Composite Two Higgs doublet models

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Higgs as a (composite) PNGB

Idea:

Strong dynamics at TeV scale or so

→ provide a natural cut-off to the theory

General expectation:

$$m_h \sim \Lambda_{strong}$$

Higgs as a (composite) PNGB

How to keep the Higgs light:

~~Higgs as a~~

~~pseudo Goldstone Boson~~

$G \to H \quad h \in G/H$

+ explicit breaking

giving h mass @ loop level

(exactly massless if true NGB)

The (PNGB) Higgs program

- Pick G containing $SU(2) \times U(1)$
- Pick H so that G/H contains (at least) one (2,2) of $SU(2)_L \times SU(2)_R$

Once the coset is assigned,

the gauge sector is fixed

The (PNGB) Higgs program

Fermionic sector:

PARTIAL COMPOSITENESS paradigm

$$\mathcal{L} = \overline{\psi}^{i}_{SM} \lambda_{iJ} \Psi^{J}_{C} = \overline{\Psi}^{J}_{SM} \Psi^{J}_{C}$$

Higgs interactions:

$$\mathcal{L} = \overline{\psi^{C}_{L}} Y H \Psi^{C}_{R} \rightarrow \overline{\Psi^{SM}_{L}} Y H \Psi^{SM}_{R}$$

↑

Integrate out
composite fermions

Minimal example

G	H	N_G	NGBs rep.$[H]$ = rep.$[SU(2)\times SU(2)]$
→ SO(5)	SO(4)	4	$\mathbf{4}=(\mathbf{2},\mathbf{2})$
SO(6)	SO(5)	5	$\mathbf{5}=(\mathbf{1},\mathbf{1})+(\mathbf{2},\mathbf{2})$
SO(6)	SO(4) × SO(2)	8	$\mathbf{4_{+2}}+\mathbf{\bar{4}_{-2}}=2\times(\mathbf{2},\mathbf{2})$
SO(7)	SO(6)	6	$\mathbf{6}=2\times(\mathbf{1},\mathbf{1})+(\mathbf{2},\mathbf{2})$
SO(7)	G_2	7	$\mathbf{7}=(\mathbf{1},\mathbf{3})+(\mathbf{2},\mathbf{2})$
SO(7)	SO(5) × SO(2)	10	$\mathbf{10_0}=(\mathbf{3},\mathbf{1})+(\mathbf{1},\mathbf{3})+(\mathbf{2},\mathbf{2})$
SO(7)	$[SO(3)]^3$	12	$(\mathbf{2},\mathbf{2},\mathbf{3})=3\times(\mathbf{2},\mathbf{2})$
Sp(6)	Sp(4) × SU(2)	8	$(\mathbf{4},\mathbf{2})=2\times(\mathbf{2},\mathbf{2}),(\mathbf{2},\mathbf{2})+2\times(\mathbf{2},\mathbf{1})$
SU(5)	SU(4) × U(1)	8	$\mathbf{4_{-5}}+\mathbf{\bar{4}_{+5}}=2\times(\mathbf{2},\mathbf{2})$
SU(5)	SO(5)	14	$\mathbf{14}=(\mathbf{3},\mathbf{3})+(\mathbf{2},\mathbf{2})+(\mathbf{1},\mathbf{1})$

Agashe, Contino, Pomarol 05

...and beyond

G	H	N_G	NGBs rep.$[H]$ = rep.$[SU(2) \times SU(2)]$
SO(5)	SO(4)	4	$\mathbf{4} = (\mathbf{2}, \mathbf{2})$
→ SO(6)	SO(5)	5	$\mathbf{5} = (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$
SO(6)	SO(4) × SO(2)	8	$\mathbf{4}_{+\mathbf{2}} + \bar{\mathbf{4}}_{-\mathbf{2}} = 2 \times (\mathbf{2}, \mathbf{2})$
SO(7)	SO(6)	6	$\mathbf{6} = 2 \times (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$
SO(7)	G_2	7	$\mathbf{7} = (\mathbf{1}, \mathbf{3}) + (\mathbf{2}, \mathbf{2})$
SO(7)	SO(5) × SO(2)	10	$\mathbf{10}_{\mathbf{0}} = (\mathbf{3}, \mathbf{1}) + (\mathbf{1}, \mathbf{3}) + (\mathbf{2}, \mathbf{2})$
SO(7)	$[SO(3)]^3$	12	$(\mathbf{2}, \mathbf{2}, \mathbf{3}) = 3 \times (\mathbf{2}, \mathbf{2})$
Sp(6)	Sp(4) × SU(2)	8	$(\mathbf{4}, \mathbf{2}) = 2 \times (\mathbf{2}, \mathbf{2}), (\mathbf{2}, \mathbf{2}) + 2 \times (\mathbf{2}, \mathbf{1})$
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Gripaios, Pomarol, Riva, Serra 09

