BEYOND THE MINIMAL COMPOSITE HIGGS MODEL

2 HIGGSES AS COMPOSITE PSEUDO-NGB'S

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WHY A COMPOSITE-NGB-HIGGS ?

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QCD inspired

NO Naturalness or Hierarchy problems

STRONG SECTOR

dynamical

EW SCALE

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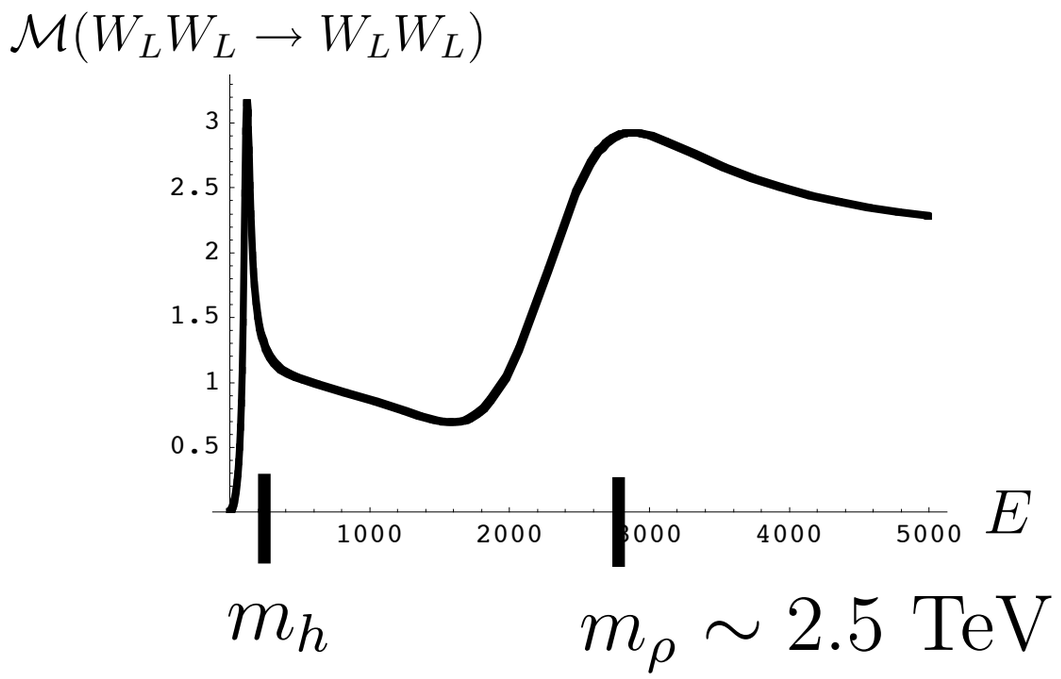
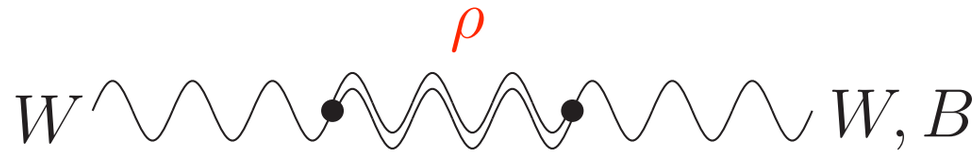


