Top partners and UV descriptions in the composite Higgs framework

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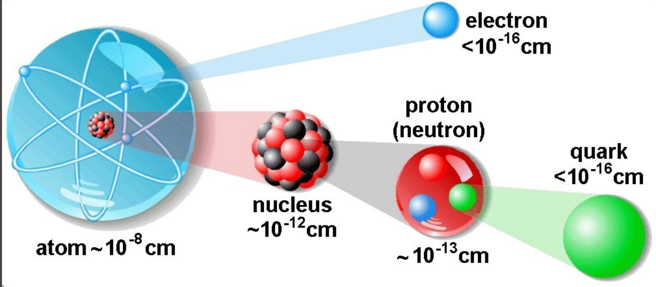
There is a long history of things that looked like elementary particles turning out to be composite objects

- Atoms
- Nuclei
- Hadrons

Splitting the atom



Can we really be sure we have reached the end of the line?

Compositeness in the SM can also solve several problems.

The hierarchy problem

If the Higgs is composite it is shielded from quantum effects above the compositeness scale ~ 1 TeV.

Kaplan, Georgi - 1984

Flavour hierarchies

Compositeness in the fermion sector naturally explains the large hierarchies in the fermion masses: $m_t/m_e = 3.4 \times 10^5$

Kaplan - 1991;
Gherghetta, Pomarol - hep-ph/0003129

Gauge coupling unification

The SM gauge couplings unify much better if the Higgs and right-handed top quark are composite objects.

Agashe, Contino, Sundrum - hep-ph/0502222

Dark matter

Many theories predict other composite states that are stabilised by global symmetries, just like the proton in the SM.

Agashe, Servant - hep-ph/0403143;
Frigerio, Pomarol, Riva, Urbano - 1204.2808

Many models describing a composite Higgs exist; the main obstacle is in dealing with the strong coupling driving confinement.

A popular approach for model building is to build low-energy effective theories using chiral Lagrangians.[1]

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[1] Giudice, Grojean, Pomarol, Rattazzi - hep-ph/0703164

Within this framework light, coloured, fermionic resonances are required[1] to explain

- EWSB
- The 126 GeV Higgs
- The large top-quark Yukawa coupling

These resonances are the top partners.

We can hope to see them at the LHC.

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[1] Matsedonskyi, Panico, Wulzer - 1204.6333; Marzocca, Serone, Shu - 1205.0770; Pomarol, Riva - 1205.6434

Coloured, fermionic resonances generically imply the existence of coloured, vector-boson resonances: gluon partners.

These have a significant impact on the relationship between the top-partner and Higgs masses.

In the minimal model the mass of top partners required for a 126 GeV Higgs is increased.[1]

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[1] JB, Gherghetta, Medina, Ray - 1307.4778

Can any of the low-energy effective theories used for composite Higgs models be UV-completed?

Can this be done without reintroducing elementary scalars?

If not the hierarchy problem is just shifted into a different sector.

Can top partners then be constructed?

We found that the answer is yes.

Many (potentially) UV-complete descriptions can be constructed from gauged NJL models, using fermions and gauge fields only.[1]

But. . .

Not all low-energy effective theories can easily be realised.

We must study models beyond the minimal $SO(5)/SO(4)$ example.

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[1] JB, Gherghetta, Ray - 1311.6562

Overview

1. Top partners in composite Higgs models
    - The Higgs as a pNGB
    - The top quark and EWSB
2. UV descriptions without elementary scalars
    - The Higgs sector
    - Top-partners

In the simplest examples of compositeness the mass of composite objects is similar to the confinement scale.

What we expect to see around the Higgs mass scale

What we actually see

There must be a little hierarchy between the Higgs mass and the confinement scale.

This is natural if the Higgs is a Nambu-Goldstone boson of a spontaneously broken global symmetry.[1]

Then it is forbidden from getting a mass and potential by a shift symmetry.

(cf pions in QCD)

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[1] Kaplan, Georgi - 1984

The standard framework assumes the existence of a strongly coupled sector with global symmetry, G.

