Higgs Physics Diversity in composite models

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work in progress with B. Gripaios, F. Riva and J. Serra

A possible solution to the hierarchy problem:

The Higgs is a composite particle

Inspired by QCD:

$$m_\pi < m_\rho, m_{a_1}, ... << M_P$$

↘

Pseudo-Goldstone Boson (PGB)

⬇

Higgs as a PGB

(from a strong sector or from extra dimensions)

Although the dynamics of the strong sector can be unknown, the low-energy effective lagrangian for a PGB Higgs can be determined by symmetries (as chiral lagrangian for pions physics). It depends on:

- Spontaneous symmetry breaking of the strong sector $G \to H$, delivering the PGB parametrizing G/H
- Explicit symmetry breaking from SM couplings:
  - a) Gauging of the SM subgroup $\in$ H
  - b) SM Fermion couplings to the new sector

Potential for the Higgs $V(h/f)$ that forces EWSB:

$\langle h \rangle \sim f$ (Higgs decay constant)

Approach here: no Little Higgs !

EWSB: $V(h/f)$ fully determined by SM loops

EWPT: From the S-parameter: $v/f < 1/2-1/3$

$\longrightarrow$ $f > 500\text{-}800$ GeV

Global Symmetry Breaking patterns $G \to H$

Requirements: G must contain SM gauge group

G must contain an O(4) symmetry under which the Higgs is a 4

When the Higgs gets a VEV, $O(4) \rightarrow O(3)$

$$H = \begin{pmatrix} 0 \\ 0 \\ 0 \\ v \end{pmatrix}$$ } O(3) unbroken subgoup: Custodial symmetry

P. Sikivie, L. Susskind, M.B. Voloshin, V.I. Zakharov

Assure no-tree contributions to T-parameter ($\Delta\rho$)

and Zbb that can be of order $(\langle h \rangle / f)^2$

Agashe, Contino,Darold, AP

Recall: SO(4)~SU(2)xSU(2)

reps: 4=(2,2)

G	H	PGB
SO(5)	O(4)	4=(2,2)
SO(6)	SO(5)	5=(2,2)+(1,1)
	O(4)xO(2)	8=(2,2)+(2,2)
SO(7)	SO(6)	6=(2,2)+(1,1)+(1,1)
	O(4)xO(3)	12=(2,2)+(2,2)+(2,2)
...	...	...

Each case gives a very different (rich) Higgs physics !!

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Agashe, Contino, AP

one Higgs

Pheno:
modifications of Higgs couplings to SM fields

Giudice, Grojean, AP, Rattazzi

See Talks of Grojean and Contino

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Here:
a) one Higgs doublet
+ Singlet
b) two Higgs doublets

Gripaios, AP, Riva, Serra

Each case gives a very different (rich) Higgs physics !!

The SO(6)/SO(5) Model

Breaking achieved by the VEV of the 6a of SU(4)~SO(6)

$$\Sigma_0 = \begin{pmatrix} i\sigma_2 & 0 \\ 0 & i\sigma_2 \end{pmatrix}$$

that is invariant under Sp(4)~SO(5)

PGB: 5=(1,1)+(2,2) of SU(2)xSU(2)

parametrizing the SU(4)/Sp(4) coset:

singlet doublet

$$\Sigma = e^{\frac{i}{\sqrt{2}}\Pi/f}\Sigma_0 \qquad \Pi = \begin{pmatrix} \eta\mathbb{1} & i(-H^c\ H) \\ -i(-H^c\ H)^\dagger & -\eta\mathbb{1} \end{pmatrix}$$

η shifts under $U(1)_\eta$: T=Diag(1,1,-1,-1)

Not broken by the SM gauging ⟶ Gauge loops do not give a mass to eta !

