The God particle at last?

Science Week, Nov 15th, 2012

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Waterford Institute of Technology

CERN July 4th 2012 (ATLAS and CMS)

"A new particle of mass 125 GeV "

Why is the Higgs particle important?

I. **Fundamental structure of matter**

Key particle in theory of matter

Outstanding particle

II. **The forces of nature**

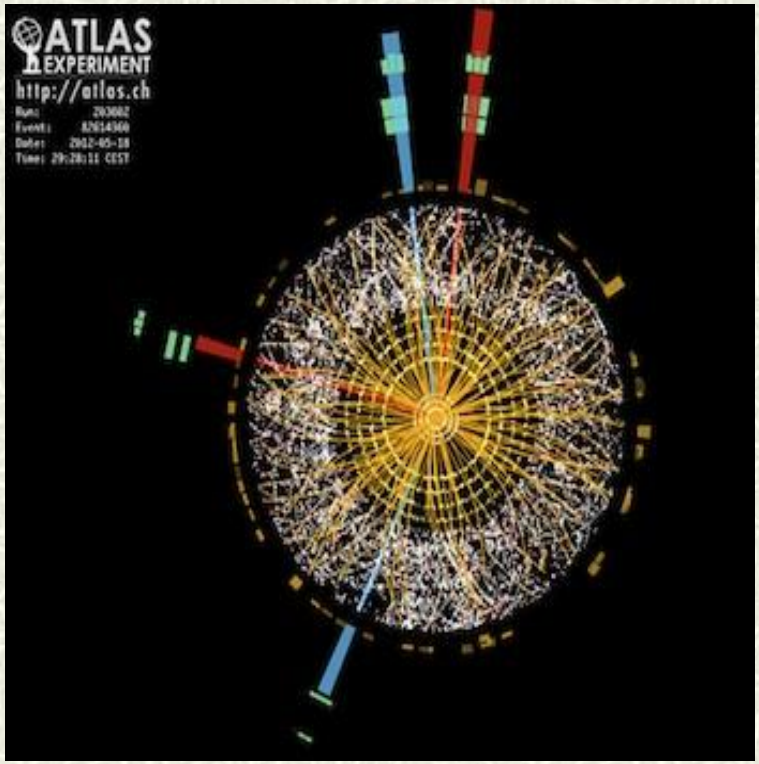
Interaction of particles and forces

Role of Higgs field in unified field theory

III. **Study of early universe**

Highest energy density since first instants

Info on origin of universe



'God particle'

Overview

I The Higgs boson

Particle physics and the Standard Model

II The Large Hadron Collider

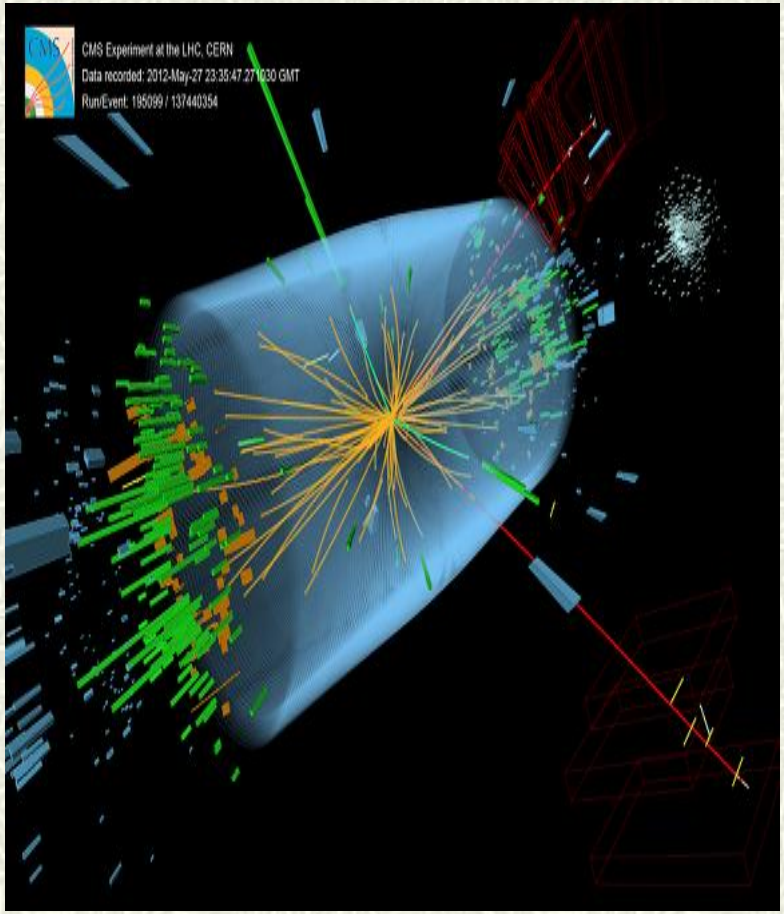
What, why, how

III The discovery

A new particle at the LHC

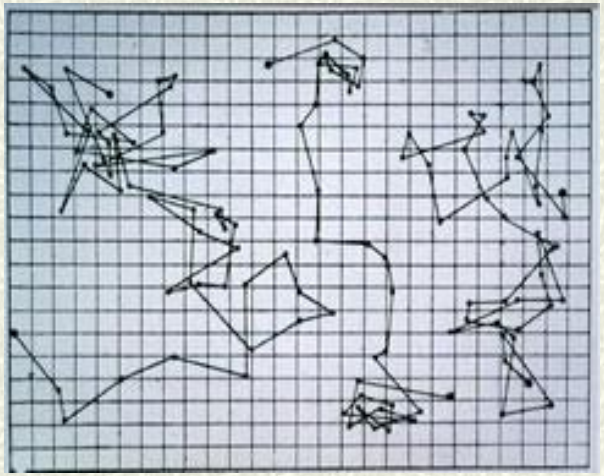
IV The future

Physics beyond the Standard Model

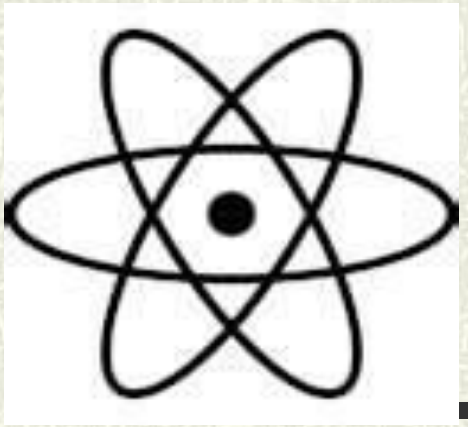


I Early particle physics (1900-1912)

- **Discovery of the atom** (1908)
  Einstein-Perrin (expected)
- **Discovery of the nucleus** (1911)
  Rutherford Backscattering (surprise)
- **Positive, tiny core**
  Fly in the cathedral
- **Negative electrons outside**
  Fundamental particles (1895)

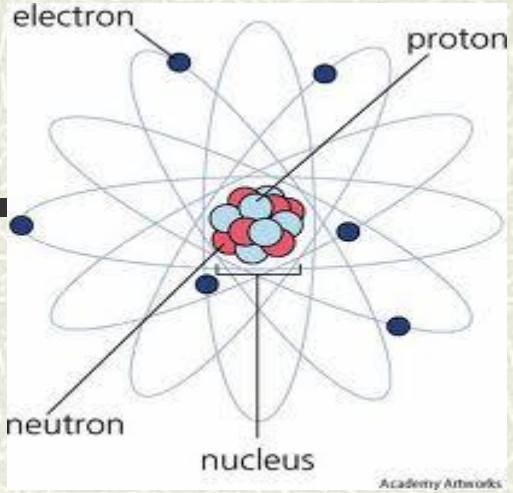


Brownian motion



- ***What holds electrons in place?***
- ***What holds nucleus together?***
- ***What causes radioactivity?***

Atoms and chemistry



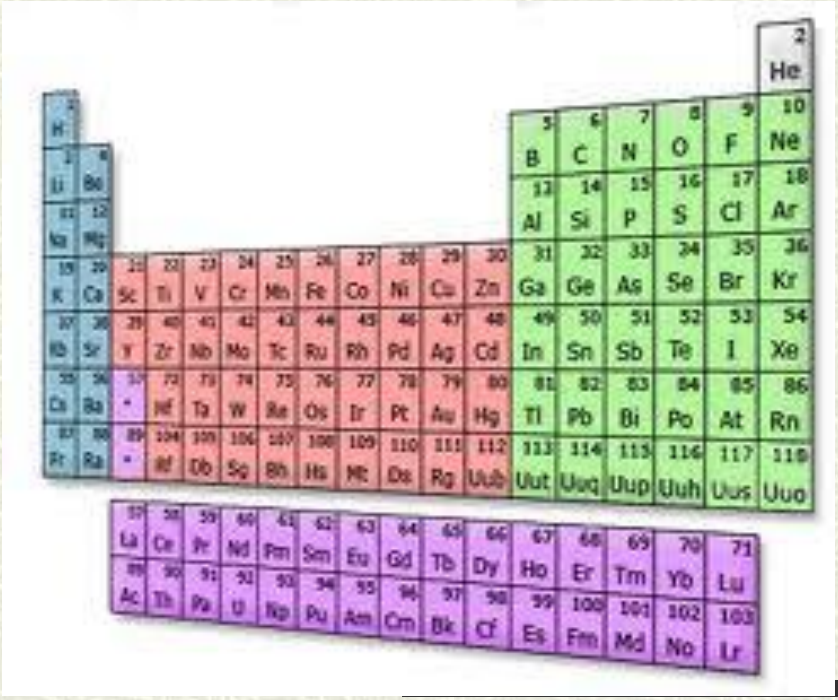
- **Discovery of the proton** (1918)
  Particles of +ve charge inside nucleus

- **Explains periodic table**
  Atoms of different elements have different number of protons in nucleus

  Number protons = number electrons (Z)
  Determines chemical properties

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

What holds nucleus together?



Strong nuclear force (1934)

- New force >> electromagnetic
- Independent of electric charge (p+, n)
- Extremely short range

- Quantum theory
- New particle associated with force
- Acts on protons and neutrons

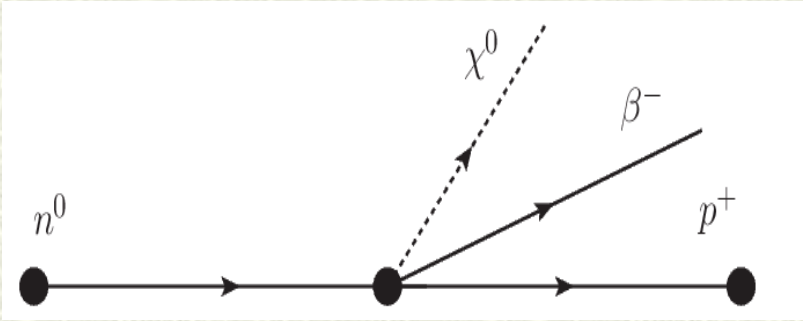
Hideki Yukawa

Yukawa pion π^-, π_0, π^+

Discovered 1947 (cosmic rays)

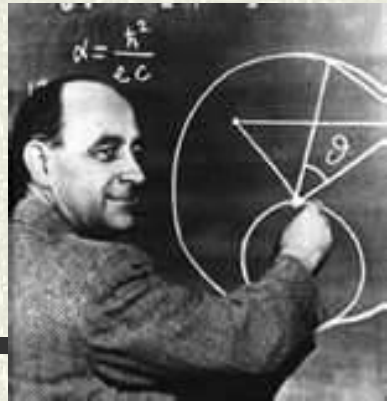
Weak nuclear force (1934)

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



$$n \rightarrow p^+ + e^- + \nu$$

Enrico Fermi



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

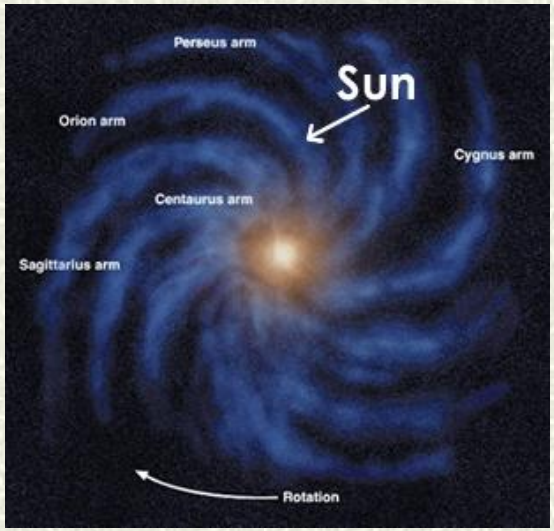
Four forces of nature (1930s)

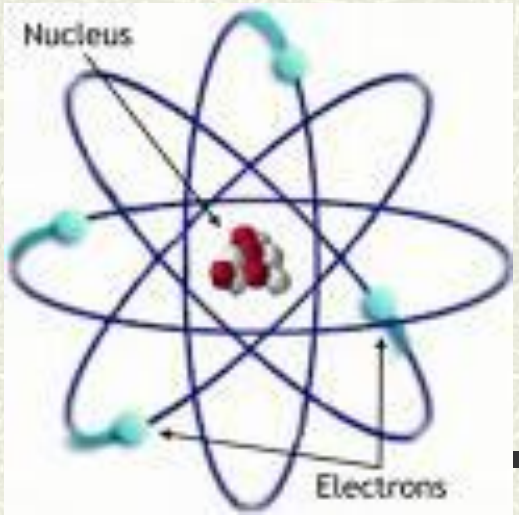
- **Force of gravity**
  Long range
  Holds cosmos together

