What don't we know about the Higgs boson?

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Argonne/Northwestern
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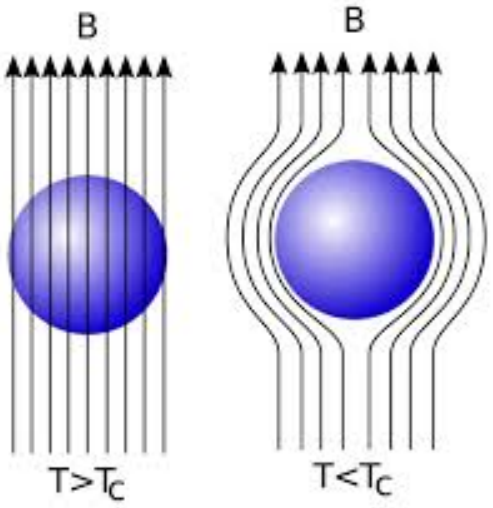
A physics Ph.D. could rephrase slightly:

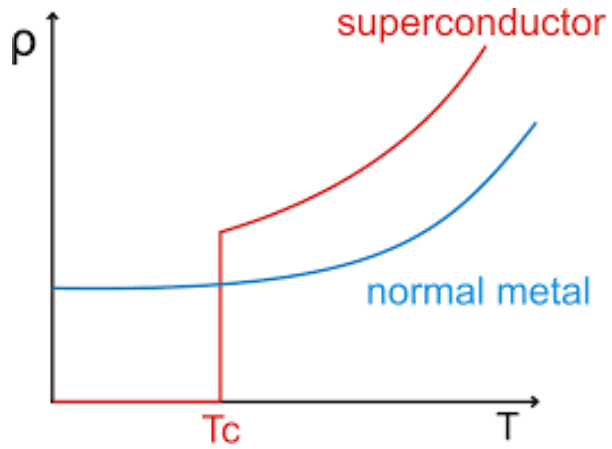
What is the microscopic theory that gives rise to the Higgs boson and its potential?

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

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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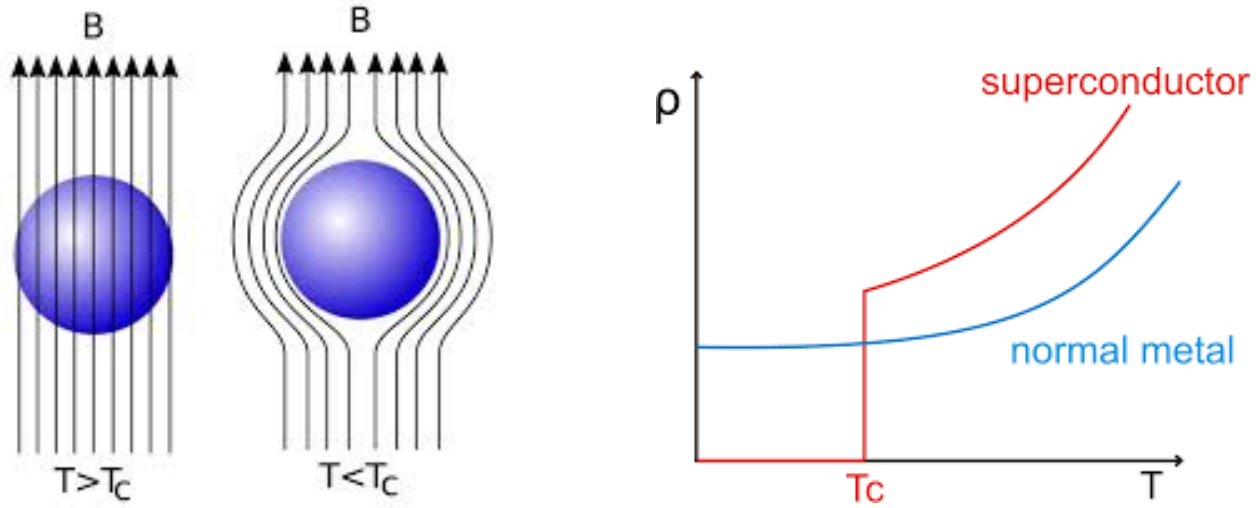

