Finding the Higgs Boson

Wesley H. Smith

U. Wisconsin - Madison

CMS Experiment at the LHC, CERN
Data recorded: 2012-May-27 23:35:47.271030 GMT
Run/Event: 195099 / 137440354
Wisconsin People @ the Large Hadron Collider

Two experiments: CMS & ATLAS:

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Engineering Staff: Neng Xu, Werner Wiedenmann, Haimo Zobernig, John Joseph
### Structure of Matter

<table>
<thead>
<tr>
<th>Crystal Molecule</th>
<th>Atom</th>
<th>Atomic Nucleus</th>
<th>Elementary Particles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Hadrons</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mesons</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Baryons</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Proton Neutron</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Leptons</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Pointlike</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Quarks</td>
</tr>
</tbody>
</table>

- **Leptons**: $e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau$
- **Pointlike**
- **Quarks**: $u, c, d, s, b, (t)$

The ‘**Standard model**’ of particle physics has been brilliantly successful but important questions remain.

- LHC $10^{-19}$ cm
Since 1969, many other experiments have been conducted to determine the underlying structure of protons/neutrons. (~GeV)

All the experiments come to the same conclusion.

Protons and neutrons are composed of smaller constituents.

Protons
2 “up” quarks
1 “down” quark

Neutrons
1 “up” charge 2/3
2 “down” -1/3

Are there any other quarks other than UP and DOWN?
### Three Families of Quarks

<table>
<thead>
<tr>
<th>Generations</th>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-1/3</td>
<td>d (down)</td>
<td>s (strange)</td>
<td>b (bottom)</td>
</tr>
<tr>
<td>+2/3</td>
<td>u (up)</td>
<td>c (charm)</td>
<td>t (top)</td>
</tr>
</tbody>
</table>

- Note: fractionally charged particles!
- Increasing mass

Also, each quark has a corresponding antiquark \( \bar{u}, \bar{d}, \bar{s}, \cdots \)

The **antiquarks** have **opposite charge** to the quarks.

Many hadrons possible: 3 quarks baryons, 1 quark +1 antiquark mesons.
Leptons: Muon

The muon was discovered in cosmic ray experiments (1937).

It was also used in the experimental test of time dilation.

We find that a muon behaves almost identical to an electron, except its mass is about 200 times more than the electron’s mass.

\[ m = 0.51 \text{ MeV}/c^2 \quad \mu = 106 \text{ MeV}/c^2 \]

Also neutral leptons: neutrinos

Neither bind to form hadrons. Don’t feel strong force

Wesley Smith, U. Wisconsin, January 21, 2014
In 1975, researchers at the Stanford Linear Accelerator discovered a third charged lepton, with a mass about 3500 times that of the electron. It was named the $\tau$-lepton.

In 2000, first evidence of the $\tau$’s partner, the tau-neutrino ($\nu_\tau$) was announced at Fermi National Accelerator Lab.

<table>
<thead>
<tr>
<th>Family</th>
<th>Leptons</th>
<th>Anti-Lepton</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$Q = -1$</td>
<td>$Q = 0$</td>
</tr>
<tr>
<td>1</td>
<td>$e^-$</td>
<td>$\nu_e$</td>
</tr>
<tr>
<td>2</td>
<td>$\mu^-$</td>
<td>$\nu_\mu$</td>
</tr>
<tr>
<td>3</td>
<td>$\tau^-$</td>
<td>$\nu_\tau$</td>
</tr>
</tbody>
</table>

3 families, just like the quarks... interesting!!!
## The Forces

<table>
<thead>
<tr>
<th></th>
<th>EM</th>
<th>Weak</th>
<th>Strong</th>
<th>Gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Couples to:</strong></td>
<td>Particles with electric charge</td>
<td>Weak charge: quarks and leptons</td>
<td>Color charge: quarks</td>
<td>All particles with mass</td>
</tr>
<tr>
<td><strong>Example</strong></td>
<td>Attraction between protons and electrons</td>
<td>Nuclear beta decay and nuclear fission</td>
<td>Holds protons and neutrons together the nucleas</td>
<td>Only attractive</td>
</tr>
<tr>
<td><strong>Quanta: Force Carrier</strong></td>
<td>Photon</td>
<td>W and Z Boson</td>
<td>Gluon</td>
<td>Graviton</td>
</tr>
<tr>
<td><strong>Mass</strong></td>
<td>0</td>
<td>80 and 91 GeV</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Strength in an Atom</strong></td>
<td>$F = 2.3 \times 10^{-8} \text{N}$</td>
<td>Decays can take thousands of years</td>
<td>$F = 2.3 \times 10^2 \text{N}$</td>
<td>$F = 2.3 \times 10^{-47} \text{N}$</td>
</tr>
</tbody>
</table>
The Standard Model

What is the Standard Model?