Lowest dim operator of the PGB lagrangian for the neutral Higgs h and eta:

$$\frac{f^2}{8}\,\mathrm{Tr}|D_\mu\Sigma|^2 = \frac{f^2}{2}(\partial_\mu h)^2 + \frac{f^2}{2}(\partial_\mu \eta)^2 + \frac{f^2}{2}\,\frac{(h\partial_\mu h + \eta\partial_\mu\eta)^2}{1-h^2-\eta^2}$$

$$+\frac{g^2 f^2}{4} h^2\left[W^{\mu+}W^-_\mu + \frac{1}{2\cos^2\theta_W} Z^\mu Z_\mu\right]$$

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$h\eta\eta$ coupling:

$$-\frac{f^2\langle h\rangle}{2}\eta^2\partial_\mu^2 h$$

can induce the decay $h \to \eta\eta$

Fixed by symmetries !!

Couplings to SM fermions

Fixed by choosing the SM fermions embedding in reps of G=SO(6)

Example: 6 of SO(6)

$$6=(2,2)_0+(1,1)_1+(1,1)_{-1} \quad \text{of} \quad SU(2)xSU(2)xU(1)_\eta$$

$\Cup$ $\Cup$

q_L u_R, d_R

To assign the proper hypercharges G must be enlarged to SO(6)xU(1)$_X$:

$$Y = T_3^R + X$$

No complete embedding possible ⟶ explicit breaking of SO(6)
Potential at one-loop level
for h and eta

But, for u_R, d_R embedded in only one of the two singlets, the U(1)$_\eta$ subgroup of SO(6) is not broken by the coupling to the SM fermions

⟶ eta does not get a potential!

Up-quark sector:

$$q_L \in 6 = \Psi_q = \frac{1}{2}\begin{pmatrix} 0 & (0\ q_L) \\ -(0\ q_L)^T & 0 \end{pmatrix}$$

$$u_R \in 6 = \Psi_d = \frac{\alpha}{2}\begin{pmatrix} 0 & 0 \\ 0 & i\sigma_2 u_R \end{pmatrix} + \frac{\beta}{2}\begin{pmatrix} i\sigma_2 u_R & 0 \\ 0 & 0 \end{pmatrix}$$

it will be useful to define $\epsilon = \alpha\beta/2$ that it is zero when the SM fermion is embedded in one of the singlets with definite charge under $U(1)_\eta$

Effective lagrangian for PGB and SM fermions

Lowest dimensional operators for the up-quark sector:

$$\sum_{r=q,u} \Pi_r tr[\bar{\Psi}_r \Sigma] \not{D}\, tr[\Psi_r \Sigma^*] + \tilde{M}_u tr[\bar{\Psi}_q \Sigma] tr[\Psi_u \Sigma^*] + h.c. + \cdots$$

$$M_u h\, \bar{u}_L u_R \left[\sqrt{1-\eta^2-h^2} + i\eta \sqrt{\frac{1-\epsilon_u}{1+\epsilon_u}} \right]$$

ϵ_u parametrizes the embedding of u_R in the singlets of 6

$\epsilon_u = 0$	Embedding in one of the singlets: No breaking of $U(1)_\eta$
$\epsilon_u = 1$	No linear coupling of eta to up-quarks: $\eta \to -\eta$ invariance

Effective lagrangian for PGB and SM fermions

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$$\sum_{r=q,u} \Pi_r tr[\bar{\Psi}_r \Sigma] \not{D}\, tr[\Psi_r \Sigma^*] + \tilde{M}_u tr[\bar{\Psi}_q \Sigma] tr[\Psi_u \Sigma^*] + h.c. + \cdots$$

