Beyond the Minimal Composite Higgs Model

2 Higgses as Composite Pseudo-NGB's

Javi Serra

(Universitat Autònoma de Barcelona)

work (to appear) in collaboration with: J.Mrazek, A.Pomarol, R.Rattazzi, M.Redi, A.Wulzer

Why a composite-NGB-Higgs ?

WHY A COMPOSITE-NGB-HIGGS ?

QCD inspired

NO Naturalness or Hierarchy problems

dynamically

EW SCALE

WHY A COMPOSITE-NGB-HIGGS ?

QCD inspired

NO Naturalness or Hierarchy problems

STRONG SECTOR

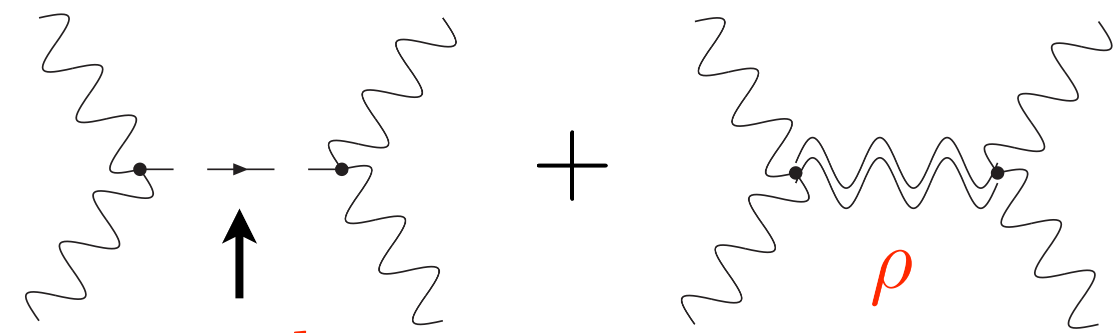
dynamically

EW SCALE

experiment

consistency with EWPT (*S* , *T*)

$$\mathcal{M}(W_L W_L \to W_L W_L)$$

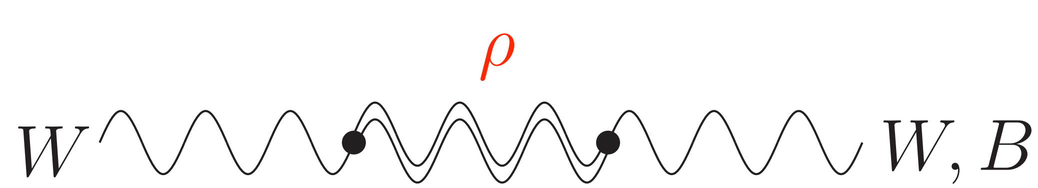


SM: h

MSSM: $h, H, A, H^{\pm}$

$m_\rho \sim 2.5$ TeV

resonances pushed up in energy



WHY A COMPOSITE-NGB-HIGGS ?

QCD inspired

NO Naturalness or Hierarchy problems

STRONG SECTOR

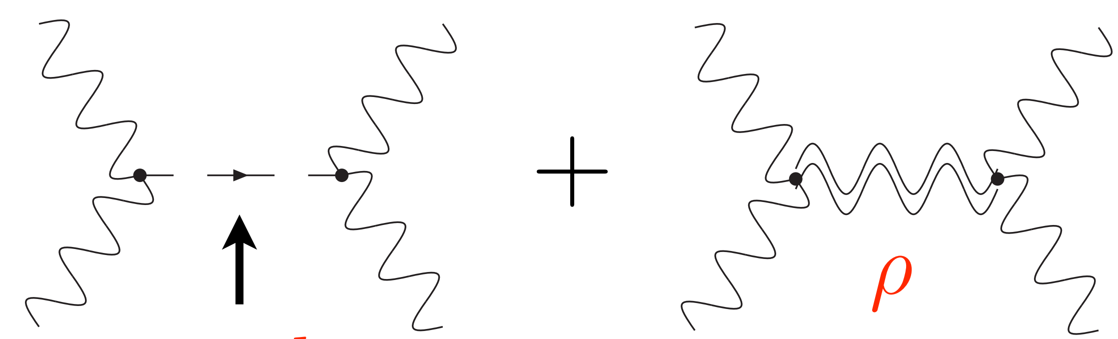
dynamically

EW SCALE

experiment

consistency with EWPT (S , T)

$$\mathcal{M}(W_L W_L \to W_L W_L)$$



SM: h

MSSM: $h, H, A, H^{\pm}$

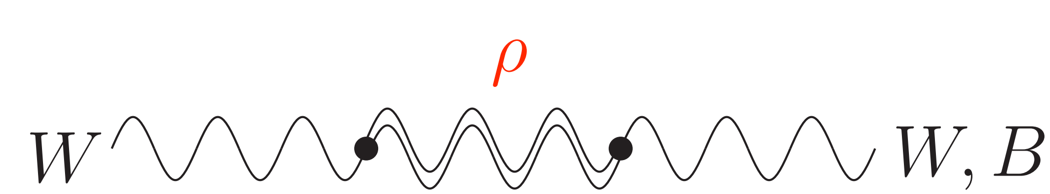
$$m_\rho \sim 2.5 \text{ TeV}$$

like QCD pions

Higgs lighter than other resonances

$$m_h \ll m_\rho$$

resonances pushed up in energy



What do we need ?