Ginzburg-Landau theory from 1950 offered a **macroscopic** (ie effective) theory for conventional superconductivity,

$$V(\Psi) = \alpha(T)|\Psi|^2 + \beta(T)|\Psi|^4 \qquad \alpha(T) \approx a^2(T - T_c) \qquad \text{and} \qquad \beta(T) \approx b^2$$

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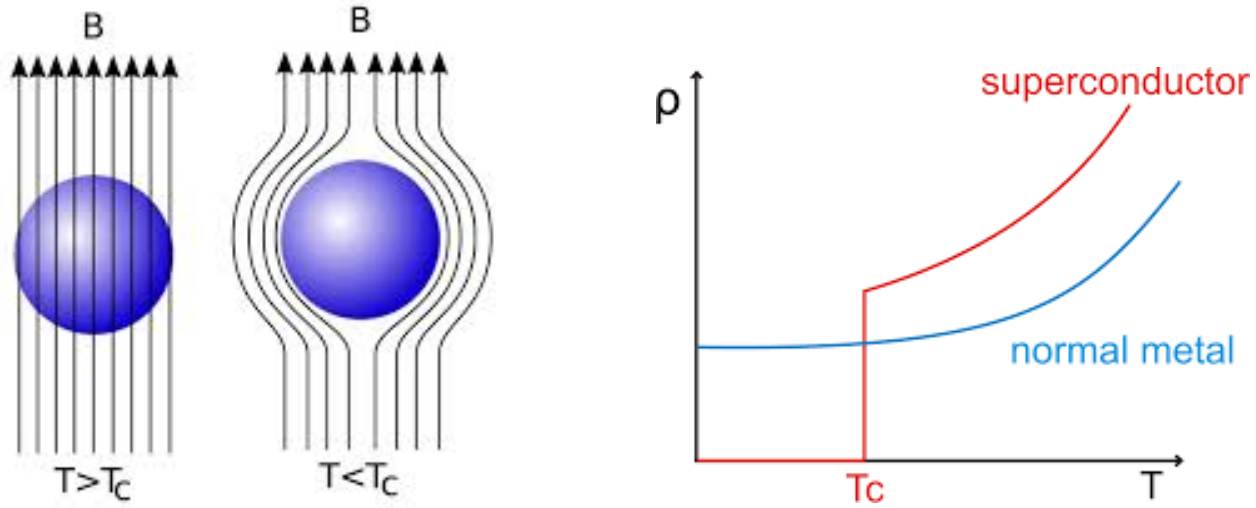

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What is the **microscopic** origin of the Ginzburg-Landau potential for superconductivity?

