I or 2 ?

COMPOSITE 2 HIGGS DOUBLET MODELS

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SUMMARY

WHY (NOT) 2HDM?

3 MAIN ISSSUES

(COMPOSITE **1**HDM)

COMPOSITE **2**HDM

2 CASE STUDIES

SUMMARY TABLE

WHY 2HDM ?

("ELUSIVE") SUSY

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

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!

WHY NOT 2HDM ?

+parameters... +constraints...

+ symmetries (discrete,...) !

ΔT = 0 — tree level anomalous T-parameter in composite/effective models

solution: custodial symmetry

FCNC — at tree-level from two Higgs exchange

solution: Weinberg-Glashow

$Zb\bar{b}$ coupling — corrections from compositeness

solution: custodial symmetry for b_L

T-PARAMETER

COUPLINGS OF HIGGS(ES) TO GAUGE BOSONS

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

$O(3)_C$: $\Delta I = 0$ $\Delta I = 2$

$\rho = 1 \Leftrightarrow \Delta I_C = 0 \Leftrightarrow$ custodial symmetry

2 Higgses must align in vacuum: $\phi_I \propto \phi_{II}$ (or $\phi_{II}=0$)

PNGB Higgs(es): composite sector must have more symmetry

I both $SU(2)_L$ and $O(3)_C$ $\Rightarrow$ $O(4) = SU(2)_L x SU(2)_R$

II 2 Higgs vev's must align to preserve $O(3)_C$ $\Rightarrow$
more symmetry: another SU(2), parities

FCNC

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

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

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

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

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

O(5) / O(4)

MINIMAL COMPOSITE 'SM' HIGGS

global O(5)→O(4) @ $\Lambda \sim f$

PNGB HIGGS (**2,2**) $\longleftrightarrow$ O(5)/O(4) = **4** of O(4) 5d sphere

NON-LINEAR REALIZATION

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

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

5-vector 5d sphere

$$\mathcal{L} = f^2 \partial_\mu u^T \partial^\mu u$$

σ - model Lagrangian

O(5) / O(4)

COUPLINGS TO SM GAUGE BOSONS

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

non-linear Higgs Lagrangian

$$D_\mu = \partial_\mu - igW^i_\mu T^i_\mu - ig' B_\mu Y$$

$\rho_{tree} = 1 \longleftrightarrow \Delta T_{tree} = 0$

O(4) → $O(3)_c$

O(5) / O(4)

COUPLINGS TO SM FERMIONS

O(5) O(4)

(vector) **5** = (**2,2**) + (**1,1**)

(symm.) **10** = (**2,2**) + (**1,3**) + (**3,1**)

t_L, b_L ↑ (2,2)

t_R, b_R ↑ (1,3)

$Zbb_{tree} = Zbb_{SM}$

2HDM

CANDIDATES

YANG-MILLS QUANTUM

1HDM $\frac{O(5)}{O(4)} = \frac{Sp(4)}{Sp(2) \times Sp(2)}$

2HDM	$\frac{O(6)}{O(4) \times O(2)}$	$\frac{SU(5)}{SU(4) \times U(1)}$	$\frac{Sp(6)}{Sp(4) \times Sp(2)}$	$\frac{O(9)}{O(8)}$
2 (2,2)	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

O(9) / O(8)

COUPLINGS TO GAUGE BOSONS

global O(9)→O(8) @ $\Lambda \sim f$

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

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

ϕ_{I} ϕ_{II}

NON-LINEAR REALIZATION

$u = U(\phi^a)u_0$ $\quad u_0^T = (0\ldots01)$ $\quad u^T u = 1$ $\quad u^T \partial^\mu u = 0$

