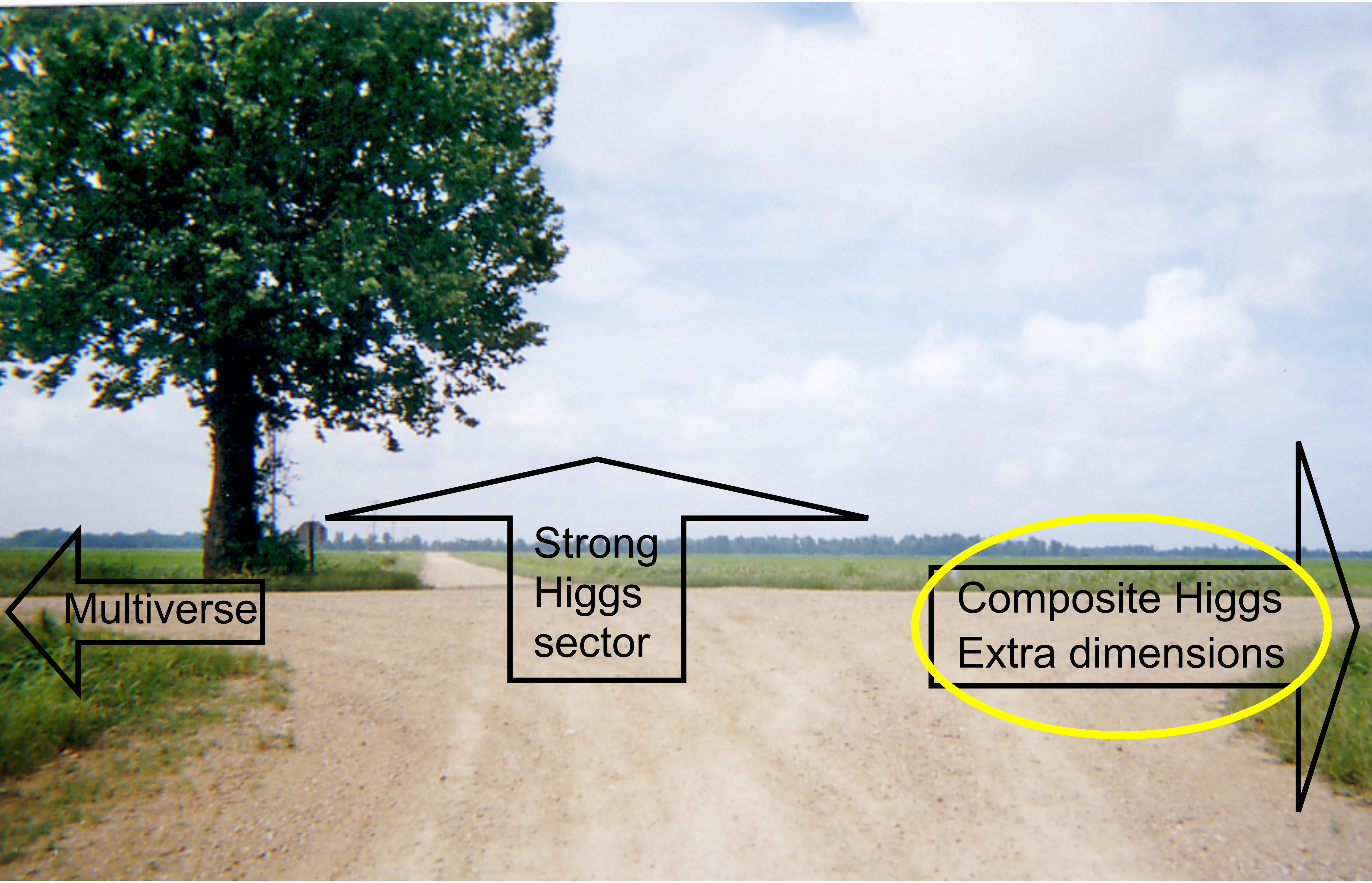

Strong
Higgs
sector
Multiverse
Composite Higgs
Extra dimensions

Composite Higgs

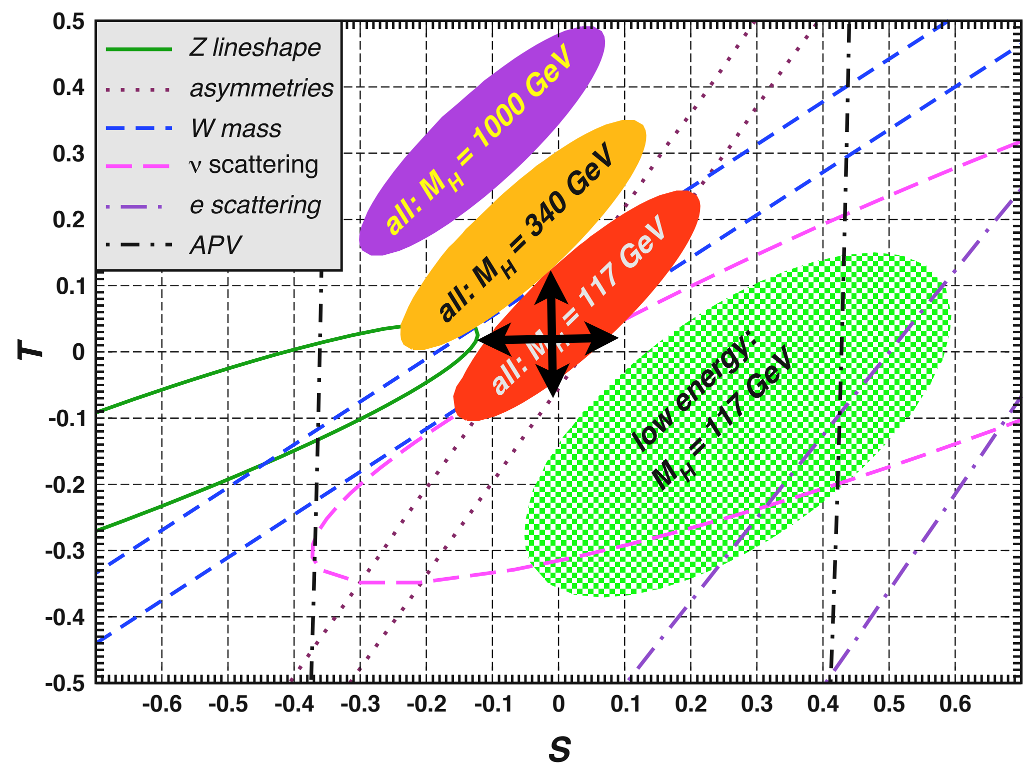
Little Hierarchy Problem

<u>Assume</u> SM is correct effective low-energy theory

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}}(h^0, \ldots) + \Delta\mathcal{L}$$
$$\Delta\mathcal{L} = \frac{1}{\Lambda_T^2}(H^\dagger D_\mu H)^2 + \frac{1}{\Lambda_S^2}(H^\dagger \tau_a H) W_a^{\mu\nu} B_{\mu\nu} + \cdots$$

$$\Rightarrow \Lambda_S \lesssim 10 \text{ TeV}$$
$$\Lambda_T \lesssim 5 \text{ TeV}$$

But SM with no new physics below 10 TeV is unnatural!



