Quest for the Higgs Boson
Closing in on the origin of mass of fundamental particles

Bernd Stelzer
SFU
Particle Physics:

Study of the *smallest building blocks of the universe*, their properties and interactions.
Big Bang Theory

1-20 min
300,000 years
500 million years
13.7 billion years (today)
The Large Hadron Collider (LHC)
What is the Mass of Particles?

“the property of a body that is a measure of its inertia and that is commonly taken as a measure of the amount of material it contains and causes it to have weight in a gravitational field”

Isaac Newton
**What is Matter?**

**PERIODIC TABLE OF THE ELEMENTS**

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Relative atomic mass is shown with five significant figures. For elements having two stable nuclides, the value enclosed in brackets indicates the major mass of the longest-lived isotope of the element.

However, these so-called rare elements (Th, Pa, and U) do have a characteristic 90% isotopic composition, and for these the atomic weight is indicated.

*Editor: Abd-Allah Manhoun (adva@netlinx.com)*

Bernd Stelzer
What is Matter made of?

- **Atoms**
  - **Nucleus**
  - **Electrons**
The Empty Space inside Atoms
Knowledge gained in the last Century

~0
atom
10^{-8} \text{ cm}

~1910
nucleus
10^{-12} \text{ cm}

~1940
proton (neutron)
10^{-13} \text{ cm}

~1970
electron
<10^{-18} \text{ cm}

quark
<10^{-18} \text{ cm}

\[ \frac{1}{10,000} \]

\[ \frac{1}{10} \]

\[ \frac{1}{100,000} \]
Knowledge gained in the last Century
The Standard Model of Particle Physics
The Standard Model of Particle Physics

Quarks
-2/3 u c t
1/3 d s b

Leptons
-1 e μ τ
0 ν_3, ν_μ, ν_τ

Forces
Z
γ
W
g

Weak
E&M
Strong

Higgs boson

PERIODIC TABLE OF THE ELEMENTS

Standard Model
The Higgs Mechanism

1964

2010 J. J. Sakurai Prize for Theoretical Particle Physics

2013 Nobel Prize in Physics

Bernd Stelzer
Simon Fraser University
The Higgs Mechanism

Why do particles have mass?

- Higgs field permeates all space and interacts with particles
- Strong interaction $\Leftrightarrow$ large mass
Spontaneous Symmetry Breaking

Nambu-Goldstone

Higgs boson
Sheldon and the Higgs Boson
Making a ripple in the Higgs Field

Higgs boson
The Higgs field gives mass to particles.
The Large Hadron Collider (LHC)

Air at room temperature: 0.04 eV
TRIUMF cyclotron: 500 000 000 eV
Large Hadron Collider: 8 000 000 000 000 000 000 eV

~20 °C
~10^{11} °C
~10^{15} °C
The Higgs Boson Mass

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.
The Large Hadron Collider (LHC)

- protons go fast: 99.999999% of the speed of light
- make a full turn 11254 times per second
Large Hadron Collider – Race Track
Collision Experiment - Typical Experience
Collision Experiments – Quantum Probability

\[ E = mc^2 \]

- Mack: 0%
- Mater: 2%
- J Bieber: 13%
- Higgs: 85%

Simon Fraser University
Bernd Stelzer
Higgs boson couples to massive particle. But constituents of the proton are light. Requires more complex interactions – Feynman tells us, these will occur very rarely, only once for every Trillion proton collision!

Feynman diagrams

“Gluon fusion”

“Vector boson fusion”

Requires many collisions (many chances to produce a Higgs)
We have collided protons on protons 1 000 000 000 000 000 000 000 times!!
LHC is a Supercollider

Higgs boson
Finding the Higgs with Photons

Higgs Production

or

Background ?
Finding the Higgs with Photons

- Higgs boson decays to two energetic photons
  - Higgs mass can be determined from decay kinematics

- Background process looks identical
  - many times larger probability

from relativity:

\[ M_H^2 c^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2 c^2 \]
Finding the Higgs with Two Photons

\[ \sqrt{s} = 7 \text{ TeV} \int L \, dt = 0.00 \text{ fb}^{-1} \]