Spontaneous Symmetry Breaking:

$$G \longrightarrow H$$

$$\Sigma(h/f)$$

= G/H sigma model scale

WHAT DO WE NEED ?

Spontaneous Symmetry Breaking: $G \longrightarrow H$

$$\Sigma(h/f)$$

= G/H sigma model scale

i) $G \supset \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$

gauged

WHAT DO WE NEED ?

Spontaneous Symmetry Breaking: $G \longrightarrow H$

$\Sigma(h/f)$

f = G/H sigma model scale

i) $G \supset \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$

gauged

ii) $H \supset \mathrm{O}(4) \cong \mathrm{SU}(2)_A \times \mathrm{SU}(2)_B \times P_{AB}$

→ $\delta g_{Zbb} = 0$

→ $\langle h \rangle = \begin{pmatrix} 0 \\ 0 \\ 0 \\ v \end{pmatrix}$ } $\mathrm{SO}(3) \cong \mathrm{SU}(2)_{A+B}$

Custodial symmetry

$\delta\rho = 0$

WHAT DO WE NEED ?

Spontaneous Symmetry Breaking: $G \longrightarrow H$

$\Sigma(h/f)$

f = G/H sigma model scale

i) $G \supset \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$

gauged

ii) $H \supset \mathrm{O}(4) \cong \mathrm{SU}(2)_A \times \mathrm{SU}(2)_B \times P_{AB}$ → $\delta g_{Zbb} = 0$

$$\langle h \rangle = \begin{pmatrix} 0 \\ 0 \\ 0 \\ v \end{pmatrix}$$

$\mathrm{SO}(3) \cong \mathrm{SU}(2)_{A+B}$

Custodial symmetry

$\delta\rho = 0$

iii) $G/H \supset \mathbf{4} = (\mathbf{2}, \mathbf{2})$

***h*, Higgs complex doublet**

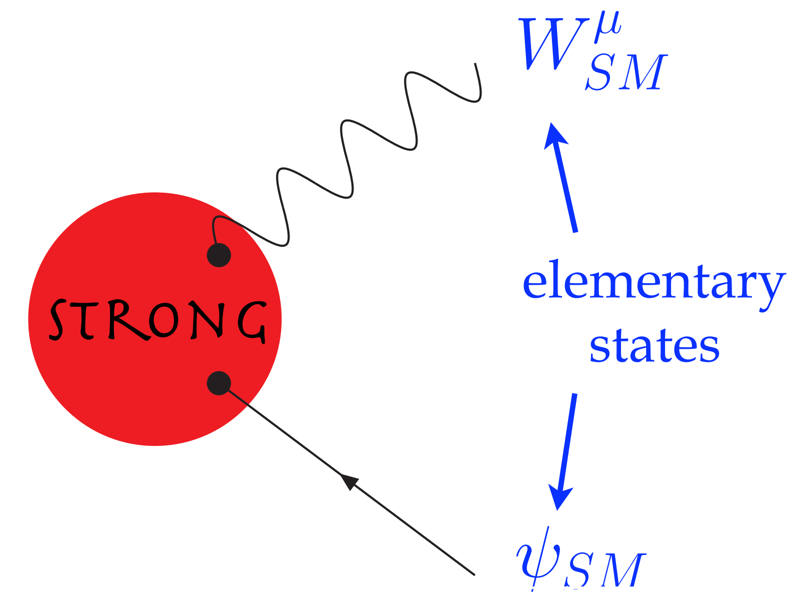
WHAT DO WE NEED ?

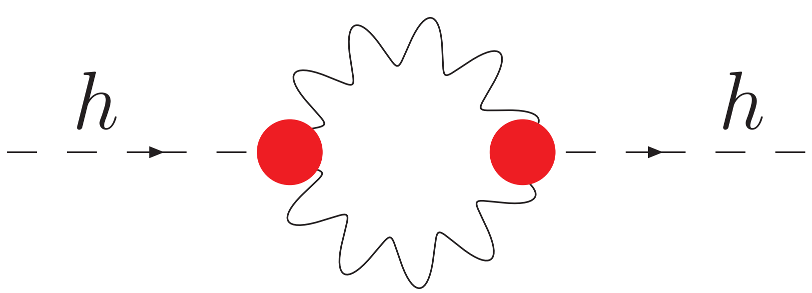
Explicit Symmetry Breaking: from the Strong Sector alone: $V(h) = 0$

from interactions with SM fields:

➡ SM gauge interactions (subgroup K of G is gauged)

➡ SM fermion interactions (proto-Yukawas, mostly the top)





$$\longrightarrow \quad V(h) \neq 0 \quad \longrightarrow \quad \langle h \rangle = v < f$$

$$\xi = \frac{v^2}{f^2} \sim \frac{1}{4}$$

$$f \gtrsim 500 \text{ GeV}$$

➡ other sources of explicit breaking? like "quark" masses,...

