The Search for the Higgs Boson at the Large Hadron Collider

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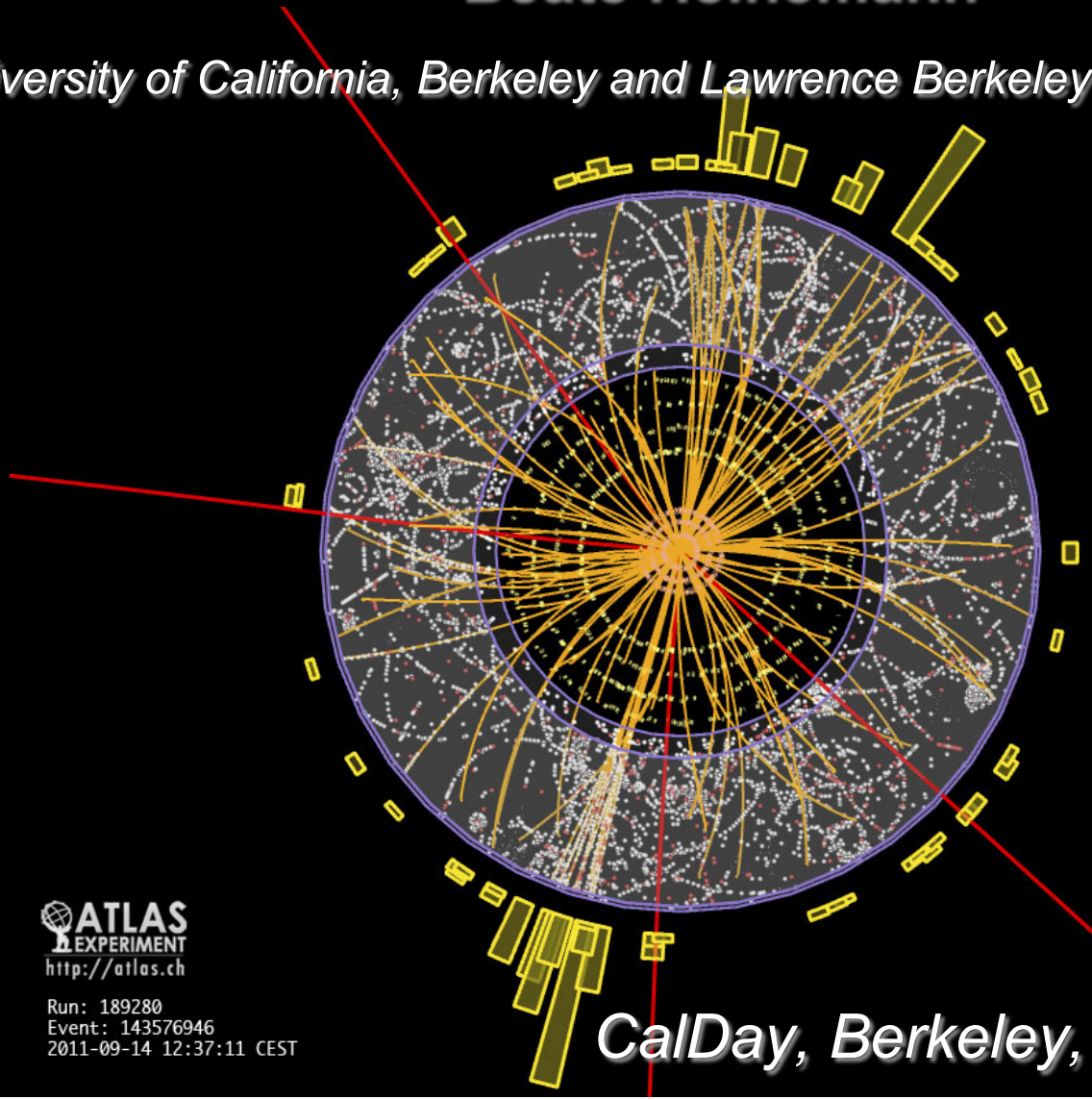


