Higgstory in the Making

Theory: Historical perspective and what have we learned from the Higgs so far

John Ellis
The BCS Theory of Superconductivity

A theory of superconductivity is presented, based on the fact that the interaction between electrons resulting from virtual exchange of phonons is attractive when the energy difference between the electrons states involved is less than the phonon energy, \( \hbar \omega \). It is favorable to form a superconducting phase when this attractive interaction dominates the repulsive screened Coulomb interaction. The normal phase is described by the Bloch individual-particle model. The ground state of a superconductor, formed from a linear combination of normal state configurations in which electrons are virtually excited in pairs of opposite spin and momentum, is lower in energy than the normal state by amount proportional to an average \( (\hbar \omega)^2 \), consistent with the isotope effect. A mutually orthogonal set of excited states in one-to-one correspondence with those of the normal phase is obtained by specifying occupation of certain Bloch states and by using the rest to form a linear combination of virtual pair configurations. The theory yields a second-order phase transition and a Meissner effect in the form suggested by Pippard. Calculated values of specific heats and penetration depths and their temperature variation are in good agreement with experiment. There is an energy gap for individual-particle excitations which decreases from about \( 3.5kT_c \) at \( T=0^\circ K \) to zero at \( T_c \). Tables of matrix elements of single-particle operators between the excited-state superconducting wave functions, useful for perturbation expansions and calculations of transition probabilities, are given.

Condensate of electron pairs of due to phonon interactions
Lowest-energy state has charge density: breaks/hides \( U(1)_{em} \)
Nambu, Anderson & “Spontaneous Breaking” of Gauge Symmetry

“Spontaneous symmetry breaking” = hidden symmetry

Gauge-invariant mass generation by plasmons in non-relativistic theory

“Spontaneous breaking” of Gauge Symmetry

Ideas and techniques known in quantum electrodynamics have been applied to the Bardeen-Cooper-Schrieffer theory of superconductivity. In an approximation which corresponds to a generalization of the Hartree-Fock fields, one can write down an integral equation defining the self-energy of an electron in an electron gas with phonon and Coulomb interaction. The form of the equation implies the existence of a particular solution which does not follow from perturbation theory, and which leads to the energy gap equation and the quasi-particle picture analogous to Bogoliubov’s.

The gauge invariance, to the first order in the external electromagnetic field, can be maintained in the quasi-particle picture by taking into account a certain class of corrections to the charge-current operator due to the phonon and Coulomb interaction. In fact, generalized forms of the Ward identity are obtained between certain vertex parts and the self-energy. The Meissner effect calculation is thus rendered strictly gauge invariant, but essentially keeping the BCS result unaltered for transverse fields.

It is shown also that the integral equation for vertex parts allows homogeneous solutions which describe collective excitations of quasi-particle pairs, and the nature and effects of such collective states are discussed.
AXIAL VECTOR CURRENT CONSERVATION IN WEAK INTERACTIONS

Yoichiro Nambu
Enrico Fermi Institute for Nuclear Studies and Department of Physics
University of Chicago, Chicago, Illinois
(Received February 23, 1960)

In analogy to the conserved vector current interaction in the beta decay suggested by Feynman and Gell-Mann, some speculations have been made about a possible conserved axial vector current. One can formally construct an axial vector nucleon current, which satisfies a continuity equation,

\[ \Gamma_A^{\mu}(p', p) = i\gamma_5 \gamma_\mu - 2M \gamma_5 q_\mu / q^2, \quad q = p' - p, \quad (1) \]

where \( p \) and \( p' \) are the initial and final nucleon momenta. Such an attempt has some appeal in view of the apparently modest renormalization effect on the axial vector beta decay constant \( g_A/g_Y \approx 1.25 \), although the second appealing point, namely, the possible forbidding of \( \pi \rightarrow e + \nu \), has now lost its relevance.

The expression (1), unfortunately, can be easily ruled out experimentally, as was pointed out by Goldberger and Treiman, since it introduces a large admixture of pseudoscalar interaction.

