Unanswered Questions in the Electroweak Theory
(Before and After the Higgs-Boson Discovery)

Chris Quigg

Fermilab

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Benjamin Whisoh Lee (1935–1977)
link to publications
Sketch of the Electroweak Theory

Three crucial clues from experiment:

- Left-handed weak-isospin doublets,

\[
\begin{pmatrix}
  \nu_e \\
  e
\end{pmatrix}_L
\quad \begin{pmatrix}
  \nu_\mu \\
  \mu
\end{pmatrix}_L
\quad \begin{pmatrix}
  \nu_\tau \\
  \tau
\end{pmatrix}_L
\]

\[
\begin{pmatrix}
  u \\
  d'
\end{pmatrix}_L
\quad \begin{pmatrix}
  c \\
  s'
\end{pmatrix}_L
\quad \begin{pmatrix}
  t \\
  b'
\end{pmatrix}_L
\]

- Universal strength of the (charged-current) weak interactions;
- Idealization that neutrinos are massless.

First two clues suggest SU(2)_L gauge symmetry
Through 1950s and 1960s . . .

Continued interest in a Yang–Mills Theory of nuclear forces.

After $V - A$ description of weak interactions, interest in a gauge theory of weak interactions. Glashow explored $SU(2)_L \otimes U(1)_Y$

Two challenges: massive weak bosons, massive fermions.

Mass term $\mathcal{L}_e = -m_e (\bar{e}_R e_L + \bar{e}_L e_R) = -m_e \bar{e} e$ violates local gauge invariance.

Key insights: hidden symmetries, Meissner effect.

Brout, Englert, Higgs, Guralnik, Hagen, Kibble (1964)

Weinberg (1967) combined with $SU(2)_L \otimes U(1)_Y$
Electromagnetism is mediated by a massless photon, coupled to the electric charge;

Mediator of charged-current weak interaction acquires a mass
\[ M_W^2 = \frac{\pi \alpha}{G_F} \sqrt{2} \sin^2 \theta_W = \frac{g^2 v^2}{4}, \]

Mediator of (new!) neutral-current weak interaction acquires mass
\[ M_Z^2 = M_W^2 / \cos^2 \theta_W; \]

Massive neutral scalar particle, the Higgs boson, appears, but its mass is not predicted;

Fermions can acquire mass—values not predicted.
Something like a Higgs boson must exist

- Role in canceling high-energy divergences

\[ S \text{-matrix analysis of } e^+ e^- \rightarrow W^+ W^- \]

\[ (a) \quad (b) \quad (c) \quad (d) \]

\[ e^+ e^- \rightarrow W^+ W^- \]

\[ e^+ e^- \rightarrow W^+ W^- \]

Individual \( J = 1 \) partial-wave amplitudes \( \mathcal{M}_\gamma^{(1)}, \mathcal{M}_Z^{(1)}, \mathcal{M}_W^{(1)} \) have unacceptable high-energy behavior \( (\propto s) \)
... But sum is well-behaved

“Gauge cancellation” observed at LEP2 (Tevatron)
$J = 0$ amplitude exists because electrons have mass, and can be found in “wrong” helicity state

$$\mathcal{M}_\nu^{(0)} \propto s^{\frac{1}{2}} : \text{unacceptable HE behavior}$$

(no contributions from $\gamma$ and $Z$)

This divergence is canceled by the Higgs-boson contribution

$$\Rightarrow \text{He}\bar{e} \; \text{coupling must be } \propto m_e,$$

because “wrong-helicity” amplitudes $\propto m_e$

If the Higgs boson did not exist, something else would have to cure divergent behavior
If gauge symmetry were unbroken . . .

- no Higgs boson
- no longitudinal gauge bosons
- no extreme divergences
- no wrong-helicity amplitudes

. . . and no viable low-energy phenomenology

In spontaneously broken theory . . .