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

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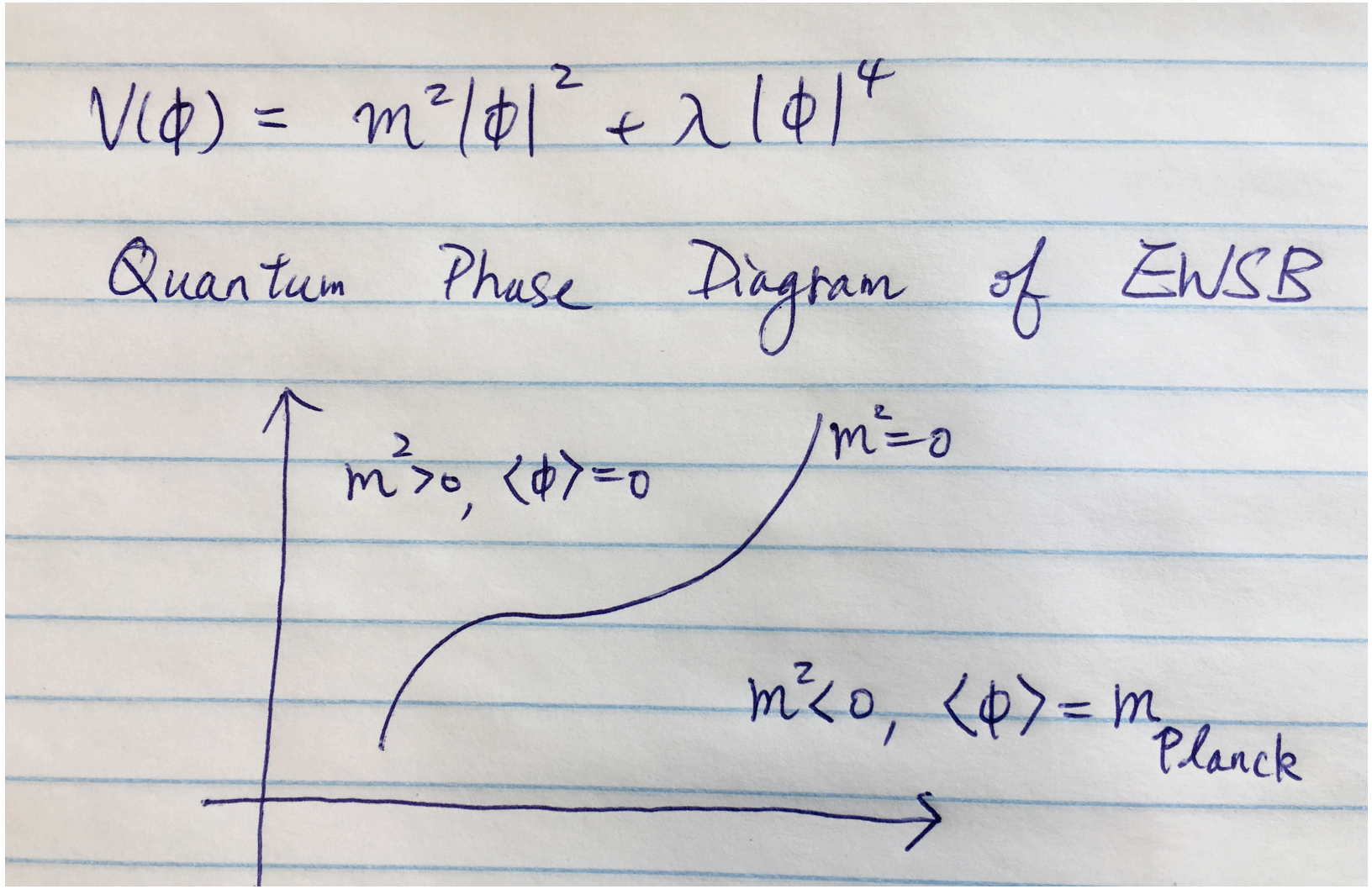
We do not have the corresponding **microscopic** theory for the Higgs boson.

In fact, we have NOT even measured the Ginzburg-Landau potential of the Higgs!

The question can be reformulated in terms of **Quantum Criticality**:



