Introduction to Particle Physics II

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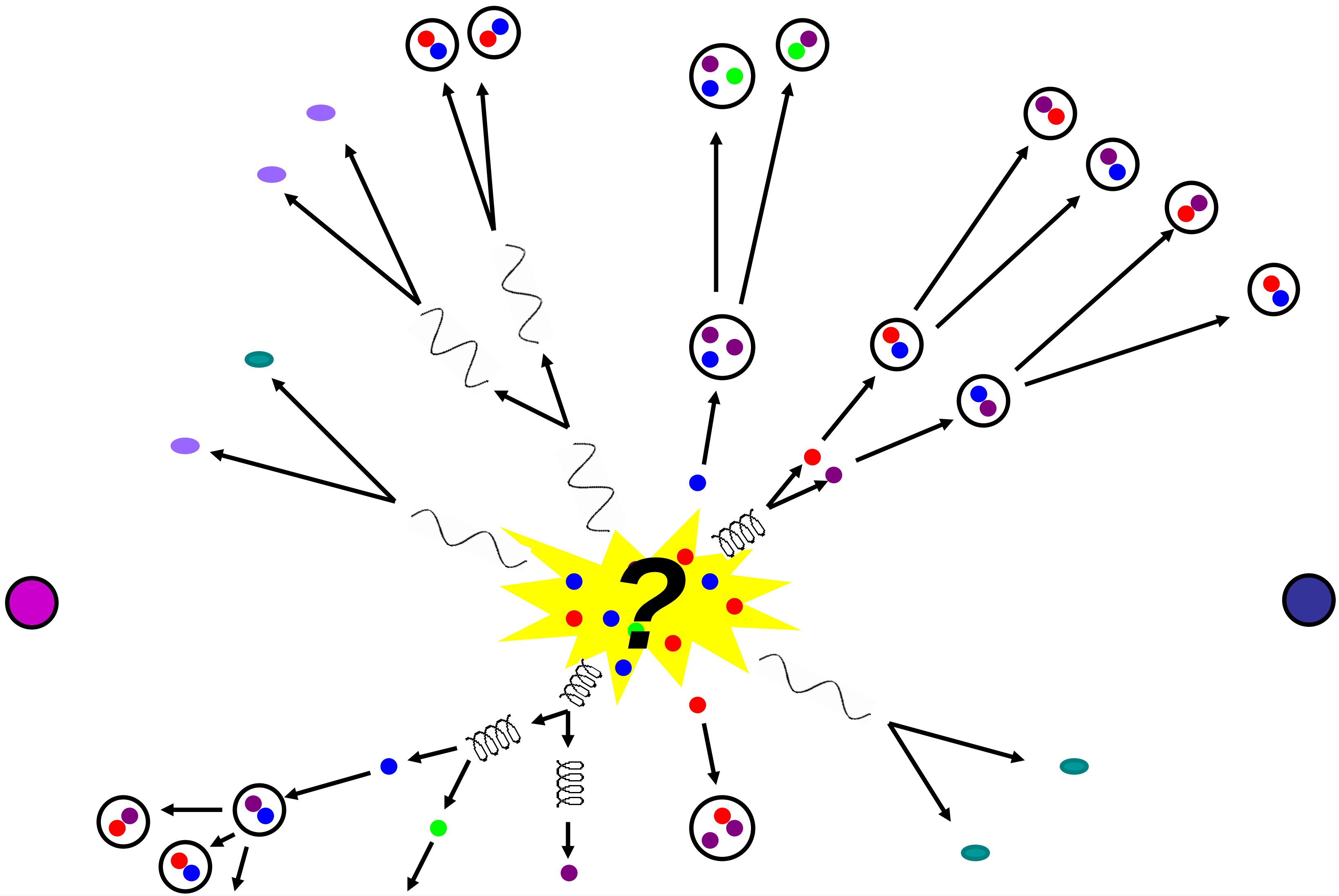
19th February 2015

Particle Collisions

Two particles collide at very high energy

New particles are produced which we detect and study



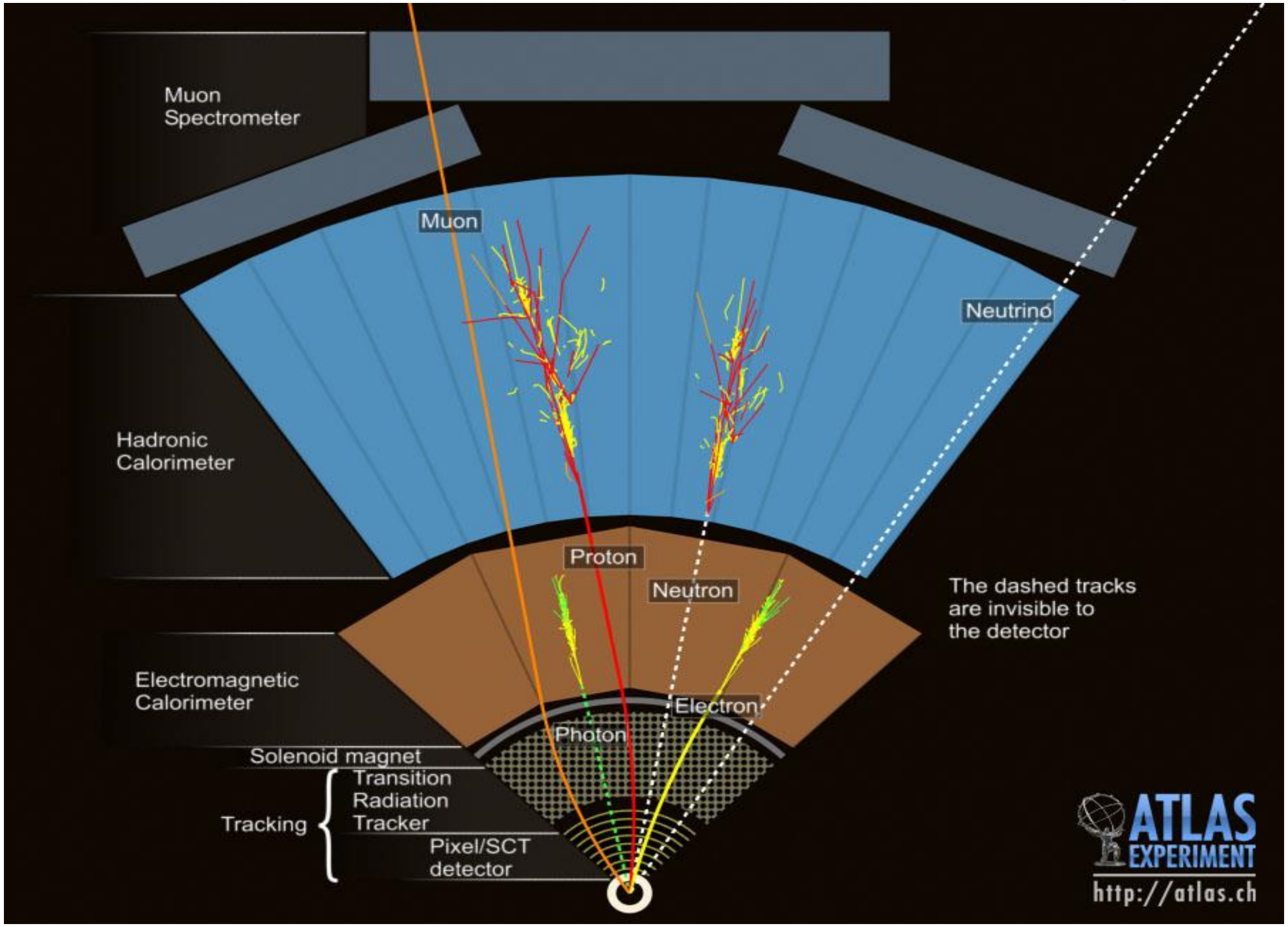
Goals of the LHC

- Understanding the generation of mass
- Searching for new phenomena to rule in or out new theories
- Searching for whatever is out there
- Remember $E=mc^2$ – the more energy we put into the collisions, the more massive the particles we can create

First, we need some data to analyse!

A Particle Detector

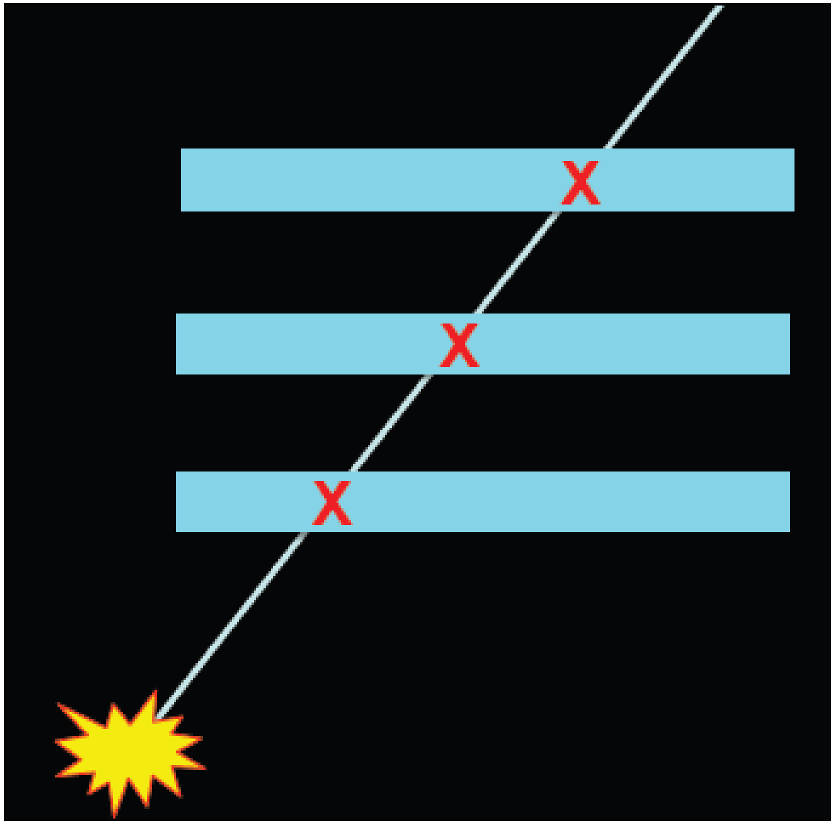
"Onion shell" structure enables reconstruction of particles



Use this capability to reconstruct particle interactions of special interest

Principles of Particle Detection

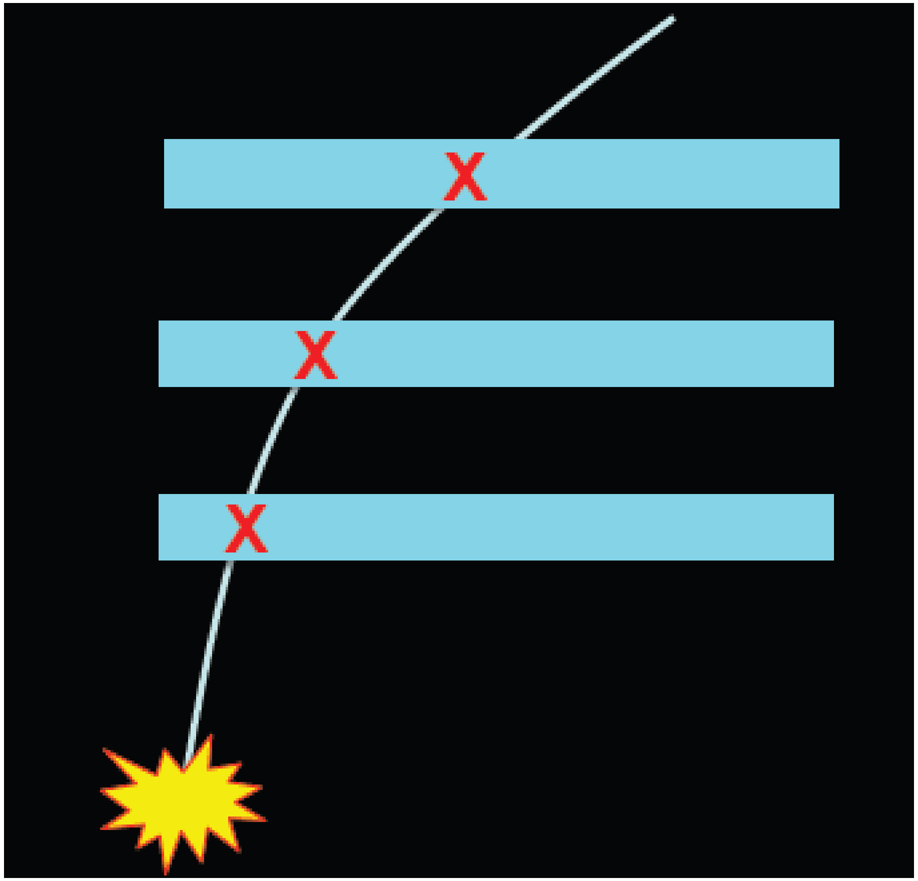
- **Detectors are designed to record**
  - Trajectories
  - For example in a silicon detector charged particles leave electron-hole pairs



