A Discovery! The “Higgs”? Why is it important? How it was done.

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A Discovery! The “Higgs”? Why it is important. How it was done. Sept. 13, 2012
Huge Interest in the Scientific Results

Two seminars from CMS and ATLAS were given on July 4, 2012 starting at 3 AM EDT at CERN.

>10,000 print stories
>1,034 television spots (worldwide)

Two publications were submitted on July 31, 2012
Introduction

My interest started with trying to answer these questions in the 1970’s when Isabelle was proposed at BNL.

Work on the CERN ISR, Tevatron at Fermilab, SSC in Texas and finally the LHC at CERN

The Standard Model – the Higgs is the last particle – why it is important

The ATLAS Detector – how it was designed to find the Higgs

Computing - BNL’s Tier 1 is the largest in ATLAS

Physics Results

Planning for the Future
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Study physics laws of first moments after Big Bang increasing Symbiosis between Particle Physics, Astrophysics and Cosmology
The Four Forces in Nature

**Strong**
- Gluons (8)
- Quarks
- Mesons
- Baryons
- Nuclei

**Electromagnetic**
- Photon
- Atoms
- Light
- Chemistry
- Electronics

**Gravitational**
- Graviton ?
- Solar system
- Galaxies
- Black holes

**Weak**
- Bosons (W,Z)
- Neutron decay
- Beta radioactivity
- Neutrino interactions
- Burning of the sun

*The particle drawings are simple artistic representations*
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Standard Model of Particle Physics

Quarks

\[
\begin{array}{cccc}
upt & c & t & \uparrow \\
\downarrow d & s & b & \downarrow \\
\end{array}
\]

Strong
Weak
Electromagnetic

Force

\[
\begin{array}{cccc}
Z & \gamma & W & g \\
\end{array}
\]

Weak
Electromagnetic

Leptons

\[
\begin{array}{cccc}
e & \mu & \tau & \\
\nu_e & \nu_\mu & \nu_\tau & \\
\end{array}
\]

\[
W \rightarrow \mu \nu, \ e\nu, \ \tau\nu \\
Z \rightarrow \mu\mu, \ e\e, \ \tau\tau \\
t \rightarrow Wb
\]
Professor Peter Higgs proposed that all of space is permeated by a field, the Higgs field.

Quantum theory says that all fields have particles associated with them, so...

in this case...a Higgs Boson.
What’s a higgs boson?
Why the Higgs is important

- The Higgs boson explains why electrons have mass
- The radius of atoms depends on the electron mass
- Atoms(life!) would not form without the Higgs boson
Things to Remember

- Bosons have integer spin: 0, 2?
  - Vector bosons have spin=1:
    - $\gamma$ (carrier of the Electromagnetic Force)
    - $W, Z$ (carrier of the weak force)
      - $W \rightarrow$ lepton + neutrino; $Z \rightarrow$ two leptons
- Fermions have spin=1/2:
  - Quarks: $u, d, s, c, b, t$
  - Leptons: $e, \mu, \tau$ and their neutrinos
Statistics: Standard Deviation

- **Wikipedia:** Particle physics uses a standard of "5 sigma" for the declaration of a discovery.\[^4\] At five-sigma there is only one chance in nearly two million that the result is wrong, i.e. the measurement seen is a random fluctuation. This level of certainty prompted the announcement that a particle consistent with the Higgs boson has been discovered in two independent experiments at CERN.\[^5\]
Invariant Mass

- The invariant mass calculated using the energy and momentum of the decay products of a single particle is equal to the mass of the particle that decayed. The mass of a system of particles can be calculated from the general formula:

\[ m^2 = (\sum E)^2 - (\sum \vec{p})^2 \]

The mass resolution means how well do we measure the invariant mass – the smaller the \( \sigma_m \), the better the resolution.
ATLAS: Di-muon invariant mass

- **Leading muon, $p_T > 15$ GeV, second**

ATLAS Preliminary

Data 2010, $\sqrt{s} = 7$ TeV

$\int \mathcal{L} \approx 40 \text{ pb}^{-1}$

EF_mu15

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We were thinking about discovering the Higgs when ATLAS was being designed.