This is spontaneously broken to a subgroup, H, that contains (part of) the SM gauge group.

The Higgs lives in the coset space G/H.

G/H must accommodate at least one complex Higgs doublet $\implies$ at least four broken generators.

Electroweak precision measurements tell us that H should also accommodate a custodial symmetry.

The minimal example[1] is $SO(5)/SO(4)$

- Four broken generators $\implies$ one Higgs doublet
- $SO(4) \sim SU(2)_L \times SU(2)_R$

Another example[2] is $SU(4)/Sp(4) \sim SO(6)/SO(5)$

- Five broken generators $\implies$ one Higgs doublet $+$ one singlet
- $SO(5) \supset SO(4) \sim SU(2)_L \times SU(2)_R$

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[1] Agashe, Contino, Pomarol - hep-ph/0412089

[2] Gripaios, Pomarol, Riva, Serra - 0902.1483

NGBs are massless and have no potential.

To give the Higgs a mass and allow for EWSB G must be explicitly broken.

As long as the breaking is weak the pseudo-NGBs remain light.

(cf pions in QCD)

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The gauging of the SM gauge symmetry explicitly breaks G as only part of G is gauged.

This results in a mass for the Higgs but often no EWSB.

EWSB usually depends on how the SM fermions are included.[1]

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[1] Matsedonskyi, Panico, Wulzer - 1204.6333; Marzocca, Serone, Shu - 1205.0770; Pomarol, Riva - 1205.6434

Elementary SM fermions communicate with the strongly coupled sector via

$$\mathcal{L}_{\rm mix} \supset \lambda_L t_L \mathcal{O}_L + \lambda_R t_R \mathcal{O}_R$$

The SM does not respect the full G symmetry so t_L and t_R do not come in complete representations of G.

Non-zero $\lambda_{L/R}$ explicitly break $G \implies V(h) \sim \lambda^2$.

Elementary fermion Yukawa couplings go like $\lambda_L \lambda_R$.

Hence these couplings are largest for the top quark.

($\lambda \ll g_\rho$ so G is only weakly broken)

Integrating out the strongly coupled sector gives a non-local effective Lagrangian for the top-Higgs sector

$$\mathcal{L}_{\text{eff}} \supset \Pi_L(p) K_L(h) \bar{t}_L \not{p} t_L + (L \to R) + [M(p) Y(h) t_L t_R + \text{h.c.}]$$

The Higgs potential is derived by calculating the one-loop effective potential from this effective Lagrangian.

K and Y are determined by group theory and $\sim \lambda^2$.

Π and M are form factors determined by two-point functions

$$\not{p}\Pi_L(p) \sim \langle \mathcal{O}_L(p) \bar{\mathcal{O}}_L(-p) \rangle \quad M(p) \sim \langle \mathcal{O}_L(p) \mathcal{O}_R(-p) \rangle$$

This is where the details of the strong sector are hidden.

Calculating the form factors is hard!

Taking a large-N limit in the strongly coupled sector

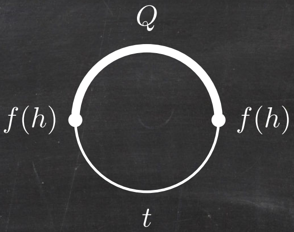
$$\Pi(p) \sim \sum \frac{a_n}{p^2 - m_{Q_n}^2} \qquad M(p) \sim \sum \frac{b_n m_{Q_n}}{p^2 - m_{Q_n}^2}$$

Q_n are coloured, fermionic resonances associated with $\mathcal{O}_{L/R}$.

These are the top-partners.

a_n, b_n are incalculable $\mathcal{O}(1)$ coefficients.

The one-loop potential comes from loops like



The extra ‘propagator’ renders it finite.

MCHM$_5$ example: $SO(5)/SO(4)$ with $\mathcal{O}_{L,R} \in \mathbf{5}$ of $SO(5)$.

