Composite Higgs and non-standard top partner decays

Rikard Enberg
Uppsala University, Sweden

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Coauthors from “SHIFT Collaboration”: Rachid Benbrik, Elin Bergeaas Kuutmann, Diogo Buarque Franzosi, Venugopal Ellajosyula, Gabriele Ferretti, Max Isacson, Yao-Bei Liu, Tanumoy Mandal, Thomas Mathisen, Stefano Moretti, Luca Panizzi
The problem

\[ V = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \]

What is this?

There’s a mass scale \( \mu^2 \) in the Higgs sector, it’s the only mass in the SM, and moreover \( \mu^2 \ll m^2_{\text{Pl}} \)

Why is \( -\mu^2 < 0 \)?

- Because then EW symmetry is broken

Why is EW symmetry broken?

- Because \( -\mu^2 < 0 \).
Composite Higgs: dynamical mechanism for EWSB

[See talk by Stefania De Curtis for details!]

Strongly interacting sector; broken global symmetry $G \rightarrow H$ where $H$ contains the SM symmetry $G_{SM}$

• No fundamental scalars needed
• The low Higgs mass is naturally explained: pseudo-Nambu-Goldstone boson (pNGB) of broken symmetry
• New sectors of composite particles
  ✓ Higgs and other scalars: pNGBs
  ✓ Partners of SM fermions: vectorlike quarks (VLQs)
  ✓ Vectors, scalar resonances …
Additional scalars

When the new symmetry is broken, $G \to H$, there are Nambu-Goldstone bosons: one per broken generator.

No. of pNGBs = dim of coset manifold $G/H$

When (subgroup of) $H$ is gauged, turn into *pseudo*-NGB.

We want $H$ to contain $\text{SU}(2)_L \times \text{SU}(2)_R \sim \text{SO}(4)$ [custodial]

Examples:

- **Minimal Composite Higgs**: $\text{SO}(5) / \text{SO}(4)$: $10 - 6 = 4$
  4 goldstones = components of SM Higgs doublet

- **Composite 2HDM**: $\text{SO}(6) / [\text{SO}(4) \times \text{SO}(2)]$: $15 - 7 = 8$
  8 goldstones = two Higgs doublets
Top partners

• In particular the top has vectorlike top partners $T$
• Partial compositeness:
  ✓ Top partners mix with the top quark
  ✓ Top quark gets mass from mixing
• After mixing, there are additional heavy top quarks
• Couplings are model-dependent
• Generically, can also have bottom partners $B$ and “exotic VLQs” $X,Y,S,\ldots$, charges $+5/3$, $-4/3$, $+8/3,\ldots$
• LHC top partner bounds so far only considering SM decays $T \to tZ, bW^+, \text{th}_{SM}$
Simplified model

We consider a simplified model that can encompass various interesting models, for example:

• **SU(4)/Sp(4) model with partial compositeness**
  E.g. Gripaios et al, Barnard et al, Ferretti et al, Cacciapaglia et al, Bizot et al.  
  [Talk by T. Flacke]

• **The composite 2HDM**
  Mrazek, Pomarol, Rattazzi, Redi, Serra, Wulzer; De Curtis, Delle Rose, Moretti, Yagyu  
  [Talk by S. De Curtis]

• **2HDM with VLQs**
  Aguilar-Saavedra, Benbrik, Heinemeyer, Pérez-Victoria; Arhrib, Benbrik, King, Manaut, Moretti, Un  
  [Talk by J. Song]
Simplified model Lagrangian

Scalar $\phi$ or pseudoscalar $\eta$ interactions with gauge bosons and SM fermions, schematically

$$\mathcal{L}_S = \eta \sum_V \frac{\kappa_V^\eta}{\bar{v}} V_{\mu\nu}^a \tilde{V}^{a\mu\nu} + \phi \sum_V \left( \kappa_V^\phi \bar{v} V_{\mu}^a {V}^{a\mu} + \frac{\kappa_V^\phi}{\bar{v}} V_{\mu\nu}^a {V}^{a\mu\nu} \right)$$

$$+ \sum_f m_f \left( \kappa_f^\phi \bar{\psi} \psi \phi + i \kappa_f^\eta \bar{\psi} \gamma_5 \psi \eta \right)$$

Interactions with VLQs given by Yukawa couplings with $t_1L, t_1R, t_2L, t_2R$

This Lagrangian can encompass the models mentioned
SU(4)/Sp(4) = SO(6)/SO(5)

Symmetry breaking: SU(4)~SO(6) \rightarrow Sp(4)~SO(5)

5 pNGBs: fit in bidoublet and singlet of SU(2)_L \times SU(2)_R (custodial symmetry) in a 5 rep of Sp(4):

\[ \mathcal{H} \oplus \eta \equiv \begin{pmatrix} H^0 & H^+ \\ -H^{++} & H^0 \end{pmatrix} \oplus \eta \in (2, 2) \oplus (1, 1) = 5 \]