- **Electromagnetic force**
  Electricity + magnetism
  Holds atoms together

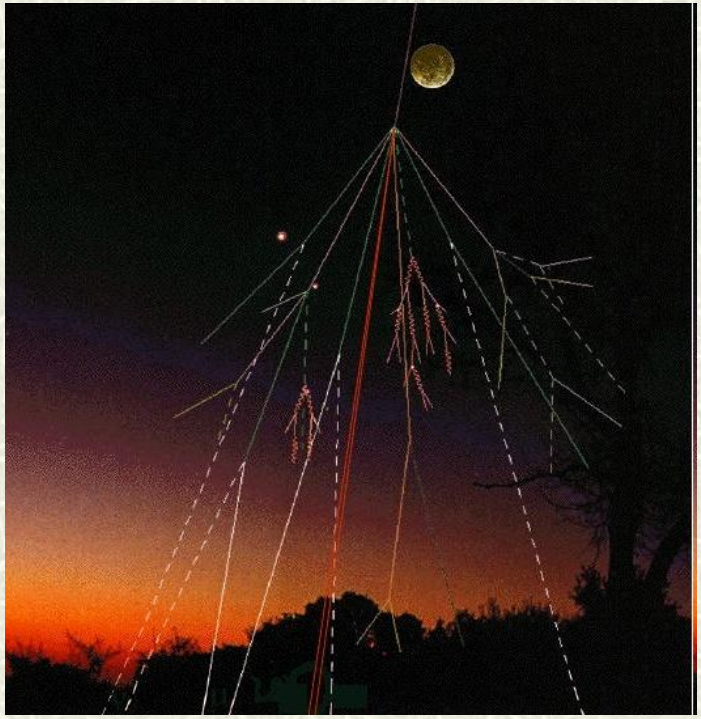
- **Strong nuclear force**
  Holds nucleus together

- **Weak nuclear force**
  Responsible for radioactivity (Fermi)

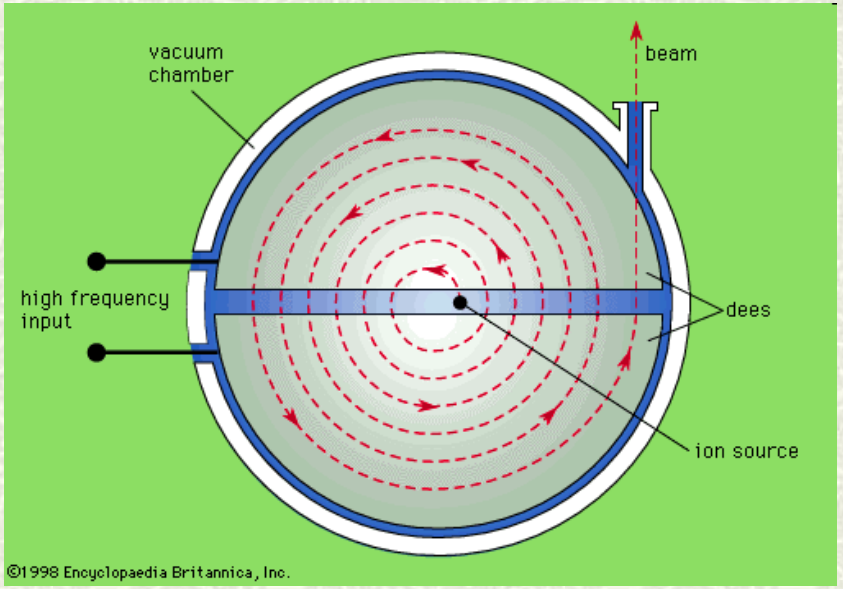




New elementary particles (1940-50)



Cosmic rays



Particle accelerators

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

Pions, muons, neutrinos, antiparticles

Walton: accelerator physics

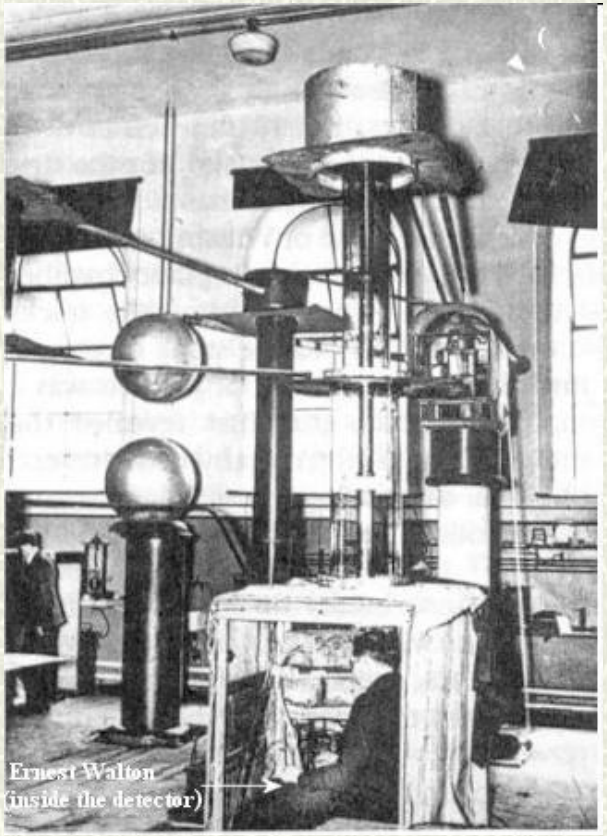
Cockcroft and **Walton**: linear accelerator

Protons used to split the nucleus (1932)

$$^{1}H_{1} + {}^{3}Li_{6.9} \rightarrow {}^{2}He_{4} + {}^{2}He_{4}$$

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

New way of creating particles?



Nobel prize (1956)

Cavendish lab, Cambridge

High-energy physics

$E = mc^2$

- Accelerate charged particles to high velocity

  High voltage

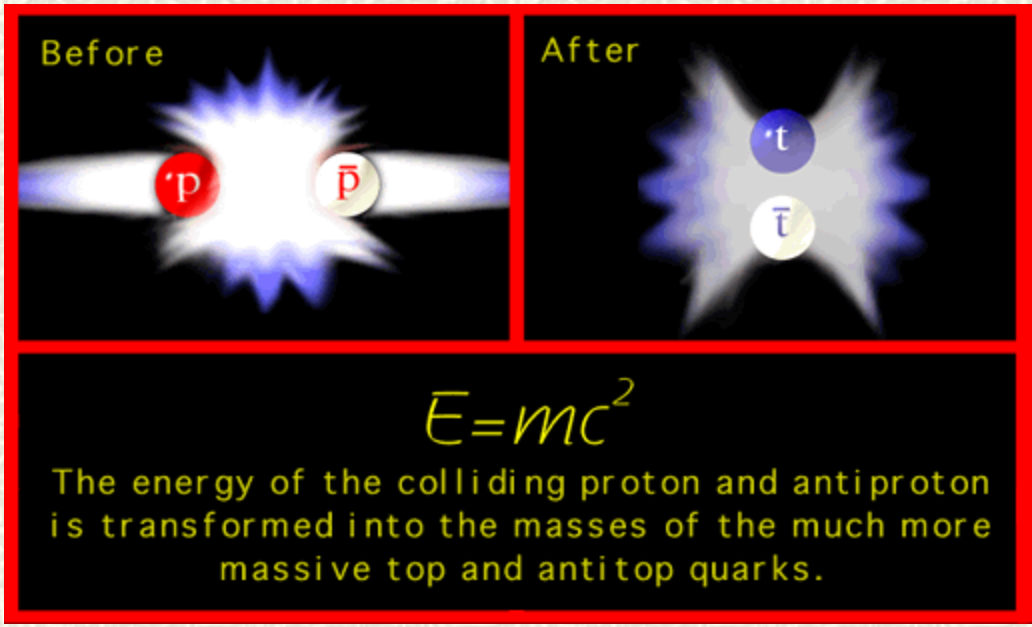
- Collisions

- High energy density

- New particles observed

- Not ‘inside’ original particles

$m = E/c^2$

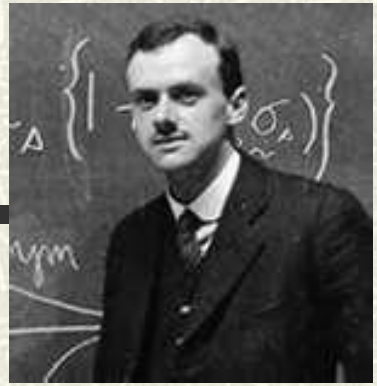


Particle Zoo (1950s, 1960s)

BARYONS		MESONS		LEPTONS		PHOTON	
Symbol	Charge	Symbol	Charge	Symbol	Charge	Symbol	Charge
p	+1	π^+	+1	e^-	−1	γ	0
$\bar{p}$	−1	π^-	−1	e^+	+1		
n	0	π^0	0	υ_e	0		
Δ	0	K^+	+1	$\bar{\upsilon}_e$	0		
		K^-	−1				
		K^0	0				

Over 100 ‘elementary’ particles

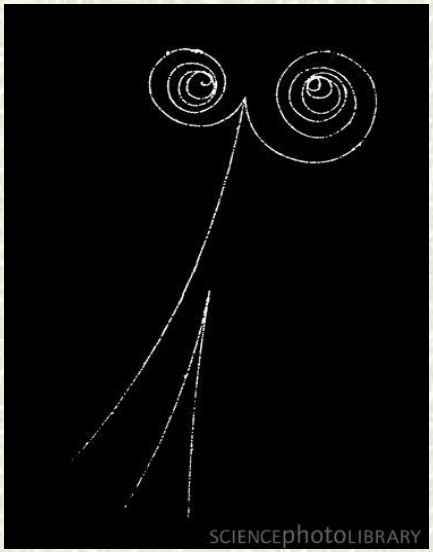
Anti-particles



Paul A.M. Dirac 1902-84

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

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

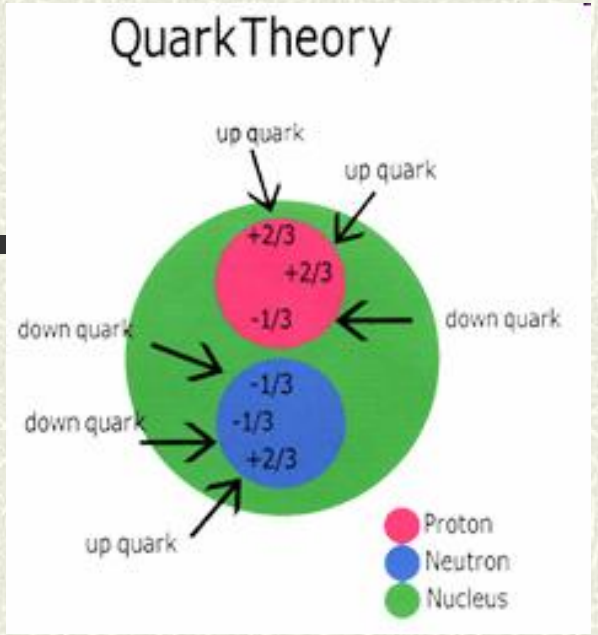


- Energy creates matter and anti-matter

Why is the universe made of matter?

$E = mc^2$

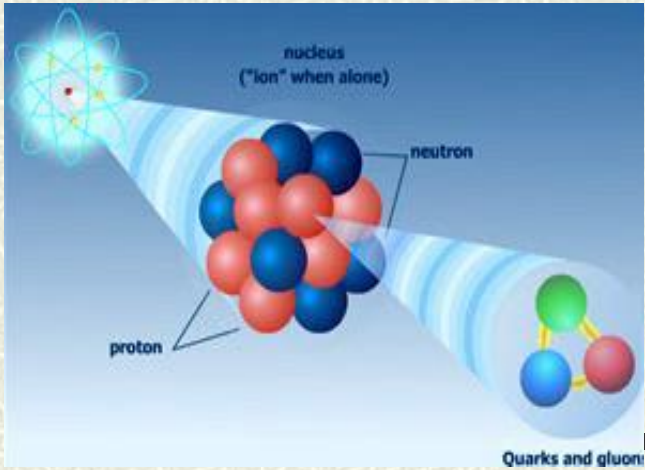
New model: quarks (1964)



- **<u>Too many particles</u>**
- Protons not fundamental
- Made up of smaller particles
- New fundamental particles
  Quarks *(fractional charge)*
- Hadrons: particles containing quarks
  Baryons (3 quarks) mesons (2 quarks)