… and beyond

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Mrazek, Pomarol, Rattazzi, Redi, Serra, Wulzer 11

… and beyond

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→ SU(5)	SU(4) × (U(1))	8	$\mathbf{4}_{-5} + \bar{\mathbf{4}}_{\mathbf{+5}} = 2 \times (\mathbf{2}, \mathbf{2})$
SU(5)	SO(5)	14	$\mathbf{14} = (\mathbf{3}, \mathbf{3}) + (\mathbf{2}, \mathbf{2}) + (\mathbf{1}, \mathbf{1})$
→ SO(9)	SO(8)	8	$8 = (2,2)_{+1} + (2,2)_{-1}$

Bertuzzo, De Sandes, Ray, Savoy 12

C2HDMs ISSUES

- At tree level $\Delta T \neq 0$ → More on this later
- Higgs mediated FCNC → All fermions with same quantum numbers coupled to only one Higgs doublet

  Glashow, Weinberg 77
- Zbb coupling →

$$q_L \in (2,2)_{2/3}$$

Agashe, Contino, Da Rold, Pomarol 06

A detour: how to write a non linear lagrangian

Two ways:

- CCWZ procedure — Callan, Coleman, Wess, Zumino 69
- ~~Using a vector to "linearly" realize the symmetry~~

Second method

Parametrize the breaking as

$$G \to H_1 \times H_2, \qquad H_2 = \emptyset, U(1), SU(2)$$

Define a matrix:

$$u = e^{i\Pi/f} u_0$$

NGB matrix

Nxp matrix,

N=dim(fundamental G),

p=1 for ∅, U(1),

p=2 for SO(2), SU(2)

B, De Sandes, Ray, Savoy 12

Second method

Properties:

$$u \to g u h_2^\dagger$$

Possible invariants (with two derivatives):

$$\begin{aligned} \mathrm{tr}\partial_\mu u^\dagger\,\partial^\mu u &= \mathrm{tr} u_0^\dagger \partial_\mu U^\dagger \partial^\mu U\, u_0 \\ \mathrm{tr} u^\dagger \partial_\mu u\,\partial^\mu u^\dagger u &= \mathrm{tr} u_0^\dagger U^\dagger \partial_\mu U\, u_0\, u_0^\dagger \partial^\mu U^\dagger U\, u_0 \end{aligned}$$

Second method

Strategy: to construct the invariant lagrangian, combine the two invariants so to obtain the CCWZ lagrangian:

$$\mathcal{L} = \mathrm{tr}\partial_\mu u^\dagger \partial^\mu u + \kappa \mathrm{tr} u^\dagger \partial_\mu u \, \partial^\mu u^\dagger u$$

Depends on the group considered

Extended cosets

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

$$\mathcal{L} = \mathrm{tr}\left(\partial_\mu u^T\,\partial^\mu u - u^T\partial_\mu u\,\partial^\mu u^T u\right)$$

- Sp(6)/Sp(4)xSp(2)

$$\mathcal{L} = \mathrm{tr}\left(\partial_\mu u^\dagger\,\partial^\mu u - \partial_\mu u^\dagger u\,u^\dagger\partial^\mu u\right)$$

- SU(5)/SU(4)[xU(1)]

$$\mathcal{L} = \mathrm{tr}\left(\partial_\mu u^\dagger\,\partial^\mu u - \left[\tfrac{3}{8}\right] u^\dagger\partial_\mu u\,\partial^\mu u^\dagger u\right)$$

- SO(9)/SO(8)

$$\mathcal{L} = \partial_\mu u^T\,\partial^\mu u$$

Back to the T-problem

$$\mathcal{L} = \mathrm{tr}\left(\partial_\mu u^\dagger \partial^\mu u - \kappa u^\dagger \partial_\mu u \, \partial^\mu u^\dagger u\right)$$

Mass of gauge bosons:

$$\frac{\mathcal{M}^2_{AB}}{g_A g_B} = u^\dagger \{T^A, T^B\} u - \kappa \, u^\dagger T^A u \, u^\dagger T^B u$$

SM-like

Breaking of custodial symmetry

Back to the T-problem

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

$$\mathcal{L} = \mathrm{tr}\left(\partial_\mu u^T \partial^\mu u - u^T \partial_\mu u\, \partial^\mu u^T u\right)$$ X

- Sp(6)/Sp(4)xSp(2)

$$\mathcal{L} = \mathrm{tr}\left(\partial_\mu u^\dagger \partial^\mu u - \partial_\mu u^\dagger u\, u^\dagger \partial^\mu u\right)$$?