- gauge structure of couplings eliminates the most severe divergences
- lesser—but potentially fatal—divergence arises because the electron has mass
  . . . due to the Higgs mechanism
- SSB provides its own cure—the Higgs boson

Similar interplay & compensation *must exist* in any acceptable theory
The importance of the electroweak (1-TeV) scale

EW theory does not predict Higgs-boson mass

Thought experiment: conditional upper bound

\[ W^+ W^-, ZZ, HH, HZ \text{ satisfy } s\text{-wave unitarity, } \]

provided \[ M_H \lesssim (8\pi\sqrt{2}/3 G_F)^{1/2} \approx 1 \text{ TeV} \]

If bound is respected, perturbation theory is “everywhere” reliable

If not, weak interactions among \( W^\pm, Z, H \) become strong on 1-TeV scale

New phenomena (\( H \) or something else) are to be found around 1 TeV

\[ \Lambda_{\text{QCD}} \sim \text{scale of confinement, chiral symmetry breaking} \]
Before ATLAS and CMS, 
*Despite what is in the textbooks,*
we did not know what the answer would be!

LHC has changed our view of the world and opened many new questions
Questions for the LHC Experiments (2009)

Will the new physics that we anticipate on the 1-TeV scale be a Higgs boson, in some guise, or new strong dynamics?
If it is a Higgs boson, will there be one or several? Will it—or they—turn out to be elementary or composite?
Is the Higgs boson indeed light, as anticipated by the global fits to electroweak precision measurements?
Does the Higgs boson give mass only to the electroweak gauge bosons, or does it also endow the fermions with mass?
Proceeding step by step, does the $H$ couple to fermions (a large $t\bar{t}H$ coupling might be inferred from its production rate)?
Are the branching fractions for decays into fermion pairs in accord with the Standard Model?
Questions for the LHC Experiments (2009)\textsuperscript{bis}

Should we find that the Higgs boson is responsible for fermion mass, what determines the masses and mixings of the fermions?

The Higgs bosons could couple to particles beyond those in the Standard Model. Does the pattern of Higgs boson decays imply new physics?

Will unexpected or rare decays of the Higgs boson reveal new kinds of matter?

If more than one, apparently elementary, Higgs boson is found, will that be a sign for a supersymmetric generalization of the Standard Model, or for a different sort of two-Higgs-doublet model?

What stabilizes the Higgs boson mass below 1 TeV?

How can a light Higgs boson coexist with the absence of signals for new phenomena?
Questions for the LHC Experiments (2009)\textsuperscript{ter}

Is electroweak symmetry breaking an emergent phenomenon connected with strong dynamics?

Is electroweak symmetry breaking related to gravity through extra spacetime dimensions?

If the new physics observed on the TeV scale is suggestive of new strong dynamics, how can we diagnose the nature of the new dynamics? What takes the place of a Higgs boson?

CQ, “Unanswered Questions in the Electroweak Theory,” Ann. Rev. Nucl. Part. Sci. 59, 505-555 (2009)
What LHC has taught us about the Higgs Boson*

Evidence is developing as it would for a “standard-model” Higgs boson

Unstable neutral particle with $M_H = 125.25 \pm 0.17$ GeV [PDG22]

Decays to $W^+W^-$, $ZZ$ implicate $H$ as agent of EWSB

Decay to $\gamma\gamma$ as expected (loop-level) \quad Indirect constraint on $\Gamma_H$

Dominant spin-parity $J^P = 0^+$

$Ht\bar{t}$ coupling from $gg$ fusion, $t\bar{t}H$ production link to fermion mass origin

$\tau^+\tau^-$ and $b\bar{b}$ at expected rates

Third-generation fermion couplings established; $\mu^+\mu^-$ constrained

reconnaissance $\leadsto$ search-and-discovery $\leadsto$ forensic investigation

*ATLAS and CMS summaries in July 4, 2022, Nature

Chris Quigg

Unanswered Questions ...
What does (should) the Higgs boson (field) do?

Hide the electroweak symmetry: \( SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{\text{em}} \)

Endow \( W^\pm, Z^0 \) with mass: \( M_W^2 = g^2 v^2 / 4 = \pi \alpha / G_F \sqrt{2} \sin^2 \theta_W \)

while leaving \( \gamma \) (couples to electric charge) massless

Generate its own Higgs-scalar mass, value not predicted

Regulate high-energy behavior of EW boson scattering

Perturbative, if \( M_H \lesssim (8\pi \sqrt{2}/3G_F)^{1/2} \approx 1 \text{ TeV} \)

Give masses to quarks, charged leptons; values arbitrary?

