The Discovery of the Higgs boson
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In the early twentieth century atomic physics was well understood

- The atom had a nucleus with protons and neutrons.
- An equal number of electrons to the protons orbited the nucleus.

The keys to understanding this were the electromagnetic (EM) force and the new ideas of quantum mechanics.

- The EM force held the electrons in their orbits.
- Quantum mechanics told us that only certain quantized orbits were allowed.
- Allowed a detailed understanding of the properties of matter.
The Periodic Table

Elements in the same column have similar chemical properties.

Different types of quantum orbits.
We Observed New Physics

Already there were some unexplained phenomena

- One type of atom could convert itself into another type of atom
  - Nuclear beta decay
  - Charge of atom changed and an electron was emitted

How could the nucleus exist?

- Positive protons all bound together in the atomic nucleus

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 = 2.3x10^{-8}N</td>
<td>Decays can take thousands of years</td>
<td>F = 2.3x10^{2}N</td>
<td>F = 2.3x10^{-47}N</td>
</tr>
</tbody>
</table>

How do we understand the Forces? Why so different in in properties?
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)
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

\[1\text{eV} = 1.6 \times 10^{-19} \text{J}\]
Weak and EM Force: Strength

- For EM force
  \[ P \propto \frac{\alpha^2}{(q^2 + M_\gamma^2)^2} \]

- For weak force
  \[ P \propto \frac{\alpha^2}{(q^2 + M_W^2)^2} \]

**Coupling strength:**
*Same as EM force*

**q momentum of the W or Z bosons**

- 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
# The Forces Revisited

<table>
<thead>
<tr>
<th>Couples to:</th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Particles with electric charge</td>
<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>
<td>Nuclear beta decay No attractive force</td>
<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>$F = 2.3 \times 10^2$ N</td>
<td>$F = 2.3 \times 10^{-47}$ N</td>
</tr>
</tbody>
</table>
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.
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

![Diagram of Higgs production and decay](image-url)
Those decays should be to particles that are easy to detect: i.e. uniquely identify and measure the momentum of Higgs production and decay to photons.
**LHC collision rates**

- LHC collides 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
CMS Experiment at the LHC, CERN

Data recorded: 2010 Jul-09 02:25:58.339811 GMT (04:25:58 CEST)
Run / Event: 139779 / 4994190

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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).
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: γγ
LHC Higgs Event: $ZZ \rightarrow \mu\mu\mu\mu$
Higgs Searches

CMS Preliminary
\( \sqrt{s} = 7 \text{ TeV}, L = 5.1 \text{ fb}^{-1} \)
\( \sqrt{s} = 8 \text{ TeV}, L = 5.3 \text{ fb}^{-1} \)

\( m_{\gamma\gamma} \) (GeV)

\( \gamma\gamma: 4.0\sigma \)

\( ZZ: 3.2\sigma \)
Higgs Observation!

Combined 5.0σ!

Simultaneously observed by ATLAS experiment as well

m_H = 125.3 ± 0.6 (stat+sys)
Higgs Properties

Couples proportional to mass
Conclusions

- LHC has observed a Higgs boson with mass $\sim 125$ 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
- More mysteries to solve. Dark matter, unification of the forces
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