Composite Higgs bosons and Callan-Coleman-Wess-Zumino

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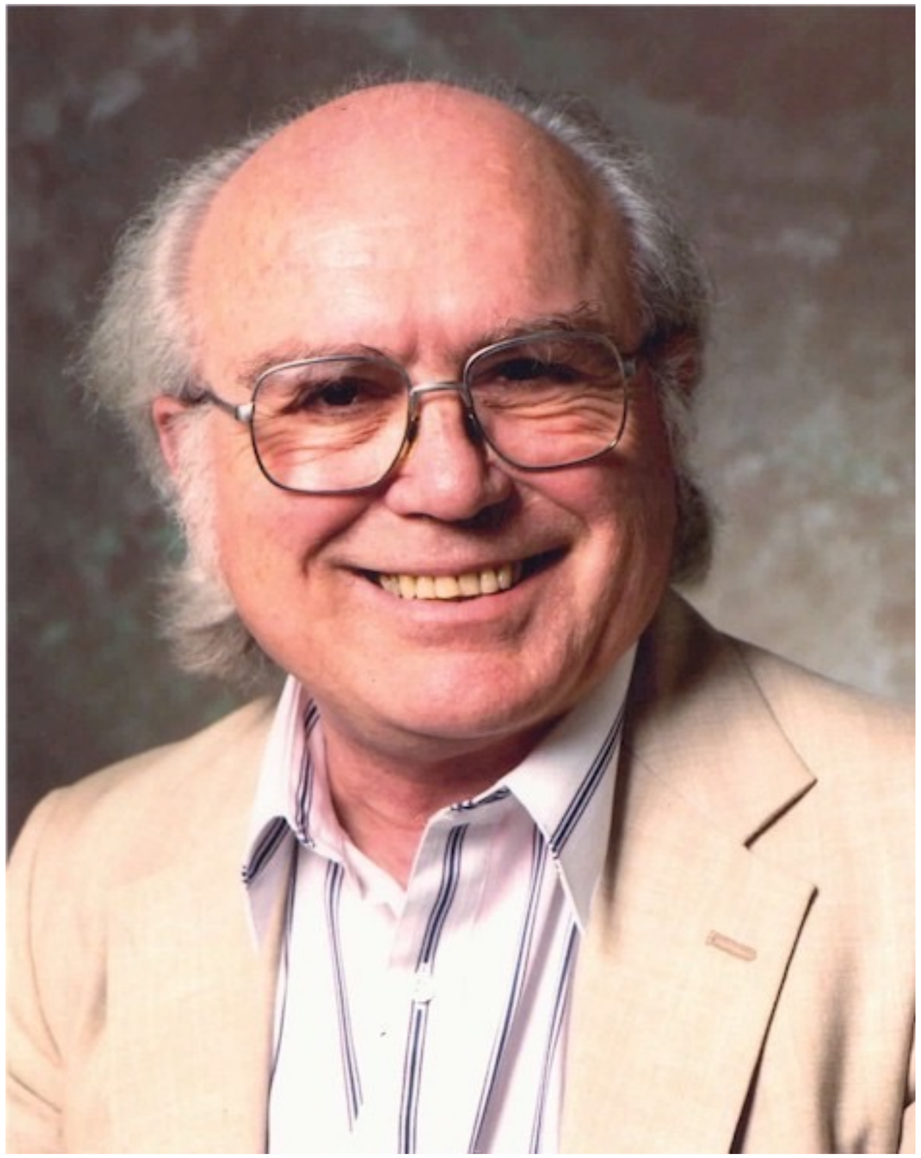
A quick, incomplete, discussion of the applications of CCWZ formalism to composite Higgs bosons models

*Based on work with E.Bertuzzo, T.S.Ray and H.Sandes

Learning from Bruno



the smile

no is no!

Dear John:

story of an ashtray

put everything!

(then, he must pay)

just dare to!