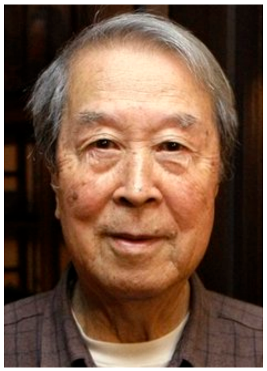
Erler, Langacker 2010

Beyond the SM

Suggests <u>adding</u> new physics to standard model

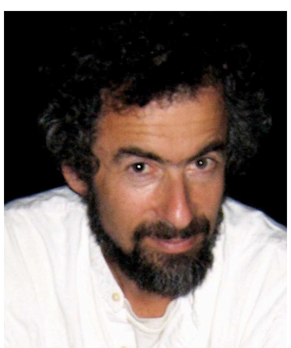
- SUSY
- Composite Higgs

Higgs as Pseudo Nambu-Goldstone Boson




- 1961: Nambu and Jona Lasinio propose dynamical explanation for small π mass

- 1962: Goldstone explains symmetry origin of mechanism

- 1984: Georgi and Kaplan propose Higgs as pseudo-Nambu-Goldstone boson

Nambu-Goldstone Bosons

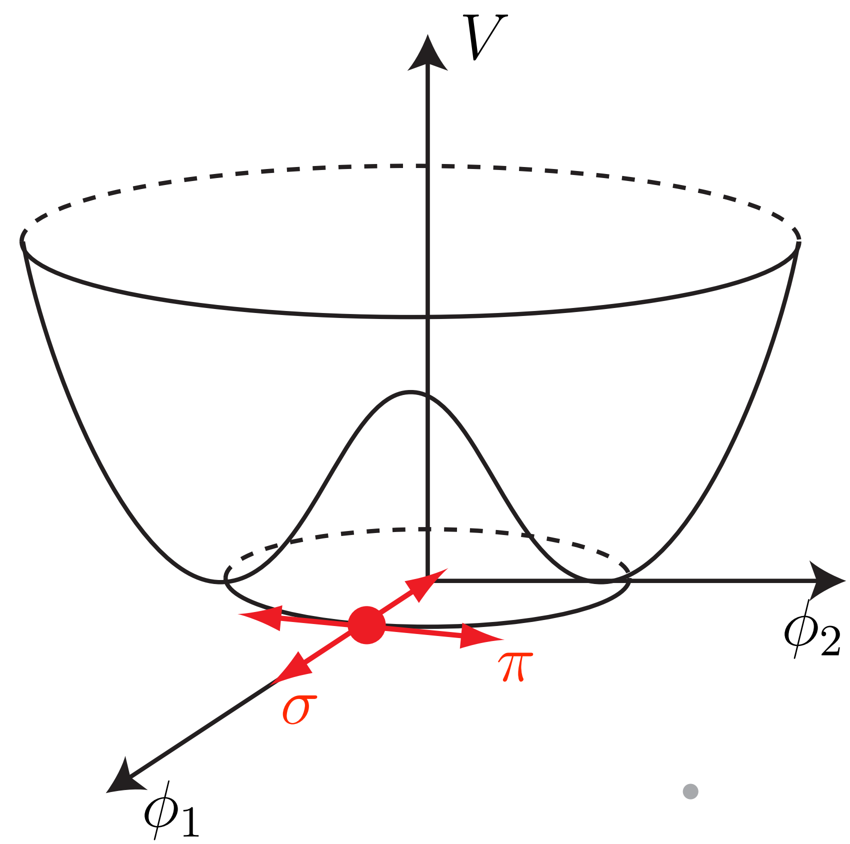
Example: broken $U(1)$

$$\Phi \mapsto e^{i\theta}\Phi \qquad \langle\Phi\rangle = \frac{f}{\sqrt{2}}$$

$$\Phi = \phi_1 + i\phi_2 = \frac{1}{\sqrt{2}} e^{i\pi/f}(f+\sigma)$$

$$\Rightarrow \sigma \mapsto \sigma$$

$$\pi \mapsto \pi + \theta f$$



Shift symmetry forbids mass for π

