Higgs Hunting at the Large Hadron Collider

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Outline

- Introduction to the Standard Model
- What is the Higgs really?
- Hunting grounds: LHC and the detectors
- How do we hunt for particles?
- How would we know we see a Higgs?
- What have we found so far?
- What's next?
A Brief History of Particles

- The idea that all matter is composed of elementary particles dates as far back as the 6th century BC.
  - Most of these were philosophical ideas
  - ‘atomos’ is a Greek word meaning indivisible
- 19th century: modern atomic theory was postulated
  - Each element is composed of a unique type of particle
- 1897: the electron was discovered
  - Plum pudding model of the atom
- 1909: Rutherford’s experiment with a gold foil and alpha rays
  - Atoms have a nucleus and electrons
More than 99% of the mass of an atom is in the nucleus, which is more than 10,000 times smaller than the atom, about $1 \text{–} 10 \text{ fm (Fermi)}$. 

$1 \text{ fm} = 10^{-5} \text{ Angstrom} = 10^{-15} \text{ m}$. 

A cloud of electrons orbits the nucleus, held in place by the mutual attraction of the electric charges.

Most of the atom is just empty space! But with a strong electromagnetic field present.

Nuclei are made up of two particles: 
**Protons** $p$: positive charge $+e$, mass $\approx 1u$ 
**Neutrons** $n$: neutral, roughly the same mass as $p$ 

Protons and neutrons are kept together by a new force: the strong force.
Sub-atomic Particles

What do we distinguish particles by?

- **participate in strong interactions?**
  - **YES:** they are called **hadrons**
    - ex: proton, neutron
  - **NO:** they are called **leptons**
    - ex: electron

- **electric charge?**
  - positive or negative
  - usually in multiples of e

- **Mass?**
  - usually measured in electronvolts (eV)
  - $1 \text{ u} \approx 0.939 \text{ GeV}$ ($\text{Giga electronvolts}, \ Giga = \text{Billion}$)

- **Spin?**
  - = Quantized angular momentum
  - Electrons, protons, neutrons: spin $\frac{1}{2} \hbar$

Particles with integer spin are called **bosons**.

Particles with half-integer spin are called **fermions**.

Electrons, protons and neutrons are fermions.
The muon $\mu^-$ (and its antiparticle $\mu^+$):
- The muon is a fermion with spin $\frac{1}{2}$
- It does not participate in the strong interaction, so it is a lepton
- It behaves like a heavier brother of the electron.

Mass 0.106 GeV
(electron: 0.000511 GeV)

Most heavier particles are unstable. They decay into lighter particles, e.g. weak decay of a muon:

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

Neutrinos $\nu_e$, $\nu_\mu$ and their antiparticles $\bar{\nu}_e$, $\bar{\nu}_\mu$:
- They are fermions with spin $\frac{1}{2}$.
- They don’t have electric charge.
- They don’t feel the strong force.
- They have an extremely small mass.

Neutrinos are ‘ghost’ particles.

They are almost undetectable because they only participate in the weak interaction.

Examples: muon decay, nuclear $\beta$-decay etc.
1968 a Rutherford-like experiment (deep inelastic scattering) confirmed that there are indeed quarks inside a proton.

- There are 6 quarks in 3 generations + their 6 anti-quarks
- Increasing in mass from 0.002 GeV (up) to 174 GeV (top).

- Have fractional electric charges
- Can only exist in bound states
- Interact via both weak and strong force

- 1st generation
- 2nd generation
- 3rd generation

- quarks
  - u (up)
  - d (down)
  - c (charm)
  - s (strange)
  - t (top)
  - b (beauty)

- discovered in 1974
- discovered (at last) in 1995

- the "original" quarks

- charge: +2/3
  - charge: -1/3
In quantum field theory forces are transmitted by force carrier particles exchanged between particles with the suitable charge.

Electromagnetic force: exchange of photons between charged particles

Strong force: exchange of gluons between particles with "color charge"

Weak force: exchange of $W^+$, $W^-$ and $Z$ bosons between particles with "weak charge"

All the force carrier particles are spin-1 bosons (vector bosons) and they should have vanishing mass.
The Standard Model

Three generations of matter (fermions)

I  II  III

mass  2.4 MeV/c²  1.27 GeV/c²  171.2 GeV/c²
charge 2/3 2/3 2/3
spin 1/2 1/2 1/2
name up charm top

Quarks

mass  4.8 MeV/c²  104 MeV/c²  4.2 GeV/c²
charge -1/3 1/2 1/2
spin 1/2 1/2 1/2
name d s b

electron neutrino 0
muon neutrino 0
tau neutrino 0

Leptons

mass  0.511 MeV/c²  105.7 MeV/c²  1.777 GeV/c²
charge -1 -1 -1
spin 1/2 1/2 1/2
name e µ τ

Gauge bosons

mass  91.2 GeV/c²  80.4 GeV/c²
charge 0 ±1
name Z° W±
What is this “Higgs” thing?