CCWZ: a gem in the field theory

Goldstone theorem: a massless state associated to each generator of spontaneously broken global symmetries: Nambu-Goldstone bosons

non-linear realization of local symmetries

CCWZ: low energy effective theory of NGB and their derivative couplings - among themselves, to gauge bosons, to fermions - in the broken phase

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Summary:

1. why composite Higgs bosons as PNGB
2. basics of CCWZ in a nut (very incomplete)
3. CCWZ theory of composite PNGB Higgs
4. extension to 2 composite Higgs doublets

   A) new problems ; B) the models

Why composite NGB Higgs boson

hierarchy problem: scalar masses are sensitive to higher scales and must be protected.
A general framework to protect scalars with respect to large scales is

COMPOSITENESS:

Indeed, in a theory (e.g., QCD) strongly coupled at a scale Λ_s, the composite particles have masses $O(\Lambda_s)$.

However, the extraordinary agreement between a large number of SM predictions and their very precise measurements and experimental limits require a composite scale way above the Fermi scale and the Higgs mass, $\Lambda_s >$ a few TeV

Step 1:

the Higgs is a massless composite NGB, with no potential $V(h)=0$, of a strongly coupled theory, with a global symmetry ***G*** spontaneously broken into a symmetry ***H*** that includes with the SM symmetries.

Their effective theory is given by the CCWZ theory, including the couplings to SM fields

Why composite **P**NGB Higgs boson(s)

Pseudo-NGB get masses and a scalar potential from radiative corrections in the presence of interactions that explicitly break the global symmetry (Coleman-Weinberg)

Step 2

The symmetry ***G*** is broken by :
1) the couplings to the SM SU(2)xU(1) gauge bosons
2) the couplings to the SM fermions (mostly the top)

The resulting Coleman-Weinberg effective potential provides an approximation for V(Higgs)

The Higgs potential defines the scale v=174 Gev and the Higgs mass m_h =125 GeV, and models depend on choices of the embeddings of SM particles into the CCWZ

Constraints on composite Higgs doublets

$\Delta T << 1$

tree level anomalous T-parameter
with 2 or more composite Higgses

solution: custodial symmetry

F C N C

tree-level contributions to flavour changing
and CP violations from two Higgs exchange

solution: Weinberg-Glashow

Zbb couplings

tree level corrections from compositeness

solution: custodial symmetry for b_L

+parameters... +constraints...

+ symmetries (discrete,...) !

Custodial symmetry

couplings of the Higgs(ses) to the electroweak vector bosons

$$\mathcal{L} = D_\mu \phi_i^\dagger D^\mu \phi^i + \frac{\kappa}{f^2} (\phi_i^\dagger D^\mu \phi^j)^2$$

$O(3)_{Custodial}$: $\Delta I_C = 0$ $\Delta I_C = 0, 2$

$\rho = 1 - \alpha T \approxeq 1 \Leftrightarrow \Delta I_C = 0 \Leftrightarrow$ custodial symmetry

⇒ composite sector must have more symmetry

A both $SU(2)_L$ and $O(3)_C$ ⇒ $O(4) = SU(2)_L x SU(2)_R$

B 2 Higgs vev's <u>must</u> align to preserve $O(3)_C$
⇒ more symmetry: another SU(2), parities

CCWZ aide-mémoire

Global G broken into $H \supset SU(2)_L \times U(1)$

G generators: $\{T^i\} \in \mathrm{alg}H$; $\{X^a\} \in G/H$

NGB $\phi_a(x)$ are associated to a local parameterization of G/H elements

$$\Pi(\phi(x)) = \sum_a \frac{\phi_a(x)}{f} X^a \in G/H \qquad U = e^{i\Pi(x)} \in G$$

$\phi_a(x) < 2\pi f$ where f defines the limit of applicability of CCWZ.

Basic property: $$g\, U(\phi(x)) = U(\phi'(x))\, h(\phi(x), g) \qquad \phi' = \phi'(\phi, g)$$

where a global $g \in G$ is replaced by a local $h(\phi(x), g) \in H$

The defining property of the effective CCWZ Lagrangian is its local H invariance, obtained by using this property of U.