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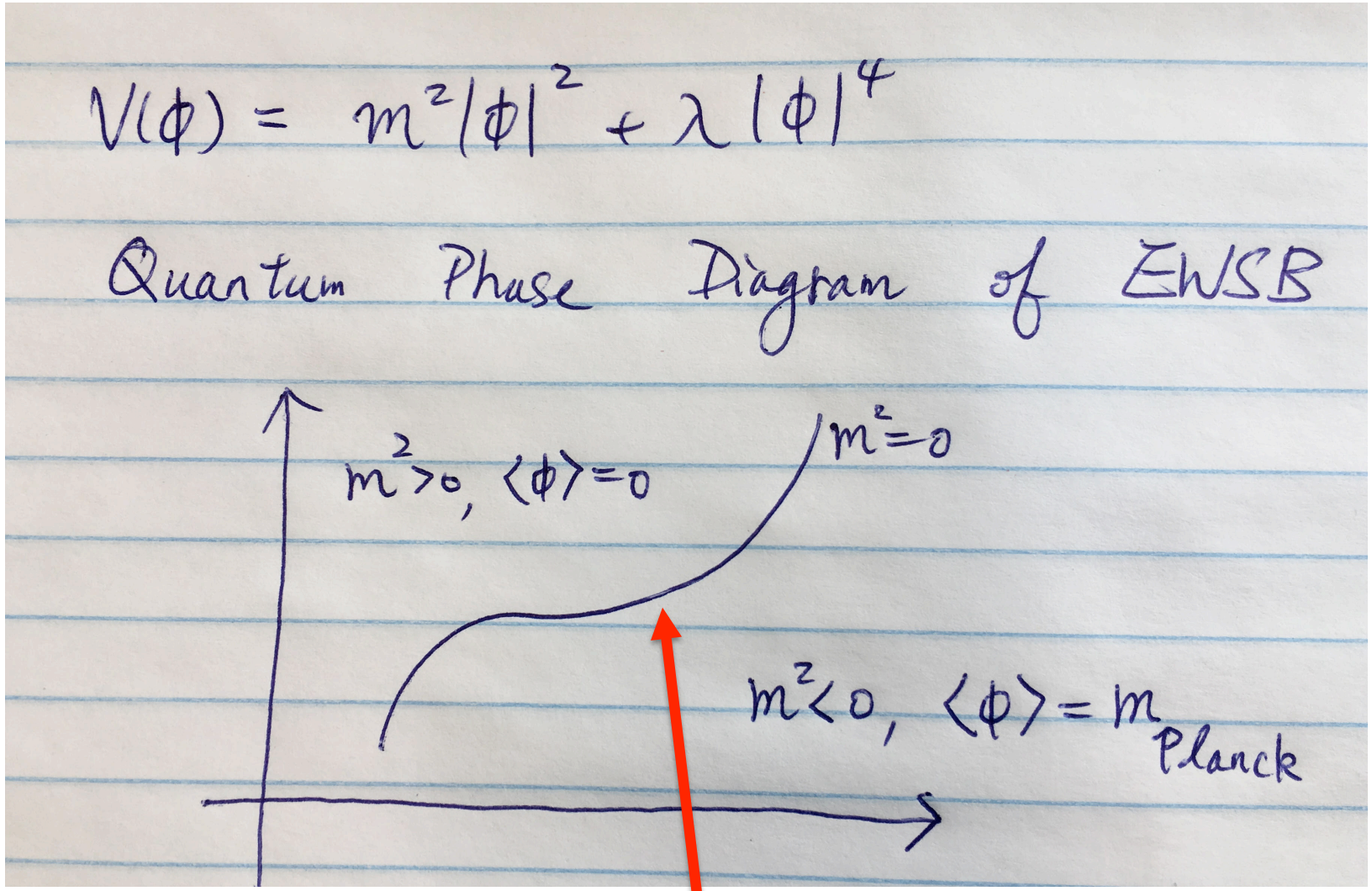

Mh=125 GeV. We are sitting extremely close to the criticality. **WHY??**

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.

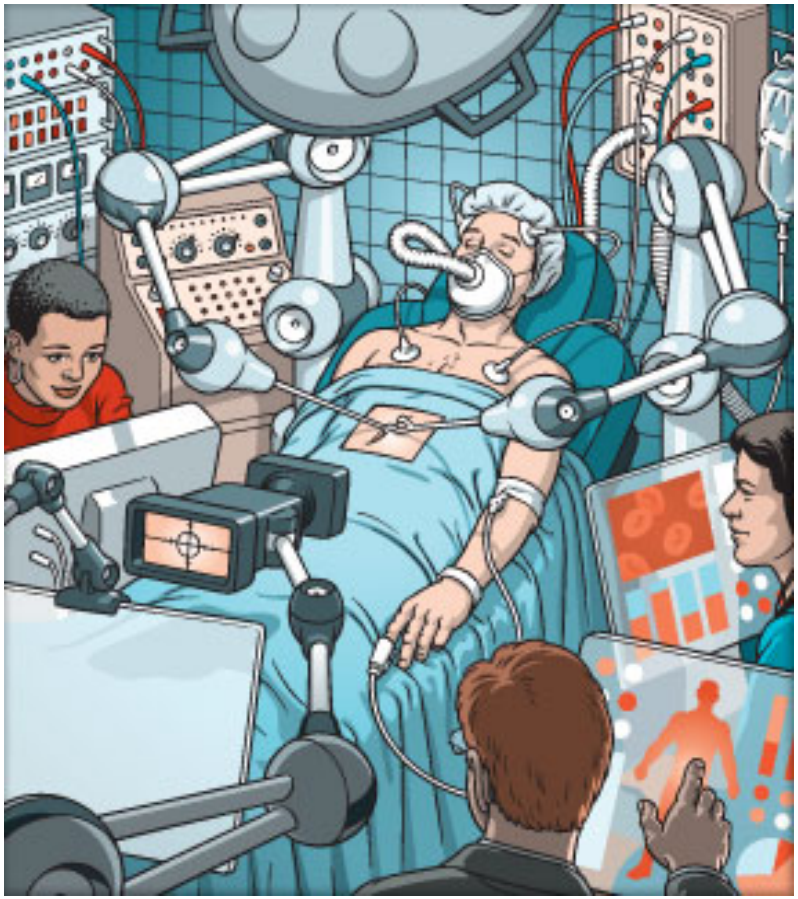
➔ This class goes by the name of "composite Higgs models."

