Recent Progresses in Composite Higgs Models

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In Pursuit of New Particles and Paradigms

ASPEN CENTER FOR **PHYSICS**

We’ve come a long way since the Higgs discovery in 2012, but there’re still many questions we have no answer to.

A few years back I was reminded by my (then) 7-year-old of one such question:

What is it made of?

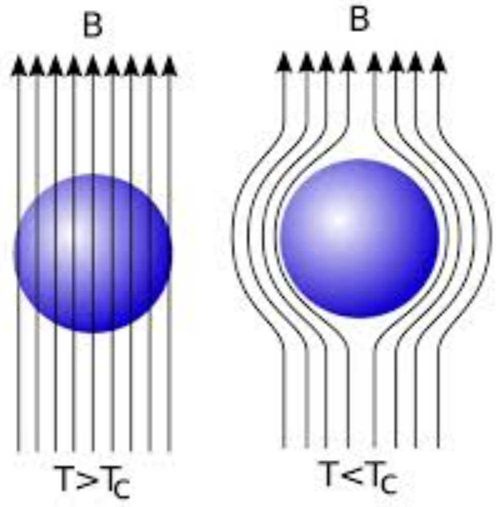
A physics Ph.D. could rephrase slightly:

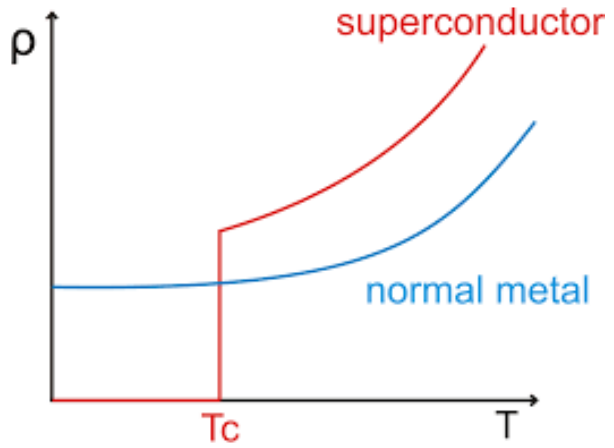
What is the microscopic theory that gives rise to the Higgs boson and its potential?

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

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:





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

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

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

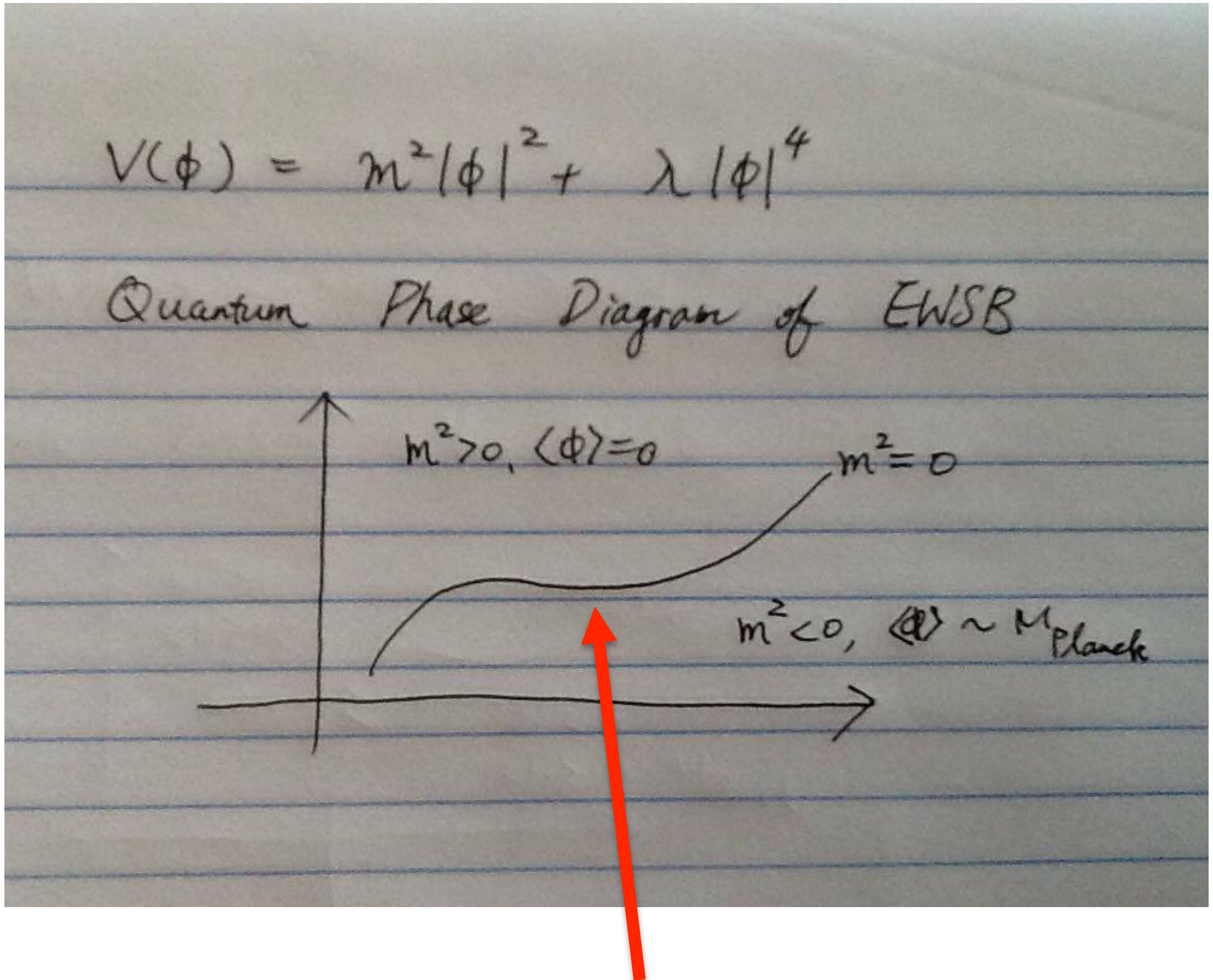
1) interpret $|\Psi|^2$ as the number density of Cooper pairs