Mar 25, 2011

**ATLAS** Preliminary

H\(\rightarrow\gamma\gamma\) channel

![Graph](image-url)
LHC is a Supercollider

Selected diphoton sample

- Data 2011+2012
- Sig+Bkg Fit ($m_H = 126.8$ GeV)
- Bkg (4th order polynomial)

**ATLAS** Preliminary

$H \rightarrow \gamma\gamma$

$\sqrt{s} = 7$ TeV, $L = 4.8$ fb$^{-1}$
$\sqrt{s} = 8$ TeV, $L = 20.7$ fb$^{-1}$

Events / 2 GeV

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CMS

$\sqrt{s} = 7$ TeV, $L = 5.1$ fb$^{-1}$
$\sqrt{s} = 8$ TeV, $L = 5.3$ fb$^{-1}$

**Total weight** 14000 t
**Overall diameter** 15 m
**Overall length** 28.7 m

**CMS ENDCAPS**
- 473 Cathode Strip Chambers (CS)
- 432 Resistive Plate Chambers (RPC)

**MUON BARREL**
- 250 Drift Tubes (DT) and 480 Resistive Plate Chambers (RPC)

**ECAL**
- 76k scintillating PoWO$_3$ crystals

**HCAL**
- Scintillator/brass
- Interleaved ~7k ch

**Preshower**
- Si Strips ~1 m$^2$, ~66M ch
- Si Strips (80-180 $\mu$m)
- ~200 m$^2$, ~8.6M ch

**Pixel Tracker**
- Pixels (1000x150 $\mu$m$^2$)
- ~1 m$^2$, ~66M ch

**Solenoid**
- 3.8T

Discussion with Bernd Stelzer
\( p_0 \): Probability that the observed data originated from background sources or measurement uncertainty (i.e. probability that is not a Higgs like particle) = Probability of 21 heads in a row.
LHC is a Supercollider

!!! BEAM AT ATLAS !!!
20-11-09 20:47
A Day to Remember

An historical day: 4th July 2012
• On July 4th, media was headlining stories about the Higgs boson
Many New Results since last year!

New particle is now confirmed to be a Higgs boson particle!

**ATLAS**

\[ m_H = 125.5 \text{ GeV} \]

**H → γγ**
\[ \mu = 1.55^{+0.33}_{-0.28} \]
\[ ±0.23 \]
\[ ±0.15 \]
\[ ±0.15 \]

Low \( p_T \)
\[ \mu = 1.6^{+0.5}_{-0.4} \]
\[ ±0.3 \]

High \( p_T \)
\[ \mu = 1.7^{+0.7}_{-0.6} \]
\[ ±0.5 \]

2 jet high mass (VBF)
\[ \mu = 1.9^{+0.8}_{-0.6} \]
\[ ±0.6 \]

VH categories
\[ \mu = 1.3^{+1.2}_{-1.1} \]
\[ ±0.9 \]

**H → ZZ∗ → 4l**
\[ \mu = 1.43^{+0.40}_{-0.35} \]
\[ ±0.33 \]
\[ ±0.17 \]
\[ ±0.14 \]

VBF/VH-like categories
\[ \mu = 1.2^{+1.6}_{-0.9} \]
\[ ±1.8 \]
\[ ±0.9 \]

Other categories
\[ \mu = 1.45^{+0.43}_{-0.36} \]
\[ ±0.35 \]

**H → WW∗ → lνlν**
\[ \mu = 0.99^{+0.31}_{-0.28} \]
\[ ±0.21 \]
\[ ±0.21 \]
\[ ±0.12 \]

0+1 jet
\[ \mu = 0.82^{+0.33}_{-0.32} \]
\[ ±0.22 \]

2 jet VBF
\[ \mu = 1.4^{+0.7}_{-0.6} \]
\[ ±0.5 \]

Comb. H → γγ, ZZ∗, WW∗
\[ \mu = 1.35^{+0.21}_{-0.18} \]
\[ ±0.14 \]
\[ ±0.15 \]
\[ ±0.11 \]

**ATLAS Preliminary**

\( \sqrt{s} = 7 \text{ TeV} \):
\[ \int L dt = 4.6-4.8 \text{ fb}^{-1} \]

\( \sqrt{s} = 8 \text{ TeV} \):
\[ \int L dt = 13-20.7 \text{ fb}^{-1} \]

- **H → γγ**
- **H → ZZ∗ → 4l**
- **H → WW∗ → lνlν**

- *Standard Model*
- *Best fit*
- 68% CL
- 95% CL

Upper left: Momentum direction
Upper right: Angular momentum direction

\( m_H = 125.5 \text{ GeV} \)
Cern scientists believe newly discovered particle is the real Higgs boson

Results of analysis at Cern in Switzerland show particle behaves precisely as expected.

