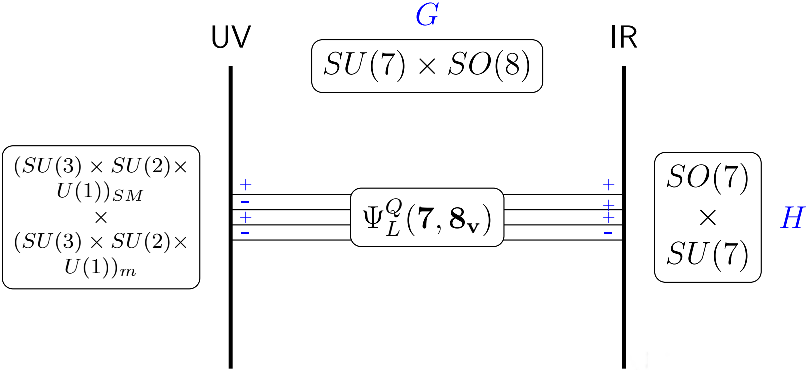
- The Higgs is in the coset $SO(8)/SO(7)$
- The elementary sector contains the SM as well as a mirror sector of SM singlets

The Model



- A bulk $SM \leftrightarrow mirror\ Z_2$ symmetry **emerges** as part of the bulk symmetry
- We choose UV B.C. and gauge kinetic terms that respect this Z_2 of the elementary (UV brane) Lagrangian

The Model



- Composite left handed "tops" in $\Psi_L^Q(\mathbf{7}, \mathbf{8_v})$ of $SU(7) \times SO(8)$
- Only the components with SM and mirror quantum numbers have Neumann boundary conditions on the UV brane
- This corresponds to a mixing of the SM and mirror states with the strong sector in 4D

The Model

- The bulk states and their representations:

Fermion	$SU(7)$	$SO(8)$	$SU(2)_4 \times U(1)_4^m \subset O(4)$
Quarks: Third Generation			
Ψ_L^Q	**7**	**8v**	**1**
Ψ_R^t	**7**	**1**	**1**
Ψ_R^b	**7**	**28**	**1**
Light Quarks and Leptons			
$\Psi_L^{Q/L}$	**7/1**	**8v**	$(\mathbf{1}, 0) \in \mathbf{6}$
$\Psi_R^{u/\nu}$	**7/1**	**28** or **1**	$(\mathbf{1}, 0) \in \mathbf{6}$
$\Psi_R^{d/e}$	**7/1**	**28**	$(\mathbf{1}, 0) \in \mathbf{6}$
New Singlets			
Ψ_R^{35}	**1**	**35v**	**1**
Ψ_L^{28}	**1**	**28**	$(\mathbf{1}, 0) \in \mathbf{6}$

- The Higgs is in a nonlinear-realizaion:

$$\Sigma(\mathbf{8_V}) = (f \sin(h/f), 0, ..., 0, f \cos(h/f))$$

The Model

- The form of the low energy Lagrangian is dictated by the representations and selection rules. The 'top' part is:

$$\mathcal{L} = \overline{\Psi_L^Q} \not{p} (\Pi_0^Q(p) + \Pi_1^Q(p)\Sigma\Sigma)\Psi_L^Q + \overline{\Psi^t}_R \not{p} \Psi_R^t + \overline{\Psi_L^Q} M_t(p)\Sigma\Psi_R^t$$

  The form factors $\Pi_0^Q(p), \Pi_1^Q(p), M_t(p)$ encode the 5D KK spectrum (Agashe, Contino, Pomarol 05').