- We knew less back in the 1990’s than recently – but we knew the mass of the Higgs > 114 GeV
- If the mass of the Higgs would be ~126 GeV
  - Channels with good mass resolution
    - \( H \rightarrow \gamma\gamma \)
    - \( H \rightarrow ZZ \rightarrow 4\) leptons (ee ee, ee \(\mu\mu\) or 4\(\mu\)'s)
  - Channels with moderate mass resolution
    - \( H \rightarrow V(W\ or\ Z)\ H \rightarrow b\bar{b} \)
  - Channels with poor mass resolution
    - \( H \rightarrow \tau\tau \)
    - \( H \rightarrow WW \rightarrow \text{lepton}+\nu, \text{lepton} + \nu \)
The ATLAS Experiment

- A Toroidal LHC ApparatuS (= ATLAS)
- Large Hadron Collider (=LHC) at CERN - Geneva, Switzerland
  - Large since it is 27 km in circumference
  - Design: 14 TeV proton-proton collisions at $10^9$ (1,000,000,000) interactions/second. That is 25 interactions every 25 nanoseconds!
    - We ran at 7 TeV in 2010/2011 and at 8 TeV in 2012
    - There are ~ $10^{11}$ protons/bunch and about 1500 bunches.
    - We ran at proton bunch spacing of 50 ns (~50’) with up to 35 interactions/crossing.
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BNL Magnet Going to the LHC

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Luminosity delivered to ATLAS since the beginning

ATLAS Online Luminosity
- 2010 pp $\sqrt{s} = 7$ TeV
- 2011 pp $\sqrt{s} = 7$ TeV
- 2012 pp $\sqrt{s} = 8$ TeV

Delivered Luminosity [fb$^{-1}$]

Month in Year

Total Data produced: $1.6 \times 10^{21}$ bytes
Or $3 \times 10^9$ 500 GB hard drives
How we produce the Higgs and how it decays.

Proton

Gluon Fusion

Top quark loop

Higgs Boson

Top Quark/W Boson loop

$\gamma^0$

$\gamma^0$
3030 active scientists:
  -- ~ 1830 with a PhD
  -- ~ 1200 students

174 Institutions, 38 Countries (44 in U.S.)
U.S. ATLAS

- The U.S. is one of 38 countries in ATLAS
- We have 376 “Ph.D.” authors (21% of ATLAS)
- There are 39 university groups and four national laboratories participating

<table>
<thead>
<tr>
<th></th>
<th>Total Heads</th>
<th>Heads at CERN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graduate Students</td>
<td>203</td>
<td>82</td>
</tr>
<tr>
<td>Post Docs</td>
<td>128</td>
<td>101</td>
</tr>
<tr>
<td>Scientists</td>
<td>92</td>
<td>17</td>
</tr>
<tr>
<td>Faculty</td>
<td>147</td>
<td>17</td>
</tr>
<tr>
<td>Technical Staff</td>
<td>158</td>
<td>35</td>
</tr>
<tr>
<td>Total</td>
<td>728</td>
<td>252</td>
</tr>
</tbody>
</table>
BNL’s Roles in ATLAS

- More than 50 people from BNL have contributed to ATLAS
- From the Physics Department, Instrumentation Division, Magnet Division, Collider Accelerator Department, Travel, Procurement, Legal, Fiscal, Public Affairs, etc.
- Built part of the Liquid Argon Calorimeter and Cathode Strip Chambers, physics analysis (former Higgs group co-convener), maintenance and operations, performance, trigger, computing (Tier 1 center and software), upgrade R&D, host lab for U.S. ATLAS, leadership positions in ATLAS and U.S. ATLAS
Length: ~ 46 m (150 ft)
Radius: ~ 12 m (40 ft)
Weight: ~ 7000 tons
~ $10^8$ electronic channels
~ 1800 miles of cables
~ 10 MW of electrical power
Even the Muppets know about ATLAS
Some people use Lego to build ATLAS
With our Pop-up Book, you can put together ATLAS by yourself!
How ATLAS Identifies Different Particles

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BNL Brought Thin Strips to the ATLAS Liquid Argon Calorimeter

Fine strips have two features:
1) Measurement of vertex with two photons
2) Help veto $\pi^0 \rightarrow \gamma\gamma$
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The Trigger System