The Higgs mass to $\mathcal{O}(\lambda^2/g_\rho^2)$ is

$$m_h^2 = \frac{8N_c v^2}{f^4}\int\frac{\mathrm{d}^4p}{(2\pi)^4}\left[\frac{1}{p^2}\left|M(p)\right|^2 + \frac{1}{4}\Pi_L(p)^2 + \Pi_R(p)^2\right]$$

This can only be finite if

$$\lim_{p\to\infty}\Pi_{L/R}(p) = 0 \qquad\qquad \lim_{p\to\infty}p^2\Pi_{L/R}(p) = 0$$

Two conditions on the Π's $\implies$ at least two resonances required.

(cf Weinberg sum rules for pion masses)

The minimal choices for M, Π that give a finite Higgs mass yield

$$m_h^2 \approx \frac{N_c}{\pi^2} \frac{m_t^2}{f^2} \frac{m_{Q_4}^2 m_{Q_1}^2}{m_{Q_4}^2 - m_{Q_1}^2} \ln \left(\frac{m_{Q_4}^2}{m_{Q_1}^2} \right)$$

so

$$m_h^2 \sim \frac{m_t^2 m_Q^2}{f^2}$$

A generic prediction of the MCHM_5 is therefore for two light top-partners to be seen at the LHC.

A strong sector producing top partners will also generically produce coloured, vector boson resonances

$$Q \in \mathbf{3} \text{ of } SU(3) \quad \Longrightarrow \quad \bar{Q}\gamma^{\mu} Q \in \mathbf{8} \text{ of } SU(3)$$

(e.g. KK gluons in a 5D realisation)

These are gluon partners.

Holographic estimates suggest strong coupling between gluon and top partners[1]

$$\alpha_G \sim 3$$

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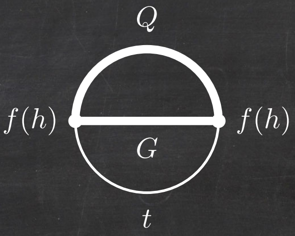
[1] Carena, Medina, Panes, Shah, Wagner - 0712.0095

The leading-order correction from gluon partners is at two loops

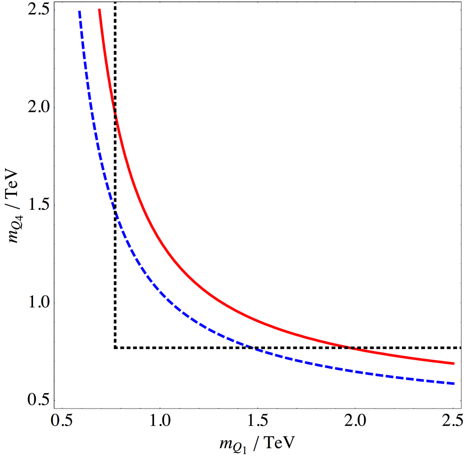


(cf the gluino correction in the MSSM)

It manifests as a mass renormalisation in the two-point functions

$$\text{e.g.}\quad M(p) \sim \sum \frac{b_n[m_{Q_n} + \Delta_n(p)]}{p^2 - [m_{Q_n} + \Delta_n(p)]^2}$$

126 GeV Higgs in the MCHM$_5$ with $m_G = 3$ TeV



The solid line includes gluon partners, the dashed line does not.

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Criteria for a ‘successful’ UV description

- Realises correct spontaneous symmetry breaking pattern
- Produces a fermionic top-partner bound state
- Constructed from fermions and gauge fields only
- Renormalisable

(supersymmetric UV descriptions exist, using Seiberg duality to deal with strong coupling, but these include elementary scalars)[1]

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[1] Caracciolo, Parolini, Serone - 1211.7290

The minimal model: $SO(5)/SO(4)$

- $SO(5)$ is not an exchange symmetry of complex fermions
  $\implies$ additional model complexity
- $SO(5)$ is broken by the VEV of a scalar in the **5** of $SO(5)$
- Build this out of, e.g. $(\psi \in \mathbf{5}) \times (\chi \in \mathbf{1})$
- Results in scalars $\psi \times \psi$ in two index representation of $SO(5)$
- Additional scalars cannot get VEVs
- Very difficult to arrange in confining theories

It is not clear how to UV-complete the minimal model.