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

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**:



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

One appealing possibility – the critical line is selected dynamically.

This is the analogy of BCS theory for electroweak symmetry breaking. It goes by the name of "technicolor," which is strongly disfavored experimentally.

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."

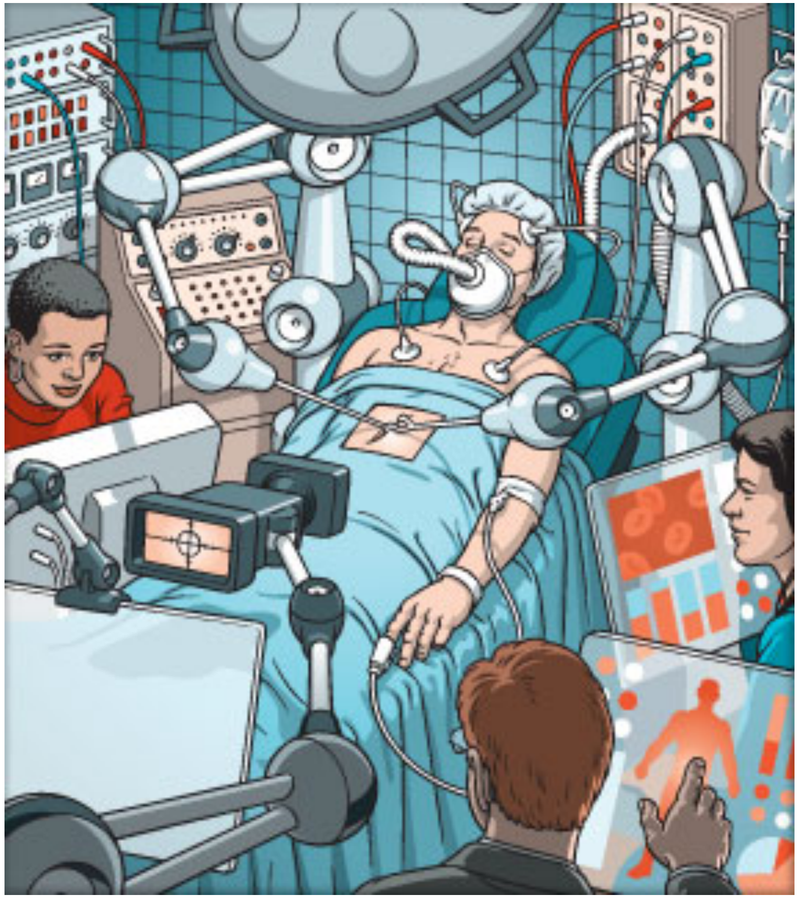
(Georgi and Kaplan '84 + …)

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…

The fact that we have not seen signs of SUSY or CHM only **deepens** the mystery, of why we are sitting close to the critical line of EWSB!

Some people argued that the SM by itself is UV-complete and, therefore, there's no need for new physics.

This is a reasoning that has failed **many times** through out the course of the history:

- QED (photons+electrons) is a UV-complete theory. But physics didn't stop there.
- QCD (gluons+quarks) is also a UV-complete theory. Again physics didn't stop there.
- SM with one generation of fermion is UV-complete. "WHO ORDERED THAT?"

Not to mention there is also all these empirical evidence for physics beyond the SM: Dark matter, Baryon asymmetry and etc.

It is a somewhat embarrassing realization that, after 40 years, our understanding of the electroweak symmetry breaking is still at the level of Ginzburg-Landau level!