In fact, π has only derivative interactions:

$$V(\Phi^\dagger\Phi) = V(\tfrac{1}{2}\sigma^2)$$

$$\partial^\mu\Phi^\dagger\partial_\mu\Phi = \tfrac{1}{2}\partial^\mu\sigma\partial_\mu\sigma + \tfrac{1}{2}\left(1+\frac{\sigma}{f}\right)^2 \partial^\mu\pi\partial_\mu\pi$$

PNGB Higgs

Simplest example: $SU(3) \to SU(2)$

$\Phi =$ triplet with $\langle \Phi^\dagger \Phi \rangle = \dfrac{f^2}{2}$

$SU(2)_W = \begin{pmatrix} 1 & 0 \\ 0 & U_2 \end{pmatrix} =$ electroweak gauge group

(ignore $U(1)_Y$ for simplicity)

Expand about vacuum with unbroken $SU(2)_W$

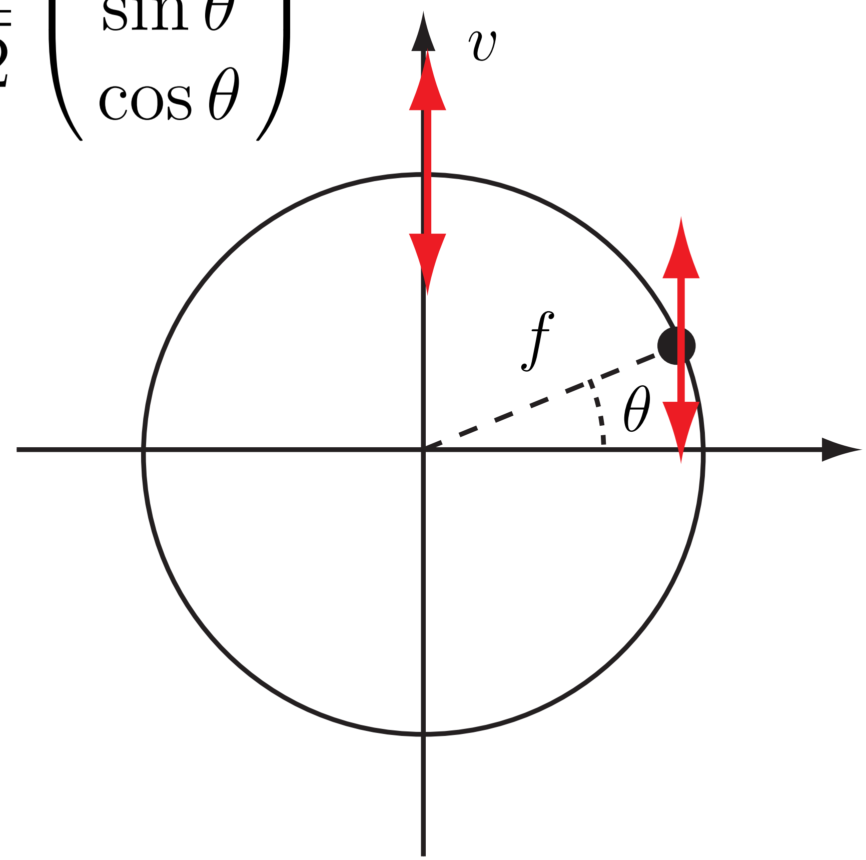
$$\Phi = \frac{1}{\sqrt{2}} e^{i\Pi/f} \begin{pmatrix} 0 \\ 0 \\ f + \sigma \end{pmatrix} \qquad \Pi = \frac{1}{\sqrt{2}} \begin{pmatrix} \eta/\sqrt{3} & 0 & H_1 \\ 0 & \eta/\sqrt{3} & H_2 \\ H_1^* & H_2^* & -2\eta/\sqrt{3} \end{pmatrix}$$