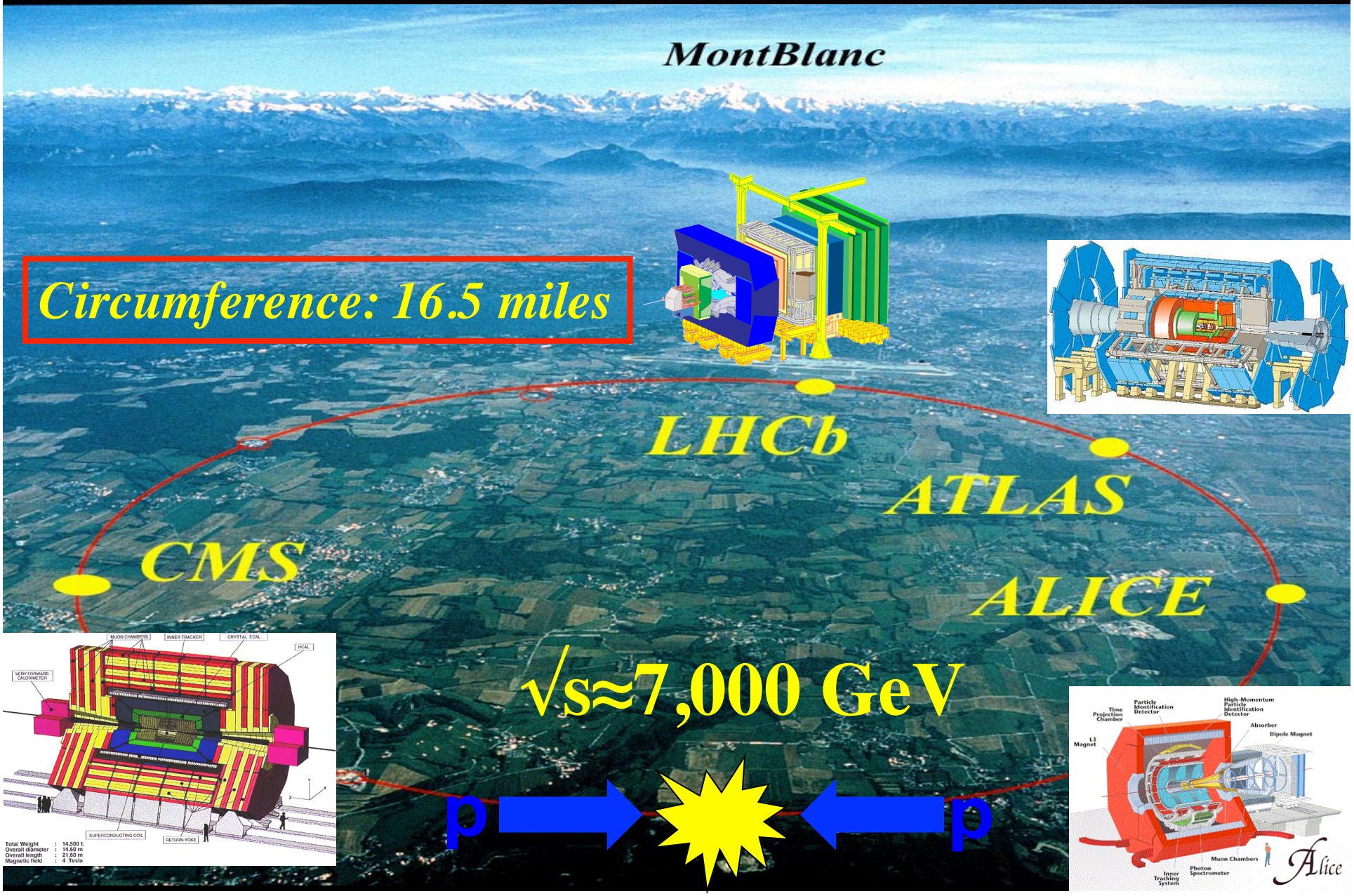
CalDay, Berkeley, April 2012

Outline

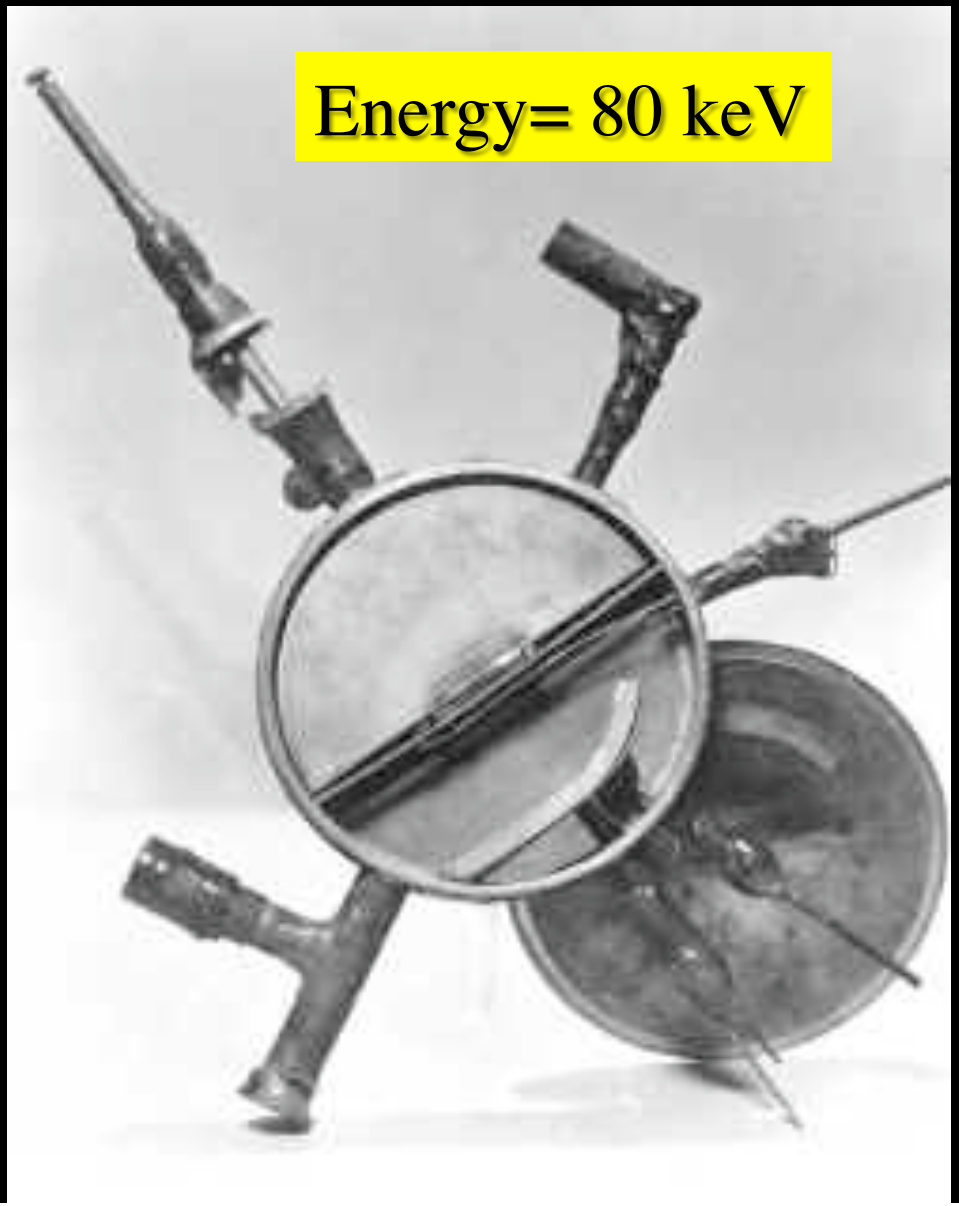
- The Large Hadron Collider
- How to find the Higgs Boson at the LHC