- Electroweak symmetry breaking: W and Z bosons shouldn’t have mass (like photons!); but we find they are very heavy!

- Idea: maybe W, Z couple to a field (the Higgs field!) that never vanishes, even in the vacuum (we say it has a non-zero vacuum expectation value).

- How can that happen? Imagine the Higgs field $\phi$ “lives” in a potential like this:
  - The preferred (lowest energy) value is at the bottom where $\phi \neq 0$. 

This costs too much energy! I think I’ll hang out down there.
What is this “Higgs” thing?

- The vacuum expectation value of the field would not be directly visible but manifests itself in 2 ways:
  - It gives masses to W and Z as they have to move through that field.
  - Excitations of the field on top of the vacuum value can be detected as a spin-0 boson (the Higgs boson!). Think of those excitations ripples (waves) on top of a body of water.
What is this “Higgs” thing?

- Now that the Higgs field explains masses for W and Z bosons we can try to blame fermion masses on the Higgs as well.
- Postulate that all fermions couple to the Higgs field. The larger the mass the stronger the coupling.
Collider Detectors

Use detectors to search for particles
Higher the energy, the more new particles can be created
And, take lots and lots and lots (!) of data

<table>
<thead>
<tr>
<th>Collisions</th>
<th>LEP</th>
<th>TeVatron</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Years</td>
<td>208</td>
<td>2000</td>
<td>14000</td>
</tr>
<tr>
<td>Max E, GeV</td>
<td>0.5fb⁻¹</td>
<td>12fb⁻¹</td>
<td>5(300)fb⁻¹</td>
</tr>
<tr>
<td>Integrated lumi.</td>
<td>0-115</td>
<td>100-180?</td>
<td>120-600</td>
</tr>
</tbody>
</table>
The LHC at CERN (known as European Organization for Nuclear Research in Geneva, Switzerland) provides the proton-proton (pp) collisions. The smashing power is 3.5 times larger than that of the Tevatron at Fermilab (Batavia, IL, USA).
Compact Muon Solenoid Detector

1992: Letter of intent
1994: LHC project approved
1999: CMS MoU signed

2000: CMS assembly began
2005: CMS Cavern inauguration
2007: CMS inside the cavern

Happy 20th Birthday, CMS!
October 1992 — October 2012

2007: Physics TDR
2008: CMS ready for beams
2009: First Physics
CMS construction timeline

February 2005
CMS cavern inauguration

February 2007
CMS barrel YB0 and solenoid lowering

December 2007
The CMS Detector

Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil

Total weight 12500 t, Overall diameter 15 m, Overall length 21.6 m, Magnetic field 4 Tesla
The ATLAS detector

Detector characteristics
- Width: 44m
- Diameter: 22m
- Weight: 7000t

Annotations:
- Muon Detectors
- Electromagnetic Calorimeters
- Solenoid
- Forward Calorimeters
- End Cap Toroid
- Barrel Toroid
- Inner Detector
- Hadronic Calorimeters
- Shielding
How are particles detected?

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

Diagram showing various components:
- Silicon tracker
- Electromagnetic Calorimeter
- Hadronic Calorimeter
- Superconducting magnet
- Iron yokes + μ chamber
Can we detect it directly?
NO! Most particles will decay very soon after being produced.
What we really observe (measure) are the end products.

So what does the Z decay into?
\[ Z \rightarrow l^+l^- \text{ where } l = e, \mu, \tau, \nu \]

We know the mass of the leptons
We can measure their energy and momenta from the detector
Choose events with with 2 clean leptons

Z invariant mass
\[
m_0^{(Z)} = \sqrt{\left(m_0^{(1)}\right)^2 + \left(m_0^{(2)}\right)^2 + 2 \left(\frac{1}{c^4} \cdot E_1 \cdot E_2 - \frac{1}{c^2} \cdot \vec{p}_1 \cdot \vec{p}_2\right)}
\]
How about the “W” Boson?

- We need to know what the W decays into
  - $W \rightarrow l \nu$ where the lepton can be an electron or a muon
  - We can measure the momentum of the lepton
  - Negative of the vector sum of the energies of all the particles in the event gives the “missing energy” in the event → this is my neutrino.
  - Compare distributions with what is expected from theory

![Graphs showing data and theory for muons and electrons]
How often can we spot a Higgs?

Higgs is way down here.
How much data do we have?

**Integrated Luminosity**

**2012**  
8 TeV

Delivered 23.3 fb\(^{-1}\)  
Recorded 21.8 fb\(^{-1}\)

**2011**  
7 TeV

Delivered 6.13 fb\(^{-1}\)  
Recorded 5.55 fb\(^{-1}\)
How do we sort through all this data?