- Spontaneous breaking of global chiral symmetry
- Pion as (almost) massless (Nambu-)Goldstone boson of chiral symmetry of strong interactions
The Founding Fathers
The Englert-Brout-Higgs Mechanism

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland
(Received 27 July 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,† and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

SPONTANEOUS BREAKDOWN OF STRONG INTERACTION SYMMETRY AND THE ABSENCE OF MASSLESS PARTICLES

A. A. Migdal and A. M. Polyakov

Submitted to JETP editor November 30, 1965; resubmitted February 16, 1966

The occurrence of massless particles in the presence of spontaneous symmetry breakdown is discussed. By summing all Feynman diagrams, one obtains for the difference of the mass...
Steps Towards the Higgs Boson
Spontaneous Symmetry Breakdown without Massless Bosons

Peter W. Higgs
Department of Physics, University of North Carolina, Chapel Hill, North Carolina
(Received 27 December 1965)

We examine a simple relativistic theory of two scalar fields, first discussed by Goldstone, in which a result of spontaneous breakdown of $U(1)$ symmetry under the Goldstone theorem, when the symmetry group of the Lagrangian is extended from global to local $U(1)$ transformations by the introduction of a vector gauge field, the Goldstone boson becomes the longitudinal state of a massive vector boson whose transverse states are the quanta of the transverse gauge field. A perturbative treatment of the model is developed in which the major features of these phenomena are present in zero order. Transition amplitudes for decay and scattering processes are evaluated in lowest order. It is shown that they may be obtained more directly from an equivalent Lagrangian in which the original symmetry is no longer manifest. When the system is coupled to other systems in a $U(1)$ invariant way, the other systems display an induced symmetry breakdown, associated with a partially conserved current which couples with itself via the massive vector boson.

I. INTRODUCTION

The idea that the apparently approximate nature of the internal symmetries of elementary-particle physics is the result of asymmetries in the stable solutions of exactly symmetric dynamical equations, rather than an indication of asymmetry in the dynamical equations themselves, is an attractive one. Within the framework of quantum field theory such a "spontaneous" breakdown of symmetry occurs if a Lagrangian, fully invariant under the internal symmetry group, has such a structure that the physical vacuum is a member of a set of (physically equivalent) states which transform according to a nontrivial representation of the group. This degeneracy of the vacuum permits nontrivial multiplets of scalar fields (which may be either fundamental dynamical variables or polynomials constructed from them) to have nonzero vacuum expectation values, whose appearance in Feynman diagrams leads to symmetry-breaking terms in propagators and vertices. That vacuum expectation values of scalar fields, or "vacuums," might play such a role in the breaking of symmetries was first noted by Schwinger and by Salam and Ward. Under the alternative name, "tadpole" diagrams, the graphs in which vacuums appear have been used by Coleman and Glashow to account for the observed pattern of deviations from $SU(3)$ symmetry.

The study of field theoretical models which display spontaneous breakdown of symmetry under an internal Lie group was initiated by Nambu, who had noticed that the BCS theory of superconductivity is of this type, and was continued by Glashow and others. All these authors encountered the difficulty that their theories predicted, rather allu, the existence of a number of massless scalar or pseudoscalar bosons, named "zeros" by Freund and Nambu. Since the models which they discussed, being inspired by the BCS theory, used an attractive interaction between massless fermions and antifermions as the mechanism of symmetry breakdown, it was at first unclear whether zeros occurred as a result of the approximations (including the usual cutoff for divergent integrals) involved in handling the models or whether they would still be there in an exact solution. Some authors, like Salam and Ward, did not include these approximations.

Symmetry Breaking in Non-Abelian Gauge Theories*

T. W. B. Kibble

Department of Physics, Imperial College, London, England

(Received 24 October 1966)

According to the Goldstone theorem, any manifestly covariant broken-symmetry theory must exhibit massless particles. However, it is known from previous work that such particles need not appear in a relativistic theory such as radiation-gauge electrodynamics, which lacks manifest covariance. Higgs has shown how the massless Goldstone particles may be eliminated from a theory with broken $U(1)$ symmetry by coupling in the electromagnetic field. The primary purpose of this paper is to discuss the analogous problem for the case of broken non-Abelian gauge symmetries. In particular, a model is exhibited which shows how the number of massless particles in a theory of this type is determined, and the possibility of having a broken non-Abelian gauge symmetry with no massless particles whatever is established. A secondary purpose is to investigate the relationship between the radiation-gauge and Lorentz-gauge formalisms. The Abelian-gauge case is reexamined, in order to show that, contrary to some previous assertions, the Lorentz-gauge formalism, properly handled, is perfectly consistent, and leads to physical conclusions identical with those reached using the radiation gauge.

