The Discovery of the Higgs boson
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Physics 301: Physics Today
The Periodic Table: The early 20\textsuperscript{th} century understanding of the atom

Different types of quantum orbits

Elements in same column have similar chemical properties

Based on a Quantum Mechanical solution of an atom held together by electromagnetic forces
How could the nucleus exist?

- Positive protons all bound together in the atomic nucleus

One type of atom could convert itself into another type of atom

- Nuclear beta decay
- Charge of atom changed and an electron was emitted

Needed a new theory
Best way to think about the problem was from the viewpoints of the forces.

Needed two new forces and at first glance they were not very similar to the familiar electromagnetic and gravitational forces!

### The Forces

<table>
<thead>
<tr>
<th></th>
<th>EM</th>
<th>Weak</th>
<th>Strong</th>
<th>Gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Couples to:</td>
<td>Particles with electric charge</td>
<td>Protons, Neutrons and electrons</td>
<td>Protons and Neutrons</td>
<td>All particles with mass</td>
</tr>
<tr>
<td>Example</td>
<td>Attraction between protons and electrons</td>
<td>Nuclear beta decay Not an attractive force</td>
<td>Attraction between protons and neutrons</td>
<td>Only attractive</td>
</tr>
<tr>
<td>Strength in an Atom</td>
<td>$F = 2.3 \times 10^{-8}N$</td>
<td>Decays can take thousands of years</td>
<td>$F = 2.3 \times 10^{2}N$</td>
<td>$F = 2.3 \times 10^{-47}N$</td>
</tr>
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How do we understand the Forces? Why so different in properties?
A New Theory

- Relativistic quantum field theory (QFT):
  - Unification of special relativity (the theory of space-time) and quantum mechanics (used to understand the atom)
  - Forces described by exchanging particles
  - Electromagnetic force comes about from exchange of photons.

Example: Electromagnetic repulsion via emission of a photon

Exchange of many photons allows for a smooth force (EM field)
Mass of the photon is 0, mass of the W and Z bosons is large

When the mass of the W boson is large compared to the momentum transfer, $q$, the probability of a weak interaction is low compared to the EM interaction! Too low to form a field and bound states.

At high energy when $q$ was much larger than the mass of the weak bosons the the weak and EM interaction have the same strength

The key missing element is to explain the mass of the W and Z bosons
Maxwell had unified electricity and magnetism

- Both governed by the same equations with the strengths of the forces quantified using a set of constants related by the speed of light

The Standard Model of Particle Physics (proposed 1960)

- QFTs for EM, Weak and Strong
- Unified EM and Weak forces - obey a unified set of rules with strengths quantified by single set of constants
- All three forces appear to have approximately the same strength at very high energies. May also unify.

A very successful theory

A Key component was missing to fully understand EM-Weak Unification
# The Forces Revisited

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<td>Couples to:</td>
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<td>Weak charge: quarks and electrons</td>
<td>Color charge: quarks</td>
<td>All particles with mass</td>
</tr>
<tr>
<td>Example</td>
<td>Attraction between protons and electrons</td>
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<td>Attraction between quarks/nucleons</td>
<td>Only attractive</td>
</tr>
<tr>
<td>Quanta: Force Carrier</td>
<td>Photon</td>
<td>W and Z Boson</td>
<td>Gluon</td>
<td>Graviton</td>
</tr>
<tr>
<td>Mass</td>
<td>0</td>
<td>80 and 91 GeV</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Decay time/Strength in an Atom</td>
<td>Decay time: $10^{-18}$ sec $F = 2.3 \times 10^{-8}N$</td>
<td>Decay time: $10^{-12}$ sec to thousands of years</td>
<td>Decay time: $10^{-23}$ sec $F = 2.3 \times 10^2N$</td>
<td>$F = 2.3 \times 10^{-47}N$</td>
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The SM Higgs Boson

SM postulates a mechanism of electroweak symmetry breaking via the Higgs mechanism (proposed 1964)

- Interaction with the Higgs field results in masses for the W and Z vector bosons
- A primary reason for the difference EM and Weak interactions
- Fills in the key missing element of the SM
- Can explain the mass of the fermions (quarks and leptons) as well
- Also expect an observable quanta of the field: Higgs boson

→ directly testable by searching for the Higgs boson!

The primary goal of the LHC Run 1
How do we search for the Higgs Boson?

In the SM particles that carry the charge of a given force can interact by absorbing or emitting the force carrier.

Also they can annihilate or pair produce.