- SU(5)/SU(4)[xU(1)]

$$\mathcal{L} = \mathrm{tr}\left(\partial_\mu u^\dagger \partial^\mu u - \left[\tfrac{3}{8}\right] u^\dagger \partial_\mu u\, \partial^\mu u^\dagger u\right)$$ X

- SO(9)/SO(8)

$$\mathcal{L} = \partial_\mu u^T \partial^\mu u$$ V

Back to the T-problem

Why is Sp(6)/Sp(4)xSp(2) special?

$$Sp(4) \times Sp(2) \supset SU(2)^3$$

Can align the vacuum for both the doublets

→ model OK

FCNC: how they arise

- Glashow–Weinberg theorem violated
- Multiple ways to embed the SM fermions in a G multiplet

Agashe, Contino 09

→ Need to assign SM fermions to G representations

Sp(6): fermions

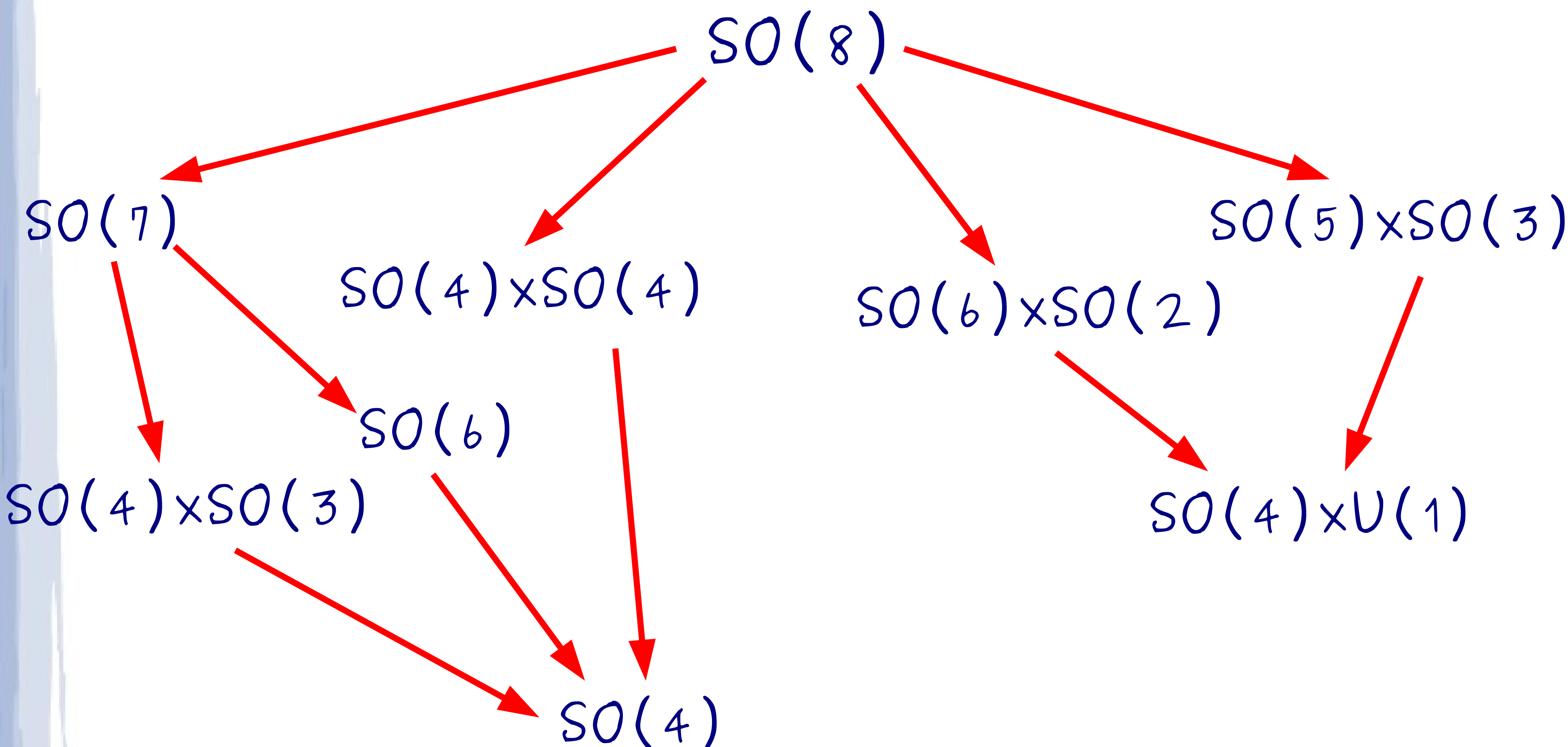
Sp(6)	Sp(4)xSp(2)
Higgs	(4,2)
14	(4,2)+(5,1)+(1,1)
21	(4,2)+(10,1)+(1,3)