Principles of Particle Detection

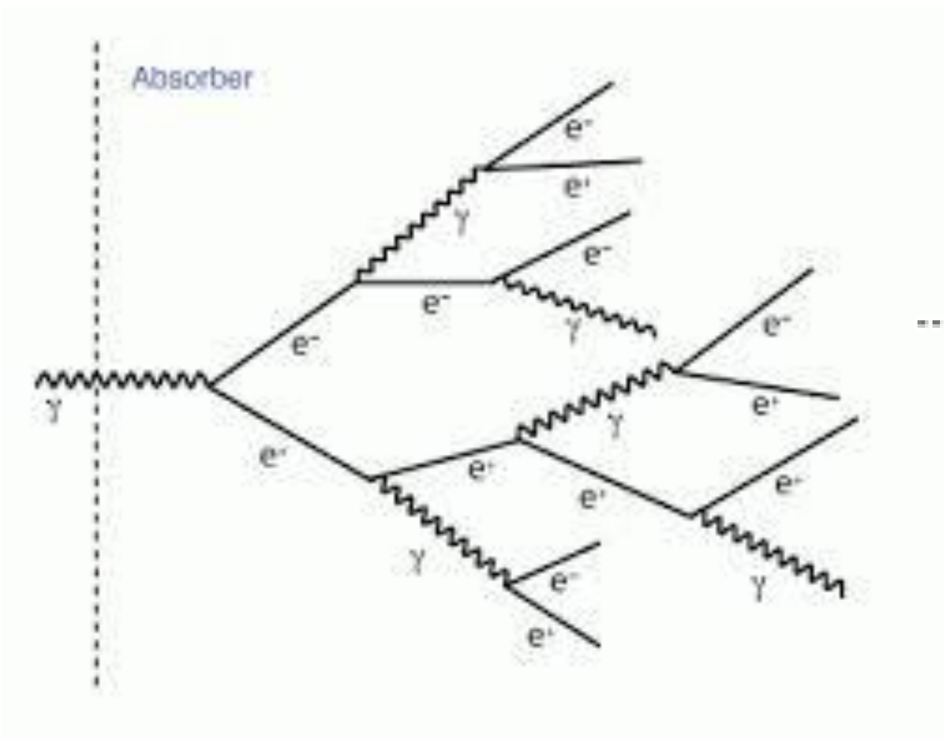
- **Detectors are designed to record**
  - Trajectories
  - For example in a silicon detector charged particles leave electron-hole pairs
  - Add a magnetic field
  - Equate centripetal and magnetic forces:

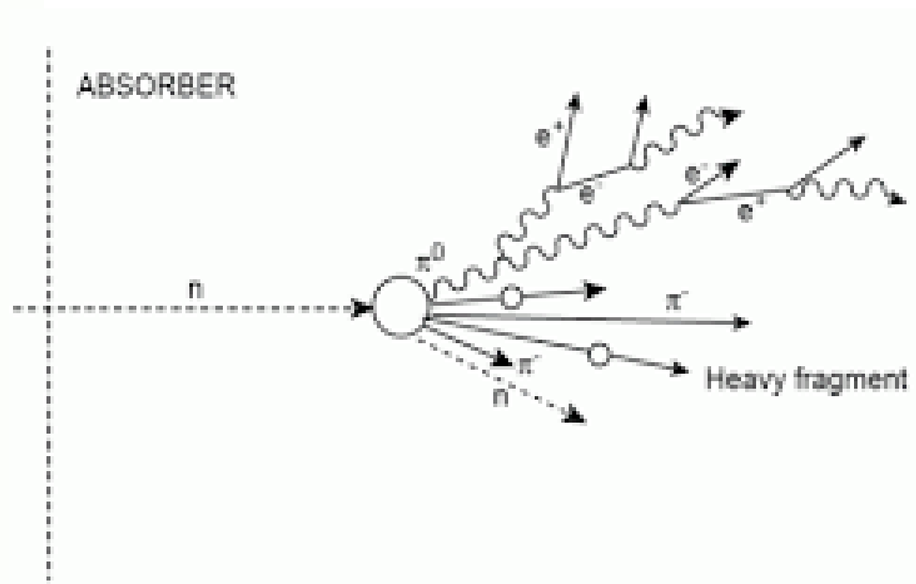
$r = \text{momentum} / qB$



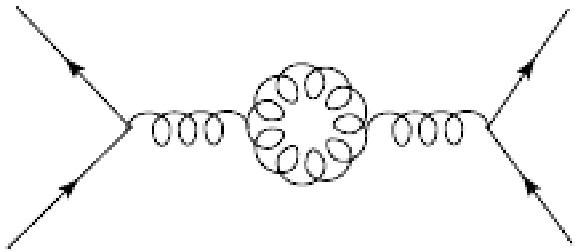
Principles of Particle Detection

- **Detectors are designed to record**
  - Trajectories
  - Energy deposits

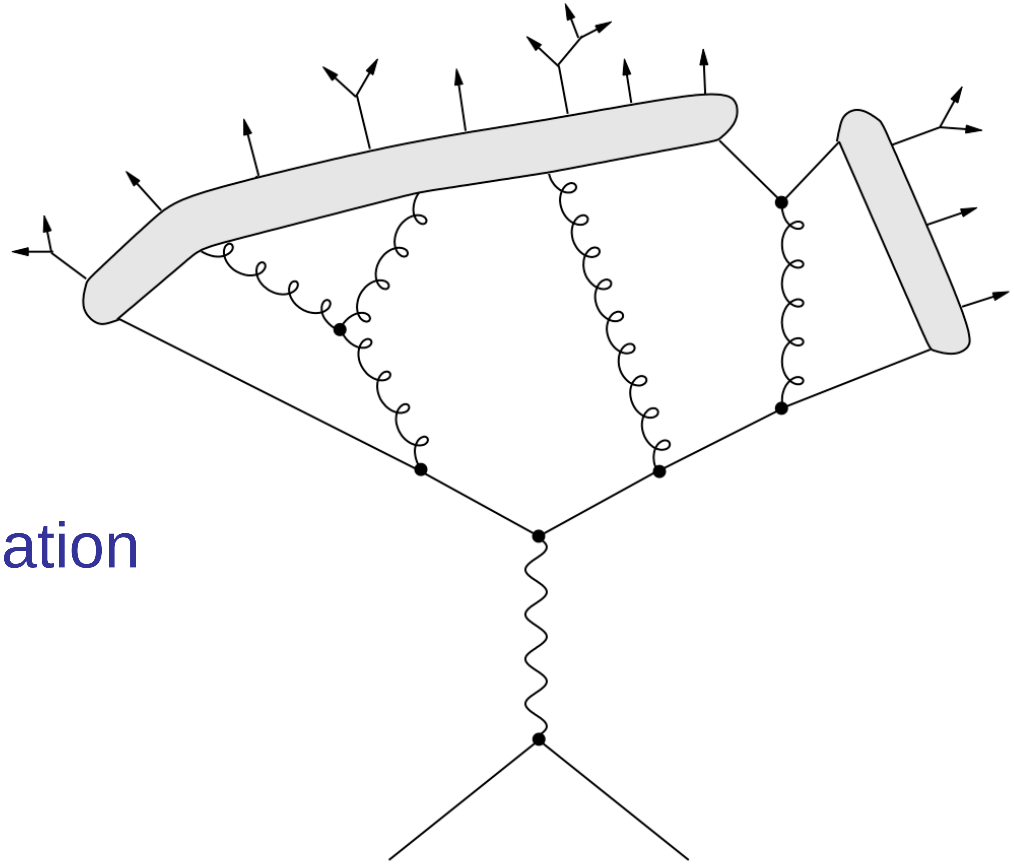




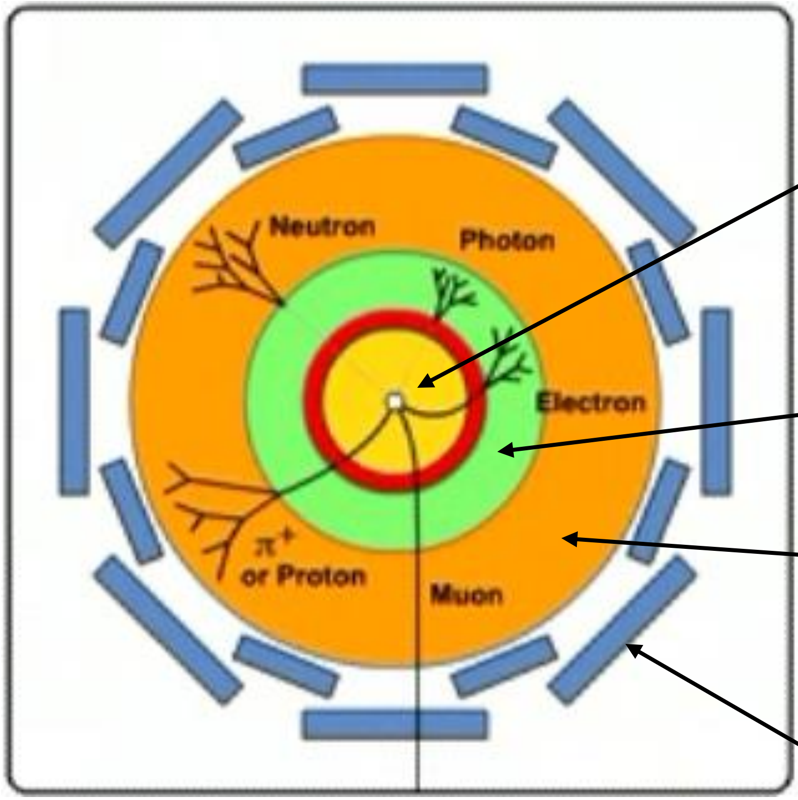
Aside: Hadronisation



String model of hadronisation



Detecting Particles



Tracking detector

−Measure charge and momentum of charged particles in magnetic field

Electro-magnetic calorimeter

−Measure energy of electrons, positrons and photons

Hadronic calorimeter

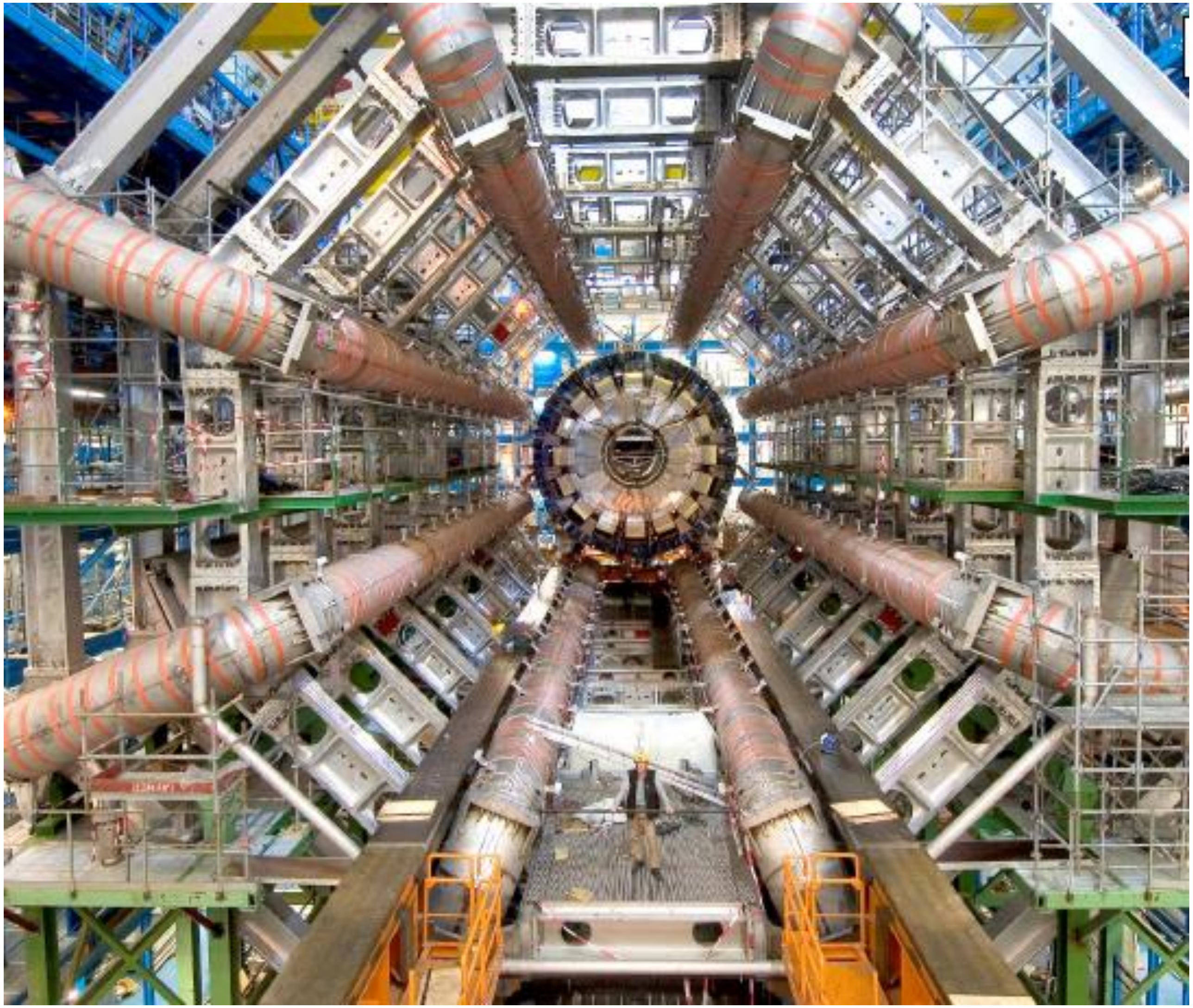
−Measure energy of hadrons (particles containing quarks), such as protons, neutrons, pions, etc.