\( m_f = \zeta_f v / \sqrt{2}, \quad v = (G_F \sqrt{2})^{-1/2} = 246 \text{ GeV} \)

Beyond standard EW theory: possible role in \( \nu \) masses?
Consequences for the everyday world

$1/M_W^4$ controls $\beta$-decay rates, energy production in Sun, etc.

No Higgs: QCD breaks EW symmetry to EM, $M_W \approx 28$ MeV

Role of Higgs boson established

Bohr radius $\propto 1/m_e$ controls size of atoms; $m_e$ sets scale of energy levels.

Role of Higgs boson not yet established

up/down quark mass difference determines proton/neutron stability

Role of Higgs boson not yet established

Quigg & Shrock, “Gedanken Worlds without Higgs . . .,” Phys. Rev. D 79, 096002 (2009)

Salam, Wang, & Zanderighi, “The Higgs boson turns ten,” Nature 607, 41–47 (2022).
Yukawa couplings (mass eigenstates) $\zeta_f$ from masses (L) or couplings (R)

Tini Veltman on masses and mixing angles:
“The Higgs boson knows something we don’t know!”
Questions about EWSB and the Higgs Sector

1. Is $H(125)$ the only member of its clan? Might there be others—charged or neutral—at higher or lower masses?

2. Does $H(125)$ fully account for electroweak symmetry breaking? Does it match standard-model branching fractions to gauge bosons? Are absolute couplings to $W$ and $Z$ as expected in the standard model?

3. Are all production rates as expected? Any surprise sources of $H(125)$?

4. What accounts for the immense range of fermion masses?

5. Is the Higgs field the only source of fermion masses? Are fermion couplings proportional to fermion masses? $\mu^+\mu^-$ soon?

How can we detect $H \rightarrow c\bar{c}$? $e^+e^-$?? (basis of chemistry)

6. What role does the Higgs field play in generating neutrino masses?
More questions about EWSB and the Higgs Sector

7. Can we establish or exclude decays to new particles? Does $H(125)$ act as a portal to hidden (dark/subliminal) sectors? When can we measure $\Gamma_H$ and compare with theory?

8. Do loop-induced decays ($gg, \gamma\gamma, \gamma Z$) occur at standard-model rates?

9. What can we learn from rare decays ($J/\psi \gamma, \Upsilon \gamma, \ldots$)?

10. Does the EW vacuum seem stable, or suggest a new physics scale?

11. Can we find signs of new strong dynamics or (partial) compositeness?

12. Can we establish the $HHH$ trilinear self-coupling?

13. How well can we test the notion that $H$ regulates Higgs–Goldstone scattering, i.e., tames the high-energy behavior of $WW$ scattering?

See Dawson, Englert, Plehn, arXiv:1808.01324 $\rightarrow$ Phys. Rep.
More new physics on the TeV scale and beyond?

Before LHC, much informed speculation—but no guarantees—about what might be found, beyond keys to EWSB.

Many eyes were on supersymmetry or Technicolor to enforce $M_W \ll$ unification scale or Planck scale.

“WIMP miracle” pointed to the TeV scale for a dark matter candidate.

Some imagined that neutrino mass might be set on the TeV scale.

No direct sign of physics beyond the standard model has come to light.

Might first hints come from precision measurements?
Conundrum of widely separated scales, interaction strengths

Unified theories of strong and electroweak interactions show how $SU(3)_c$, $SU(2)_L$, $U(1)_Y$ gauge couplings may be related, so account for different low-energy coupling strengths.

14 How does our accumulating knowledge of (spontaneous) electroweak symmetry breaking inform how $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ emerges from a unifying group?

15 Might we find indirect evidence for a new family of strongly interacting particles, such as those that are present in SUSY, by seeing a change in the evolution of $1/\alpha_s(Q^2)$?

16 What separates the electroweak scale from higher scales?

17 Why is gravity so weak?
Did existence of two once-and-done candidate solutions to the hierarchy problem (SUSY and technicolor) lead us to view the discipline of naturalness too simplistically?