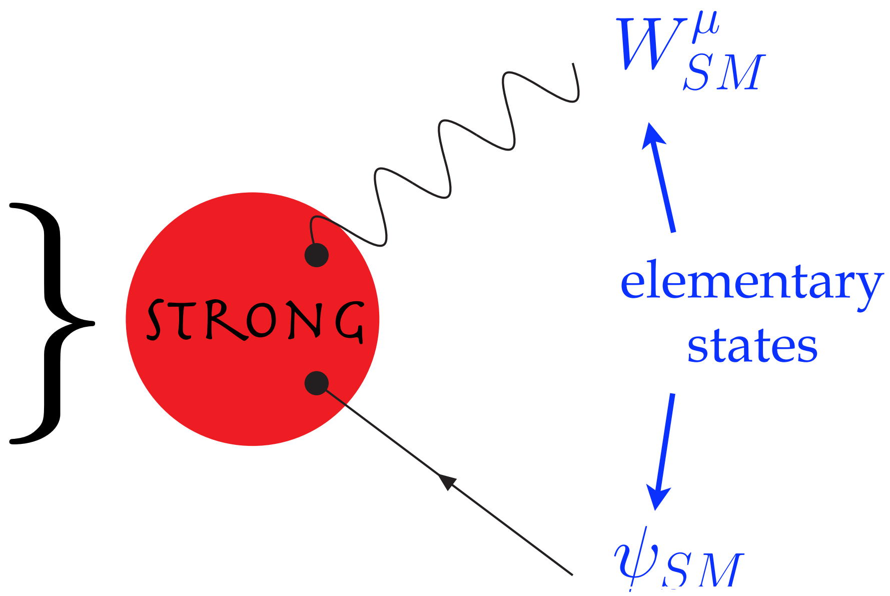
WHAT DO WE NEED ?

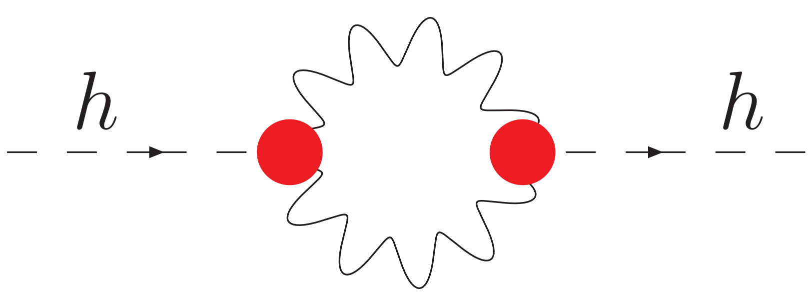
Explicit Symmetry Breaking: from the Strong Sector alone: $V(h) = 0$

from interactions with SM fields:

➡ SM gauge interactions (subgroup K of G is gauged)

➡ SM fermion interactions (proto-Yukawas, mostly the top)





$\longrightarrow$ $V(h) \neq 0$ $\longrightarrow$ $\langle h \rangle = v < f$

$$\xi = \frac{v^2}{f^2} \sim \frac{1}{4}$$

➡ other sources of explicit breaking? like "quark" masses,...