Muon detector

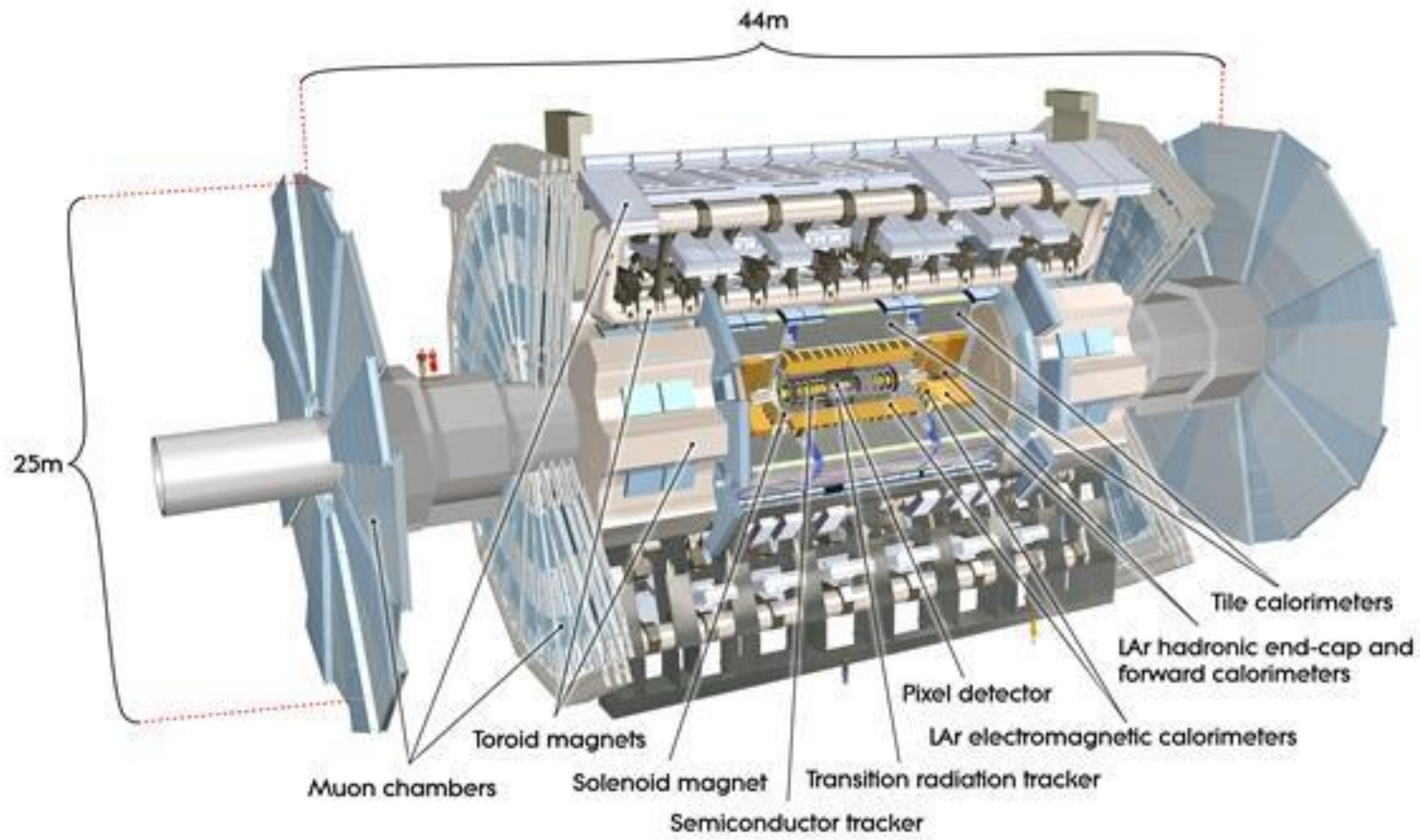
−Measure charge and momentum of muons

Neutrinos are only detected indirectly via 'missing energy' not recorded in the calorimeters