The theory space of composite Higgs models is large:

$\mathcal{G}$	$\mathcal{H}$	C	N_G	$\mathbf{r}_{\mathcal{H}} = \mathbf{r}_{\mathrm{SU(2)\times SU(2)}}\,(\mathbf{r}_{\mathrm{SU(2)\times U(1)}})$	Ref.
SO(5)	SO(4)	✓	4	$\mathbf{4} = (\mathbf{2},\mathbf{2})$	[11]
SU(3) × U(1)	SU(2) × U(1)		5	$\mathbf{2}_{\pm 1/2} + \mathbf{1}_0$	[10, 35]
SU(4)	Sp(4)	✓	5	$\mathbf{5} = (\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$	[29, 47, 64]
SU(4)	$[\mathrm{SU(2)}]^2 \times$ U(1)	✓*	8	$(\mathbf{2},\mathbf{2})_{\pm 2} = 2\cdot(\mathbf{2},\mathbf{2})$	[65]
SO(7)	SO(6)	✓	6	$\mathbf{6} = 2\cdot(\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$	–
SO(7)	G_2	✓*	7	$\mathbf{7} = (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$	[66]
SO(7)	SO(5) × U(1)	✓*	10	$\mathbf{10}_0 = (\mathbf{3},\mathbf{1}) + (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$	–
SO(7)	$[\mathrm{SU(2)}]^3$	✓*	12	$(\mathbf{2},\mathbf{2},\mathbf{3}) = 3\cdot(\mathbf{2},\mathbf{2})$	–
Sp(6)	Sp(4) × SU(2)	✓	8	$(\mathbf{4},\mathbf{2}) = 2\cdot(\mathbf{2},\mathbf{2})$	[65]
SU(5)	SU(4) × U(1)	✓*	8	$\mathbf{4}_{-5} + \bar{\mathbf{4}}_{+5} = 2\cdot(\mathbf{2},\mathbf{2})$	[67]
SU(5)	SO(5)	✓*	14	$\mathbf{14} = (\mathbf{3},\mathbf{3}) + (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{1})$	[9, 47, 49]
SO(8)	SO(7)	✓	7	$\mathbf{7} = 3\cdot(\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$	–
SO(9)	SO(8)	✓	8	$\mathbf{8} = 2\cdot(\mathbf{2},\mathbf{2})$	[67]
SO(9)	SO(5) × SO(4)	✓*	20	$(\mathbf{5},\mathbf{4}) = (\mathbf{2},\mathbf{2}) + (\mathbf{1}+\mathbf{3},\mathbf{1}+\mathbf{3})$	[34]
$[\mathrm{SU(3)}]^2$	SU(3)		8	$\mathbf{8} = \mathbf{1}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{3}_0$	[8]
$[\mathrm{SO(5)}]^2$	SO(5)	✓*	10	$\mathbf{10} = (\mathbf{1},\mathbf{3}) + (\mathbf{3},\mathbf{1}) + (\mathbf{2},\mathbf{2})$	[32]
SU(4) × U(1)	SU(3) × U(1)		7	$\mathbf{3}_{-1/3} + \bar{\mathbf{3}}_{+1/3} + \mathbf{1}_0 = 3\cdot\mathbf{1}_0 + \mathbf{2}_{\pm 1/2}$	[35, 41]
SU(6)	Sp(6)	✓*	14	$\mathbf{14} = 2\cdot(\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{3}) + 3\cdot(\mathbf{1},\mathbf{1})$	[30, 47]
$[\mathrm{SO(6)}]^2$	SO(6)	✓*	15	$\mathbf{15} = (\mathbf{1},\mathbf{1}) + 2\cdot(\mathbf{2},\mathbf{2}) + (\mathbf{3},\mathbf{1}) + (\mathbf{1},\mathbf{3})$	[36]

Table 1: Symmetry breaking patterns $\mathcal{G} \to \mathcal{H}$ for Lie groups. The third column denotes whether the breaking pattern incorporates custodial symmetry. The fourth column gives the dimension N_G of the coset, while the fifth contains the representations of the GB's under $\mathcal{H}$ and $\mathrm{SO}(4) \cong \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ (or simply $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ if there is no custodial symmetry). In case of more than two SU(2)'s in $\mathcal{H}$ and several different possible decompositions we quote the one with largest number of bi-doublets.

Bellazzni, Csaki and Serra:1401.2457

In fact, the theory space of composite Higgs models is infinite:

Different composite Higgs models choose different symmetry-breaking patterns G/H.

Conventional wisdom:

Effective actions based on different G/H are different.

Each time a young hot shot comes up with a new model, we need to work out the experimental consequences all over again.

This begs the question:

Are there universal predictions of a composite Higgs boson that are independent of the symmetry-breaking pattern?

- Recall Nambu-Goldstone bosons were studied vigorously in the context of pions in the ’60s.

