The God particle at last?

Astronomy Ireland, Oct 8th, 2012

Cormac O'Raifeartaigh

Waterford Institute of Technology

CERN July 4th 2012 (ATLAS and CMS)

A new particle of mass 125 GeV

Overview

I The Higgs boson

Particle physics and the Standard Model

II The Large Hadron Collider

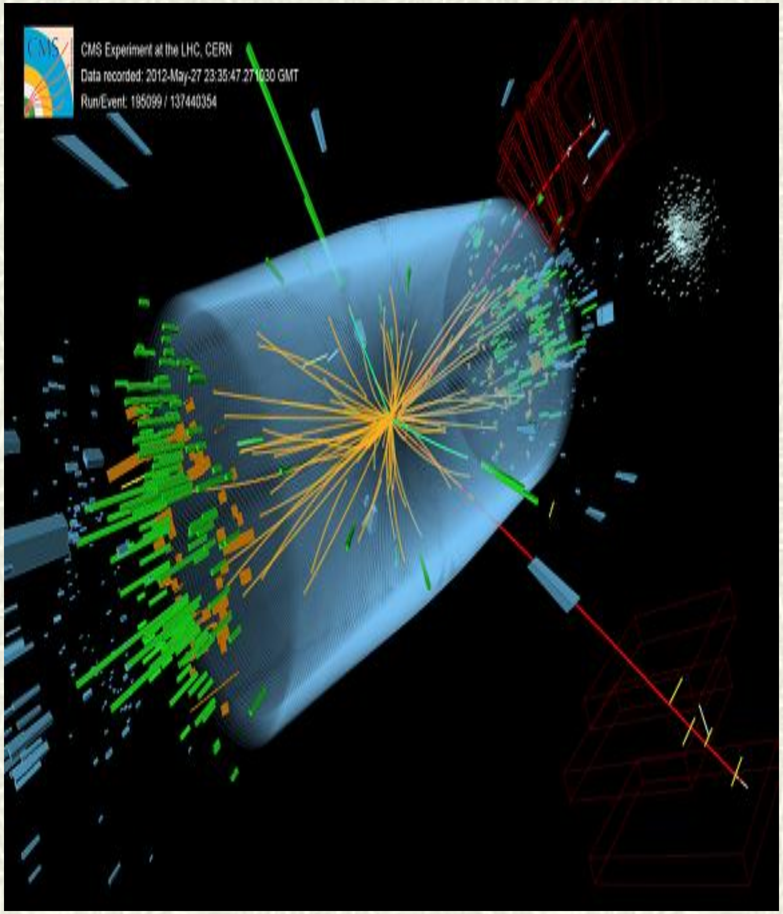
What, why, how

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

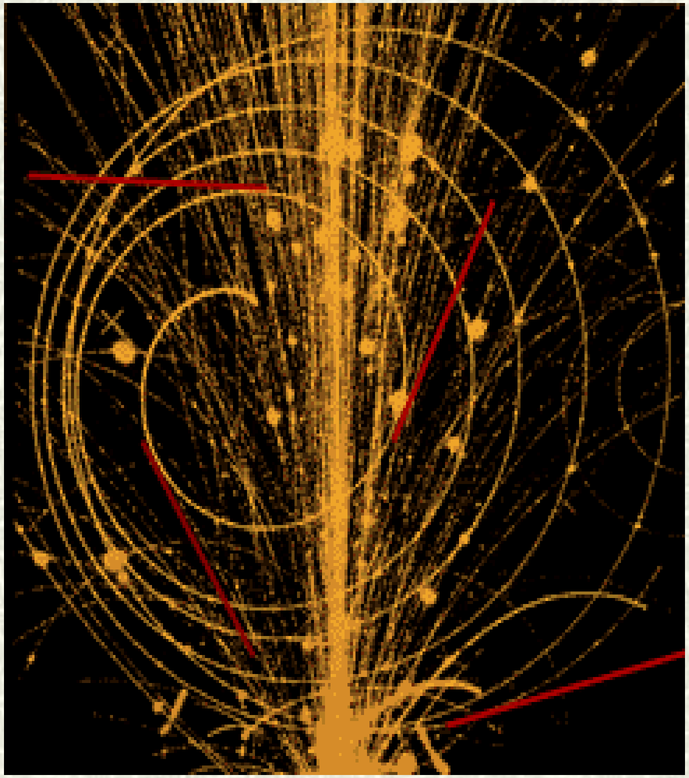
Unified field theory?

III. **Snapshot of early universe**

Highest energy density since BB

Puzzle of dark matter, dark energy

$T = 10^{19}$ K, $t = 1 \times 10^{-12}$ s



'God particle'

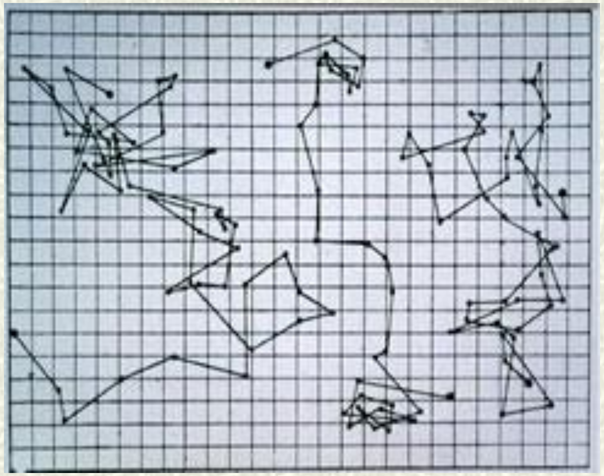
I Early particle physics (1900-1912)

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

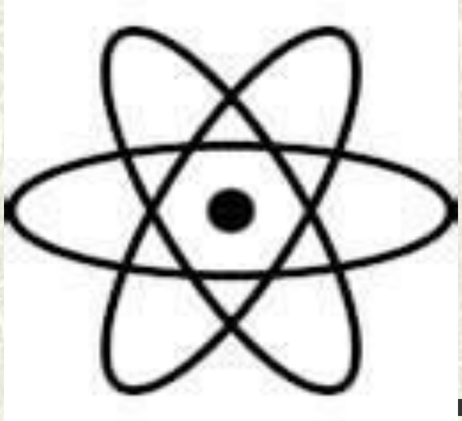
- **Discovery of the nucleus** (1911)
  Rutherford Backscattering

- **Positive, tiny core**
  Fly in the cathedral

- **Negative electrons outside**
  Fundamental particles (1895)

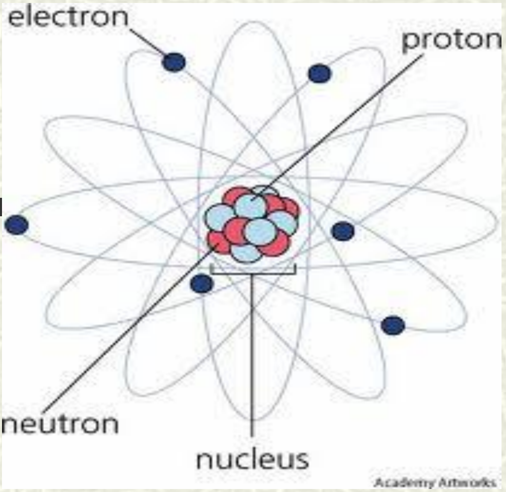


Brownian motion



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

Atoms and chemistry



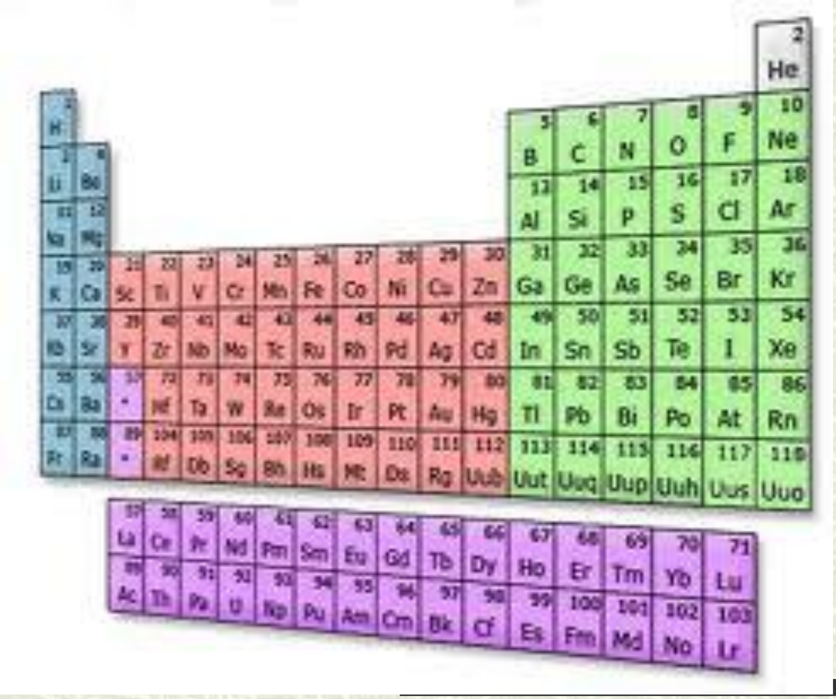
- **Discovery of the proton** (1918)
  Particle of +ve charge inside nucleus

- **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

<u>***What holds nucleus together?***</u>



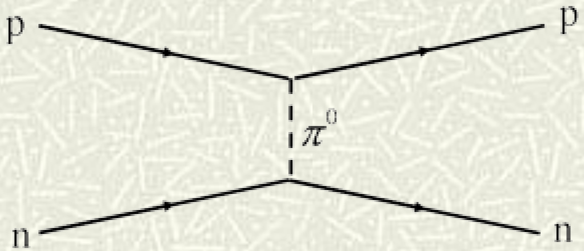
Strong nuclear force (1934)

- 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

Hideki Yukawa

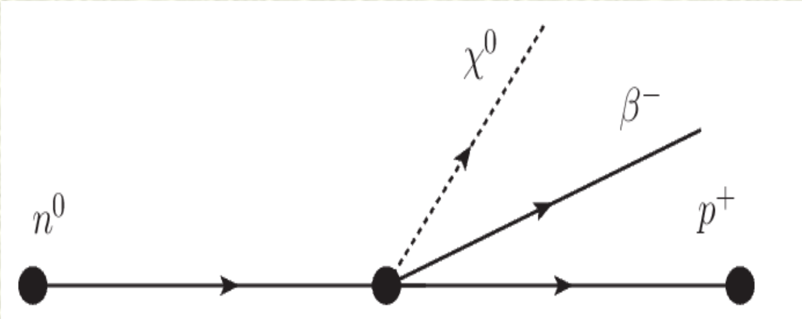
Yukawa pion $\pi^-, \pi_{0,} \pi^+$



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



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

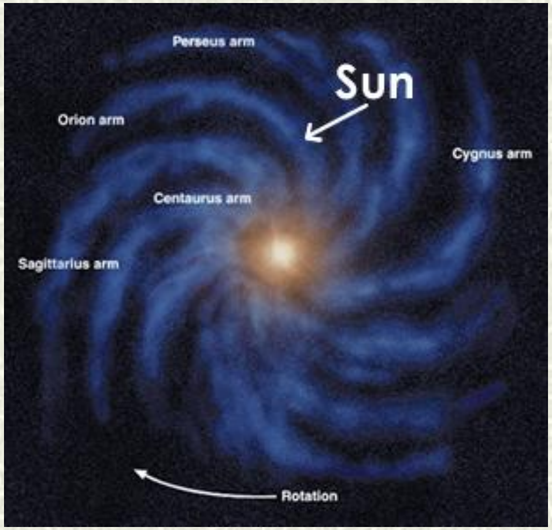
- New particle: neutrino
- Discovered 1956
- Fermi's theory of the weak force
- Four interacting particles

Enrico Fermi

Mechanism?