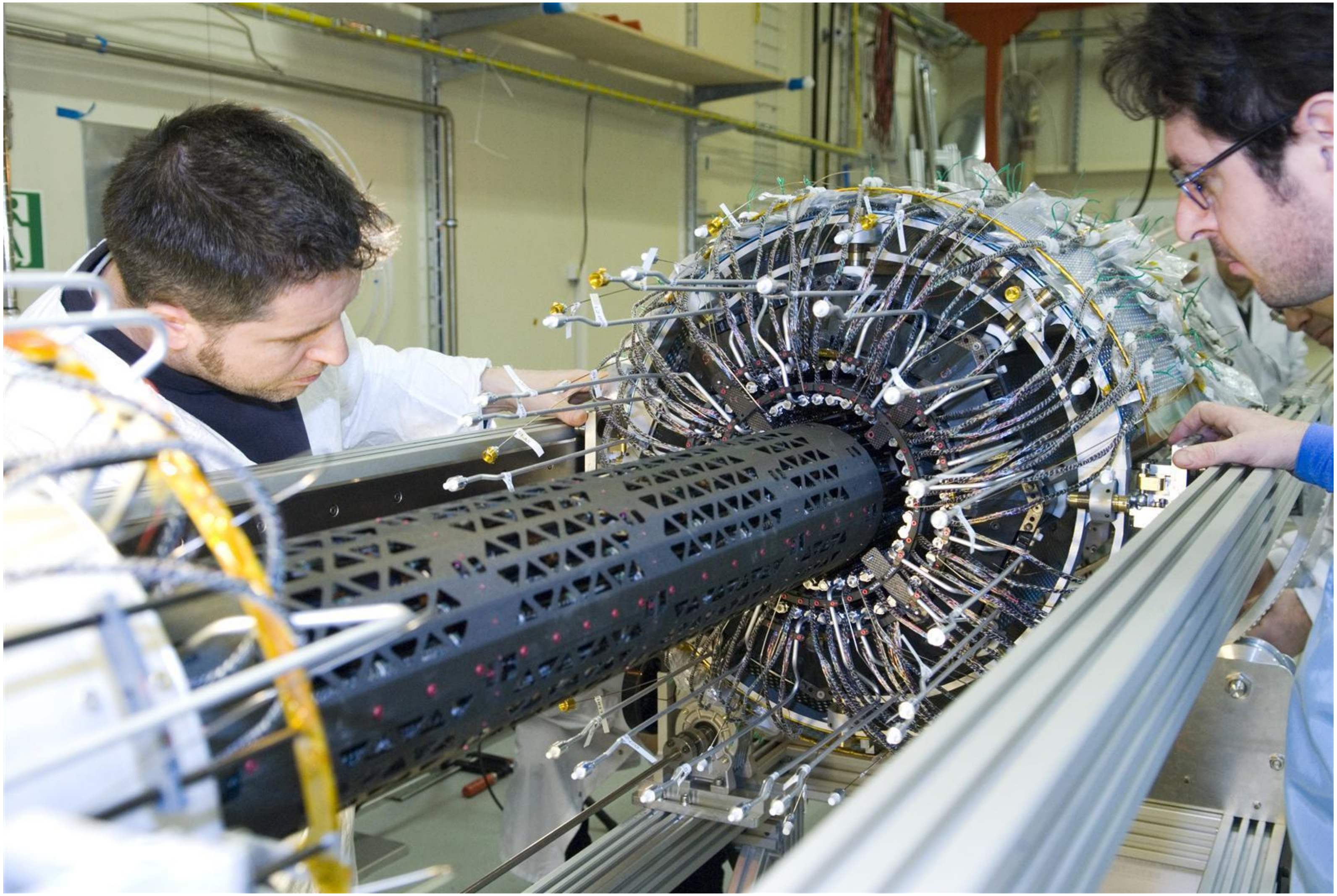
The ATLAS experiment



The ATLAS experiment

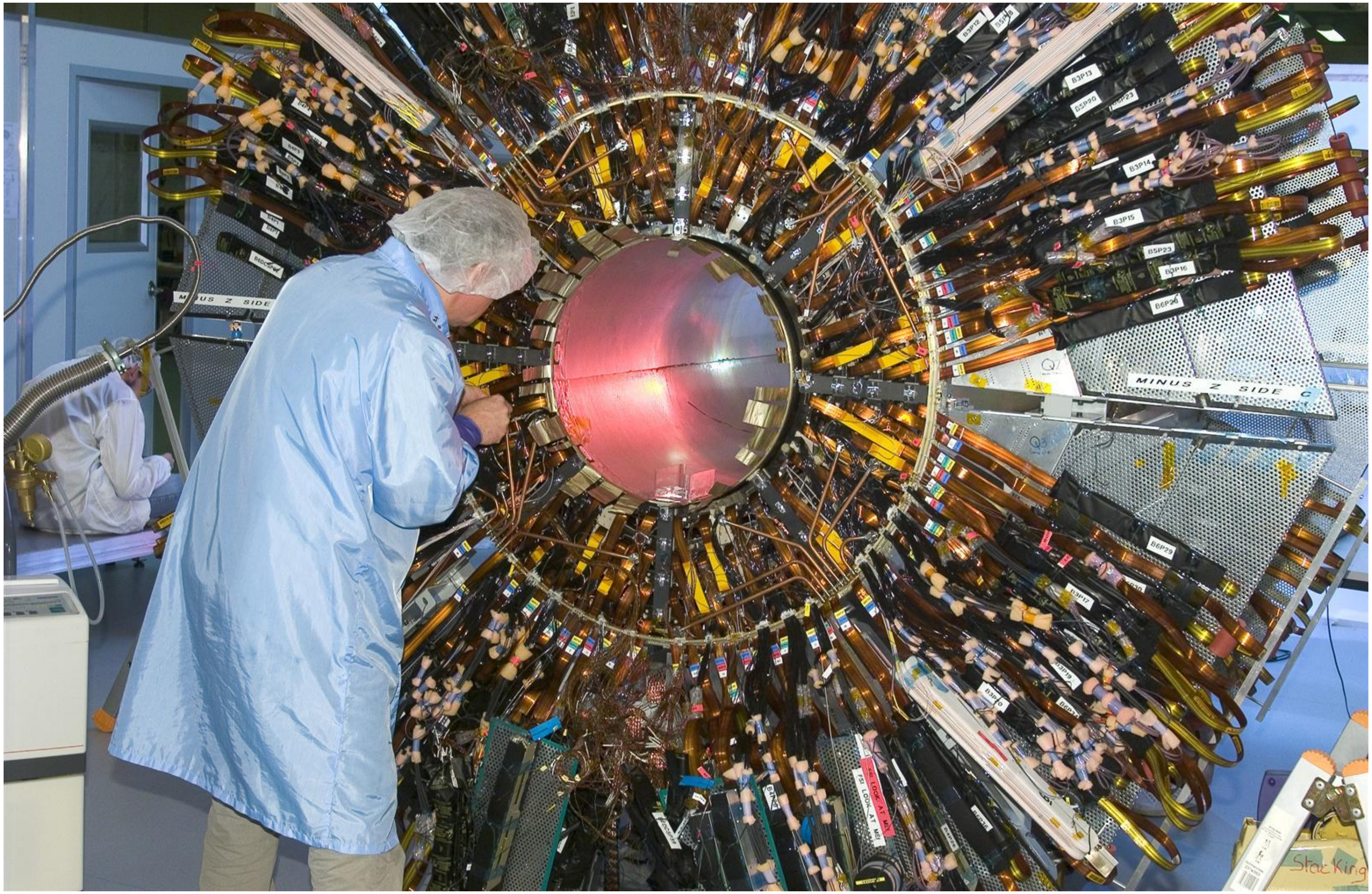


The ATLAS experiment

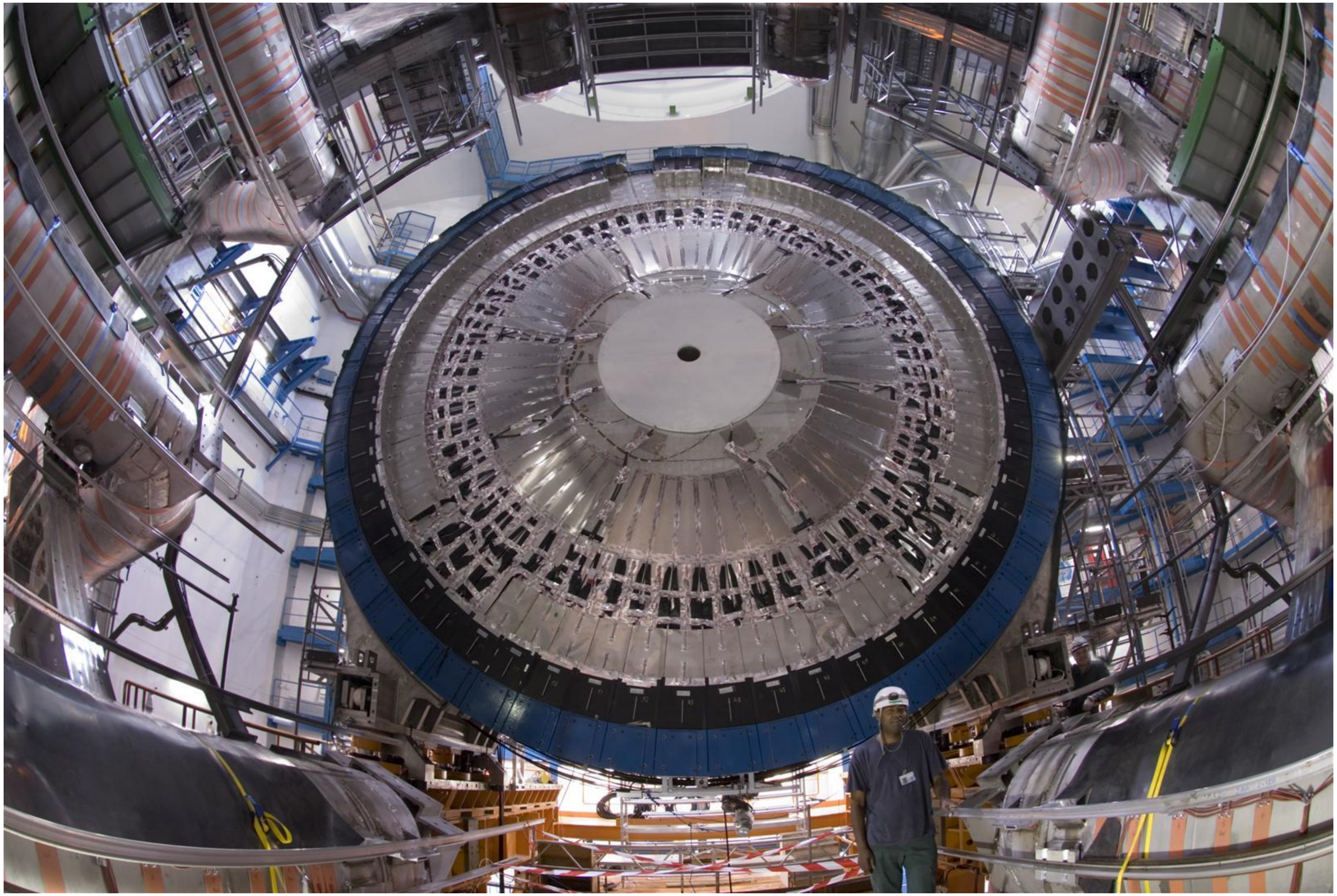


The ATLAS experiment

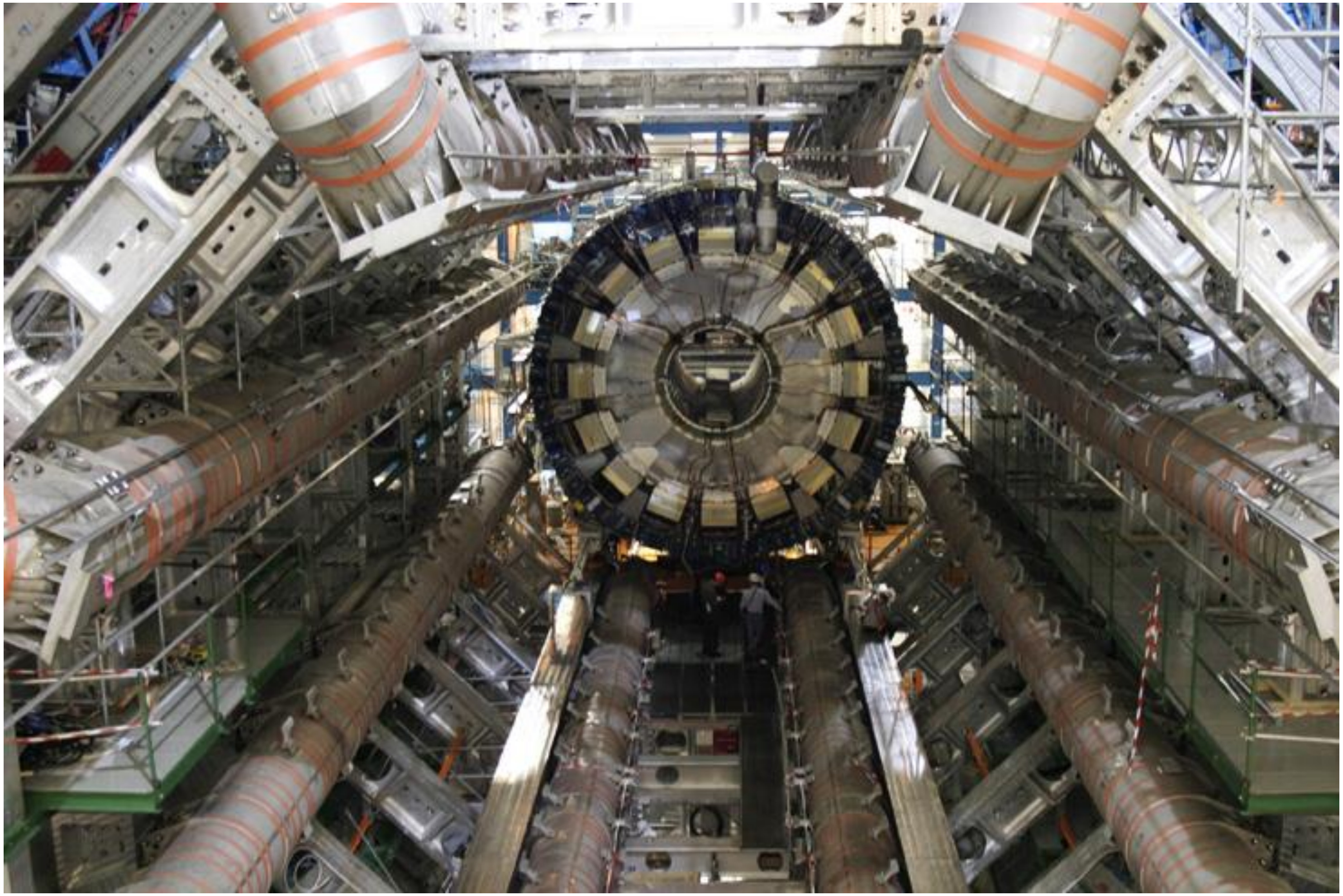
The ATLAS experiment



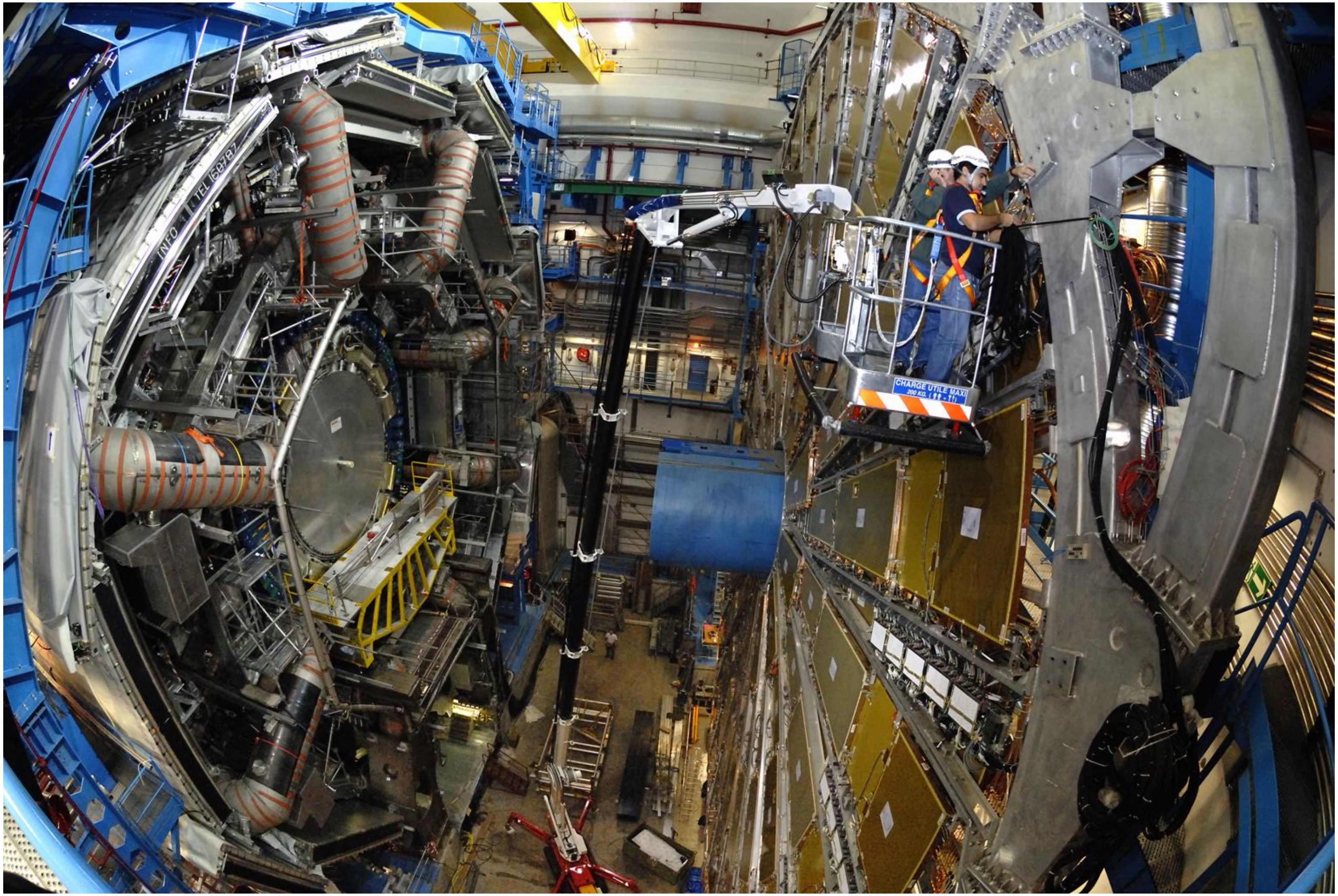
The ATLAS experiment



The ATLAS experiment



The ATLAS Experiment



Recording the data

- **The data is recorded at CERN**
- **Thereafter, distributed computing is key**
  - Use tens of thousands of computers around the world (the GRID)

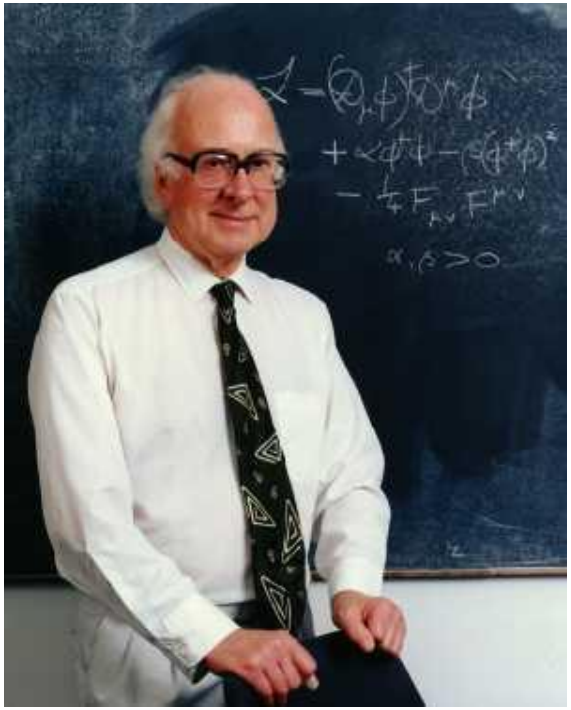
The Higgs Search

Particle masses (MeV)

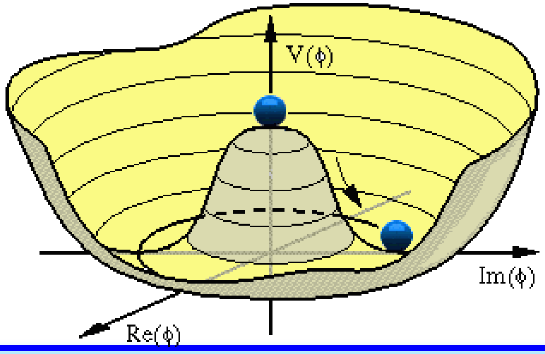
• Neutrinos	~ 0
• Electron	0.5
• Down quark	6
• Muon	106
• Tau	1,780
• Bottom quark	4,200
• Top quark	175,000

The Higgs Boson

- **Professor Peter Higgs**
  - Emeritus Professor at Edinburgh

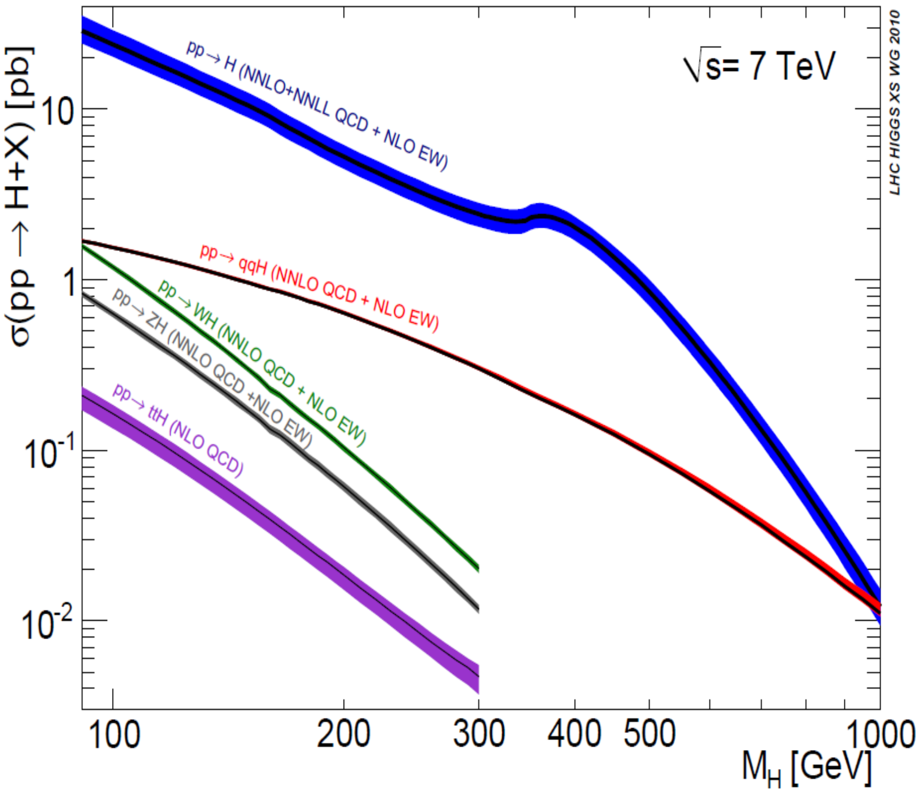


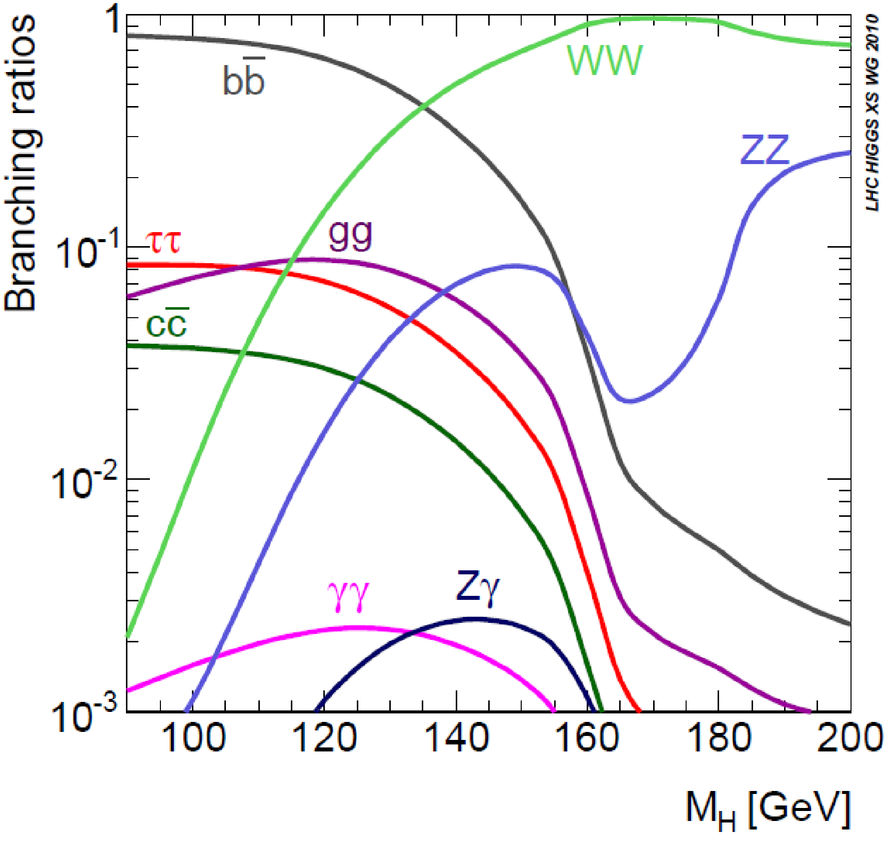
- **Devised a mechanism to account for the generation of mass**
- **Predicts one new particle, the Higgs boson**



