Lessons from the Higgs: What your Taxes have taught us about Mass

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Outline

- Introduction:
  - History of Mass
  - Mass and the Higgs
- The Higgs Search:
  - The LHC
  - Higgs Decay; Experimental Signatures
  - ATLAS and CMS
  - Search Results
- What is Next for the LHC
- Lessons beyond the Science

Thanks to:

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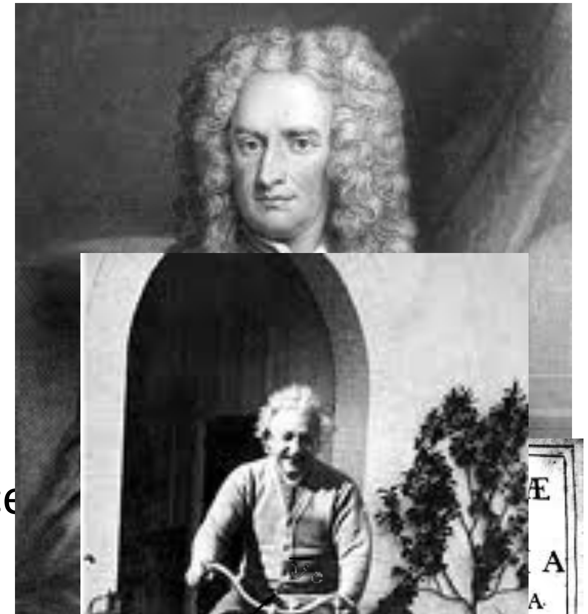
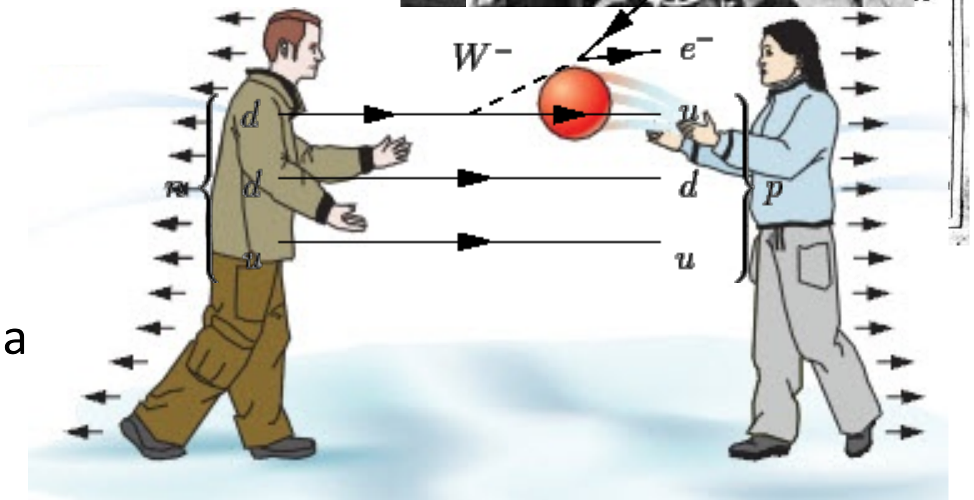
A Brief History of Fields

- Before Faraday: E&M, gravitational Fields=a math convenience
- Faraday: Fields contain *energy*
- Maxwell: Light comprised of oscillating E&M fields
- Einstein: Fields an independent entity w/o medium
- Alter the space they subtend

A Brief History of Mass

- Newton: (1687) and his mechanics, Lavoiser (1760)
  - **Mass** is an inherent essential property of an object
  - It is conserved, neither created or destroyed
- After Einstein, DeBroglie and Quantum Mechanics
  - Both light and building-blocks of matter (quarks and leptons) are quantized oscillating massless fields.
- Yukawa: (1935) Particles interact by exchanging other force mediating particles
  - γ for E&M
  - W,Z bosons for Weak force
  - Gluon for strong force=QCD
  - Graviton(?) for gravity
- Feynman taught us how to do the calcula easily, pictorially





One More Thing: Some 3rd year QM

- If you start with SE:

$$\left(\frac{1}{2m}\right)(-i\overrightarrow{\nabla})^2\Psi(\overrightarrow{r},t) = i\frac{\partial\Psi(\overrightarrow{r},t)}{\partial t}$$

- And require local U(1) Gauge invariance:

$$\Psi'(\overrightarrow{r},t) = e^{i\alpha(\overrightarrow{r},t)}\Psi(\overrightarrow{r},t)$$

- Then Ψ' will not satisfy SE unless it is modified to be

$$[\left(\frac{1}{2m}\right)(-i\overrightarrow{\nabla}-\mathbf{q}\overrightarrow{A})^2 + \mathbf{qV}]^2\Psi(\overrightarrow{r},t) = i\frac{\partial\Psi(\overrightarrow{r},t)}{\partial t}$$

- With

$$\overrightarrow{A}' = \overrightarrow{A} + \left(\frac{1}{q}\right)\overrightarrow{\nabla}\alpha(\overrightarrow{r},t)$$

$$V' = V - \left(\frac{1}{q}\right)\frac{\partial\alpha(\overrightarrow{r},t)}{\partial t}$$

3rd Year QM, Cont.

- By requiring local U(1) gauge invariance we arrive at S.E. for Electrodynamics…very suggestive…
- Mills and Yang (1954):

"Perhaps the dynamics of all field theories can be derived from local gauge invariance"

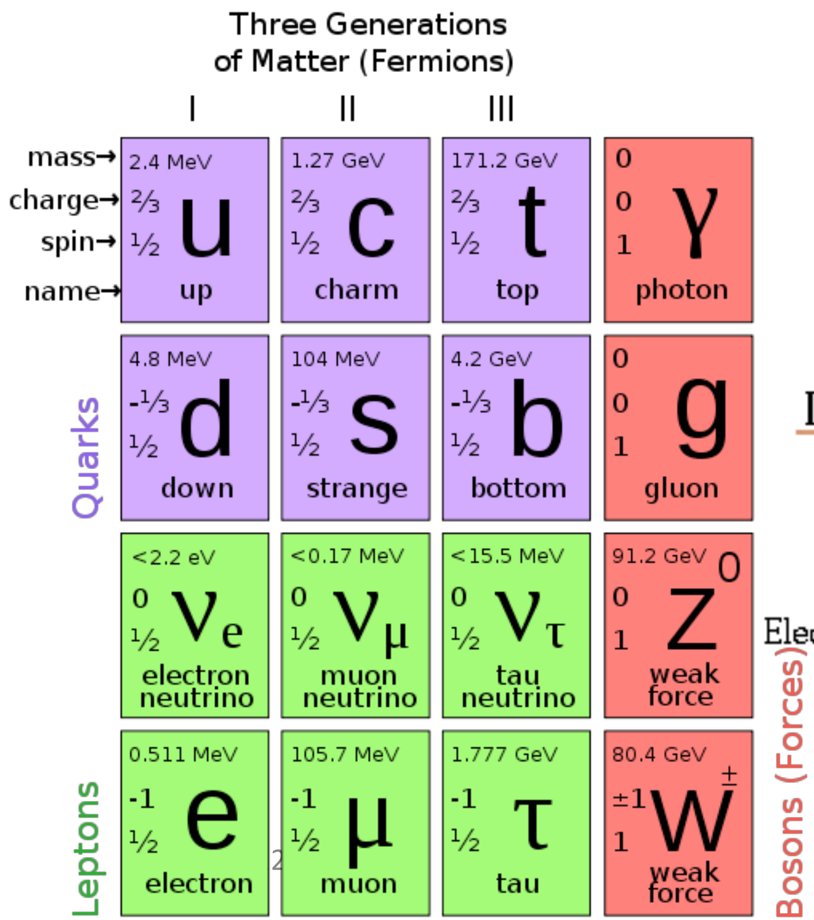
- The answer appears to be:

Yes

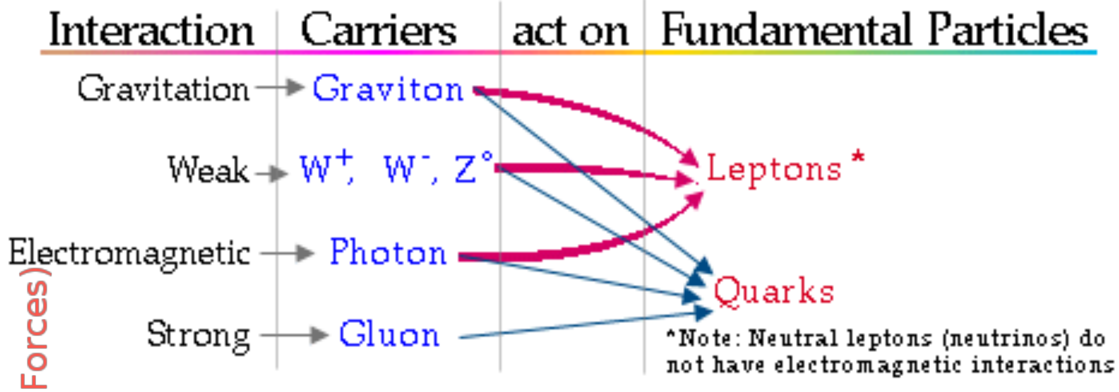
The Essence of the Standard Model (SM) of Particle Physics

Gauge group of SM: $SU(3)_C x\ SU(2)_L x\ U(1)_Y$

Gives properties of Strong Weak EM forces



In detail!

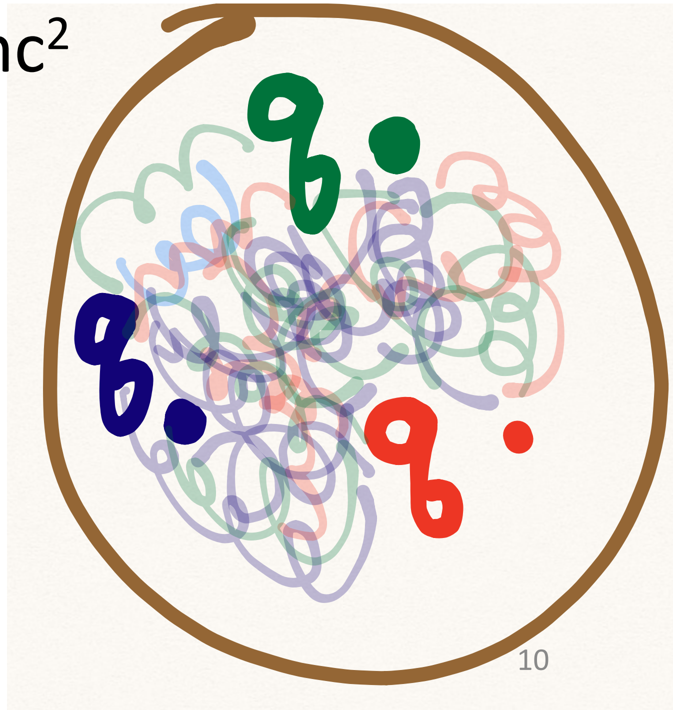


One Last Big Problem

- Flaw in theory: all fundamental objects want to be massless like photons
- The Fix: add a ubiquitous Higgs field
  - Mass of quarks, leptons, W and Z arise via a *dynamical* interaction with the Higgs field
- One prediction of this theory:
  - The Higgs field self-interacts giving rise to a new particle, **the Higgs Boson**