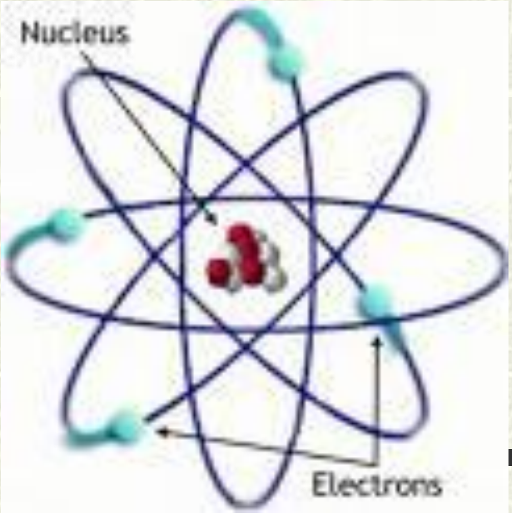
Four forces of nature (1930s)

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



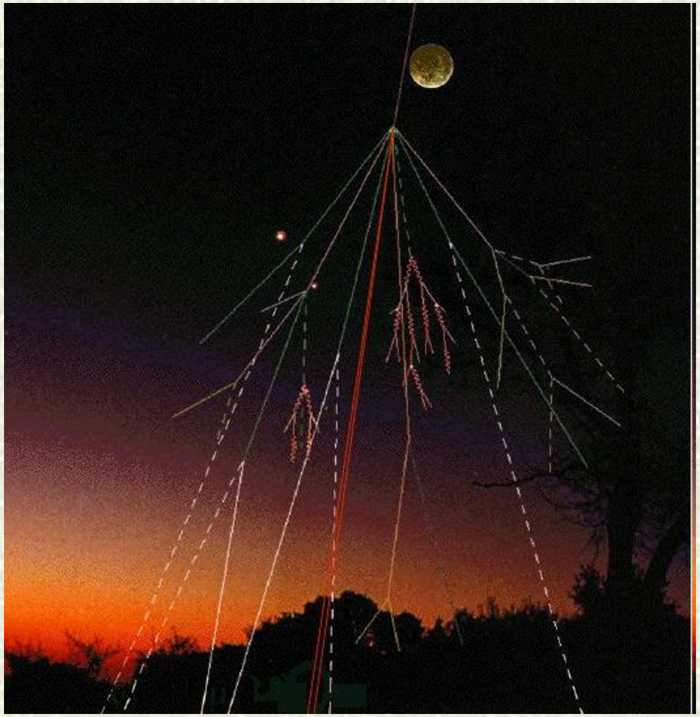
- **Electromagnetic force**
  Holds atoms together

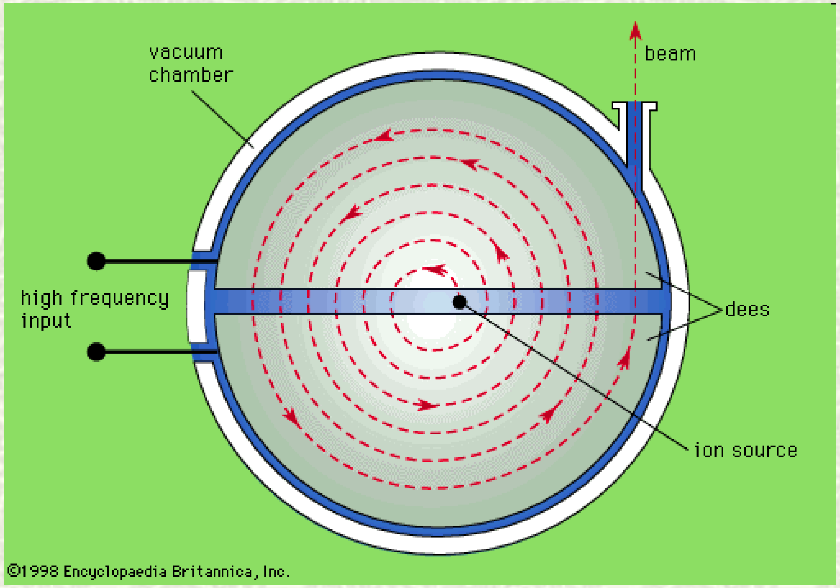
- **Strong nuclear force**
  Holds nucleus together



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

New elementary particles (1940-50)





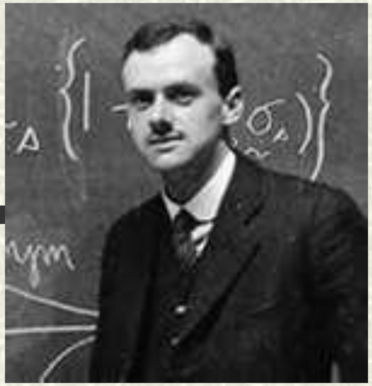
Particle accelerators

Cosmic rays

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

Pions, muons, neutrinos, antiparticles

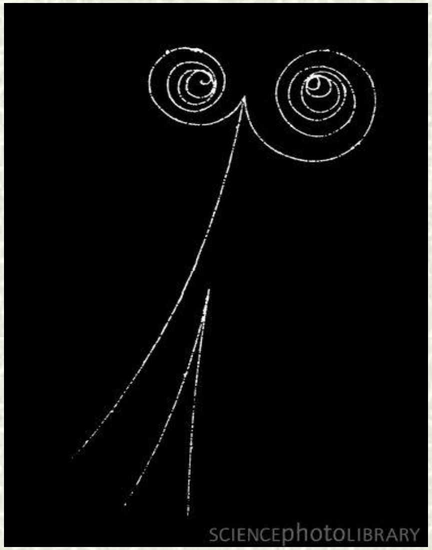
Antimatter



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?

$E = mc^2$

Walton: accelerator physics

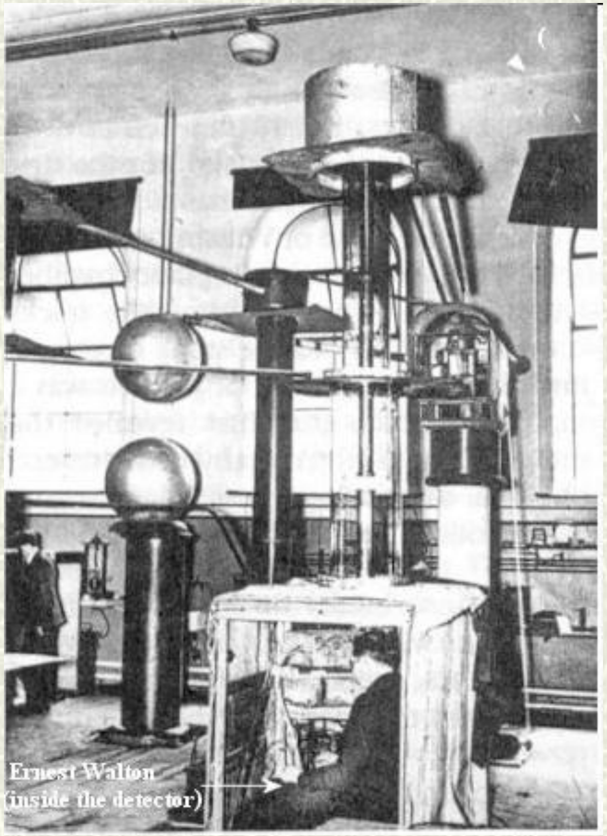
Cockcroft and **Walton**: linear accelerator

Protons used to split the nucleus (1932)

$$^{1}\mathbf{H}_{1} + {}^{3}\mathbf{Li}_{6.9} \rightarrow {}^{2}\mathbf{He}_{4} + {}^{2}\mathbf{He}_{4}$$

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

Nobel prize (1956)



Cavendish lab, Cambridge

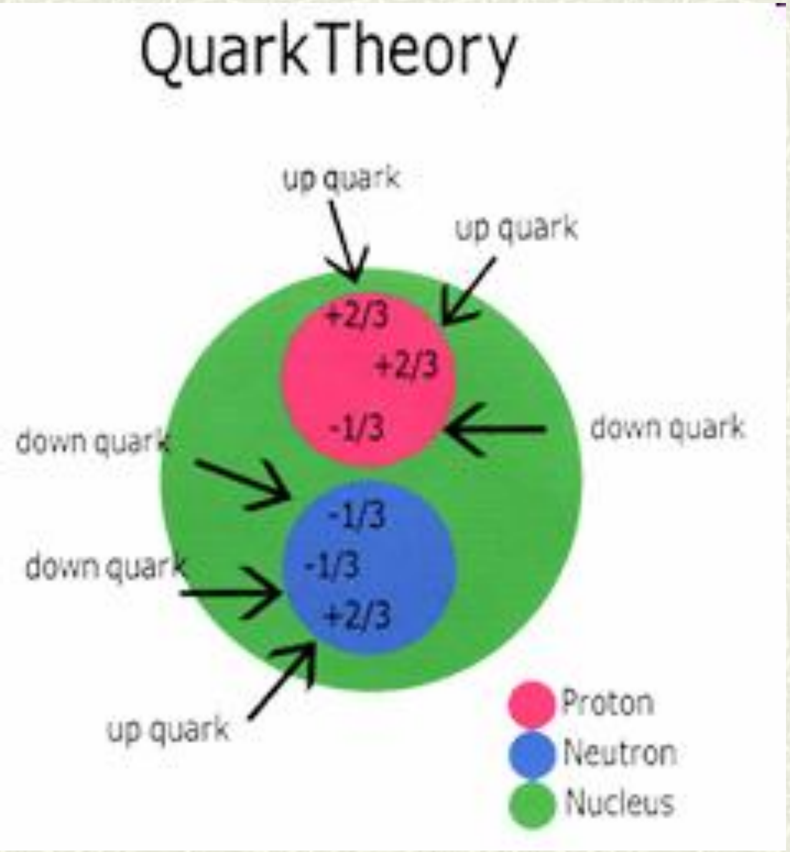
Particle Zoo (1950s, 1960s)

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	ν_e	0		
Δ	0	K^+	+1	$\bar{\nu}_e$	0		
		K^-	−1				
		K^0	0				

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)



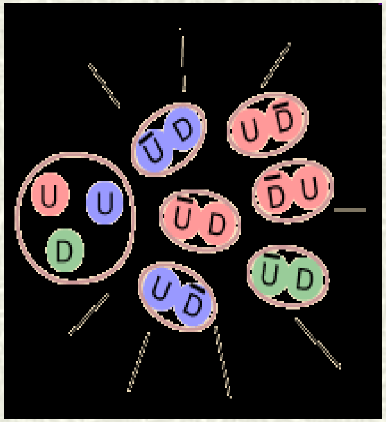
Prediction of Ω^-

Gell-Mann, Zweig

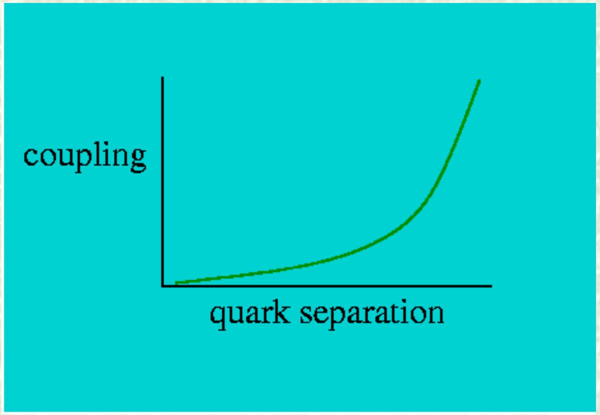
Quarks (experiment)

Stanford/MIT 1969

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



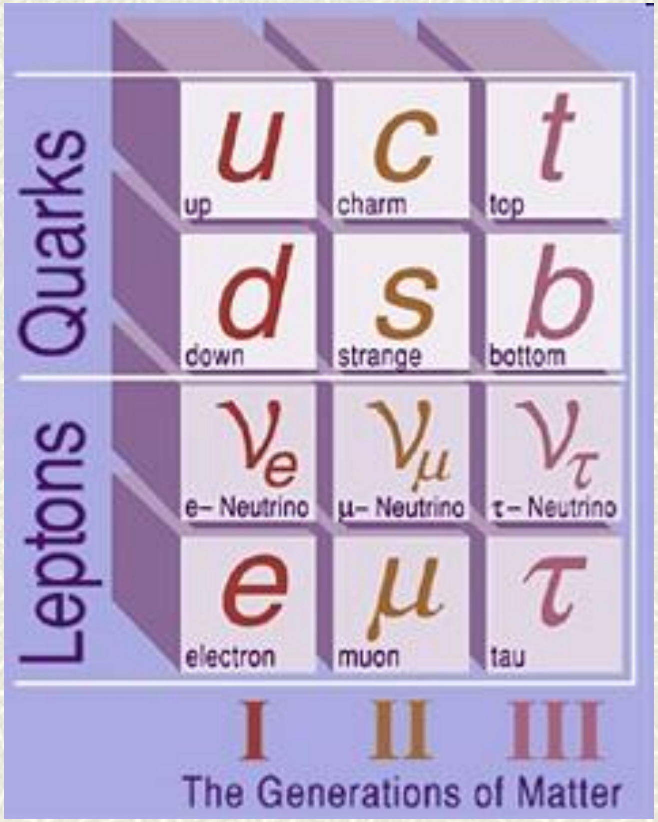
- Defining property = ***colour***
- Quark confinement
- Infra-red slavery



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

The quark model (1970s –1990s)

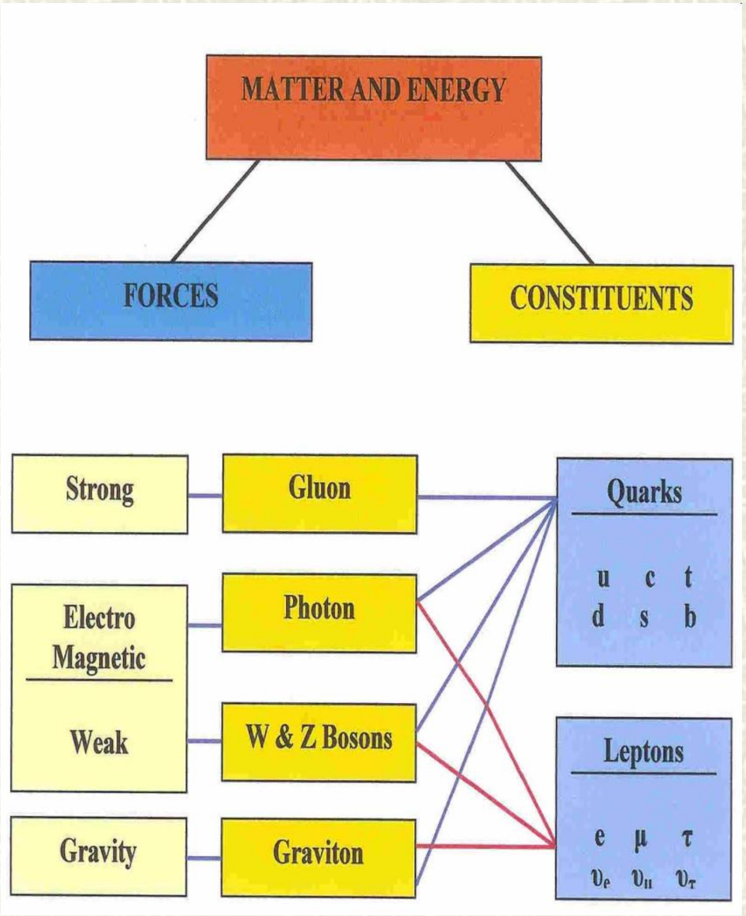
- 30 years experiments
- Six different quarks *(u,d,s,c,b,t)*
- Six corresponding leptons *(e, μ, τ, ν_e, ν_μ, ν_τ)*
- Gen I: all of ordinary matter
- Gen II, III redundant?