- Current Results for the Higgs Boson Search
- Conclusions

The Large Hadron Collider

The Large Hadron Collider (LHC)



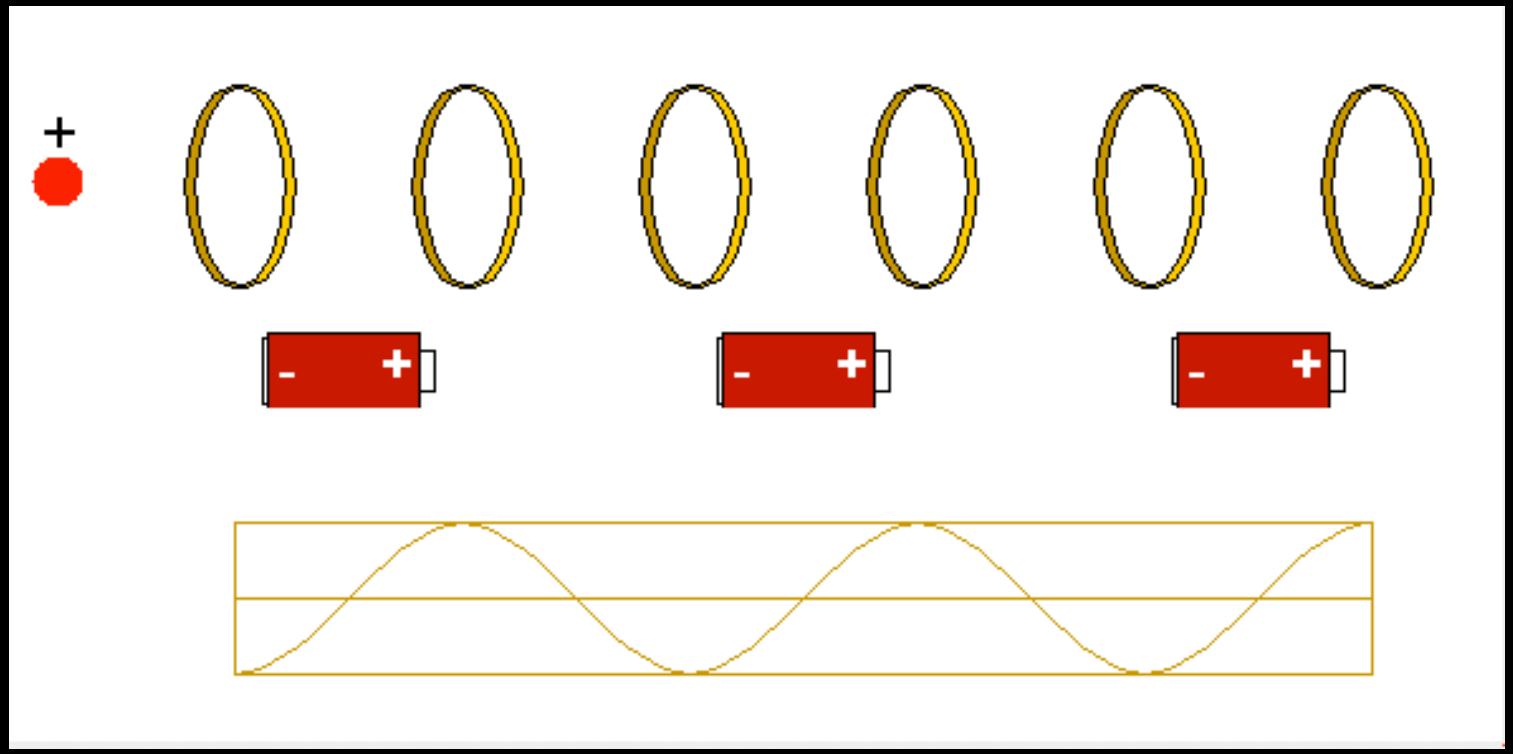
The World's first accelerator: 5-inch Cylcotron in Berkeley



