The Higgs Discovery
Elliot Lipeles

• What is the LHC?
• General Idea of why we build colliders
• Some sense of scale
• What we were looking for
• What we found
• What is left to find
The LHC: A Really Big Experiment
The LHC: A Really Big Experiment

Two Large Experiments looking for the Higgs

Protons

Protons
The LHC: A Really Big Experiment

Relative Size of RHIC ring

Specialized Heavy Ion Experiment

Pb

ALICE
A view underground
A view underground

Inside the tunnel

Magnets
Why Collisions?...because $E=mc^2$

We are searching new high mass particles

We make them used $E=mc^2$
Energy = mass \times (\text{speed of light})^2

1 \text{ liter of water weighs 1 kg (2.2 lbs) at room temperature}

Just before boiling, the same liter of water weighs 3 nanograms more
How high energy is the LHC?

Collision Energy is $8 \text{ TeV} = 8 \text{ Trillion Electron Volts (eV)}$

1.5 eV = 1.5 “electron volts” is the energy an electron gains by going from one end of a AA battery to the other.

8 TeV is the energy an electron would gain from lining up about 5.3 trillion AA batteries end-to-end.

In 2015 we will increase the energy to 13 TeV.
How high energy is the LHC?

Collision Energy is $8 \text{ TeV} = 8 \text{ Trillion Electron Volts (eV)}$

1.5 eV = 1.5 “electron volts” is the energy an electron gains by going from one end of a AA battery to the other

8 TeV is the energy an electron would gain from lining up about 5.3 trillion AA batteries end-to-end

Making a proton takes 1 GeV
Making a Higgs takes 125 GeV = 1/64 of the beam energy
Why is the LHC a ring?

A line of 5.3 Trillion AA batteries would be 270,000,000 km long (almost twice the distance to the sun).

Protons travel around the circle 11,000 times per second.

They accelerate to 8 TeV in about an hour:
- gaining 200,000 eV per turn
- traveling a total distance that is 7.2 times the distance to the sun.
Understanding the Energy Scale

In the ring we keep many (1380) bunches of about 100 billion protons each
• That is about billionth of a grain of sand

The beam has 70 megajoules of energy which is the kinetic energy of a car moving 25 mph

So the beam is a speck one billionth of grain of sand, that feels like car moving 25 mph to the beam stop (target where we put the beam when we were done with it).
How data is collected...

Machine is Empty
How data is collected...

Machine is Empty
Turn Magnets on to Low Energy
How data is collected...

Machine is Empty
Turn Magnets on to Low Energy
Inject Proton Beam #1
How data is collected...

- Machine is Empty
- Turn Magnets on to Low Energy
- Inject Proton Beam #1
- Inject Proton Beam #2
How data is collected...

- Machine is Empty
- Turn Magnets on to Low Energy
- Inject Proton Beam #1
- Inject Proton Beam #2
- Ramp Energy
How data is collected...

- Machine is Empty
- Turn Magnets on to Low Energy
- Inject Proton Beam #1
- Inject Proton Beam #2
- Ramp Energy
- Slow Decline in Beam Intensity
How data is collected...

1. Machine is Empty
2. Turn Magnets on to Low Energy
3. Inject Proton Beam #1
4. Inject Proton Beam #2
5. Ramp Energy
6. Slow Decline in Beam Intensity
7. Dump Beams
How data is collected...

1. Machine is Empty
2. Turn Magnets on to Low Energy
3. Inject Proton Beam #1
4. Inject Proton Beam #2
5. Ramp Energy
6. Slow Decline in Beam Intensity
7. Dump Beams
8. Turn off Magnets
How data is collected...

Machine is Empty
Turn Magnets on to Low Energy
Inject Proton Beam #1
Inject Proton Beam #2

Ramp Energy
Slow Decline in Beam Intensity
Dump Beams
Turn off Magnets

And then repeat...
Remember, we are colliding pinballs to make bowling balls
But, $E=mc^2$ goes the other direction too....
Remember, we are colliding pinballs to make bowling balls

But, $E=mc^2$ goes the other direction too....

The new massive particles very quickly “decay” back to lighter particles
One More Complication

The proton not just one particle!
Protons are really a sack of particles

Get lots of collisions in addition to the interesting one

The particles from the high mass particles tend to have larger energies
A real collision

A spray of particles emerges from the collision
We have to measure as much about it as we can....
Detector is like a camera which takes pictures of the collisions.
Detectors

Detector is like a camera which takes pictures of the collisions.

Detector tells us the directions and energies of the particles emerging.
Detectors

Detector is like a camera which takes pictures of the collisions. People for scale.

Detector tells us the directions and energies of the particles emerging.
Different Particles in the Detector
Triggering

ATLAS makes 20 million pictures ("events") per second.

We can afford to store only 400 of those.

Trigger makes the difficult choice of what to keep.
Summary Video
What we are searching for...

Fundamental Forces of Nature and the Role the Higgs Plays

Electromagnetism
Weak Interaction
Strong Interaction
Gravitation
The Fundamental Forces

Electricity and Magnetism (EM)

Pretty much all the “forces” in everyday life other than gravity

- Gravity pulls me down
- EM holds me up

Magnets

The Atom
... and most of chemistry

Light
The Fundamental Forces

Electricity and Magnetism (EM)

My feet on the floor
• Gravity pulls me down
• EM holds me up

Pretty much all the “forces” in everyday life other than gravity

You might be amazed to learn all these things can be described by just one force

This is one of the goals of physics!