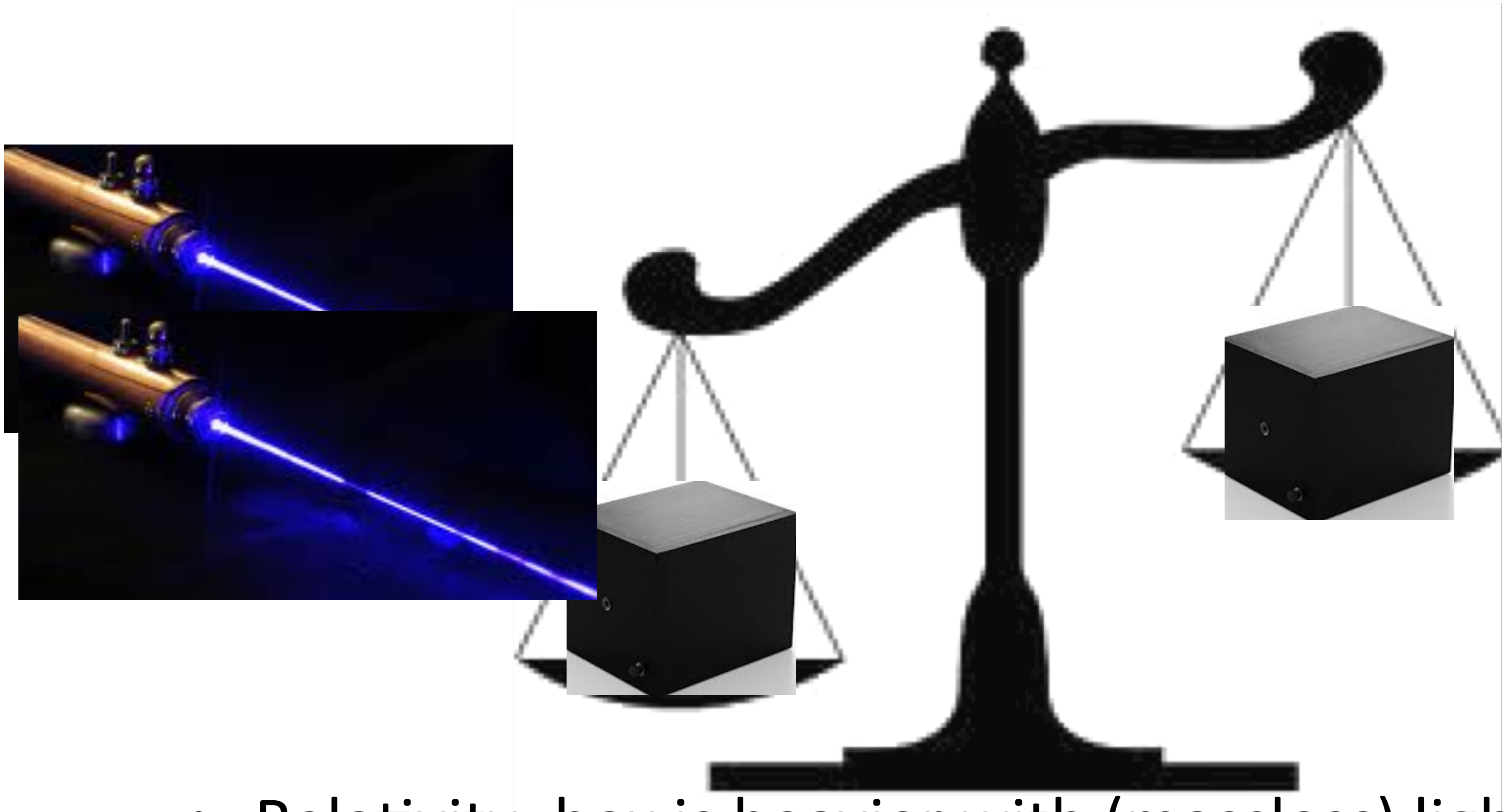
Lies in Newsprint

- "… the Higgs field is responsible for all mass in the universe…" **NOT TRUE**
- ~99% of (our) mass arises *dynamically* within the proton, without the Higgs field
  - Swarms of gluons around quarks
  - Energy in gluon field = mass via $E=mc^2$



Mass From Massless Fields

- How can a massless field give a massive object?
- Consider a Laser beam sent into a mirrored box.



- Relativity: box is heavier with (massless) light trapped inside, like a proton filled with gluons

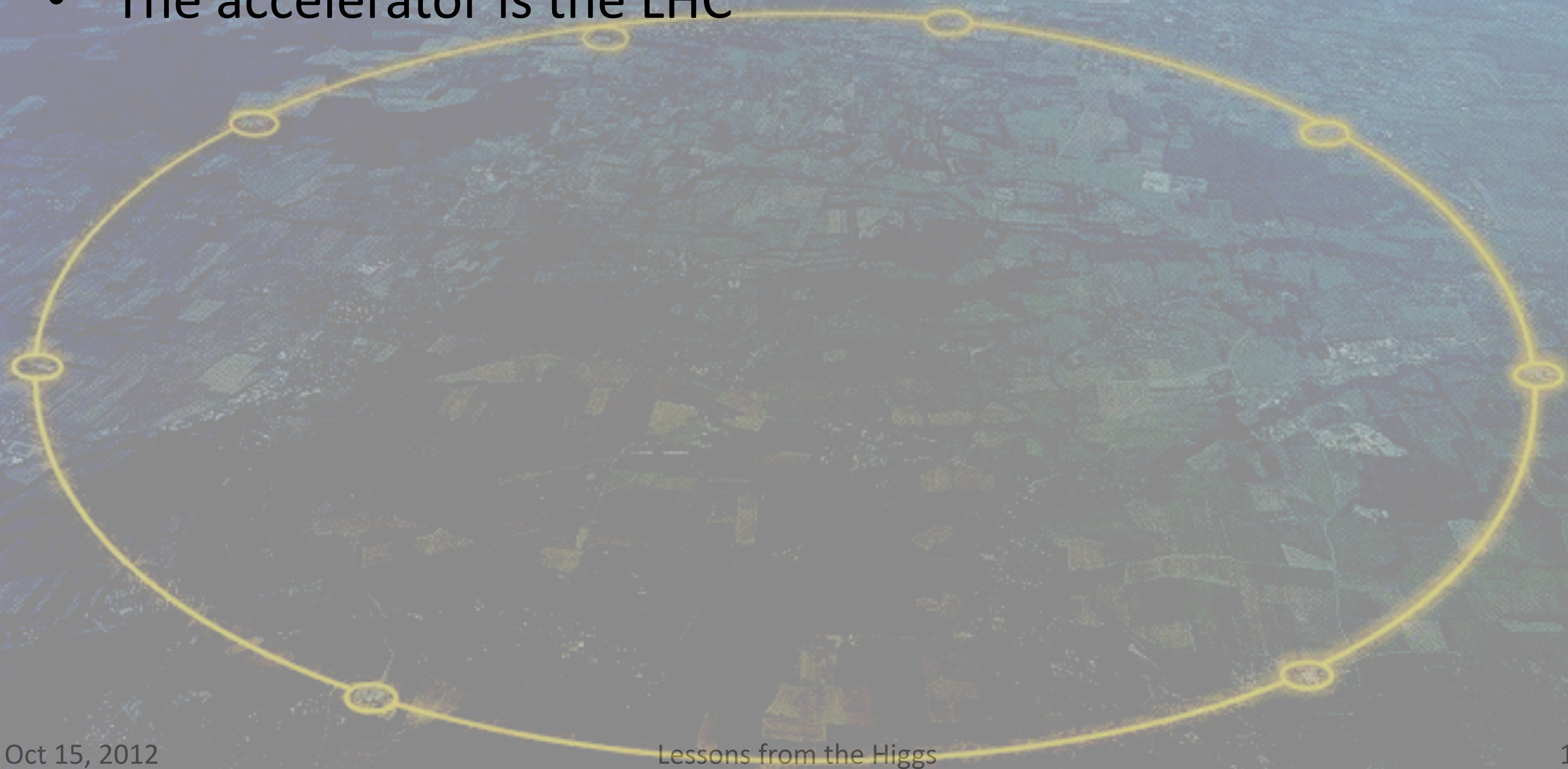
To Summarize So Far

- In ~1812, mass was real, fields were mathematical
- In 2012, all that is real (particles, light) is comprised of quantized fields
- Mass is dynamically generated, not inherent
- Many mysteries swept into the ubiquitous Higgs field
- If this theory is `correct': One more piece :