Gell-Mann, Zweig

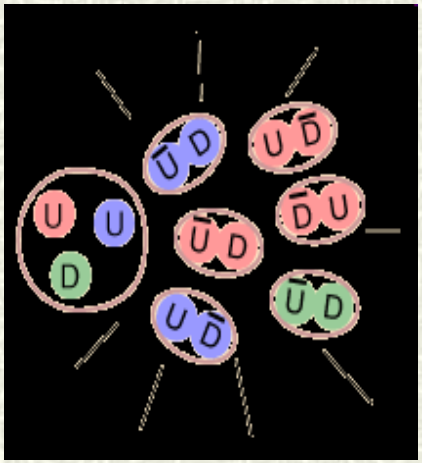
<u>Prediction of Ω^-</u>



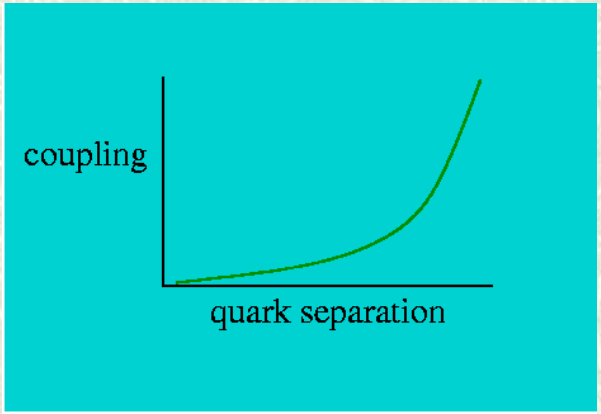
Finding quarks

Stanford/MIT 1969

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



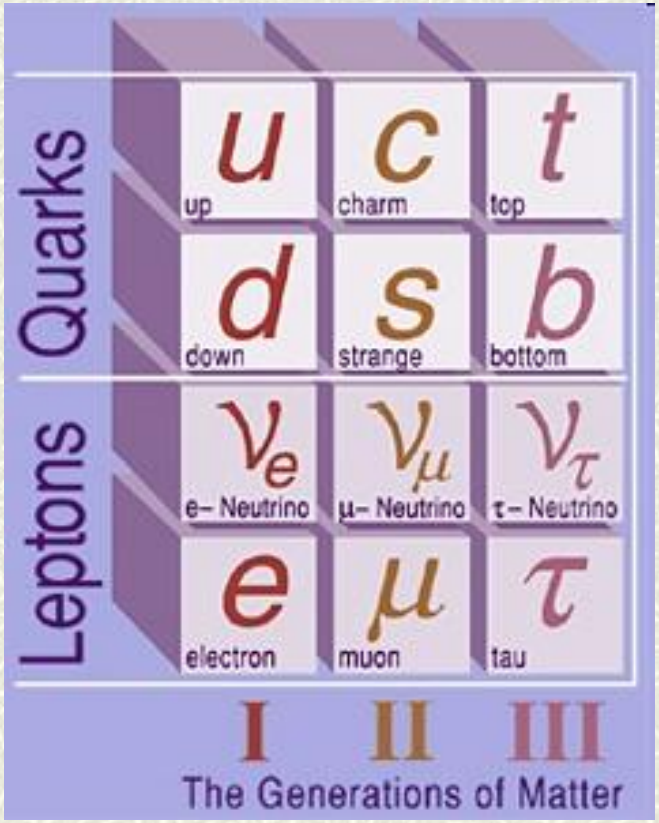
- Defining property = ***colour***
- Strange behaviour
- Quark confinement



The energy required to produce a separation far exceeds the pair production energy of a quark-antiquark pair

Six quarks (1970s –1990s)

- 30 years experiments
- Six different quarks
  (u,d,s,c,b,t)
- Six corresponding leptons
  (e, μ, τ, υ_e, υ_μ, υ_τ)
- Gen I: all of ordinary matter
- Gen II, III redundant?



New periodic table

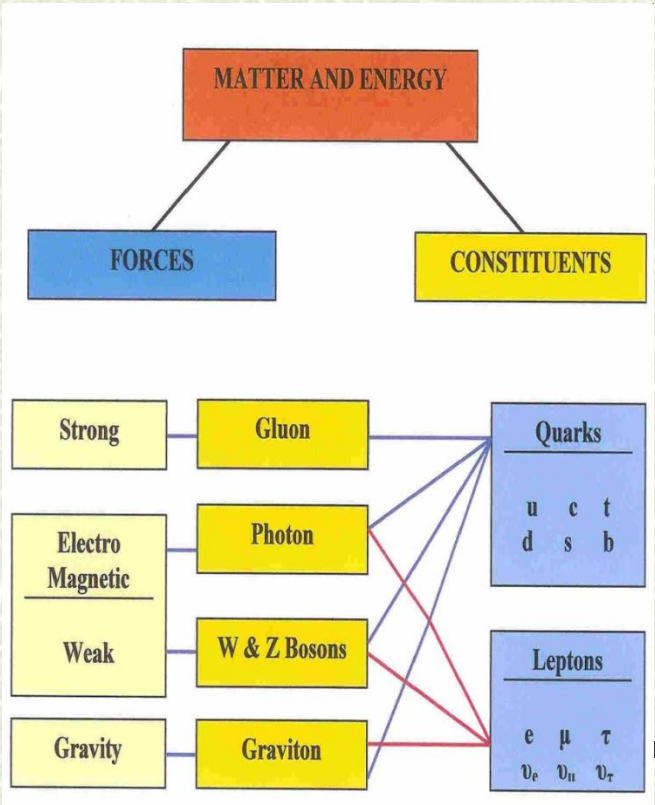
Bosons and the Standard Model

Satyendra Nath Bose

Bosons: particles associated with forces

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

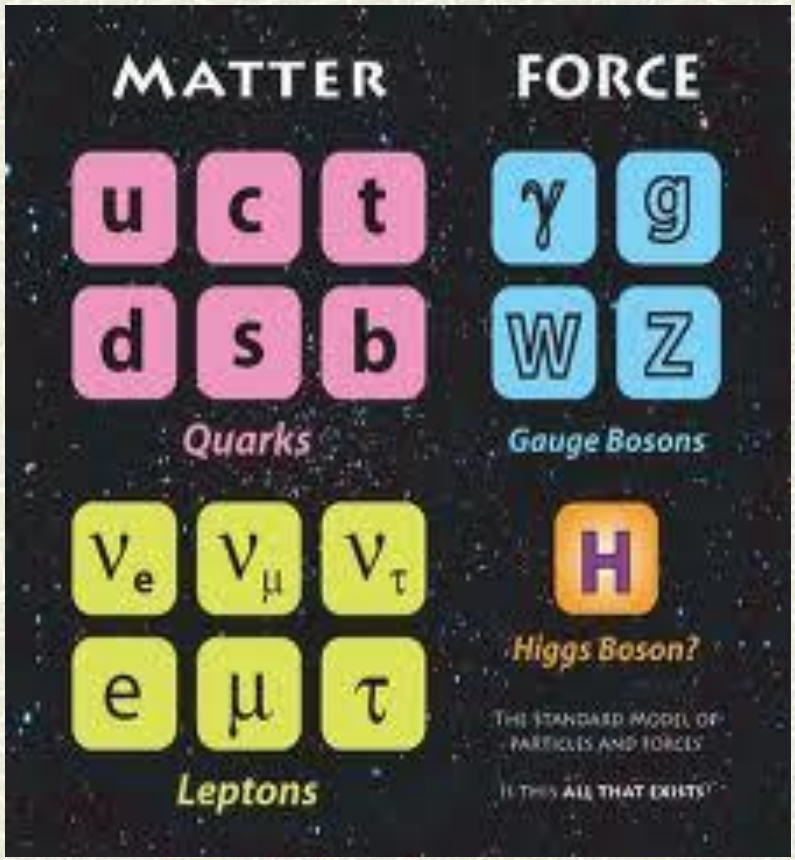
- *Em* + *w*: single interaction above 100 GeV
- Quantum field causes symmetry breaking
- Separates *em*, weak interactions
- Endows *W*, *Z bosons* with mass
- Called the Higgs field



The 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)

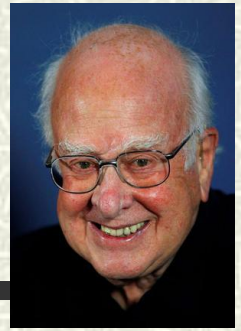


Experimental tests

- *Top, bottom , charm, strange quarks*
- *Leptons*
- *W^{+-},Z^0 bosons*

Higgs boson outstanding

The Higgs field



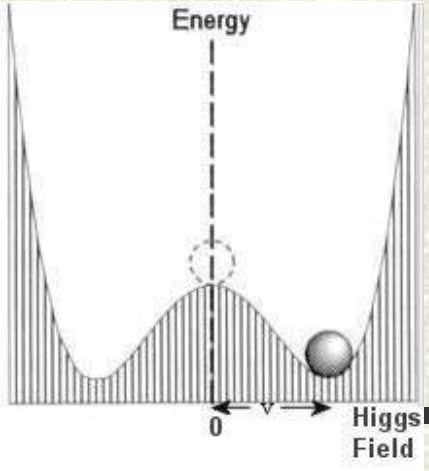
Peter Higgs

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

W and Z bosons (CERN, 1983)

Kibble, Guralnik, Hagen, Englert, Brout

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



Particle masses not specified

The Higgs field

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

Mass not specified by SM

II The Large Hadron Collider

$E = mc^2$

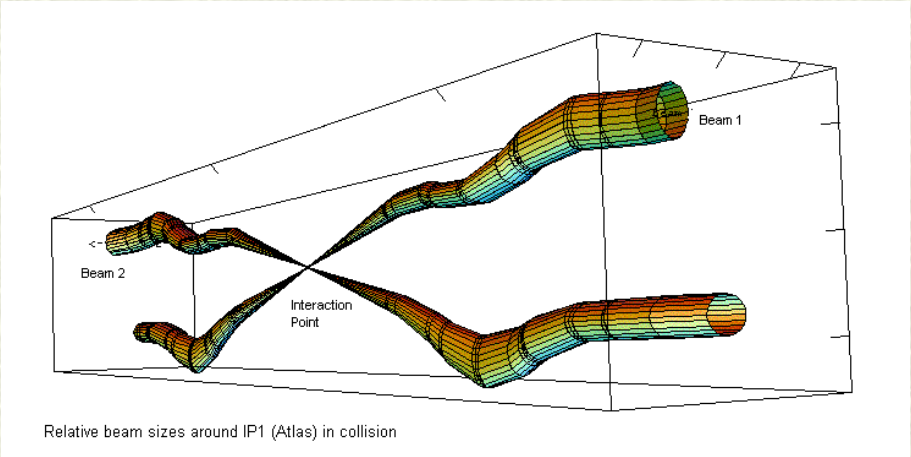
- Particle accelerator (8TeV)
- High-energy collisions (10^{12}/s)
- Huge energy density
- Create new particles

$m = E/c^2$

- Detect particle decays
- Four particle detectors

How

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



Relative beam sizes around IP1 (Atlas) in collision

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

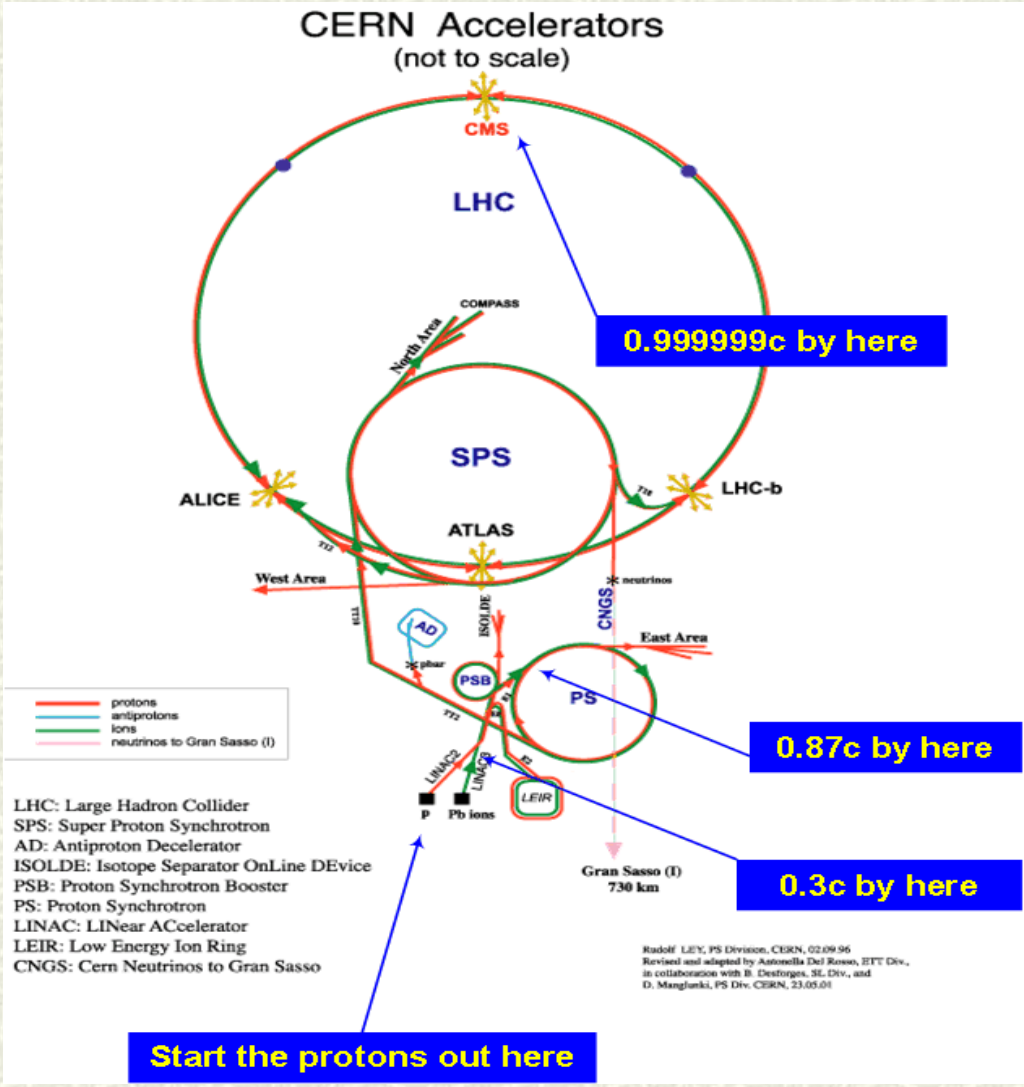
LEP tunnel: 27 km

Luminosity: 5.8 fb^{-1}

Around the ring at the LHC

- Nine accelerators
- Cumulative acceleration
- Velocity increase?
- *K.E = 1/2mv²*
- Mass increase *x1000*