New periodic table

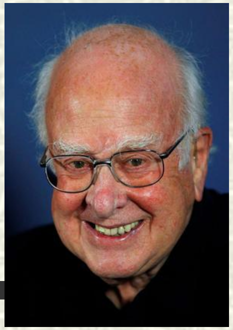
Particle theory and forces (1960 -)

- 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



Peter Higgs

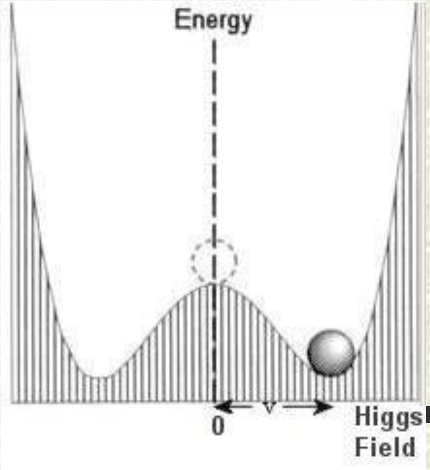
- Electro-weak symmetry breaking
- Mediated by scalar field
- Higgs field
- Generates mass for W, Z bosons

W and Z bosons (CERN, 1983)

Kibble, Guralnik, Hagen, Englert, Brout

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

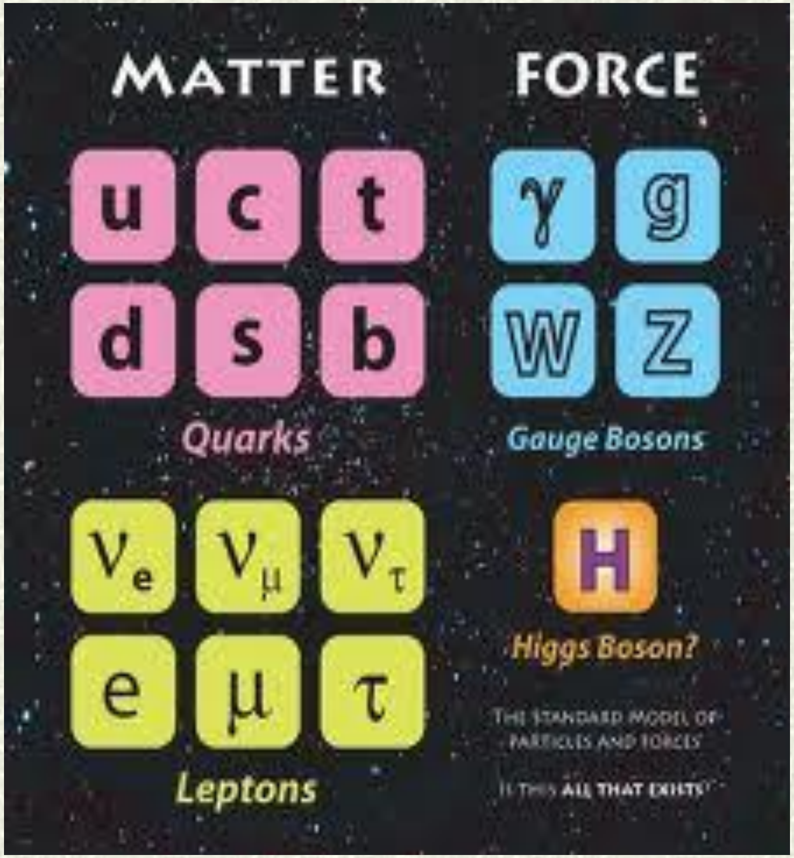
Particle masses not specified



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)



<u>Experimental tests</u>

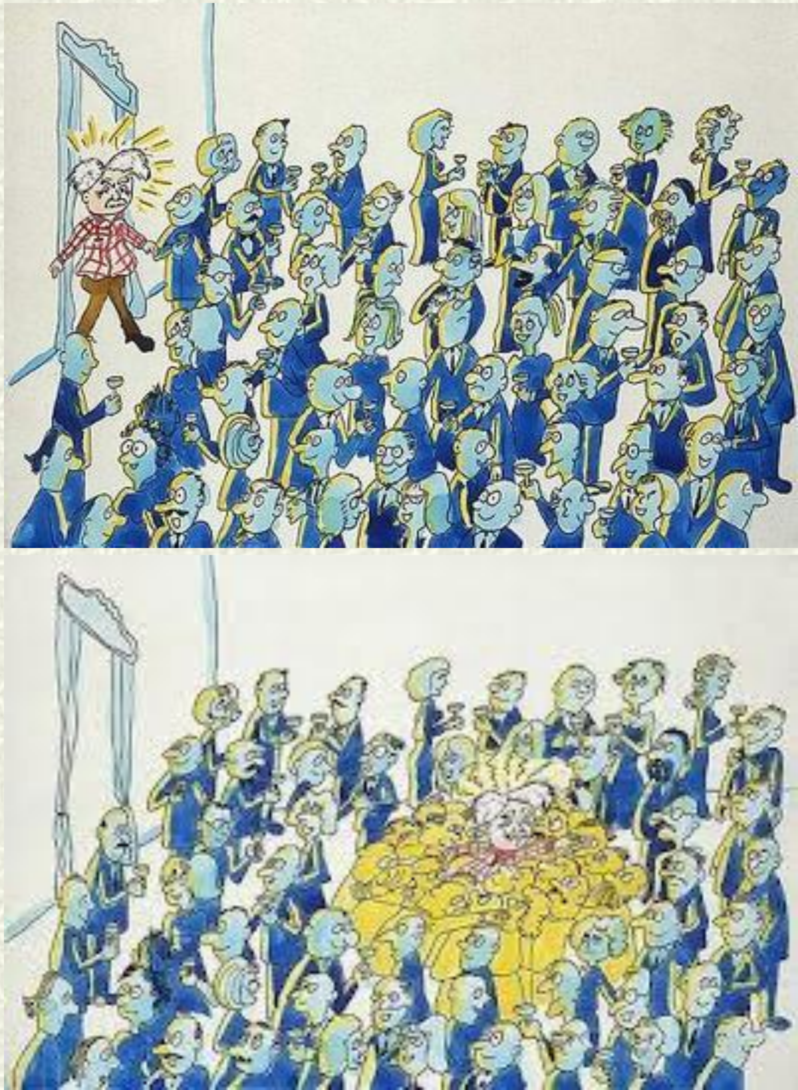
- *Top, bottom , charm, strange quarks*
- *Leptons*
- *W^{+-},Z^0 bosons*

<u>Higgs boson</u> outstanding

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 (CERN)