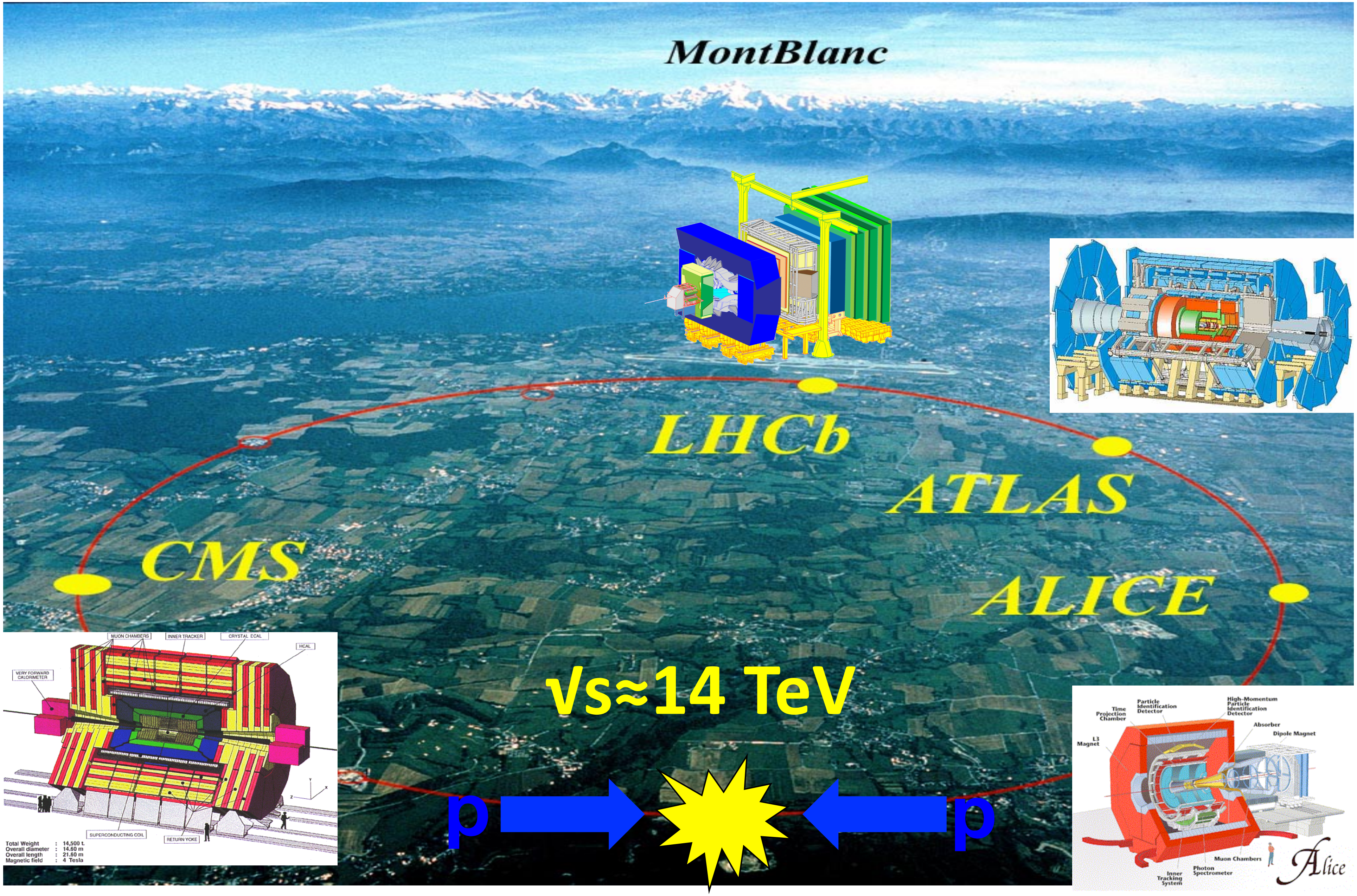
The Higgs Boson

Finding the Higgs

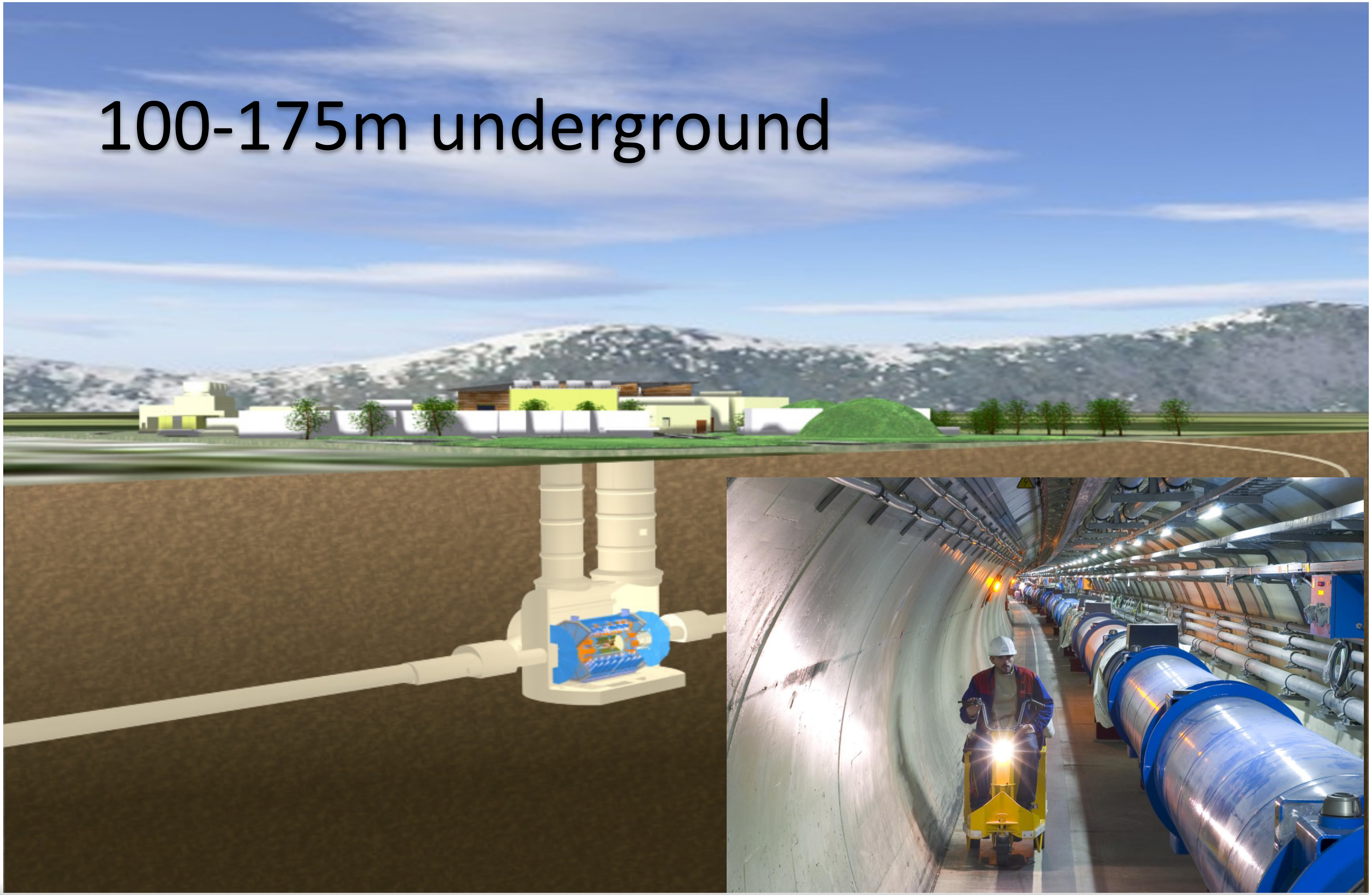
- The Higgs Boson is very unstable
  - Can't find one, need to create it with an accelerator
  - Use $E=mc^2$, turn energy into matter
- The accelerator is the LHC



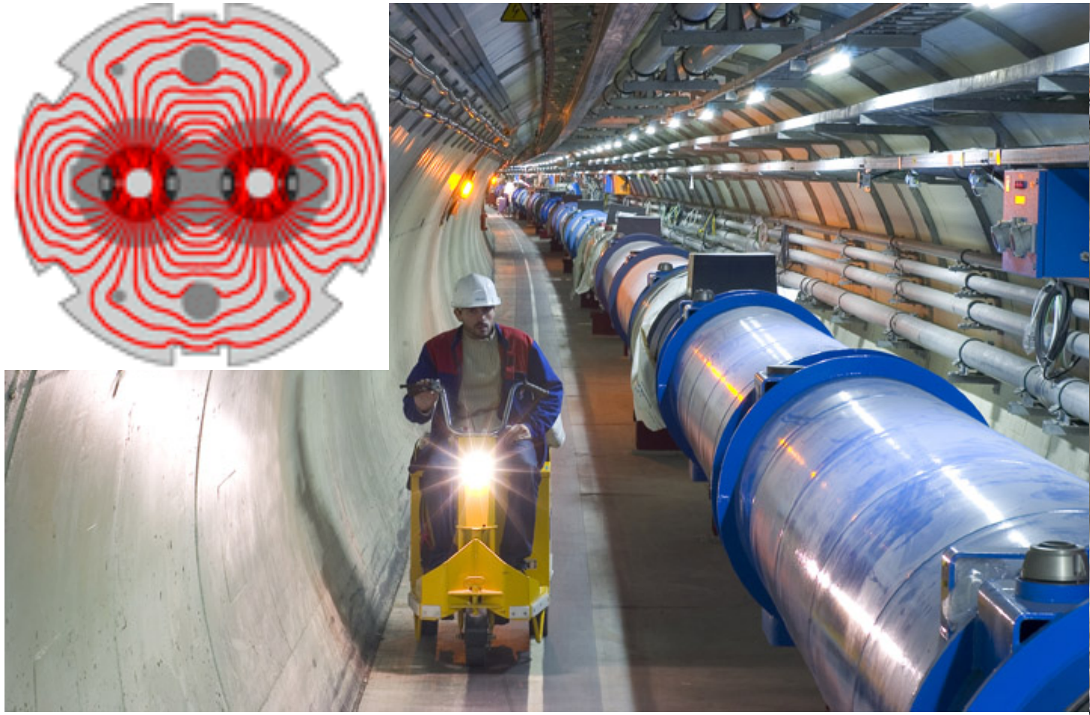
The Large Hadron Collider (LHC)



LHC Tunnel (26.7 km)



LHC Accelerator



- ~1600 8.4T SC magnets 5-15m long
- Cooled to 1.9K with 96 tons of liquid helium

April 26th 2007, last magnet lowered

The LHC Design Parameters

- Large: 27-km circumference
  - Maximum energy scales with radius and magnetic dipole field
- Collide Hadrons (protons)
  - The more massive the particles the smaller their energy loss due to synchrotron radiation
- Number of interactions depends on
  - Number of particles in each bunch: 1.1×10^{11}
  - Collision frequency: 40 MHz
  - Number of bunches: 2808
  - Beam cross-section: 16 µm
- Huge Stored Energy:
  - 700 MJ in the beams (think 400 ton passenger train at 95 mph)
  - 11GJ stored in the magnets/magnetic field (think 15 such trains)

First LHC Data

- We have collision data from September 2008

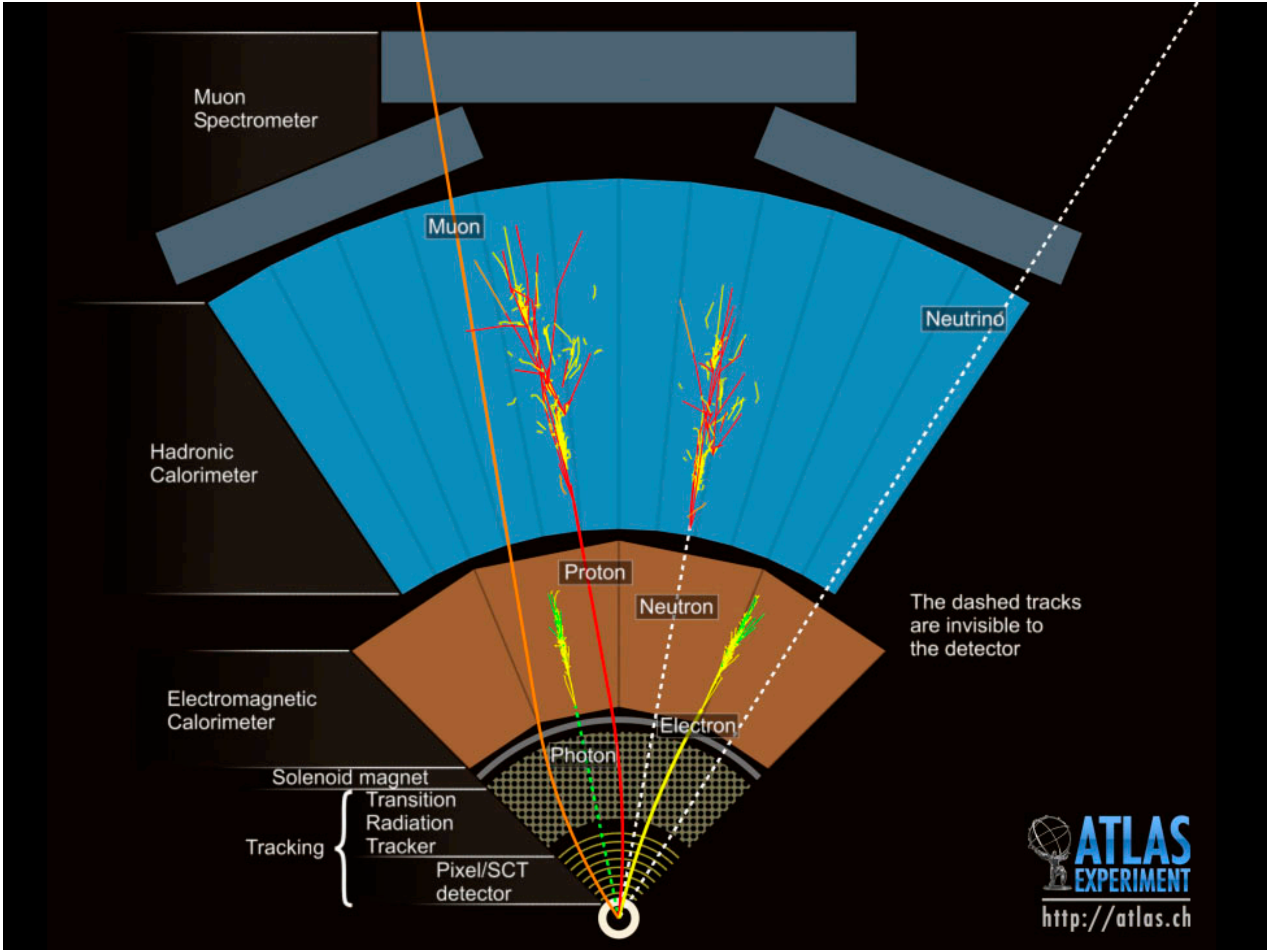
- Unfortunately they were magnet-magnet collisions