$$M_u h\, \bar{u}_L u_R \left[\sqrt{1 - \eta^2 - h^2} \right.$$

ϵ_u parametrizes the embe

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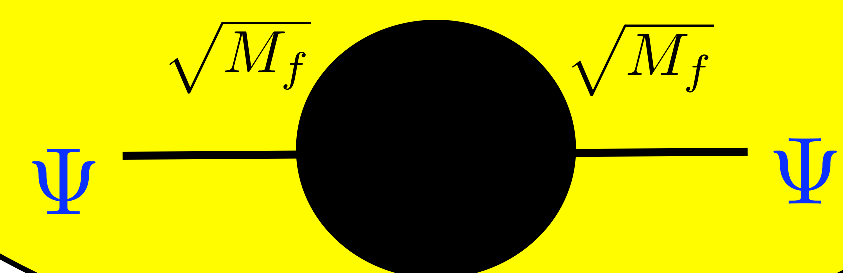
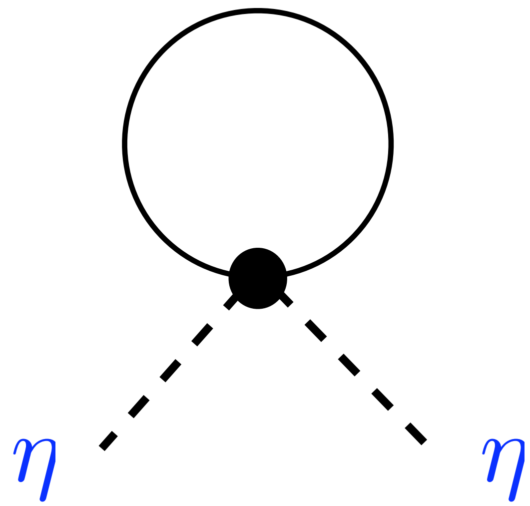
$\epsilon_u = 1$	No linear coupling of eta

Resonable assumption:

SM fermion couplings
to the strong sector
proportional to $\sqrt{M_f}$



$\epsilon_f \neq 0$



$$m_\eta^2 \sim m_f / 16\pi^2$$

$\epsilon_f \neq 1$

$$\eta \to f\bar{f} \qquad \Gamma \propto m_f$$

If $\epsilon_f = 1$ $\forall$ fermion, eta can be stable !

Higgs phenomelogy

two scalars $\left\{ \begin{array}{l} \text{h (CP-even) ~ SM Higgs} \\ \text{eta (CP-odd) coupled to fermions unless } \epsilon_f = 1 \end{array} \right.$

Pheno strongly depending on the values of epsilons:

For 0< epsilons < 1, eta potential from top-loops

$$m_\eta \sim m_h \sim 100 - 200 \text{ GeV}$$

eta behaves similarly to the CP-odd scalar A of the MSSM
One important difference: No Zhη coupling

If eta gets a VEV, CP-violation in the Higgs sector:

hep-ph/0608079

could be seen in decays to WW/ZZ or taus

Light-η scenario

For $\epsilon_f \to 0$, eta mass goes to zero ⟶ eta = PQ-axion

Mass only from anomalies

Unfortunately, ruled out by searches on $K \to \pi + a$

Other possibilities:

a) For $\epsilon_u = 0$ (only for all up-type quarks):
η-mass from bottom loops:

$$m_\eta^2 \simeq \frac{h_b \Lambda^3}{16\pi^2 f} \simeq (30\,\mathrm{GeV})^2 \left(\frac{\Lambda}{2\,\mathrm{TeV}}\right)^3 \left(\frac{500\,\mathrm{GeV}}{f}\right)$$

In this case, h decays mainly into 2 η:

$$\frac{\Gamma(h \to \eta\eta)}{\Gamma(h \to b\bar{b})} \simeq 8.5 \left(\frac{m_h}{120 \text{ GeV}}\right)^2 \left(\frac{500 \text{ GeV}}{f}\right)^4$$

Dominant decay chain

$$h \to \eta\eta \to b\bar{b}b\bar{b}$$

But if $\epsilon_d = 1$

$$h \to \eta\eta \to \tau\bar{\tau}\tau\bar{\tau}$$

or if $\epsilon_d = \epsilon_l = 1$

$$h \to \eta\eta \to c\bar{c}c\bar{c}$$

In all these cases,
Higgs h can be lighter
than LEP bound 114 GeV

Chang, Dermisek, Gunion, Weiner

Interesting possibility:

As in QCD, where the anomalies of the chiral group predict (WZW term):

$$-\frac{N_c}{48\pi^2}\frac{1}{F_\pi}\pi^0 F^{(\gamma)}_{\mu\nu}\widetilde{F}^{(\gamma)\,\mu\nu} \longrightarrow \pi \to \gamma\gamma$$

Here, similarly, we can expect

$$\frac{\eta}{32\pi^2 f}(n_B B\tilde{B} + n_W W_a \tilde{W}^a + n_G G_A \tilde{G}^A)$$

where n_B, n_W, n_G are related with the anomalies of the global group

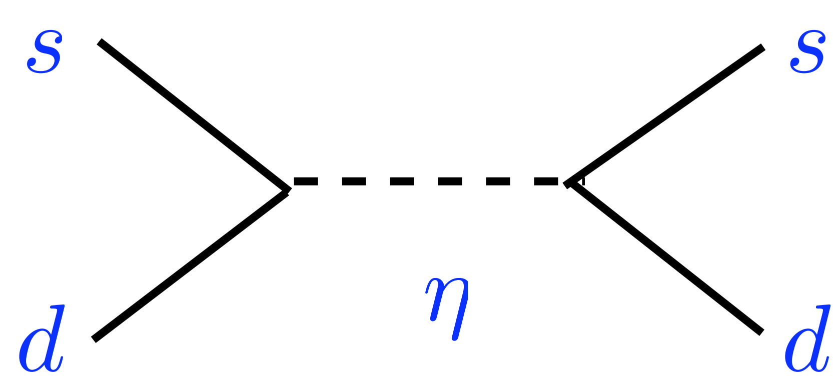
$$\longrightarrow \eta \to \gamma\gamma$$

Detecting this channel will give us information about the strong group

b) Non Family universal values for $\epsilon_{f\,i}$

→ FCNC effects from η

For example:



$$\Delta m_K \simeq \frac{m_s^2}{2m_\eta^2 f^2}\langle K|(\bar{s}_L d_R)^2|\bar{K}\rangle$$

but bound not very severe:

$$m_\eta \geq 40 \text{ GeV}$$

Predictions close to experimental bound for Δm_D

Interesting pheno: if η is heavier than the top

$\eta \longrightarrow t\bar{c}$ with BR ~ 1

Leptonic sector: OK with bounds from μ → 3 e, ...

Predictions: possibility of sizable $\eta \longrightarrow \tau\bar{\mu}$

The SO(6)/[SO(4)xSO(2)] Model

Breaking achieved by the VEV of the traceless 15 of SU(4)

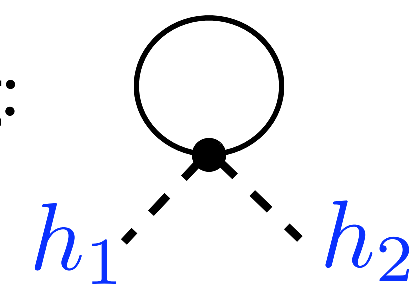
$$\Omega_0 = \mathrm{Diag}(1, 1, -1, -1)$$

that is invariant under SU(2)xSU(2)xU(1)~SO(4)xSO(2)

PGB: $8=(2,2)_1+(2,2)_{-1}$ of SU(2)xSU(2)xU(1)

Two Higgs doublets: Problem with this model:

Both Higgs get a VEV due to the presence of the mixing:



$$h_1 = \begin{pmatrix} 0 \\ 0 \\ 0 \\ v_1 \end{pmatrix} \qquad h_2 = \begin{pmatrix} 0 \\ 0 \\ v_2 \\ 0 \end{pmatrix}$$

Custodial O(3) symmetry broken by the second doublet

→ Large contributions to the T-parameter

Conclusions

- Models of PGB composite Higgs can have a very rich phenomenology
- Here we presented some example, the SO(6)/SO(5) model, which contains an extra singlet, η, and can drastically change the Higgs decays: h can decay to η, FCNC, ...
- Other PGB models worth also to explore