Beyond the Higgs Boson

further questions and expectations for the Large Hadron Collider

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Even if you are not a high-energy physicist, you probably did not miss the media frenzy over the discovery of the “Higgs-like-boson” on July 4, 2012. Here is the image of the lecture hall at CERN from the front page of the New York Times:
The discovery is “owned” by a multitude of experimental physicists, the 6,000 members of the ATLAS and CMS collaborations.
The discovery of the Higgs boson was a very impressive experimental achievement, but the existence of the Higgs was not a surprise.

The properties of this particle as they have been revealed by the experiments continue to obey the textbook predictions.

Yet, something is missing.

And that portends confusion, surprises, revolution!
What is the Higgs boson? Why is there a Higgs boson?

“the God Particle” - Leon Lederman

“The origin of all mass in the universe ...” ??
Why do we need a particle to give mass to other particles?

Doesn’t stuff just have mass?
In relativistic quantum theory, a massive particle is an assemblage of different pieces.

The pieces do not fit together unless the Higgs boson comes into play.
“spin 1/2”

“spin 1”

Wigner Bargmann
The weak interactions are known to couple preferentially to left-handed spinning leptons and quarks.
Electromagnetism couples to elementary particles through the derivate of the Schrodinger wavefunction

\[ \vec{\nabla} \Psi \rightarrow \vec{D} \Psi \]

where

\[ \vec{D} \Psi = (\vec{\nabla} - i \frac{e}{\hbar c} \vec{A}) \Psi \]

This allows a **local symmetry** of rotation of the phase of the Schrodinger wavefunction.

\[ \Psi \rightarrow e^{i \alpha(\vec{x})} \Psi \quad \vec{A} \rightarrow \vec{A} + \frac{\hbar c}{e} \vec{\nabla} \alpha(\vec{x}) \]
To have more interactions, we require a larger local symmetry and thus more $A$ fields.

In the 1960’s and 1970’s, this idea was used to build models of the strong and weak interactions.

Glashow, Salam, and Weinberg described the weak interactions by a theory with local symmetry $SU(2)\times U(1)$. 
Ingredients of this theory:

vector bosons:
\[ \tilde{A}, \tilde{W}^\pm, \tilde{Z}^0 \]

quarks and leptons:
\[ I = \frac{1}{2} : \begin{pmatrix} \nu \\ e^-_L \\ d^-_L \end{pmatrix} \begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad I = 0 : e^-_R, u_R, d_R \]

\[ W^\pm \text{ couples to } \ell_L, q_L \text{ only} \]

\[ Z^0 \text{ couples to } Q_Z = I^3 - \sin^2 \theta_w Q \]
Over the past 30 years, this theory has been subjected to many precise experimental tests, and no significant gap has been found. Now we call it “the Standard Model”.

In the 1990’s, experiments at CERN and SLAC verified the predictions of the Standard Model for the processes

$$e^+e^- \rightarrow Z^0 \rightarrow q\bar{q} \ , \ \ell^+\ell^-$$

to tenths-percent accuracy.
$e^+ e^- \rightarrow Z^0 \rightarrow e^+ e^-$
The specific charge assignments

\[ Q_Z = I^3 - \sin^2 \theta \, Q \]

are tested in the decays of the \( Z^0 \).
\[ \tau_L \rightarrow \text{slow } \pi^- \]

\[ \tau_R \rightarrow \text{fast } \pi^- \]
\[ e^+ e^- \rightarrow b\bar{b} \]
The mixing that we need to give mass to the electron or the quarks mixes states with different values of the Z charge.

There is also a problem in generating the large masses of the W and Z bosons.
This situation is often encountered in condensed-matter physics.

The energy spectra of two excitations are forbidden to mix by symmetry. But, energy is minimized if mixing can take place. This leads to spontaneous symmetry breaking.