- On to better times:

2011+2012, LHC performing flawlessly

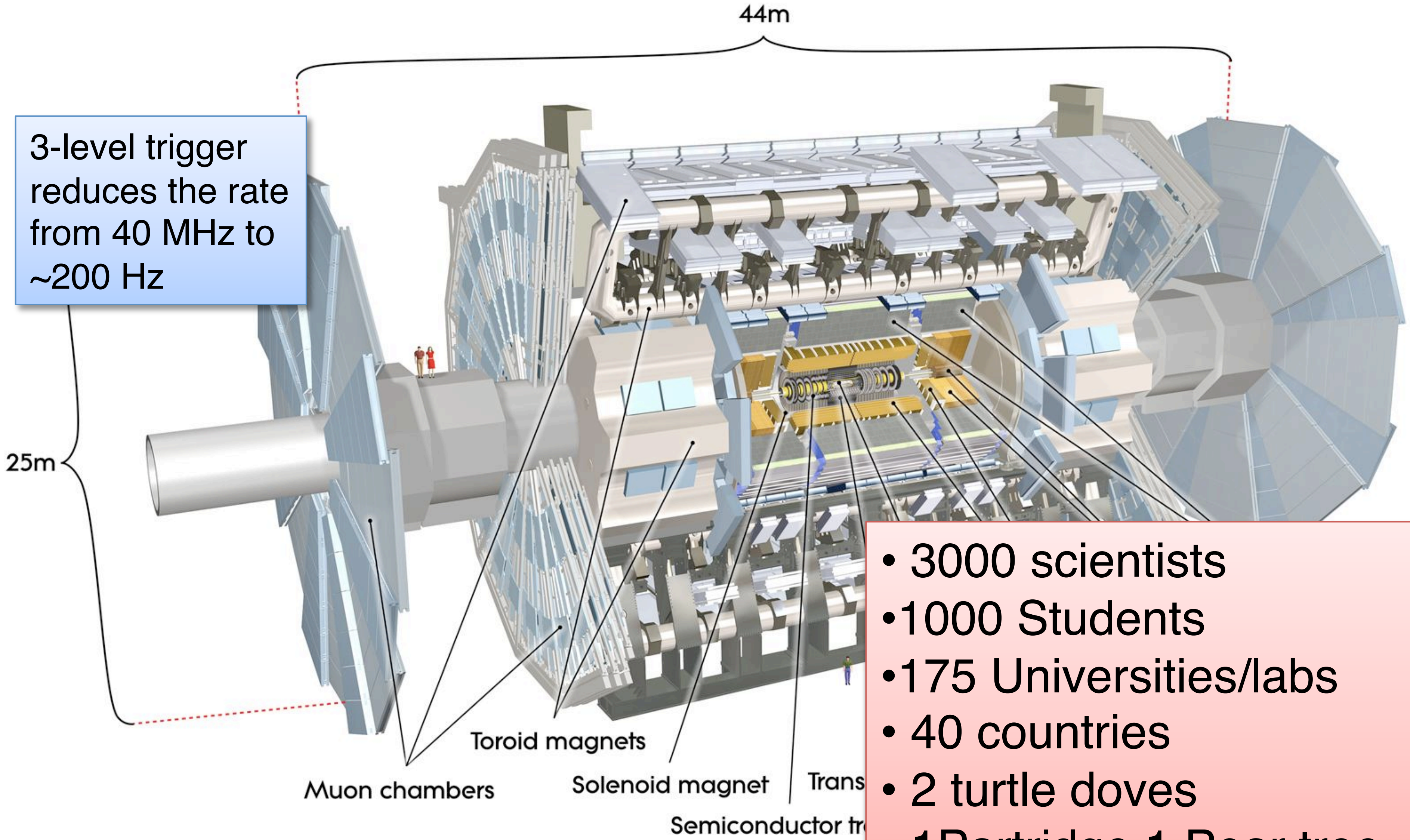
Finding the Higgs: Detection

- We detect the Higgs by observing its decay products
- **A SM Higgs at ~125 GeV would decay into:**
- 2 b-quarks: ~60% (huge QCD background)- **Quarks (and Gluons) appear as sprays of particles called jets**
- WW: ~20% (easy identification in di-lepton mode, complex background)
- $\tau\tau$: ~6% (complex final states with τ leptonic and/or hadronic decays)
- ZZ*: ~3% ("golden-plate", clean signature of 4-lepton, high S/B, excellent mass peak)
- $\gamma\gamma$: ~0.25% (excellent mass resolution, high sensitivity)



Muon Spectrometer
Hadronic Calorimeter
Electromagnetic Calorimeter
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
Muon
Proton
Neutron
Electron
Photon
Neutrino
The dashed tracks are invisible to the detector
ATLAS EXPERIMENT
http://atlas.ch

The ATLAS Detector

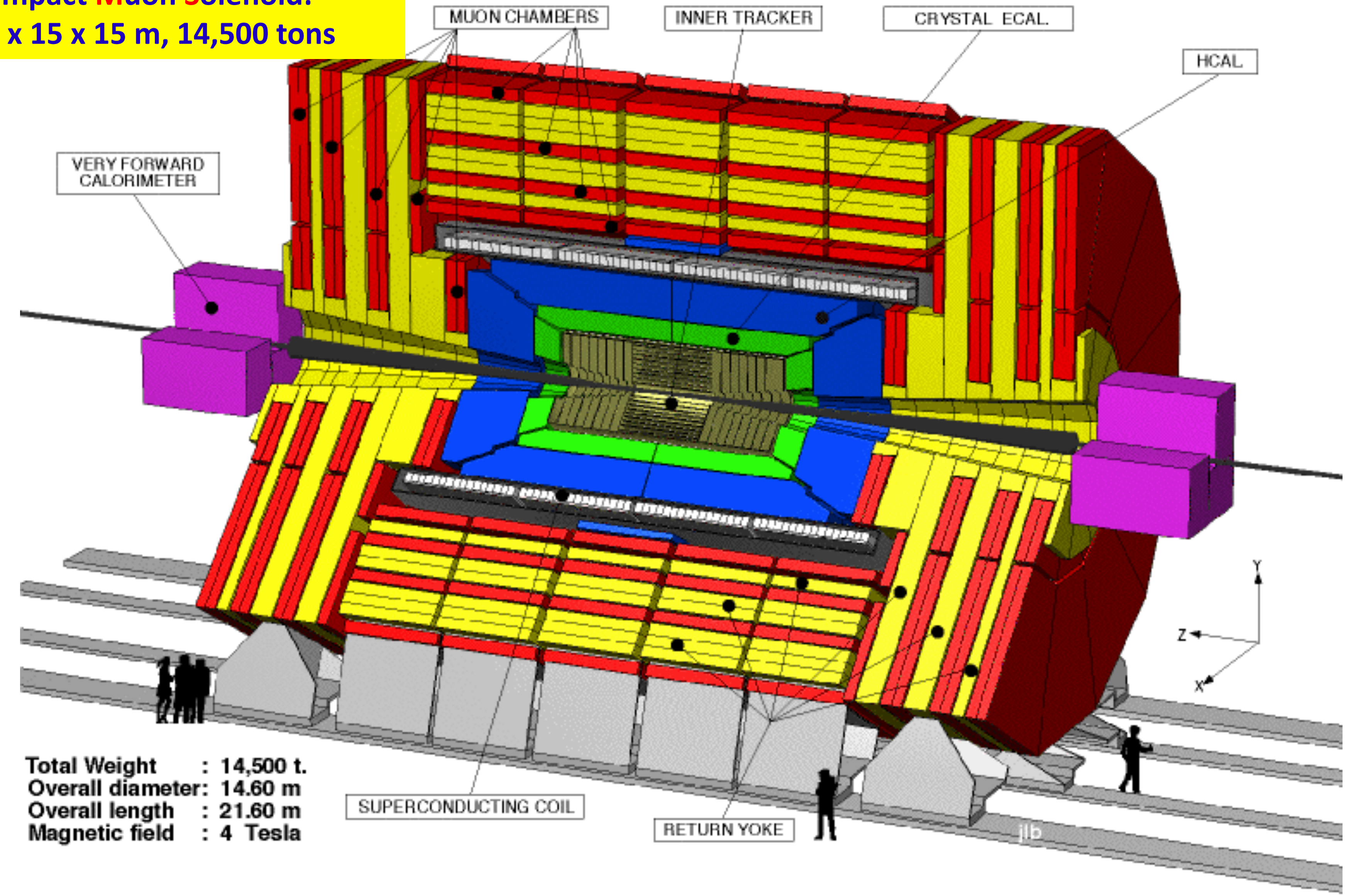


3-level trigger reduces the rate from 40 MHz to ~200 Hz

- 3000 scientists
- 1000 Students
- 175 Universities/labs
- 40 countries
- 2 turtle doves
- 1Partridge,1 Pear tree