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 →

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

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

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

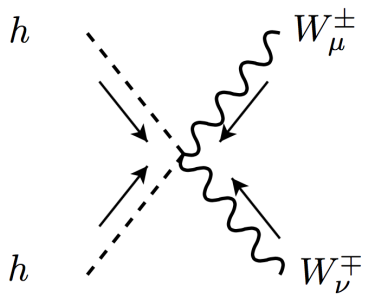
Self-couplings is being probed in the double Higgs production channel:

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

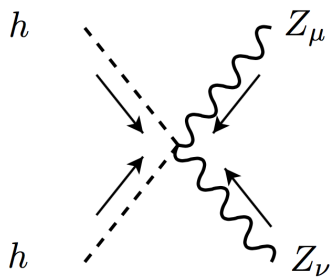
- Limits at 95% CL on self-coupling scale factor κ_λ:
  - ATLAS: $-5.0<\kappa_\lambda<12.1$
  - CMS: $-11.8<\kappa_\lambda<18.8$

What is missing still is the HHVV coupling:

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



$$\frac{i}{2}\, g^2\, g_{\mu\nu}$$



$$\frac{i}{2}\frac{g^2}{\cos^2\theta_W} g_{\mu\nu}$$

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:

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^n} \mathcal{O}_i^{(n-4)}$$

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At the weak scale, the HVV and HHVV couplings deviate from their SM expectations, both in <u>coupling strength</u> and the <u>tensor structure</u>,

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

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There are also operators carrying "four-derivative":

$$\frac{h}{v} V_{1\,\mu} \mathcal{D}^{\mu\nu} V_{2\,\nu}\ , \qquad \frac{h}{v} V_{1\,\mu\nu} V_2^{\mu\nu}\ , \qquad \mathcal{D}^{\mu\nu} = \partial^\mu \partial^\nu - \eta^{\mu\nu}\partial^2$$

$$\frac{h^2}{v^2} V_{1\,\mu} \mathcal{D}^{\mu\nu} V_{2\,\nu}\ , \qquad \frac{h^2}{v^2} V_{1\,\mu\nu} V_2^{\mu\nu}\ , \qquad \frac{\partial_\mu h \partial_\nu h}{v^2} V_1^\mu V_2^\nu$$

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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.

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$$b_h = 1 - 2\xi \qquad b_{2h} = 2\sqrt{1-\xi}\ ,$$

$$b_{3h} = -\frac{4}{3}\xi\sqrt{1-\xi}\ , \qquad b_{4h} = \frac{1}{3}\xi(2\xi - 1)\ ,$$

$$b_{5h} = \frac{4}{15}\xi^2\sqrt{1-\xi}\ , \qquad b_{6h} = \frac{2}{45}\xi^2(1-2\xi)\ ,$$

$$\ldots \qquad \ldots$$

For this class of theories, the two-derivative Lagrangian can be written in a compact way:

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

$$\sin^2\theta = \xi = \frac{v^2}{f^2}$$

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In the unitary gauge, the "symmetry" that enforces this particular form is highly disguised and non-trivial.