V. A SIMPLE MODEL

As an illustration of the discussion in the preceding section, we shall consider here a simple model of broken $U(2)$ symmetry in which no massless particles remain.

The model contains a complex three-component field $\phi=(\phi_i)$ and four vector fields $A_\mu$ and $A^{\mu}=(A^{\mu}_i)$. It is
Weinberg: A Model of Leptons

- Electroweak sector of the Standard Model
- SU(2) x U(1)
- Mixing of Z, photon
- Neutral currents
- Higgs-lepton couplings
- No quarks
Higgs Boson Couplings

\[ \Gamma(H \rightarrow f \bar{f}) = N_c \frac{G_F M_H}{4\pi\sqrt{2}} m_f^2, \quad N_C = 3 \text{ (1) for quarks (leptons)} \]

\[ \Gamma(H \rightarrow VV) = \frac{G_F M_H^3}{8\pi\sqrt{2}} F(r) \left( \frac{1}{2} \right)_Z, \quad r = \frac{M_V}{M_H} \]

Weinberg 1967
Higgs 1966
Summary of the Standard Model

- Particles and SU(3) × SU(2) × U(1) quantum numbers:

<table>
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<tr>
<th></th>
<th>$L_L$</th>
<th>$E_R$</th>
<th>$(\nu_e, e^-)<em>L$, $(\nu</em>\mu, \mu^-)<em>L$, $(\nu</em>\tau, \tau^-)_L$</th>
<th>$(1,2,-1)$</th>
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</thead>
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<td>$(3,2,1/3)$</td>
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<tr>
<td></td>
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<td>$D_R$</td>
<td>$u_L$, $c_L$, $t_L$, $e_L$, $\mu_L$, $\tau_L$</td>
<td>$(3,1,4/3)$</td>
</tr>
</tbody>
</table>

Ignored for several years

- Lagrangian:

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu}^a F^{\alpha \mu\nu} + i \bar{\psi} /D\psi + h.c. + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

gauge interactions, matter fermions, Yukawa interactions, Higgs potential

No direct evidence until 2012

High-precision tests at LEP, …
Gauge Theories taken Seriously

1971/2

- 't Hooft and Veltman: renormalizable

1973

- Kobayashi and Maskawa show how to include CP violation in the Standard Model

1973

- Neutral currents in Gargamelle

1974

- J/Ψ discovered

1975/6

- Tau lepton and charmed particles discovered
A Phenomenological Profile of the Higgs Boson

- First attempt at systematic survey

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPoulos **
CERN, Geneva
Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson $H$ expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of $H$, we should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons, we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.
A Phenomenological Profile of the Higgs Boson

- Previous mass limit ~ 15 MeV
- Decay into photons via loop diagrams
- Production in association with Z boson
Next Steps in Phenomenology

Volume 40, Number 11

Physical Review Letters
13 March 1978

Higgs Bosons from Two-Gluon Annihilation in Proton-Proton Collisions

H. M. Georgi, S. L. Glashow, M. E. Machacek, and D. V. Nanopoulos
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 27 December 1977)

We estimate the cross section for Higgs-boson production in proton-proton collisions. We find that most of the cross section comes from a two-gluon annihilation process, in which the gluons couple to Higgs bosons via heavy-quark loops.

Physical Review D
Volume 18, Number 5
1 September 1978

Associated production of Higgs bosons and Z particles

S. L. Glashow, D. V. Nanopoulos, and A. Yildiz
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 25 April 1978)

We estimate the cross section for Higgs-boson production via bremsstrahlung from intermediate vector bosons produced in \( pp \) and \( \bar{p}p \) collisions.
Prospects for LEP Searches

THE PRODUCTION AND DETECTION OF HIGGS PARTICLES AT LEP

ECFA/LEP Specialized Study Group 3 "Exotic Particles"

G. Barbiellini - INFN, Frascati and CERN
G. Bonneaud - Strasbourg and CERN
G. Coignet - LAPP, Annecy-le-Vieux
J. Ellis - CERN
M. K. Gaillard - LAPP, Annecy-le-Vieux
J. F. Grivaz - LAL, Orsay
C. Matteuzzi - CERN
B. H. Wiik - DESY

Part of ECFA/LEP Study to develop physics case for LEP
1983

Discovery of the W and Z

How did they get so heavy?