The CMS Detector

Compact Muon Solenoid:
21 x 15 x 15 m, 14,500 tons



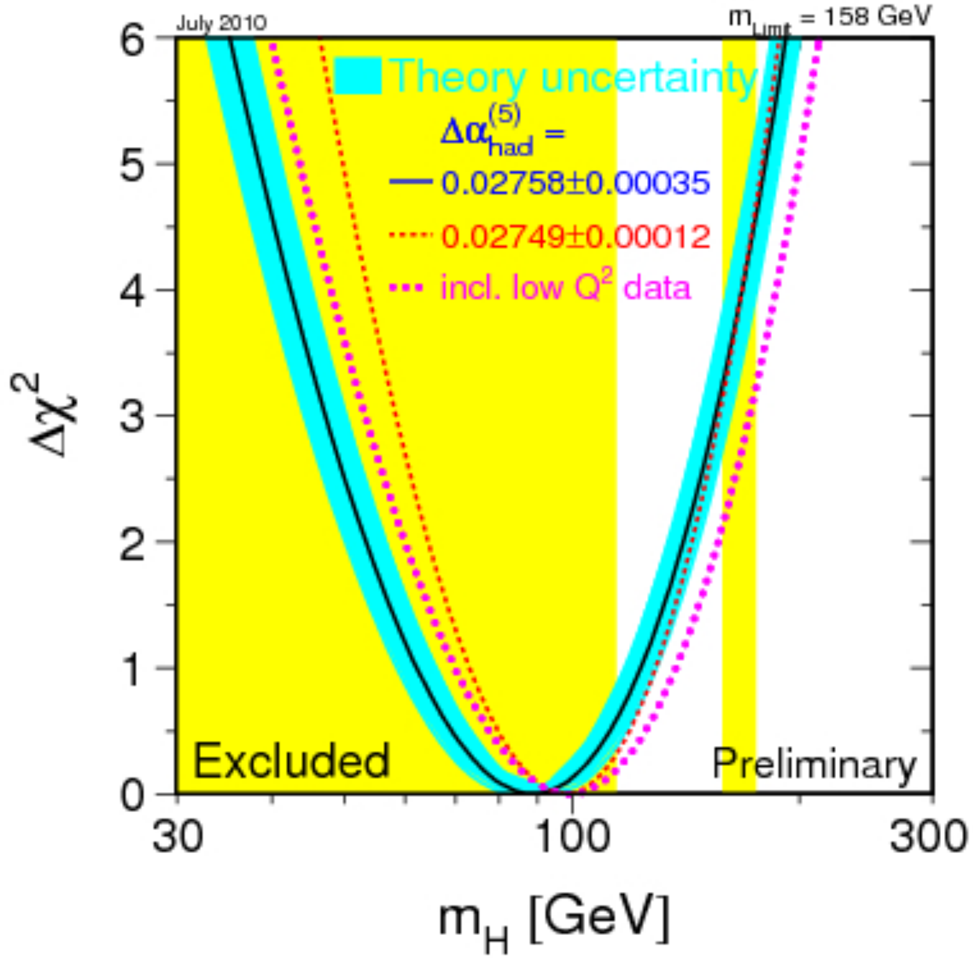
Total Weight : 14,500 t.
Overall diameter: 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

Detector Mass in Perspective

CMS is 30% heavier than the Eiffel tower

The Higgs Search

Experimental Constraints on the Higgs Mass, circa 2011



Not excluded: 115 GeV < m_H<158 GeV

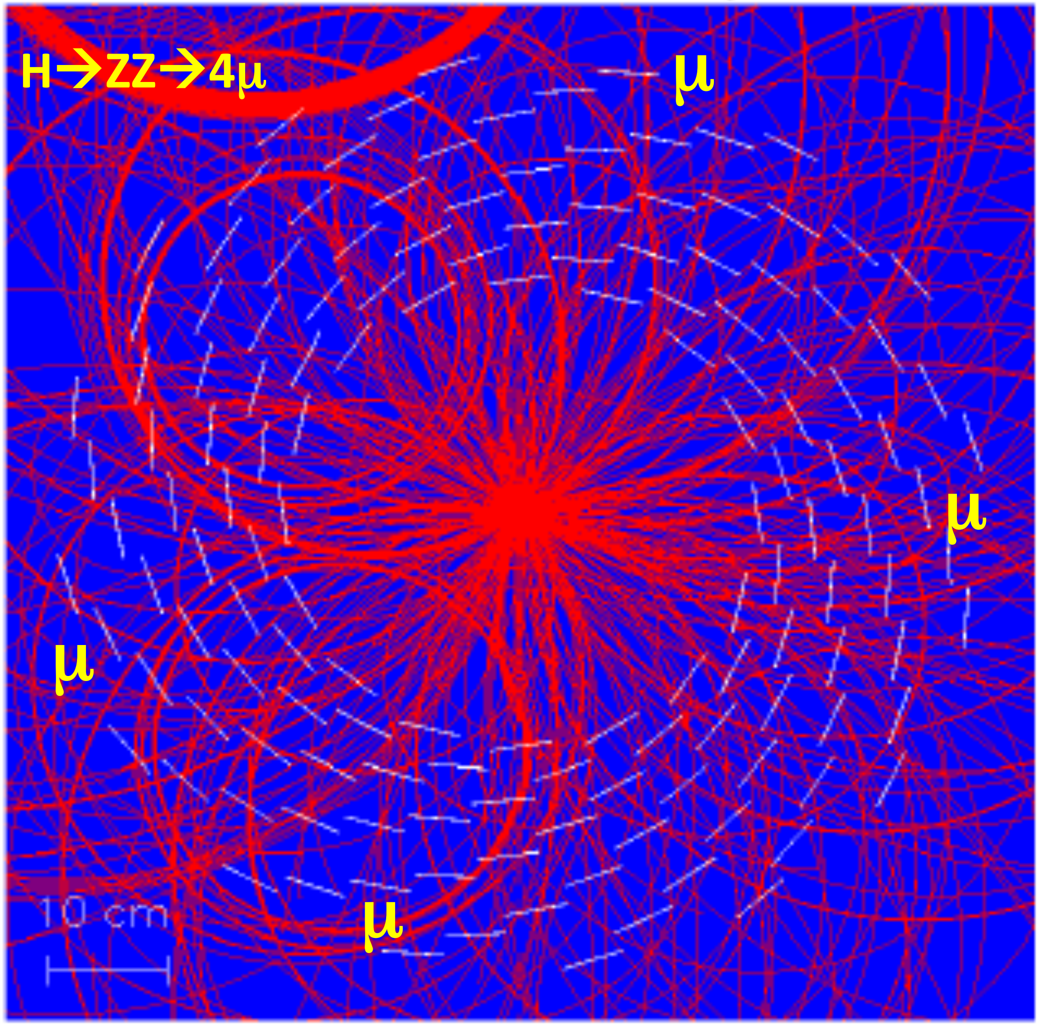
Higgs Rate from LHC

Unfortunately: Higgs boson production rate:
1 out of 10^{12} pp interactions

- **7 TeV data samples (2011)**
  - 4.8 fb^{-1} of data ~70,000 Higgs in ~10^{17} interactions
  - Peak luminosity $3.6\times10^{33} cm^{-2}s^{-1}$ ~10 interactions per beam crossing
- **8 TeV data samples (2012)**
  - 5.8 fb^{-1} of data ~120,000 Higgs in ~$2x10^{17}$ interactions
  - Peak luminosity $6.8\times10^{33} cm^{-2}s^{-1}$ ~20 interactions per beam crossing
- **Also unfortunate: only capture ~0.2% of Higgs (the rest look too much like background)**

Challenges due to High collision Rate

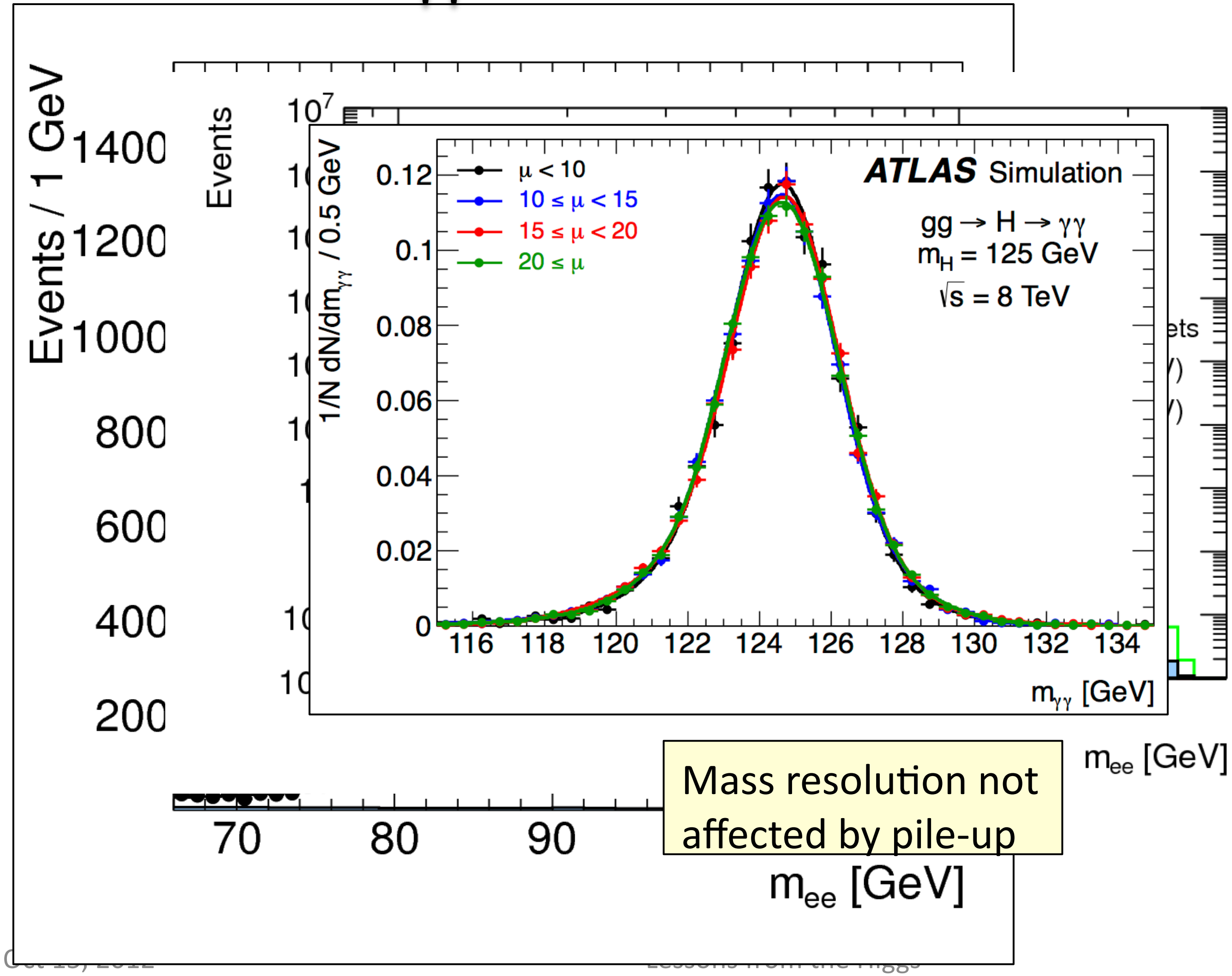
- The physics we care about



Background from other pp collisions!