Earnest O. Lawrence
1939 Nobel Prize

How particles get accelerated

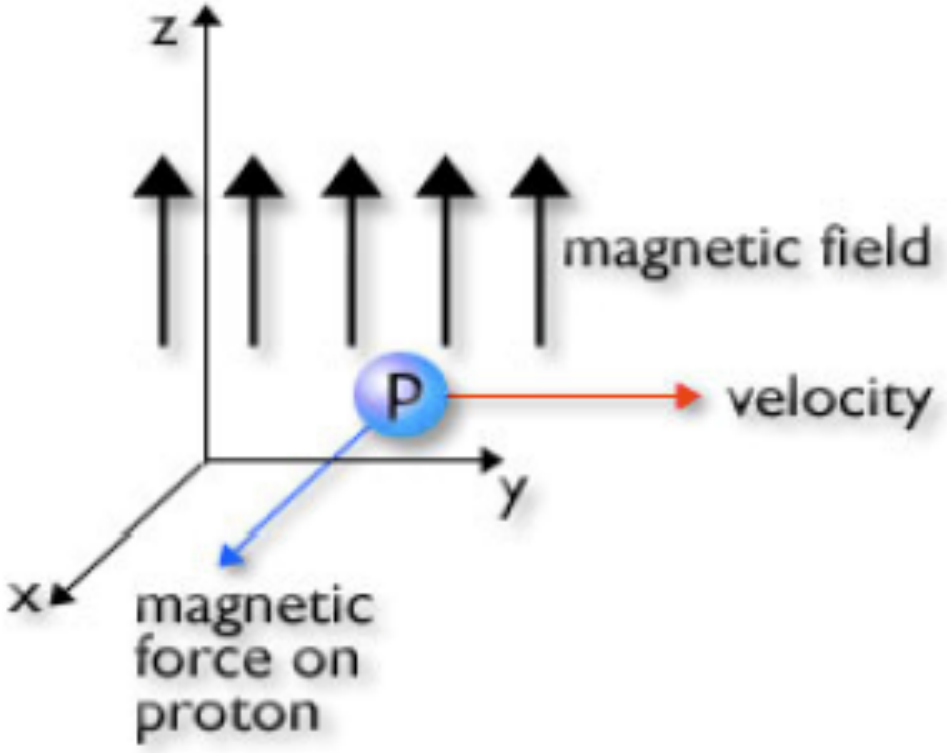
With F=qE (Maxwell) and F=ma (Newton)
Acceleration: **a = qE/m**