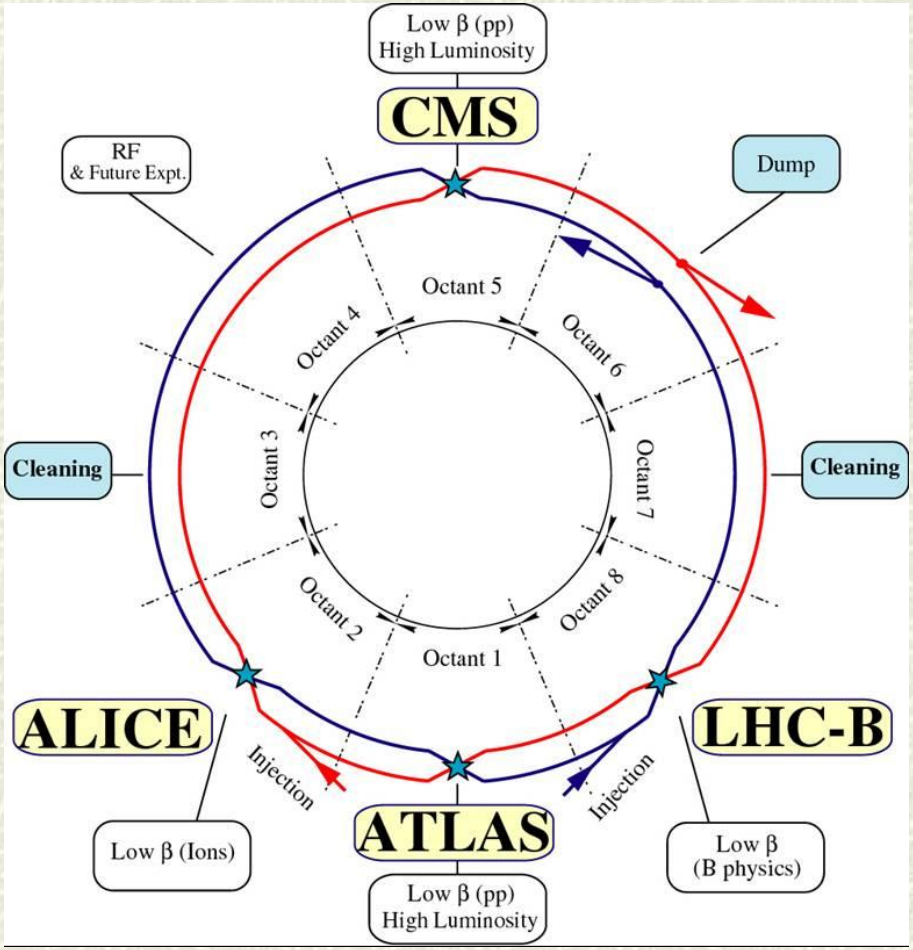
$$m = \frac{m_0}{\sqrt{1 - v^2/c^2}}$$



Particle detectors

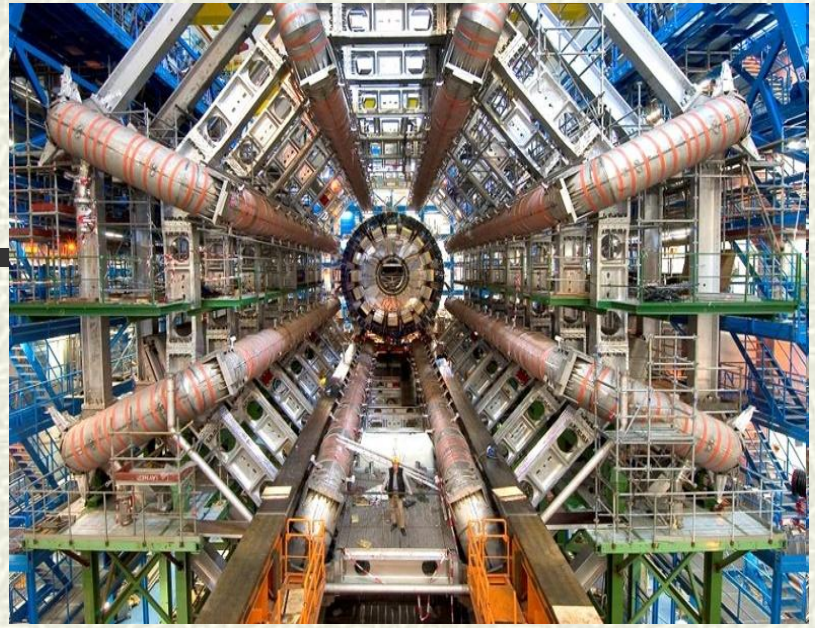
Detectors at crossing pts

- **CMS** *multi-purpose*
- **ATLAS** *multi-purpose*
- **ALICE** *quark-gluon plasma*
- **LHC-b** *antimatter decay*

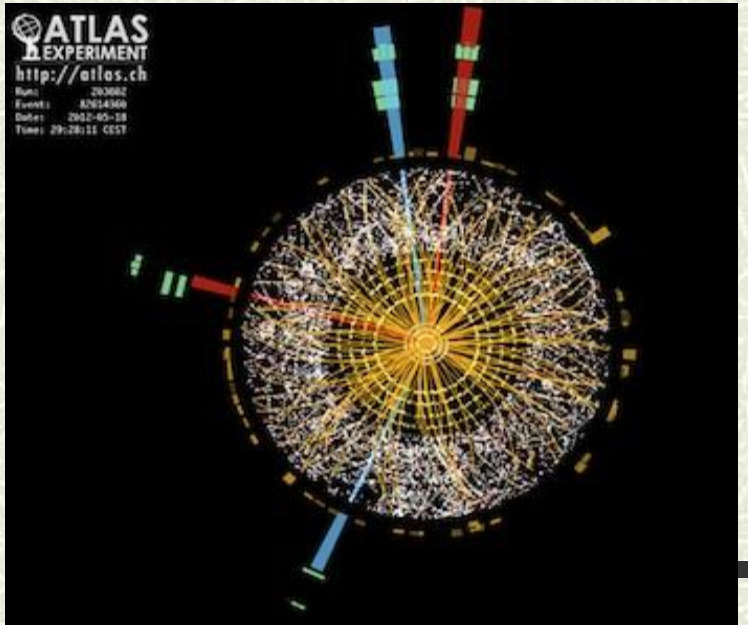


Particle detection

- Tracking device
  Measures particle momentum
- Calorimeter
  Measures particle energy
- Identification detector
  Measures particle velocity
  Cerenkov radiation
- Analysis of decay tracks
  GRID computing



ATLAS



III A Higgs at the LHC?

- Search for excess events

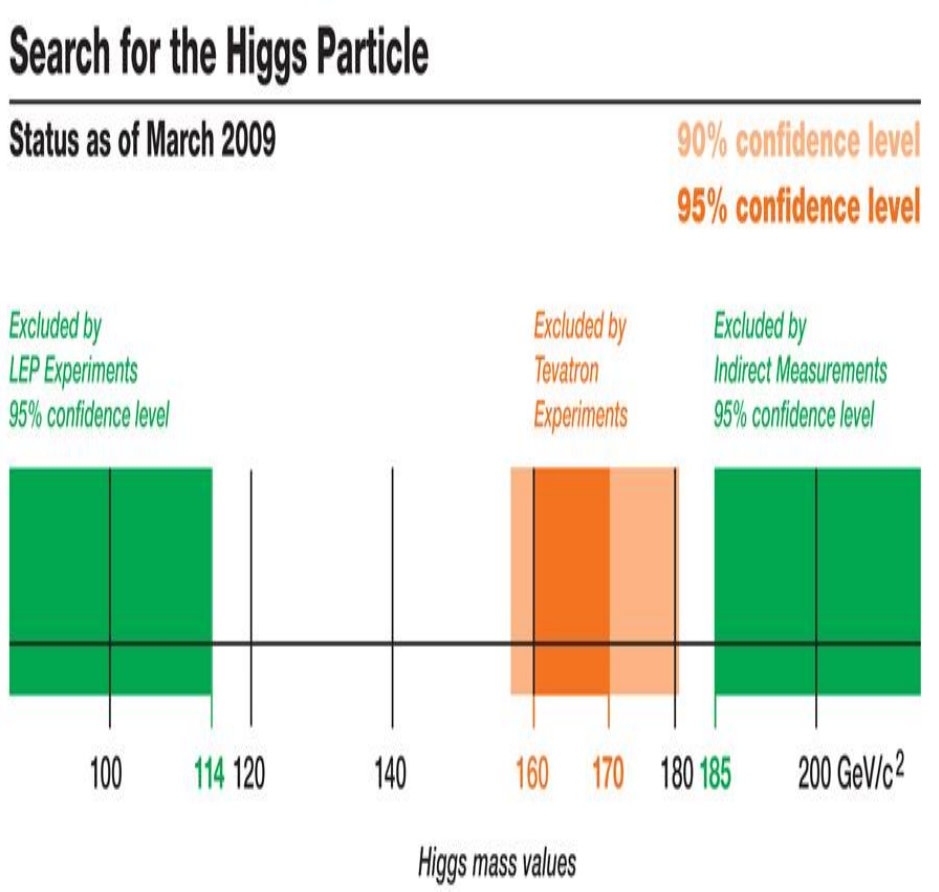
  Mass not specified?

- Close windows of possibility

- 120-160 GeV (1999)

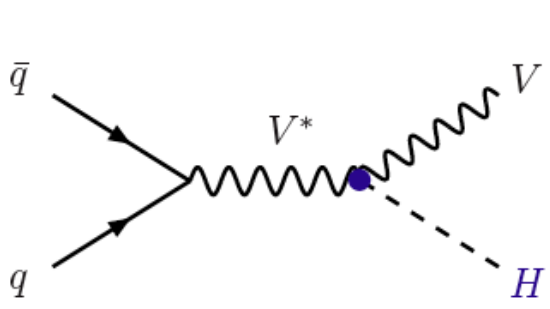
- Set by mass of top quark, Z boson

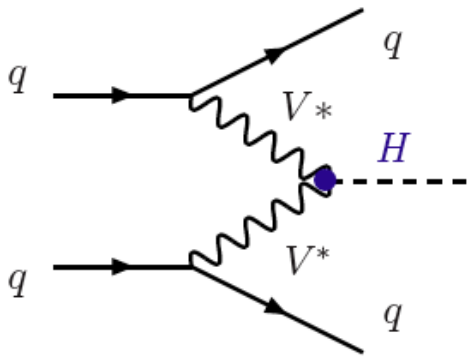
- Search…running out of space!

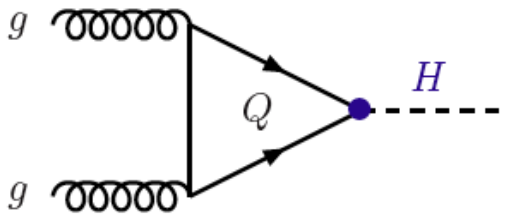


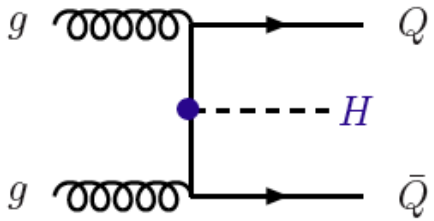
Higgs production in LHC collisions

associated production with W/Z :	$q\bar{q} \longrightarrow V + H$
vector boson fusion :	$qq \longrightarrow V^*V^* \longrightarrow qq + H$
gluon – gluon fusion :	$gg \longrightarrow H$
associated production with heavy quarks :	$gg, q\bar{q} \longrightarrow Q\bar{Q} + H$