Control Samples for the Higgs

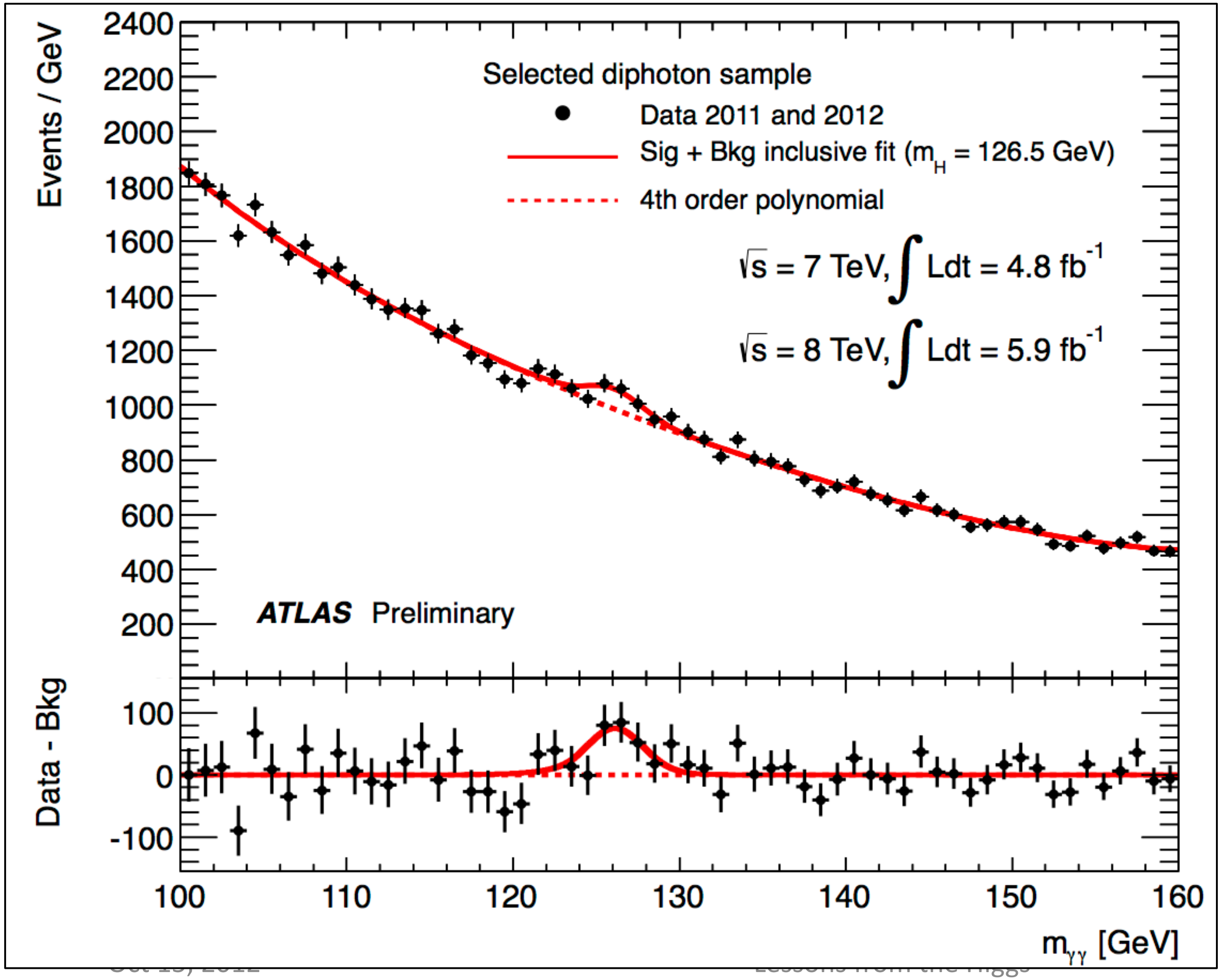
- Z->e+e-, helps to understand two higgs decay modes.
- H->ZZ* and H→γγ



Mass resolution not affected by pile-up

The Signal: H→γγ

- $m_{\gamma\gamma}$ spectrum fit (in 10 categories of photon quality) for signal plus background model
- Selection optimized using Monte Carlo
- Systematic: Max deviation of background model from expected background distribution



→ Excess of ~190 Events

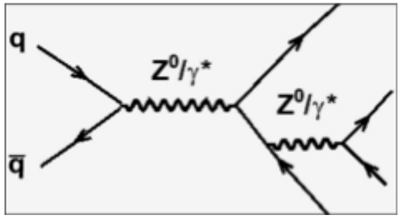
→ Expected 2.4σ

→ Observed 4.5σ (LEE, 3.6σ)

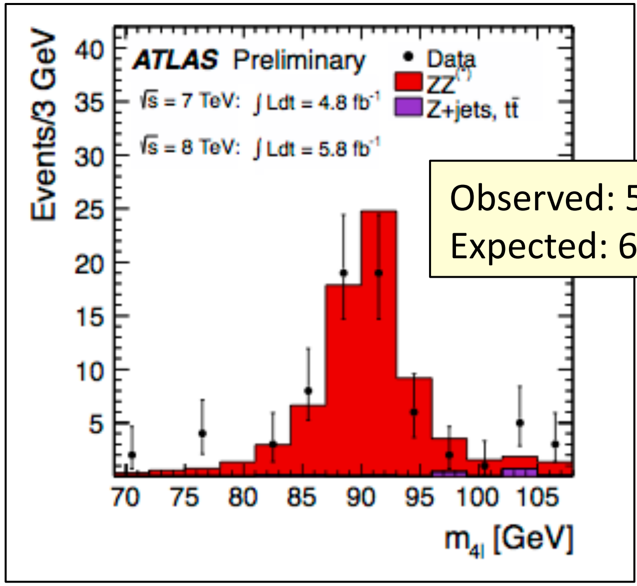
→ Signal strength: σ/σ_{SM} = 1.9 ±0.5

H→ 4l mass spectrum after all selections: 2011+2012

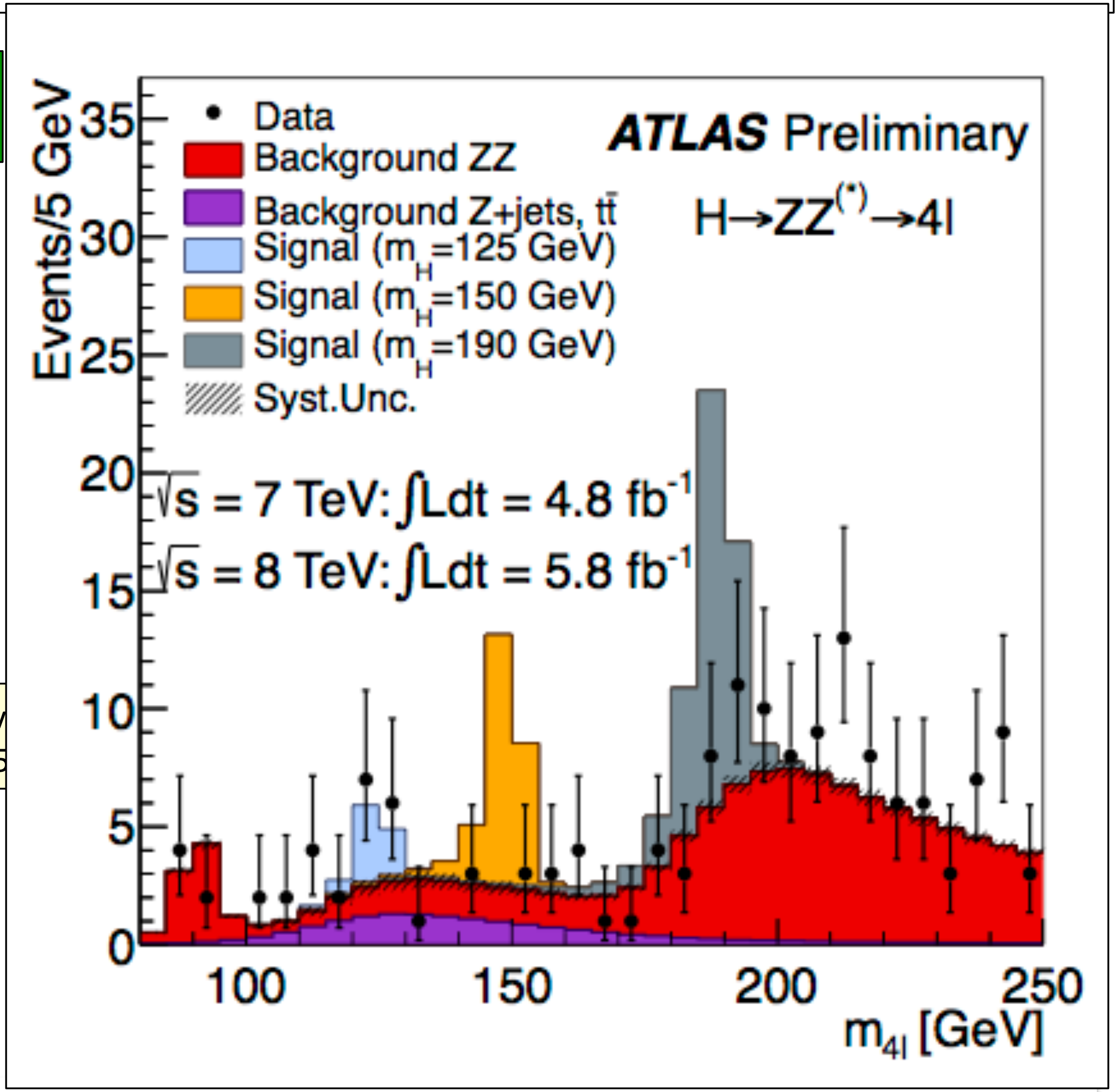
Peak at m(4l) ~ 90 GeV from single-resonant Z→ 4l production