- The “trigger” is crucial in selecting the events which could be the Higgs boson.
- There are ~500,000,000 pp interactions per second and we can only write out 400 per second – less than 1 in a million!
- If we do not choose correctly, we lose those events forever…. So the trigger must be very selective and efficient.
- We choose the topology – such as events with two $\gamma$’s above a certain momentum threshold in a three level “Trigger System”
Computing infrastructure and operation

ATLAS wLCG world-wide computing: ~ 70 sites
(including CERN Tier0, 10 Tier-1s, ~ 40 Tier-2 federations)
Invariant Mass of $\gamma\gamma$

ATLAS

Data S/B Weighted

$\Sigma$ weights / 2 GeV

$\Sigma$ weights - Bkg

$m_{\gamma\gamma} [\text{GeV}]$

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

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

$H \rightarrow \gamma\gamma$

$\text{Sig+Bkg Fit (} m_H = 126.5 \text{ GeV})$

$\text{Bkg (4th order polynomial)}$

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2011 data
Excluded (95% CL): 112-122.5 GeV, 132-143 GeV
Expected: 110-139.5 GeV

2012 data

2011+2012 data
Consistency of data with background-only expectation

### Table 1: Higgs Mass and Significance

<table>
<thead>
<tr>
<th>Data Sample</th>
<th>(m_H) of Max Deviation</th>
<th>Local p-value</th>
<th>Local Significance</th>
<th>Expected from SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>126 GeV</td>
<td>3 \times 10^{-4}</td>
<td>3.5 \sigma</td>
<td>1.6 \sigma</td>
</tr>
<tr>
<td>2012</td>
<td>127 GeV</td>
<td>3 \times 10^{-4}</td>
<td>3.4 \sigma</td>
<td>1.9 \sigma</td>
</tr>
<tr>
<td>2011+2012</td>
<td>126.5 GeV</td>
<td>2 \times 10^{-6}</td>
<td>4.5 \sigma</td>
<td>2.4 \sigma</td>
</tr>
</tbody>
</table>

Global 2011+2012 (including LEE over 110-150 GeV range): 3.6 \sigma
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\[ H \rightarrow ZZ^* \rightarrow 4 \text{ leptons} \]
2 Z bosons → positron(e⁺) electron(e⁻)+µ⁺µ⁻

- The file on this page uses QuickTime –
The ATLAS Data for $ZZ^* \rightarrow 4$ leptons

- We’re obviously dealing with small statistics.
  - At 125 GeV, it’s 13 events over a predicted background of 5

- The background is almost entirely ZZ and ZZ*
  - Except under the peak at 125 GeV: more on that later.
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Yields and Limits

ATLAS Preliminary

$H \rightarrow ZZ^{(*)} \rightarrow 4l$

$\sqrt{s} = 7 \text{ TeV}: \int \text{L} \text{d}t = 4.8 \text{ fb}^{-1}$

$\sqrt{s} = 8 \text{ TeV}: \int \text{L} \text{d}t = 5.8 \text{ fb}^{-1}$

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Combined results ($\gamma\gamma$ and $ZZ\rightarrow4$ leptons): an excess!

- Maximum excess observed at $m_H = 126.5$ GeV
- Local significance (including energy-scale systematics): 5.0 $\sigma$
- Probability of background up-fluctuation: $3 \times 10^{-7}$
- Expected from SM Higgs $m_H = 126.5$
- Expected from SM Higgs $m_H = 126.5$
- Global significance: 4.1–4.3 $\sigma$ (for LEE over 110–600 or 110–150 GeV)
Additional Evidence

• ATLAS submitted a paper for publication on July 31, 2012 which includes the WW channel which increases the significance to 5.9 $\sigma$ corresponding to a background fluctuation probability of $1.7 \times 10^{-9}$ which is compatible with the production and decay of the Standard Model Higgs boson.
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\[ \gamma\gamma + ZZ^* + WW \]