resonances pushed up in energy



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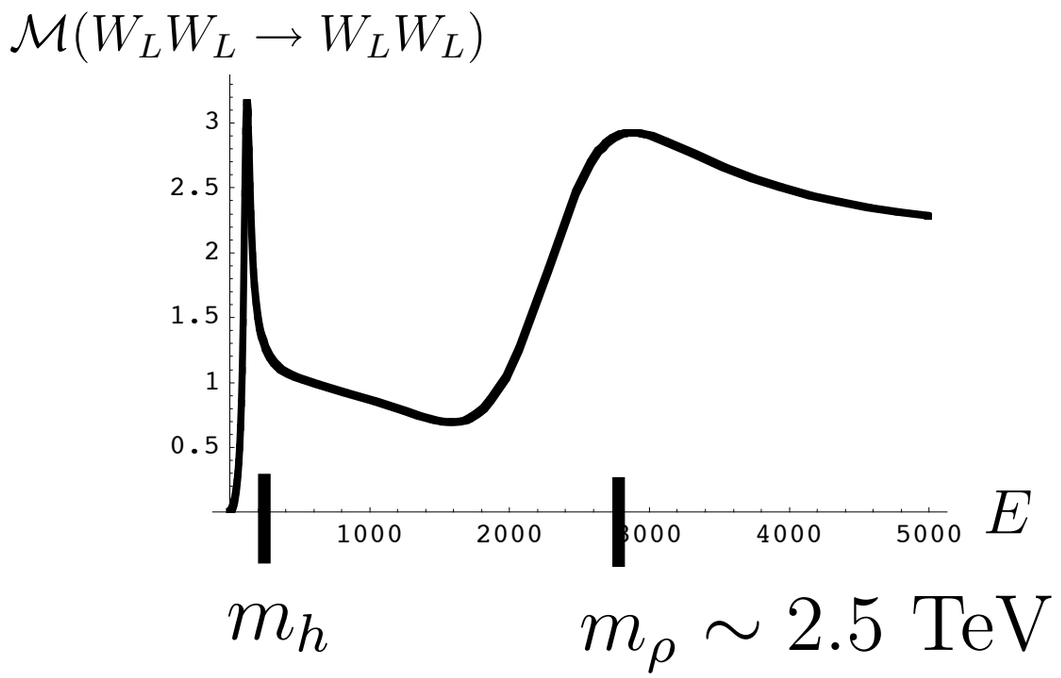
EW SCALE

like QCD pions

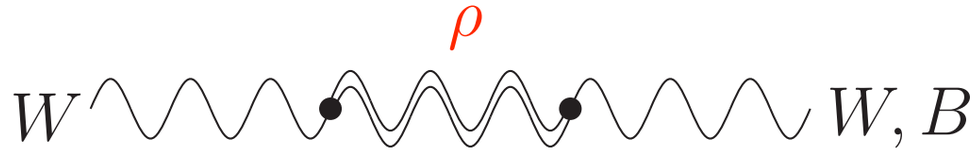
consistency with EWPT (S , T)



Higgs lighter than other resonances

$$m_h \ll m_\rho$$

resonances pushed up in energy



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$$G \longrightarrow H$$

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

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

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***h,* Higgs complex doublet**

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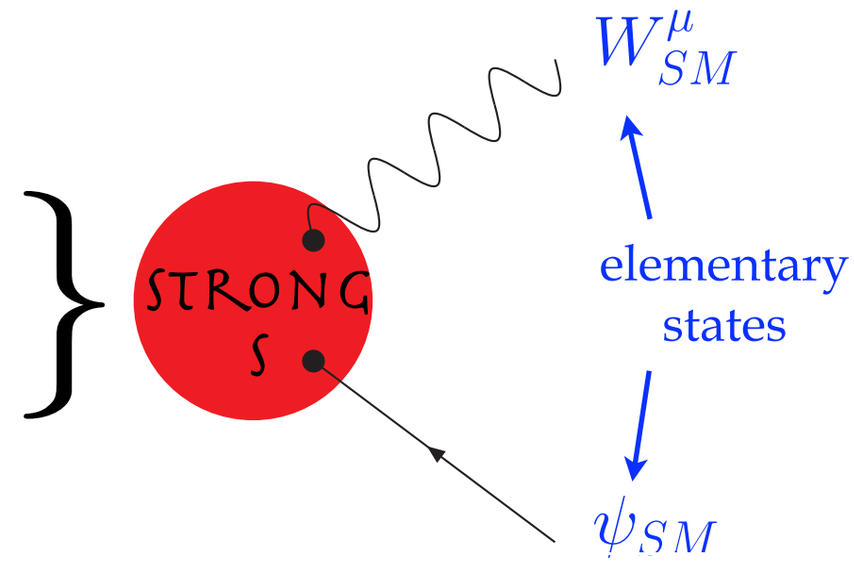
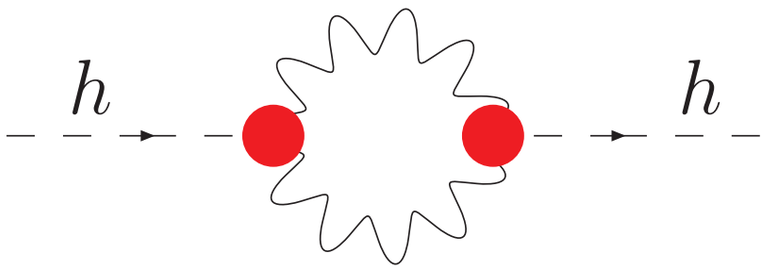
Explicit Symmetry Breaking: from the Strong Sector alone: $V(h) = 0$