This is the reason that we have organized states of matter in magnets, superconductors and superfluids, liquid crystals, ...
\[ E = pc \]

\[ E = \sqrt{(pc)^2 + (mc^2)^2} \]
Spontaneous symmetry breaking can give the photon mass. Here are the equations:

\[ \mathcal{L} = -\frac{1}{4}(F_{\mu\nu})^2 + |D_\mu \varphi|^2 - V(|\varphi|) \]

\[ D_\mu = \partial_\mu \varphi - igA_\mu \varphi \]

\[ \langle \varphi \rangle = \frac{v}{\sqrt{2}} \]

\[ \mathcal{L} \sim \frac{1}{2}m_A^2(A_\mu)^2 \quad \text{with} \quad m_A = gv \]
These equations are familiar from the Landau-Ginzburg theory of superconductivity.

\[ \lambda = \frac{\hbar}{m_A} \] is the length scale in the Meissner effect.
The field $\varphi$ supplies the needed third state of a massive photon at rest. This is a mixing of a matter excitation with the photon field.

In a superconductor, $\varphi$ is the field of Bose-condensed electron pairs.

Brout, Englert, Higgs, and others studied the theory of superconductivity and used it as the backbone of a general theory of vector boson masses.
The field responsible for the symmetry breaking of the W, Z interactions is a complete mystery. We give it a name -- the Higgs field -- but this does not make it less mysterious.

We would like to know:

**Does the Higgs field exist?**

**Why does this field have a spontaneously broken symmetry?**

**Does the Higgs field have partners, or even a Higgs spectroscopy?**
One way to prove that the Higgs field exists is to find its quantum excitation, the **Higgs boson**.

This particle has the property that it couples to each quark, lepton, and vector boson proportionally to the mass of that particle.

A **very heavy** Higgs boson would decay primarily into pairs of W and Z bosons.

This Higgs production and decay process has been searched for intensively, and excluded.
For a lighter Higgs, the dominant decays are to the heaviest available quark, the b quark, and the heaviest available lepton, the $\tau$ lepton.

$$h^0 \rightarrow b\bar{b}, \quad h^0 \rightarrow \tau^+\tau^-$$

Other higher-order processes compete with these, including

decay to off-shell W, Z

$$h^0 \rightarrow WW^*, \quad ZZ^*$$

decays through t, W loop diagrams

$$h^0 \rightarrow gg, \quad \gamma\gamma, \quad \gamma Z^0$$
Next, how can we produce the Higgs boson in high-energy collider experiments?

There is a problem. The Higgs couples strongly only to very massive particles

\[ W, \quad Z, \quad t \]

However, there is no technology for colliding these particles. In our experiments, all we have available to collide are light particles

\[ e, \quad u, \quad d, \quad g \]

To make the Higgs from these particles, we need very clever and exotic reactions.

This is primary reason that the Higgs boson has not been discovered long ago.
A possible strategy is to create very high energy proton-proton collisions.

Gluons in the wavefunction of the proton can react through the higher-order $ggh$ coupling to create the Higgs boson as a resonance.

The rate of this reaction is $2 \times 10^{-10}$ of the total rate for proton-proton collisions.
This brings us to the **Large Hadron Collider** at CERN, a proton-proton collider with in a tunnel of 27 km circumference. With 7 Tesla superconducting magnets, it is designed to achieve **14 TeV** in the center of mass.

So far, it has run as high as **8 TeV** in the center of mass.
the ATLAS experiment
arrival of a superconducting muon toroid at CERN

Paula Collins, CERN
A Compact Solenoidal Detector for LHC

- Total Weight: 14,500 t.
- Overall diameter: 14.60 m
- Overall length: 21.60 m
- Magnetic field: 4 Tesla

Components:
- Muon Chambers
- Inner Tracker
- Crystal ECAL
- Very Forward Calorimeter
- Superconducting Coil
- Return Yoke
- HCAL
Collision events at the LHC are impressive in their complexity. However, viewed carefully, they give amazing confirmations of the predictions of the Standard Model of particle physics.
ATLAS 6-jet event
ATLAS

$R=0.4, \int L \, dt=2.4 \, \text{pb}^{-1}$

Data ($\sqrt{s}=7 \, \text{TeV}) + \text{syst.}$

ALPGEN+HERWIG AUET1 $\times 1.11$

PYTHIA AMBT1 $\times 0.65$

ALPGEN+PYTHIA MC09' $\times 1.22$

SHERPA $\times 1.06$

Inclusive Jet Multiplicity

MC/Data

$0.5, 1, 1.5$
ZZ+4\mu candidate in 7 TeV collisions

primary Z mass : 89.18 GeV
p_T(\mu_1) = 61.60 GeV
p_T(\mu_2) = 25.68 GeV

secondary Z mass : 88.03 GeV
p_T(\mu_3) = 42.69 GeV
p_T(\mu_4) = 38.60 GeV

Run Number: 183602, Event Number: 282919
Date: 2011-06-18, 06:36:40 CET
\[ M c^2 = \sqrt{(E_+ + E_-)^2 - (\vec{p}_+ + \vec{p}_-)^2} c^2 \]
$pp \rightarrow ZZ \rightarrow e^+ e^- q\bar{q}$
Table of cross-sections:

- Single Lepton (8 TeV): 241 ± 32 pb
- Single Lepton (7 TeV): 179 ± 12 pb
- Dilepton: 173 ± 17 pb
- All-hadronic: 167 ± 81 pb
- Combined: 177 ± 11 pb
Observing the Higgs boson in the dominant decay channel $pp \rightarrow h \rightarrow b\bar{b}$ is very challenging. For example, QCD events that resemble this mode are $10^6$ times more numerous.

For Higgs discovery at the LHC, the best option was to use the rare decay modes

$$h \rightarrow \gamma\gamma \quad BR = 0.23\%$$

$$h \rightarrow ZZ^* \rightarrow 4 \text{ leptons} \quad BR = 0.16\%$$

In these channels, the Higgs boson appears as a peak in invariant mass. ATLAS and CMS have good resolution ($\Delta m \sim 2$ GeV).

These channels represent 1 in $2 \times 10^{12}$ pp collisions.
$m(4l) = 124.3 \text{ GeV}$

ATLAS candidate

$h^0 \rightarrow Z^0 Z^0 \rightarrow \mu^+ \mu^- e^+ e^-$
CMS candidate

$h^0 \rightarrow \gamma\gamma$
The CMS experiment reports data at two different center-of-mass energies: $\sqrt{s} = 7$ TeV with luminosity $L = 5.1$ fb$^{-1}$ and $\sqrt{s} = 8$ TeV with $L = 5.3$ fb$^{-1}$. The figure shows a plot of the ratio of signal-to-background weighted events per 1.5 GeV bin, $S/(S+B)$, as a function of the di-photon mass, $m_{\gamma\gamma}$, in GeV. The data points are shown with error bars, and the solid line represents the sum of signal and background fit (S+B Fit). The dashed line indicates the background fit component (B Fit Component). The inset graph illustrates the unweighted distribution of events per 1.5 GeV bin.
SM $H \rightarrow \gamma \gamma$ expected $p_0$  

ATLAS Preliminary

Observed $p_0$

Data 2011 $\sqrt{s} = 7$ TeV
\[ L_{\text{dt}} = 4.8 \text{ fb}^{-1} \]

Data 2012 $\sqrt{s} = 8$ TeV
\[ L_{\text{dt}} = 13.0 \text{ fb}^{-1} \]

$m_H$ [GeV]
VBF candidate event for $H \rightarrow \tau \tau \rightarrow \mu \tau_h$
The discovery of “a Higgs” only sharpens one of our earlier questions. Some energy principle must drive the mixing of states with different charges.

Why does this happen?

In condensed matter physics, there are many systems with spontaneously broken symmetry. Each has an interesting story: superconductivity, magnetism, charge density wave, ...

The vector bosons of the Standard Model are not strong enough to break its symmetry.

New interactions are needed.
The mass of the Higgs boson is relatively low:

\[ m_h = 125 \text{ GeV} \quad \langle \phi \rangle = 246 \text{ GeV} \]

and the Higgs is a prominent quantum excitation in the symmetry breaking sector. This would be unusual in a condensed matter system.

In condensed matter systems, it is easy to find the Goldstone modes (phonon, magnon) or vector boson modes (plasmon). The Higgs is the fluctuation of the condensate or order parameter (amplitude mode), and this is typically much harder to find.

In superconductivity, the amplitude mode appears experimentally only in special systems, e.g. NbSe\(_2\) near its CDW transition (Littlewood and Varma).
Two classes of models have been proposed to explain the light Higgs boson: In both cases, special structure is needed.

1. **The Higgs field is a fundamental field.** But there is a symmetry that forbids its mass term. For example, in Supersymmetry, \( \Delta H = m^2 |\varphi|^2 \) or \( \delta \varphi = \epsilon \cdot \tilde{\psi} \).