CCWZ Lagrangian

$$U^\dagger(\phi)\partial_\mu U(\phi) \;=\; d^a_\mu(\phi)\,X^a \;+\; E^i_\mu(\phi)\,T^i$$

in alg$G$ in G/H in alg$H$

Under local H transformations $h(x)$ $\left\{ \begin{array}{ll} d_\mu{}^a & \text{transform linearly as } \phi_a(x) \\ E_\mu{}^a & \text{transforms as gauge fields} \end{array} \right.$

Introduce the covariant derivative: $D_\mu = \partial_\mu + iE_\mu(\phi) + W_\mu$

and the field strength in alg$H$: $E_{\mu\nu}(\phi)$

The locally invariant CCWZ Lagrangian is a general function of d_μ, $E_{\mu\nu}$, and their covariant derivatives

$$\mathcal{L}_{\rm CCWZ} = f^2(\mathrm{tr}\, d^\mu d_\mu + \text{ expansion in powers of } f^{-1}\partial_\mu)$$

Additional fields transforming linearly under H are introduce by the redefinition:

$$\hat\Psi = U(\phi)\,\Psi\,, \quad \text{so that, under G,} \;\; g\hat\Psi = U' h(\phi, g)\Psi$$

composite 'SM' Higgs: O(5) / O(4)

global O(5)→O(4) @ $\Lambda \sim f$

Higgs ~ (2,2) ⟷ O(5)/O(4) = <u>4</u> of O(4)   5d sphere

non-linear realization of local O(4)

$$U(\phi^a) = \exp\left(i\Sigma_a \frac{\phi^a}{f} M_{a5}\right) \qquad M_{a5} \in O(5)/O(4)$$

$$u = U(\phi^a) u_0 \qquad u_0^T = (00001) \qquad u^T u = 1 \qquad u^T \partial^\mu u = 0$$

5-vector   5d sphere

$$\mathcal{L} = f^2 \partial_\mu u^T \partial^\mu u + \text{higher derivatives}$$

O(5) / O(4) phenomenology

Couplings to the SM gauge bosons

$$\mathcal{L} = \mathsf{f}^2 \mathsf{D}_\mu \mathsf{u}^\dagger \mathsf{D}^\mu \mathsf{u}$$

non-linear Higgs Lagrangian

$$\mathsf{D}_\mu = \partial_\mu - i g W^i_\mu T^i_\mu - i g' B_\mu Y$$

$$\mathsf{u} = \mathsf{U}(\phi \mathsf{u}_0 = \begin{pmatrix} \frac{\sin(\varphi/f)}{\varphi}\phi \\ \cos(\varphi/f) \end{pmatrix} \qquad \varphi = \sqrt{\phi^T\phi}$$

$$\mathcal{L}_m = \frac{1}{2} g^2 f^2 \sin^2(\varphi/f)\left(W^+_\mu W^-_\mu + \frac{1}{2\cos\theta_W} Z_\mu Z_\mu\right)$$

$$\sin^2(\varphi/f) = \frac{v^2}{f^2}$$ measures the deviations from the SM ("compositeness")

The NGB Lagrangian describes the interactions between the Higgs and its NGB partners that correspond to longitudinal components *W* and *Z* by the equivalence theorem and deviations from the SM predictions are $O(v^2/f^2)$

2 composite Higgs doublets models

1 Higgs

$$\frac{O(5)}{O(4)} = \frac{Sp(4)}{Sp(2)\times Sp(2)}$$

2 Higgs

2 (2,2)

$\frac{O(6)}{O(4)\times O(2)}$	$\frac{SU(5)}{SU(4)\times U(1)}$	$\frac{Sp(6)}{Sp(4)\times Sp(2)}$	$\frac{O(9)}{O(8)}$
1 complex	1 complex	2 quaternions	2 real

NB: many extensions with O(4) singlet PNGB = axion-like, disregarded because not easy to make the axion invisible

Method to check for $O(3)_C$ in G

Consider cosets $G/H_1 \times H_2$ with $H_2 = \emptyset$, $U(1)$, $SU(2)$ and as coordinates p orthonormal vectors u^α $(\alpha = 1, \ldots, p)$ in some representation of G with $p = 1$ for $H_2 = \emptyset$, $U(1)$ and $p = 2$ for $H_2 = O(2)$, $SU(2)$.