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

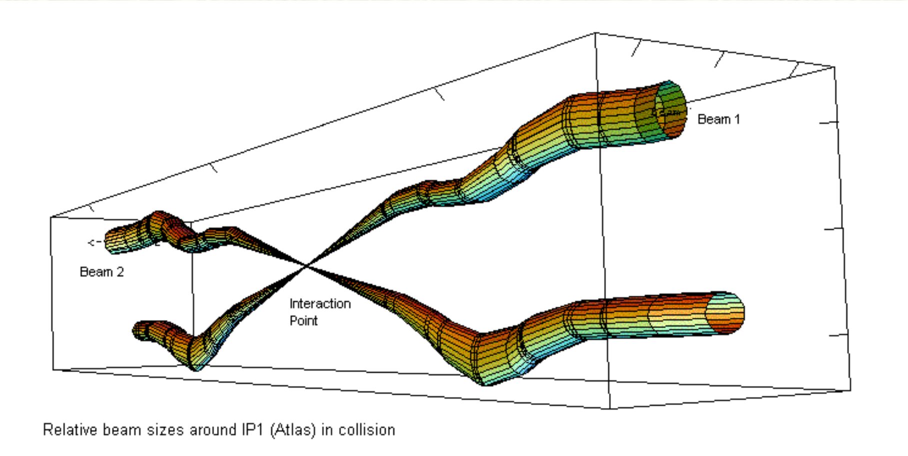
$$E = mc^2$$

- Detect particle decays
- Four particle detectors

No black holes

How

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



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

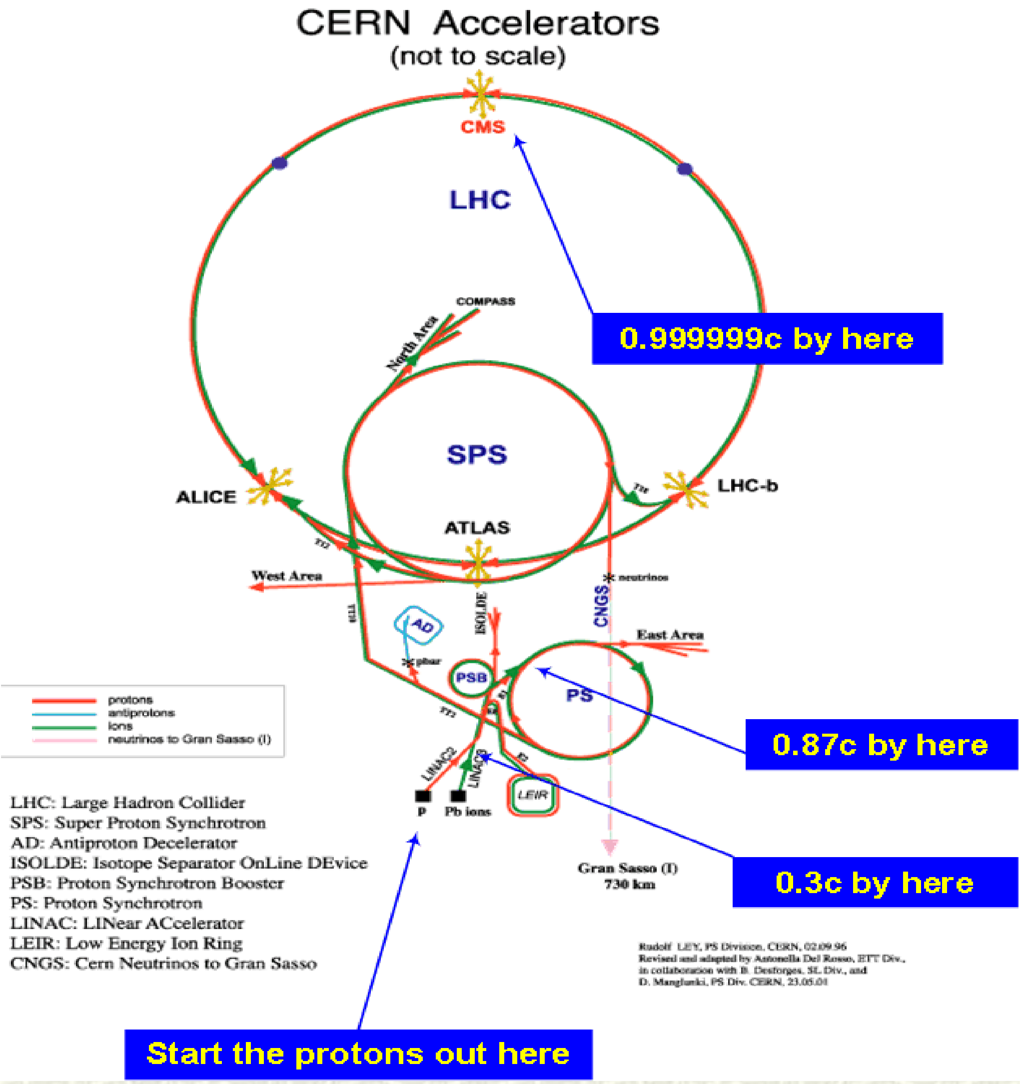
LEP tunnel: 27 km

Luminosity: 5.8 fb^{-1}

Around the ring at the LHC

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

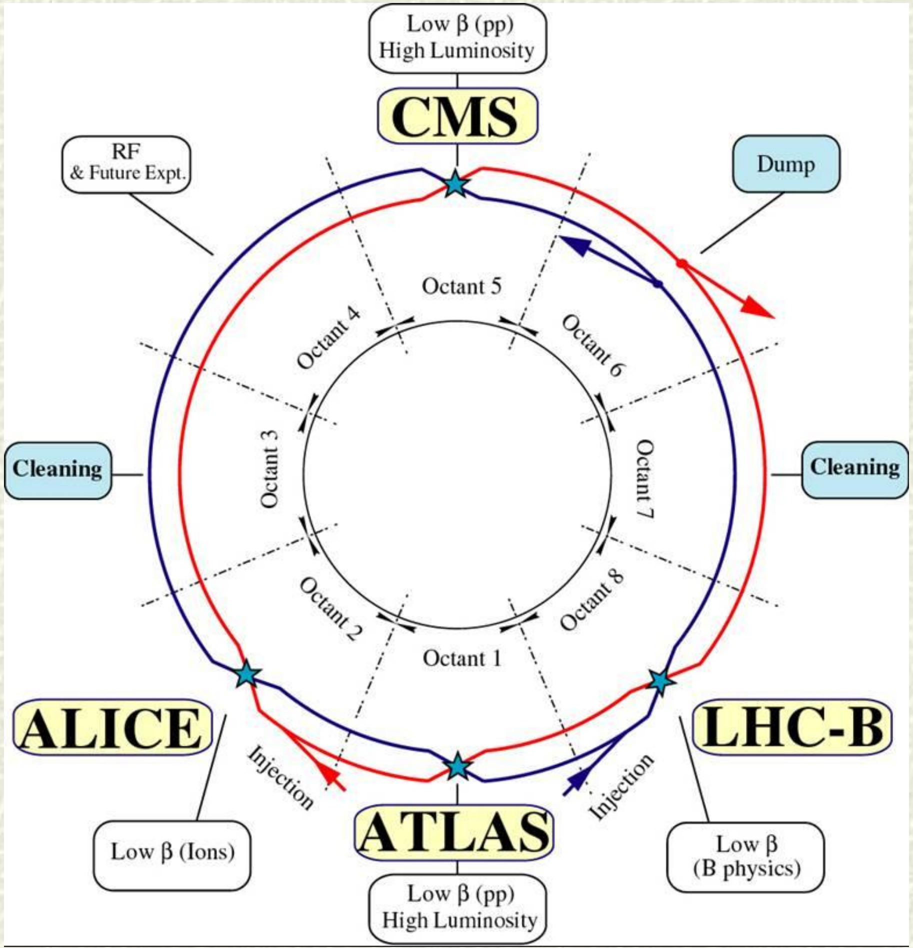
$$m = \frac{m_0}{\sqrt{1 - v^2/c^2}}$$



Particle detectors

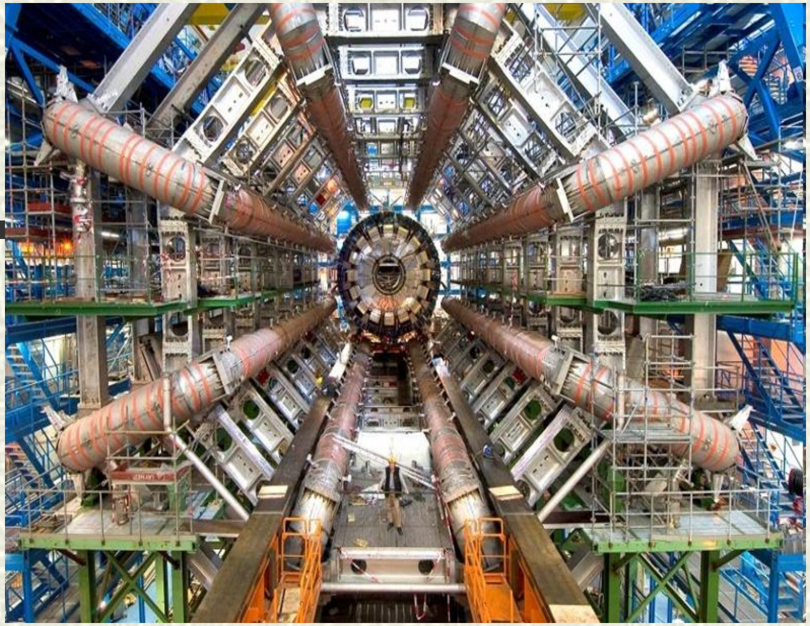
<u>Detectors at crossing pts</u>

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

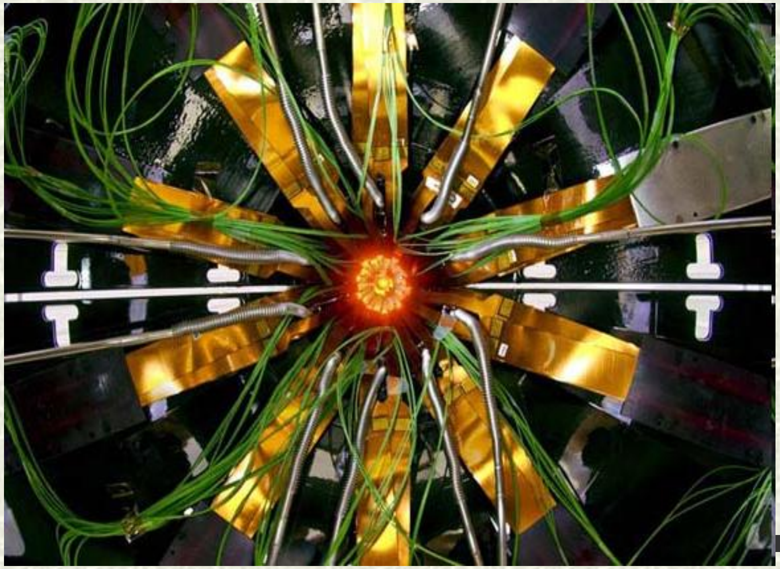


Particle detection

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

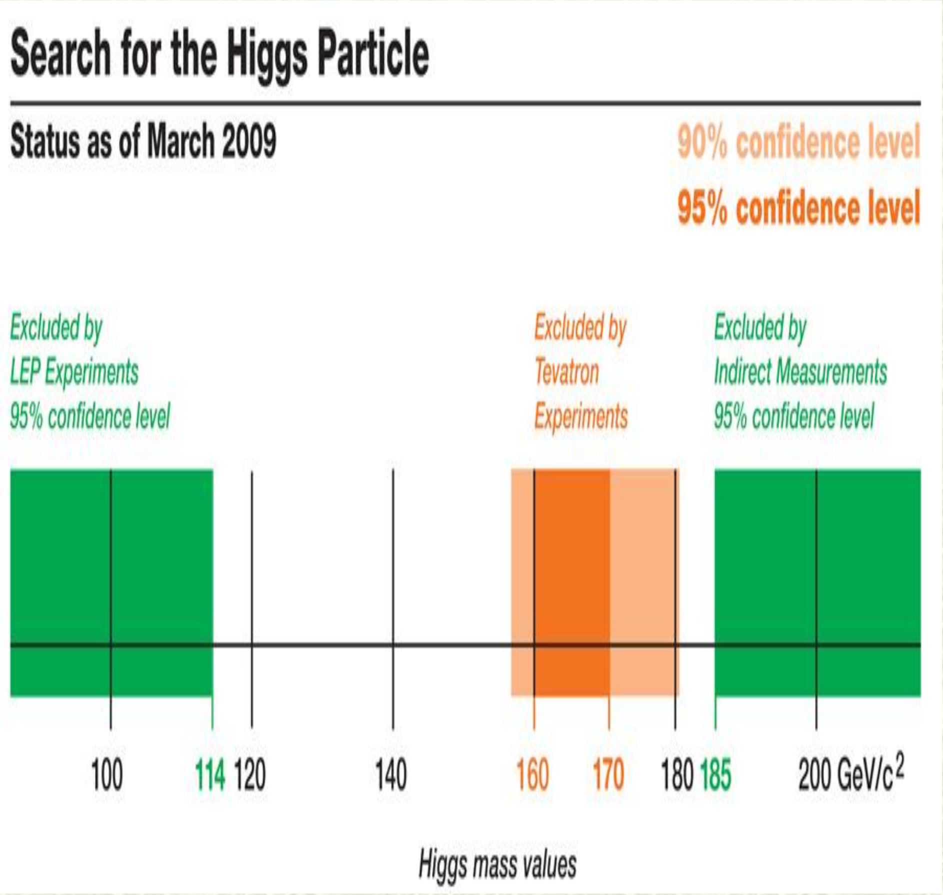


ATLAS



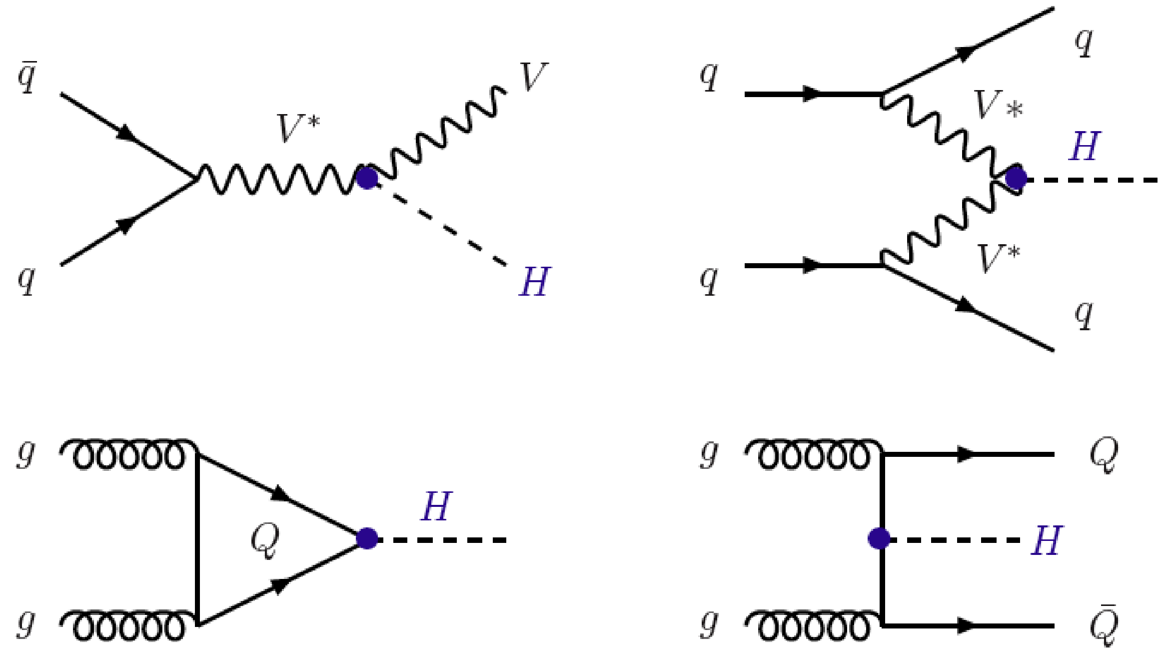
III A Higgs at the LHC?