There are also 5 VLQs: three top partners, one bottom partner and one exotic X with charge 5/3:

\[ \Psi \equiv \begin{pmatrix} T & X \\ B & T' \end{pmatrix} \oplus \tilde{T} \in (2, 2) \oplus (1, 1) = 5 \]

Lightest VLQ, degenerate with X
SU(4)/Sp(4)

No diagonal couplings of the scalars to the VLQs:

\[ \mathcal{L}_{t_2S} = \kappa_S^L \bar{t}_2 L t_1 R \phi + \kappa_S^R \bar{t}_1 L t_2 R \phi + \kappa_S^L \bar{t}_2 L t_1 R \eta + \kappa_S^R \bar{t}_1 L t_2 R \eta + \text{h.c.} \]

Couplings of \( \eta \) to gauge bosons from dim-5 operators from the anomaly have no \( \gamma \gamma \) or \( gg \) couplings:

\[ \mathcal{L}_{\etaVV} = \frac{A \cos \theta}{16\pi^2 f} \eta \left( \frac{g^2 - g'^2}{2} Z_{\mu\nu} \tilde{Z}^{\mu\nu} + gg' F_{\mu\nu} \tilde{Z}^{\mu\nu} + g^2 W_{\mu\nu}^+ \tilde{W}^{-\mu\nu} \right) \]

\( \rightarrow \) No \( \gamma \gamma \) or \( gg \) decay/production from dim-5 or loops
SU(4)/Sp(4)

BR(\eta) where \eta = \text{singlet pseudoscalar}

Plot from Bizot, Cacciapaglia, Flacke, 1803.00021
2HDM + VLQ

Minimal fundamental Higgs model with these decays: $T \rightarrow tA, tH$

Arhrib et al, 1607.08517, add a singlet $T$ to 2HDM type II

Example BR:

We are investigating singlet, doublet, triplet VLQs in 2HDM, [Arhrib, Benbrik, RE, Manaut, Moretti, Panizzi, Rouchad, Taj]
ATLAS studies

Non-standard decays of VLQ; pair production

\[ pp \rightarrow T \bar{T} \]

where T is the lightest top partner and we consider scalars or pseudoscalars S of the model

Assume \[ T \rightarrow tS \] with \[ S = \eta \text{ or } \phi \]

and scalar decays \[ S \rightarrow \gamma\gamma, \gamma Z, W^+W^- \]

Simulate everything using MG5, Pythia, Delphes (developed Delphes card to mimic ATLAS conditions)
Current LHC bounds only consider SM decay channels: We need to establish bounds from existing data on our decay channels: do a *recasting* of published analyses.

For example: We recast the following ATLAS searches:

**ATLAS 1707.04147**: “Search for new phenomena in high-mass *diphoton final states* using 37 fb\(^{-1}\) of proton–proton collisions collected at \(\sqrt{s} = 13\) TeV with the ATLAS detector”

**ATLAS 1807.11883**: “Search for new phenomena in events with *same-charge leptons and b-jets* in pp collisions at \(\sqrt{s} = 13\) TeV with the ATLAS detector”
Recasting

Simulate using Delphes, mimic ATLAS conditions. E.g.: the $\gamma\gamma$ analysis. Right plot: validate expt acceptance.

ATLAS 1707.04147
Combined bounds

\[ pp \rightarrow T\bar{T} \text{ with } T \rightarrow tS \]

\[ S \rightarrow \gamma\gamma \quad S \rightarrow Z\gamma \quad S \rightarrow ZZ \]

\[ M_T > 600 \text{ GeV} \quad M_T > 600-700 \text{ GeV} \quad M_T > 800-900 \text{ GeV} \]

Also using HiggsBounds to check bounds on scalars from Higgs searches
Can we test scalar/pseudoscalar?

$$pp \rightarrow T\bar{T} \rightarrow tS\bar{t}S$$

with

$$S = \eta \text{ or } \phi$$

$$M_T = 1\text{TeV}, \ M_\eta = 300\text{GeV}$$

$$t \rightarrow W^+ b \rightarrow e^+ \nu b$$

$$\bar{t} \rightarrow W^- \bar{b} \rightarrow \mu^- \bar{\nu} b$$

$$S \rightarrow \gamma Z \rightarrow \gamma jj$$

$$(\text{Distributions in } \eta \text{ and } \Delta R \text{ do not show any difference})$$
LHC searches

Theory study of the sensitivity of LHC experiments to searches with pair production and T decay as above and

\[ S \rightarrow \gamma\gamma \text{ or } Z\gamma \]

Diphoton + jets in first case
Photon(s) + dileptons + jets in second case

- Phenomenology paper on these searches
  [Will be arXiv:190x.yyyyy]
Summary

• Top quark important to understand for Higgs physics
• Models for composite Higgs with dynamical EWSB typically have vectorlike top partners
• Existing bounds only consider SM decays (minimal)
• We are considering non-minimal models with decays to new scalars and LHC phenomenology
• Results to appear very soon