Define: $u^\alpha(\phi) = U(\phi) u^\alpha(0)$ where G acts as $u \to g u h_2^\dagger(g, \xi)$, when organized in a matrix of p columns, so that $u(0)$ is invariant under $H_1 \times H_2$.

With $U^\dagger \partial_\mu U = i d_\mu + i E_\mu$ one finds

$$\partial^\mu u^\dagger \partial_\mu u = \mathrm{tr}\, d_\mu d^\mu + c_0 \mathrm{tr}\, E_\mu^{(2)} E^{(2)\mu}$$
$$u^\dagger \partial^\mu u^\dagger u \partial_\mu u^\dagger u = c_1 \mathrm{tr}\, E_\mu^{(2)} E^{(2)\mu}.$$

where the components in the H_1 directions were projected out and the $E_\mu^{(2)} E^{(2)\mu}$ term of H_2 is eliminated in the combination:

$$\mathcal{L}_{PNGB} = f^2 \mathrm{tr}\, d_\mu d^\mu = f^2 \mathrm{tr} \left(\partial^\mu u^\dagger \partial_\mu u - \frac{c_0}{c_1} u^\dagger \partial_\mu u\, \partial^\mu u^\dagger u \right)$$

The $O(3)_C$ violating contribution to the $T-$ parameter is proportional to c_0/c_1 is so obtained.

Summary for two Higgs models

G/H	T	$O(3)_c$	ψ_L ψ_R	Zbb	FCNC Type	axion
O(6)/O(4)xO(2)	✗	✗	6	✓	✗	✓
O(6)/O(4)xO(2)xZ_2	✓	✗	6	✓	I	✓
SU(5)/SU(4)xU(1)	✗	✗	10	✓	II	✓
Sp(6)/Sp(4)x Sp(2)	✓	✓	14	✓	✗	✓
O(9)/O(8)	✓	✓	16	✓	I	✓
O(9)/O(8)	✓	✓	16	✓	II	✗

@ICHEP '83:

Supersymmetry and Supergravity

Bruno ZUMINO

Abstract:

A discussion of recent attempts to relate N = 1 Supersymmetry and Supergravity to particle phenomenology.

Last paragraph:

Clearly the best justification for all the recent theoretical work based on N = 1 SUSY would be the experimental discovery of SUSY partners of known particles. However, if the SUSY gap is sufficiently large no SUSY partners will be found for quite a while. The appeal of supersymmetry is in its theoretical beauty and elegance, but supersymmetry is a general framework rather than a specific theory. What we need is an equally appealing specific model whose consequences could be tested experimentally, even if the supersymmetry gap is very large.

THANKS A LOT, BRUNO

BACKUPS

O(9) / O(8)

COUPLINGS TO GAUGE BOSONS

global O(9)→O(8) @ $\Lambda \sim f$

PNGB HIGGS 2x(**2,2**) ⟷ O(9)/O(8) = $\mathbf{8}_s$ of O(8) ⊃ O(4) [xU(1)]

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

$$\phi_{I} \qquad \phi_{II}$$

NON-LINEAR REALIZATION

$$u = U(\phi^a) u_0 \qquad u_0^T = (0 \ldots 01) \qquad u^T u = 1 \qquad u^T \partial^\mu u = 0$$

real 9-vector

9d sphere

$$\mathcal{L} = f^2 D_\mu u^T D^\mu u$$

non-linear Higgs Lagrangian

⇒ $\rho_{tree} = 1$ ⟷ $\Delta T_{tree} = 0$

$O(4) \times U(1)_X$

QUARK HYPERCHARGE

$$Y = T^3_R + X$$

$X(\phi) = 0$

quark masses $\Rightarrow X(q_L) = X(q_R)$

$X(t)$	$X(b)$	$T^3_R(t_R)$	$T^3_R(b_R)$	$O(4)$	!
$2/3$	$-1/3$	0	0	(1,1)	need brane mass
$2/3$	$2/3$	0	-1	(1,3)	X=2B

SU(5) / SU(4)xU(1)