from interactions with SM fields:

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

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





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

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

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

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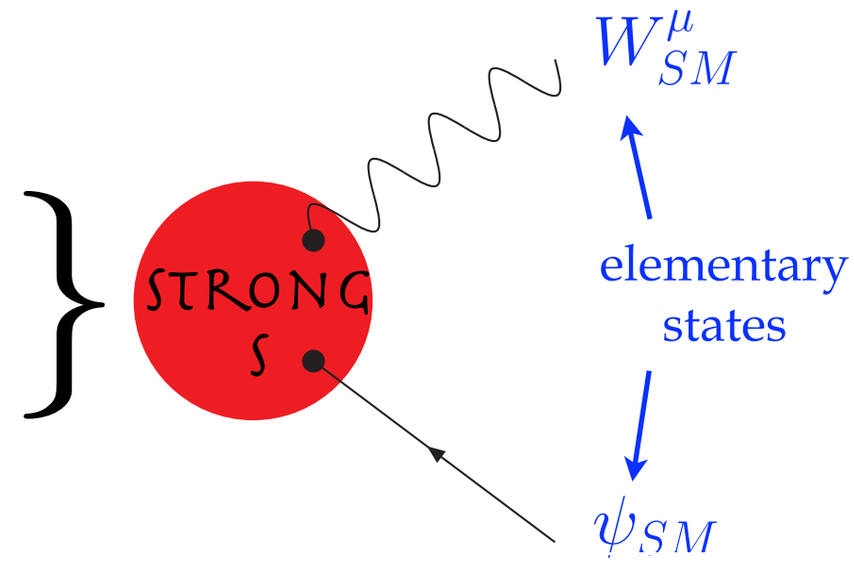

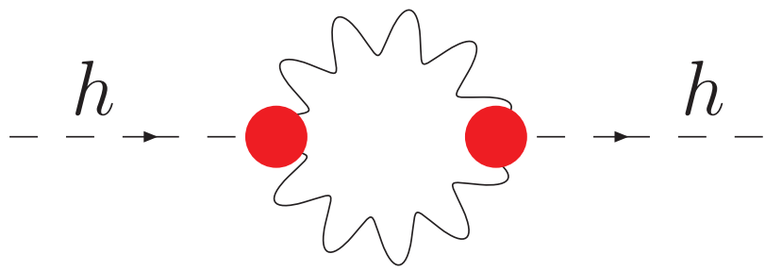

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Calculability:

Effective low-energy "chiral" Lagrangian

+

Holography and Warped extra-d

WHAT DO WE GET ?

Minimal Composite Higgs Model: $G = \mathbf{SO(5)} \longrightarrow H = \mathbf{O(4)}$

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

Pheno: new resonances + modifications of Higgs couplings

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

$\mathrm{SU}(4) \longrightarrow \mathrm{Sp}(4)$ $\quad G/H = \mathbf{5} = \mathbf{4} + \mathbf{1} = \mathbf{(2,2)} + \mathbf{(1,1)}$ ← extra singlet

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

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→ models with 2 Higgs doublets