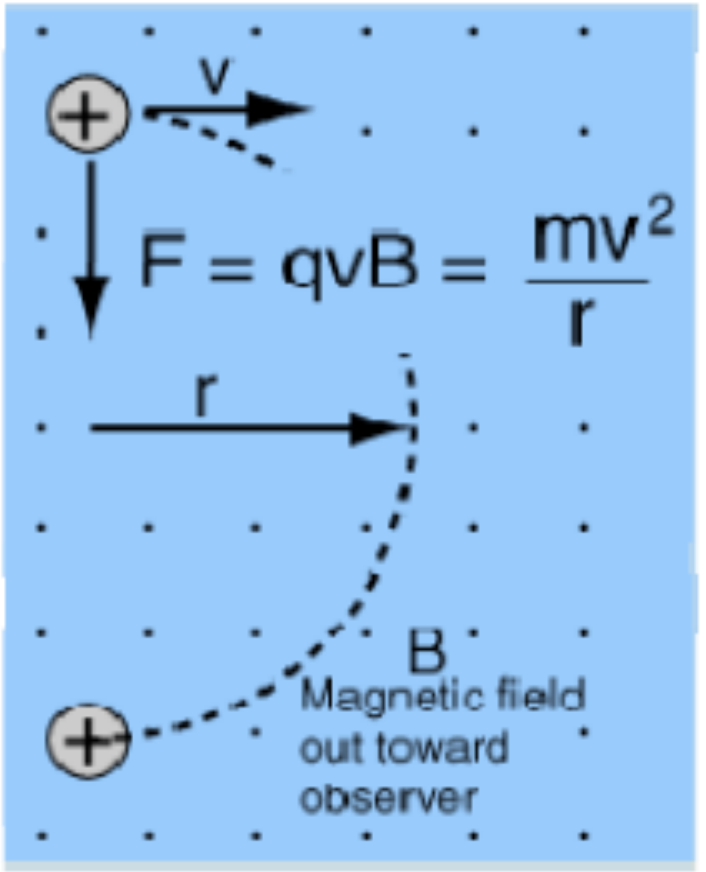


eV= "electron Volt" = energy of one electron after passing through field with voltage of 1V

How particles get bent in circle

Magnets are used to steer the beam in circle using the Lorentz force ($F=qvB = mv^2/r$)



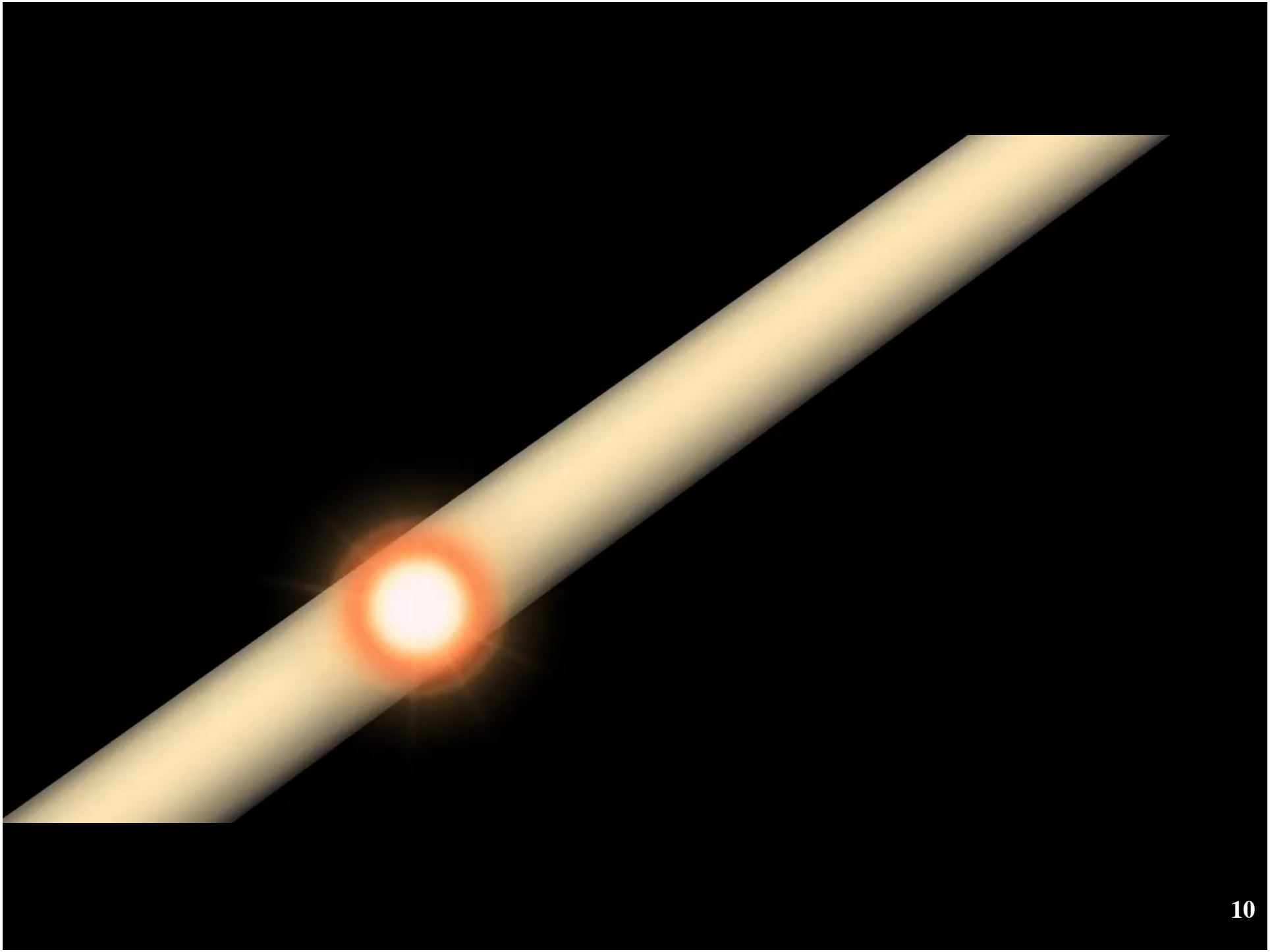


LHC Accelerator

- Energy 80 million times larger than 5” cyclotron
- Cost = $8 billion
- 17 years since US joined

