The Discovery of the Higgs Boson: one step closer to understanding the beginning of the Universe

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Kane Hall, University of Washington
November 1, 2012
Particle Physics
or
High Energy Physics

Aim to answer two basic questions:

- What are the fundamental constituents of matter?
- What are the fundamental forces that control their behavior?
Constituents of Matter

Sizes and distance scales

- Virus: $10^{-7}$ m, 0.0000001 m, One ten millionth of a meter
- Molecule: $10^{-9}$ m, 0.000000001 m
- Atom: $10^{-10}$ m, 0.0000000001 m
- Nucleus: $10^{-14}$ m, 0.000000000000001 m
- Proton: $10^{-15}$ m, 0.000000000000001 m
- Quark (Particle Physics now)
Fundamental Particles

**Leptons**

- **Tau**: Electric Charge -1, Tau Neutrino: Electric Charge 0
- **Muon**: Electric Charge -1, Muon Neutrino: Electric Charge 0
- **Electron**: Electric Charge -1, Electron Neutrino: Electric Charge 0

**Quarks**

- **Bottom**: Electric Charge -1/3, Top: Electric Charge 2/3
- **Strange**: Electric Charge -1/3, Charm: Electric Charge 2/3
- **Down**: Electric Charge -1/3, Up: Electric Charge 2/3

Each quark: R, B, G 3 colors

Antiparticles: same mass but opposite charge as particles

Where does the mass of the particles come from?
Forces

- Strong force binds the nucleus
- Electromagnetic force binds atoms
- Weak force in radioactive decay
- Gravitational force binds the solar system
How are forces felt?

Matter

• Particles interact at a distance, force is mediated through fields
• Fields can vibrate/oscillate
• Vibrations/oscillations/excitations are quantized → Particles

Forces are mediated by the exchange of “force particles” between “matter particles”
It turns out (mathematically and verified experimentally) that the electromagnetic and weak forces are manifestations of the same force: the Electroweak force.
A lesson from history: Unification

Terrestrial mechanics

Universal Gravitation
Inertial vs. Gravitational mass
(I. Newton, 1687)

Celestial mechanics

Electricity

Electromagnetism
Electromagnetic waves (photon)
(J.C. Maxwell, 1860)

Magnetism

Electroweak
Intermediate bosons W, Z
(1970-83)

Electromagnetism

Weak force

Probing shorter distances reveals deeper regularities

UNIFIED DESCRIPTIONS
Standard Model

Constituents

Forces

Electromagnetism (QED)
  - magnetism
  - electricity

Electroweak

Weak force (weak theory)

Strong force (QCD)

SM does not incorporate Gravity

Verified to a high precision level
Open Questions in the Standard Model – and beyond

• Are there undiscovered new symmetries? New physical laws?
  – What breaks the Electroweak symmetry?
  – How is the Strong force related to the Electroweak?
  – What about Gravity?
  – Do all the forces become one?

• What gives mass to particles? ← We now know!!!

• What is the structure of the space-time?

• What is Dark Matter? What is Dark Energy?

These are some of the questions we are trying to answer…
What is Mass?

What gives mass to the W and Z bosons while the photon is massless?

What breaks the Electroweak Symmetry?
How to restore the symmetry...

- Imagine a field which describes the energy of a particle and has two minima. In equilibrium, it will choose one of the two.

- Fundamental law is left-right symmetric, but equilibrium state is NOT

- Left-right symmetry is ‘spontaneously broken’ (but is really hidden) by choosing an equilibrium state
The Higgs mechanism

- All particles are massless to begin with

- Postulate extra field which permeates the universe and has non-zero value in the vacuum: the Higgs field

- The Higgs field has infinite number of minima ⇒ choosing a particular minimum “breaks” the symmetry

- Particles interacting with this field acquire mass - the stronger the interaction, the larger the mass

- The Higgs field is a quantum field - the quantum is the Higgs boson. Finding the Higgs particle establishes the presence of the field.
Think of “identical” boats on a lake:

The Higgs field
Think of “identical” boats on a lake:

Underneath:

Shape of keel (=coupling to Higgs) determines Resistance (=mass) in Lake (=Higgs field)
Our ‘microscope’: Accelerators
‘Microscope’

Wavelength of radiation should be smaller than the object to be resolved

\[ \lambda \ll \frac{\hbar}{p} = \frac{\hbar c}{E} \]