Other models have similar problems.[1]

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[1] Ferretti, Karateev - 1312.5330

The next-to-minimal model: $SU(4)/Sp(4)$

It has long been known that this spontaneous symmetry breaking pattern is realised in simple gauge theories with fermionic matter.[1]

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[1] Coleman, Witten - 1980; Peskin - 1980

Take an $Sp(2N)$ gauge theory with four flavours of Weyl fermion.

Four complex fermions $\implies$ $SU(4)$ exchange symmetry.

	$Sp(2N)$	$SU(4)$
ψ	$\square$	$\mathbf{4}$

This theory is confining for any value of N.

The only scalar meson is $\Omega_{ij}\psi^{ia}\psi^{jb}$ $(\Omega_{ij} = -\Omega_{ji})$.

This is in the antisymmetric $= \mathbf{6}$ representation of $SU(4)$ so breaks $SU(4) \to Sp(4)$ as desired.

The Higgs sector seems to work out fine but what about the top-partners?

How can a composite, fermionic operator be built out of fermions?

We need to combine at least three elementary fermions.

Hence the mixing terms required for EWSB

$$\mathcal{L}_{\mathrm{mix}} \supset \lambda_L t_L \mathcal{O}_L$$

must be at least four-fermion operators.

For them to be large enough we need large anomalous dimensions.

Consider adding the four-fermion operator

$$\mathcal{L}_{\mathrm{int}} = \frac{\kappa}{2N}(\psi\psi)(\bar{\psi}\bar{\psi})$$

where brackets denote $Sp(2N)$ singlets (cf the NJL model).[1]

(other operators are allowed but do not impact the following)

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[1] Nambu, Jona-Lasinio - 1961

A standard trick is to add an auxiliary scalar to describe the VEV of the fermion bilinear

$$M = -\frac{\kappa}{2N}(\psi\psi)$$

and rewrite

$$\mathcal{L}_{\text{int}} = -\left[M^*(\psi\psi) + \text{h.c.}\right] - \frac{2N}{\kappa}M^* M$$

Now the model looks like a Yukawa theory with a massive scalar.

The one-loop effective potential for $m \propto \langle M \rangle$ is minimised when

$$1 - \frac{m^2}{\Lambda^2} \ln\left(\frac{m^2 + \Lambda^2}{m^2}\right) = \frac{16\pi^2}{\kappa\Lambda^2} \equiv \frac{1}{\xi}$$

and a non-trivial minimum only exists when $\xi > 1$.

Hence $\xi = 1$ defines a critical point

- $\xi > 1 \implies SU(4) \to Sp(4)$
- $\xi < 1 \implies SU(4)$ unbroken

What about the regularisation scale, Λ?

Two possible interpretations are

- Λ is a physical cutoff scale denoting the scale at which an effective four-fermion operator is generated
- Λ is a renormalisation scale and it is possible to take the limit $\Lambda \to \infty$ with m finite

If Λ is considered to be a renormalisation scale[1] the minimisation condition

$$1 - \frac{m^2}{\Lambda^2} \ln\left(\frac{m^2 + \Lambda^2}{m^2}\right) = \frac{1}{\xi}$$

defines a β-function for ξ

$$\beta(\xi) = \Lambda \frac{\partial \xi}{\partial \Lambda} \approx 2\xi(1 - \xi)$$

Hence there is a UV fixed point at the critical point $\xi = 1$.