$H = \begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = SU(2)$ doublet

$SU(3)$ exact ⇒ shift symmetry $H \mapsto H + \lambda + \cdots$

PNGB Higgs (cont'd)

Most general VEV: $\langle \Phi \rangle = \frac{f}{\sqrt{2}} \begin{pmatrix} 0 \\ \sin\theta \\ \cos\theta \end{pmatrix}$



Breaks electroweak symmetry

$v = f \sin\theta$

$f \sim$ scale of new physics

$\sin\theta \ll 1 \Leftrightarrow f \gg v$ (SM limit)

$\Rightarrow \langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$

"Electroweak symmetry breaking by vacuum misalignment"

PNGB Higgs

$H \mapsto H + \lambda$ forbids Higgs mass

Forbids all non-derivative couplings

gauge, Yukawa, $(H^\dagger H)^2$,...

Must break shift symmetry

Breaking terms can be naturally small

$$V = \epsilon F\left(\frac{H}{f}\right)$$

$\epsilon \ll 1$

$f =$ scale of new physics

$\langle H \rangle$ determined by $F' = 0$ independent of ϵ

$\Rightarrow \langle H \rangle \sim f$ without special structure

Genericallyy ⇒ new physics at TeV

Models of PNGB Higgs

Mild tuning
"Composite Higgs"

Collective symmetry breaking
"Little Higgs"

"When you come to a fork in the road, take it." Yogi Berra

Composite Higgs

Accept some tuning as the price for a realistic theory

$$V(H) = \epsilon_1 F_1(H) + \epsilon_2 F_2(H)$$

$$F_i = a_i f^2 H^\dagger H + b_i (H^\dagger H)^2 + \cdots \qquad i = 1, 2$$

$$\Rightarrow m_H^2 = (\epsilon_1 a_1 + \epsilon_2 a_2) f^2$$

$$\lambda = \epsilon_1 b_1 + \epsilon_2 b_2$$

$$v^2 = \frac{m_H^2}{\lambda} = \frac{\epsilon_1 a_1 + \epsilon_2 a_2}{\epsilon_1 b_1 + \epsilon_2 b_2} f^2$$

$v \ll f$ due to accidental cancelation

"Little tuning"

Minimal Technicolor

(Evans, ML, Galloway, Tacchi 2010)

$SU(2)_{\rm TC}$ strong gauge group

$$\Psi_L = \begin{pmatrix} U_L \\ D_L \end{pmatrix} \qquad \Psi_R = \begin{pmatrix} U_R \\ D_R \end{pmatrix}$$

$\Psi_L \simeq \Psi_R^c \Rightarrow$ approximate $SU(4)$ acting on $\Upsilon_L = \begin{pmatrix} U_L \\ D_L \\ U_R^c \\ D_R^c \end{pmatrix}$

$$\langle \Upsilon_L^a \Upsilon_L^b \rangle = -\langle \Upsilon_L^b \Upsilon_L^a \rangle \Rightarrow SU(4) \to Sp(4)$$

$$(SO(6) \to SO(5))$$

General VEV

$$\langle \Upsilon_L^a \Upsilon_L^b \rangle \propto \begin{pmatrix} \cos\theta\,\epsilon & \sin\theta\,1_2 \\ -\sin\theta\,1_2 & -\cos\theta\,\epsilon \end{pmatrix} \qquad \epsilon = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

