THE HIGGS BOSON

WINDOW ON THE BIG BANG
Science

21 Dec 2012

BREAKTHROUGH
OF THE YEAR
Higgs Boson

- What is the Higgs Boson?
- Why is it important?
- What was its role in the early universe (the Big Bang)?
1929 - Hubble Discovered Universe is Expanding

Edwin Powell Hubble
(1889-1953)
1929 - Hubble Discovered Universe is Expanding

Edwin Powell Hubble (1889-1953)

Hubble's Plot of Galaxy Velocity & Distance

nearby galaxies can be moving towards us

Jim Brau
Oregon QuarkNet
June 26, 2013
1929 - Hubble Discovered Universe is Expanding

First evidence that Universe began with a Big Bang

Edwin Powell Hubble (1889-1953)
Universe’s Glow in Microwaves discovered in 1965

predicted following Hubble’s discovery

confirmed early universe of Big Bang
Big Bang
Big Bang

History of the Universe

Key:
- W, Z bosons
- quark
- gluon
- electron
- neutrino
- photon
- meson
- baryon
- galaxy
- ion
- atom
- black hole

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Oregon QuarkNet
June 26, 2013
Particles and Forces

“interactions”
A diagram illustrating the mass of different particles, categorized under FERMIONS and BOSONS. The diagram shows the mass on a logarithmic scale for particles like electron, muon, neutrinos, quarks, and Higgs boson. The mass values range from $10^{-12}$ to $10^{3}$ giga-electron-volts.
Forces
“interactions”

1850
• Gravity
• Electricity
• Magnetism
Are Forces Related?

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- Electricity
- Magnetism
Are Forces Related?

1864

Unified theory
- Electromagnetism
- Light (photons)

J.C. Maxwell

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“interactions”

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Are Forces Related?

**Early 20th Century**

- Gravity
- Electromagnetism
Are Forces Related?

Early 20th Century

- Gravity
- Electromagnetism

Einstein worked for years on a unified theory of Electromagnetism and Gravity UNSUCCESSFULLY
Forces

“interactions”

1950

• Gravity
• Electromagnetism
• Weak Nuclear
• Strong Nuclear

Are Forces Related?
Are Forces Related?

Forces “interactions”

2000
- Gravity

{ Electroweak
- Strong Nuclear

• Gravity

Electroweak

Strong Nuclear
Are Forces Related?

Anticipated - discovery of the Higgs Boson at accelerators

P. Higgs

Forces

“interactions”

2000

- Gravity

• Electroweak

• Strong Nuclear

Jim Brau             Oregon QuarkNet         June 26, 2013
Are Forces Related?

2000
- Gravity
- Electroweak
- Strong Nuclear

Are all forces related? New particles would be involved in any unification

Forces "interactions"
Indirect evidence of Higgs Before the LHC

- Since the Higgs boson interacts with fundamental particles (in theory) experiments can detect indirect evidence for it and "measure" its mass.
Indirect evidence of Higgs Before the LHC

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Indirect evidence for Higgs Before the LHC

- pre-LHC experiments find
  \[ M_H = 129^{+74}_{-49} \text{ GeV} \] (assuming Standard Model)
Large Hadron Collider (LHC)
Geneva, Switzerland
Large Hadron Collider
Large Hadron Collider

17 mile circumference main ring
300 feet underground
Large Hadron Collider

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300 feet underground
Proton beams of particles circulate in both directions
Large Hadron Collider

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Proton beams of particles circulate in both directions
1600 SuperC magnets @ 8.3 Tesla
Temp= 2 K
10,000 MegaJoules stored energy
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600,000,000 collisions per second
at 14,000,000,000,000 eVolts
Large Hadron Collider

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300 feet underground
Proton beams of particles circulate in both directions
1600 SuperC magnets @ 8.3 Tesla
Temp= 2 K
10,000 MegaJoules stored energy
600,000,000 collisions per second
at 14,000,000,000,000 eVolts
So far at 7 and 8,000,000,000,000 eV (7, 8 TeV)
Proton beam stores 700 MegaJoules equiv. to 747 energy on take-off enough to melt 1/2 ton copper
UO Group Worked on Search for the Higgs Boson at LHC
UO Group Worked on Search for the Higgs Boson at LHC