Enhanced by relaxing cuts on m_{12}, m_{34} and $p_T(\mu_4)$

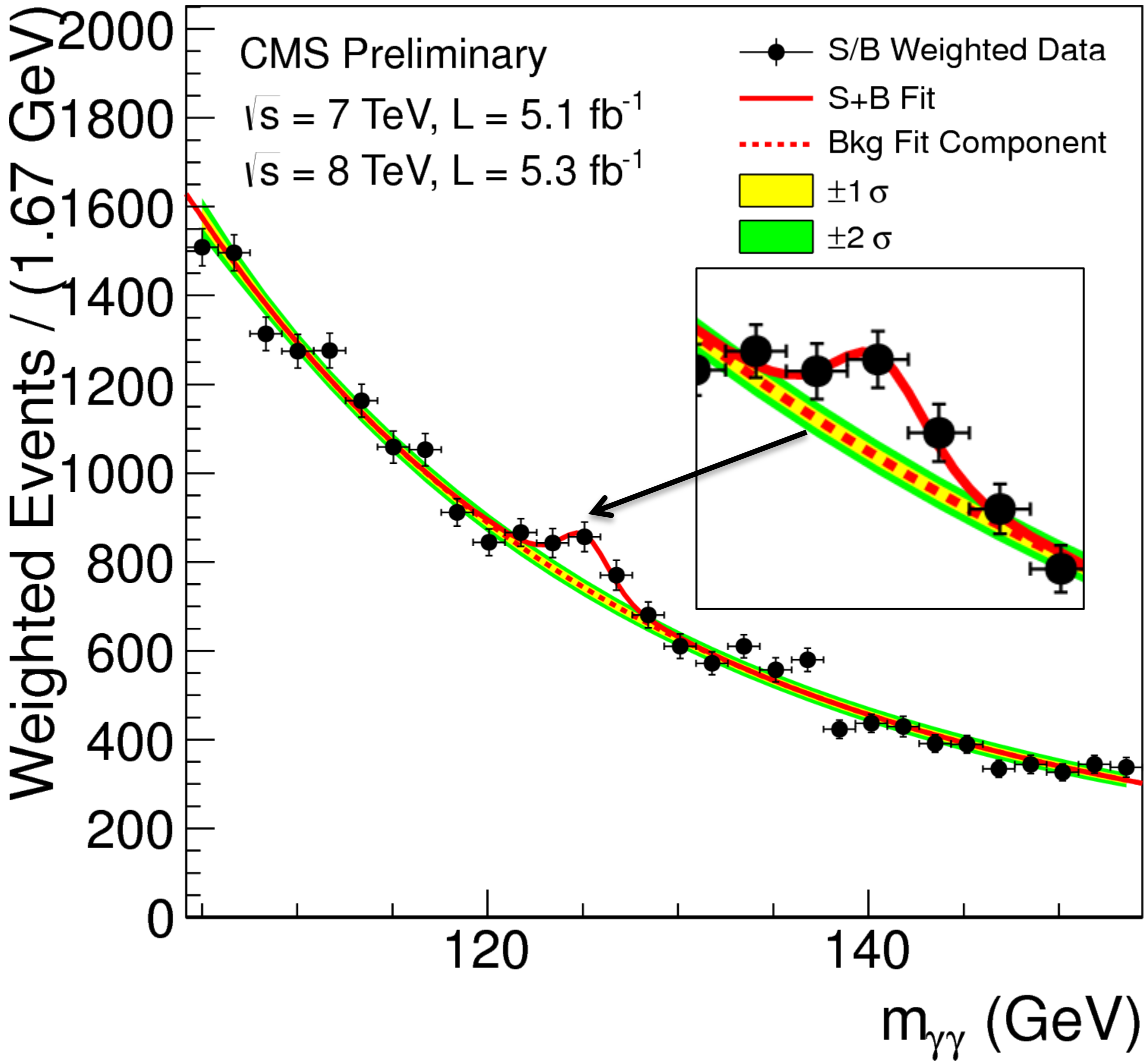


Observed: 57 ev
Expected: 65 ± 5



Obs. 13, expected BG: 3.1, 3.6 σ, expect 2.7σ

Results from CMS on H→γγ

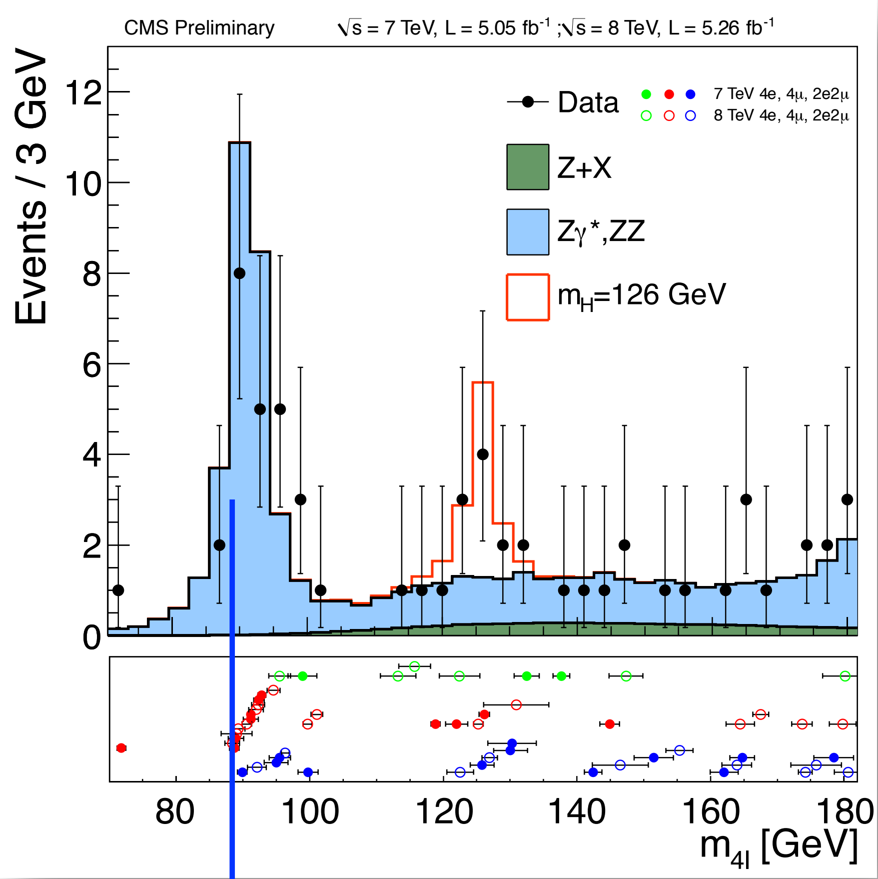


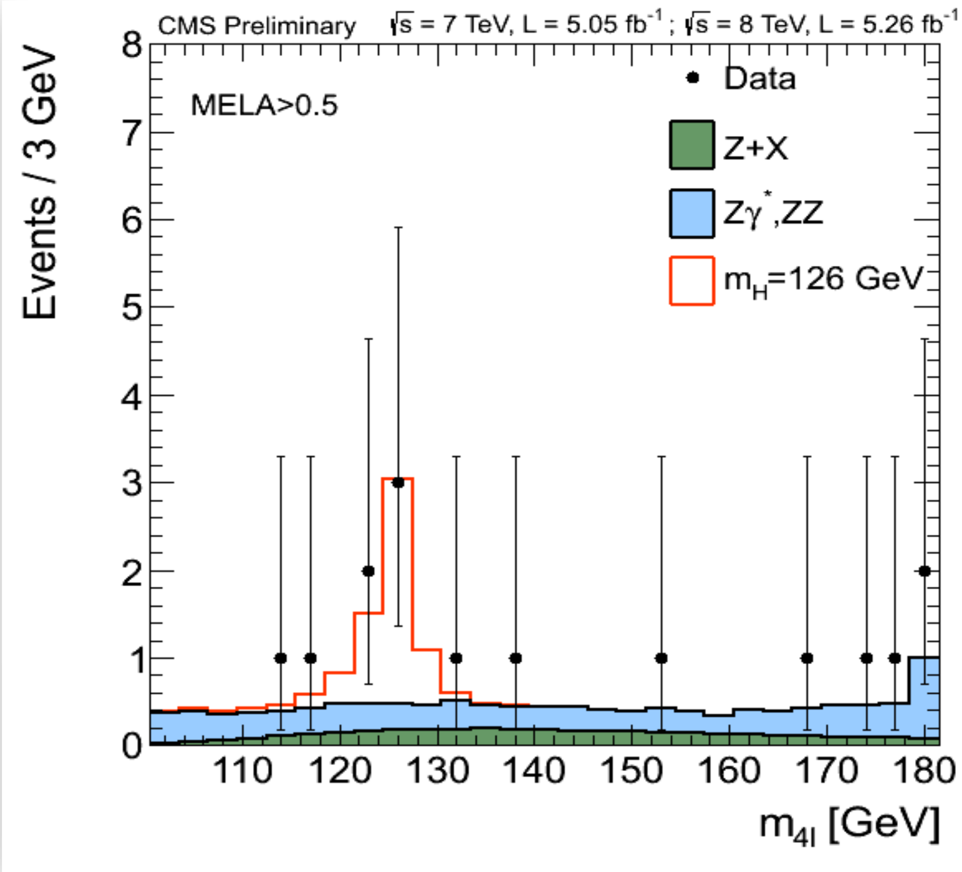
➔ Expected 2.5 σ

➔ Observed 4.1σ (LEE, 3.2σ)

➔ Signal strength:
σ/σ_{SM} = 1.56 ±0.43

Results from CMS (H→ZZ*→4ℓ)



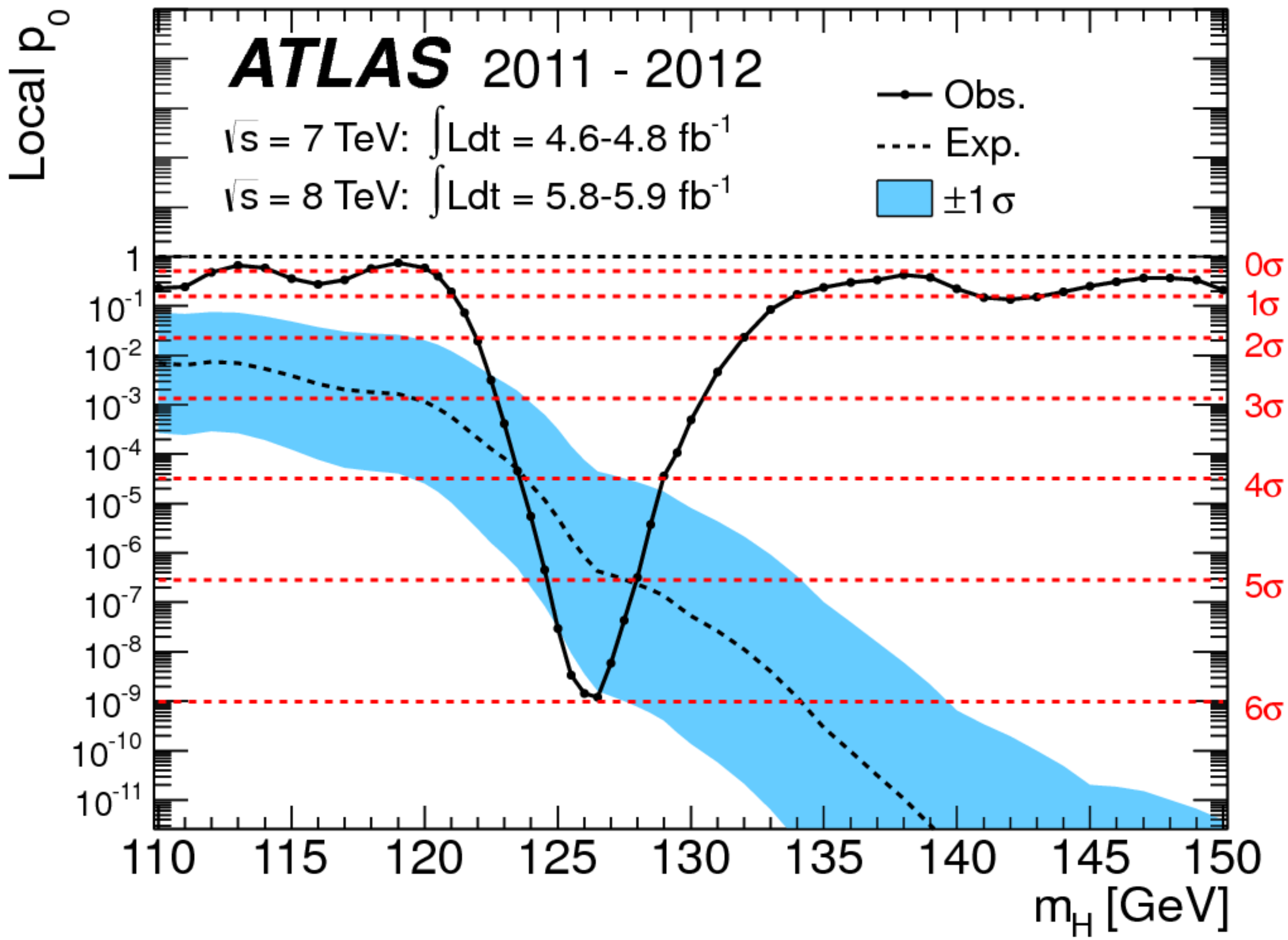


Single resonant Z→4ℓ using loose selection cuts

Enrich the Higgs signal by tightening the selection cuts

Significance: 3.8σ (expected), 3.2σ (observed)