- 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

$$\begin{aligned}
\text{associated production with } W/Z: &\quad q\bar{q} \longrightarrow V + H \\
\text{vector boson fusion}: &\quad qq \longrightarrow V^*V^* \longrightarrow qq + H \\
\text{gluon} - \text{gluon fusion}: &\quad gg \longrightarrow H \\
\text{associated production with heavy quarks}: &\quad gg, q\bar{q} \longrightarrow Q\bar{Q} + H
\end{aligned}$$



1 in a billion collisions

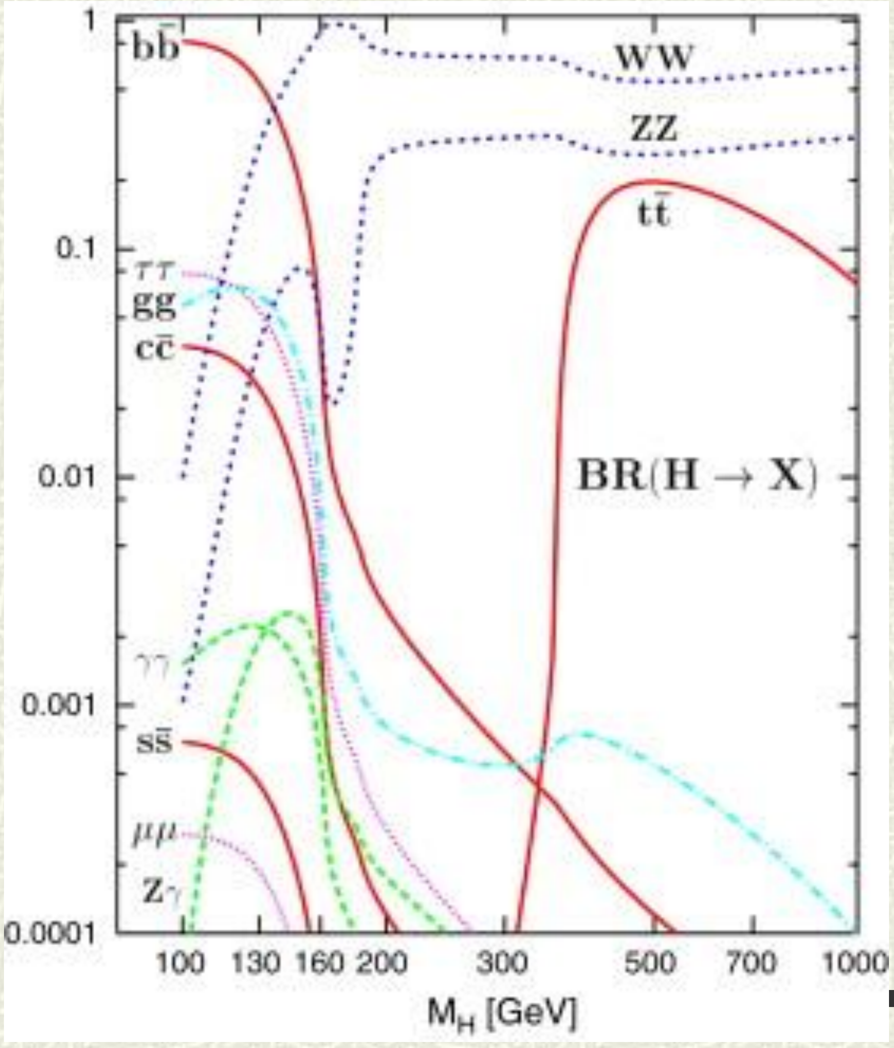
Higgs decay channels

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

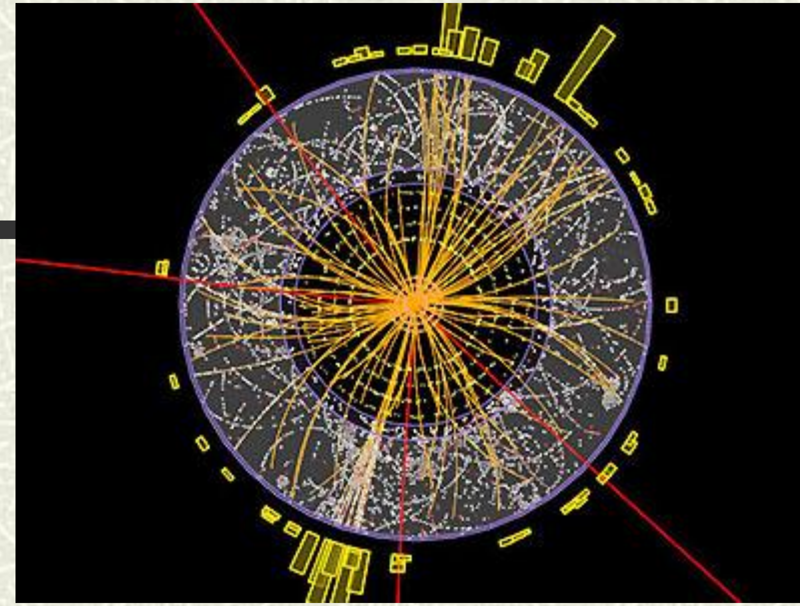
Needle in haystack of needles

<u>High luminosity required</u>

$$N = \sigma \int L \, dt$$



Analysis



- Huge number of collisions
  Data analysis

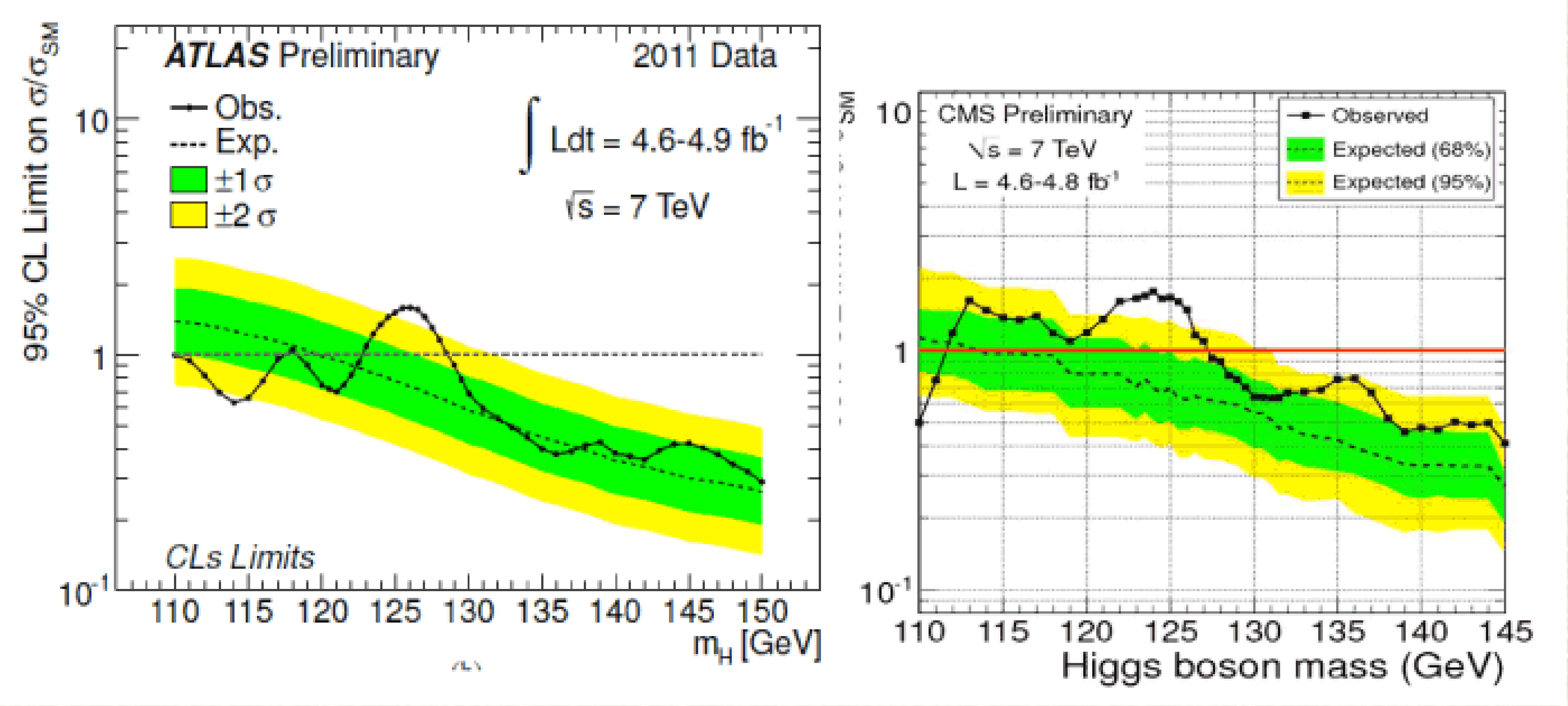
- World Wide Web
  Platform for sharing data

- GRID
  Distributed computing

- World-wide analysis

- Huge increase in computing power

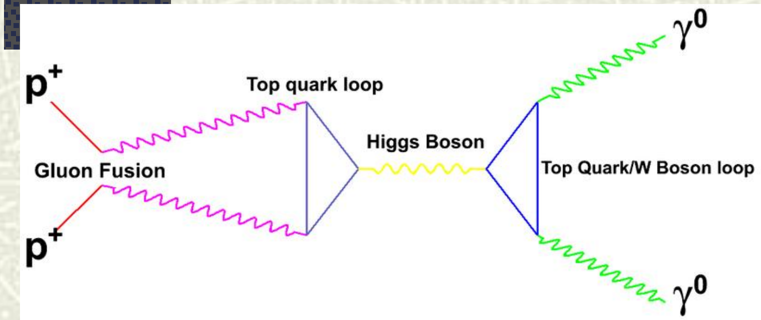
Higgs search at LHC (2011)

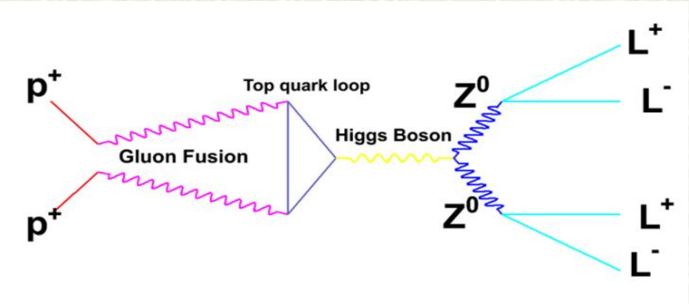


Excess events at 125 GeV in ATLAS and CMS detectors

Higher luminosity required 4.8 fb^{-1}

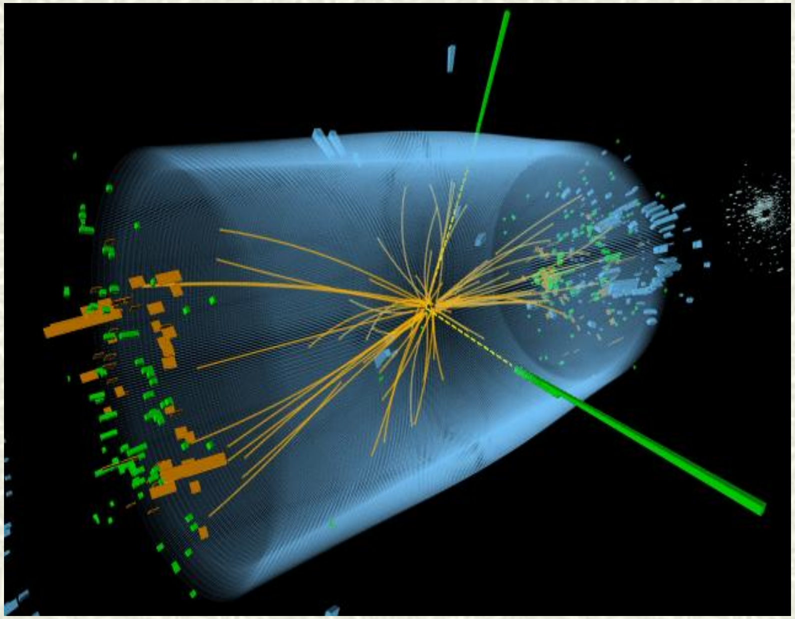
April-July 2012: *8 TeV*, *5.8* fb^{-1}

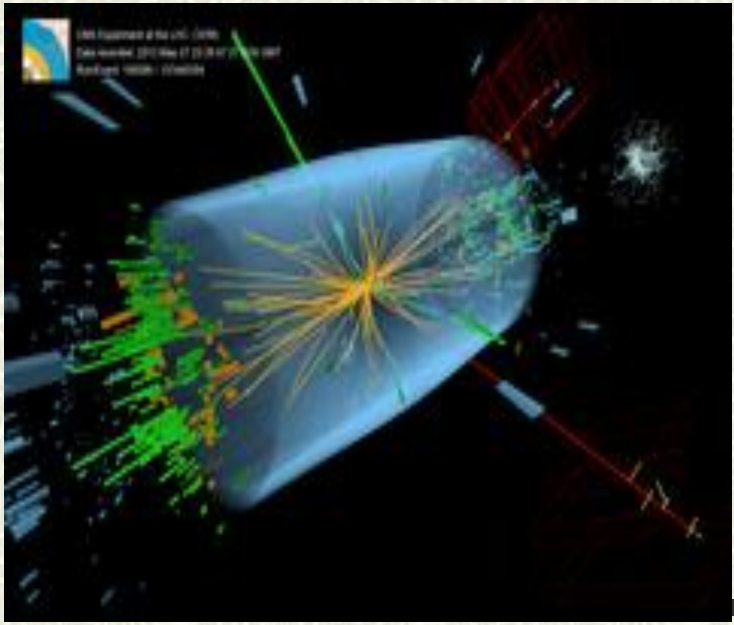




Measure energy of <u>photons</u> emitted

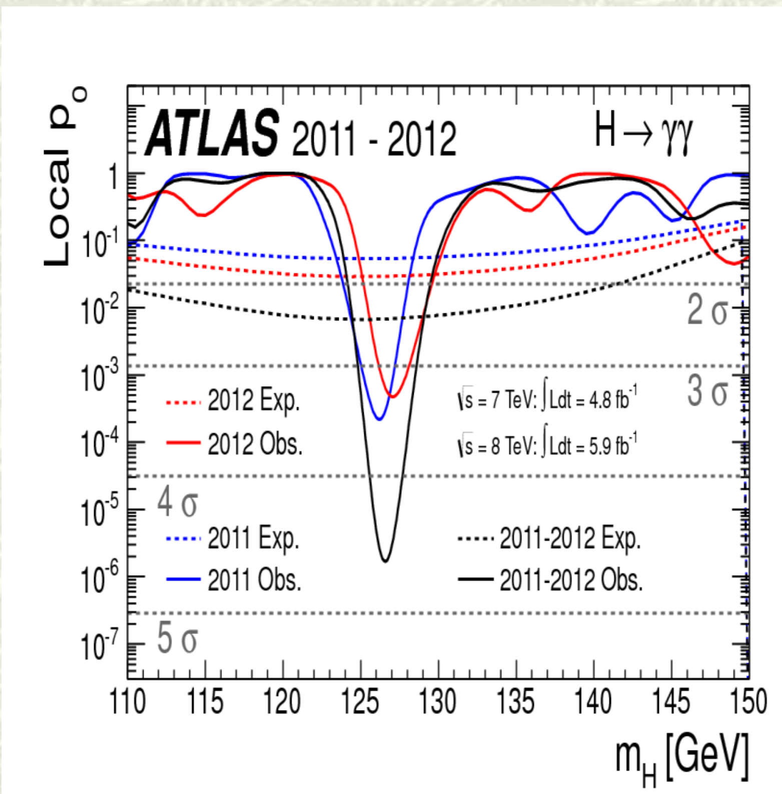
Measure decay products of <u>Z bosons</u>