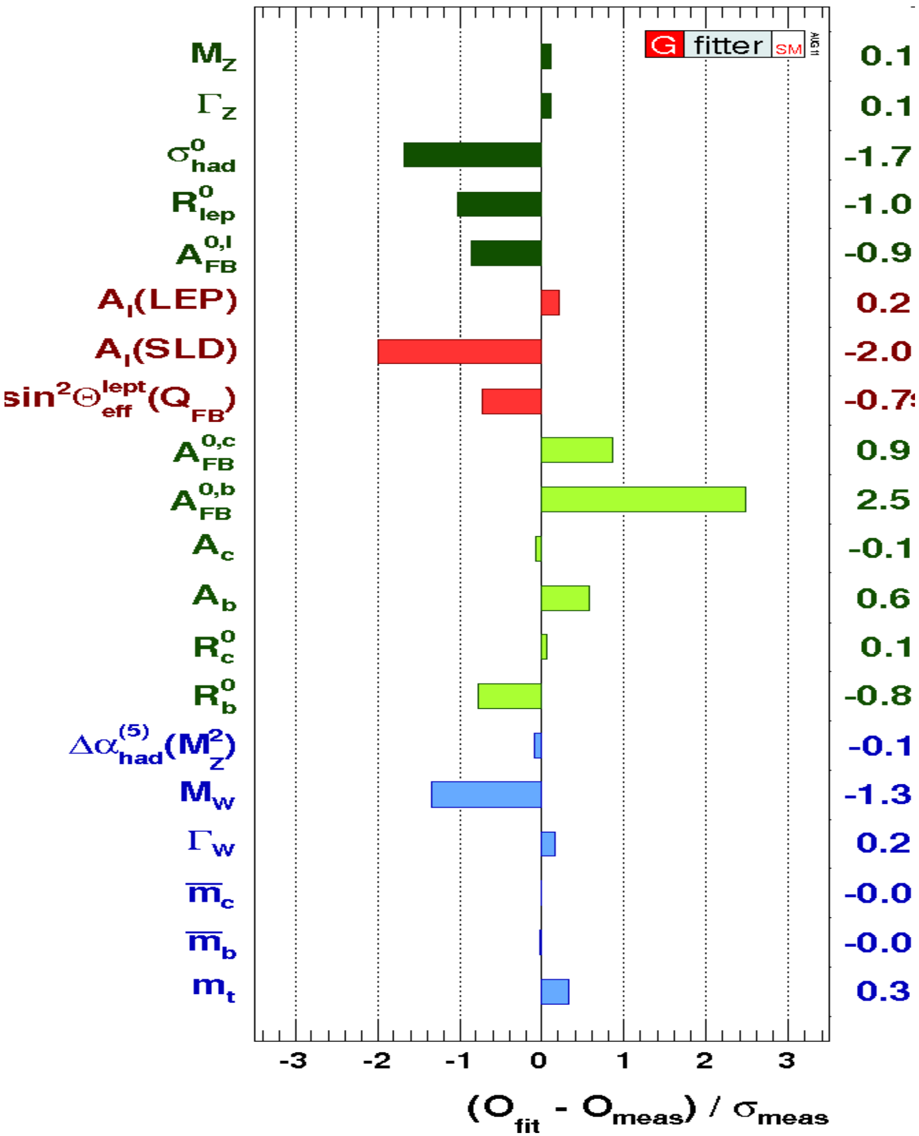
Where to look for the Higgs?

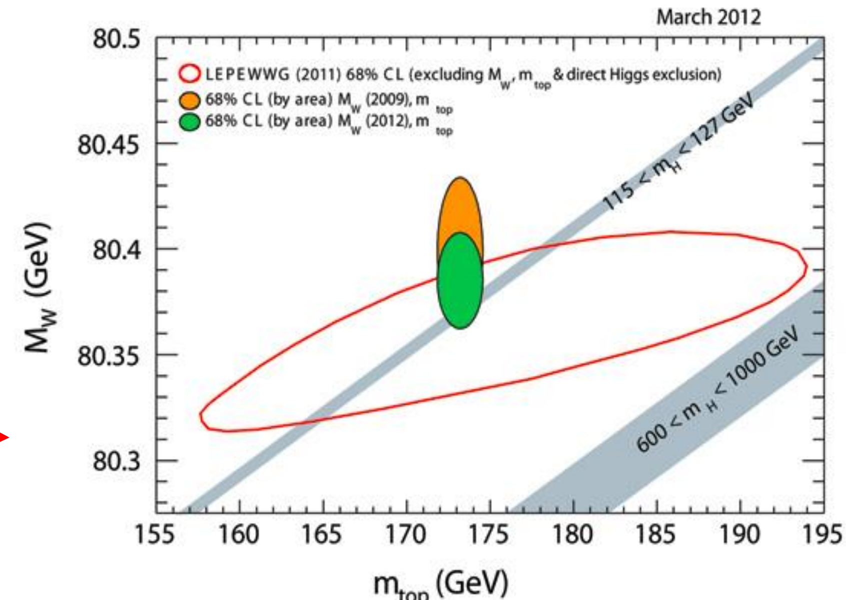
- We didn't know the Higgs Boson's mass
- Very different composition of PRODUCTION and DECAY mechanisms depending on mass





Are (were) there any clues?





Most likely Higgs mass:

95^{+30}_{-24} GeV

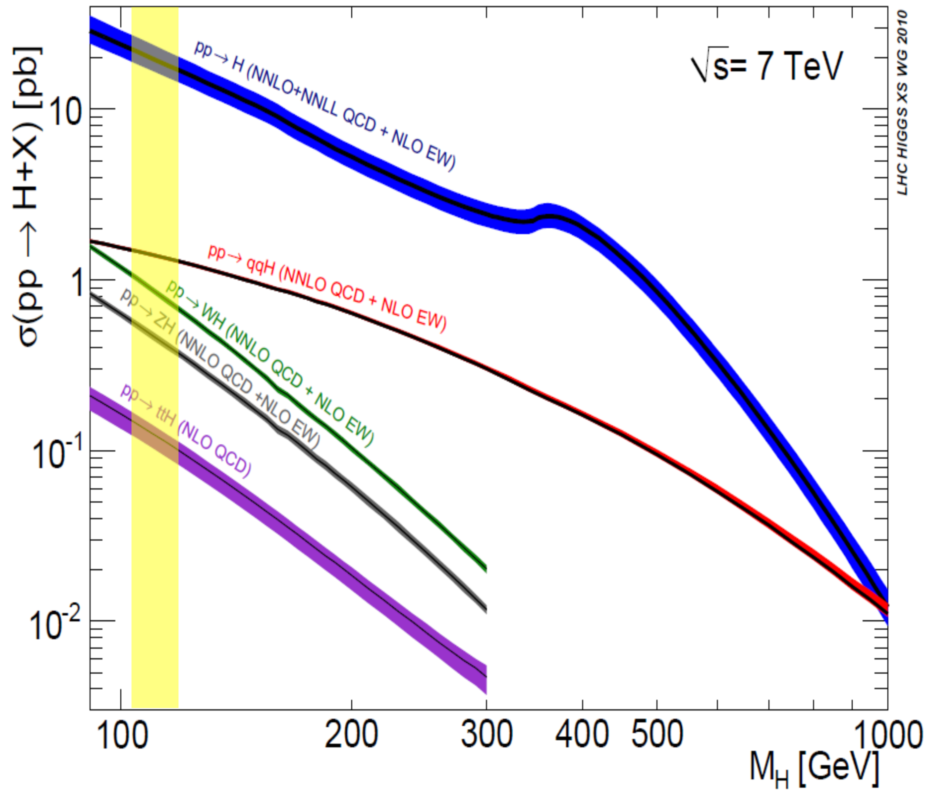
(from indirect evidence)

Mass > 115 GeV

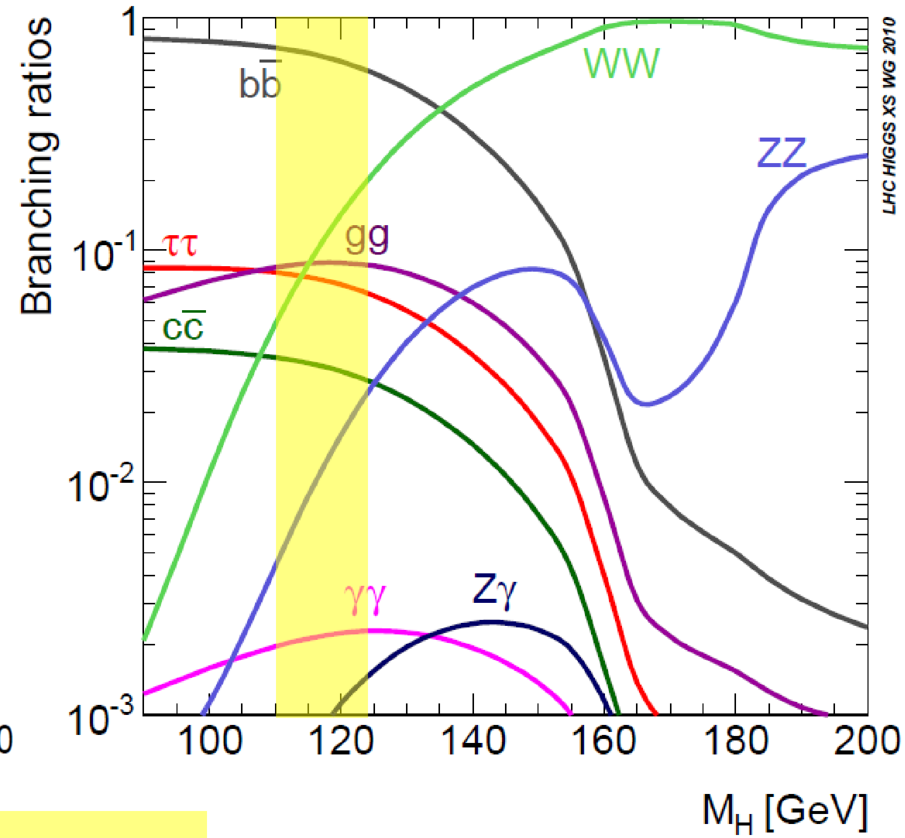
(direct evidence until now)