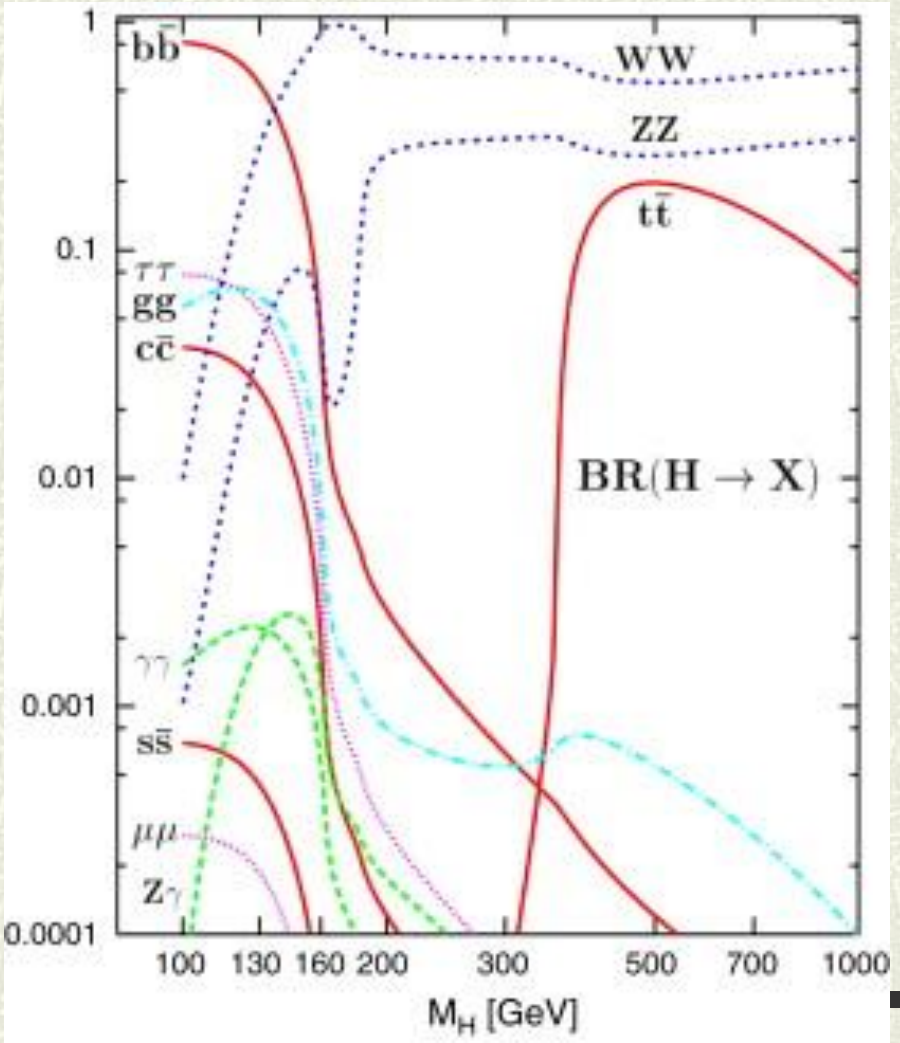
1 in a billion collisions

Detect Higgs by decay products

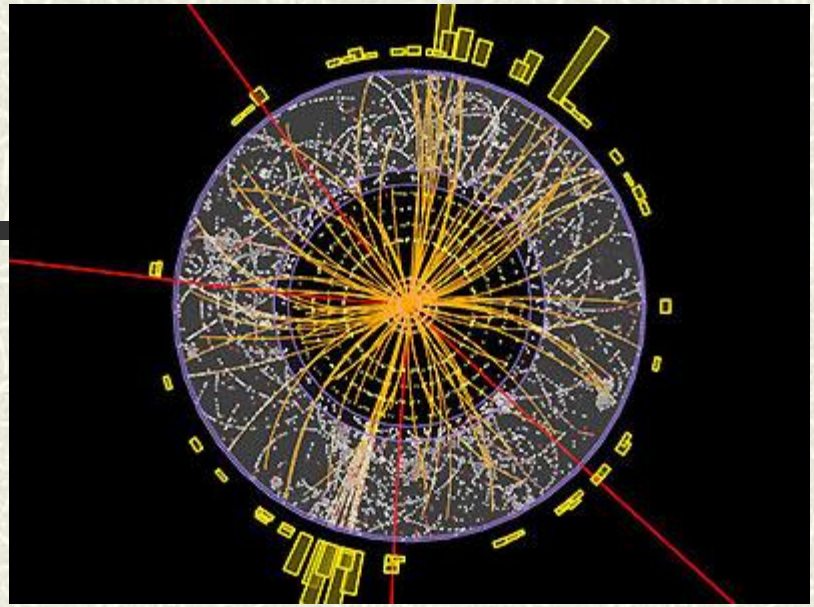
- Most particles interact with Higgs
- Variety of decay channels
- Massive particles more likely
- Difficult to detect from background
- Needle in a haystack

Needle in haystack of needles

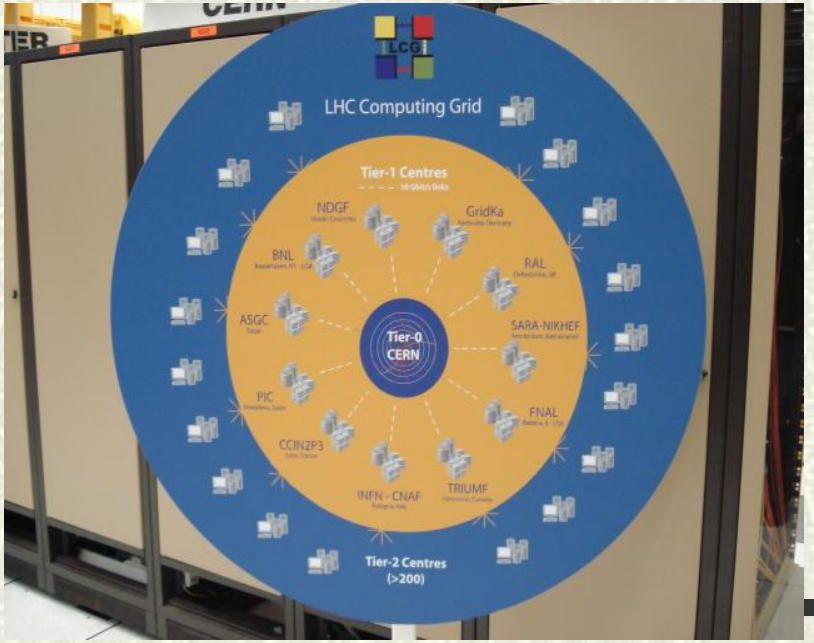
High luminosity required



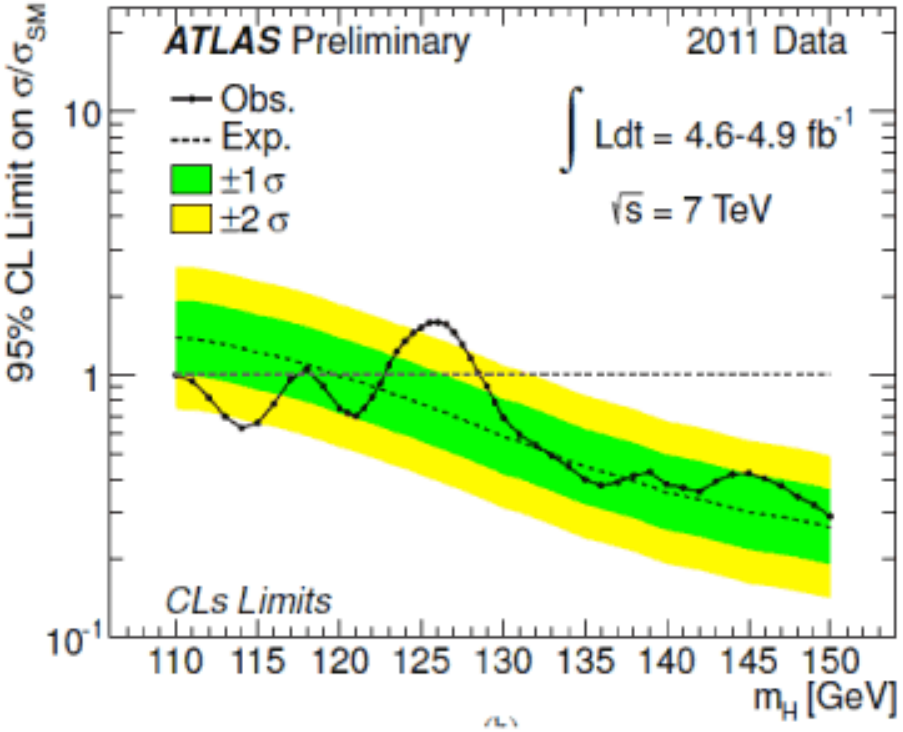
Analysis: GRID

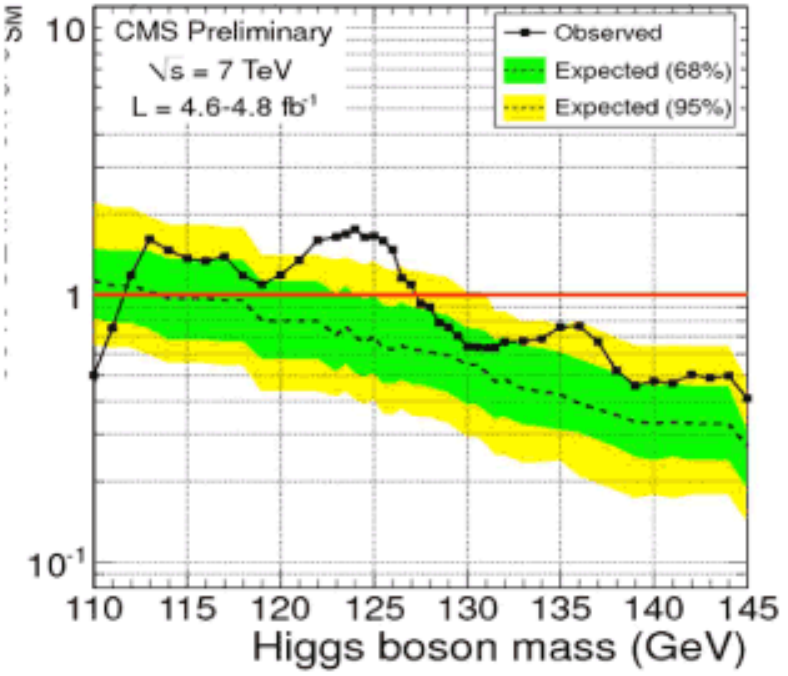


- Huge number of collisions
  Data analysis
- World Wide Web (1992)
  Platform for sharing data
- GRID (2012)
  Distributed computing
- World-wide network
- Huge increase in computing power



Higgs search at LHC (2011)