- The work was collectively known as “soft pion theorems,”
  → a significant part of them does not depend on the particular symmetry breaking pattern!

- One example is the Adler’s zero condition:

  On-shell scattering amplitudes of Goldstone bosons must vanish in the limit the momentum of one Goldstone boson is taken to zero.

(Often this is simplified as saying “Goldstone boson is derivatively coupled.”)

In the past few years, we have come to realize that

The Adler's zero condition can be taken as the "defining property" of Goldstone bosons

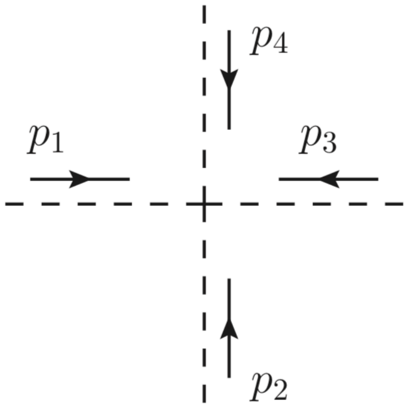
without reference to a spontaneously broken symmetry in the UV.

This program is now known as the "Soft Bootstrap".

Low: 1412.2145; 1412.2146
Cheung, Kampf, Novotny, Trnka: 1412.4095
Cheung, Kampf, Novotny, Shen, Trnka: 1509.03309; 1611.03137
Low, Yin: 1804.08629
Elvang, Hadjiantonis, Jones, Paranjape: 1806.06079
Low, Yin: 1904.nnnnn

Consider the 4-pt amplitude of a set of massless scalars (NGB).

Assuming there is a notion of "ordering" among the NGBs, then the Adler's zero condition uniquely determines

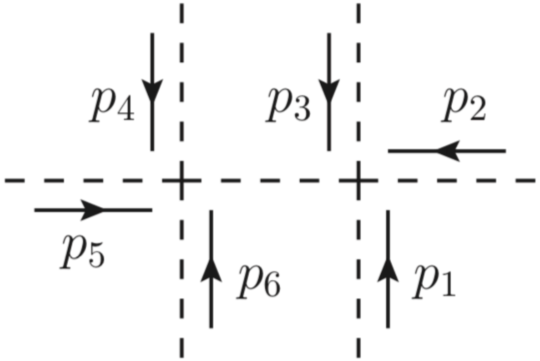


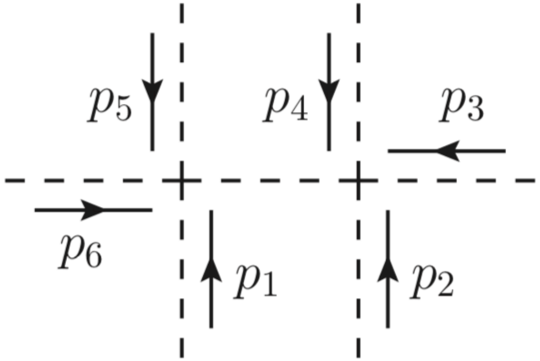
$$p_i^2 = 0 \; ; \sum_{i=1}^{4} p_i = 0$$

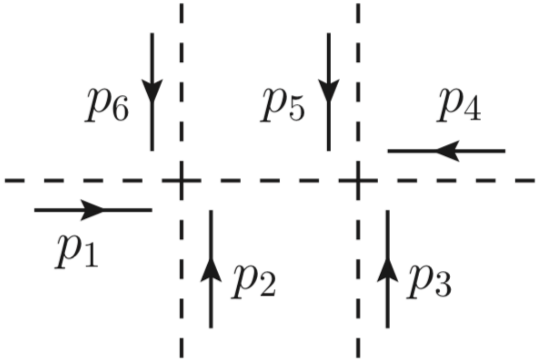
$$M_4(p_1, p_2, p_3, p_4) = c\frac{p_2 \cdot p_4}{f^2} = c\frac{p_1 \cdot p_3}{f^2}$$

"f" is a dimensionful parameter, while "c" is an arbitrary number, which could be absorbed into the normalization of "f".

Once we have the 4-pt amplitude, we can build up the 6-pt amplitude from the 4-pt amplitude:





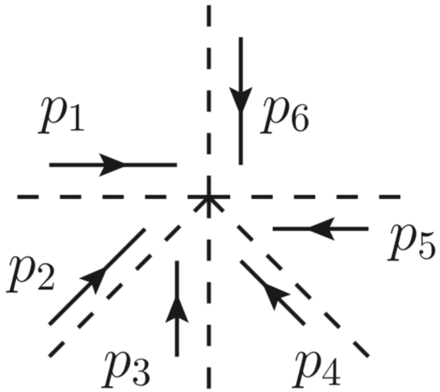


$$\frac{1}{f^2}\left(\frac{s_{13}s_{46}}{P_{123}^2}+\frac{s_{24}s_{15}}{P_{234}^2}+\frac{s_{35}s_{26}}{P_{345}^2}\right)$$

$$s_{ij} = (p_i + p_j)^2$$
$$P_{ijk}^2 = (p_i + p_j + p_k)^2$$

This expression doesn't satisfy the Adler's zero condition!