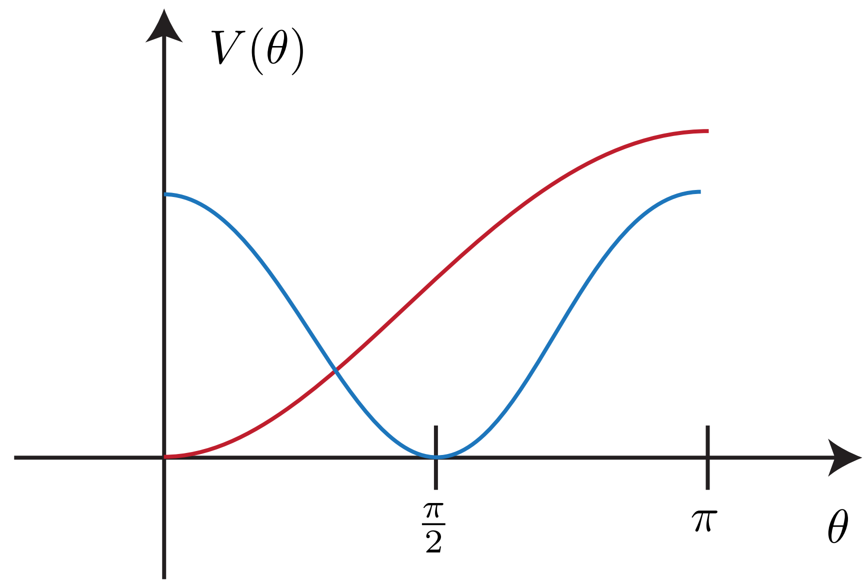
- $\sin\theta \to 0$ EW unbroken
- $\sin\theta \to 1$ technicolor limit

Minimal technicolor = composite Higgs

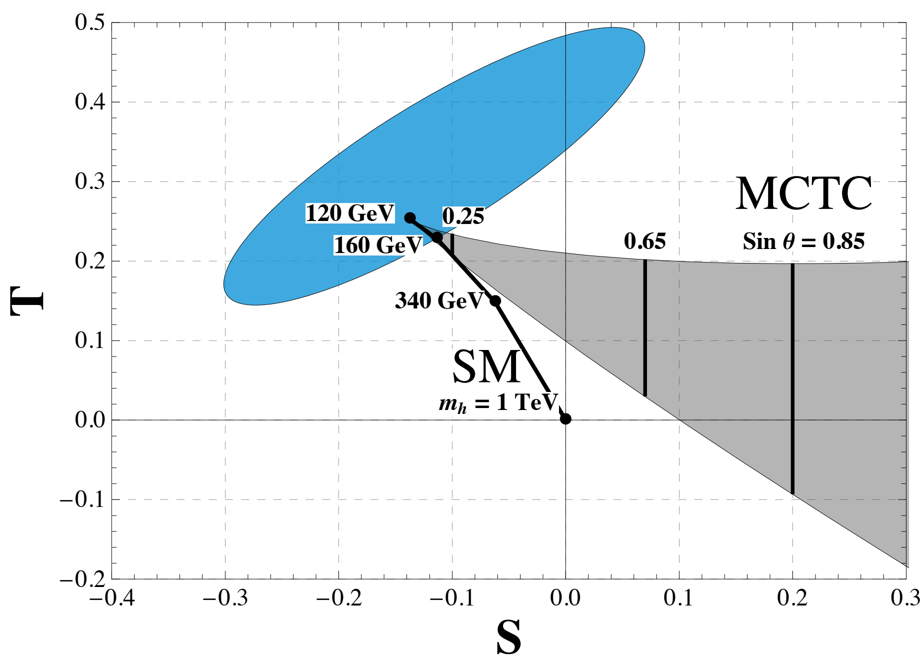
Minimal Technicolor (cont'd)

5 NGBs - 3 eaten = 2 physical scalars: h^0, A

$V(h^0, A)$ from $SU(4)$ breaking



- EW, top loops
- $\Delta\mathcal{L} = m_L \Psi_L \Psi_L + m_R \Psi_R \Psi_R$



tuning $\sim \frac{v^2}{f^2} \sim \sin^2\theta \sim 10\%$

Minimal Composite Higgs

(Agashe, Contino, Pomarol 2005)

Based on symmetry breaking pattern $SO(5) \to SO(4)$

4 NGBs - 3 eaten = 1 physical scalar: h^0

Minimal from bottom-up perspective

But: UV completion appears to require extra dimensions
(string theory?)