2 COMPOSITE-NGB-HIGGS: IS IT VIABLE?

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

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

$$\langle h_1 \rangle = \begin{pmatrix} 0 \\ 0 \\ 0 \\ v_1 \end{pmatrix} \quad \langle h_2 \rangle = \begin{pmatrix} 0 \\ 0 \\ v_2 \\ 0 \end{pmatrix} \Bigg\} \; \mathrm{SO}(2) \cong \mathrm{U}(1)_Q \quad \text{custodial SO(3) breaking}$$

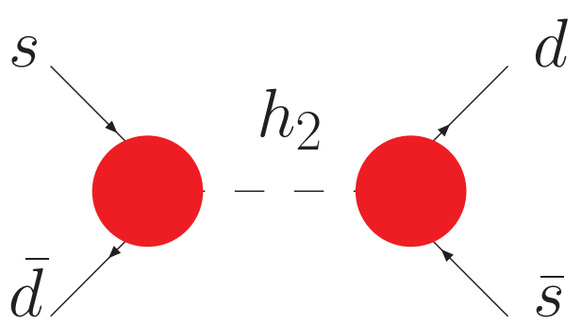
misaligned VEV's

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

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

➡ **Dangerous Flavor transitions:**

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



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

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 $(h_2)^{2n}$ couplings

immediate consequences:

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

EXAMPLE: $G = \mathbf{O(6)} \longrightarrow H = \mathbf{O(4)\ x\ O(2)}$

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

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

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

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

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

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

$W^\mu_{SM} \in \mathbf{15}$

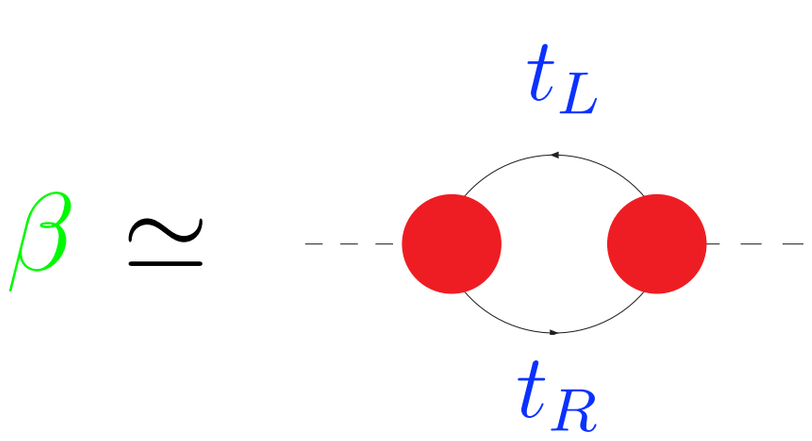
$\mathbf{15} = (\mathbf{1},\mathbf{1})_+ + (\mathbf{3},\mathbf{1})_+ + (\mathbf{1},\mathbf{3})_+ + (\mathbf{2},\mathbf{2})_+ + (\mathbf{2},\mathbf{2})_-$

W_L $\quad$ B_Y

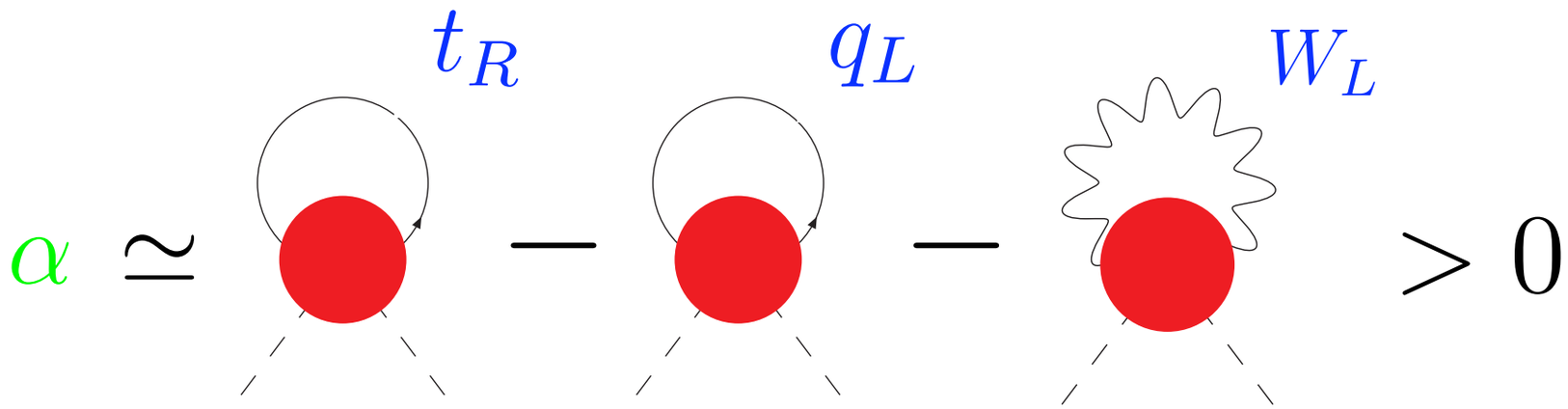
INERT HIGGS: O(6)/O(4)XO(2)

