The God particle at last?

Astronomy Ireland, Oct 8th, 2012

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A new particle of mass 125 GeV
Overview

I  The Higgs boson
   Particle physics and the Standard Model

II  The Large Hadron Collider
   What, why, how

III  The discovery
   A new particle at the LHC

IV  The future
   Physics beyond the Standard Model
Why is the Higgs particle important?

I. **Fundamental structure of matter**
   Undetected particle of the Standard Model
   Key particle; Higgs field bestows mass

II. **Fundamental interactions**
   Interaction of particles and forces
   Role of Higgs field in electro-weak unification
   Unified field theory?

III. **Snapshot of early universe**
   Highest energy density since BB
   Puzzle of dark matter, dark energy
   
   \[ T = 10^{19} \text{ K, } t = 1 \times 10^{-12} \text{ s} \]
   
   ‘God particle’
I Early particle physics (1900-1912)

- Discovery of the atom (1908)
  *Einstein-Perrin*

- Discovery of the nucleus (1911)
  *Rutherford Backscattering*

- Positive, tiny core
  *Fly in the cathedral*

- Negative electrons outside
  *Fundamental particles (1895)*

  - What holds electrons in place?
  - What holds nucleus together?
  - What causes radioactivity?
Atoms and chemistry

- **Discovery of the proton** (1918)
  Particle of +ve charge inside nucleus

- **Explains periodic table**
  Atoms of different elements have different number of protons in nucleus
  Determines chemical properties
  Number protons = number electrons (Z)

- **Discovery of the neutron** (1932)
  Uncharged particle in nucleus
  Explains atomic masses

What holds nucleus together?
Strong nuclear force (1934)

- New force >> electromagnetic
- Extremely short range
- Independent of electric charge (p+, n)
- Quantum field theory
- New particle associated with force
- Acts on protons and neutrons
- Three possible charge states

Yukawa pion $\pi^-, \pi_0, \pi^+$

Discovered 1947 (cosmic rays)
Weak nuclear force (1934)

- Radioactive decay of nucleus
- Changes number of protons in nuc
- Neutrons changing to protons?
- Beta decay of the neutron

\[ n \rightarrow p^+ + e^- + \nu \]

- New particle: neutrino
- Discovered 1956
- Fermi’s theory of the weak force
- Four interacting particles

Mechanism?
Four forces of nature (1930s)

- **Force of gravity**
  - Long range
  - Holds cosmos together

- **Electromagnetic force**
  - Holds atoms together

- **Strong nuclear force**
  - Holds nucleus together

- **Weak nuclear force**
  - Responsible for radioactivity (Fermi)
New elementary particles (1940-50)

Cosmic rays

$$\pi^+ \rightarrow \mu^+ + \nu$$

Particle accelerators

Pions, muons, neutrinos, antiparticles
Antimatter

- Dirac equation for the electron
- Twin solutions
- Negative energy values?

- Particles of opposite charge (1928)
- Anti-electrons (detected 1932)
- Anti-particles for all particles

- Energy creates matter and anti-matter
- Why is the universe made of matter?
Walton: accelerator physics

Cockcroft and **Walton**: linear accelerator

Protons used to split the nucleus (1932)

\[
^1\text{H}_1 + ^3\text{Li}_{6.9} \rightarrow ^2\text{He}_4 + ^2\text{He}_4
\]

Verified mass-energy \((E = mc^2)\)

Verified quantum tunnelling

*Nobel prize (1956)*

_Cavendish lab, Cambridge_
Particle Zoo (1950s, 1960s)

<table>
<thead>
<tr>
<th>BARYONS</th>
<th>MESONS</th>
<th>LEPTONS</th>
<th>PHOTON</th>
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<td>Charge</td>
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Over 100 ‘elementary’ particles
Quark model (1964)

- Symmetry arguments
- Protons not fundamental
- Made up of smaller particles
- New fundamental particles **Quarks** *(fractional charge)*
- Hadrons: particles containing quarks
  - Baryons (3 quarks)
  - Mesons (2 quarks)

*Prediction of $\Omega^-$*

Gell-Mann, Zweig
Quarks (experiment)

**Stanford/MIT 1969**

- Scattering experiments (similar to RBS)
- Three centres of mass inside proton
- Strong force = inter-quark force!

- Defining property = *colour*
- Quark confinement
- Infra-red slavery

The energy required to produce a separation far exceeds the pair production energy of a quark-antiquark pair
The quark model (1970s – 1990s)

- 30 years experiments
- Six different quarks \((u,d,s,c,b,t)\)
- Six corresponding leptons \((e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau)\)
- Gen I: all of ordinary matter
- Gen II, III redundant?

New periodic table
Particle theory and forces (1960 -)

- Strong force mediated by gluons
- Electromagnetic force mediated by photons
- Weak force mediated by $W$ and $Z$ bosons
- Problems constructing theory of weak force

- $Em + w$: single interaction above 100 GeV
- Quantum field causes symmetry breaking
- Separates $em$, weak interactions
- Endows $W$, $Z$ bosons with mass
- Called the Higgs field
The Higgs field

- Electro-weak symmetry breaking
- Mediated by scalar field
- Higgs field
- Generates mass for W, Z bosons

W and Z bosons (CERN, 1983)

- Generates mass for all massive particles
- Self-interaction
- Associated particle: scalar boson
- Higgs boson

Particle masses not specified
The Standard Model (1970-90s)