$$f \gtrsim 500 \text{ GeV}$$

partial-SUSY might play a role

R.Sundrum

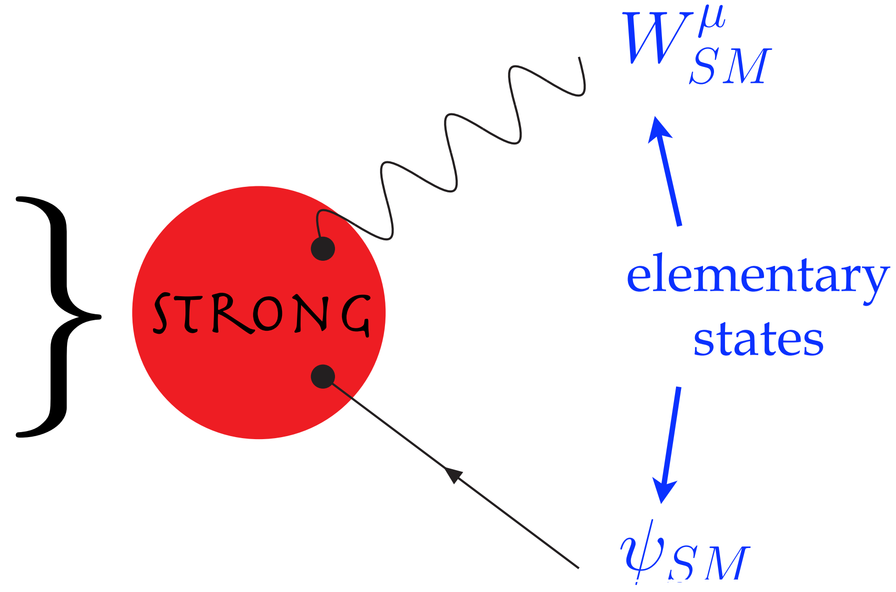
B.Gripaios, M.Redi

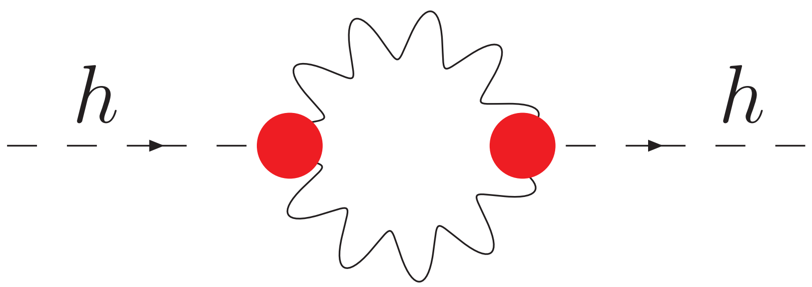
WHAT DO WE NEED ?

Explicit Symmetry Breaking: from the Strong Sector alone: $V(h) = 0$

from interactions with SM fields:

- ➡ SM gauge interactions (subgroup K of G is gauged)
- ➡ SM fermion interactions (proto-Yukawas, mostly the top)





$$\longrightarrow \quad V(h) \neq 0 \quad \longrightarrow \quad \langle h \rangle = v < f$$

$$\xi = \frac{v^2}{f^2} \sim \frac{1}{4}$$

$$f \gtrsim 500 \text{ GeV}$$

- ➡ other sources of explicit breaking? like "quark" masses,...

Calculability: **Effective low-energy "chiral" Lagrangian**

+

Holography and Warped extra-d

WHAT DO WE GET ?

Minimal **Composite Higgs Model:**

$$G = SO(5) \longrightarrow H = O(4) \qquad G/H = \mathbf{4} = (\mathbf{2},\mathbf{2})$$

Pheno: new resonances + modifications of Higgs couplings

WHAT DO WE GET ?

***Minimal* Composite Higgs Model:**

$$G = SO(5) \longrightarrow H = O(4) \qquad G/H = \mathbf{4} = (\mathbf{2},\mathbf{2})$$

Pheno: new resonances + modifications of Higgs couplings

Minimality = number of NGB's is that a good guide?

WHAT DO WE GET ?

***Minimal* Composite Higgs Model:**

$$G = SO(5) \longrightarrow H = O(4) \qquad G/H = \mathbf{4} = \mathbf{(2,2)}$$

Pheno: new resonances + modifications of Higgs couplings

Minimality = number of NGB's   is that a good guide?

Example of ***minimal*** cosets from constituent "quarks":

extra singlet

$$SU(4) \longrightarrow Sp(4) \qquad G/H = \mathbf{5} = \mathbf{4} + \mathbf{1} = \mathbf{(2,2)} + \mathbf{(1,1)}$$

$$SU(5) \longrightarrow SO(5) \qquad G/H = \mathbf{14}$$

B.Gripaios, A.Pomarol, F.Riva, JS
J.Galloway, J.Evans, M.Luty, R.Tacchi

WHAT DO WE GET ?

Minimal **Composite Higgs Model:**

$$G = SO(5) \longrightarrow H = O(4) \qquad G/H = \mathbf{4} = \mathbf{(2,2)}$$

Pheno: new resonances + modifications of Higgs couplings

Minimality = number of NGB's   is that a good guide?

Example of ***minimal*** cosets from constituent "quarks":

extra singlet

$$SU(4) \longrightarrow Sp(4) \qquad G/H = \mathbf{5} = \mathbf{4} + \mathbf{1} = \mathbf{(2,2)} + \mathbf{(1,1)}$$

$$SU(5) \longrightarrow SO(5) \qquad G/H = \mathbf{14}$$

B.Gripaios, A.Pomarol, F.Riva, JS

J.Galloway, J.Evans, M.Luty, R.Tacchi

$$SO(6) \longrightarrow SO(4)xU(1) \qquad G/H = \mathbf{8} = \mathbf{4}_{+2} + \mathbf{4}_{-2} = 2 \text{ x } \mathbf{(2,2)}$$