Signals

- SM-like Higgs boson
- Anomalous Higgs couplings

$$g_{hVV} = g_{hVV}^{(\mathrm{SM})} \cos\theta \quad (V = W,\, Z)$$

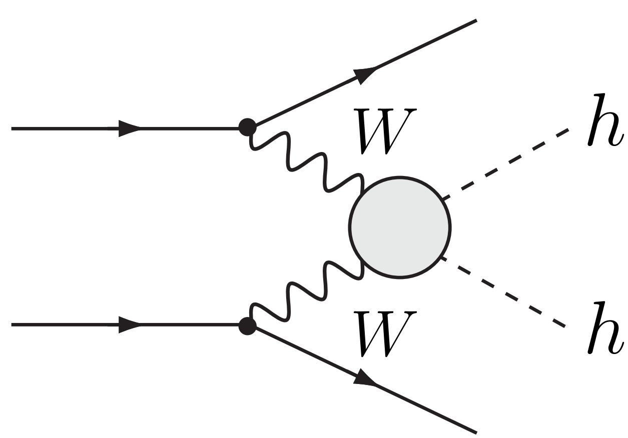
$$g_{h\bar{f}f} = g_{h\bar{f}f}^{(\mathrm{SM})} \cos\theta$$

$$\sin\theta = \frac{v}{f}$$

Similar to $\tan\beta$ effects in 2 Higgs doublet models

- "Smoking gun" signal: strong Higgs production

(Giudice, Grojean, Pomarol, Rattazzi 2007)



Little Higgs

Arkani-Hamed, Cohen, Georgi, 2001

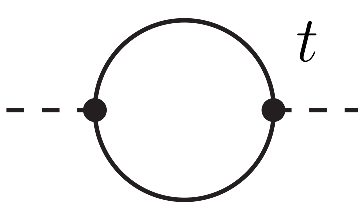
Little Higgs

Bottom-up view of naturalness

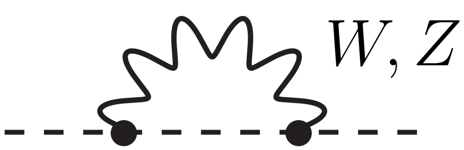
Non-derivative couplings of Higgs ⇒ naturalness problems

Add new physics to cancel loop effects (c.f. SUSY)

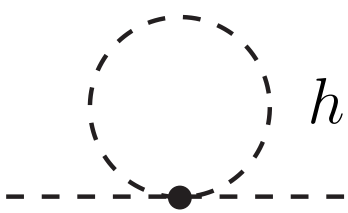
Require tuning $\lesssim 10\%$



$$\Delta m_H^2 \sim \frac{3y_t^2}{16\pi^2}\Lambda_t^2 \qquad \Rightarrow \Lambda_t \lesssim 2\ \mathrm{TeV}$$



$$\Delta m_H^2 \sim \frac{g^2}{16\pi^2}\Lambda_g^2 \qquad \Rightarrow \Lambda_g \lesssim 5\ \mathrm{TeV}$$



$$\Delta m_H^2 \sim \frac{\lambda}{16\pi^2}\Lambda_h^2 \qquad \Rightarrow \Lambda_g \lesssim 10\ \mathrm{TeV}$$

Collective Symmetry Breaking

Example: $SU(3) \rightarrow SU(2)$ (ignore $U(1)_Y$ again)

$$\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ f_1 \end{pmatrix} \qquad \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ {}_2 \end{pmatrix}$$

Gauge full $SU(3)$ ⇒ exact symmetry

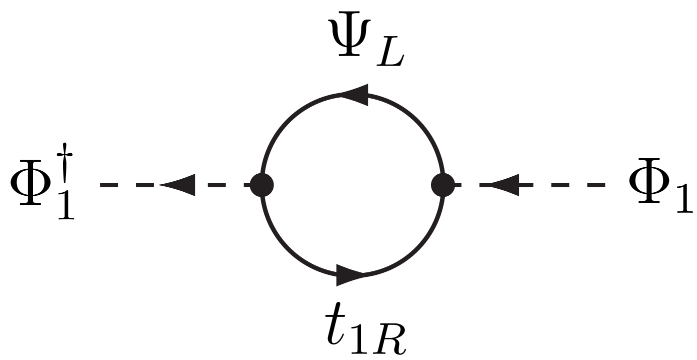
$$\Psi_L = \begin{pmatrix} t_L \\ b_L \\ T_L \end{pmatrix} \qquad t_{1R},\, t_{2R},\, b_R$$

$$\mathcal{L}_{\mathrm{Yukawa}} = y_1 \bar{\Psi}_L \Phi_1 t_{1R} + y_2 \bar{\Psi}_L \Phi_2 t_{2R}$$