<table>
<thead>
<tr>
<th>Object</th>
<th>Size</th>
<th>Probing energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atom</td>
<td>$10^{-10}$ m</td>
<td>0.00001 GeV</td>
</tr>
<tr>
<td>Nucleus</td>
<td>$10^{-14}$ m</td>
<td>0.01 GeV</td>
</tr>
<tr>
<td>Proton</td>
<td>$10^{-15}$ m</td>
<td>0.1 GeV</td>
</tr>
<tr>
<td>Quarks</td>
<td>$&lt;10^{-18}$ m</td>
<td>$&gt; 1$ GeV</td>
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</tbody>
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Radioactive sources give energies in the range of 0.001 GeV

Need accelerators for higher energies!
Large Hadron Collider (LHC)

CERN
Geneva, Switzerland

17 miles in circumference
Total superconducting magnets ~ 8000

Magnetic fields keep protons in circular orbit.

Electric fields accelerate protons to almost the speed of light.
A Toroidal LHC Apparatus (ATLAS)

Muon detectors

UW led design of mechanical support and built large fraction of muon detectors

Calorimeters

Tracking detectors
Fun facts about the ATLAS detector

- Weighs 7000 tonnes, same as 100 Boeing 747 jets (empty)
- Half the size of the Cathedral of Notre Dame in Paris
- Can measure position with precision of 0.0004 inches
- Took 8 years to plan, 12 years to build
- At design LHC conditions:
  - About 1 billion proton-proton collisions/second occur in detector
  - One $H \rightarrow ZZ \rightarrow 4e$ produced every 2 hours and 48 minutes
  - If all data would be recorded, this would fill 100,000 CDs/second
  - Trigger selects for storage about 200 “interesting” events/second
- 3000 scientists (including 1000 graduate students) from 174 universities and labs from 38 countries built, operate, analyze data from the ATLAS detector
ATLAS Collaboration
Some of the people who built and operate ATLAS...

And some of the UW students and postdocs based at CERN...
Particle Signatures in the Detector
The proton constituents (quarks and gluons) collide with each other. The scattered quarks and gluons form new stable composite particles (hadrons) that move collimated along a direction (jets).

Sometimes rare particles are produced during a high energy collision, e.g., a W or Z boson (or a Higgs boson?). These live only for a tiny fraction of a second, then decay into quarks and/or leptons or photons.
Particles in the Detector

- Particles moving out of the interaction point:
  - Photons
  - Electrons
  - Muons
  - Taus
  - Jets of Hadrons (e.g., protons, neutrons, pions, etc.)

- They interact with the matter of the detector and:
  - leave TRACKS (if electrically charged)
  - deposit their ENERGIES

- From the tracks and the energy deposits, we can reconstruct what happened during the collision.
A generic HEP detector

neutrinos

photons

$e^\pm$

muons

$\pi^\pm, p$

n

Innermost Layer...

...Outermost Layer
A detector cross-section, showing particle paths

- Beam Pipe (center)
- Tracking Chamber
- Magnet Coil
- E-M Calorimeter
- Hadron Calorimeter
- Magnetized Iron
- Muon Chambers

Particles:
- Neutron
- Photon
- Electron
- $\pi^\pm$, Proton
- Muon
The search for the Higgs
Life of a Higgs particle

• It lives only for $10^{-25}$ seconds

• It decays into a pair of lighter particles:
  - pair of photons
  - pair of quarks or leptons
  - pair of W or Z bosons (which also decay very fast)

• The Standard Model predicts how many decays of each type

• From the decay products, we can identify the Higgs boson
Higgs $\rightarrow$ ZZ $\rightarrow$ $ee\mu\mu$ candidate event
Higgs $\rightarrow$ 2 photons

ATLAS

Data

Sig+Bkg Fit ($m_H=126.5$ GeV)

Bkg (4th order polynomial)

SM with Higgs

SM without Higgs

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

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

$H \rightarrow \gamma \gamma$

Data consistent with Higgs-like particle!
Conclusions and Outlook

• We are now measuring detailed properties of the new particle to verify it is indeed the Standard Model Higgs

• Discovery of the Higgs-like particle is the most important discovery in Particle Physics in the last 40 years

• Understand mechanism to give mass to fundamental particles

• Understand the unification of the ElectroMagnetic and Weak interactions

• Next: can we unify with the Strong? with Gravity?

Now (15 billion years)

Stars form (1 billion years)

Atoms form (300,000 years)

Nuclei form (180 seconds)

Protons and neutrons form ($10^{-10}$ seconds)

Quarks differentiate ($10^{-34}$ seconds)

Gravity separates ($10^{-43}$ seconds)

???
Blogs for further reading...

• Of Particular Significance
  - http://profmattstrassler.com/

• Cosmic Variance