• Explains the hundreds of common particles: atoms - protons, neutrons and electrons
• Explains the interactions between them

Basic building blocks

• 6 quarks: up, down…
• 6 leptons: electrons…
• Bosons: force carrier particles

All common matter particles are composites of the quarks and leptons and interact by exchange of the bosons
The ‘Standard Model’ (SM) describes how particles interact, how different particles behave, how the forces between particles are manifested.

However, the SM cannot be used to calculate or predict masses of ANY of fundamental particles – not of the electron, not of the muon, not of the quarks, not of the Z and W particles and so on ……

The Higgs field was proposed to “solve” this.

Nobel Prize in Physics October 2013
Origin of mass - the Higgs mechanism

Simplest theory – all particles are massless !!

A field pervades the universe

Particles interacting with this field acquire mass – the stronger the interaction the larger the mass

The field is a quantum field – the quantum is the Higgs boson

Finding the Higgs particle establishes the presence of the field
Which of these falls slower safely?

- An unopened parachute
- Fully opened parachute

The more interaction with the medium (air) the lower the speed of the drop.

Higgs field permeates all space, particles interact with differing strengths with the higgs field. The higher the interaction the larger the particle’s mass.

The simplest theory with higgs fields results in a new self-interacting particle: the Higgs boson, which itself has a mass – but, theory can’t predict its mass.
How the Higgs Mechanism Works

Einstein Analogy:

1. Numerous physicists chat quietly in a fairly crowded room.
2. Einstein enters the room causing a disturbance in the field.
3. Followers cluster and surround Einstein as this group of people forms a “massive object”.

Source: David Miller (University College London)
The Higgs Mechanism operates in a way similar to the case of Einstein in the crowded room.

Particles that normally would have mass (e.g. Fermions, weak force carriers) move through the Higgs field interacting with Higgs particles.

Through this interaction or disturbance particles may acquire mass. Heavier particles interact more with the Higgs field taking on more mass.

Those particles that normally do not have mass, do not interact with the Higgs field, and therefore do not acquire it.
LHC & the Big Bang

The Big Bang

LHC $10^{-10}$ seconds after start of Big Bang

A world rich with sub-atomic particles
At the instant of the Big Bang, the universe was comprised of particles of pure energy.

Milliseconds after the event, the universe cooled and the Higgs field developed.

Particles began to acquire mass as they cooled, slowed down and moved through the newly created Higgs field. Particles lost kinetic energy and gained mass (E=mc²).

Elementary particles developed and the Higgs field continued to permeate spacetime.

In unification theory, physicists look to the big bang for evidence of a single superforce. Each of the four fundamental forces is thought of as a manifestation of a single force at low energies.

Particle accelerators attempt to recreate the original conditions of the Big Bang.
Finding the Higgs Requires……

1. **Accelerators:** powerful machines capable of accelerating particles to extremely high energies and bring them into collision with other particles.

2. **Detectors:** gigantic instruments that record the particles as they “stream” out from the point of collision.

3. **Computers:** to collect, store, distribute and analyse the vast amount of data produced by the detectors.

4. **People:** Only a worldwide collaboration of thousands of scientists, engineers, technicians & support staff can design, build and operate such complex “machines.”
Particle Accelerators

accelerate particles to high energies.

The higher energies allow us

i) To look deeper into matter \( (E \propto \frac{1}{\text{size}}) \),
   ("powerful microscopes")

ii) To discover new heavier particles \( (E = mc^2) \)

iii) To probe conditions of early universe \( (E = kT) \)

Revisit the earlier moments of our ancestral universe
   ("powerful telescopes"),
   to observe phenomena and particles normally no longer
   visible or existing in our time.

All in a controlled way in the laboratory
The CERN & LHC Complex

7 years of construction to replace LEP: 1989-2000

in the same 26.7 km tunnel by LHC: 2008-2020+
The Particle Accelerator

Overall view of the LHC experiments.