EMBEDDING SM FERMIONS

SU(5)	U(4)	O(4)xU(1)	
	$\phi_I + i\phi_{II} \in 4$	$(2,2) + i(2,2)$	t and b couple to two orthogonal combinations of ϕ_I and ϕ_{II} of (Type II)
10	$\psi_L \in 4^*$	$(2,2) + i(2,2)$	
	$\psi_R \in 6$	$(1,3) + (3,1)$	

$\phi_I + i\phi_{II}$

t_L b_L

t_R, b_R

Type II $\Rightarrow$ no FCNC & $b_L \in (2,2) \Rightarrow Zbb_{tree} = Zbb_{SM}$

SU(5) / SU(4)xU(1)

COUPLINGS TO GAUGE BOSONS

HIGGS=2x(**2,2**) $\longleftrightarrow$ SU(5)/U(4) = **4†+4** of U(4) ⊃ O(4) [xU(1)]

= (**2,2**) + i(**2,2**)

$\phi_{I} + i\phi_{II}$

NON-LINEAR REALIZATION

$$u = U(\phi^a)u_0 \qquad u_0^T = (00001) \qquad u^\dagger u = 1$$

complex 5-vector

$$\mathcal{L} = f^2 D_\mu u^\dagger D^\mu u + f^2 (u^\dagger D^\mu u)^2$$

$(\Delta I = 2)$

non-linear Higgs Lagrangian

$$\frac{(\Delta M_Z^2)_{I=2}}{M_Z^2} \leq O(v^2/f^2) \Rightarrow \Delta T_{tree} \neq 0$$

(unnatural)

O(9) / O(8)

EMBEDDING SM FERMIONS

O(9)	O(8)	O(4)xU(1)
9	$\phi_{I,II} \in 8_s$	$(2,2)_{+1} + (2,2)_{-1}$
16	$\psi_L \in 8_c$	$(2,2)_{-1} + (2,2)_{+1}$
	$\psi_R \in 8_v$	$(1,3)_0 + (3,1)_{+1} + (1,1)_{-2} + (1,1)_{+2}$

ϕ_I → $(2,2)_{+1}$; ϕ_{II} → $(2,2)_{-1}$

t_L, b_L → $(2,2)_{-1}$

t_R, b_R → $(1,3)_0$

U(1) ⇒ Type I ⇒ no FCNC & $b_L \in (2,2)$ ⇒ $Zbb_{tree} = Zbb_{SM}$

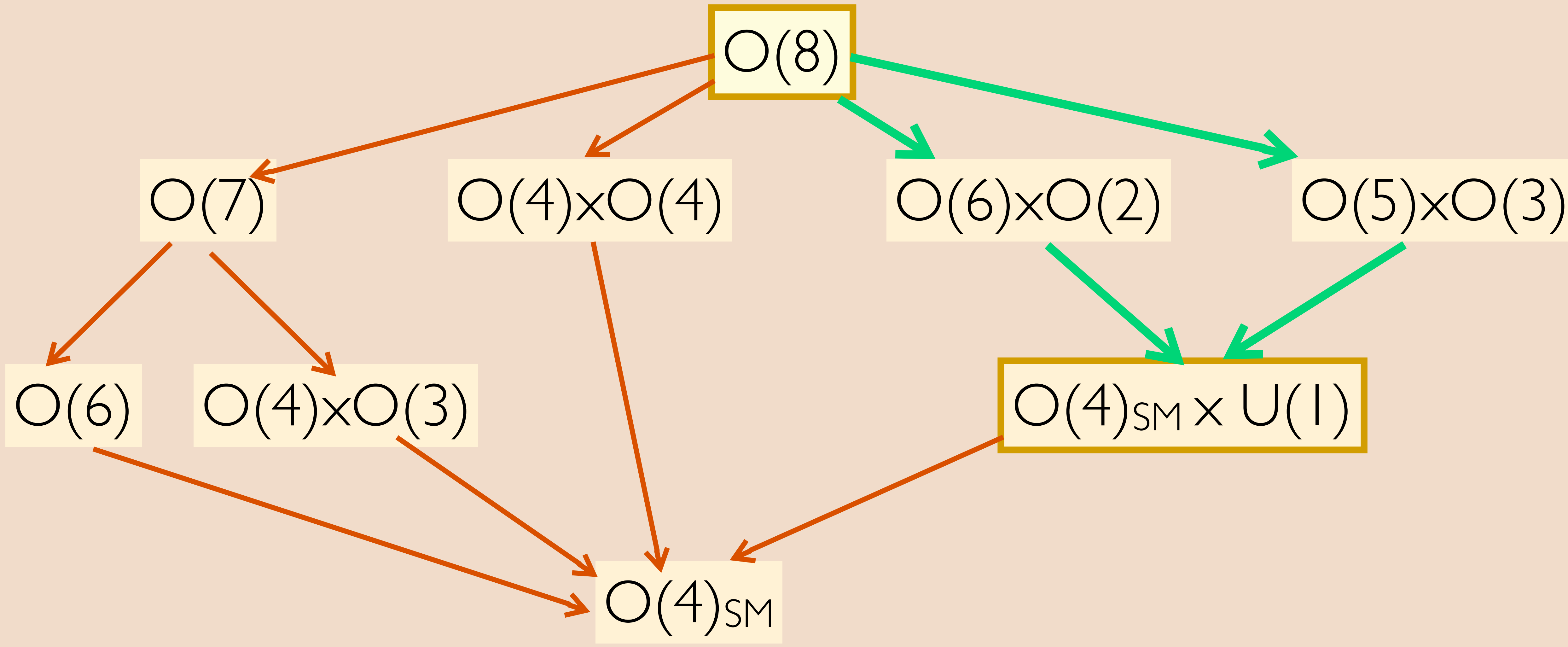
O(9) / O(8)