- We generate much more data than we record
  - can't control what we generate
  - limited by readout (electronics)
  - limited by computing (CPU)
  - limited by hardware (storage)
  - not all events are interesting

- So we filter the data
  - We use "Triggers" to do this
  - CMS has a 2 level trigger system
    - The L1 trigger and the High Level Trigger
    - Triggers are based in hardware as well as software
    - Of 40 MHz of incoming data 100 Hz is stored to tape.
How do we find the Higgs?
How is the Higgs Produced?

1) $g \rightarrow t \rightarrow H$

2) $q \rightarrow W/Z \rightarrow H$

3) $\bar{q} \rightarrow W/Z \rightarrow H$

4) $g \rightarrow H^0$

$\sigma(pp \rightarrow H+X) [pb]$ vs $M_H [GeV]$ for $\sqrt{s}=8$ TeV

- $pp \rightarrow H$ (NNLO+NNLL QCD + NLO EW)
- $pp \rightarrow q\bar{q}H$ (NNLO QCD + NLO EW)
- $pp \rightarrow WH$ (NNLO QCD + NLO EW)
- $pp \rightarrowZH$ (NNLO QCD + NLO EW)
- $pp \rightarrow t\bar{t}H$ (NLO QCD)
How does the Higgs Decay?

- $H \rightarrow \gamma\gamma$
- $H \rightarrow t^*W^*$
- $H \rightarrow b\bar{b}$
- $H \rightarrow WW$, $H \rightarrow ZZ$
- $H \rightarrow \tau\tau$
- $H \rightarrow gg$
- $H \rightarrow ZZ$
- $H \rightarrow bb$

Branching ratios as a function of $M_H$ [GeV].

- $b\bar{b}$
- $WW$
- $ZZ$
- $\tau\tau$
- $gg$
- $c\bar{c}$
- $\gamma\gamma$
- $Z\gamma$

LHC Higgs XS WG 2010
Higgs decaying to 2 photons

- $H \rightarrow \gamma\gamma$ is the fundamental decay channel for the discovery and mass measurement of the Higgs
- We have a nice final state with 2 well identified photons - thanks to ECAL
- We get a clean peak for the diphoton invariant mass
- Backgrounds can be dealt with easily
A candidate for $H \rightarrow \gamma \gamma$
Higgs decaying to 4 leptons

- $H \rightarrow ZZ \rightarrow 4l$ is a very clean signature
  - Hard to find many events with exactly 4 leptons
- There are 11 channels due to lepton flavor
- Leptons with large transverse momentum can be identified and measured very precisely
  - so also the Higgs mass can be calculated very precisely
- We can model the main backgrounds well using our knowledge of theory
- Can use this channel to measure spin and parity of the Higgs Boson
A candidate for $H \rightarrow ZZ \rightarrow 2e2\mu$
What about the other decay channels?

- We also have measurements from the other channels but these are more challenging.

- \( H \rightarrow WW \rightarrow 2l2\nu \)
  - Need to know our backgrounds very precisely.
  - Having 2 neutrinos makes it hard to reconstruct mass.

- \( H \rightarrow \tau\tau \) and \( H \rightarrow bb \)
  - Both have high Branching ratios but are rather challenging experimentally.
The mass $m_H$ is determined using the $\gamma\gamma$ and ZZ decay modes. The best fit gives us this value:

$$m_H = 125.3 \pm 0.4 \text{ (stat.)} \pm 0.5 \text{ (syst.) GeV} \rightarrow \text{July 2012}$$

$$m_H = 125.8 \pm 0.4 \text{ (stat.)} \pm 0.4 \text{ (syst.) GeV} \rightarrow \text{Nov. 2012}$$
Both experiments independently see a Higgs like Boson with a mass of about 125 GeV @ 7σ
What’s next?

- What we have so far seems to indicate that we have found a SM Higgs
  - Need to further verify that
  - Analyze full collected data
  - Make sure there are no other Higgs lurking out there
  - Measure the mass and other properties of the Higgs Boson more precisely
  - Measure the coupling constants
  - Try to come up with a new theory to explain what is still unknown!!
At CERN for the Higgs discovery announcement in July 2012

At CMS in April 2008
Backup Slides
July 4:
We show frequency of invariant mass for each four-lepton event.

CMS, ATLAS both see excess near 125 GeV!
July 4:
CMS, ATLAS both see excess near 125 GeV!

CMS and ATLAS each conclude “observation” of a new particle!
CERN announces discovery.
Think of the Higgs this way....

- All particles in Physics (photons, electrons, quarks) are viewed as a sort of quantum field.
- Most have a zero “vacuum expectation value”
  - In empty space we expect no photons, no electrons etc

- The Higgs is a special sort of quantum field.
- It has a non-zero “vacuum expectation value”
  - The Higgs field permeates all of space – it is everywhere
  - All particles acquire mass due to their interactions with this field.
  - The Higgs boson is a manifestation of the Higgs field