Higgs Boson is VERY HEAVY
UO Group Worked on Search for the Higgs Boson at LHC

Higgs Boson is VERY HEAVY
Equivalent to 133 Hydrogen atoms
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Equivalent to 133 Hydrogen atoms
or one Cesium atom
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126,000,000,000 eV = 126 GeV
Search for the Higgs Boson at the LHC
Search for the Higgs Boson at the LHC

slow motion
Search for the Higgs Boson at the LHC

slow motion
Search for the Higgs Boson at the LHC

slow motion

$E=mc^2$
Search for the Higgs Boson at the LHC

slow motion

\[ E = mc^2 \]

or Energy equals Mass
Producing the Higgs Boson at the LHC
Producing the Higgs Boson at the LHC
Producing the Higgs Boson at the LHC
Producing the Higgs Boson at the LHC
July 4, 2012

• The experiments ATLAS and CMS announced evidence for the Higgs Boson
July 4, 2012

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 $m_H = 126.5$ $4.6\sigma$

Global significance: $4.1 - 4.3\sigma$ (for LEE over 110-600 or 110-150 GeV)
July 4, 2012

ATLAS Collaboration, including UO Group, Announced Discovery
July 4, 2012

Combined results: consistency of the data with the background-only expectation and significance of the excess

Excellent consistency (better than 2σ) of the data with the background-only hypothesis over full mass spectrum
July 4, 2012

Combined results: consistency of the data with the background-only expectation and significance of the excess

ATLAS Preliminary

Excellent consistency (better than 20%) of the data with the background-only hypothesis over full mass spectrum

Peter Higgs
**Combined results: the excess**

**Maximum excess observed at**

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- Probability of background up-fluctuation: $3 \times 10^{-7}$
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Five Sigma Confidence
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- Five sigma is the threshold particle physics requires for DISCOVERY (very high standard)
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• THEN, randomness could produce the same result ONLY once in 3.5 million times
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- Example - flip coin 22 times and heads EVERY time
Five Sigma Confidence

• Five sigma is the threshold particle physics requires for DISCOVERY (very high standard)

• THEN, randomness could produce the same result ONLY once in 3.5 million times

• Example - flip coin 22 times and heads EVERY time possible, but very unlikely for normal coin
Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC

The ATLAS Collaboration

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

Abstract

A search for the Standard Model Higgs boson in proton-proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^{-1} collected at $\sqrt{s} = 7$ TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s} = 8$ TeV in 2012. Individual searches in the channels $H \to ZZ^{(*)} \to 4\ell$, $H \to yy$ and $H \to WW^{(*)} \to e\mu\nu$ in the 8 TeV data are combined with previously published results of searches for $H \to ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$ and $\tau^+\tau^-$ in the 7 TeV data and results from improved analyses of the $H \to ZZ^{(*)} \to 4\ell$ and $H \to yy$ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of $125.0 \pm 0.4$ (stat) $\pm 0.4$ (sys) GeV is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of $1.7 \times 10^{-9}$, is compatible with the production and decay of the Standard Model Higgs boson.
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ATLAS Detector

Weight- 7000 tons
July 4, 2012

- Evidence for the Higgs Boson that ATLAS and CMS resulted from:
July 4, 2012

• Evidence for the Higgs Boson that ATLAS and CMS resulted from:
  – 1 in $1,000,000,000,000,000$ collisions appear to produce two photons from a new particle

  – Data collected in 2011 and early 2012
What is the Higgs Boson?

Peter Higgs (1929-)

Satyendra Nath Bose (1894-1974)
What is the Higgs Boson?

• Theory postulated in 1964

by P. Higgs, R. Brout, F. Englert, G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble
What is the Higgs Boson?

• Theory postulated in 1964 –historical era

The Beatles arrive in USA, Kennedy Airport, Feb 1964

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Mad Men, AMC

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June 26, 2013
Higgs Boson

• Higgs bosons carry no spin - unique!
• Distributed throughout space, they create a Higgs condensate - a pure vacuum with energy
• This very stable vacuum field results from the mutual interactions of Higgs bosons
• To make them visible we must create a disturbance in the uniform Higgs field
The Higgs Boson is Different

• The Higgs is **both** force and matter particle
• Particle properties unique to known fundamental particles
  — spinless
• Possible key to unity of forces and the underpinnings of the universe
• Could be the first discovered member of a new form of matter (scalars)
The Higgs Field
The Higgs Field

• Familiar fields

Earth’s gravity

Magnetism
The Higgs Field

- Familiar fields

Earth’s gravity

Magnetism
The Higgs Field

- Familiar fields
  - Earth’s gravity
  - Magnetism

- The Higgs is both a field and a particle
Higgs Boson Theory

Peter Higgs

Kibble, Guralnik, Hagen, Englert, Brout
Higgs Boson Theory

• Higgs field fills the universe
Higgs Boson Theory

- Higgs field fills the universe

- Interacts with fundamental particles to give them mass
Higgs Boson Theory

• Higgs field fills the universe

• Interacts with fundamental particles to give them mass

• Separates electromagnetism and the weak nuclear force
  – photon remains massless
Why is the Higgs Important?