**5.9 \sigma!**
Signal Strength

ATLAS 2011 - 2012

\[ W, Z, H \rightarrow bb \]
\[ \sqrt{s} = 7 \text{ TeV; } L_{\text{int}} = 4.7 \text{ fb}^{-1} \]

\[ H \rightarrow \tau\tau \]
\[ \sqrt{s} = 7 \text{ TeV; } L_{\text{int}} = 4.6-4.7 \text{ fb}^{-1} \]

\[ H \rightarrow WW^{(*)} \rightarrow l^+l^-\nu\nu \]
\[ \sqrt{s} = 7 \text{ TeV; } L_{\text{int}} = 4.7 \text{ fb}^{-1} \]
\[ \sqrt{s} = 8 \text{ TeV; } L_{\text{int}} = 5.8 \text{ fb}^{-1} \]

\[ H \rightarrow \gamma\gamma \]
\[ \sqrt{s} = 7 \text{ TeV; } L_{\text{int}} = 4.8 \text{ fb}^{-1} \]
\[ \sqrt{s} = 8 \text{ TeV; } L_{\text{int}} = 5.9 \text{ fb}^{-1} \]

\[ H \rightarrow ZZ^{(*)} \rightarrow 4l \]
\[ \sqrt{s} = 7 \text{ TeV; } L_{\text{int}} = 4.8 \text{ fb}^{-1} \]
\[ \sqrt{s} = 8 \text{ TeV; } L_{\text{int}} = 5.8 \text{ fb}^{-1} \]

Combined
\[ \sqrt{s} = 7 \text{ TeV; } L_{\text{int}} = 4.6 - 4.8 \text{ fb}^{-1} \]
\[ \sqrt{s} = 8 \text{ TeV; } L_{\text{int}} = 5.8 - 5.9 \text{ fb}^{-1} \]

\[ \mu = 1.4 \pm 0.3 \]

\[ m_H = 126.0 \text{ GeV} \]

Signal strength (\( \mu \))
Plans for the Immediate Future

- Determine if this is the Standard Model Higgs boson
  - Measure more precisely the ZZ* and WW modes
  - Measure decays to fermions
  - Measure spin
  - We expect perhaps 4 times as much data by the end of 2012 as we have now – this might be enough
Planning for the Future

LHC plans (LS1, LS2, LS3)

- 2009: LHC startup, $\sqrt{s} = 900$ GeV
- 2010: $\sqrt{s} = 7$ TeV (8 TeV?), $L = 4 \times 10^{33} \text{cm}^2\text{s}^{-1}$, bunch spacing 50/25ns
- 2011:
- 2012:
- 2013: LS1
- 2014:
- 2015:
- 2016:
- 2017:
- 2018: LS2
- 2019:
- 2020:
- 2021:
- 2022: LS3
- 2023:
- 2030?

- Go to design energy, nominal luminosity
- $\sqrt{s} = 13$–14 TeV, $L = 1 \times 10^{34} \text{cm}^2\text{s}^{-1}$
- Injector and LHC Phase-1 upgrade to full design luminosity
- $\sqrt{s} = 14$ TeV, $L = 2 \times 10^{34} \text{cm}^2\text{s}^{-1}$
- HL-LHC Phase-2 upgrade, crab cavities?, $\gamma$-rays
- $\sqrt{s} = 14$ TeV, $L = 5 \times 10^{34} \text{cm}^2\text{s}^{-1}$, luminosity levelling

We are planning a new Construction Project for Phase 1. CD-0 Soon
Conclusions

- CMS observes approximately the same signal with about the same significance!
- The LHC Physics Program has observed a new particle at about 126 GeV which may be the Standard Model “Higgs” boson
  - More data is required to measure all the properties of this new particle
  - This will probably take several years
- Running in 2015 and beyond will be at >13 TeV which will open a larger window for discovering other new particles.
  - Source of Dark Matter? Supersymmetry?
Essential Websites

- This Talk Today: https://indico.bnl.gov/conferenceDisplay.py?confld=535
- Our BNL website: www.bnl.gov/atlas
- Must see LHC Rap: http://www.youtube.com/watch?v=j50ZssEojtM
- US LHC site (blogs) http://uslhc.us/
- ATLAS Public Web Page: http://atlas.ch/
- Youtube! http://www.youtube.com/watch?v=leGHWCzq964

The Particle Adventure http://www.particleadventure.org

LEO Models: http://atlas-model.mehlhase.info/#name_introduction

Virtual Tours
http://virtualvisit.web.cern.ch/VirtualVisit/ATLAS_dev/HTML/VThi.html