2 Higgs doublets! and not MSSM

2 Composite-NGB-Higgs: is it viable?

$$h_i = (\mathbf{2}, \mathbf{2}), \quad i = 1, 2$$

➡ **Large contributions to $\delta\rho$:**

$$\langle h_1 \rangle = \begin{pmatrix} 0 \\ 0 \\ 0 \\ v_1 \end{pmatrix} \langle h_2 \rangle = \begin{pmatrix} 0 \\ 0 \\ v_2 \\ 0 \end{pmatrix} \Bigg\} \; \mathrm{SO}(2) \cong \mathrm{U}(1)_Q$$

custodial SO(3) breaking

misaligned VEV's

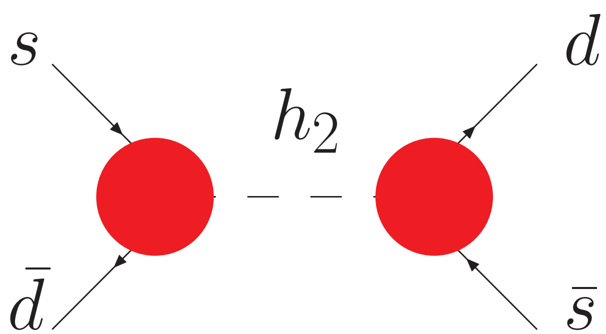
$$\frac{c_T}{f^2} (h_1^T D_\mu h_2)^2 \longrightarrow \delta\rho \sim c_T \frac{v^2}{f^2}$$

$$v^2/f^2 \lesssim 1 \times 10^{-3}$$

➡ **Dangerous Flavor transitions:**

$$\bar{q}_L \left(y_1^u \tilde{h}_1 + y_2^u \tilde{h}_2 \right) u_R + \bar{q}_L \left(y_1^d h_1 + y_2^d h_2 \right) d_R$$

misaligned Yukawa's



$$\sim \frac{m_s^2 V_{us}^2}{2 m_{h_2}^2} (\bar{s}_L d_R)^2 \longrightarrow m_{h_2} \gtrsim 2\ \mathrm{TeV}$$

Inert Composite-Higgs Model

Defined by extra Z_2:

$$h_1 \to +h_1$$

$$h_2 \to -h_2 \qquad + \qquad \langle h_2 \rangle = 0$$

$$\mathrm{SM} \to +\mathrm{SM}$$

Z_2 exactly conserved

NO $(h_2)^{2n+1}$ couplings

Immediate consequences:

➡ **Automatic solution of $\delta\rho$ and Flavor problems.**

➡ Stability of lightest h_2 component (DM candidate).

➡ Double h_2 production @ colliders.

Inert Composite-Higgs Model

Defined by extra Z_2:

$$h_1 \to +h_1$$

$$h_2 \to -h_2 \qquad + \qquad \langle h_2 \rangle = 0$$

$$\mathrm{SM} \to +\mathrm{SM}$$

Z_2 exactly conserved

NO $(h_2)^{2n+1}$ couplings

Immediate consequences:

- ➡ **Automatic solution of $\delta\rho$ and Flavor problems.**
- ➡ Stability of lightest h_2 component (DM candidate).
- ➡ Double h_2 production @ colliders.

$$G = \mathbf{O(6)} \longrightarrow H = \mathbf{O(4) \times O(2)}$$

Z_2 **= outer automorphism of SO(6)**

INERT HIGGS: O(6)/O(4)xO(2)

Breakings:

$(\mathrm{SU}(2)_L, \mathrm{SU}(2)_R)_{Z_2}$

spontaneous, $\Sigma(h_1, h_2) = \mathrm{SO}(6)/\mathrm{SO}(4) \times \mathrm{SO}(2) \in \mathbf{20'}$

$$= (\mathbf{2}, \mathbf{2})_+ + (\mathbf{2}, \mathbf{2})_-$$

explicit, $\psi_{SM} \in \mathbf{6}$ $\quad \mathbf{6} = (\mathbf{2}, \mathbf{2})_+ + (\mathbf{1}, \mathbf{1})_+ + (\mathbf{1}, \mathbf{1})_-$

$q_L = (u_L, d_L)$ $\quad u_R,\, d_R$

$W^{\mu}_{SM} \in \mathbf{15}$

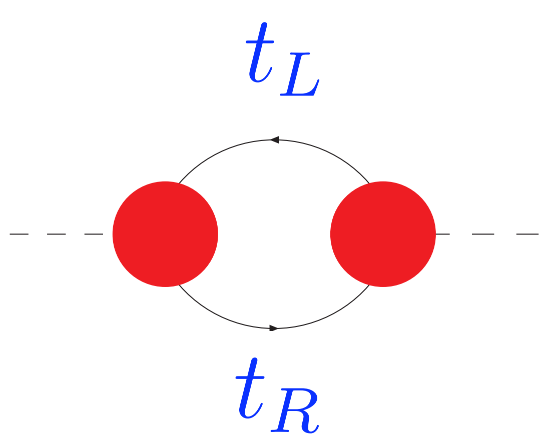
$$\mathbf{15} = (\mathbf{1}, \mathbf{1})_+ + (\mathbf{3}, \mathbf{1})_+ + (\mathbf{1}, \mathbf{3})_+ + (\mathbf{2}, \mathbf{2})_+ + (\mathbf{2}, \mathbf{2})_-$$