• The top quark still undiscovered
• The search for the Higgs moved up the agenda
D. Production of Higgs Bosons

In the standard electroweak theory, a single neutral scalar particle remains as a vestige of the spontaneous breakdown of the \( SU(2)_L \otimes U(1)_Y \) gauge symmetry. As we have already noted in §I.B, the mass of this Higgs boson is not specified by the theory, but consistency arguments suggest (Linde, 1976; Weinberg, 1976a; Veltman, 1977; Lee, Quigg, and Thacker, 1977)

\[
7 \text{ GeV/c}^2 < M_H \leq 1 \text{ TeV/c}^2.
\]

(4.80)

The interactions of the Higgs boson are of course prescribed by the gauge symmetry. It is therefore straightforward to write down the partial widths for kinematically-allowed decays. The partial width for decay into a fermion-antifermion pair is

\[
\Gamma(H \rightarrow f
ddot f') = \frac{G_F m_f^2 M_H N_c}{4 \pi \sqrt{2}} \left(1 - \frac{4 m_f^2}{M_H^2}\right)^{3/2},
\]

(4.81)

where \( N_c \) is the number of fermion colors. For \( M_H \leq M_W \), the preferred decay of the Higgs boson is into the heaviest accessible pair of quarks or leptons.
Supercollider Phenomenology

\[ \sigma_{p^+p^- \rightarrow H + \text{anything}} \]

\[ \sqrt{s} = 40 \text{ TeV} \]

\[ gg \text{ fusion} \]

\[ m_b = 70 \text{ GeV/c}^2 \]
A Preview of the Higgs Boson @ LHC

- Presented at LHC Lausanne workshop 1984
Prospects for LEP Searches

PHYSICS AT LEP

Edited by
John Ellis and Roberto Peccei

NEW PARTICLES

H. Baer, J. Berdugo, F. Bianchi, F. Carminati, Y. Chang, M. Chen,
C. Dionisi, J. Ellis, F. Folegati, M. Martinez, C. Matteuzzi, F. Mättig,
G. Mikhenberg, S. Ritz, P. Sorba, X. Tata, W. Venev, H.-G. Wu,
Sau Lan Wu, A. Yajid, G. Tekutzieli and G. Toberniq

CONTENTS

1. General introduction and formulae
2. Higgs bosons
   2.1 Introduction and organization
   2.2 Minimal Higgs mechanism in the Standard Model
   2.3 Decay modes of the neutral Higgs $H^0$
   2.4 Higgs production processes
   2.5 Non-minimal Higgses in the Standard Model
   2.6 Technipion processes

GENEVA
1986
Previous searches and prospects in $e^+e^-$ collisions

Prospects at the SSC
The Higgs Hunter’s Guide

- Production at the LHC, SSC and Eloisatron (~FCC)
Estimating Masses with Electroweak Data

• High-precision electroweak measurements are sensitive to quantum corrections

\[ m_w^2 \sin^2 \theta_W = m_Z^2 \cos^2 \theta_W \sin^2 \theta_W = \frac{\pi \alpha}{\sqrt{2} G_F} (1 + \Delta r) \]

• Sensitivity to top mass is quadratic:

\[ \frac{3 G_F}{8 \pi^2 \sqrt{2}} m_t^2 \]

• Sensitivity to Higgs mass is logarithmic:

\[ \frac{\sqrt{2} G_F}{16 \pi^2} m_W^2 \left( \frac{11}{3} \ln \frac{M_H^2}{m_Z^2} + ... \right), M_H >> m_W \]

• Measurements at LEP et al. gave indications first on top mass, then on Higgs mass

\[ \Delta \rho = 0.0026 \frac{m_t^2}{m_Z^2} - 0.0015 \ln \left( \frac{M_H}{M_W} \right) \]
Estimating the BEH mass

- Early attempts

- Difficult before the discovery of the top quark
Higgs Mass in Supersymmetry

Pushed beyond reach of LEP2 by radiative corrections? Could be 125 GeV!
Combining Information from Previous Direct Searches and Indirect Data

\[ m_H = 125 \pm 10 \text{ GeV} \]
“... we do not want to encourage big experimental searches for the Higgs boson, but ...”

EGN 1975
Higgsdependence Day!
The Particle Higgsaw Puzzle

Did the LHC find the missing piece?
Is it the right shape? Does it have the right size?
LHC Measurements

Agree with the Standard Model

Higgs production

All results at: http://cern.ch/go/pNj7
It Walks and Quacks like a Higgs

- Do couplings scale ~ mass? With scale = v?
...to make an end is to make a beginning.
The end is where we start from.