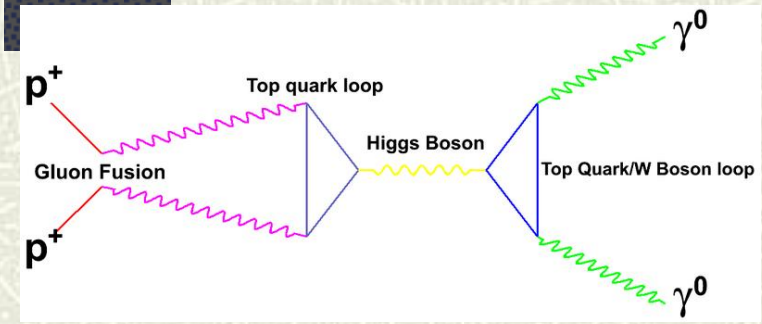


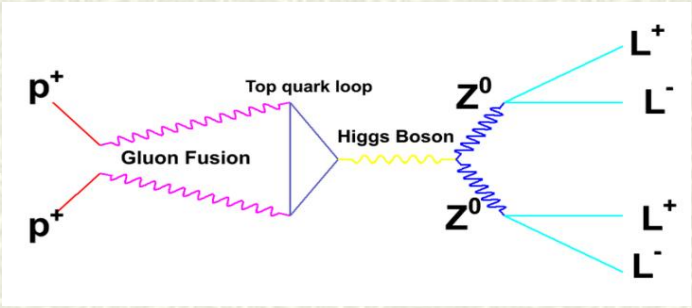


Excess events at 125 GeV in ATLAS and CMS detectors

Higher luminosity required 4.8 fb^{-1}

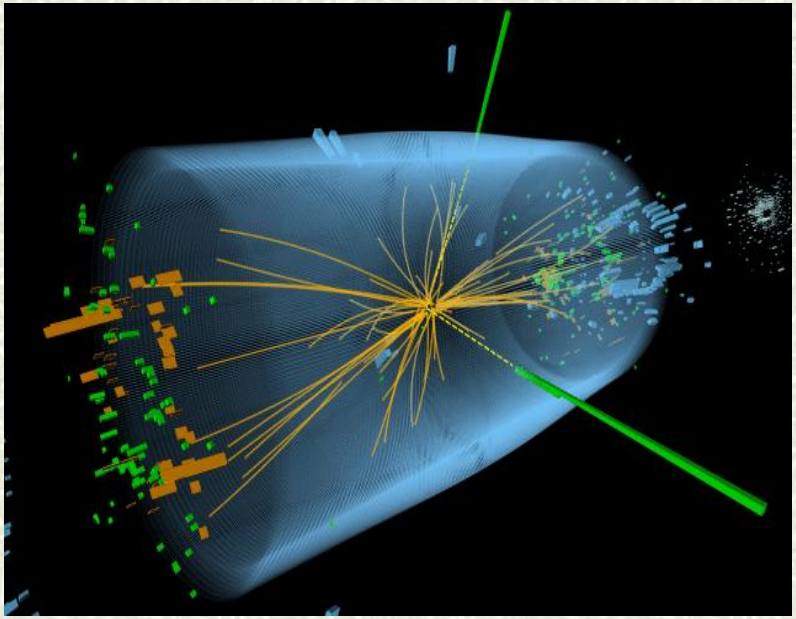
April-July 2012: *8 TeV*, *5.8* fb^{-1}

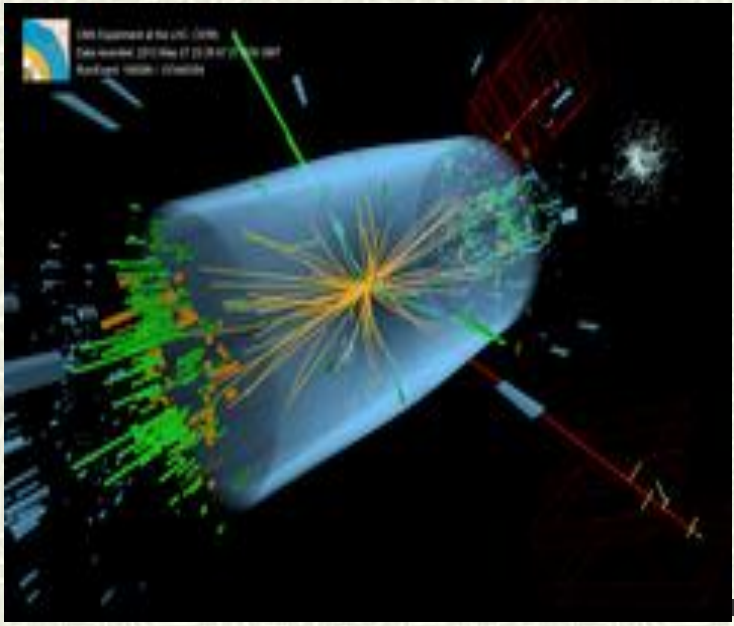




Measure energy of photons emitted

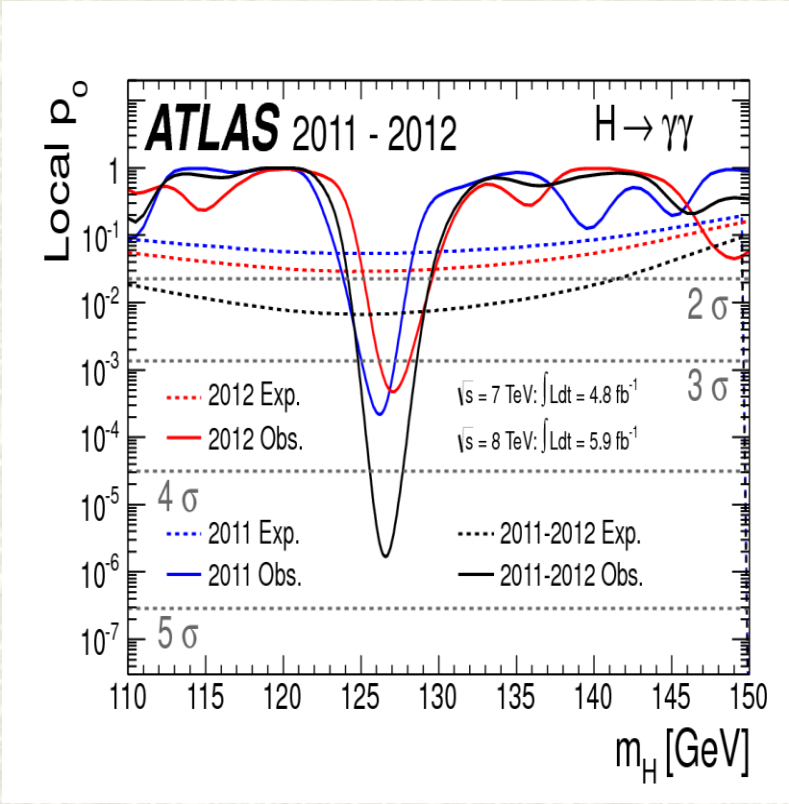
Measure decay products of Z bosons

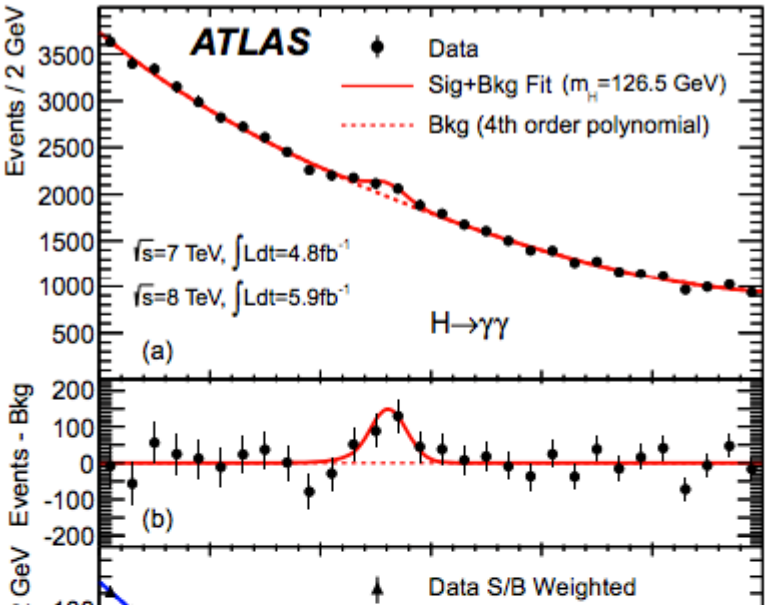


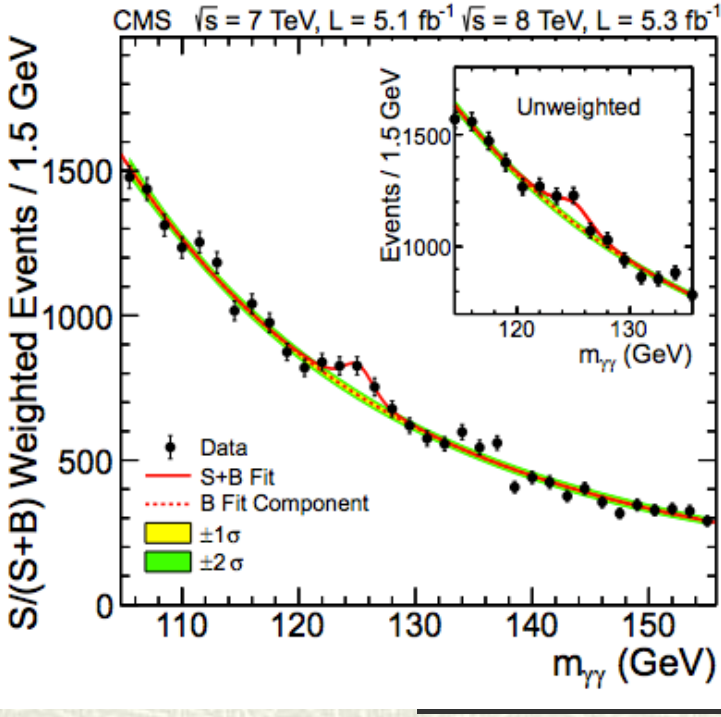


Results (July, 2012)

H→ γγ **(*8 TeV*, 5.3 fb^{-1})**

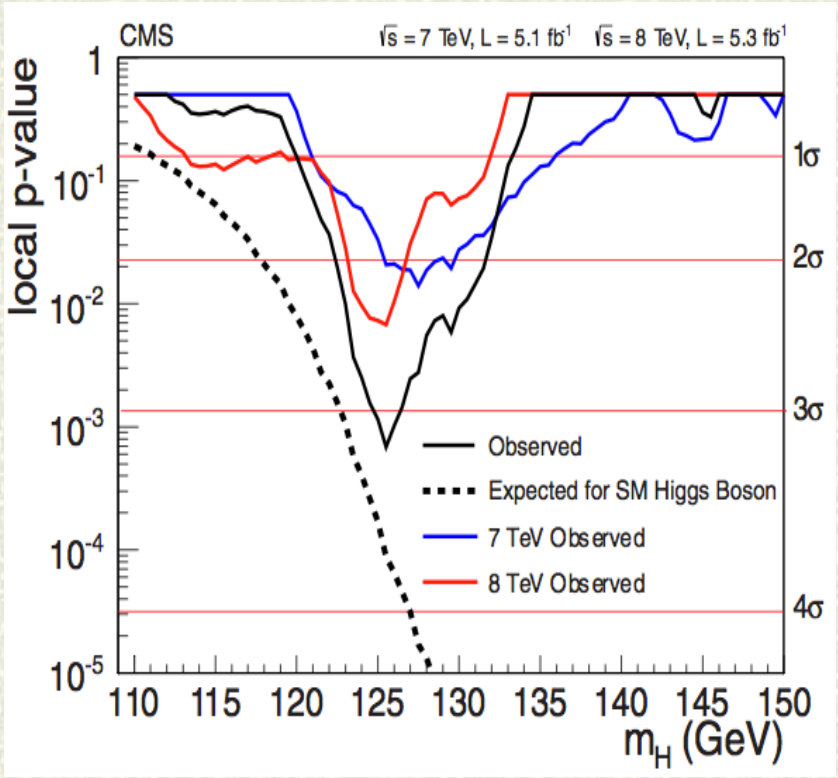


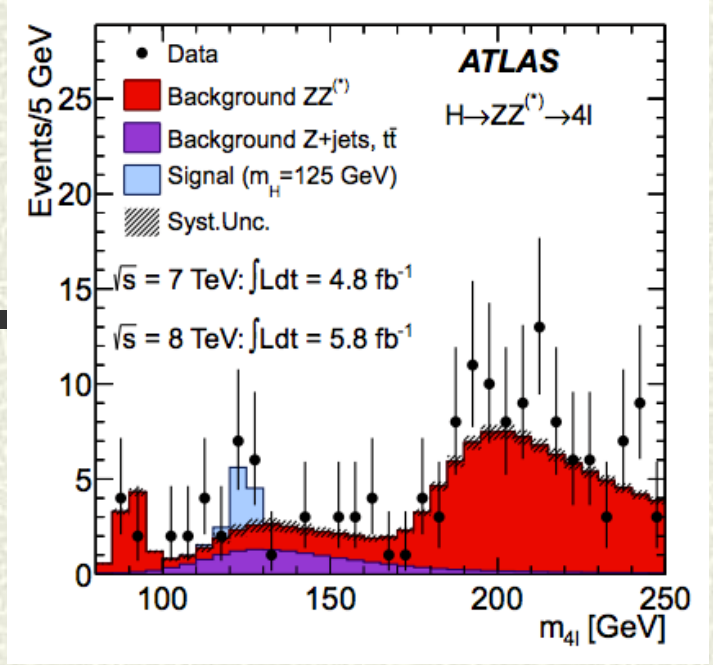


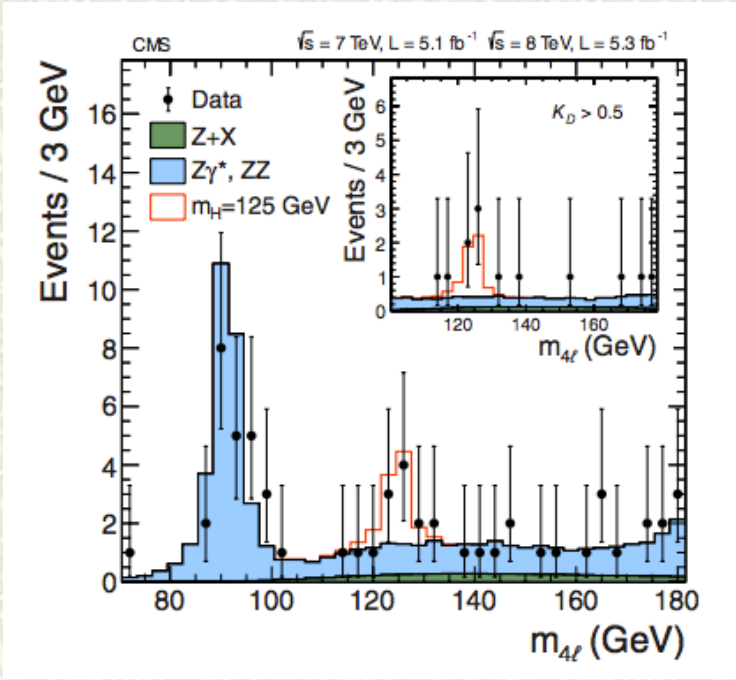


Results (July, 2012)

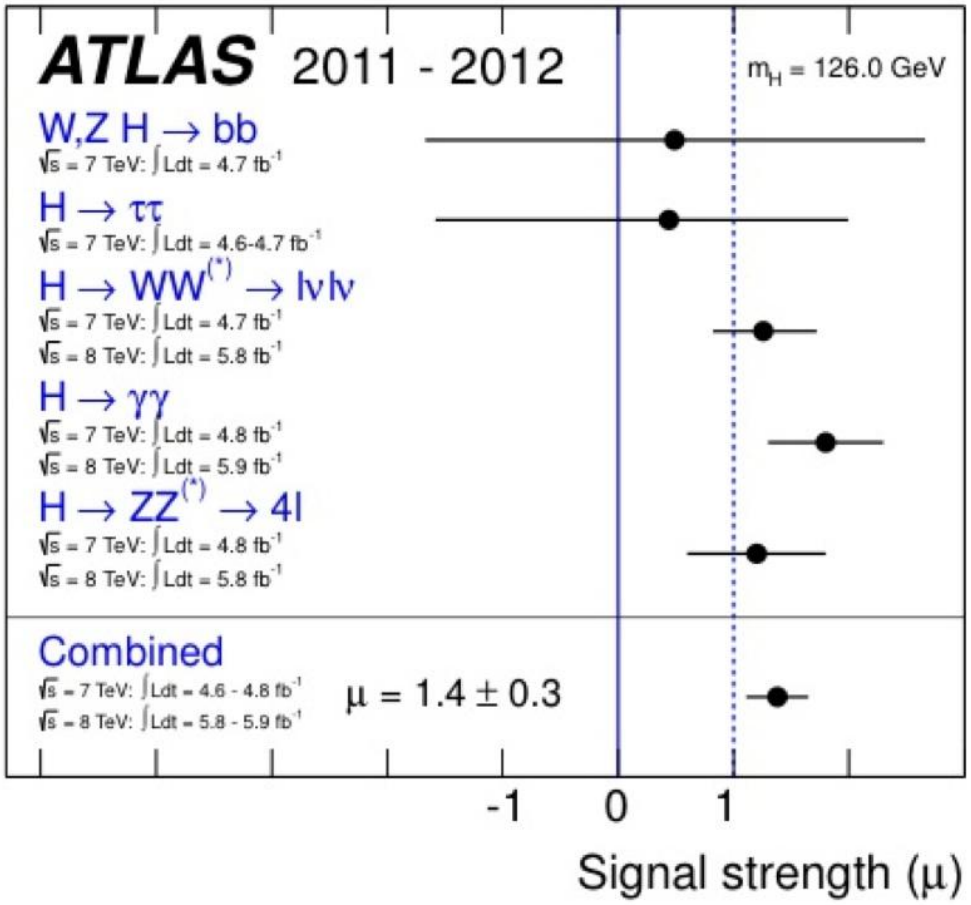
H→ZZ (8 TeV, 5.3 fb^{-1})