PARTICLE PHYSICS

• It gives mass to the fundamental particles of Nature
  – quarks, leptons, fundamental bosons, ....
  – without mass electrons would zip along at the speed of light and atoms would not form

• It produces differences in the fundamental forces
  – electromagnetism and the weak nuclear force
Why is the Higgs Important?

COSMOLOGY
Why is the Higgs Important?

COSMOLOGY

• Big Bang produced massless particles
  –13.8 billion years ago
Why is the Higgs Important?

COSMOLOGY

• Big Bang produced massless particles
  – 13.8 billion years ago
• Higgs field appeared everywhere
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• Universe expanded and cooled
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• Big Bang produced massless particles
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• Fundamental particles of Nature, initially massless, acquired mass from the Higgs field
Why is the Higgs Important?

COSMOLOGY

- Big Bang produced massless particles –13.8 billion years ago
- Higgs field appeared everywhere
- Universe expanded and cooled
- Fundamental particles of Nature, initially massless, acquired mass from the Higgs field
- Particles slowed, bunched up and eventually formed atoms, and atoms formed ...
History of the Universe

Key: $W, Z$ bosons, $\gamma$ photon, quark, meson, galaxy, gluon, baryon, electron, $\mu$, neutrino, $\nu$, star, ion, atom, black hole

Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

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What is Matter?
What is Matter?
What is Matter?
What is Matter?
What is Matter?

all Atomic
composed of quarks and leptons
We know galaxies are surrounded by dark halos of mysterious, unidentified stuff (dark matter).
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Expected-based on stellar mass
We know galaxies are surrounded by dark halos of mysterious, unidentified stuff (dark matter).

Expected—based on stellar mass

Observed—reveals invisible (“dark”) mass

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This pie represents all the “stuff” in the universe.
This pie represents all the “stuff” in the universe.

- 22% Dark Matter
- 4% Atoms
The Matter Crisis

- not enough matter (atomic or dark matter) to “make-up” known stuff of the Universe

This pie represents all the “stuff” in the universe

4% Atoms

22% Dark Matter
Acceleration Component called “Dark Energy”
Acceleration Component called “Dark Energy”

- Solves “Matter” Crisis
- The dominant “stuff” of the universe is dark matter and dark energy
The Dark Side Controls the Universe
The Dark Side Controls the Universe

Dark Matter HOLDS IT TOGETHER
The Dark Side Controls the Universe

Dark Matter HOLDS IT TOGETHER

Dark Energy DETERMINES ITS DESTINY
The Dark Side Controls the Universe

- Dark Matter HOLDS IT TOGETHER
- Dark Energy DETERMINES ITS DESTINY
- Dark Matter is strange!
- Dark Energy stranger?
Linear Collider
electron-positron collider
Linear Collider
electron-positron collider

FUTURE
Offers more precise studies of Higgs and other possible new physics
World-wide collaboration (including UO team) has developed the technology
Ready to start construction
LHC / ILC comparison
Higgstrahlung at ILC

\[
\begin{align*}
&\nu^- e^+ \\
&Z^* \\
&H \longrightarrow Z
\end{align*}
\]
Higgstrahlung at ILC

• Controlled production of the Higgs boson
Higgstrahlung at ILC

- Controlled production of the Higgs boson
- Tag events looking only at the Z (independent of behavior of the Higgs - then look at the Higgs
Higgstrahlung at ILC

• Controlled production of the Higgs boson
• Tag events looking only at the Z (independent of behavior of the Higgs - then look at the Higgs
• Is Higgs consistent with Standard Model, or not?
Higgstrahlung at ILC
Higgstrahlung at ILC

\[ \tilde{p}_e + \tilde{p}_e = \tilde{p}_Z + \tilde{p}_H \quad (4 \text{ vectors } \Rightarrow \ E \text{ and } \vec{p}) \]
Higgstrahlung at ILC