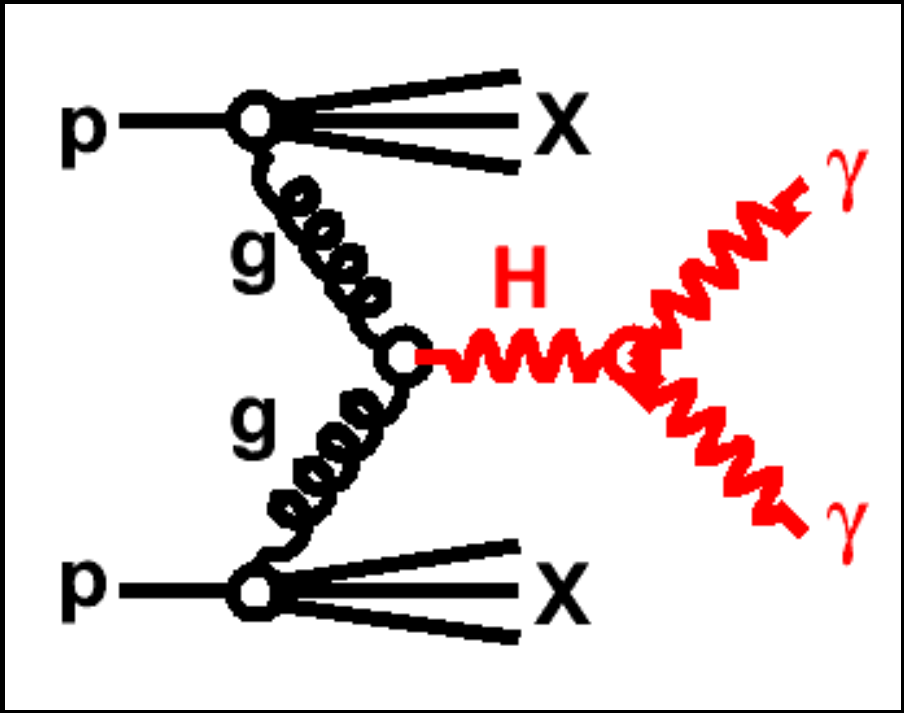
LHC in the Bay

- protons go really fast: 99.999999% of the speed of light
- make a full turn 11254 times per second