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:

$$\mathcal{L}_{\rm NL} = \sum_i \frac{m_W^2}{m_\rho^2}\left(C_i^h \mathcal{I}_i^h + C_i^{2h}\mathcal{I}_i^{2h} + C_i^{3V}\mathcal{I}_i^{3V}\right)$$

$\mathcal{I}_i^h$
(1) $\frac{h}{v} Z_\mu \mathcal{D}^{\mu\nu} Z_\nu$
(2) $\frac{h}{v} Z_{\mu\nu} Z^{\mu\nu}$
(3) $\frac{h}{v} Z_\mu \mathcal{D}^{\mu\nu} A_\nu$
(4) $\frac{h}{v} Z_{\mu\nu} A^{\mu\nu}$

$\mathcal{I}_i^{2h}$
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An example of “Universal Relations” is

$$\frac{C_3^{2h}}{C_3^h} = \frac{C_4^{2h}}{C_4^h} = \frac{1}{2}\cos\theta \;= \frac{1}{2}\sqrt{1-\xi}$$

Z. Yin, D. Liu and IL: 1805.00489; 1809.09126

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.

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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

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

$$\mathcal{L}^{(2)} = \tfrac{1}{4} f^2 \,\mathrm{Tr}[\mathrm{D}_\mu U (\mathrm{D}^\mu U)^\dagger]$$

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:

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

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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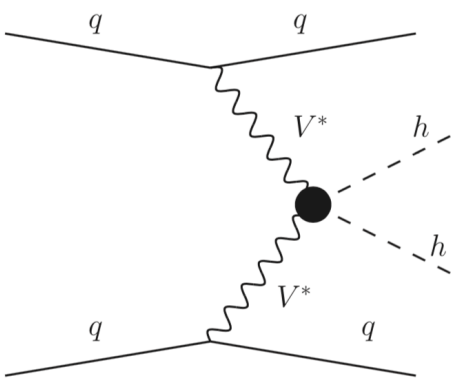
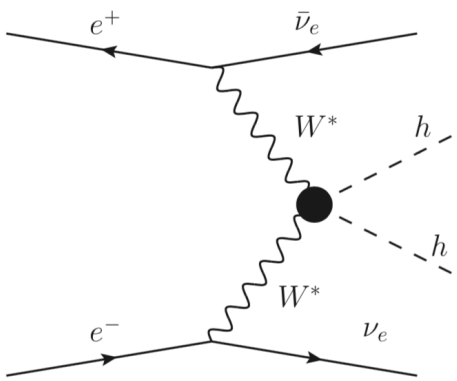
Similarly, if we detect relations among HVV and HHVV couplings, it's the smoking-gun signal that the 125 GeV Higgs is a (pseudo-)Nambu-Goldstone boson!

→ Opens up a new experimental frontier.

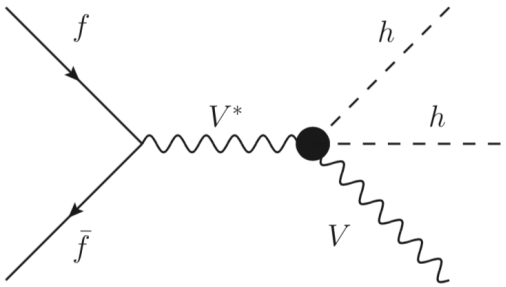
Four different ways to test HHVV couplings at high-energy colliders:



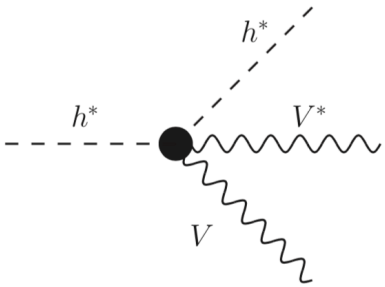
(a) Double Higgs production through vector boson fusion at a hadron collider.