- 100 m below the surface
- 27 km in circumference
The Environment: Collisions at LHC

2012/3: 4 TeV ⇒ 7 TeV Proton Proton colliding beams

7x10^{12} \text{ eV} \hspace{1cm} \text{Beam Energy}
10^{34} \text{ cm}^{-2} \text{ s}^{-1} \hspace{1cm} \text{Luminosity}
2835 \hspace{1cm} \text{Bunches/Beam}
10^{11} \hspace{1cm} \text{Protons/Bunch}

One per day?
Raw $\Sigma E_T \sim 2$ TeV

14 jets with $E_T > 40$ GeV

Estimated PU $\sim 50$
Compact Muon Solenoid

12500 tons
As much iron as the Eiffel Tower!

CMS
2930 Scientists
184 Institutions

Barrel rings each 1300 tons
Endcap disks

Note the person!
Compact Muon Solenoid

- Muon chambers
- Iron flux return
- Solenoid
- Hadron Calorimeter
- Electromagnetic Calorimeter
- Silicon Tracker

The barrel section of CMS completed
ATLAS Detector Design

Muon Spectrometer
air-core toroids with muon chambers

Calorimetry

Tracking
To select and record signals from the 400 million proton collisions per second & measure particles traces with high precision

100 million electronic channels to track hundreds of particles per event and reconstruct their trajectories with ~10 $\mu$m precision
Travelling at 99.999999% the speed of light, carrying 8000 GeV of energy each.

The energy allows them to overcome their mutual electromagnetic repulsion and allows their quarks and gluons to interact via the strong nuclear force.
Quarks of different protons begin to feel each other through gluons because they are so close!
The newly formed gluon is under high tension now!

And so may be the other gluons since the whole proton received a tremendous shock.
Top quarks are quite heavy and hence couple strongly to the Higgs boson.

Here they could “radiate” a real Higgs boson!

Gluons snap forming quark–antiquark pairs!

Protons fragment into sprays of newly formed hadronic debris. Don’t interest us usually.

The stretched gluon snaps into a top & antitop quark pair of virtual particles!
Muons and anti-muons are long-lived particles that can be directly observed with our detectors.
Higgs discovery channel #1

H → two photons

**ATLAS**

Data S/B Weighted

- Sig+Bkg Fit ($m_H=126.5$ GeV)
- Bkg (4th order polynomial)

- $s=7$ TeV, $\int dt=4.8 fb^{-1}$
- $s=8$ TeV, $\int dt=5.9 fb^{-1}$

**H → $\gamma\gamma$**

**Mass = 126.5 GeV**

(1 GeV = $10^9$ eV)

$$M_{\gamma\gamma}^2 = 2E_{\gamma_1}E_{\gamma_2}(1 - \cos \theta)$$

$\theta$ is the angle between the pair
Higgs discovery channel #1

H → two photons

CMS Preliminary

<table>
<thead>
<tr>
<th>s</th>
<th>L</th>
<th>Data</th>
<th>Fit</th>
<th>Bkg Fit Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV</td>
<td>5.1 fb⁻¹</td>
<td>S/B Weighted Data</td>
<td>S+B Fit</td>
<td>Bkg Fit Component</td>
</tr>
<tr>
<td>8 TeV</td>
<td>5.3 fb⁻¹</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mass = 125 GeV
(1 GeV = 10⁹ eV)
Higgs discovery channel #2: $H \rightarrow 4$ leptons

Mass = 125 GeV

$m_{4\mu} = 125.1$ GeV
Higgs discovery channel #2: $H \rightarrow 4$ leptons

4-lepton Mass: 126.9 GeV

- $\mu^+(Z_1) p_T : 43$ GeV
- $e^-(Z_2) p_T : 10$ GeV
- $\mu^-(Z_1) p_T : 24$ GeV
- $e^+(Z_2) p_T : 21$ GeV

8 TeV DATA

Events / 3 GeV

CMS Preliminary

$\sqrt{s} = 7$ TeV, $L = 5.05$ fb$^{-1}$; $\sqrt{s} = 8$ TeV, $L = 5.26$ fb$^{-1}$
Combining the results of the two discovery channels $H \to 2$ photons and $H \to$ four leptons (2011+2012 datasets):

(plus 2011 data from less strong channels $H \to WW$, $H \to \tau \tau$, $H \to bb$)

The chances that the events observed were due to random fluctuations are less than one in three million – corresponding to the stringent “five sigma” gold standard particle physicists insist on to claim a discovery.