Many ways to search for the Higgs

PRODUCTION

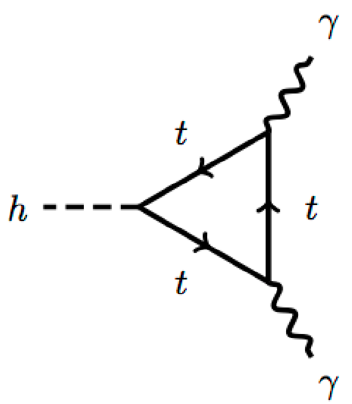


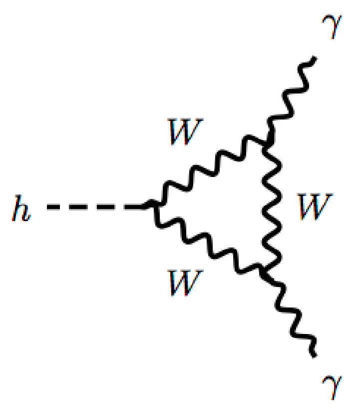
DECAY

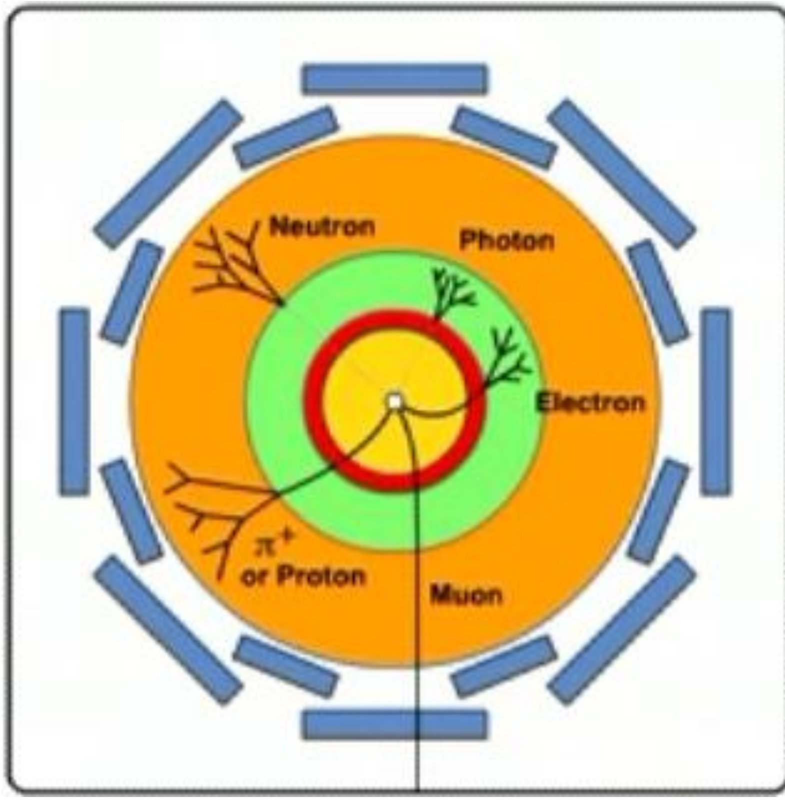


Most likely mass ranges

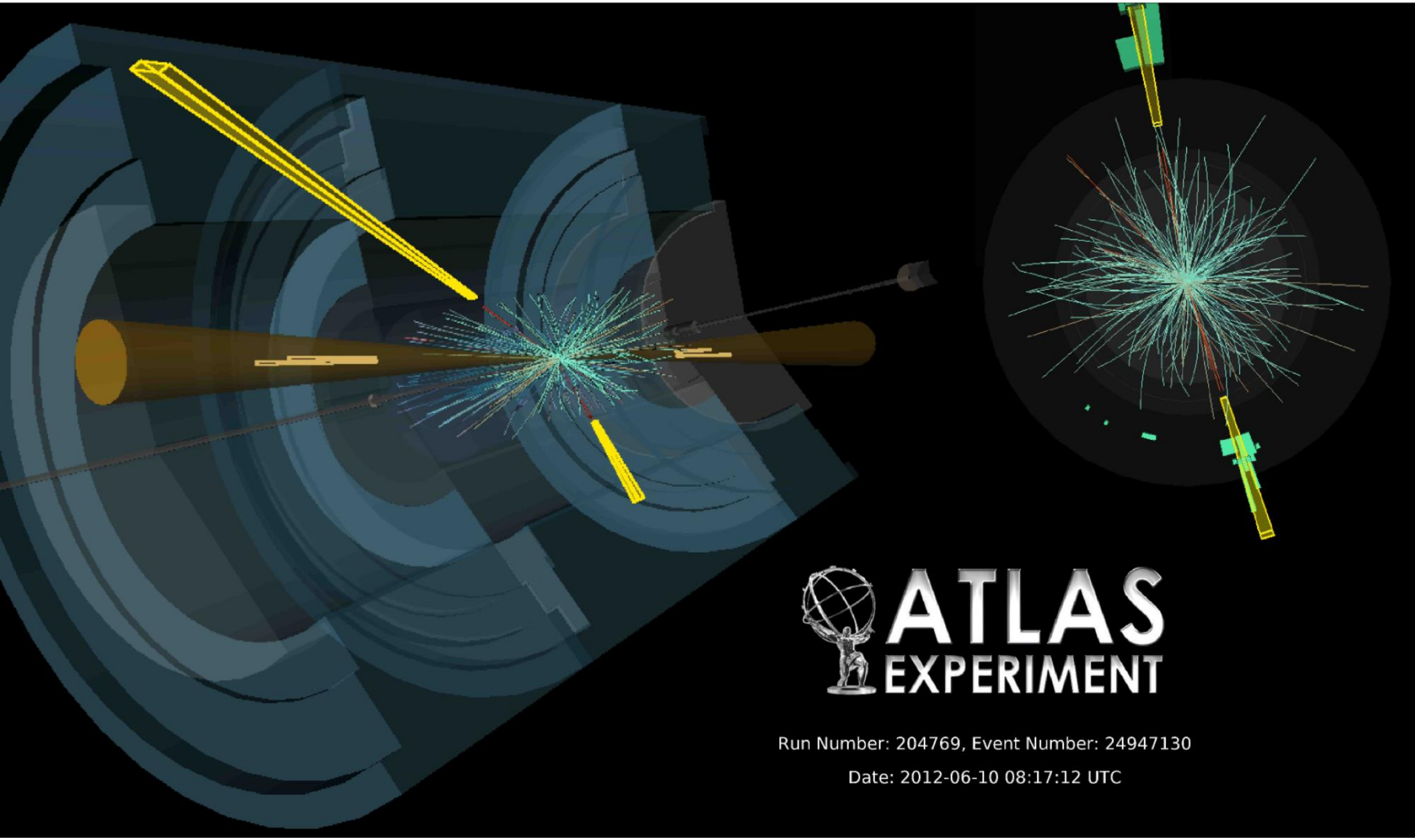
What does a Higgs decay look like?







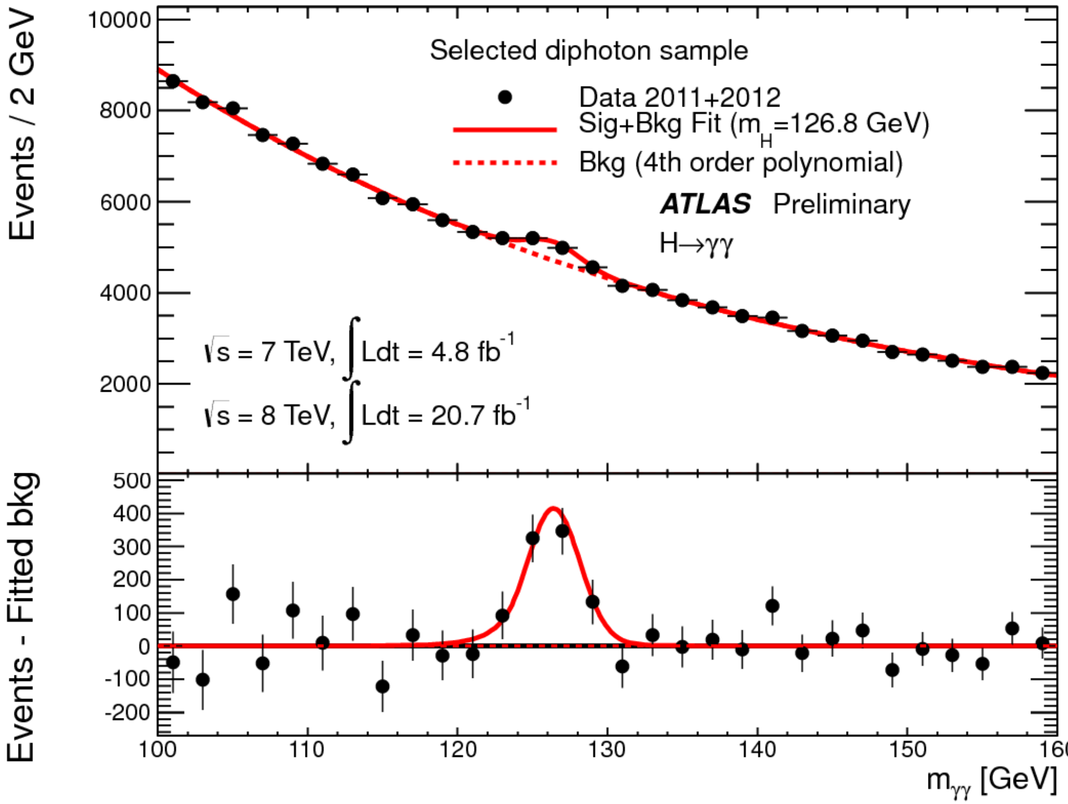
- **Decay to two photons**
  - Experimental signature
    - 2 deposits in electromagnetic calorimeter and absence of matching charged particle trajectories
  - Experimental challenges
    - Calibration
    - Background source: photons produced in other ways


ATLAS
EXPERIMENT
Run Number: 204769, Event Number: 24947130
Date: 2012-06-10 08:17:12 UTC

Higgs→γγ Results

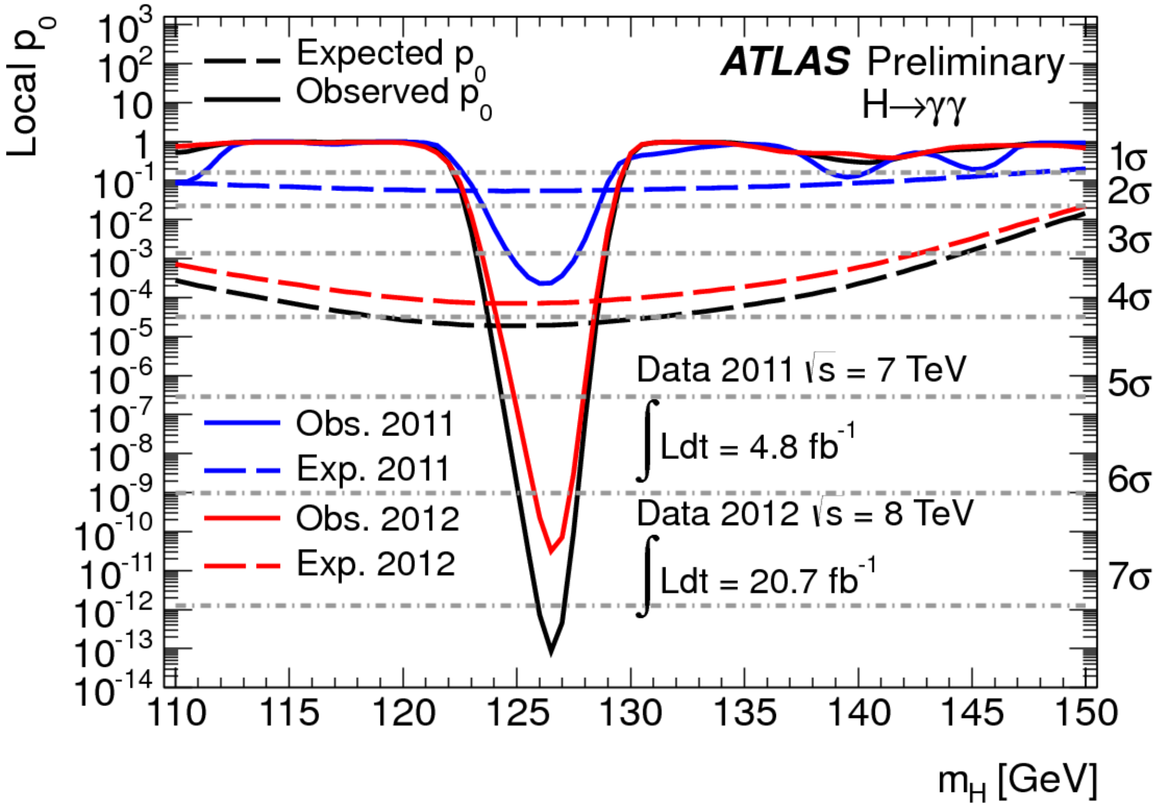
1) Plot the invariant mass

- $M=E^2-|p|^2$



Higgs→γγ Results

2) Evaluate probability for the "signal" to be a statistical fluke



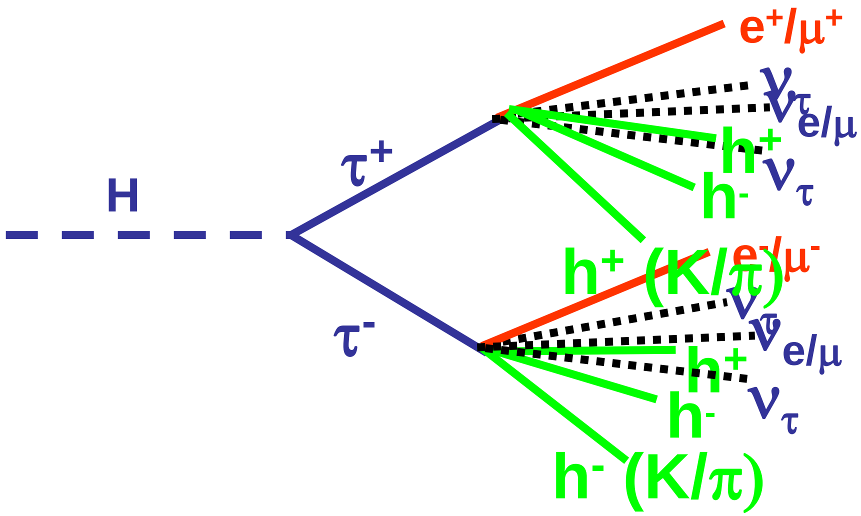
Most significant indication of signal is at 126.5 GeV:

- 7.4 σ

Gold standard of observation 5 σ

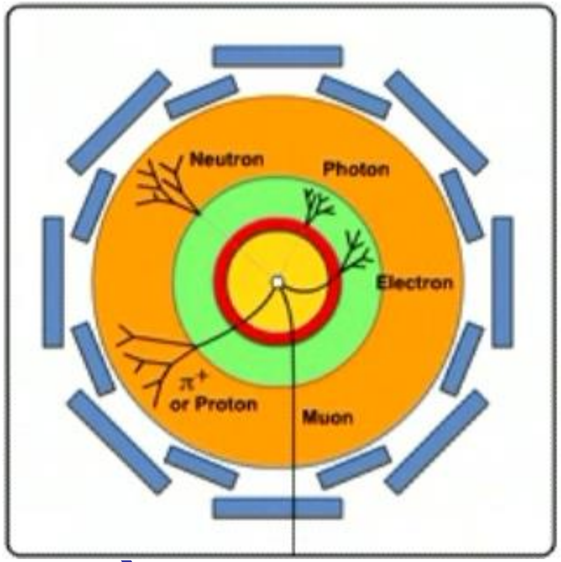
(Corresponds to 1 in 2 million chance)

$H \rightarrow \tau\tau$



H➔ $\tau\tau$

- **Experimental signature**
  - Electron or muon with neutrinos (missing energy)
    - Electron or muon identified fairly cleanly
  - Hadrons
    - Large rate for tau leptons to decay this way



- **Experimental challenges (significant)**
  - Difficult to differentiate these signatures from backgrounds
    - Production of generic jets of hadrons
    - Z+jet production, W+jet production, pairs of top quarks

H➔ ττ challenges

- Background sources calibrated with several control regions

Signal region:

$$m_{\mathrm{T}} = \sqrt{2p_{\mathrm{T}}^{\ell}E_{\mathrm{T}}^{\mathrm{miss}}(1-\cos\Delta\phi)} < 30\ \mathrm{GeV}$$

Modeling the backgrounds:

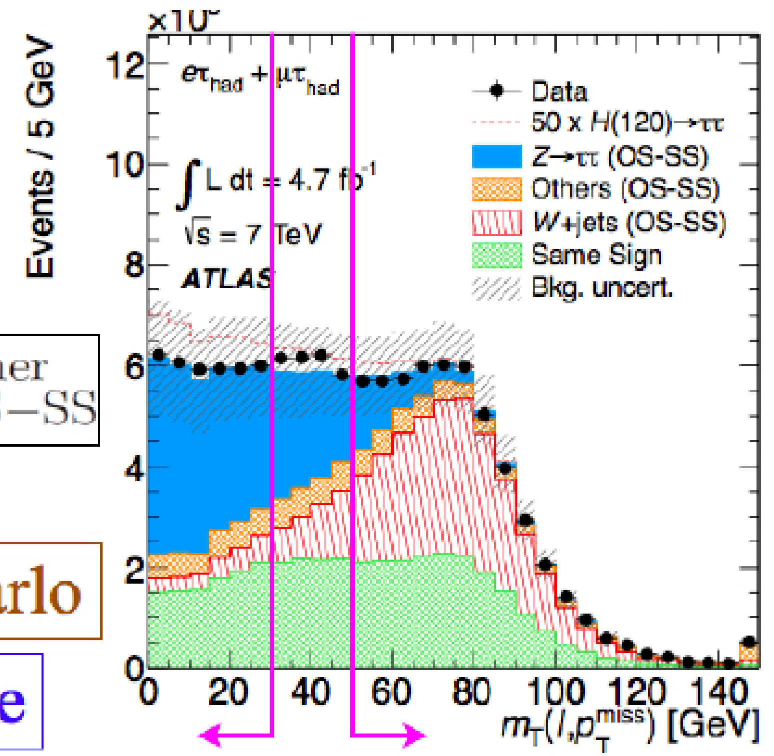
$$n_{\mathrm{OS}}^{\mathrm{bkg}} = n_{\mathrm{SS}}^{\mathrm{all}} + n_{\mathrm{OS-SS}}^{W+\mathrm{jets}} + n_{\mathrm{OS-SS}}^{Z\rightarrow\tau\tau} + n_{\mathrm{OS-SS}}^{\mathrm{other}}$$

Multi-jet

Control region with $m_{\mathrm{T}} > 50$ GeV

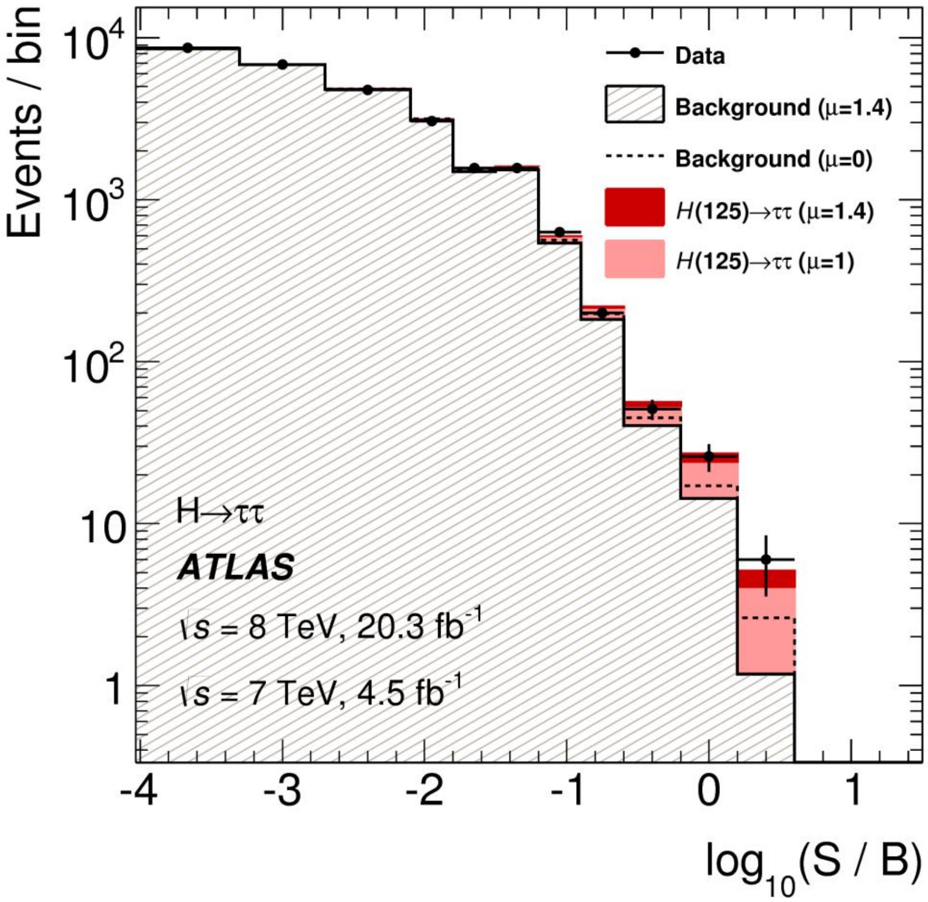
Embedded Sample

Monte Carlo



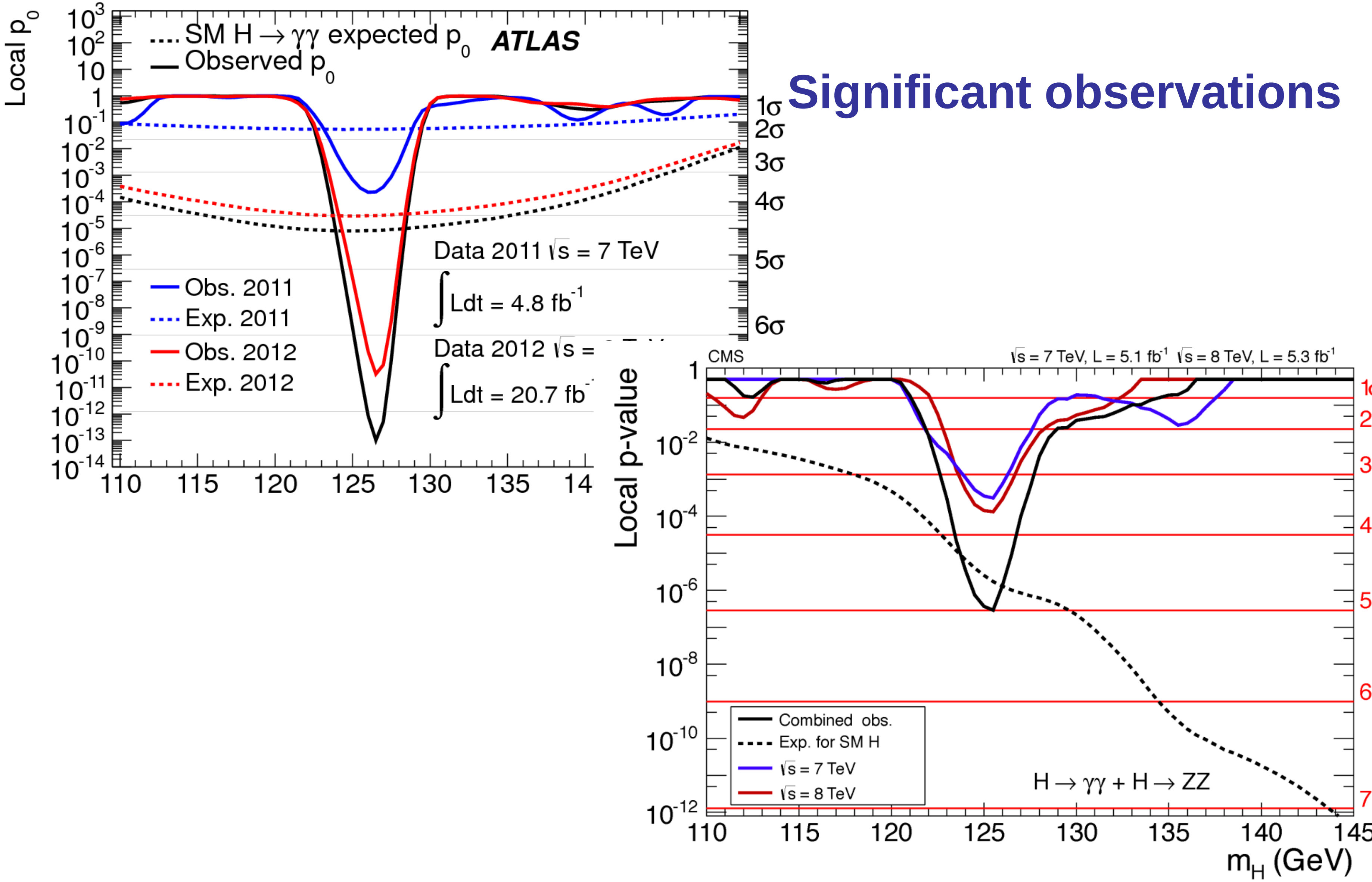
H→ ττ results

- **Observation at 4.5σ**
- **Evidence that the Higgs boson decays to fermions and so can give them mass**

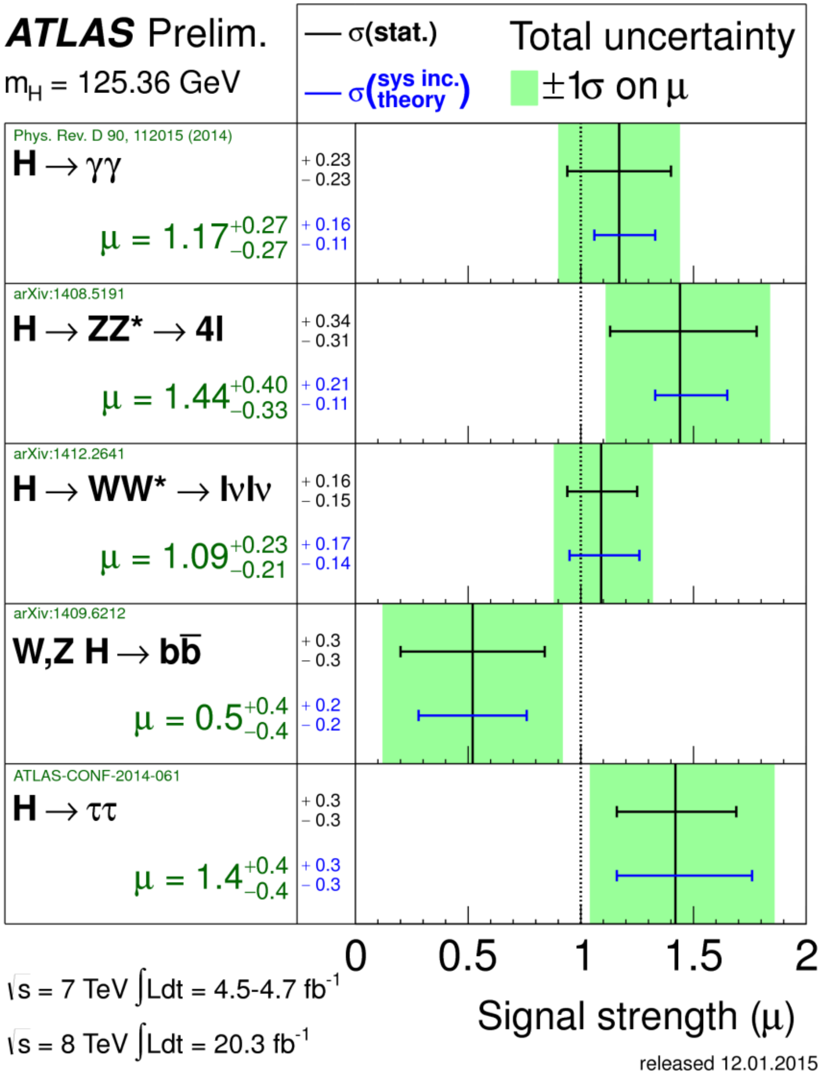


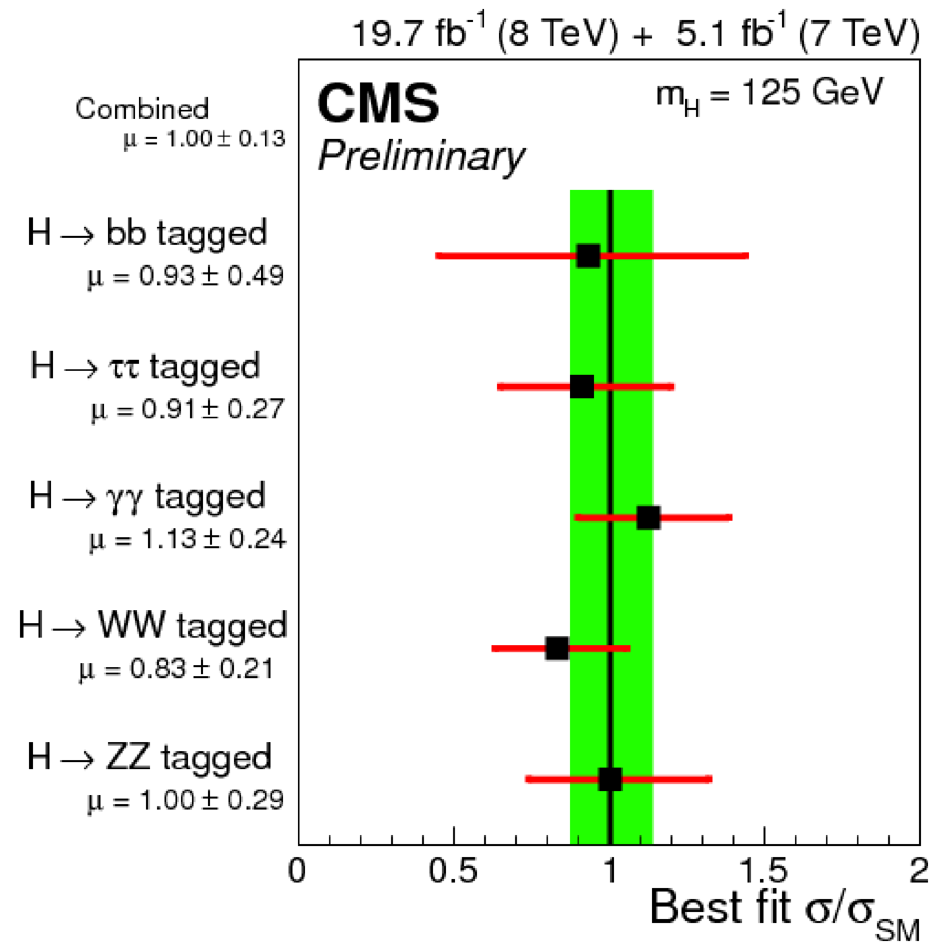
Combination

Significant observations



What have we discovered?