The resolution is to introduce an additional contribution, the “contact interaction,”



It turns out imposing the Adler’s condition uniquely fixes this 6-pt contact interaction:

$$M_6 = \frac{1}{f^2}\left(\frac{s_{13}s_{46}}{P_{123}^2} + \frac{s_{24}s_{15}}{P_{234}^2} + \frac{s_{35}s_{26}}{P_{345}^2}\right) - \frac{1}{f^2}P_{135}^2$$

This process is then continued to 8-pt amplitudes and so on.

In the end all interaction vertices of NGB's can be constructed simply by assuming:

- There is a notion of "ordering," which arises due to some discrete quantum numbers, given by the "unbroken group" H.
- The vanishing "soft limit" in the scattering amplitudes.

Only infrared data are needed.

It is not necessary to know the full symmetry group "G", unless one is interested in the absolute normalization of "f".

The modern perspective on NBG:

- The Adler’s zero can be taken as the defining property of NGB.
- There is a universality class for each NGB carrying the same charge under the unbroken group.
- The nonlinearity in the NGB interactions arises entirely from IR physics.
- What’s being “broken” in the UV is irrelevant, other than determining the normalization of “f”.

A common ingredient for all composite Higgs models:

The unbroken group H always contains a SO(4) subgroup, under which the 125 GeV Higgs is the fundamental representation.

“Soft Bootstrap” implies nonlinear interactions of the 125 GeV Higgs in a composite Higgs model are universal, up to the normalization of “f”.

In particular, we can show that the (multi)Higgs couplings to two electroweak gauge bosons are universal.

Da Liu, IL and Zhewei Yin: 1805.00489; 1809.09126

Schematically, the universality predicts that

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

$$\begin{aligned} b_h &= 1 - 2\xi & b_{2h} &= 2\sqrt{1-\xi}\ , \\ b_{3h} &= -\frac{4}{3}\xi\sqrt{1-\xi}\ , & b_{4h} &= \frac{1}{3}\xi(2\xi - 1)\ , \\ b_{5h} &= \frac{4}{15}\xi^2\sqrt{1-\xi}\ , & b_{6h} &= \frac{2}{45}\xi^2(1-2\xi)\ , \\ &\cdots & &\cdots \end{aligned}$$

There is a “shift symmetry” relating all these different couplings.

Experimental confirmation of the shift symmetry would be a striking indication on the NGB nature of the 125 GeV Higgs boson.

→ Opens up a new experimental frontier.

One way to “detect” the presence of such a symmetry is to measure deviations in HVV and HHVV couplings to see if they are controlled by the same parameter.

Consider the following "anomalous" HVV and HHVV couplings:

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

$\mathcal{I}_i^h$
(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) $\frac{h}{v} Z_{\mu\nu} A^{\mu\nu}$

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

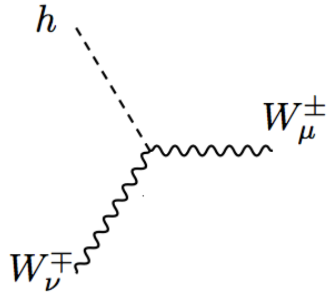
$$\frac{C_3^{2h}}{C_3^h} = \frac{C_4^{2h}}{C_4^h} = \frac{1}{2}\cos\theta = \frac{1}{2}\sqrt{1-\xi}$$

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

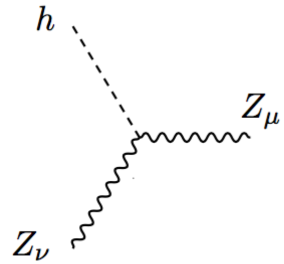
Universal Relations: Ratios of anomalous HVV and HHVV couplings that depend on only one parameter ξ.

These are universal predictions of a PNGB Higgs boson.

Recall that establishing and studying HVV couplings was the top priority of the Higgs program at the LHC Run 1:



$ig\, m_W\, g_{\mu\nu}$



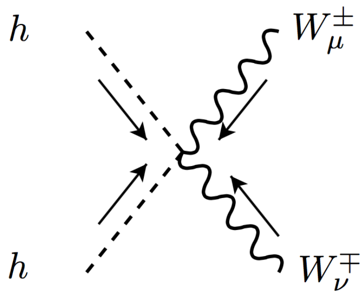
$i \frac{g}{\cos\theta_W} m_Z\, g_{\mu\nu}$

The goal of the program includes both the coupling strength and the tensor structure:

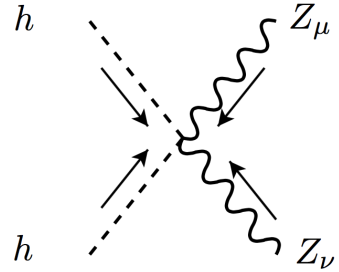
$$A \sim \left[a_1^{\mathrm{VV}} - \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} - \frac{\kappa_3^{\mathrm{VV}} (q_1 + q_2)^2}{\left(\Lambda_Q^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V}1}^2 \epsilon_{\mathrm{V}1}^* \epsilon_{\mathrm{V}2}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\,\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\,\mu\nu}$$

On the other hand, the HHVV coupling has received little attention,

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



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



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

The Ginzburg-Landau potential and HHVV coupling are the last predictions of the SM Higgs boson that have yet to be verified experimentally!

A program to study the couplings strength and tensor structures of HHVV coupling should be pursued vigorously --

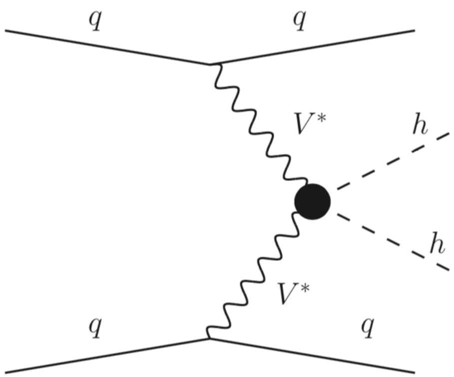
Reason 1:

Among the least understood/measured coupling of the 125 GeV Higgs!

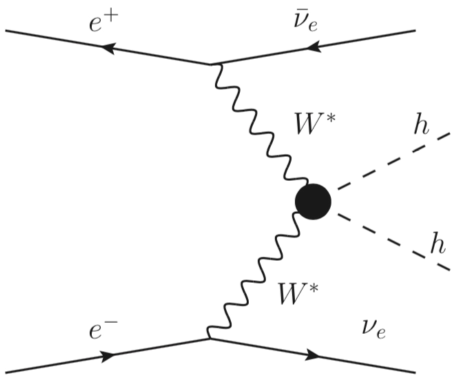
Reason 2:

Simultaneous measurements on HVV and HHVV couplings coud shed light on the UV nature of the 125 GeV Higgs.

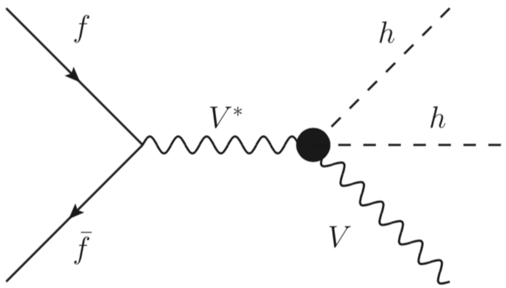
Four different ways to test HHVV couplings at future colliders:



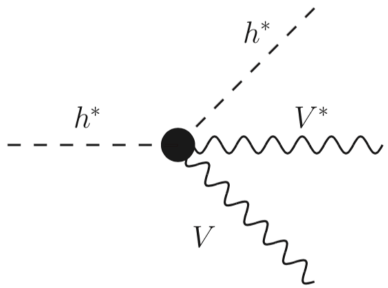
(a) Double Higgs production through vector boson fusion at a hadron collider.



(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.

Liu, IL and Yin: 1809.09126

This is the future frontiers of precision Higgs measurements!

Even today, we have NOT fully exploited the potential of current Higgs data.

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.