W_L $\quad B_Y$

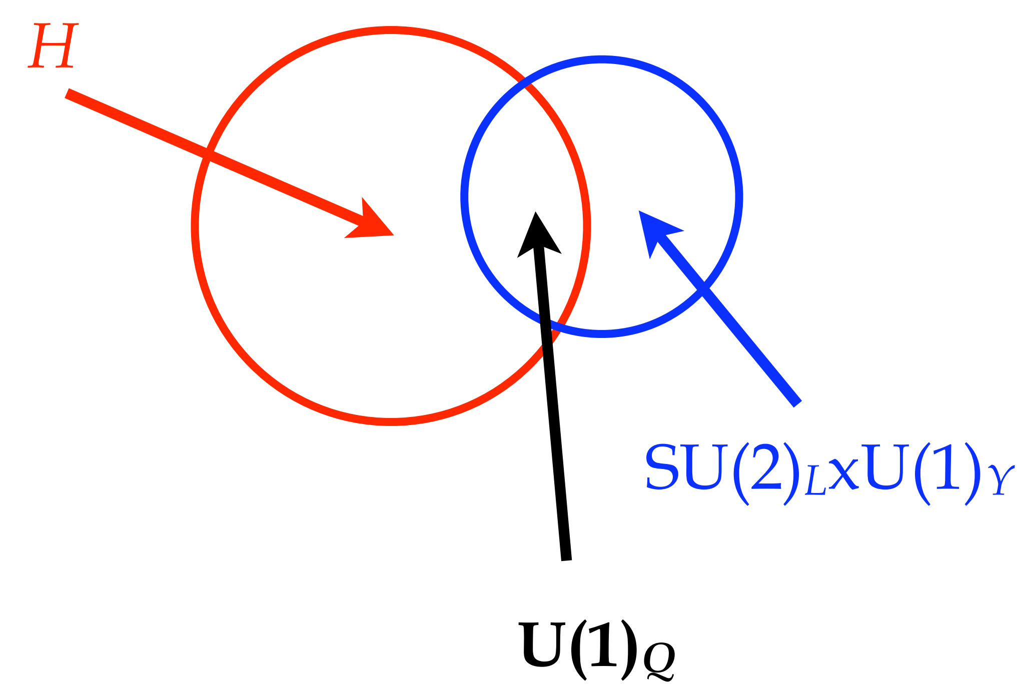
INERT HIGGS: O(6)/O(4)xO(2)

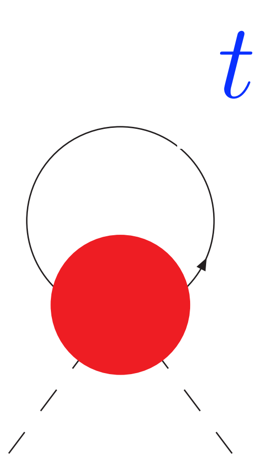
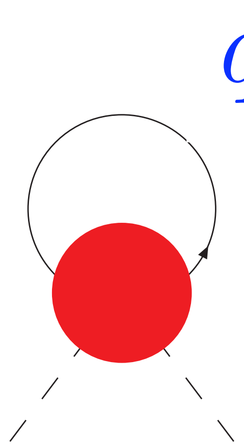
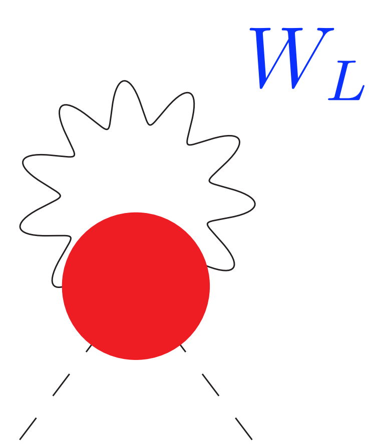
EW Symmetry Breaking: $\langle h_2 \rangle = 0$

$$V(h_1) = \alpha \cos(h_1/f) - \beta \sin^2(h_1/f) \rightarrow \cos(h_1/f) = -\alpha/2\beta$$

$\beta \simeq$ 

thanks to large top-loops

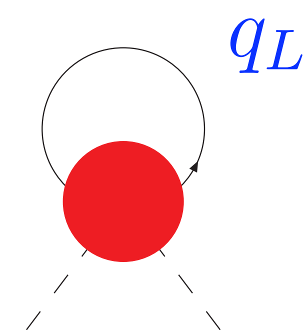


$\alpha \simeq$  $-$  $-$  > 0

Inert Higgs: O(6)/O(4)xO(2)