Compatible with Standard Model!

Future of Higgs Physics

- **Key properties of this new boson will take some time to ascertain**
  - This was always anticipated
  - In fact we are fortuitous in nature's choice for the Higgs mass – all decay modes are accessible at this point
- **Key to characterising this particle are**
  - Production and decay rates (to greater precision)
  - Intrinsic quantum numbers
- **Switch from search mode to precision physics**

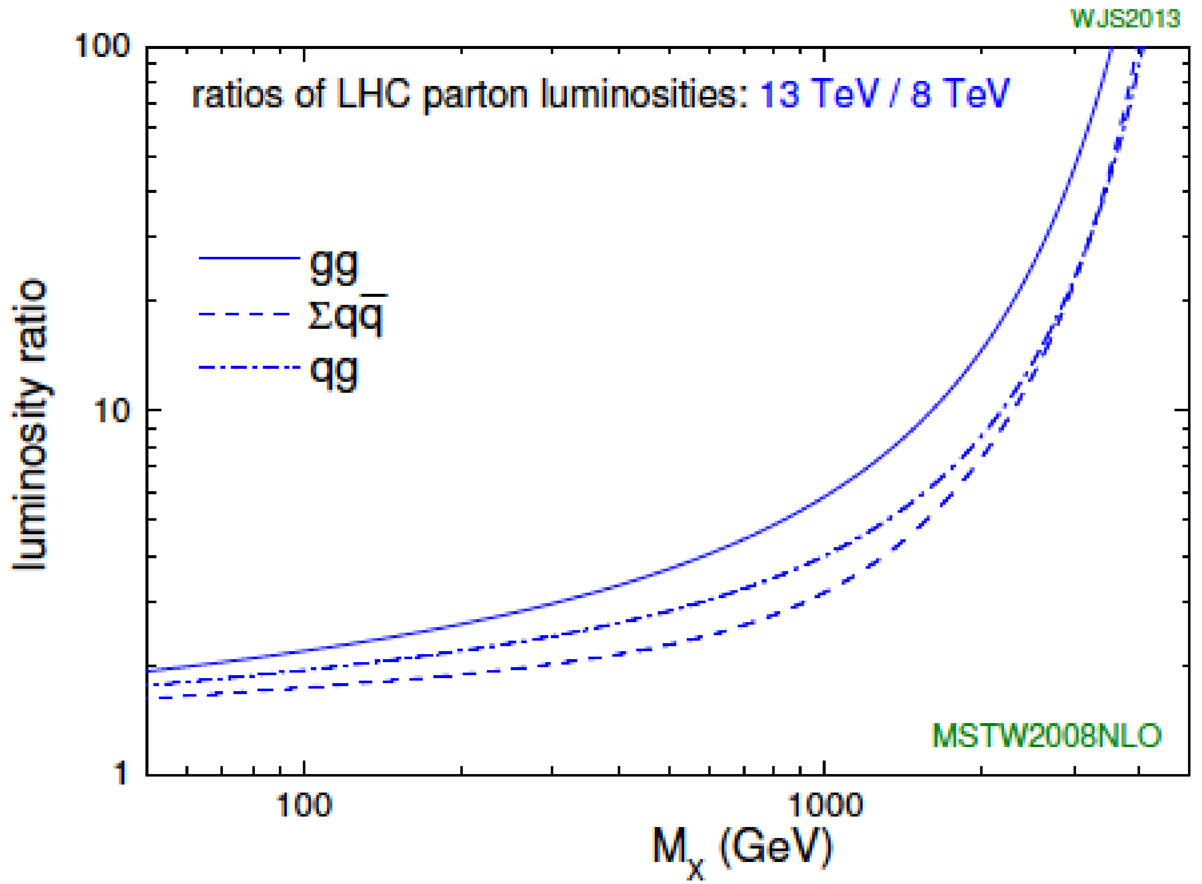
What we don't know

- Nature of neutrinos
- Mass hierarchy of neutrinos
- CP violation (how did the universe come to be matter-dominated?)
- Is there only one Higgs boson?
- Is supersymmetry realised in nature?
- Why three generations?
- Nature of dark matter
- …which questions to ask?

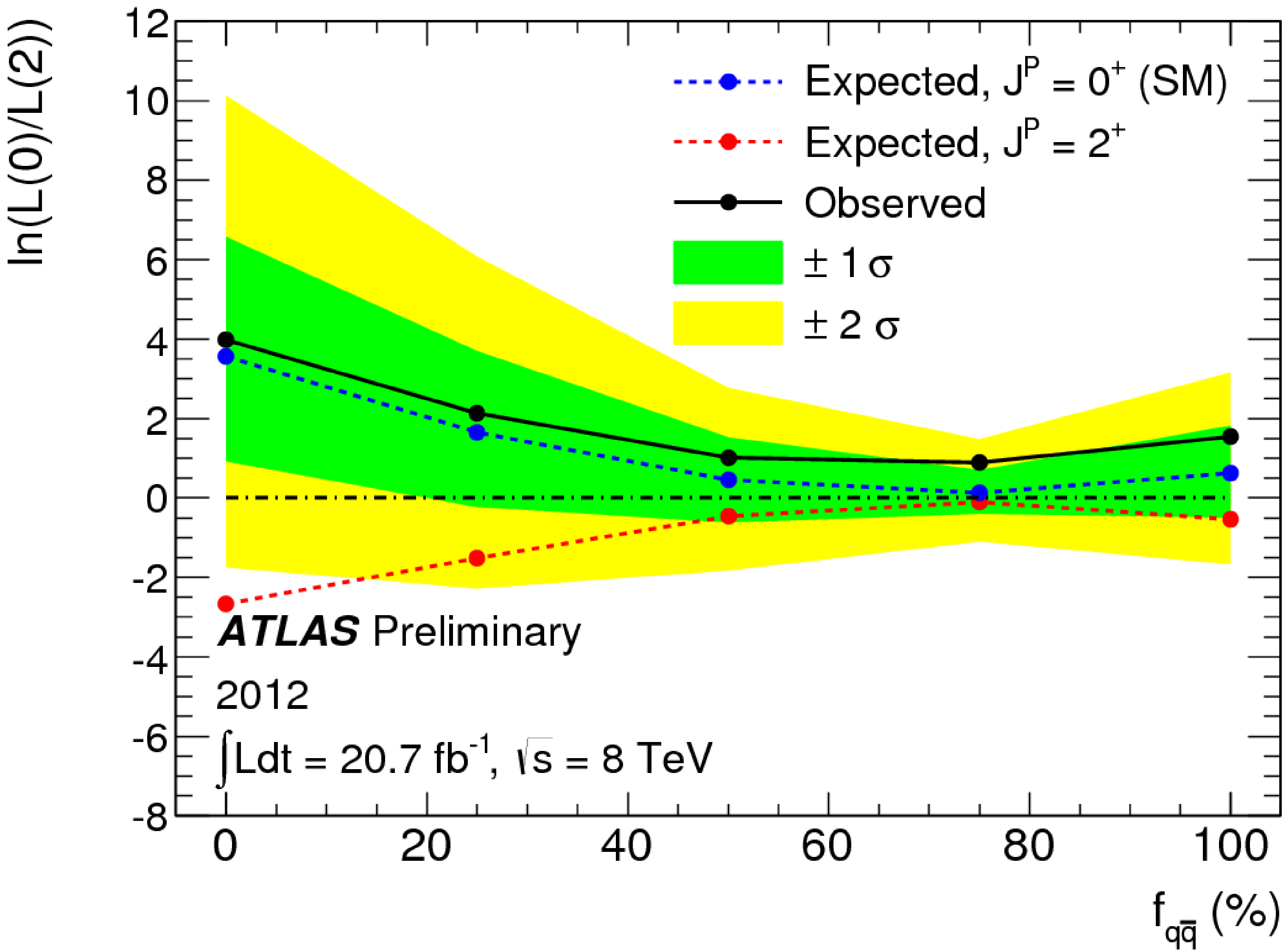
Outreach in the UK

- **Many opportunities in the UK**
  - Particle Physics UK had a stand at the Royal Society Summer Exhibition in London for the past two years
  - This year a similar stand will be at the Big Bang Science Fair at the NEC in Birmingham 11-14 March
  - BA Science Festival has attendance from particle physicists
  - All UK universities involved in particle physics run outreach events (usually called "masterclasses") and most will be happy to send someone to give a talk at your school if you ask them

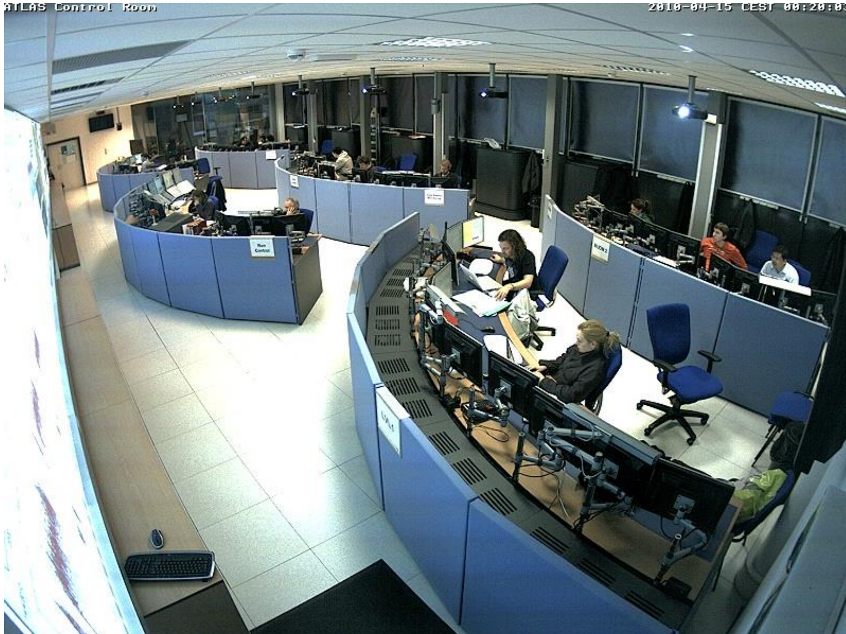
Supersymmetry



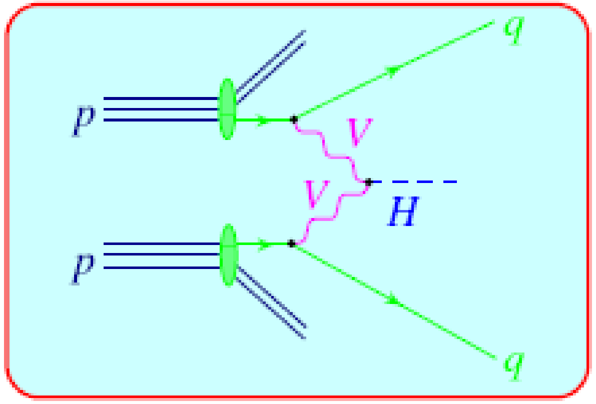
First Spin Measurements

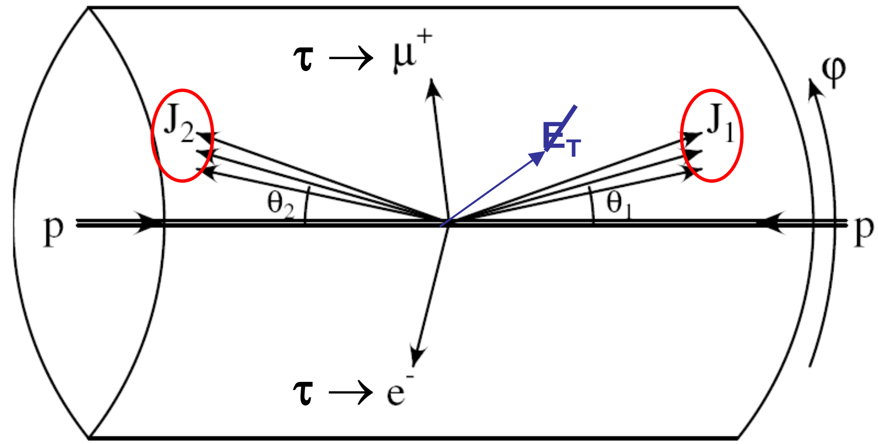


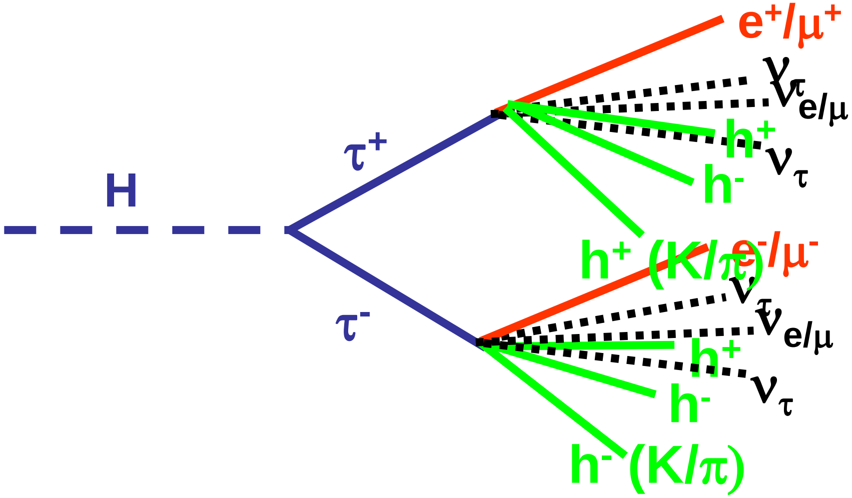
Higgs seen at CERN



What does a Higgs event look like?







- Distinctive signature
- Reconstruct each element

The CMS Experiment