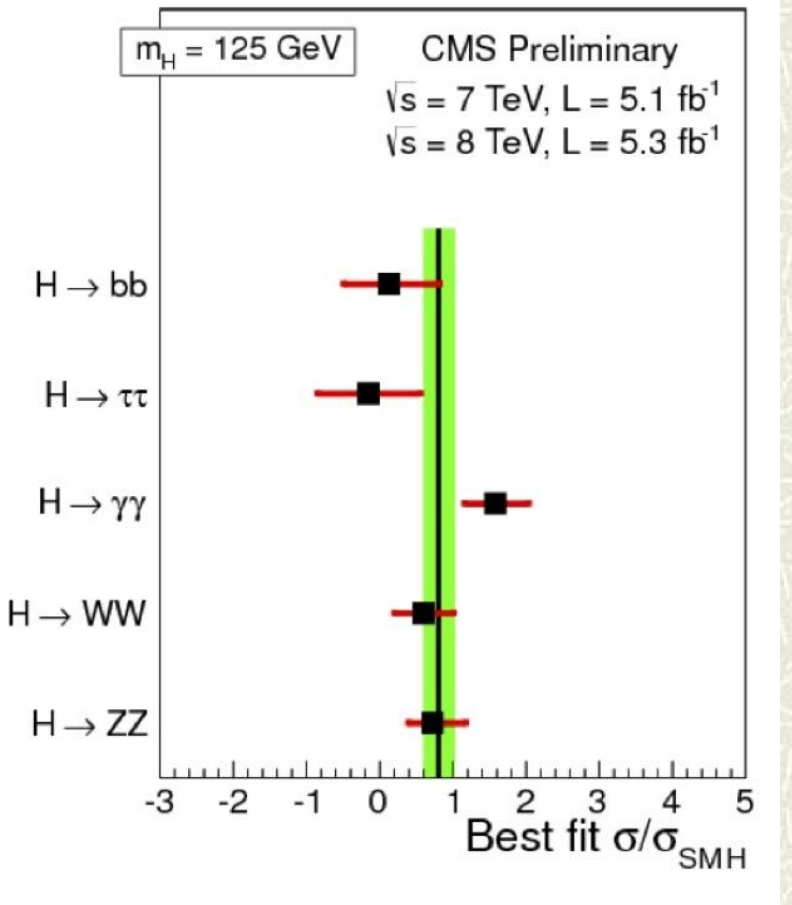






Results: all decay channels

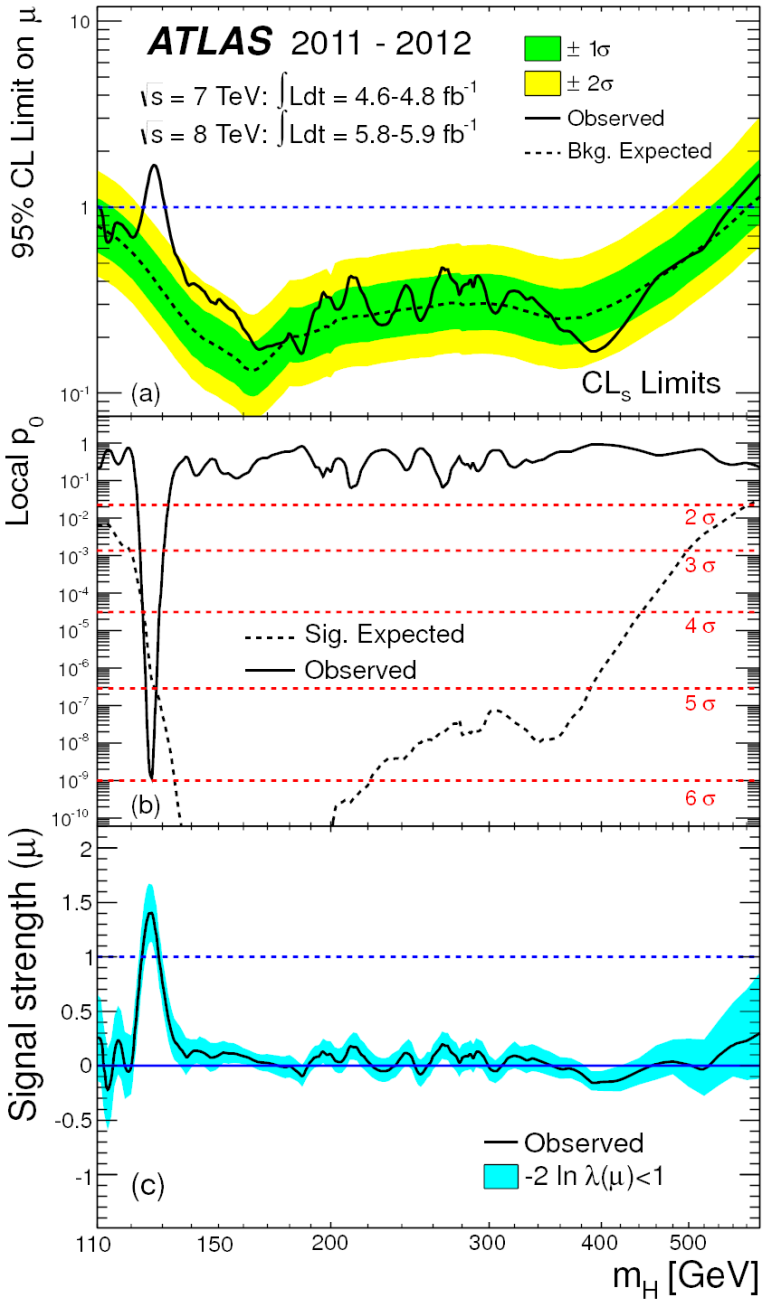




Results summary

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

Higgs boson?

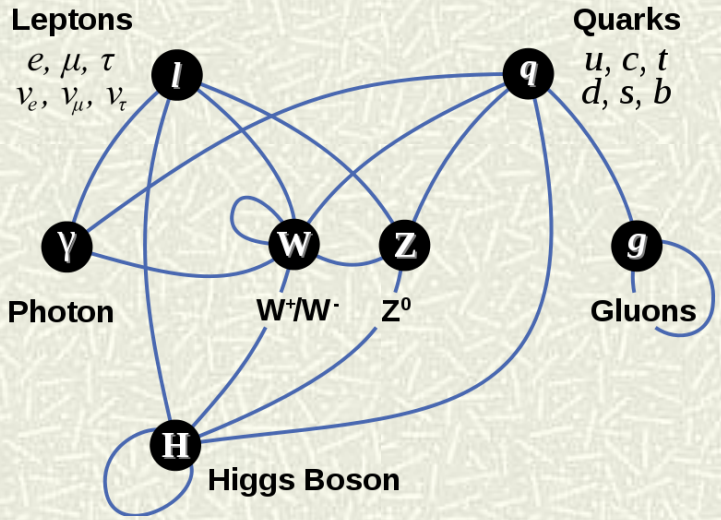


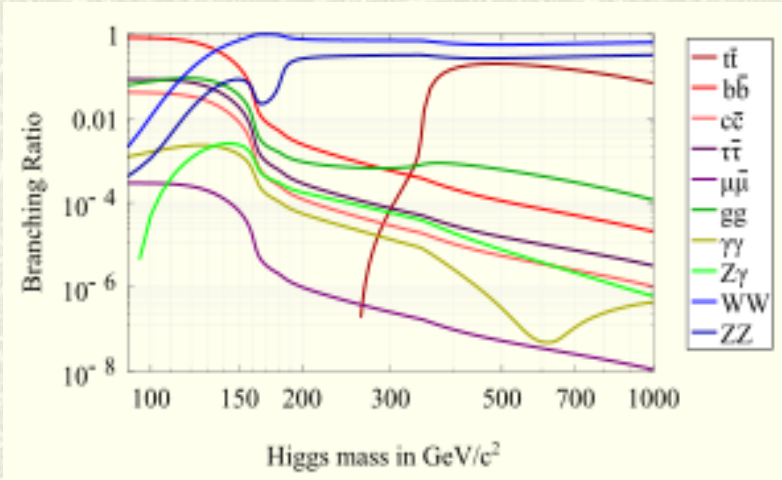
IV Next at the LHC

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

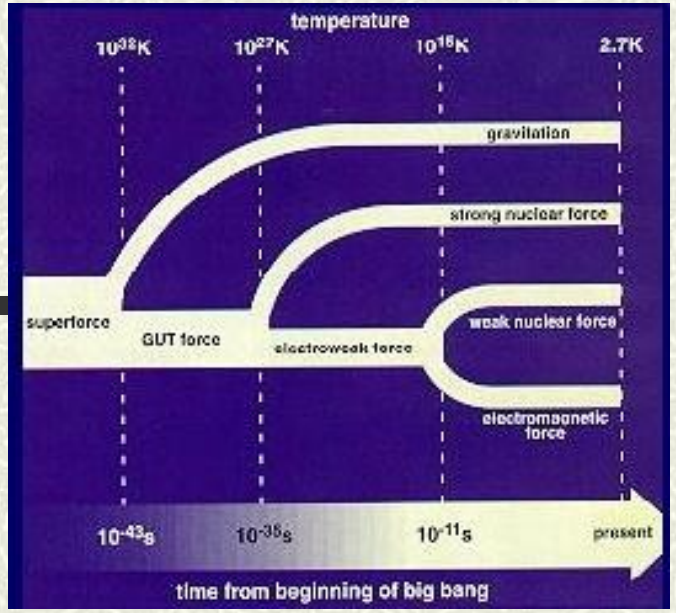
- **Supersymmetry**
  Numerous Higgs?
  Other supersymmetric particles
  Implications for unification