(2,2)+(2,2)

two different ways to embed LH doublet → ~~FCNC~~

SO(9): fermions

How to embed $O(4)_{SM}$



SO(9): fermions

SO(9)	SO(8)	SO(4)xU(1)
(vec) 9	$8_V + 1$	$(2,2)_- + (2,2)_+ + (1,1)_0$
(spin) 16	$8_C +$	$(2,2)_+ + (2,2)_-$
	8_A	$(1,3)_0 + (3,1)_0 +$
		$(1,1)_{-2} + (1,1)_{+2}$

SO(9): fermions

SO(9)		
		H1 → $(2,2)_-$; H2 → $(2,2)_+$
9		$(2,2)_- + (2,2)_+ + (1,1)$
16	qL →	$(2,2)_+ + (2,2)_-$
	tR, bR →	$(1,3)_0 + (3,1)_0 +$
		$(1,1)_{-2} + (1,1)_{+2}$

TYPE I 2HDM (Glashow–Weinberg OK)

U(1) avoids multiple embeddings

Zbb protected

Conclusions

- 125 GeV Higgs → what's keeping it light? Compositeness + PNGB a possibility
- Assuming extended Higgs sector: T-problem, flavor problem, Zbb
- Sp(6)/Sp(4)xSp(2) and SO(9)/SO(8) are T-safe (coset properties)
- SO(9)/SO(8) is also flavor safe + Zbb protected

Back up

CCWZ procedure

Define U=matrix containing NGBs

Transformation: $\mathrm{U} \to g U h^{\dagger}$

Useful quantity: (Maurer–Cartan 1–form)

$$\mathrm{i}\,\mathrm{U}^{\dagger}\partial_{\mu}U = d_{\mu}^{\hat{a}}T^{\hat{a}} + E_{\mu}^{a}T^{a}$$

Broken generators

Unbroken generators

CCWZ procedure

Transformation properties:

$$d_\mu^{\hat{a}} \to h d_\mu^{\hat{a}} h^\dagger$$

$$E_\mu^a \to h E_\mu^a h^\dagger - i h \partial_\mu h^\dagger$$

Building blocks for the lagrangian:

$$\mathcal{L} = \frac{f^2}{4} d_\mu^{\hat{a}} d_\mu^{\hat{a}}$$

Alternative way (SO(5)/SO(4))

- Define a vector u(0) to parametrize SO(5)→SO(4) breaking:

$$u(0) = (0,0,0,0,1)^T$$

- Dress the vector with U to obtain a linear realization of G: $\Phi = U u(0)$
- Invariant lagrangian: $\mathcal{L} = \frac{f^2}{4} \partial_\mu \Phi^T \partial_\mu \Phi$

Alternative way (SO(5)/SO(4))

Equivalence with CCWZ procedure:

$$
\begin{aligned}
\mathcal{L} &\propto \partial_\mu \Phi^T \partial_\mu \Phi \\
&\propto u(0)^T \partial_\mu U^\dagger \partial_\mu U \, u(0) \\
&\propto u(0)^T (d_\mu + E_\mu)^2 u(0) \\
&\propto d_\mu^{\hat{a}} d_\mu^{\hat{b}} u(0)^T \left\{ T^{\hat{a}}, T^{\hat{b}} \right\} u(0) \\
&\propto d_\mu^{\hat{a}} d_\mu^{\hat{a}}
\end{aligned}
$$

Alternative way (SO(5)/SO(4))

Advantage:

the computation of $\Phi = e^{i\Pi/f} u(0)$

is simplified by the projection on the u(0) vector → much easier to resum the series