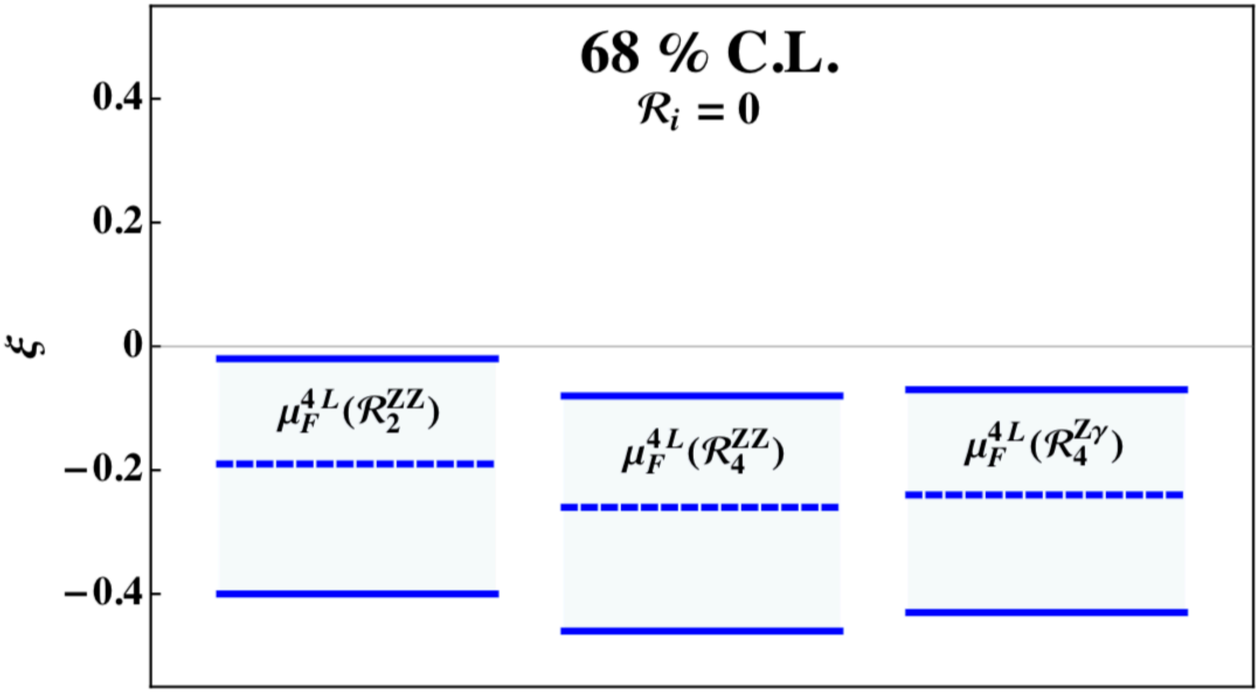
Using the "Golden 4L channel", we can

- obtain a more proper experimental limit on the nonlinear parameter ξ.

- constrain the Wilson coefficients of O(p^4) operators in the nonlinear Higgs Lagrangian, for the first time!

$$\mathcal{L}^{(1h)} = \frac{m_W^2}{M_\rho^2}\left[C_1^h\ \frac{h}{v} Z_\mu \mathcal{D}^{\mu\nu} Z_\nu + C_2^h\ \frac{h}{v} Z_{\mu\nu} Z^{\mu\nu} + C_3^h\ \frac{h}{v} Z_\mu \mathcal{D}^{\mu\nu} A_\nu \right.$$
$$\left. + C_4^h\ \frac{h}{v} Z_{\mu\nu} A^{\mu\nu} + C_5^h\ \frac{h}{v}(W_\mu^+ \mathcal{D}^{\mu\nu} W_\nu^- + \text{h.c.}) + C_6^h\ \frac{h}{v} W_{\mu\nu}^+ W^{-\mu\nu}\right]$$

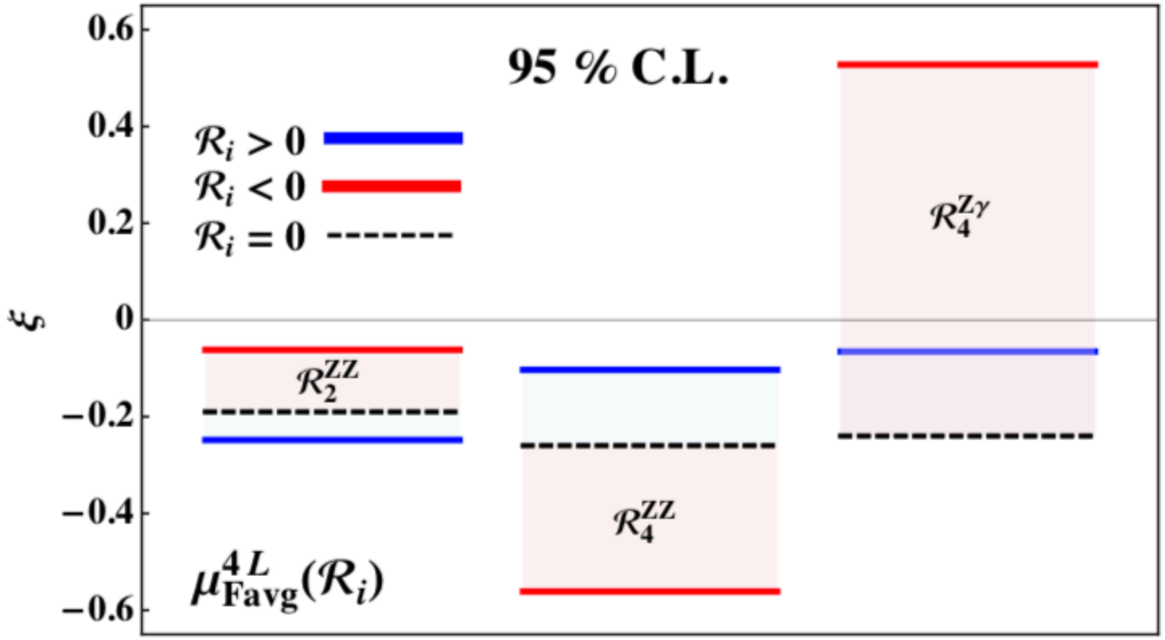
Measurements on the nonlinear parameter ξ using "rate information:"



- Signal strength in 4L channel prefers a negative ξ, which corresponds to a non-compact coset structure in the UV.