- The low energy Lagrangian is obtained by keeping only the componetnts with Neumann UV boundary conditions (SM+mirror+higgs)

The Model

- The top mass and Coleman-Weinberg potential for the Higgs are:

$$\begin{aligned} m_t &= \frac{1}{2}\frac{v}{f}\frac{M_t(p\to 0)}{\sqrt{\Pi_0^Q(p\to 0)}} \\ V(h) &= \alpha_0 \sin^2(h/f) + \alpha \sin^4(h/f) + (\sin \leftrightarrow \cos) \\ &= -\alpha \sin^2(h/f)\cos^2(h/f) + \ldots \end{aligned}$$

  where α is a function of the fermion KK spectrum
- Due to the exact $\sin \leftrightarrow \cos$ symmetry, $v = f/\sqrt{2}$ automatically: no hierarchy between SM and mirror states, incorrect EWSB
- Need to break the Z_2 symmetry "softly" (same as in the original Twin Higgs)

Breaking Z_2 in the strong sector

- We present a mechanism to break Z_2 **soft** in the bulk
- Given a multiplet Ψ of $SU(7) \times SO(8)$, we can 'split' it by giving different bulk masses to the SM and mirror part:

$$\Psi = \begin{pmatrix} \Psi_{SM} \\ \Psi_m \end{pmatrix} \begin{matrix} \nearrow c_{SM} \\ \\ \searrow c_m \end{matrix}$$

- The spliting is done softly by postulating an additional bulk $SO(4)$, and taking the multiplet in the **6**
- $SO(4) \to SU(2) \times U(1)$ at a high scale, splitting the multiplet
- Only the $SM \times m$ components get UV Neumann B.C.

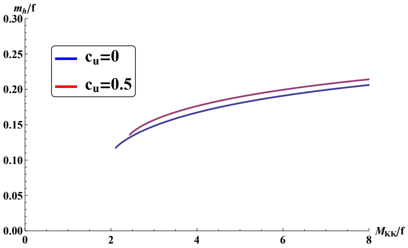
Breaking Z_2 in the strong sector

- We use the splitting mechanism to lift the light mirror d.o.f
- Additionally, we introduce exotic SM singlets, giving a Z_2 breaking contribution to the Higgs potential:

$$\begin{aligned}\Delta V(H) &= \mu_{s1}^2(c_{28}, c_{35v}, m_7) f^2 \sin^2\frac{h}{f} \\ &- \mu_{s2}^2(c_{28}, c_{35v}, m_7) f^2 \sin^2\frac{h}{f}\cos^2\frac{h}{f}\end{aligned}$$

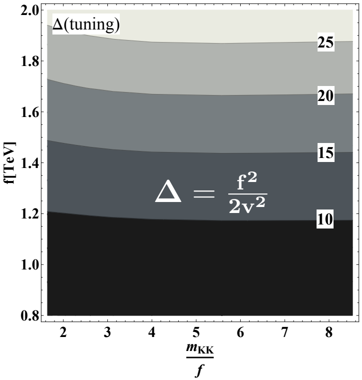
- The new contribution can be tuned to get the correct v, m_h. The tuning is the minimal $\Delta \sim (f^2/2v^2)$ for composite Higgs models - $\mathcal{O}(10\%)$ for $f = 1$Tev.

Results



The Higgs mass generated by the top and gauge sector

Only Log dependence on m_{KK}



The tuning as a function of m_{KK} and f

Phenomenology

10Tev — Λ

m_{KK} - Composite states → VLQ in a 100Tev collider

1Tev — $f_{G/H}$ - new SM singlets, mirror top, mirror Gauge → Higgs production

v - SM top, SM Gauge, Higgs → $(1 - \frac{v^2}{f^2})$ factor to Higgs partial widths,
Higgs invisible
Hidden valley
DM

light mirror states

The Composite Twin Higgs

See Chris Verhaaren & David Curtin's talks

Conclusions

- The model is the first UV completion of the twin Higgs in a composite Higgs framework

- The bulk Z_2 **emerges** from the bulk symmetry (UV brane Z_2 is postulated)
- **Soft** Z_2 breaking in the bulk

- The tuning in the model is $\mathcal{O}(10\%)$, (even in case of LHC non-discovery)
- Hidden valley phenomenology, Higgs invisible width, DM candidates

Thank You!