real 9-vector

9d sphere

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

non-linear Higgs Lagrangian

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

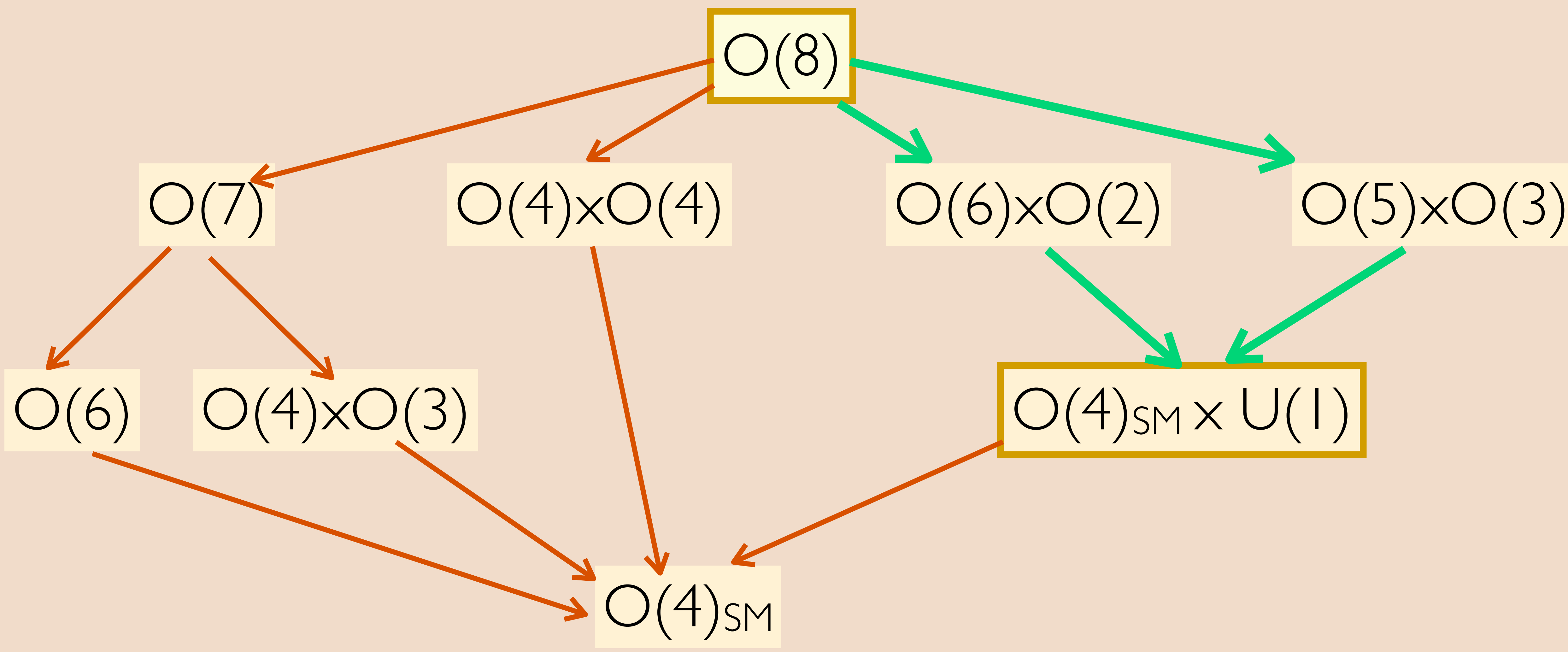
O(9) / O(8)

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

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

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

ϕ_I ϕ_{II}



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	$\psi_L \in 8_c$	$(2,2)_{-1} + (2,2)_{+1}$
	$\psi_R \in 8_v$	$(1,3)_0 + (3,1)_0 + (1,1)_{-2} + (1,1)_{+2}$

O(9) / O(8)

EMBEDDING SM FERMIONS

O(9)	O(8)	O(4)xU(1)
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	$\psi_R \in 8_v$	$(1,3)_0 + (3,1)_{+1} + (1,1)_{-2} + (1,1)_{+2}$

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

t_L b_L: $(2,2)_{-1}$ t_R, b_R: $(1,3)_0$

$U(1) \Rightarrow$ Type I $\Rightarrow$ 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

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

complex 5-vector

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

non-linear Higgs Lagrangian

($\Delta I = 2$)

$$\frac{(\Delta M_Z^2)_{I=2}}{M_Z^2} \leq O(v^2/f^2)$$

$\Rightarrow$ $\Delta T_{tree} \neq 0$ (unnatural)

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 & $b_L \in (2,2) \Rightarrow Zbb_{tree} = Zbb_{SM}$

SUMMARY

G/ H	T	$O(3)_c$	ψ_L ψ_R	Zbb	FCNC Type	Higgs-gauge unifictn
O(6)/O(4)xO(2)	✗	✗	$\underline{6}$	✓	✗	✗
O(6)/O(4)xO(2)xZ_2	✓	✗	$\underline{6}$	✓	I	✗
SU(5)/SU(4)xU(1)	✗	✗	$\underline{10}$	✓	II	✓
Sp(6)/Sp(4)x Sp(2)	✓	✓			I	
O(9)/O(8)	✓	✓	$\underline{16}$	✓	I	✓