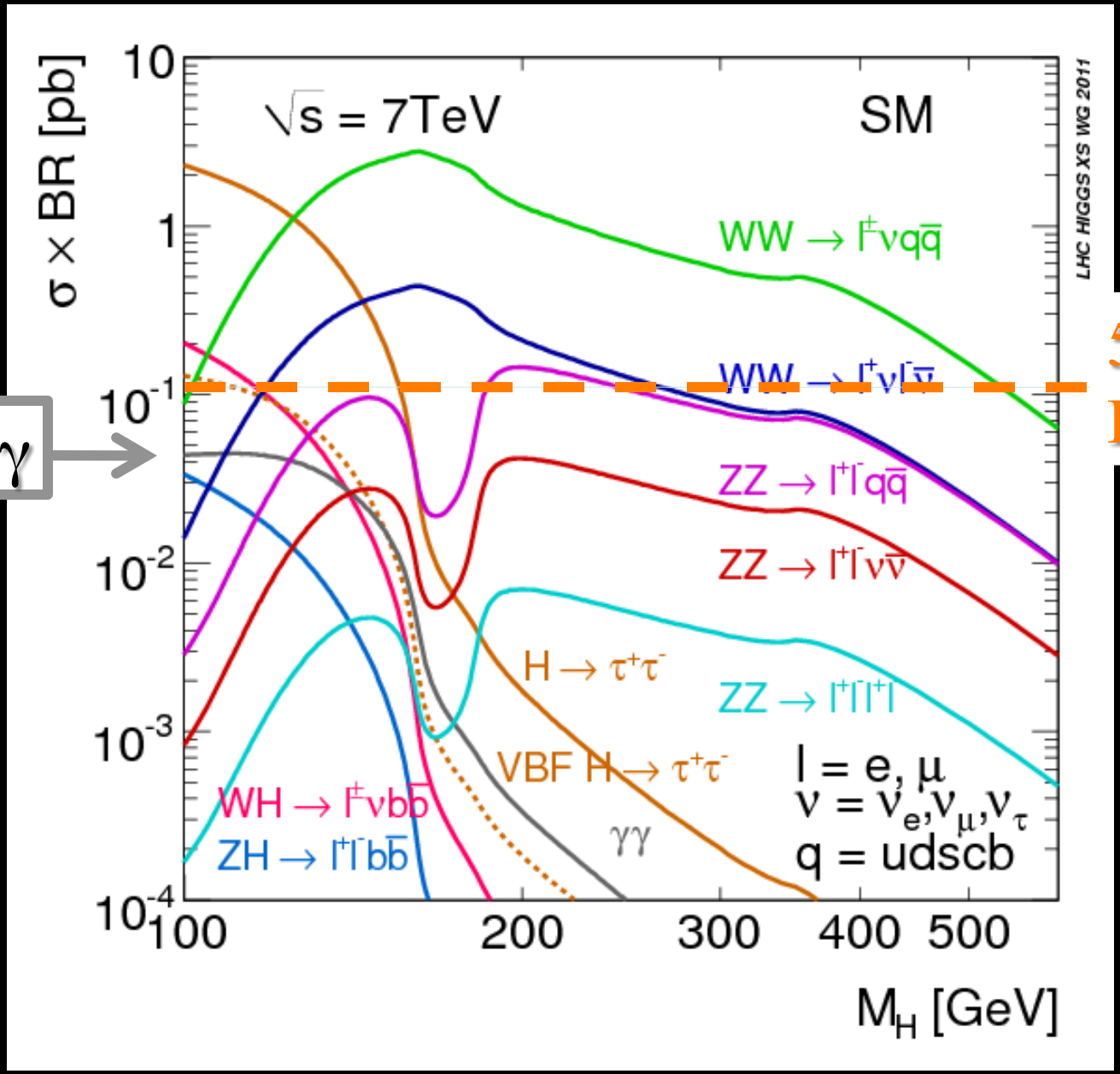
How to find the Higgs Boson at the LHC

Production and Decay of a 125 GeV Higgs Boson



- Higgs boson is unstable and decays very quickly
  - 0.2% decay into two photons
  - 99.8% decay in manner which is harder to observe
    - Also analyzed and important but will not explain here

Rate of Events produced



γγ

500 events
In 2011

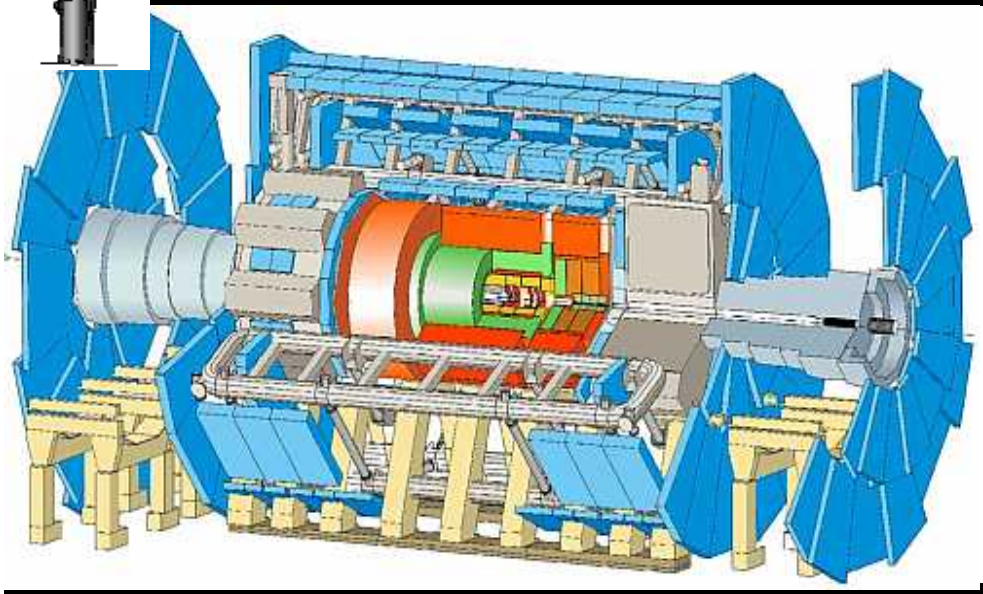
Number of Expected Higgs Events

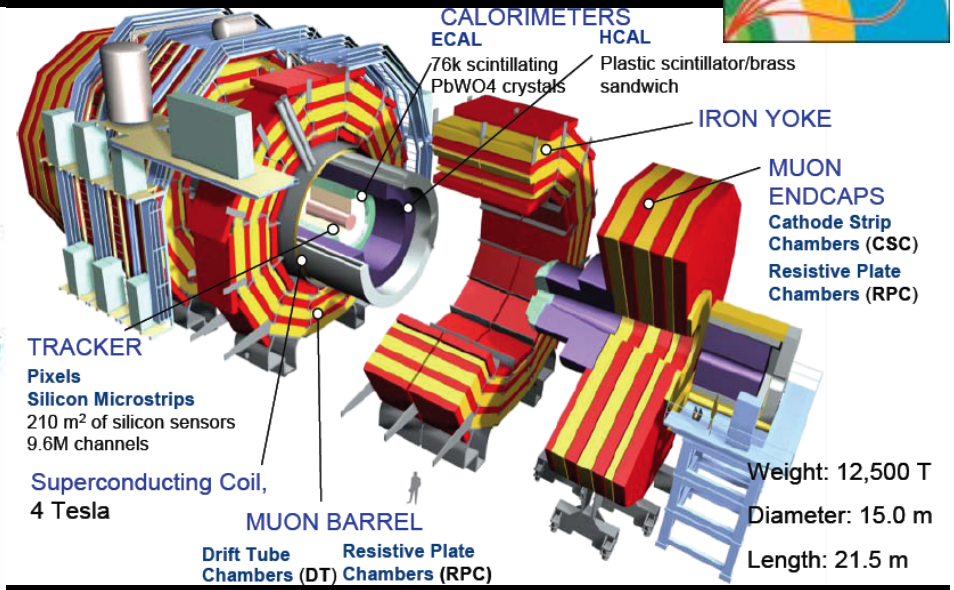
- Assuming a given Higgs boson mass we can calculate how many Higgs bosons we should see
  - Precision of calculation is about 15%