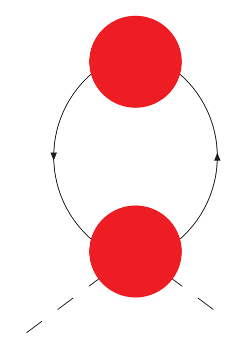
Spectrum:

$$\sim m_{h_2} \sim \sqrt{\lambda_2}\, f \sim 450\ \text{GeV}$$



$$\lambda_2 \sim \frac{y_L^2 g_\rho^2}{16\pi^2}$$

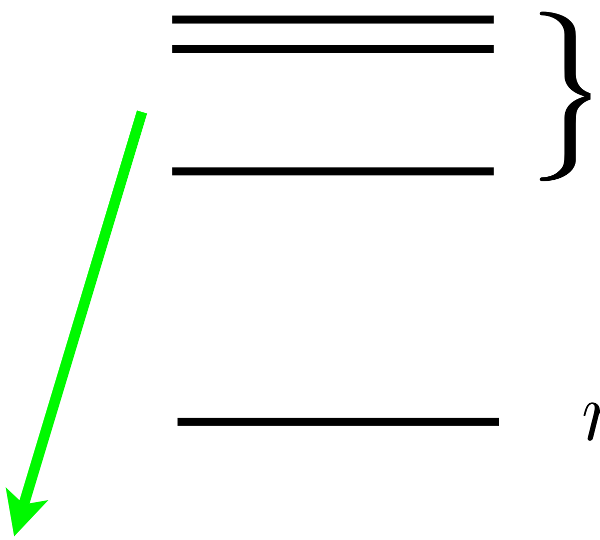
$$m_{h_1} \sim \sqrt{\lambda_1}\, v \sim 150\ \text{GeV}$$



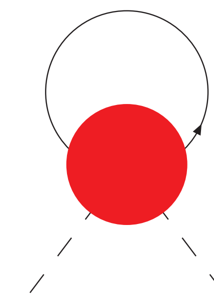
$$\lambda_1 \sim \frac{y^4}{16\pi^2}$$

INERT HIGGS: O(6)/O(4)xO(2)

Spectrum:

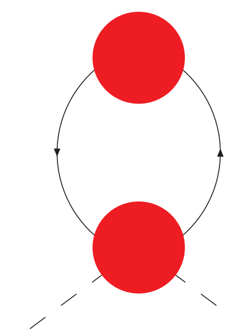


$$\sim m_{h_2} \sim \sqrt{\lambda_2}\, f \sim 450 \text{ GeV}$$



$$\lambda_2 \sim \frac{y_L^2 g_\rho^2}{16\pi^2}$$

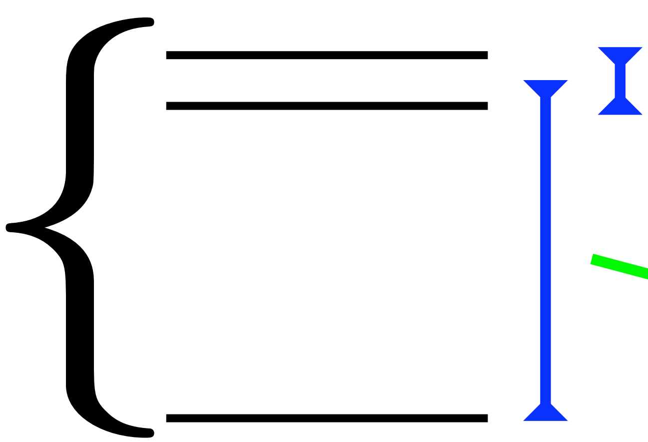
$$m_{h_1} \sim \sqrt{\lambda_1}\, v \sim 150 \text{ GeV}$$



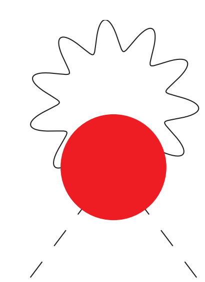
$$\lambda_1 \sim \frac{y^4}{16\pi^2}$$

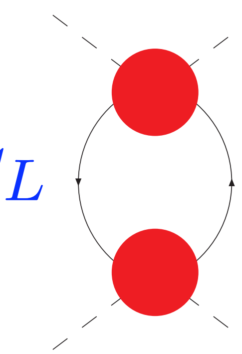
splittings, $h_2 \rightarrow T = (H^\pm, A) \oplus S$

$$\text{SO}(4) \quad \mathbf{4} = \mathbf{3} + \mathbf{1} \quad \text{SO}(3)$$

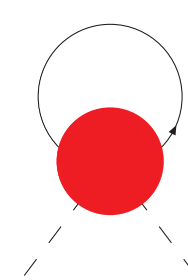


$$\frac{|m_H^\pm - m_A|}{m_T} \sim \left(\frac{g'^2}{y_L^2} \pm \frac{y_L^2}{g_\rho^2}\right) \frac{v^2}{f^2} \sim \boxed{\frac{1}{40}}$$





$$\frac{|m_S - m_T|}{m_T} \sim \frac{v^2}{f^2} \sim \boxed{\frac{1}{4}}$$



PSEUDO-INERT HIGGS: EXPLICIT Z_2 BREAKING

explicit, $\psi_{SM} \in \mathbf{6}$ $\quad \mathbf{6} = (\mathbf{2},\mathbf{2})_+ + (\mathbf{1},\mathbf{1})_+ + (\mathbf{1},\mathbf{1})_-$

u_R

$$O(2) \longrightarrow Z'_2 \qquad u_R \in (\mathbf{1},\mathbf{1})_+,$$

we need collective breaking

$$v_2 \sim \frac{(y_R^t)^2 (y_R^b)^2}{y_L^2 g_\rho^2} \frac{1}{16\pi^2} v_1 \qquad \textbf{large} \tan\beta$$