(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 → 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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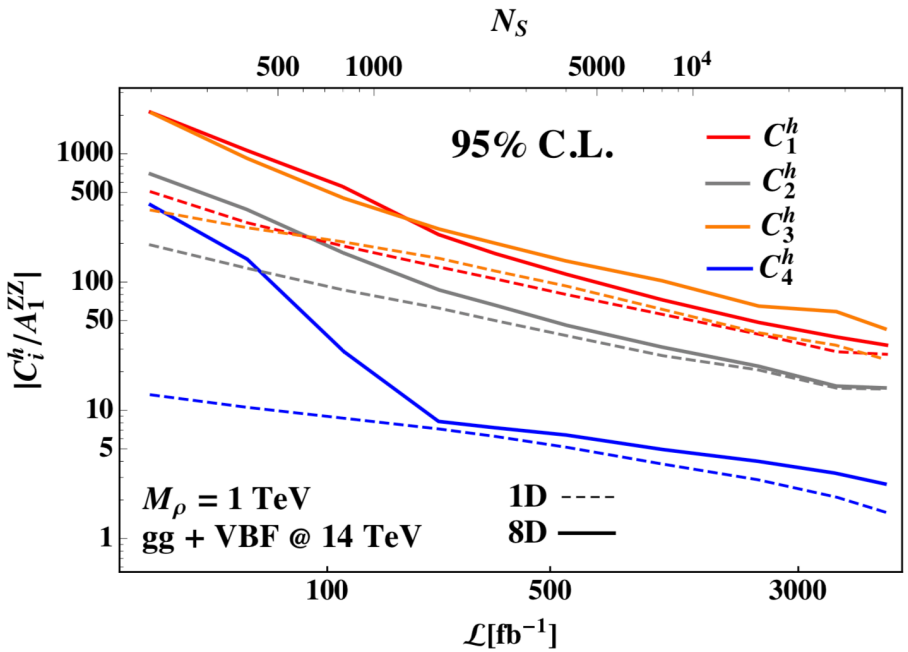
Projections at HL-LHC:



Liu, IL, Vega-Morales: 1904.00026

In some cases, the necessary theoretical tools have not been developed…

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

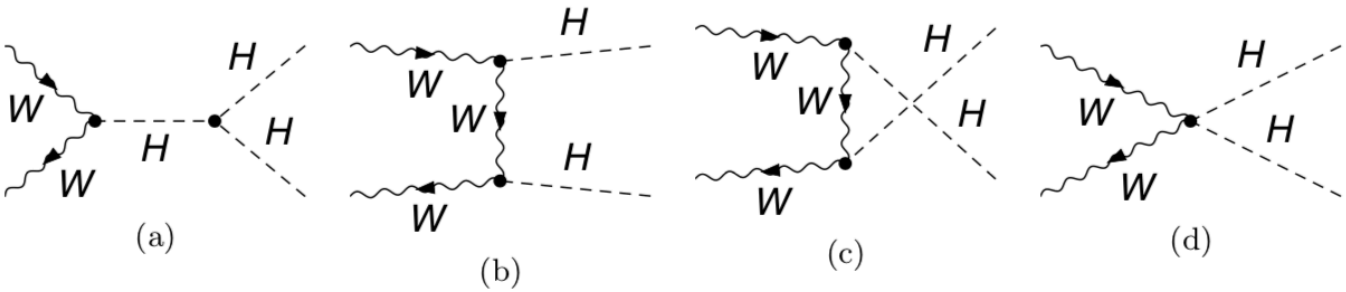


Figure 1: Feynman diagrams contribute to the scattering $W^+W^- \to hh$.

Helicity	Diagram	SM	C_5^h	C_6^h	C_5^{2h}	C_6^{2h}	C_9^{2h}	C_{10}^{2h}
$(0,0)$ $(\pm,\pm)$	s-channel	✓	✓	✓	✗	✗	✗	✗
	t-channel	✓	✓	✓	✗	✗	✗	✗
	u-channel	✓	✓	✓	✗	✗	✗	✗
	4-point	✓	✗	✗	✓	✓	✓	✓
$(\pm,\mp)$	s-channel	✗	✗	✗	✗	✗	✗	✗
	t-channel	✓	✓	✗	✗	✗	✗	✗
	u-channel	✓	✓	✗	✗	✗	✗	✗
	4-point	✗	✗	✗	✗	✗	✗	✓
$(\pm,0)$ $(0,\pm)$	s-channel	✗	✗	✗	✗	✗	✗	✗
	t-channel	✓	✓	✓	✗	✗	✗	✗
	u-channel	✓	✓	✓	✗	✗	✗	✗
	4-point	✗	✗	✗	✗	✗	✗	✓

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.