What don’t we know about the Higgs boson?

Ian Low
Argonne/Northwestern
July 31, 2019
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A physics Ph.D. could rephrase slightly:

What is the microscopic theory that gives rise to the Higgs boson and its potential?

\[ V(H) = -\mu^2|H|^2 + \lambda|H|^4 \]

Our colleagues in condensed matter physics are very used to asking, and studying, this kind of questions.
One of the most beautiful examples is the superconductivity discovered in 1911:
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Ginzburg-Landau theory from 1950 offered a macroscopic (ie effective) theory for conventional superconductivity,

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What is the microscopic origin of the Ginzburg-Landau potential for superconductivity?
In 1957 Bardeen, Cooper and Schrieffer provided the *microscopic* (fundamental) theory that allows one to

1) interpret $|\Psi|^2$ as the number density of Cooper pairs

2) calculate coefficients of $|\Psi|^2$ and $|\Psi|^4$ in the potential.
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2) calculate coefficients of $|\Psi|^2$ and $|\Psi|^4$ in the potential.

We do not have the corresponding **microscopic** theory for the Higgs boson.

In fact, we have NOT even measured the Ginzburg-Landau potential of the Higgs!
The question can be reformulated in terms of **Quantum Criticality**:

\[ V(\phi) = m^2|\phi|^2 + \lambda |\phi|^4 \]

Quantum Phase Diagram of EWSB

- \( m > 0, \langle \phi \rangle = 0 \)
- \( m = 0 \)
- \( m < 0, \langle \phi \rangle = m_{\text{Planck}} \)
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$M_h = 125$ GeV. We are sitting extremely close to the criticality. Why??
One appealing possibility – the critical line is selected dynamically.

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Two popular “explanations:”

1. Postulate new global symmetries above the weak scale, and the Higgs boson arises as a (pseudo) Nambu-Goldstone boson.
   ➔ This class goes by the name of “composite Higgs models.”

2. The critical line is a locus of enhanced symmetry.
   ➔ This is the (broken) supersymmetry.
Supersymmetry v.s. Composite Higgs:

Neither of them is doing great --
Although that may be a difference of opinion...
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Not to mention there is also all these empirical evidence for physics beyond the SM: Dark matter, Baryon asymmetry and etc.
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In the following I will propose that, in order to understand the microscopic nature of the Higgs,

we need to pursue a program to simultaneously study HVV and HHVV couplings.
At the LHC we have measured the following Higgs couplings with uncertainties of 10 – 30 % or larger:

**Couplings to massive gauge bosons** → \( \left( \frac{2m_W^2}{v} h W^+_\mu W^-\mu + \frac{m_Z^2}{v} h Z\mu Z^\mu \right) \)

**Couplings to massless gauge bosons** →

\[
+ c_g \frac{\alpha_s}{12\pi v} h G^{a\mu} G^{a\mu} + c_\gamma \frac{\alpha}{8\pi v} h F_{\mu\nu} F^{\mu\nu} + c_{Z\gamma} \frac{\alpha}{8\pi v s_w} h F_{\mu\nu} Z^{\mu\nu}
\]

\( c_g^{(SM)}(125 \text{ GeV}) = 1 \), \( c_\gamma^{(SM)}(125 \text{ GeV}) = -6.48 \), \( c_{Z\gamma}^{(SM)}(125 \text{ GeV}) = 5.48 \).

**Couplings to fermions** → \( \sum_f \frac{m_f}{v} h \bar{f} f \) for \( bb, tt, \) and \( \tau\tau \)!

**Self-couplings** is being probed in the double Higgs production channel:

\[
\frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{v} h^3 + \frac{2m_h^2}{v^2} h^4
\]

- **Limits at 95% CL on self-coupling scale factor \( \kappa_h \):**
  - ATLAS: \(-5.0 < \kappa_h < 12.1\)
  - CMS: \(-11.8 < \kappa_h < 18.8\)
What is missing still is the HHVV coupling:

$$D_\mu H^\dagger D^\mu H \supset g^2 h^2 V_\mu V^{\mu}$$

The self-coupling and HHVV coupling are two important predictions of SM that have NOT been tested experimentally.
Let me elaborate –
Suppose the SM is just an effective description:

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^n} \mathcal{O}_i^{(n-4)} \]
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At the weak scale, the HVV and HHVV couplings deviate from their SM expectations, both in coupling strength and the tensor structure,

\[ \mathcal{L}^{(2)} = \frac{1}{2} \partial_\mu h \partial^\mu h + b_{nh} \left( \frac{h}{v} \right)^n \left( m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu \right) \]
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There are also operators carrying “four-derivative”:

\[ \frac{h}{v} V_{1\mu} D^{\mu\nu} V_{2\nu}, \quad \frac{h}{v} V_{1\mu\nu} V_{2}^{\mu\nu}, \quad D^{\mu\nu} = \partial^{\mu} \partial^{\nu} - \eta^{\mu\nu} \partial^2 \]

\[ \frac{h^2}{v^2} V_{1\mu} D^{\mu\nu} V_{2\nu}, \quad \frac{h^2}{v^2} V_{1\mu\nu} V_{2}^{\mu\nu}, \quad \frac{\partial_\mu h \partial_\nu h}{v^2} V_{1\mu} V_{2\nu} \]
In a given BSM model, coefficients of these corrections can be calculated.

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However, in composite Higgs models these anomalous HVV and HHVV couplings are controlled by only a small number of parameters because there is a symmetry relating the coefficients.

$$\mathcal{L}^{(2)} = \frac{1}{2} \partial_\mu h \partial^\mu h + b_{nh} \left( \frac{h}{v} \right)^n \left( m_W^2 W^+ W^- + \frac{1}{2} m_Z^2 Z_\mu Z^\mu \right)$$
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\mathcal{L}^{(2)} = \frac{1}{2} \partial_\mu h \partial^\mu h + b_{nh} \left( \frac{h}{v} \right)^n \left( m_W^2 W^+ \Gamma_{\mu} W^{-\mu} + \frac{1}{2} m_Z^2 Z_{\mu} Z^{\mu} \right)
\]

\[
\begin{align*}
&b_h = 1 - 2\xi \\
&b_{3h} = -\frac{4}{3} \xi \sqrt{1 - \xi} \\
&b_{5h} = \frac{4}{15} \xi^2 \sqrt{1 - \xi}, \\
&\ldots
\end{align*}
\]

\[
\begin{align*}
&b_{2h} = 2 \sqrt{1 - \xi} , \\
&b_{4h} = \frac{1}{3} \xi (2\xi - 1) , \\
&b_{6h} = \frac{2}{45} \xi^2 (1 - 2\xi) , \\
&\ldots
\end{align*}
\]
For this class of theories, the two-derivative Lagrangian can be written in a compact way:

\[
\mathcal{L}^{(2)} = \frac{1}{2} \partial_{\mu} h \partial^{\mu} h + \frac{g^2 f^2}{4} \sin^2(\theta + h/f) \left( W^+_{\mu} W^{-\mu} + \frac{1}{2 \cos^2 \theta_W} Z_{\mu} Z^{\mu} \right)
\]

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\sin^2 \theta = \xi = \frac{v^2}{f^2}
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In the unitary gauge, the “symmetry” that enforces this particular form is highly disguised and non-trivial.
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In the unitary gauge, the “symmetry” that enforces this particular form is highly disguised and non-trivial.

One way to “detect” the presence of such a disguised symmetry is to measure HVV and HHVV couplings to see if they are controlled by the same parameter.
More concretely, consider the following “anomalous” HVV and HHVV couplings:

\[
\mathcal{L}_{\text{NL}} = \sum_i \frac{m_W^2}{m^2_{\rho}} \left( C^h_1 T^h_1 + C^{2h}_1 T^{2h}_1 + C^{3V}_1 T^{3V}_1 \right)
\]

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An example of “Universal Relations” is

\[
\frac{C^{2h}_3}{C^h_3} = \frac{C^{2h}_4}{C^h_4} = \frac{1}{2} \cos \theta = \frac{1}{2} \sqrt{1 - \xi}
\]
Simultaneous measurements on HVV and HHVV coupling tensor structures allows to detect the presence of new symmetry relating the multi-Higgs couplings to electroweak gauge bosons.