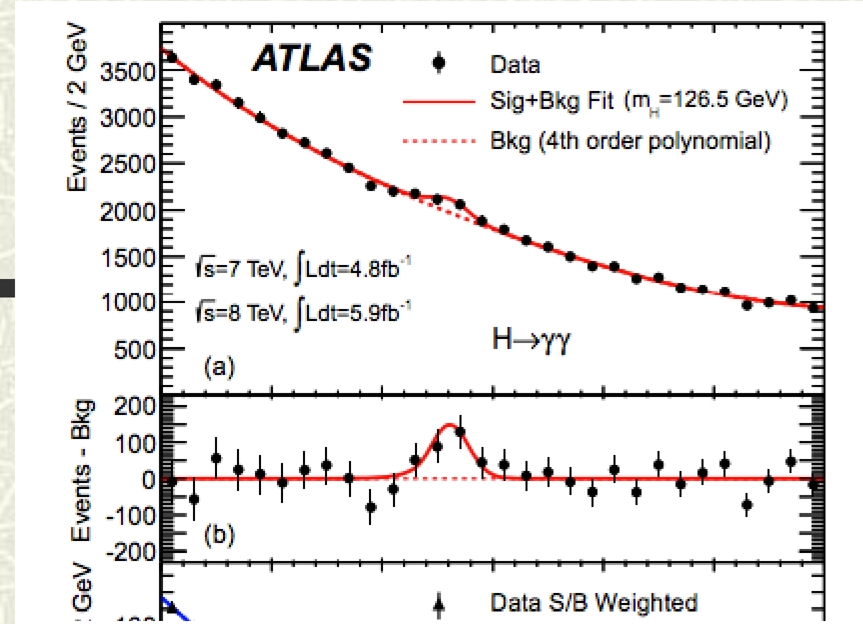


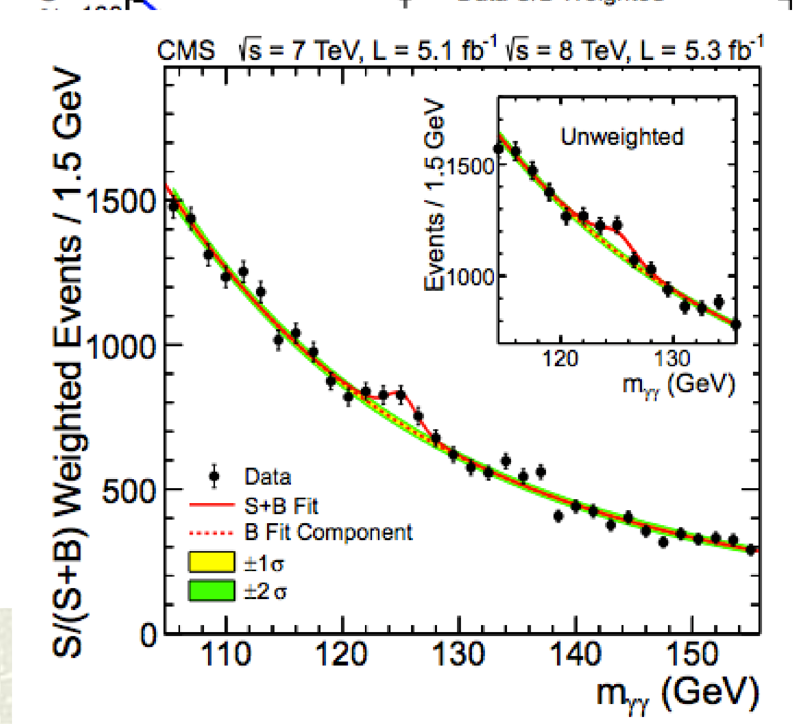


Results (July, 2012)

H $\rightarrow$ ***γγ*** (*8 TeV*, 5.3 fb^{-1})

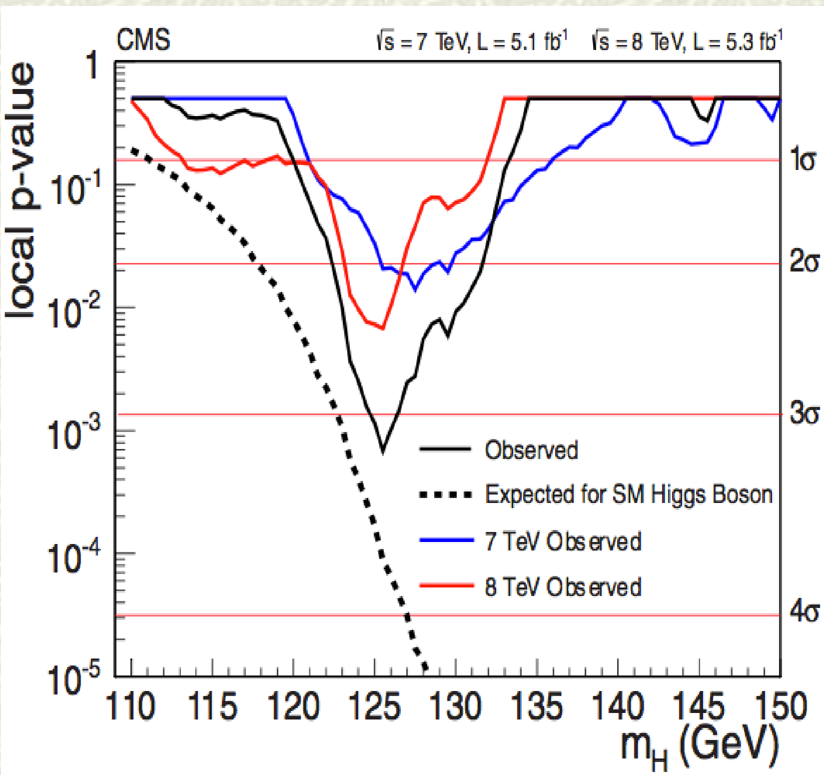


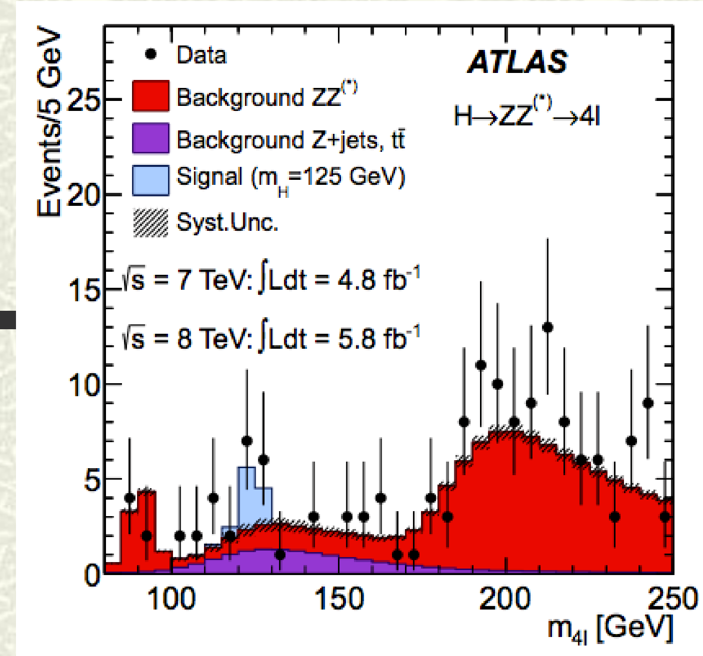


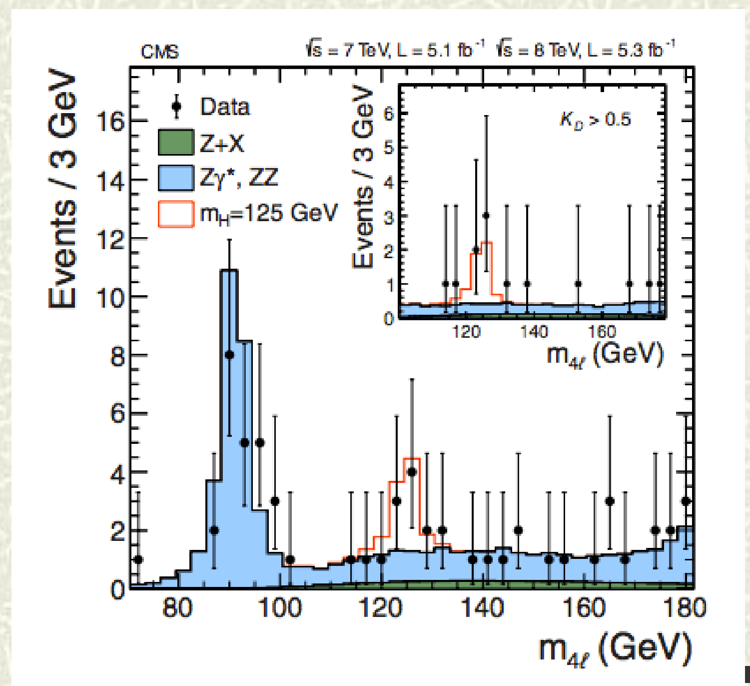


Results (July, 2012)

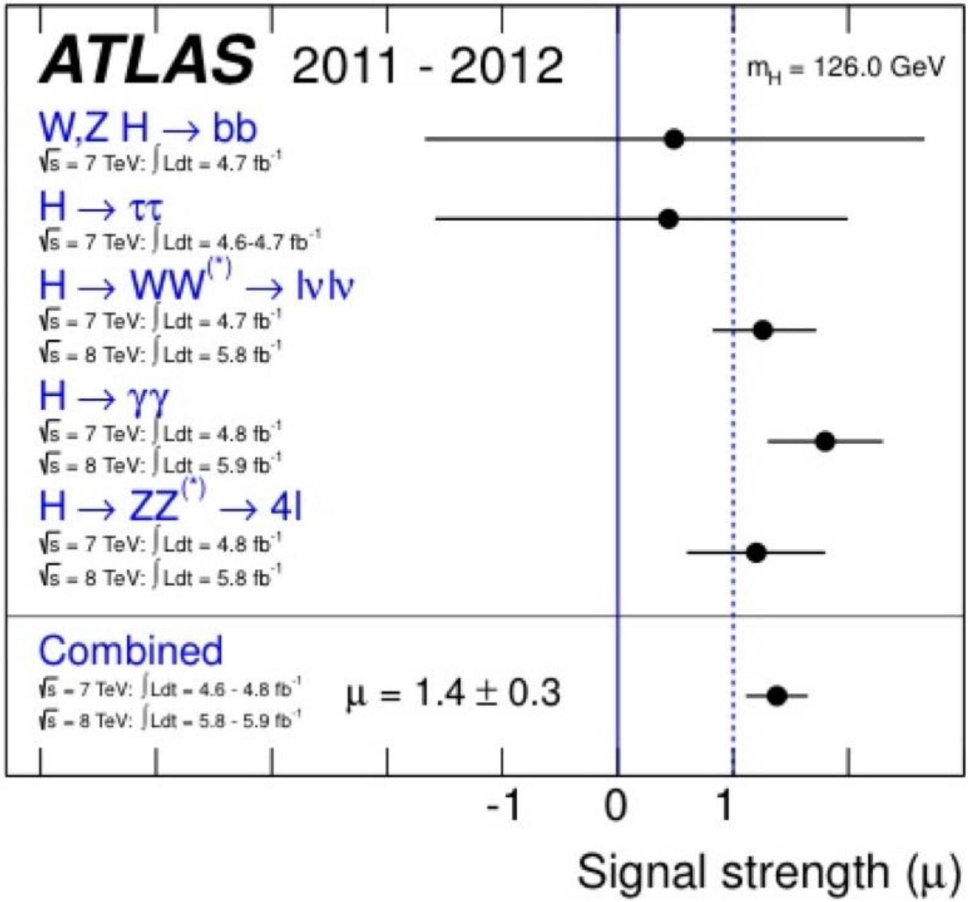
H→ZZ (8 TeV, 5.3 fb^{-1})