2. **The Higgs field is composite.** And, there is an approximation in which its mass is zero. For example, in Little Higgs, the Higgs fields are Goldstone bosons.

Traditionally, there is a third option: The Higgs field results from strong interactions (Technicolor), and the Higgs boson is heavy. This is now excluded.
To test these models, we need to find the new particles predicted by the theory.

In Supersymmetry, we are helped by a symmetry

\[ \varphi \rightarrow \varphi \quad \tilde{\psi} \rightarrow -\tilde{\psi} \]

and also

\[ q \rightarrow q \quad \tilde{q} \rightarrow -\tilde{q} \]

This keeps the lightest superparticle stable. If this particle is neutral (e.g. the partner of the photon), it can make up the dark matter of the universe.

Events with SUSY particle production thus include invisible particles, leading to unbalanced visible momentum.
CMS Experiment at LHC, CERN
Data recorded: Sat Aug 6 22:12:09 2011 CDT
Run/Event: 172822 / 2588491408
Lumi section: 2034
Missing momentum is a tricky variable to understand. If part of the detector is not working, we will observe spurious missing momentum.

It is thus necessary to carefully qualify each element of the hadron calorimeter, correcting for dead or hyperactive regions.
Beyond these, we come to “irreducible” sources of background to new particle production.

These are Standard Model reactions that produce the known heavy particles - $W, Z, t\bar{t}$ - plus extra jets from QCD radiation.

These reactions already offer missing energy, leptons, and multiple jets. The cross sections are still large compared to our signals:

$$W(\rightarrow \ell\nu) \quad 10 \text{ nb}$$
$$Z(\rightarrow \ell^+\ell^-) \quad 1 \text{ nb}$$
$$t\bar{t}(\rightarrow \ell\nu jjj) \quad 0.3 \text{ nb}$$

new particles $10^{-3}$ nb

7 TeV
W-ev candidate in 7 TeV collisions

- $p_T(e+) = 34 \text{ GeV}$
- $\eta(e+) = -0.42$
- $E_T^{\text{miss}} = 26 \text{ GeV}$
- $M_T = 57 \text{ GeV}$
CMS Experiment at LHC, CERN
Run 135149, Event 125426133
Lumi section: 1345
Sun May 09 2010, 05:24:09 CEST

Muon $p_T = 67.3, 50.6$ GeV/c
Inv. mass = 93.2 GeV/c$^2$
and remember

\[ BR(Z \rightarrow \nu \bar{\nu}) = 20\% \]
CMS $\geq 3$ Jets

$\int L \, dt = 35 \text{ pb}^{-1}, \sqrt{s} = 7 \text{ TeV}$

- Data
- Standard Model
- QCD Multijet
- $t\bar{t}, W, Z + \text{Jets}$
- LM0
- LM1
Standard Model

Heavy Particle

“razor”

data
ATLAS search for b jets + missing visible momentum
Squark-gluino-neutralino model, $m(\chi_1^0) = 195$ GeV

ATLAS

Combined
- Observed limit ($\pm 1\sigma_{\text{theory}}$)
- Expected limit ($\pm 1\sigma_{\text{exp}}$)

$\int L dt = 4.7$ fb$^{-1}$, $\sqrt{s} = 7$ TeV

$\sigma_{\text{SUSY}} = 1$ fb

$\sigma_{\text{SUSY}} = 10$ fb

$\sigma_{\text{SUSY}} = 100$ fb

PLB 710 (2012) 67-85, 1.04 fb$^{-1}$
In all, a very wide variety of signatures of new particles have been searched for, but no new particles -- beyond the Higgs -- have been found thus far.
What should we conclude?

There are three options to pursue:

1. There are new particles that drive the Higgs symmetry-breaking. But, they are too heavy to be seen at the 8 TeV LHC.

2. There are new particles with $M \sim \langle \varphi \rangle$. But, they are hidden from the LHC searches.

3. The simple Higgs field gives a complete model on its own.
Models in which the Higgs boson is approximately a Goldstone boson have a very high mass scale (10 TeV), but some particles in these theories must be lighter.