Consistency of Data with BG only Hypothesis

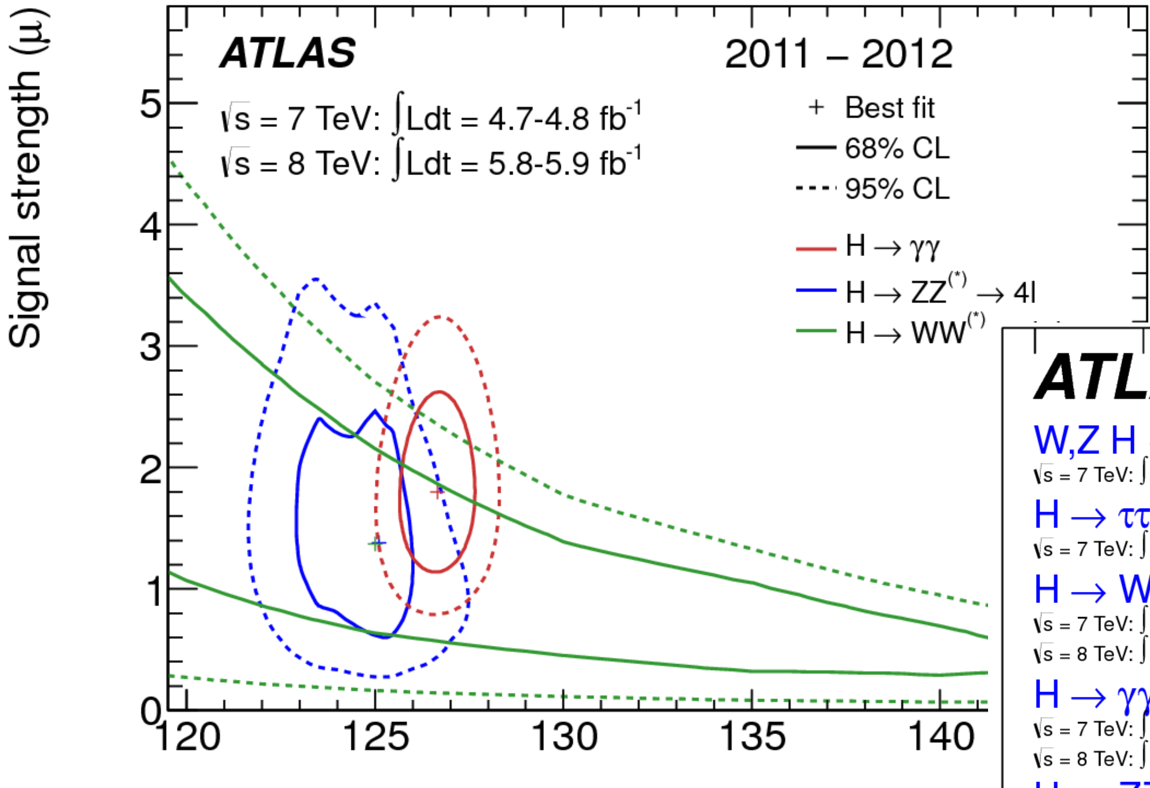


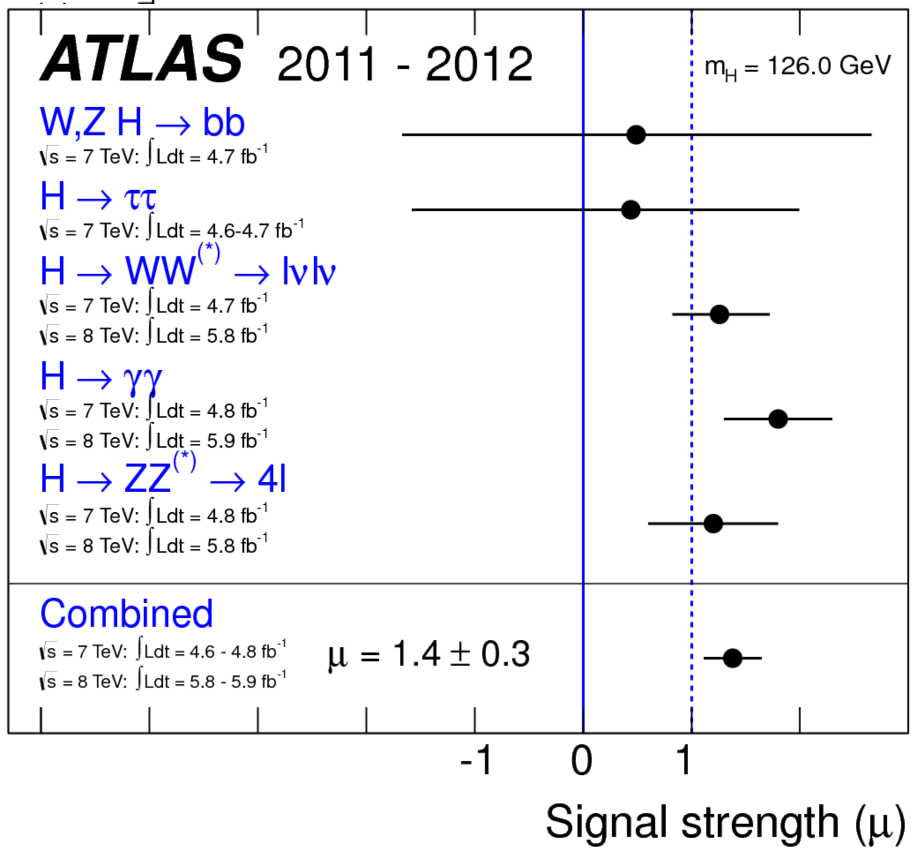
Observed significance 5.9σ (expected 5.0σ)

prob. of BG only fluctuation: 1.7×10^{-9}

Fitted mass: 126.0 ± 0.4 (stat) ± 0.4 (syst) GeV

Is everything consistent?





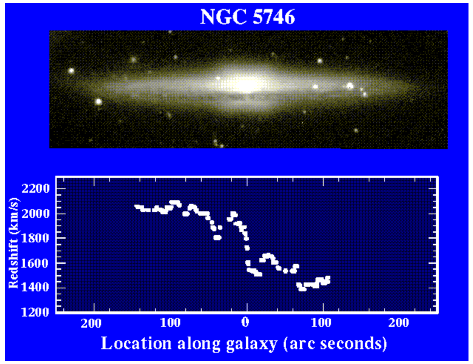
Prob. that difference in mass and rate is due to statistics: 8%

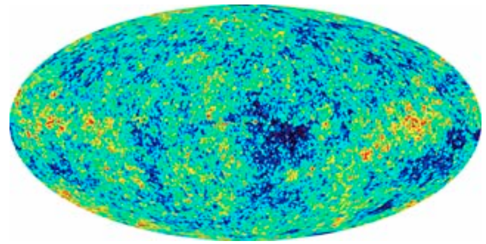
Are we finished?

- Is the Standard Model complete, is it the end?
- First need to make sure 125 GeV object is the Higgs
- Measure its quantum numbers via angular distribution of decay products
- Then……

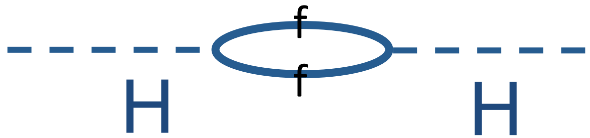
Problems in the Standard Model include:

- Doesn't address what is apparently 95% of the Universe
    - No dark matter candidate (DM)
    - No dark energy (or gravity, for that matter)
- Hierarchy Problem
    - EW radiative corrections to the M_H
    - integrated to scale Λ, shifts bare Mass by:





$$\delta m_H^2 \cong (115 GeV)^2 [\frac{\Lambda}{400 GeV}]^2$$

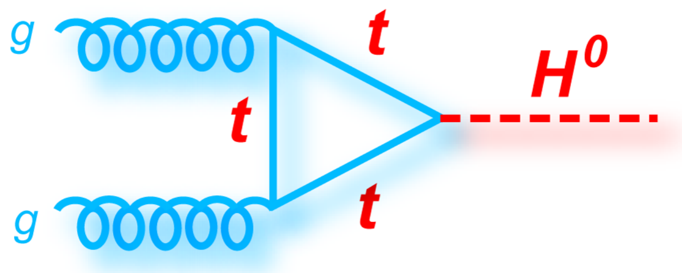


❖Need either:

- canceling counter terms (CT)
- some other New Physics by ~ 1-few TeV to maintain fine tuning at $O(10^{-3})$

Direct and Indirect Search for New Physics

- **Direct** searches for event signatures common to many BSM but rare in SM
  - Mulitple Leptons, rare in SM, common in NP
  - Excess missing energy as search for DM Candidate
- **Indirect** searches:
  - Higgs decay signatures could give indirect evidence for something heavy in virtual loops needed to explain Higgs decays
  - Motivates precision, high statistics study of this new object



What it all means (my opinion)

Science Lessons:

- We have a (relatively) `complete' picture of mass:
- Mass is beautifully complicated and elegantly revealed in Quantum Mechanics:
  - In ~1810, matter was real, fields were math
  - Now everything is comprised of quantized fields
  - Mass is dynamic in origin, not innate. It arises from fundamental interactions and is calculable (at some level)
- Last puzzle piece, Higgs Boson; intellectual & experimental tour-de-force

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What it all means (my opinion)

Beyond the Science:

- **The higgs discovery was global:**
  - **International Cooperation 1** — **Nationalistic Rancor 0**
- **Publically Supported, by practically all taxpayers:**
- **Glory and Virtue of Taxation 1** — **Hyper Individualism 0**
  - **Higgs Boson 1** — **Boson 0**
- **Human Curiosity trumped all else:**
  - Human Curiosity **1** — Other motives lower on Maslow's hierarchy **0**
- **Opportunity Cost:**
  - Everything else **0** — Big Science **1**

False Dichotomy