The diagrams (Feynman diagrams) can be converted into equations to calculate the probability of the process occurring.
Searching for the Higgs

The “charge” that the Higgs boson interacts with is mass

- Particles with high mass will interact with higher probability with a Higgs boson
- W and Z bosons: 80 and 91 GeV - mass of a krypton atom
- The top quark: 172.6 GeV - mass of a gold atom

However, the LHC collides protons made of quarks and gluon

- Some thought needed to understand the best way to make Higgs bosons
Searching for the Higgs

- Also look for decay to massive particles
Searching for the Higgs

Those decays should be to particles that are easy to detect: i.e. uniquely identify and measure the momentum of...
LHC collision rates (Run 1)
- LHC collided protons every 50 ps
- 20 proton-proton interactions each time

Probability of a Higgs interaction
- 11 orders of magnitude less.
- 1/100000000000 collisions produces a Higgs boson
- ~1 Higgs every 10 minutes
- 100-1000 less, easily detected Higgs
Plan of action

- Calculate the probability of Higgs production and decay expected in proton-proton collisions
  - A decade of work by dozens of theorists
- Build a collider to collide the protons at high energy and high enough rate
  - A decade of work by hundreds of collider physicists
- Build experiments that can detect the Higgs boson
  - A decade of work by thousands of experimental physicists
- Apply our best ideas to achieve the above
- All built on decades of experience from previous experiments.
SM Higgs Production and Decay

- Take advantage of large $gg \rightarrow H$ production cross section
  - Had to calculate as a function of mass as Higgs mass was not predicted
- Alternative production mechanisms
  - Primarily VBF: $qq \rightarrow Hqq$
- Decay modes: $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$, Sensitive since they are well reconstructed
The Large Hadron Collider

- 14 TeV proton-proton collider (now 8 TeV)
- 27 Km tunnel 100m underground
- $10^9$ collisions/second
The CMS Detector

Detector designed to measure all the SM particles

- Tracker
- Electromagnetic Calorimeter
- Hadronic Calorimeter
- Solenoid
- Muon System
Particle Detection in CMS

Key:
- Blue: Muon
- Red: Electron
- Green: Charged Hadron (e.g., Pion)
- Gray: Neutral Hadron (e.g., Neutron)
- Green dashed: Photon

- Silicon Tracker
- Electromagnetic Calorimeter
- Hadron Calorimeter
- Superconducting Solenoid

Transverse slice through CMS

Iron return yoke interspersed with Muon chambers
LHC Collision

CMS Experiment at the LHC, CERN

Data recorded: 2010 Jul 09 02:25:58.839511 GMT(04:25:58 CEST)
Run / Event: 139779 / 4994190
As of 2012 the Higgs boson not yet been found but the mass was constrained to the range $m_H: 115-130$ GeV.

Plot shows convolution of production, decay and detector capabilities.

Strong sensitivity to 5 decay modes led by $\gamma\gamma$ and ZZ.

(below 1 means sensitivity to SM Higgs production)
Multiboson Physics

Some preparation: Other SM processes with decays to bosons.
Once you have your best calculations, collider, detector and have applied all your ideas the final analysis in essence consists of looking for events with two photons or two Z bosons where the combined mass of the two bosons adds up to a consistent mass.
LHC Higgs Event: $\gamma\gamma$
LHC Higgs Event: ZZ → μμee

CMS Experiment at the LHC, CERN
Data recorded: 2012-May-27 23:35:47.271930 GMT
Run/Event: 195099 / 137440354
Higgs Searches

CMS Preliminary

\[ \sqrt{s} = 7 \text{ TeV}, L = 5.1 \text{ fb}^{-1} \]
\[ \sqrt{s} = 8 \text{ TeV}, L = 5.3 \text{ fb}^{-1} \]

\[ m_{\gamma\gamma} (\text{GeV}) \]

\[ \text{S/B Weighted Data} \]
\[ \text{S+B Fit} \]
\[ \text{Bkg Fit Component} \]
\[ \pm 1 \sigma \]
\[ \pm 2 \sigma \]

\[ \gamma\gamma: 4.0\sigma \]

\[ \text{ZZ} 3.2\sigma \]

CMS Preliminary \[ \sqrt{s} = 7 \text{ TeV}, L = 5.05 \text{ fb}^{-1} \]
\[ \sqrt{s} = 8 \text{ TeV}, L = 5.26 \text{ fb}^{-1} \]

\[ m_{4l} (\text{GeV}) \]

\[ m_H = 126 \text{ GeV} \]
Higgs Observation!

Combined 5.0σ!

$m_H = 125.3 \pm 0.6\text{(stat+sys)}$

Simultaneously observed by ATLAS experiment as well
Higgs Properties

Couples proportional to mass
Conclusions

- LHC has observed a Higgs boson with mass ~125 GeV!
  - Observed at the gold standard of statistical significance.
  - Simultaneous observation by independent experiments providing both discovery and proof of reproducibility.
  - Now observed with the event rates expected for both W and Z interactions with the Higgs.
  - All properties very consistent with SM expectation.

- The last piece of the SM confirmed!

- A beginning, not an end, for the LHC story

- What could be next for the LHC? - We think Dark Matter!