EMBEDDING $O(4)_{SM} \subset O(8)$

$$O(9)/O(8) = \mathbf{8_s} \text{ of } O(8) \supset O(4)\ [\times U(1)]$$

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

ϕ_I ϕ_{II}



O(5) / O(4)

COUPLINGS TO SM FERMIONS

O(5) O(4)

(vector) $\mathbf{5} = (2,2) + (1,1)$

(symm.) $\mathbf{10} = (2,2) + (1,3) + (3,1)$

$(2,2)$ ↑ t_L, b_L

$(1,3)$ ↑ t_R, b_R

$$Zbb_{tree} = Zbb_{SM}$$

F C N C

COUPLINGS OF HIGGS(ES) TO SM FERMIONS

GLASHOW-WEINBERG PRESCRIPTION

Q=-1/3 Q=2/3

Type I

b,s,d —— ϕ_I —— u,d,t ϕ_{II}

Type II

b,s,d —— ϕ_I u,d,t —— ϕ_{II}

⇒ symmetry to discriminate between ϕ_I and ϕ_{II}, extended to fermions

&

⇒ symmetry might also impose $\langle\phi_{II}\rangle = 0$ and save T, $\rho = 1$

$Zb\bar{b}$

COUPLING OF Z TO b_L

m_t and radiative EWSB in (CW) $V(\phi)$ suggest <u>more composite</u> $q_L=(t_L, b_L)$

measured b_L coupling to Z, close to SM value, suggests <u>more elementary</u>, SM, b_L

custodial symmetry for b_L :

$\mathbf{I_C} = \mathbf{I_L} + \mathbf{I_R}$ conserved

& $\mathbf{I_{L3}}(b_L) = \mathbf{I_{R3}}(b_L) = -\frac{1}{2}$

$\Rightarrow b_L \in (2,2)$ $\Big\}$ $++ \quad +- \leftarrow t_L$

$-+ \quad -- \leftarrow b_L$

WHY 2HDM ?

("ELUSIVE") SUSY

2 HD's but MUCH MORE!!
Here: only non-susy models

SPONTANEOUS BREAKING OF THE SYMMETRY

EW-BARYOGENESIS

more phases, more scalars, but w/ 125GeV Higgs looks marginal

FLAVOUR MODELS

2 vev's: $\tan\beta = v_I / v_{II}$ can help in accounting for m_t / m_b ratio...

RARE DECAYS

strongly constrain 2HDM, not quite the reverse (by now)

IMO: no really sound reason!