But what is this “symmetry”? 
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But what is this “symmetry”?

**Observation:**

*Secretly this is a symmetry relating multi-Higgs self-interactions –*

Recall in the unitary gauge the longitudinal components of the W/Z gauge bosons are related to the 125 GeV Higgs by SU(2)xU(1).
In fact, everyone knows an example of such a symmetry.
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The example is pions in low-energy QCD. There are many ways to write down the effective Lagrangian of pions. One possibility is

\[ U(x) = \frac{1}{f} \left[ \sigma(x) + i \vec{r} \cdot \vec{\pi}(x) \right], \quad \sigma(x) = \sqrt{f^2 - \vec{\pi}^2(x)}, \]

\[ \mathcal{L}^{(2)} = \frac{1}{4} f^2 \text{Tr}[D_\mu U(D^\mu U)^\dagger] \]

When expanding the two-derivative in “1/f”, all “multi-pion” vertices are controlled by one single parameter “f”.
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When expanding the two-derivative in “1/f”, all “multi-pion” vertices are controlled by one single parameter “f”.

This is similar to the case we discussed in composite Higgs:

\[ \mathcal{L}^{(2)} = \frac{1}{2} \partial_\mu h \partial^\mu h + \frac{g^2 f^2}{4} \sin^2(\theta + h/f) \left( W_\mu^+ W^{-\mu} + \frac{1}{2 \cos^2 \theta_W} Z_\mu Z^\mu \right) \]
Pions are (pseudo)-Nambu-Goldstone bosons arising from the chiral symmetry breaking:

$$SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$$

The “symmetry” enforcing relations among multi-pion vertices is the result of degenerate vacua and the unbroken $SU(2)_V$ isospin symmetry.
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Similarly, if we detect relations among HVV and HHVV couplings, it’s the smoking-gun signal that the 125 GeV Higgs is a (pseudo-)Nambu-Goldstone boson!

⇒ Opens up a new experimental frontier.
Four different ways to test HHVV couplings at high-energy colliders:

(a) Double Higgs production through vector boson fusion at a hadron collider.

(b) Double Higgs production through vector boson fusion at a lepton collider.

(c) Double Higgs production in association with a vector boson.

(d) Off-shell Single Higgs decay.

One could also measure the triple gauge boson couplings (TGC) to test the nonlinear symmetry.

Liu, IL and Yin: 1809.09126
The required precision is high and it’s important to employ advanced analysis technique!

One example is the $H \rightarrow 4L$ decays, where the full kinematic distributions can be constructed.
Both “rate information” (in signal strength) and “shape information” (in differential spectra) are available.
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Projections at HL-LHC:

Liu, IL, Vega-Morales: 1904.00026
In some cases, the necessary theoretical tools have not been developed...

We are computing the helicity amplitudes of $W^- W^+ \rightarrow hh$

![Feynman diagrams](image)

Figure 1: Feynman diagrams contribute to the scattering $W^+ W^- \rightarrow hh$.

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<th>Helicity</th>
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Tao Han, Da Liu, IL and Xing Wang: in progress,
Concluding Remarks:

• The Higgs boson is the most exotic state of matter in Nature.

• The electroweak criticality is the most bizarre type of quantum criticality.

• Our understanding is still preliminary, at the level of Ginzburg-Landau theory for the superconductivity.

  Need to pin down a microscopic picture.

• Nonlinear dynamics of a pNGB Higgs is the most salient feature, and is universal among viable composite Higgs models.
• Testing the nonlinear Higgs interaction opens up a new experimental frontier:

  – HHVV coupling is the least studied coupling in Higgs physics.

  – Need to verify the tensor structure of the coupling, in the same fashion as in the studies of HVV coupling.

  – Simultaneous measurements of HVV, HHVV and TGCs could test the underlying symmetry in nonlinear Higgs interactions.

  – The required precision to test the universal relations is high. Need to introduce advanced analysis techniques.