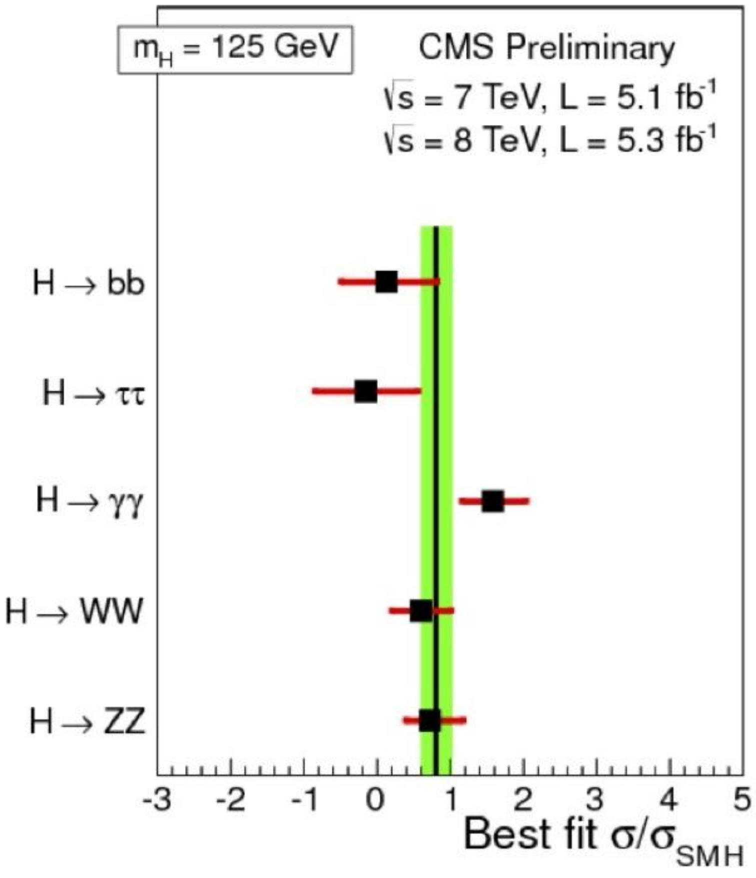






Results: all decay channels

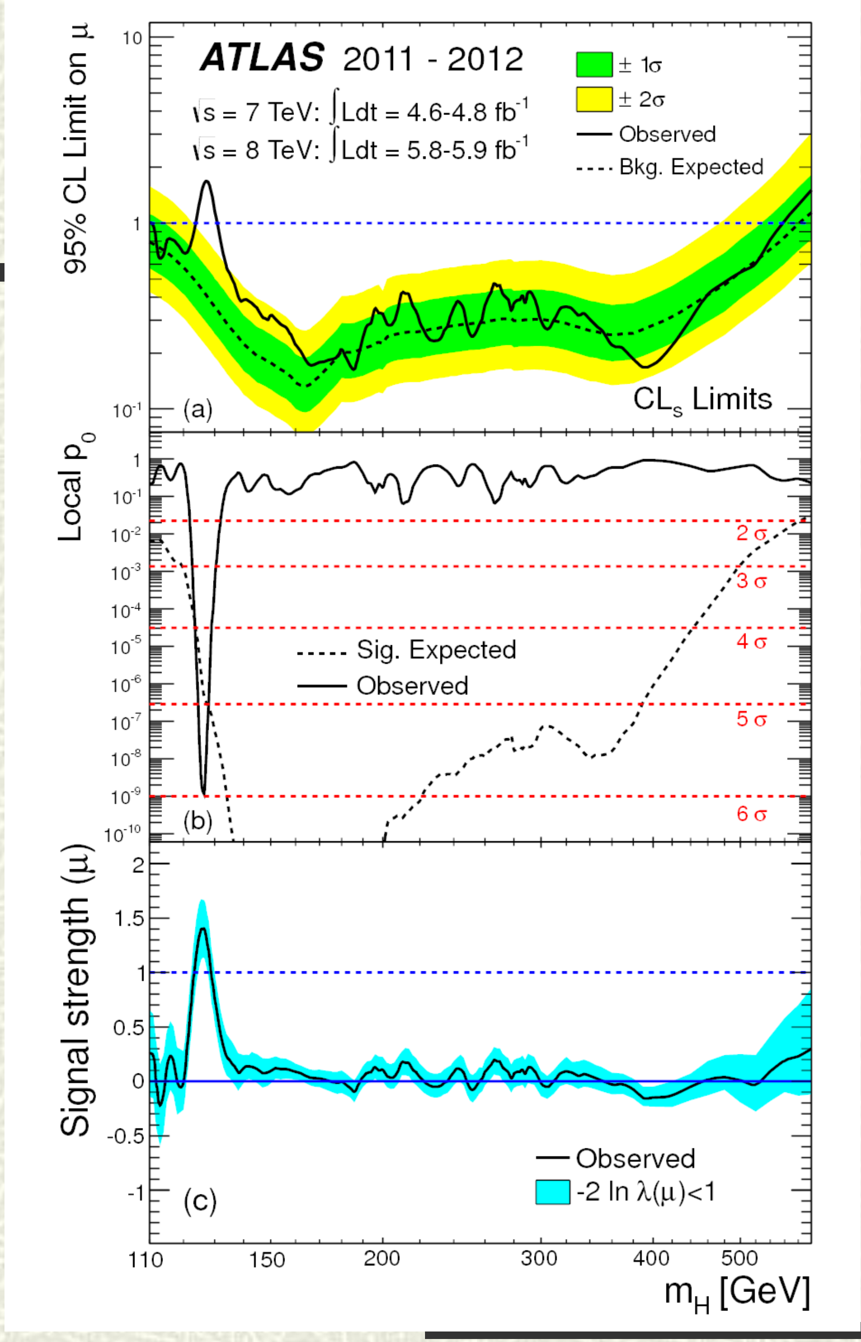




Results summary

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

Higgs boson?

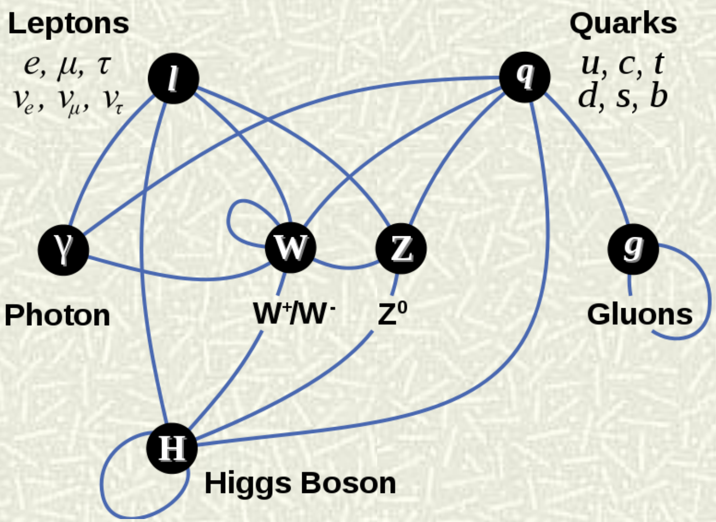


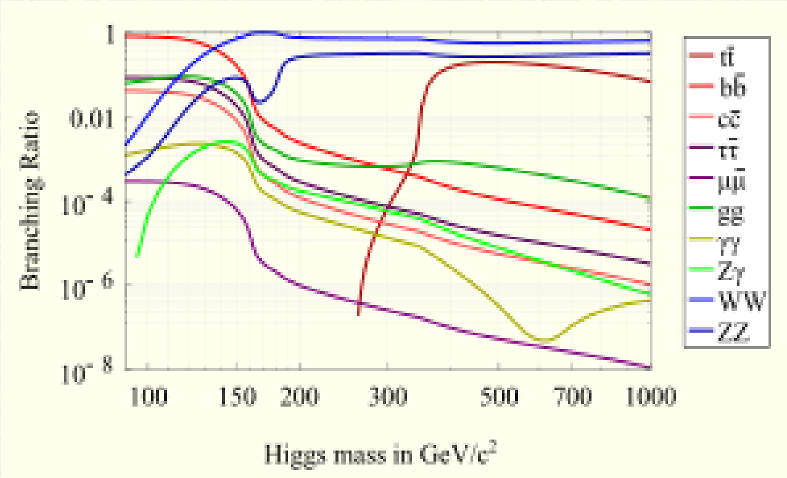
IV Next at the LHC

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

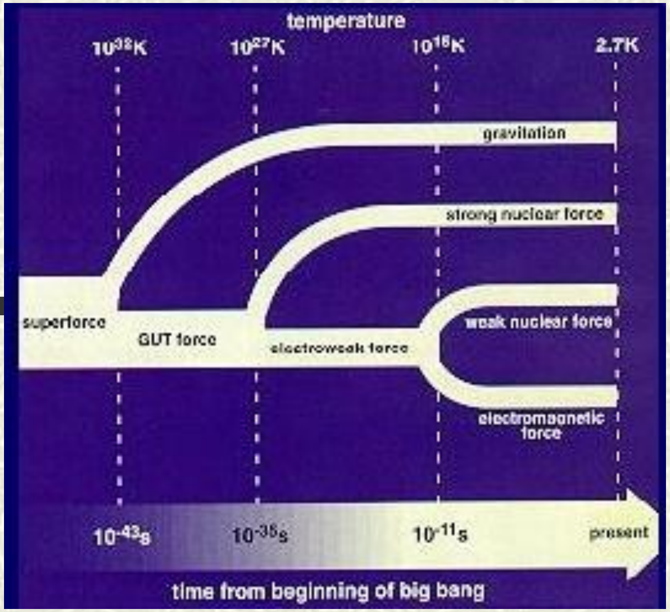
- **Supersymmetry**
  Numerous Higgs?
  Other supersymmetric particles
  Implications for unification

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

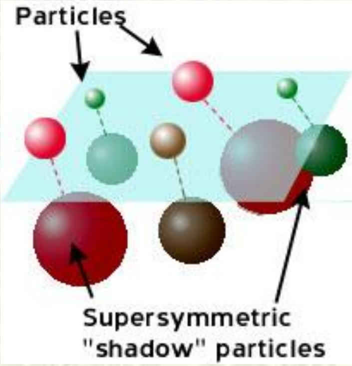




Supersymmetry

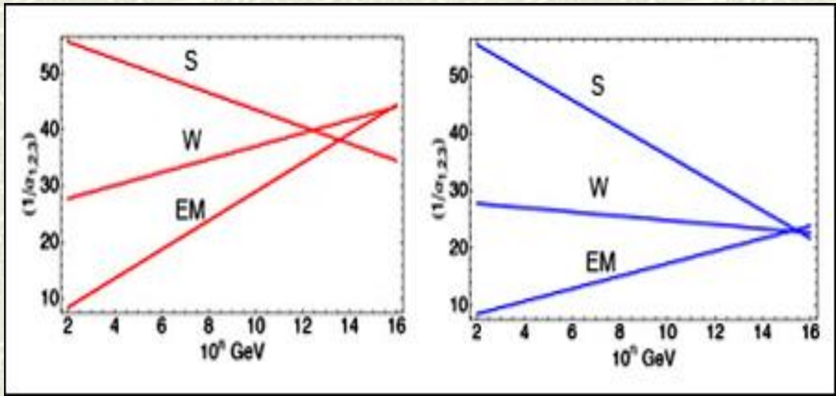


- Success of electro-weak unification
- Extend program to all interactions?
- Super-force - theory of everything
- No-go theorems (1960s)

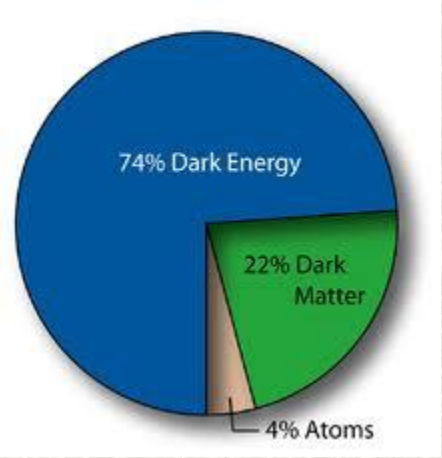


- Unification by supersymmetry (1970s)
- Symmetry between bosons and fermions
- New families of particles (incl Higgs)

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)