$y_1 \rightarrow 0$ ⇒ exact $SU(3)_2 \rightarrow SU(2)_2$ and *vice versa*

Both $y_1, y_2 \neq 0$ required for non-derivative couplings of PNGB Higgs

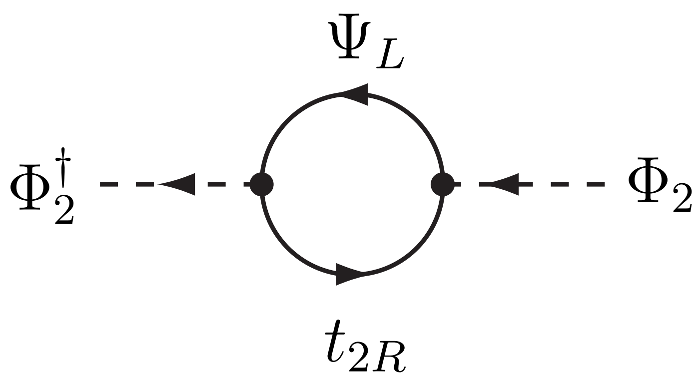
Collective Symmetry Breaking



$$\sim \underbrace{\frac{y_1^2}{16\pi^2}\Lambda^2}$$

preserves $SU(3)_2 \rightarrow SU(2)_2$

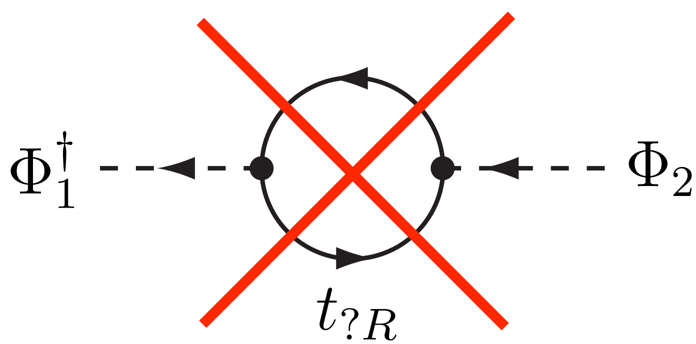
$\Rightarrow$ no PNGB Higgs mass



$$\sim \underbrace{\frac{y_2^2}{16\pi^2}\Lambda^2}$$

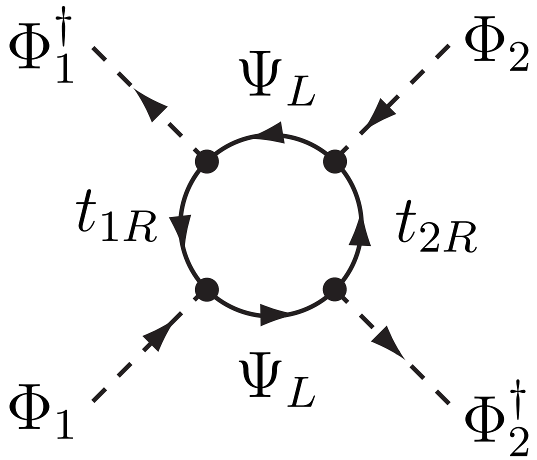
preserves $SU(3)_1 \rightarrow SU(2)_1$

$\Rightarrow$ no PNGB Higgs mass



Not allowed

Collective Symmetry Breaking



$$\sim \underbrace{\frac{y_1^2 y_2^2}{16\pi^2} \ln \Lambda}$$

$\Rightarrow$ PNGB mass

Only logarithmically sensitive to new physics

Note that quadratic divergences are canceled by "partner" particles with same spin

$$t \to T_L, T_R \qquad m_T \lesssim 2 \text{ TeV}$$

$$W \to W' \qquad m_{W'} \lesssim 5 \text{ TeV}$$

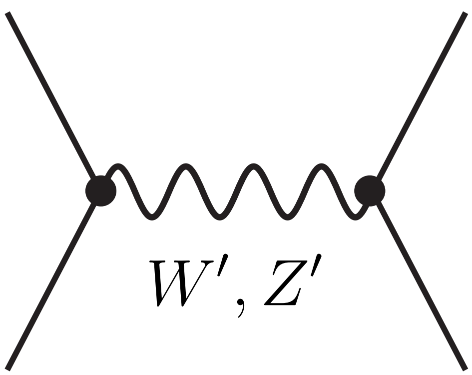
$$h \to h \qquad m_{h'} \lesssim 10 \text{ TeV}$$

Realistic Models

Requirements:

- Custodial $SU(2)$
- Collective symmetry breaking for top and gauge loops (separate mechanisms)

Precision electroweak fit <u>not</u> automatic



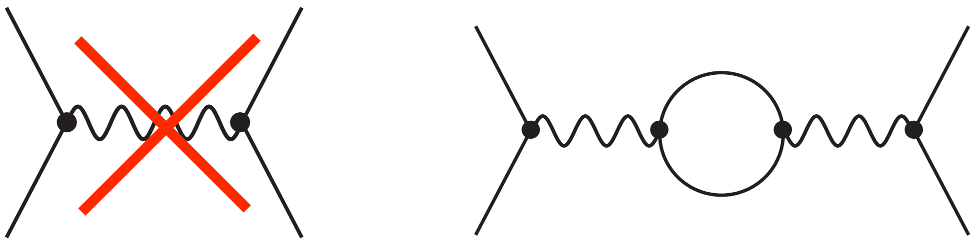
$\Rightarrow$ corrections large enough to spoil SM-like fit

But that was the original motivation...