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[1] Yamawaki - hep-ph/9603293

The definition of the auxiliary scalar

$$M = -\frac{\kappa}{2N}(\psi\psi)$$

relates the fermion condensate (the physical order parameter) to the dynamical fermion mass

$$m = -\frac{8\pi^2\xi}{N\Lambda^2}\langle\psi\psi\rangle$$

Near the critical point $\xi \approx 1$ is constant and this defines a running fermion mass

$$m(\Lambda) = \left(\frac{\mu}{\Lambda}\right)^2 m(\mu)$$

Now define an anomalous dimension for the running mass

$$\gamma_m \equiv -\frac{\partial \ln[m(\Lambda)/m(\mu)]}{\partial \ln \Lambda} = 2$$

Then the fermion bilinear $\psi\psi$ has scaling dimension

$$3 - \gamma_m = 1$$

and the four-fermion operator has scaling dimension 2.

The model appears, surprisingly, to have become renormalisable!

The preceding analysis is too naive.

More thorough analyses for similar models include effects of the $Sp(2N)$ gauge coupling[1] to find

$$1 \leq \gamma_m < 2$$

For $\gamma_m \approx 1$ $Sp(2N)$ gauge interactions drive confinement.

For $\gamma_m \approx 2$ the four-fermion operator drives confinement.

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[1] Bardeen, Leung, Love - 1986; Kondo, Mino, Yamawaki - 1989

In addition to large anomalous dimensions we require

- A two-index representation of $Sp(2N)$
- A fermion charged under both $Sp(2N)$ and $SU(3)$ colour

to build a top-partner bound state.

A simple option is to add a fundamental and antifundamental of $SU(3)$ colour (for anomaly cancellation).

Both transform in the two-index antisymmetric representation of $Sp(2N)$.

	$Sp(2N)$	$SU(4)$	$SU(3)_c \times U(1)$
ψ	$\square$	$\mathbf{4}$	$\mathbf{1}_0$
χ	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\mathbf{1}$	$\mathbf{3}_{+2/3}$
$\tilde{\chi}$	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\mathbf{1}$	$\bar{\mathbf{3}}_{-2/3}$

These form fermionic $Sp(2N)$ singlet states such as

$$\Psi = (\psi\chi\psi) \qquad\qquad \tilde{\Psi} = (\psi\tilde{\chi}\psi)$$

transforming as

	$Sp(2N)$	$SU(4)$	$SU(3)_c \times U(1)$
Ψ	$\mathbf{1}$	$\mathbf{6}$	$\mathbf{3}_{+2/3}$
$\tilde{\Psi}$	$\mathbf{1}$	$\mathbf{6}$	$\bar{\mathbf{3}}_{-2/3}$

providing many suitable top-partner candidates.

Are the top-partner anomalous dimensions large enough?

In the models of interest four-fermion operators drive confinement.

So four-fermion interactions are stronger than gauge interactions.

A $\psi\chi\psi$ bound state can be approximated as a tightly bound $\psi\psi$ pair bound to χ by $Sp(2N)$ gauge interactions.

(cf the diquark approximation for baryons)[1]

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[1] Ball - 1990

The top-partner anomalous dimension is then approximated by the $\psi\psi$ anomalous dimension

$$\dim \Psi \approx \frac{3}{2} + (3 - \gamma_m) \approx \frac{5}{2} + \mathcal{O}\left(\frac{\alpha}{\xi}\right)$$

The mixing operators

$$\mathcal{L}_{\mathrm{mix}} \supset \lambda_L t_L \mathcal{O}_L$$

remain marginally irrelevant but are only suppressed by one order of magnitude when running down from the Planck scale.

A more thorough analysis would likely show that these operators are actually marginal in the UV.

Summary

Modern composite Higgs models identify the Higgs as a pNGB and use partially-composite top quarks to induce EWSB.

The observed Higgs mass places an upper limit on the mass of the associated top partners.

This upper limit is reduced by $\sim 10\%$ in the minimal model by including NLO effects from gluon partners.

Composite Higgs models can have renormalisable UV descriptions in terms of fermions and gauge fields only.

To accommodate a partially-composite top quark the UV descriptions involve operators with large anomalous dimensions.

The framework presented here clearly favours the next-to-minimal composite Higgs model over the minimal one.