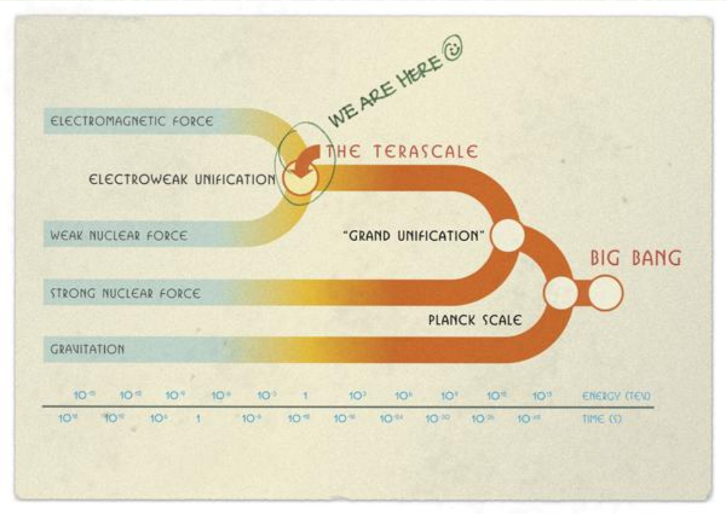
- **Dark energy ?**

  Scalar field

- **Higher dimensions?**

  Kaluza Klein particles

- **String theory?**

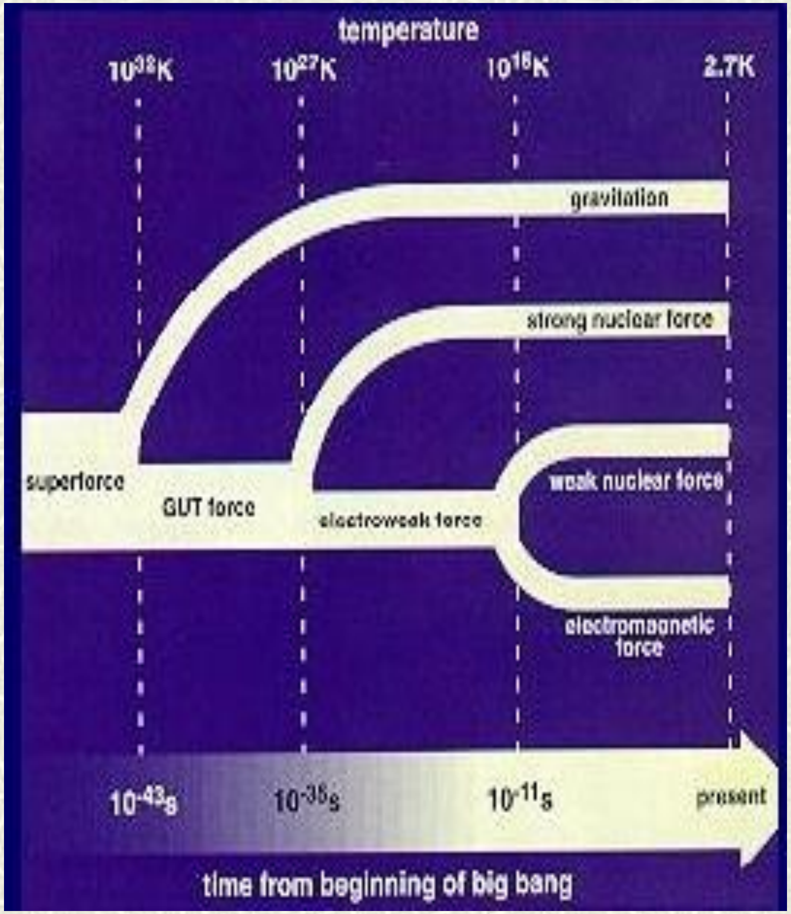


$T = 10^{19}$ K, $t = 1x10^{-12}$ s, V = football

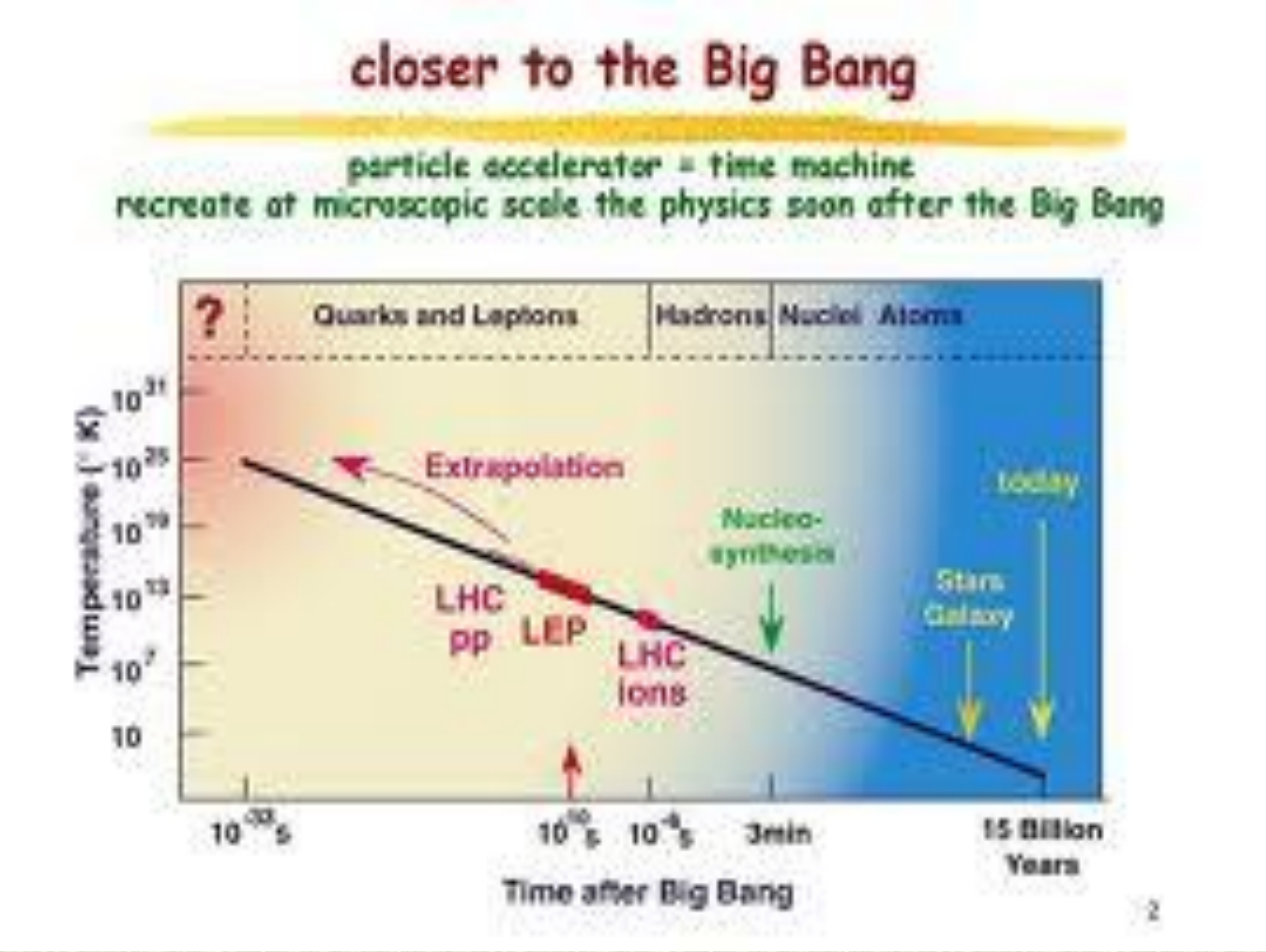
Summary (2012)

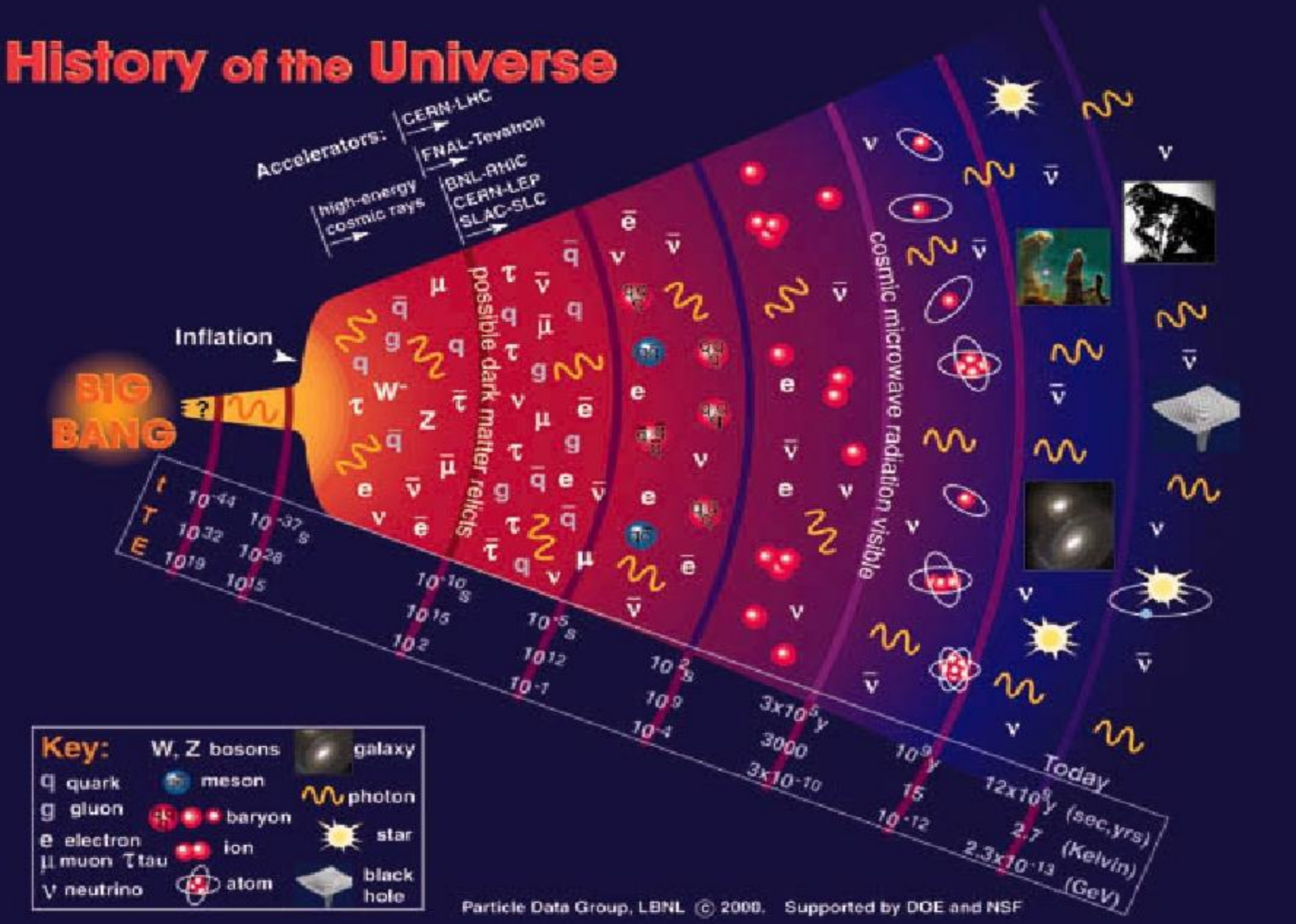
- New particle detected at LHC
- Mass 126 +/- 0.5 GeV
- Zero charge, integer spin (zero?)
- Consistent with Higgs boson
- Confirmation of *e-w* unification
- SM right so far

En route to a theory of everything ?



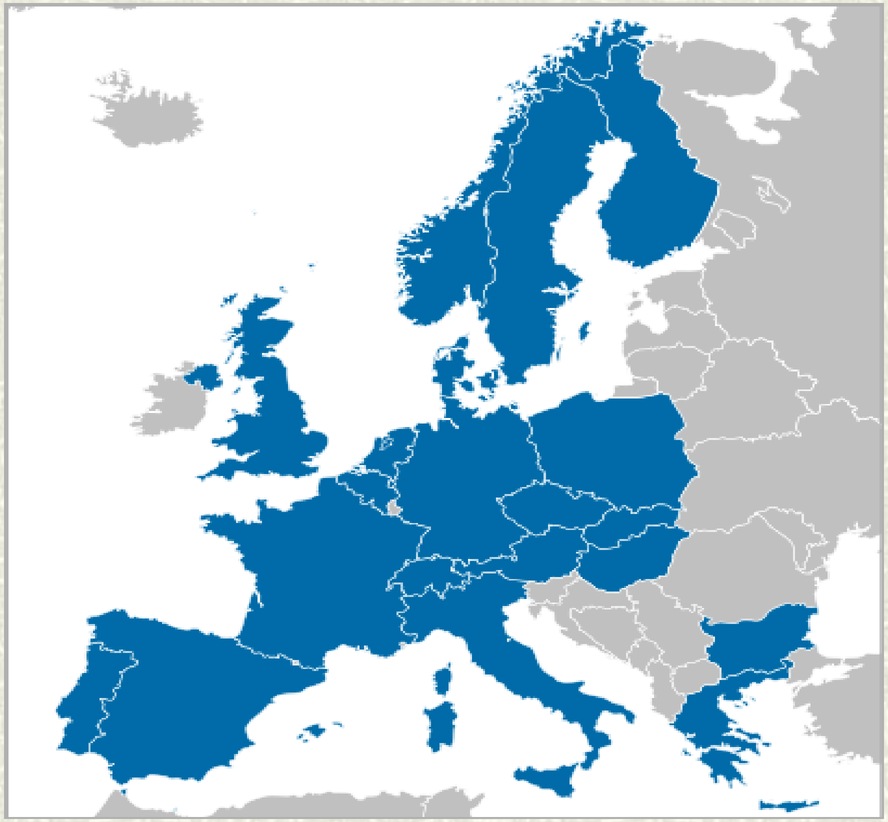
LHC and cosmology




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 relics
cosmic microwave radiation visible
t
T
E
10^-44
10^32
10^19
10^-37 s
10^28
10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 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
Particle Data Group, LBNL © 2000. Supported by DOE and NSF

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