Liu, IL, Vega-Morales: to appear

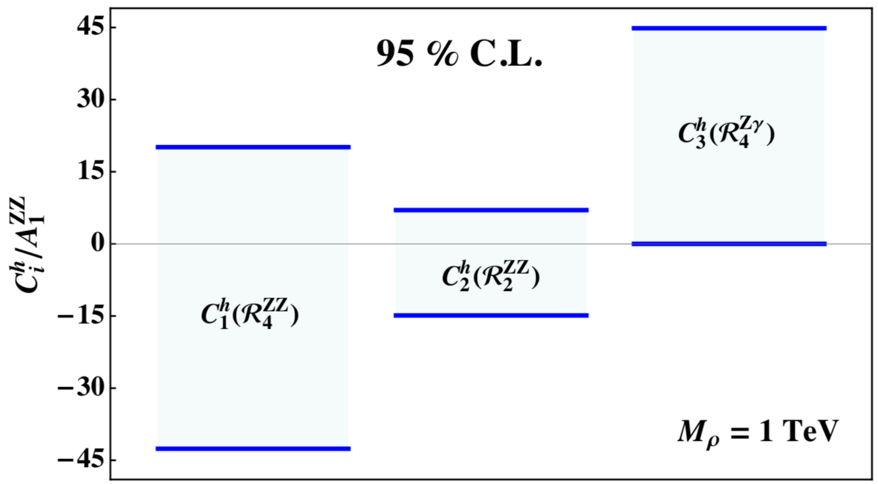
Measurements on the nonlinear parameter ξ using fully differential spectra:



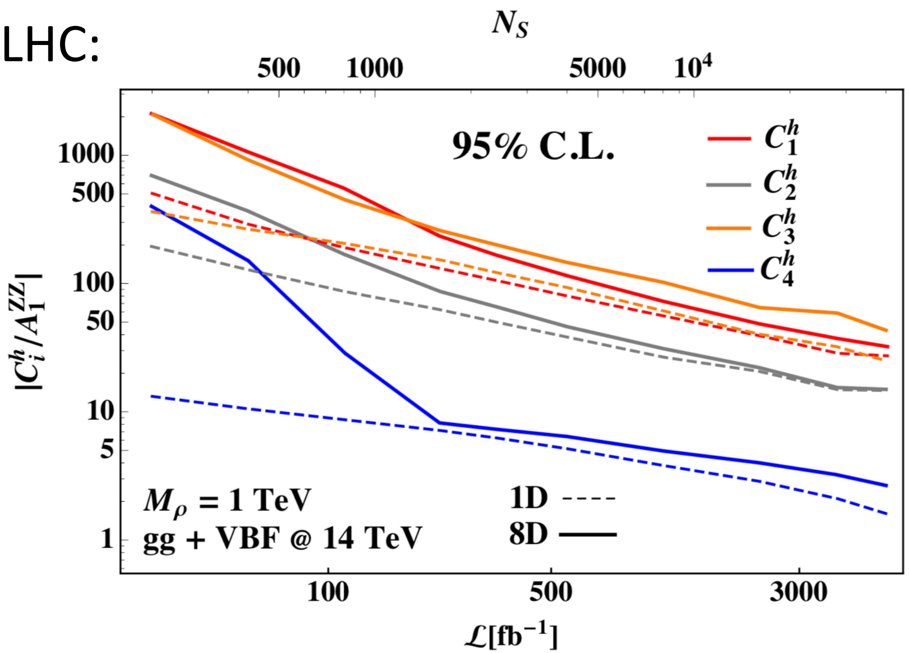
- Depends on which anomalous HVV coupling is "turned on," ξ < 0.5 or > -0.5 is still allowed.

Liu, IL, Vega-Morales: to appear

First limits on the Wilson coefficients in nonlinear Lagrangian:



Projections at HL-LHC:



Liu, IL, Vega-Morales: to appear

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 picture for the superconductivity.

  Need to pin down a microscopic picture.

- Higgs as a pseudo-Nambu-Goldstone boson offers an appealing explanation, with the nonlinear dynamics being the most salient and generic feature.

- Nonlinear Higgs interaction is universal among viable composite Higgs models.

- Testing the nonlinear Higgs interaction opens up a new experimental frontier:
  - Simultaneous measurements of HVV, HHVV and TGCs could test the underlying shift symmetry in nonlinear Higgs interactions.
  - 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.
  - The required precision to test the universal relations is high. Need to introduce advanced analysis techniques.