- $\tilde{p}_e + \tilde{p}_e = \tilde{p}_Z + \tilde{p}_H$ (4 vectors $\Rightarrow$ $E$ and $\vec{p}$)
- $\tilde{p}_H = \tilde{p}_e + \tilde{p}_e - \tilde{p}_Z$ $\Rightarrow$ $\tilde{p}_H^2 = M_H^2 = (\tilde{p}_e + \tilde{p}_e - \tilde{p}_Z)^2$
Higgstrahlung at ILC

• $\tilde{p}_e + \tilde{p}_e = \tilde{p}_Z + \tilde{p}_H$ (4 vectors $\Rightarrow$ E and $\vec{p}$)
• $\tilde{p}_H = \tilde{p}_e + \tilde{p}_e - \tilde{p}_Z \Rightarrow \tilde{p}_H^2 = M_H^2 = (\tilde{p}_e + \tilde{p}_e - \tilde{p}_Z)^2$
Higgs boson decays
Hierarchy Problem
Hierarchy Problem

- Mass of the Higgs boson is affected by radiative corrections (very large)
Hierarchy Problem

- Mass of the Higgs boson is affected by radiative corrections (very large)

relation for Higgs mass:

- \( m_H^2 = \) bare mass\(^2 + (R.C.)^2 \)
Hierarchy Problem

- Mass of the Higgs boson is affected by radiative corrections (very large)

  relation for Higgs mass:

  \[ m_H^2 = \text{bare mass}^2 + (\text{R.C.})^2 \]

- New physics needed to keep mass small (125 GeV) by canceling R.C.
Fine tuning

The large radiative corrections look particularly absurd, if, say, \( \Lambda_{\text{new physics}} = M_P \). Says something like

\[
m_H^2 = 36, 127, 890, 984, 789, 307, 394, 520, 932, 878, 928, 933, 023
\]

\[-36, 127, 890, 984, 789, 307, 394, 520, 932, 878, 928, 917, 398\]

This looks crazy!
Possible solutions to Hierarchy Problem

• Supersymmetry
  – new particles truncate radiative corrections
• Extra dimensions
  – motivated by string theory
• Composite Higgs
  – not fundamental scalar - rather, composite particle
  – new force, eg. Technicolor, binds heavy particles into Higgs boson
Are there any practical applications?
1897 - J.J. Thomson
1897 - J.J. Thomson  Electron

Credit: American Institute of Physics

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J.J. Thomson, On 1897 Discovery
Speaking in 1934
J.J. Thomson, On 1897 Discovery

Could anything at first sight seem more impractical than a body which is so small

Speaking in 1934

From the soundtrack of the film, Atomic Physics

Credit: American Institute of Physics
J.J. Thomson, On 1897 Discovery

Speaking in 1934

Could anything at first sight seem more impractical than a body which is so small that its mass is an insignificant fraction of the mass of an atom of hydrogen? --


Credit: American Institute of Physics
J.J. Thomson, On 1897 Discovery

Speaking in 1934

Could anything at first sight seem more impractical than a body which is so small that its mass is an insignificant fraction of the mass of an atom of hydrogen? -- which itself is so small

From the soundtrack of the film, Atomic Physics

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Speaking in 1934

Could anything at first sight seem more impractical than a body which is so small that its mass is an insignificant fraction of the mass of an atom of hydrogen? -- which itself is so small that a crowd of these atoms equal in number to the population of the whole world

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Could anything at first sight seem more impractical than a body which is so small that its mass is an insignificant fraction of the mass of an atom of hydrogen? -- which itself is so small that a crowd of these atoms equal in number to the population of the whole world would be too small to have been detected by any means then known to science.


Credit: American Institute of Physics
Summary:

Higgs Boson: Window on the Big Bang

• Higgs boson aims to explain mysteries of physics and early universe

• Higgs boson-like particle discovered in 2012 by large, international collaborations at the LHC in Switzerland (including strong UO team)

• Detailed properties of new particle will be measured in more detail to determine its full nature

• LHC experiments search for more - eg. Dark Matter

• Future - International Linear Collider
Acknowledgements

RESEARCH SUPPORTED BY

Department of Energy
OFFICE OF SCIENCE

NATIONAL SCIENCE FOUNDATION

Philip H. Knight

Acknowledgement: images from http://www.AstroPics.com