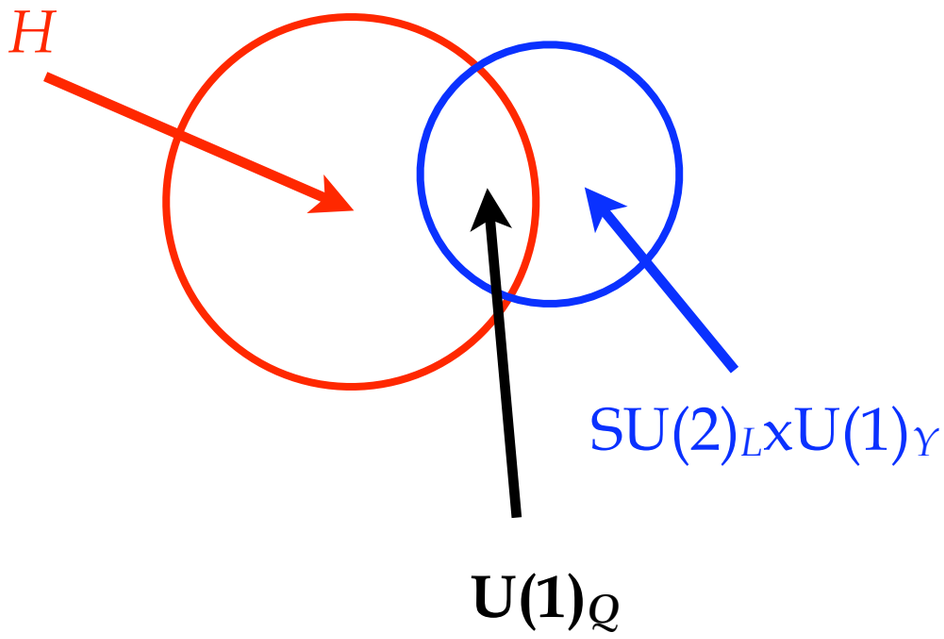
EW Symmetry Breaking: $\langle h_2 \rangle = 0$