$p_0$: probability that the background fluctuates to the observed data (or higher)

$p_0(5\sigma) = 2.87 \times 10^{-7}$
CMS also looked at other SM channels:

- W-boson pair
- b-quark pair
- τ-lepton pair

No strong evidence in these less sensitive modes.
Indirect constraints from other SM measurements indicate that the higgs should be where we found this new particle!

\[ M_H = 125 \text{ GeV} \]
CMS ZZ → e⁺e⁻μ⁻μ⁻ candidate
CMS: $\mathbf{H \rightarrow ZZ^* \rightarrow 4l}$

Peak around 125 GeV is filling in nicely.

Significance = $4.6\,\sigma$
CMS Combination of Higgs Results

Observed: 6.9σ expected: 7.8σ  [ signal strength: 0.88 ± 0.21 ]
CMS Combination of Higgs Results

Mass and production strength

\[ m_X = 125.8 \pm 0.4 \text{(stat)} \pm 0.4 \text{ (syst)} \text{ GeV} \]

- Signal strengths consistent with each other and with SM

Couplings consistent

- Also effective gluon versus photon couplings (loops)
Including 13 fb$^{-1}$ 8 TeV data

- 3.3 $\sigma$ expected local significance
- 6.1 $\sigma$ Observed

\[ m_H = 126.6 \pm 0.3 \text{ (stat)} \pm 0.7 \text{ (syst)} \text{ GeV} \]

\[ \hat{\mu} = 1.8 \pm 0.3 \text{ (stat)}^{+0.29}_{-0.21} \text{ (syst)} \]
ATLAS Updates: ZZ*

Including 13 fb$^{-1}$ 8 TeV data

- 3.1 $\sigma$ expected local significance
- 4.1 $\sigma$ Observed

$m_H = 123.5 \pm 0.9 \ (\text{stat}) ^{+0.4}_{-0.2} \ (\text{syst}) \ \text{GeV}$

$\hat{\mu} = 1.3 \pm 0.4$
$H\rightarrow \gamma\gamma$ and $H\rightarrow 4l$ combination

Best fit signal strength $\hat{\mu} = 1.5^{+0.33}_{-0.29}$

Combined Mass Measurement:

$$m_H = 125.2 \pm 0.3 \text{ (stat)} \pm 0.6 \text{ (syst)} \text{ GeV}$$
Further investigations: The Problems of Standard Model

Higgs self energy corrections

- Higgs couples to itself
- However, this coupling becomes infinite!
- Contributions to this from fermions (leptons and quarks) and vector bosons (W, Z) come with opposite sign
- SM particles can mitigate to about 1 TeV energy scale
- However, new physics should show up at ≈ few TeV

Super-symmetry

- What if there are equal number of fermions and bosons in the real theory at high masses (~few TeV)?
  - Many new fundamental scalar and fermionic fields ⇒ must be massive to fit observations
- But, this could solve the problem of higgs divergences 😊
Supersymmetry

A new physics theory which doubles known particles again – but the new particles have very large mass

LHC may be able to produce them

Dark matter candidates

Quarks
Leptons
Force particles

Squarks
Sleptons
SUSY force particles
Outstanding Mysteries – Dark Matter

The Bullet Cluster (1E 0657-56). Two galaxies colliding. Red shows concentration of visible matter. Blue shows dark matter inferred by gravitational lensing.

What is dark matter composed of?

• *Supersymmetric* particles perhaps? The lightest supersymmetric particle predicted by theory has all the right properties!
Don’t know what Dark Matter is
Don’t know what Dark Energy is
but SOMETHING is accelerating the expansion of our Universe

Supersymmetry?
The ‘Neutralino’ particle?
A new force field particle, like the Higgs,
Summary

LHC discovered the Higgs

- Both ATLAS & CMS see and have further confirmed that they observe the Higgs Boson

Is it the Standard Model Higgs Boson?

- It is a boson – because it decays to bosons
- Its mass is in the right window – consistency with SM
- Other properties look like the SM Higgs Boson
- However, its properties are yet to be fully determined to confirm that it is the SM Higgs Boson

There are many mysteries remaining

- The LHC will increase its energy from 8 to > 13 TeV and its luminosity by up to a factor of 10 over the next decade
- Next run in 2015: Much to explore!