Unification and symmetry play a central role
You might be amazed to learn all these things can be described by just one force. This is one of the goals of physics!

Unification and symmetry play a central role.
The nucleus is about $10^5$ times smaller than an atom... hence the name “strong force”
The Weak Force

The Weak Force is part of the burning of protons in the sun.

Deuterium = (one proton + one neutron)

The Neutrino only interacts weakly and will pass right through earth.
We don’t have a theory for how gravity works on very small scales. I.e. very very close to the electron.

E.g. if instead of the LHC I had a Very Very Large Hadron Collider, $10^{16}$ times larger, gravity would matter, but we don’t know how to calculate it.
Symmetry is really when we realize the two things are manifestations of the same thing.
The Higgs does a funny job of breaking a symmetry.
The Weak and Electromagnetic Forces seem different but they secretly the same.
Symmetry Breaking

Before symmetry breaking:
3 identical + 1 other force carriers

After symmetry breaking:
4 difference kinds of force carriers

Predicts relationships between....
W and Z masses, and strength of the weak and electromagnetic forces
Higgs and Mass

Higgs breaks symmetry between Electromagnetism and Weak force by giving things mass

• It takes more energy to have no Higgs field

• Think of Higgs field like the electric field... it has a value at every point
Higgs and Mass

Higgs breaks symmetry between Electromagnetism and Weak force by giving things mass

- It takes more energy to have no Higgs field
- The Higgs field is everywhere
- When a particle “couples” to the Higgs it takes energy to displace the Higgs field
- $E=mc^2$ ... particles get mass
Higgs and Mass

Higgs breaks symmetry between Electromagnetism and Weak force by giving things mass

- It takes more energy to have no Higgs field
- The Higgs field is everywhere
- When a particle “couples” to the Higgs it takes energy to displace the Higgs field
- $E=mc^2$ ... particles get mass

*Higgs Particle is a wave in the Higgs field*
Why was the Higgs so hard to find?

The Problem:

1) Particles that couple well to the Higgs are heavy

2) Heavy particles decay fast

3) We can only collide particles stable enough to put them in an accelerator
Why was the Higgs so hard to find?

The Solution:

- **Gluon Fusion**
  - $g \rightarrow t \rightarrow t \rightarrow H$

- **Associated Production**
  - $q \rightarrow W, Z \rightarrow H$

- **Vector Boson Fusion**
  - $W^-, W^+ \rightarrow H$

These are not allowed in classical physics... but quantum mechanics lets them happen at small rates (so we need lots of data)
The Higgs Discovery

Quantum Mechanics is probabilistic
• The Higgs can decay into many different things
• The Higgs has been seen in....
  • $H \rightarrow \gamma \gamma$ (in “other”)
  • $H \rightarrow ZZ$
  • $H \rightarrow WW$
• Still searching in ...
  • $H \rightarrow \tau \tau$
  • $H \rightarrow bb$
  • $H \rightarrow \mu \mu$ (in “other”)
  • $H \rightarrow$ dark matter?!  

• Each “channel” has different challenges
$H \rightarrow \gamma \gamma$: an example event

$\gamma$ is a photon which is just very high energy light.
$E=mc^2$ so the sum of the energy of the two photons is the Higgs mass

$H \rightarrow \gamma \gamma$: the key plot

Number of Collisions

Energy of the two photons
H → γγ: the key plot

E = mc² so the sum of the energy of the two photons is the Higgs mass. There are other sources of two photons. Excess of collisions in one place means they come from a particle with that mass.
The Future

Many Big Questions Remain

The Higgs itself is an enigma

• Quantum Mechanics tends to make the Higgs very heavy ($10^{16}$ GeV), but it’s only 125 GeV

This effect should change the Higgs mass be a very large number

• Could be solved by a new symmetry

“Supersymmetry” is one proposed solution
Making Dark Matter in the Lab?

Gravity of the stars in the middle of a galaxy pulls stars on edges to keep them in moving in circles

But there aren't enough stars!

We need something in the middle pull in the stars... Something invisible... = DARK MATTER
The Future: Big Questions Remain

Making Dark Matter in the Lab?

Much more evidence of Dark Matter from the early universe
The Future: Big Questions Remain

Making Dark Matter in the Lab?

How do you detect the invisible?

- Outgoing particles moving in opposite directions
- Momentum balanced
- Nothing missing

- Momentum not balanced
- Something Missing!
- Discover Dark Matter?!
Are there simpler models?
- Relating particles to each other by symmetry ("Grand Unified theory")

Diagram:
-Gravity
-Strong Force
-Weak Force
-Magnetism
-Electricity
-Light

Unifications/Symmetries

Higgs!
Summary

Former directors of CERN at the July 4th, 2012 discovery announcement

We found it! ... and the future is bright
Backup Slides
A “Z” is like a heavy photon
Because it’s heavy it decays (recall $E=mc^2$)
This is a $H \rightarrow ZZ \rightarrow \mu\mu\mu\mu$ event
Excess indicating new particle

Plot energy of all four leptons (muons or electrons)
Excess at 125 GeV indicates the presence of the Higgs
Extra difficult because $W$ decays to an electron or muon and a neutrino... but our detector can’t see neutrinos at all!

Advantage is that it is much more common

Use momentum conservation to figure out something about what you are missing

Very detailed predictions of all known sources of events
Symmetry is really when we realize the two things are manifestations of the same thing
How do you break a symmetry?

The Pencil will pick a direction to fall

The Higgs is setup to pick a direction