5. BLUNDERs AND A BIZARRE EPISODE

In the early 1970s, I committed several blunders that deserve a brief mention. The blunders all occurred in the same article [27]: a 1971 article about the possibility of applying the renormalization group matching equations found between the discovery of asymptotic freedom. My first blunder was not recognizing that asymptotic freedom was possible. In my 1971 article, my intent was to identify all the distinct alternatives for the behavior of the Gell-Mann–Low function $\beta(g)$, which is negative for small $g$ in the case of asymptotic freedom. But I ignored this possibility. The only examples I knew of such beta functions were positive at small coupling. This fact led to me that gauge theories could have positive beta functions for small $g$. Fortunately, my blunder did not delay the discovery of asymptotic freedom to my knowledge. The articles of Gross and Wilczek [6] and Politzer [7] soon established that asymptotic freedom was possible, and ‘t Hooft had found a negative beta function for a non-Abelian gauge theory even earlier [2].

The second blunder concerns the possibility of limit cycles, discussed in sect. IIII of [27]. A limit cycle is an alternative to a fixed point. In the case of a three-body sector, but not for the physical values of the up and down quark masses. Instead these masses would have to be adjusted to place the neutron exactly at threshold for binding, and the di-neutron also [28].

The final blunder was a claim that scalar elementary particles were unlikely to occur in elementary particle physics at currently measurable energies unless they were associated with some kind of broken symmetry [23]. The claim was that, otherwise, their masses were likely to be far higher than could be detected. The claim was that it would be unnatural for such particles to have masses small enough to be detectable soon. But this claim makes no sense when one becomes familiar with the history of physics. There have been a number of cases where numbers arose that were unexpectedly small or large. An early example was the very large distance to the nearest star as compared to the distance to the Sun, as needed by Copernicus, because otherwise the nearest stars would have exhibited measurable parallax as the Earth moved around the Sun. Within elementary particle physics, one has unexpectedly large ratios of masses, such as the large ratio of the muon mass to the electron mass. There is also the riddle of dark energy in cosmology, with its implication of possibly unexpectedly small masses was discovered: the neutrino masses. There is also the very small value of the weak coupling constant. In the time since my paper was written, another set of unexpectedly small masses was discovered: the neutrino masses. There is also the riddle of dark energy in cosmology, with its implication of possibly unexpectedly small value for the cosmological constant in Einstein’s theory of general relativity.

This blunder was potentially more serious, if it
The Vacuum Energy Problem

Why is empty space so nearly massless?

Higgs field pervades the entire universe, contributes $\sim 10^8 \text{ GeV}^4$ to vacuum energy density

BUT

Observations (critical density) indicate $\lesssim 10^{-46} \text{ GeV}^4$

How do we interpret the mismatch by 54 orders of magnitude?
Flavor: the problem of identity

What makes an electron an electron, a top quark a top quark, . . . ?

We do not have a clear view of how to approach the diverse character of the constituents of matter

CKM paradigm: extraordinarily reliable framework in hadron sector

BUT—many parameters: no clue what determines them, nor at what energy scale they are set

Even if Higgs mechanism explains how masses and mixing angles arise, we do not know why they have the values we observe

Physics beyond the standard model!
Flavor: the problem of identity (continued)

Parameters of the Standard Model

| Count | Description                                      |
|-------|--------------------------------------------------|
| 3     | Coupling parameters, $\alpha_s$, $\alpha_{em}$, $\sin^2 \theta_W$ |
| 2     | Parameters of the Higgs potential                 |
| 1     | Vacuum phase (QCD)                                |
| 6     | Quark masses                                     |
| 3     | Quark mixing angles                              |
| 1     | CP-violating phase                               |
| 3     | Charged-lepton masses                            |
| 3     | Neutrino masses                                  |
| 3     | Leptonic mixing angles                           |
| 1     | Leptonic CP-violating phase (+ Majorana phases?)  |
| 26+   | Arbitrary parameters                             |

Will we see or diagnose a break in the SM?
Where are flavor-changing neutral currents in quark transitions? In the standard model, these are absent at tree level and highly suppressed by the Glashow–Iliopoulous–Maiani mechanism. They arise generically in proposals for physics beyond the standard model, and need to be controlled. And yet we have made no sightings! Why not?