T Parity

(Cheng, Low 2003)

Introduce new discrete symmetry where partners = odd



Partners only appear in loop diagrams

⇒ automatic precision electroweak fit

Lightest T-odd particle is dark matter candidate

(c.f. SUSY)

But models become even more complicated...

Signals

- Top partner:

  $$gg \to T, \; Wb \to T$$

  $$T \to th, \, tZ, \, bW$$

  can be seen at LHC up to $m_T \simeq 3 \text{ TeV}$ (100 fb^{-1})

- Z partner:

  $$\bar{q}q \to Z' \to \bar{\ell}\ell$$

  can be seen up to $m_{Z'} \simeq 2.5 \text{ TeV}$

(See e.g. Burdman, Perelstein, Pierce 2002;
Han, Logan, McElrath, Wang 2003)

Summary

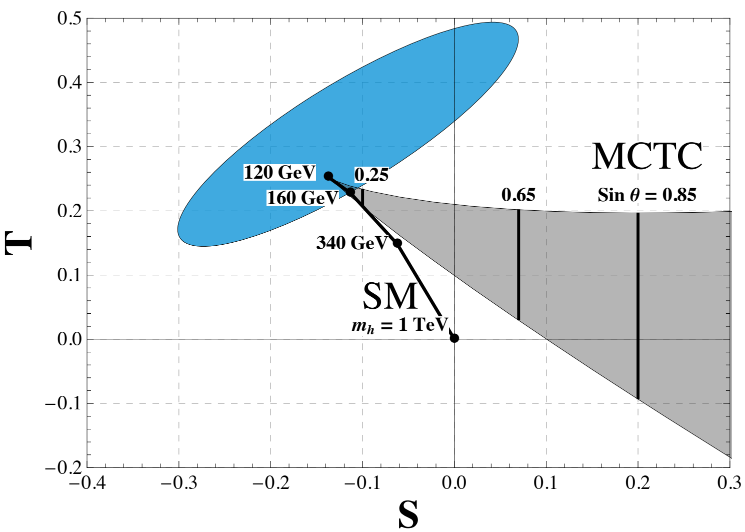
- Shift symmetry can screen Higgs mass from
  UV scales

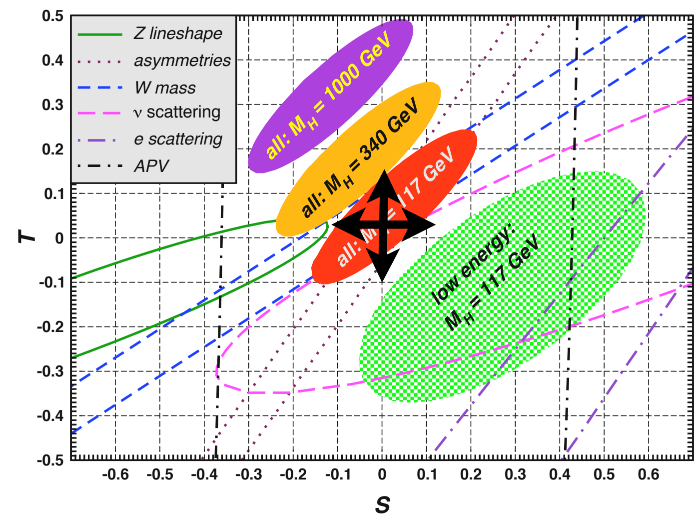
- Higgs as pseudo Nambu-Goldstone boson
  is a natural realization

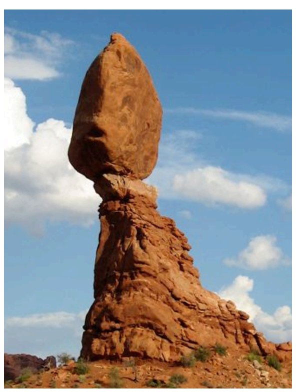
- SM-like precision electroweak fit
  requires either mild tuning
  or additional structure (collective breaking, T parity)

IMHO

Composite Higgs ⟷ Little Higgs ⟷ Little Higgs with T parity







Simple, but needs some luck

Stable, but looks man-made