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



thanks to large top-loops





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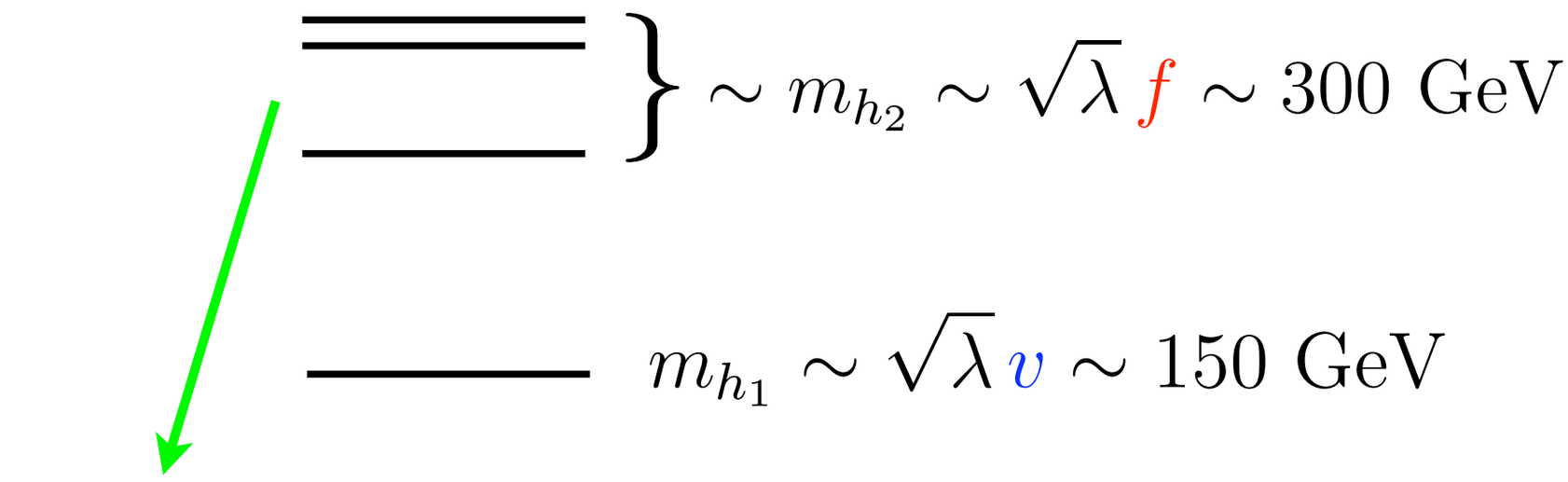
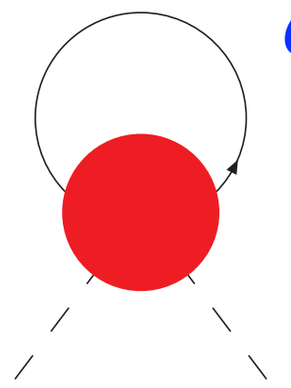
Spectrum:

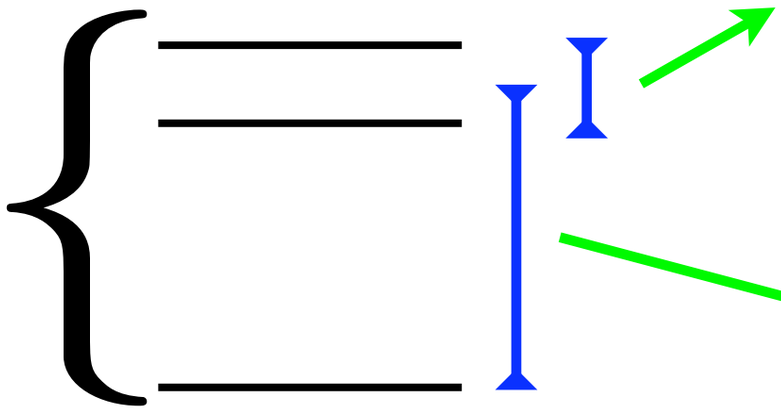




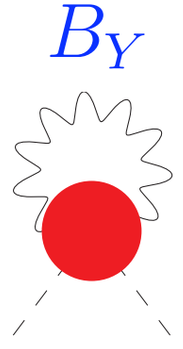
$$\lambda \sim \frac{y_L^2 g_\rho^2}{16\pi^2}$$

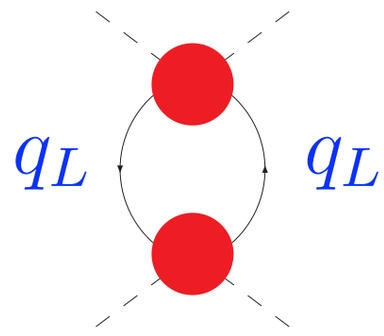
splittings, $h_2 \longrightarrow T = (H^\pm, A) \oplus S$