T.S. Eliot, Little Gidding
Everything about Higgs is Puzzling

\[ \mathcal{L} = y H \bar{\psi} \psi + \mu^2 |H|^2 - \lambda |H|^4 - V_0 + \ldots \]

- Pattern of Yukawa couplings \( y \):
  - Flavour problem
- Magnitude of mass term \( \mu \):
  - Naturalness/hierarchy problem
- Magnitude of quartic coupling \( \lambda \):
  - Stability of electroweak vacuum
- Cosmological constant term \( V_0 \):
  - Dark energy

Higher-dimensional interactions?
Theoretical worries about the Higgs boson

Elementary Higgs or Composite?

- Higgs field: \( v = \langle 0 | H | 0 \rangle \neq 0 \)
- Quantum loop problems
- \( M_h, v, \) other masses have quadratic divergences

\[ m_h^2 \sim (200 \text{ GeV})^2 \]

Cutoff \( \Lambda = 10 \text{ TeV} \)

Cut-off \( \Lambda \sim 1 \text{ TeV} \) with Supersymmetry?

- Fermion-antifermion condensate?
- Just like \( \pi \) in QCD, Cooper pairs in BCS superconductivity
- Need new ‘technicolour’ force
  - Heavy scalar resonance?
  - (Problems with precision electroweak data)
  - Pseudo-Nambu-Goldstone boson?
Is “Empty Space” Unstable?

Depends on masses of Higgs boson and top quark, strong coupling

Instability scale \( \sim 10^{12} \) GeV

1979

Politzer & Wolfram, Hung, Cabibbo, Maiani, Parisi & Petronzio;

Buttazzo et al, arXiv:1307.3536; Franceschini et al, 2203.17197
Is “Empty Space” Unstable?

- Dependence of instability scale on masses of Higgs boson and top quark, and strong coupling:
  \[
  \log_{10} \frac{\Lambda}{\text{GeV}} = 10.5 - 1.3 \left( \frac{m_t}{\text{GeV}} - 172.6 \right) + 1.1 \left( \frac{m_H}{\text{GeV}} - 125.1 \right) + 0.6 \left( \frac{\alpha_s(m_Z) - 0.1179}{0.0009} \right)
  \]

- New CMS value of \(m_t\):
  \[
  m_t = 171.77 \pm 0.38 \text{GeV}
  \]

- Particle Data Group values:
  \[
  m_H = 125.25 \pm 0.17 \text{GeV}, \alpha_s(m_Z) = 0.1179 \pm 0.0009
  \]

- Instability scale:
  \[
  \log_{10} \frac{\Lambda}{\text{GeV}} = 11.7 \pm 0.8
  \]

- Dominant uncertainties those in \(\alpha_s\) and \(m_t\)
Will the Universe Collapse? Should it have Collapsed already?

Fluctuate over barrier in the early Universe? Tunnel through barrier now?

Quantum fluctuations

Not if infinite barrier: Supersymmetry?

We are here

The Big Crunch
Looking Beyond the Standard Model with Effective Field Theory?

“...the direct method may be used...but indirect methods will be needed in order to secure victory....”

“The direct and the indirect lead on to each other in turn. It is like moving in a circle....”

Who can exhaust the possibilities of their combination?”

Sun Tzu
Effective Field Theories (EFTs)  
a long and glorious History

• 1930’s: “Standard Model” of QED had d=4

• Fermi’s four-fermion theory of the weak force

• Dimension-6 operators: form = S, P, V, A, T?  
  – Due to exchanges of massive particles?

• V-A → massive vector bosons → gauge theory

• Yukawa’s meson theory of the strong N-N force  
  – Due to exchanges of mesons? → pions

• Chiral dynamics of pions: \((\partial \pi \partial \pi)\pi\pi\) clue → QCD
Standard Model Effective Field Theory
a more powerful way to analyze the data

- Assume the Standard Model Lagrangian is correct (quantum numbers of particles) but incomplete
- Look for additional interactions between SM particles due to exchanges of heavier particles
- Analyze Higgs data together with electroweak precision data and top data
- Most efficient way to extract largest amount of information from LHC and other experiments
- **Model-independent way to look for physics beyond the Standard Model (BSM)**
• Including 2- and 4-fermion operators
• Different colours for different data sectors
• Grey cells violate SU(3)^5 symmetry
• Important when including top observables