- Strong force = quark force (QCD)
- EM + weak force = electroweak force
- Higgs field causes e-w symmetry breaking
- Gives particle masses

- Matter particles: fermions (1/2 integer spin)
- ‘Force’ particles: bosons (integer spin)

Experimental tests

- Top, bottom, charm, strange quarks
- Leptons
- $W^+, Z^0$ bosons

*Higgs boson* outstanding
The Higgs field

- Particles acquire mass by interaction with the field
- Some particles don’t interact (massless)
  \textit{Photons travel at the speed of light}
- Heaviest particles interact most
  \textit{Top quarks}
- Self-interaction = Higgs boson

\textit{Mass not specified by SM}
II The Large Hadron Collider (CERN)

- Particle accelerator (8TeV)
- High-energy collisions ($10^{12}$/s)
- Huge energy density
- Create new particles
  \[ E = mc^2 \]
- Detect particle decays
- Four particle detectors

No black holes
How

- Two proton beams
- $E = (4 + 4) \text{ TeV}$
- $v = \text{speed of light}$
- $10^{12}$ collisions/sec

- Ultra high vacuum
- Low temp: 1.6 K
- Superconducting magnets

**LEP tunnel:** 27 km
**Luminosity:** 5.8 fb$^{-1}$
Around the ring at the LHC

- Nine accelerators
- Cumulative acceleration
- Velocity increase?
- \( K.E = \frac{1}{2}mv^2 \)
- Mass increase \( \times 1000 \)

\[
m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}}\]
Particle detectors

Detectors at crossing pts

- CMS  
  multi-purpose

- ATLAS  
  multi-purpose

- ALICE  
  quark-gluon plasma

- LHC-b  
  antimatter decay
Particle detection

- **Tracking device**
  Measures particle momentum

- **Calorimeter**
  Measures particle energy

- **Identification detector**
  Measures particle velocity
  Cerenkov radiation

- **Analysis of decay tracks**
  GRID computing
III  A Higgs at the LHC?

- Search for excess events
  Mass not specified?

- Close windows of possibility


- Set by mass of top quark, Z boson

- Search…running out of space!
Higgs production in LHC collisions

associated production with $W/Z$: $q\bar{q} \rightarrow V + H$

vector boson fusion: $qq \rightarrow V^*V^* \rightarrow qq + H$

associated production with heavy quarks: $gg, q\bar{q} \rightarrow Q\bar{Q} + H$

$g \rightarrow H$

$g \rightarrow \bar{Q}$
Higgs decay channels

- Most particles interact with Higgs
- Variety of decay channels
- Massive particles more likely
- Difficult to detect from background
- Needle in a haystack

*Needle in haystack of needles*

*High luminosity required*

\[ N = \sigma \int L \, dt \]
Analysis

- Huge number of collisions
  *Data analysis*

- World Wide Web
  *Platform for sharing data*

- GRID
  *Distributed computing*

- World-wide analysis

- Huge increase in computing power
Higgs search at LHC (2011)

Excess events at 125 GeV in ATLAS and CMS detectors

Higher luminosity required 4.8 fb⁻¹
April-July 2012: 8 TeV, $5.8 \text{ fb}^{-1}$

Measure energy of photons emitted

Measure decay products of Z bosons
Results (July, 2012)

$H \rightarrow \gamma \gamma$  \hspace{1em} (8 TeV, 5.3 fb$^{-1}$)
Results (July, 2012)

$H \rightarrow ZZ$  (8 TeV, 5.3 fb$^{-1}$)
Results: all decay channels
Results summary

- New particle
- Mass 126 +/- 0.5 GeV
- Zero charge
- Integer spin (zero?)
- Scalar boson
- 6 sigma signal (August, 2012)

*Higgs boson?*
IV  Next at the LHC

- **Characterization of new boson**
  Branching ratios, spin
  Deviations from SM?

- **Supersymmetry**
  Numerous Higgs?
  Other supersymmetric particles
  Implications for unification

- **Cosmology**
  Dark matter particles?
  Dark energy?
  Higher dimensions?
Supersymmetry

- Success of electro-weak unification
- Extend program to all interactions?
- Super-force - theory of everything
- No-go theorems (1960s)

- Unification by supersymmetry (1970s)
- Symmetry between bosons and fermions
- New families of particles (incl Higgs)

*Broken symmetry – particles not seen
Heavy particles (LHC?)*
Cosmology at the LHC

- Snapshot of early universe
  *Highest energy density since BB*

- Dark matter particles?
  *Neutralinos (SUSY)*

- Dark energy?
  *Scalar field*

- Higher dimensions?
  *Kaluza Klein particles*

- String theory?

\[ T = 10^{19} K, \ t = 1 \times 10^{-12} \ s, \ V = \text{football} \]
Summary (2012)

- New particle detected at LHC
- Mass 126 +/- 0.5 GeV
- Zero charge, integer spin (zero?)
- Consistent with Higgs boson
- Confirmation of $e$-$\nu$ unification
- SM right so far

*En route to a theory of everything?*
LHC and cosmology

closer to the Big Bang

particle accelerator = time machine
recreate at microscopic scale the physics soon after the Big Bang

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<td>$10^{-23}$</td>
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Time after Big Bang

- LHC pp
- LEP
- LHC Ions
- Nucleosynthesis
- Stars
- Galaxy

Today
Epilogue: CERN and Ireland

European Centre for Particle Research

- World leader
- 20 member states
- 10 associate states
- 80 nations, 500 univ.
- Ireland not a member

No particle physics in Ireland.....almost