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

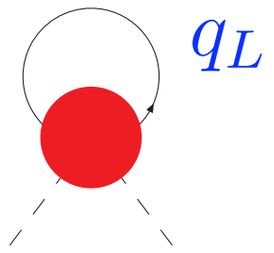


$$\frac{|m_H^\pm - m_A|}{m_T} \sim \left(\frac{g'^2}{y_L^2} \pm \frac{y_L^2}{g_\rho^2}\right) \frac{v^2}{f^2} \sim \boxed{\frac{1}{40}}$$





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



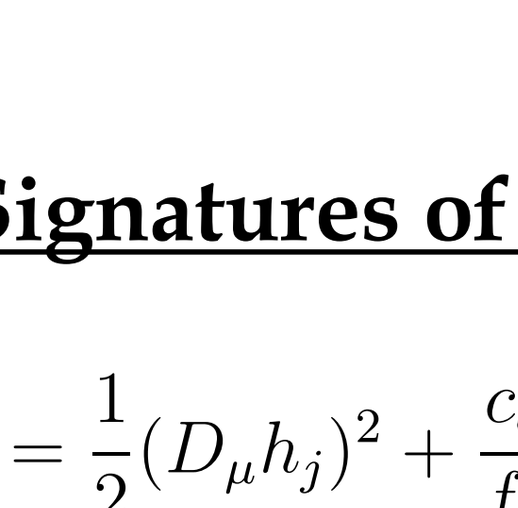
SO(6)/SO(4)xSO(2)

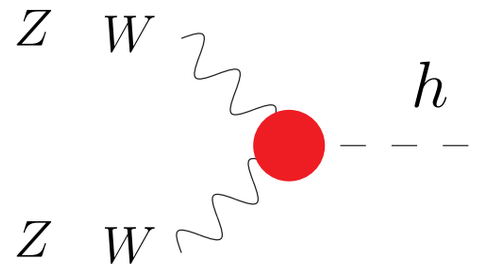
Signatures of composite-NGB: $\mathcal{L}_{coset}[h_1/f, h_2/f] = \frac{f^2}{2}\mathrm{Tr}[|D_\mu \Sigma|^2]$

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

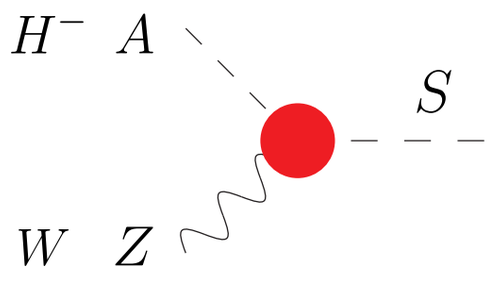
$$\langle h_1 \rangle = v, \ \langle h_2 \rangle = 0$$

non-unitarity of amplitudes,

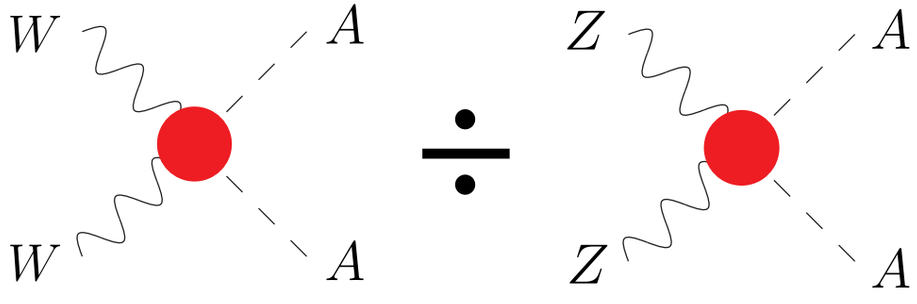




$$\sum_i g^2_{h^0_i WW} = g^2 m_W^2 \left(1 - \frac{2}{3}\frac{v^2}{f^2}\right)$$



$$\sum_i g^2_{h^0_i AZ} = \frac{g^2}{\cos^2\theta_W}\left(1 - \frac{1}{6}\frac{v^2}{f^2}\right)$$



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

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, $m_{h2} \sim 300$GeV**
  small custodial splittings, $\Delta m_T \sim 10$GeV
  $O(v^2/f^2) \sim 20\%$ deviations in couplings