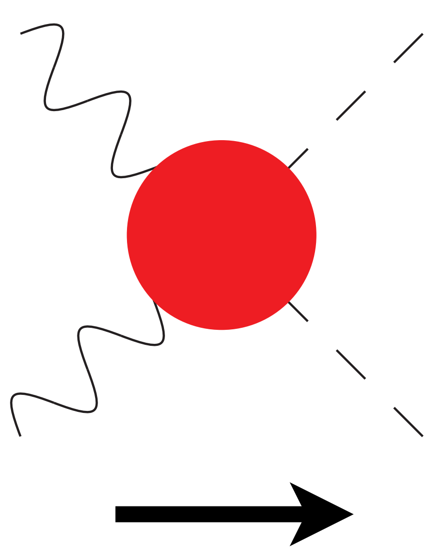
COSET INTERACTIONS: O(6)/O(4)xO(2)

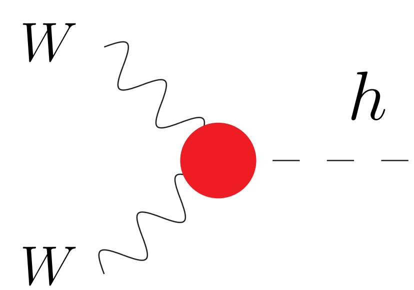
Signatures of composite-NGB: $\mathcal{L}_{coset}[h_1/f, h_2/f] = \frac{f^2}{2}\mathrm{Tr}[|D_\mu \Sigma|^2]$

$$= \frac{1}{2}(D_\mu h_j)^2 + \frac{c_\partial}{f^2}(h_i \partial_\mu h_i)^2 + \frac{c_W}{f^2}(h_i W_\mu h_j)^2 + \frac{c_{\partial W}}{f^2}(h_i \partial_\mu h_i)(h_j W^\mu h_j)$$

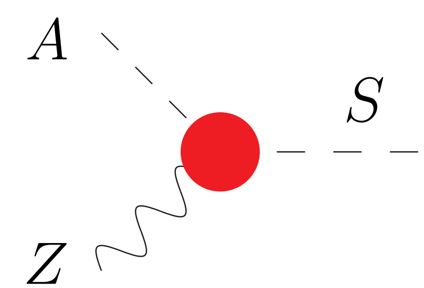
(no *CPV* or large $\delta\rho$)

non-unitarity of amplitudes,

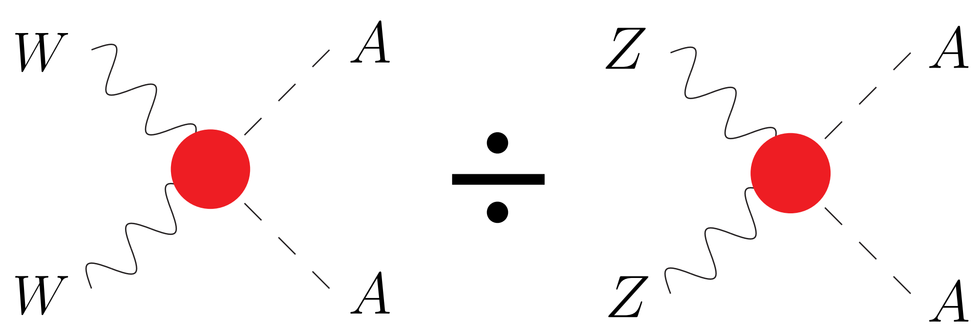




$$\sum_i g^2_{h_i^0 WW} = g^2 m_W^2 \left(1 - \frac{1}{2}\frac{v^2}{f^2}\right)$$



$$\sum_i g^2_{h_i^0 AZ} = \frac{g^2}{\cos^2\theta_W}\left(1 - \frac{1}{2}\frac{v^2}{f^2}\right)$$



$$= \cos^2\theta_W \left(1 + \frac{v^2}{f^2}\right)$$

CONCLUSIONS

If the hierarchy problem is solved by strong dynamics, we can expect rich phenomenology of pseudo-NGB's.

↓

motivated framework for extended Higgs sectors

example, Inert composite-Higgs model (not near MSSM)

- ➡ **completely viable**
- ➡ **predictions:**
  - **large h_2 masses, $m_{h2} \sim 450$ GeV**
  - **small custodial splittings, $|m_{H+} - m_A| \sim 10$ GeV**
  - **$O(v^2/f^2) \sim 20\%$ deviations in couplings**