Anomalous magnetic moments

Flavour anomalies

Baryon decay

Global SMEFT Fit

to Top, Higgs, Diboson, Electroweak Data

• Global fit to dimension-6 operators using precision electroweak data, $W^+W^-$ at LEP, top, Higgs and diboson data from LHC Runs 1, 2

• Search for BSM

• Constraints on BSM
  • At tree level
  • At loop level

Dimension-6 Constraints with Flavour-Universal SU(3)$^5$ Symmetry

- Individual operator coefficients
- Marginalised over all other operator coefficients

High-precision measurement of the $W$ boson mass with the CDF II detector

CDF Collaboration, Science 376 (2022) p170
CDF Measurement of $m_W$ compared with previous measurements

- Tension: 7-$\sigma$ discrepancy with Standard Model?
Global SMEFT Fit to Top, Higgs, Diboson, Electroweak Data

- Global fit to dimension-6 operators using precision electroweak data, $W^+W^-$ at LEP, top, Higgs and diboson data from LHC Runs 1, 2
- Search for BSM
- Constraints on BSM
  - At tree level
  - At loop level

Positive contributions to $m_W$

SMEFT Operators that can Contribute to W Mass

- Relevant SMEFT operators

\[
\mathcal{O}_{H WB} = H^\dagger \tau I H W_{\mu \nu}^I B^{\mu \nu}, \quad \mathcal{O}_{HD} = \left( H^\dagger D^\mu H \right)^* \left( H^\dagger D_\mu H \right)
\]

\[
\mathcal{O}_{\ell \ell} = (\bar{\ell}_p \gamma_\mu \ell_r) (\bar{\ell}_s \gamma_\mu \ell_t), \quad \mathcal{O}^{(3)}_{H \ell} = \left( H^\dagger i \bar{D}_\mu^I H \right) (\bar{\ell}_p \tau^I \gamma_\mu \ell_r)
\]

- Three out of four involve the Higgs field!

- Contributions to W mass

\[
\frac{\delta m_W^2}{m_W^2} = -\frac{\sin 2\theta_w}{\cos 2\theta_w} \frac{\sin \theta_w}{4\Lambda^2} \left( \frac{\cos \theta_w}{\sin \theta_w} C_{HD} + \frac{\sin \theta_w}{\cos \theta_w} \left( 4C^{(3)}_{H\ell} - 2C_{ll} \right) + 4C_{H WB} \right)
\]

- Contributions to S and T oblique parameters

\[
\frac{v^2}{\Lambda^2} C_{H WB} = \frac{g_1 g_2}{16\pi} S, \quad \frac{v^2}{\Lambda^2} C_{HD} = -\frac{g_1 g_2}{2\pi (g_1^2 + g_2^2)} T
\]
SMEFT Fit with the Mass of the W Boson

Non-zero coefficients for any of four operators can fit W mass

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260
## Single-Field Extensions of the Standard Model

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<thead>
<tr>
<th>Name</th>
<th>Spin</th>
<th>SU(3)</th>
<th>SU(2)</th>
<th>U(1)</th>
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<th>Spin</th>
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# Single-Field Models that can Contribute to W Mass

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<th>$C_{H\Box}$</th>
<th>$C_{\tau H}$</th>
<th>$C_{t H}$</th>
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<td>$-y_{t \over 2}$</td>
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</table>

Operators contributing to $m_W$
68 and 95% CL ranges of masses assuming unit coupling
- Masses proportional to couplings
- Large masses consistent with SMEFT approximation

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260
Searching for Models Fitting the Mass of the W Boson

- $W$: Isotriplet vector boson, mass $\sim 3$ TeV x coupling, electroweak production, accessible at LHC?

- $B$: Singlet vector boson, mass $\sim 8$ TeV x coupling, phenomenology depends on fermion couplings, too heavy for LHC?

- $\Xi$: Isotriplet scalar boson, mass $\sim 3$ TeV x coupling, detectable in LHC searches for heavy Higgs bosons?

- $N$: Isosinglet neutral fermion, mass $\sim 4$ TeV x coupling, similar to (right-handed) singlet neutrino

- $E$: Isosinglet charged fermion, mass $\sim 6$ TeV x coupling, similar to (right-handed) singlet electron

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260
Higgstorical Summary

- Speculation
- Hypothesis
- Theory
- Search
- Discovery
- Building-block

\{ Repeat? \}