Ian Sample, science correspondent
The Guardian, Friday 15 March 2013

One year ago, several hours before cities across the United States started their annual fireworks displays, a different type of fireworks were set off at the European Center for Nuclear Research (CERN) in Switzerland. At 9:00 a.m., physicists announced to the world that they had found something they had been searching for for nearly 50 years: the elusive Higgs boson.
Why the Higgs Field Matters?

What if we could **switch off** the Higgs field?

1. Good news: we loose some weight!
2. Bad news: **there will be no atoms**!
3. Protons will not be stable, but decay
4. No nuclear fusion **no suns** – **dark universe**

Bohr radius:

\[ a_0 = \frac{4\pi\varepsilon_0 h^2}{m_e e^2} \]
3000 Physicists from 38 countries and 174 institutes
Rob McPherson, Spokesperson (University of Victoria, IPP)
Richard Teuscher, Deputy Spokesperson (University of Toronto, IPP)
Reda Tafirout, Computing Coordinator (TRIUMF)
Bernd Stelzer, Physics Coordinator (Simon Fraser University)

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University of Alberta
University of British Columbia
Carleton University
McGill University
Université de Montréal
Simon Fraser University
University of Toronto
TRIUMF, Vancouver
University of Victoria
York University

(150 Canadians from 10 institutes)
• About 10,000 magnets (15m long, 35 tons, 8.4 Tesla)
• Operated at colder than outer space (superconductors)

April 26th 2007
Canada made important contributions to the LHC machine.

Canadians made substantial contributions to the construction of the LHC through TRIUMF. This involved upgrades to the injector synchrotrons to provide the LHC beams with higher brightness, ferrite rings and high voltage power supplies for the PS booster upgrade, booster to PS transfer lines, twin-aperture quadrupole magnets for beam injection cleaning, pulse forming networks and injection kicker magnets to the LHC and beam position monitors.
100 million electronic signals ("pixel")
3000 km of wires

<table>
<thead>
<tr>
<th></th>
<th>Weight (tons)</th>
<th>Length (m)</th>
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<tbody>
<tr>
<td>ATLAS</td>
<td>7,000</td>
<td>42</td>
<td>22</td>
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<tr>
<td>CMS</td>
<td>12,500</td>
<td>21</td>
<td>15</td>
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Canadian Contribution to ATLAS

TRIUMF: detector completed in 2004

Calorimeter measure energy of particles
Building the ATLAS Experiment

Feb 2000

July 2002

Feb 2004

Dec 2004
Moving Calorimeters in Place

Feb 2007

May 2008, side A
Closing the LHC Beamline

(June 2008)
Canada will build 40% of the upgraded ATLAS NSW sTGC muon detectors (to cope with high intensity LHC beam)
Build your own ATLAS Detector
Grid Computing

In Canada:
Tier-1 center: TRIUMF/SFU
Tier-2 center: SFU, UVic, Alberta, Toronto, McGill

260 sites
>140,000 CPU cores
>25 PB disk
≈39 PB tape
Computing Challenge – Fun Facts

• The ATLAS experiment records about 3 PetaBytes of data/year (3 Million GigaBytes/year).

• Imagine a stack of DVDs twice the height of Shangri-la building every year!

> 140 000 CPUs, interconnected to a supercomputer around the World

TRIUMF

CERN Tier-0
Other Questions the LHC could answer!

1. What is the Origin of mass?  
   Find Higgs boson(s).

2. What is Dark Matter?  
   LHC should be able to produce it!

3. Where did the anti-matter go?  
   We only know part of the story

4. Grand Unified Theory (GUT):  
   Unify all forces to a super force

5. Are there additional space-time dimensions?

6. Explore the unknown  
   Surprises can happen at any time

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Simon Fraser University

Bernd Stelzer
The Team

ATLAS EXPERIMENT

Bernd Stelzer
Simon Fraser University
SFU ATLAS Group

http://higgs.phys.sfu.ca/