In the Standard Model, a large mass for the Higgs is generated by radiative corrections.

\[ \mu^2 = \mu^2_{\text{bare}} + \frac{\lambda}{8\pi^2} \Lambda^2 - \frac{3y_t^2}{8\pi^2} \Lambda^2 + \cdots \]

Some new particles must exist whose loops cancel these large terms. The masses predicted are 1 - 3 TeV.
search for $T \rightarrow W^+ b$

CMS

$\sqrt{s} = 8$ TeV

19.5 fb$^{-1}$

Opposite-sign dileptons

- Data
- Drell-Yan
- Single top quark
- $t\bar{t}$
- Uncertainty

$\min(M_{lb})$ [GeV]

Pull

Events/25 GeV
$\int L \, dt = 14.2 \, \text{fb}^{-1}$

- Data
- $5 \times Z'$ (1.5 TeV)
- $5 \times g_{kk}$ (2.0 TeV)
- $t\bar{t}$
- Multi-jets
- $W$+jets
- Other Backgrounds

$\sqrt{s} = 8$ TeV
$\sigma_{g_{KK}} \times \text{BR}(g_{KK} \rightarrow t\bar{t}) [\text{pb}]$

$\sqrt{s} = 8 \text{ TeV}$

$\int L \, dt = 14.3 \text{ fb}^{-1}$

- Obs. 95% CL upper limit
- Exp. 95% CL upper limit
- Exp. 1 $\sigma$ uncertainty
- Exp. 2 $\sigma$ uncertainty
- Kaluza-Klein gluon (LO)

**ATLAS** Preliminary
To answer these questions, we need much more data with higher energy collisions.

Starting in 2015, the LHC will run at an energy close to 14 TeV and accumulate roughly 20 times more data than at present.

A projected High Luminosity LHC will accumulate about 150 times more data than at present.

So, LHC will access new particles of the predicted masses. But, not yet.
In models of SUSY, the SUSY partner particles supply the needed cancellations in radiative corrections.

The masses of the Higgs partners and top quark partners must be relatively low. The masses of other particles in the SUSY spectrum are much less restricted.

Partners of the top quark are relatively more difficult to discover at the LHC. The production rates are lower, and the final states are more complex.

Partners of the Higgs bosons are almost impossible to observe above Standard Model backgrounds.
\sigma_{\text{tot}}[\text{pb}]: \text{pp} \rightarrow \text{SUSY}
In models of this type, the best target for discovery is the **gluino**, the partner of the gluon.

The gluino should lie below 3 TeV. We will get there at the High-Luminosity LHC.
There is a third attitude that one now hears from the “theoretical theory” community:

Earlier, I wrote the equation:

\[ \mu^2 = \mu_{\text{bare}}^2 + \frac{\lambda}{8\pi^2} \Lambda^2 - \frac{3y_t^2}{8\pi^2} \Lambda^2 + \cdots \]

In principle, the Standard Model could be a complete theory of particle physics. We only need to fix \( \mu^2 \) by delicate adjustment of the parameters of the theory. After this adjustment, the theory is finite and predictive.

There is no specific answer to the question of why \( \mu^2 < 0 \). Maybe it is an accident.
The sharpest picture of this type follows from ideas of Andrei Linde. In Linde’s view of inflationary cosmology, new inflating universes are constantly being born. Outside of our universe (say, 100 Gpc away), there are other universes, which might have different laws of physics. There is no problem in having $10^{100}$ of these. Maybe there is no explanation for the special value of $\mu^2$ in our universe, except chance.

Maybe the explanation is the anthropic principle: We live at a place in the multiverse where apes can live.
This is reminiscent of the great divide between physics and biology:

**Laplace:**

Nature is described by fundamental equations with a unique solution, leading to definite predictions and understanding.

**Darwin:**

Nature is described by random processes governed by simple general principles. Accidents of history determine the solution consistent with these principles.
Linde argues that physics explanations must eventually become Darwinian. But at what energy scale?

My opinion is that arguments of this type have never been helpful and sometimes, in the history of physics, have been seriously misleading. This is especially true when there are missing, undiscovered, pieces of the puzzle.

We must keep seeking “physics explanations”.
There is much that we do not know about the laws of nature, even at the hundred GeV energy scale.

In the next decade, we will explore further with the LHC and other probes of particle interactions. Our searches will access many models that are untested today.

My expectation is that the truth underlying the Higgs field will be found there.

If this proves so, we will see discoveries, beautiful measurements, and new laws of physics beyond our current horizon.