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

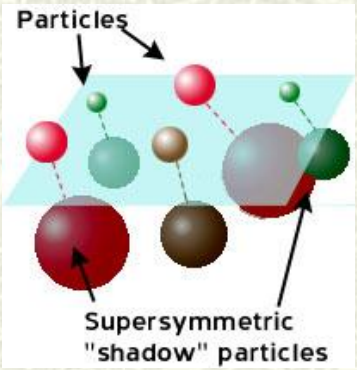




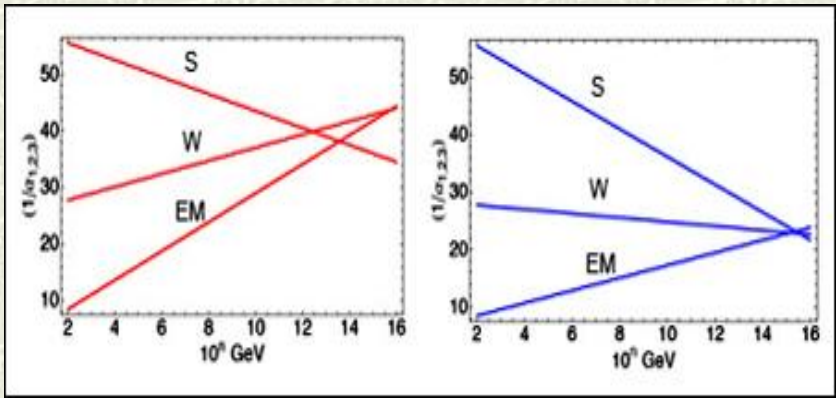
Supersymmetry



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

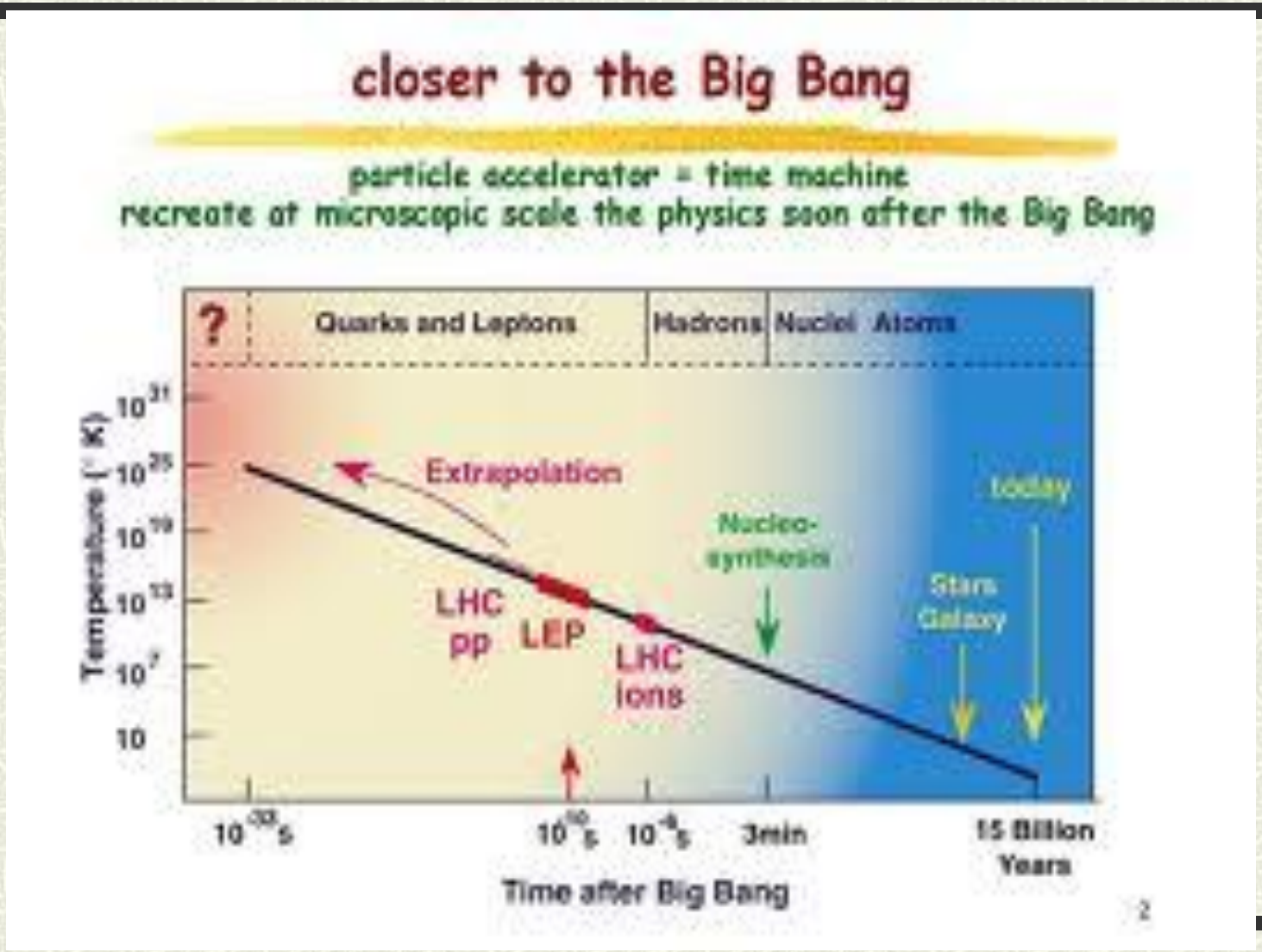


- Relation between bosons and fermions?
- **Supersymmetry (**1970s)
- New families of particles

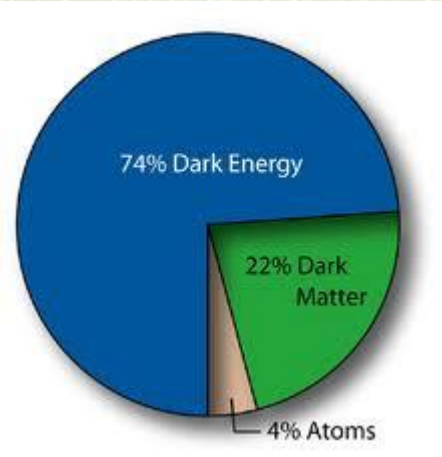


Broken symmetry – particles not seen
Heavy particles (LHC?)

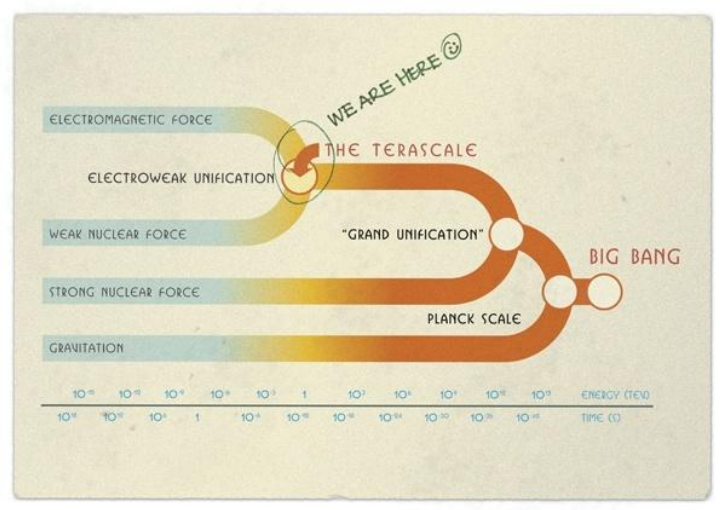
LHC and cosmology



Cosmology at the LHC



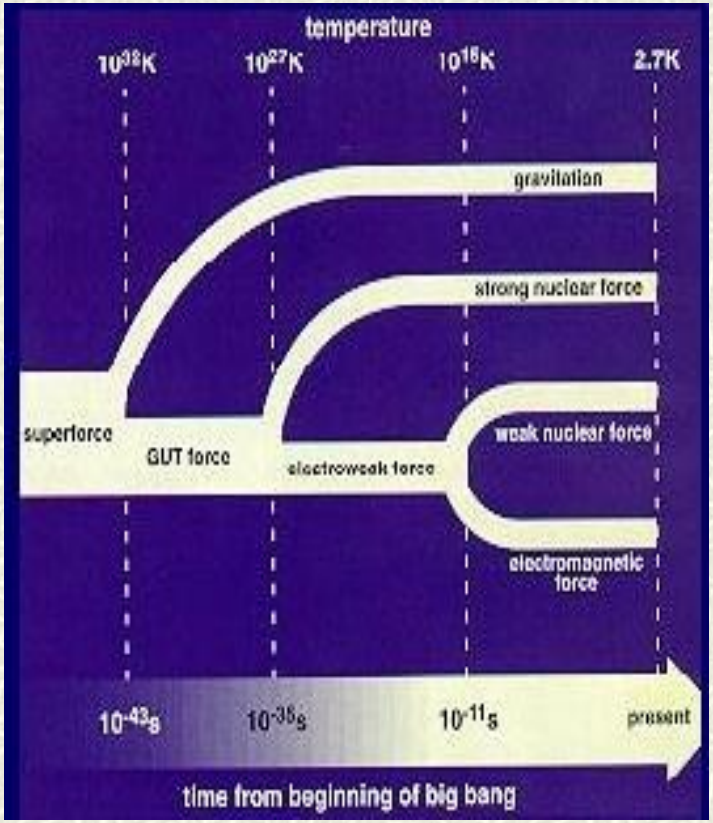
- **Snapshot of early universe**
  Highest energy density since BB
- **Dark matter particles?**
  Neutralinos (SUSY)
- **Dark energy ?**
  Scalar field
- **Higher dimensions?**
  Kaluza Klein particles
- **String theory?**



$T = 10^{19}$ K, $t = 1x10^{-12}$ s, V = 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-w* unification**
- Particle theory right so far

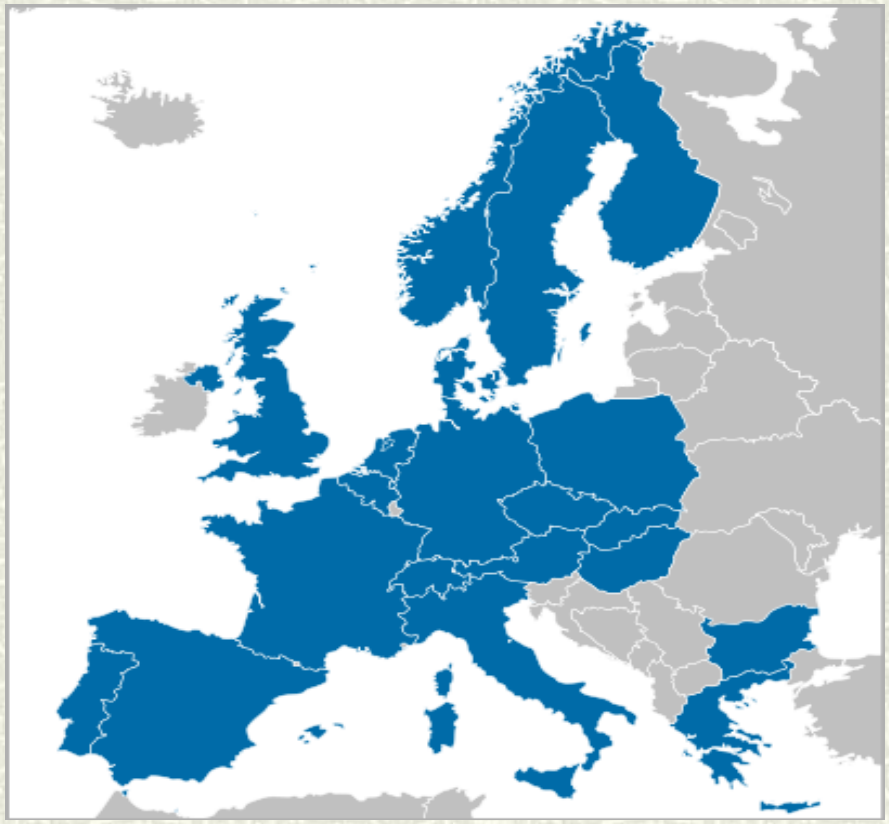


En route to a theory of everything ?

Slides on ***Antimatter***

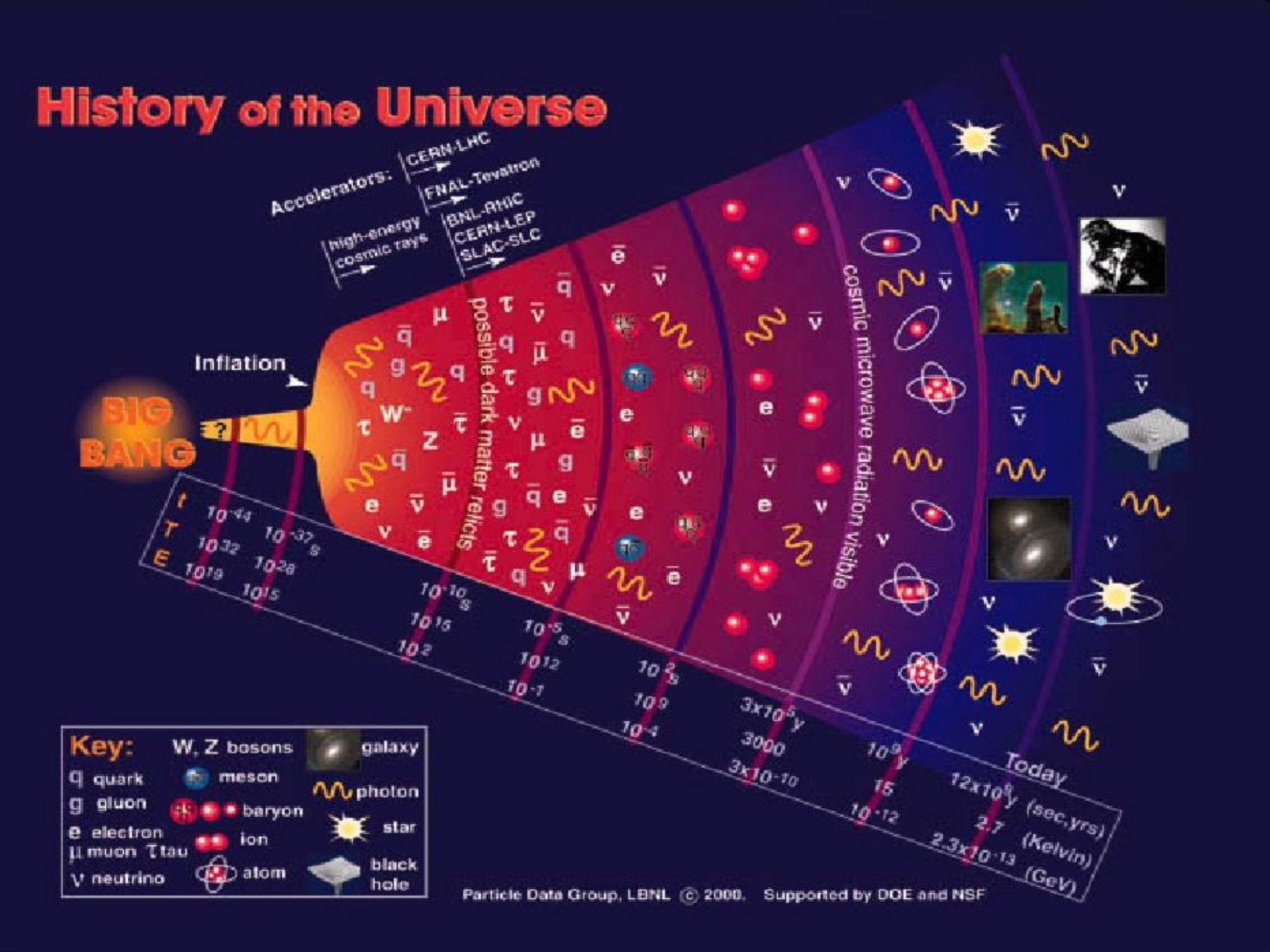
Epilogue: CERN and Ireland

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


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
Today
t
T
E
10-44
10-37 s
1032
1028
1019
1015
10-10 s
1015
102
10-5 s
1012
10-1
1 s
103
10-4
3x105 y
3000
3x10-10
109 y
15
10-12
12x109 y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
galaxy
photon
star
black hole
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