Can we detect flavor-violating decays $H(125) \rightarrow \tau^\pm \mu^\mp$, $B_{s,d} \rightarrow \mu^+\mu^-$, $K^+ \rightarrow \pi^+\nu\bar{\nu}$, $\ldots$?
Questions concerning the problem of identity

Can we find evidence of right-handed charged-current interactions? Is nature built on a fundamentally asymmetrical plan, or are the right-handed weak interactions simply too feeble for us to have observed until now, reflecting an underlying hidden symmetry?

What is the relationship of left-handed and right-handed fermions?

Are there additional electroweak gauge bosons, beyond $W^\pm$ and $Z$?

Are there additional kinds of matter?

Is charged-current universality exact?

What about lepton-flavor universality?

Can we find evidence for charged-lepton flavor violation?
Have we found the “periodic table” of elementary particles?

Pointlike spin-1/2 constituents \((r < 10^{-18} \text{ m})\)

\[ \text{SU}(3)_c \otimes \text{SU}(2)_L \otimes \text{U}(1)_Y \rightarrow \text{SU}(3)_c \otimes \text{U}(1)_{\text{em}} \]

30. What do generations mean? Is there a family symmetry?
31. Why are there three families of quarks and leptons? (Is it so?)
32. Are there new species of quarks and leptons? exotic charges?
How to pursue our study of the Higgs sector?

Note spectacular advances in theory: breadth and precision!
Applying established theory, testing models, exploring effective field theories

- Exploit the Large Hadron Collider: Run 3 and High-Luminosity
- Construct and exploit an $e^+e^-$ Higgs factory:
  high luminosity (few ab$^{-1} \sim 10^{42}$ cm$^{-2}$) at $\sqrt{s} \approx 250$ GeV
  + $WW$ threshold and $Z^0$ pole
  Dawson, “The Case for Precision Higgs Physics,” Snowmass 2022
  Contenders: ILC, CLIC, FCC-ee, CEPC, CCC, HELEN
- A great leap in energy: $pp$ or possibly $\mu^+\mu^-$ collider
Where is the next important scale?

(Higher energies needed to measure $HHH$, verify that $H$ regulates $W_L W_L$)

Planck scale $\sim 1.2 \times 10^{19}$ GeV (3 + 1-d spacetime); $\sim 1.6 \times 10^{-35}$ m

Unification scale $\sim 10^{15–16}$ GeV

13. At what scale are charged-fermion masses set (Yukawa couplings)?
14. At what scale are neutrino masses set?
15. Will new physics appear at $1 \times, 10 \times, 100 \times, \ldots$ EW scale?
16. Might new phenomena appear at macroscopic scales?
Motivations for unified theories

Neutrality of atoms, balance of electron and proton charges

Quarks and leptons are spin-$\frac{1}{2}$ particles that come in matched sets as required by anomaly cancellation for a renormalizable $\text{SU}(2)_L \otimes \text{U}(1)_Y$ theory

$\text{SU}(3)_c \otimes \text{SU}(2)_L \otimes \text{U}(1)_Y$ couplings tend to converge at high scales

Historical impulse for amalgamation / unification
Questions about unified theories

37. What is the relationship of quarks to leptons?
38. Should we regard lepton number as the “fourth color?”
39. Are there new gauge interactions that link quarks with leptons?
40. What is the (grand) unifying symmetry?
41. What determines the low-energy gauge symmetries?
42. What are the steps to unification? One more, or multiple?
43. Is perturbation theory a reliable guide to coupling unification?
44. What sets the mass scale for the additional gauge bosons in a unified theory? ... for the additional Higgs bosons?
45. Is the proton unstable? How does it decay?
46. Is neutron–antineutron oscillation observable?
The Higgs Sector and Some Other Great Questions

Why is there more matter than antimatter in the universe?

Are there CP-violating Higgs decays?

Does $H$ self-coupling indicate a strong first-order EW phase transition in the early universe?

Are there multiple Higgs sectors?

What triggers inflation in the early universe?

Can we find any lessons from the EW phase transition, or any footprints of the Higgs boson(s)?
Au-delà du visible l’invisible, au-delà de l’invisible l’inconnu.

—Victor Hugo, Choses de l’infini (1864)