- In full LHC dataset we expect for m(H)=120 GeV for each experiment

Higgs Decay mode	Number of Events / 5 fb^{-1}
H->2 photons	70
H->ZZ->4 leptons	2.5

ATLAS and CMS Detectors





	Weight (tons)	Length (m)	Height (m)
ATLAS	7,000	42	22
CMS	12,500	21	15

Detector Mass in Perspective

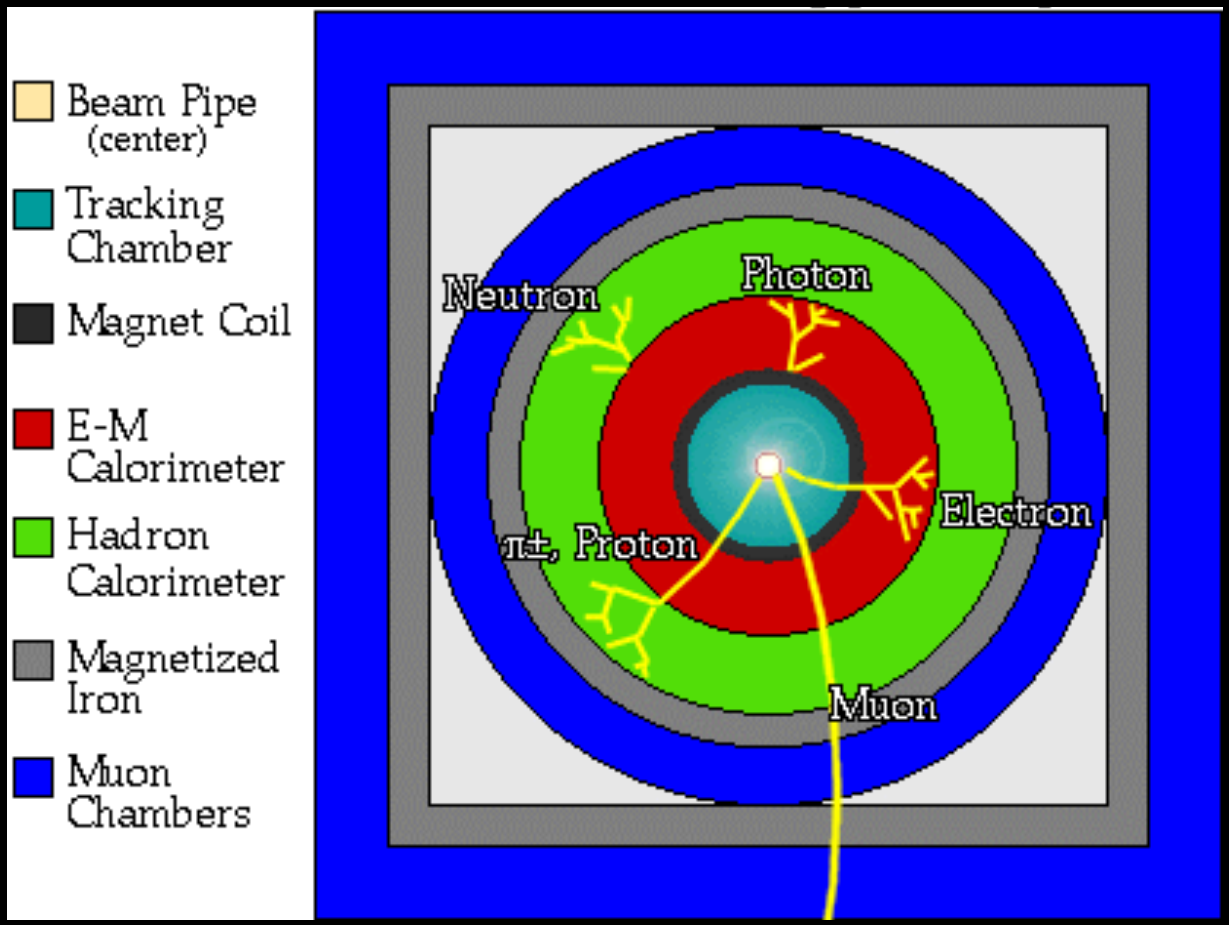
CMS is 30% heavier than the Eiffel tower

3000 Physicists from all over the World

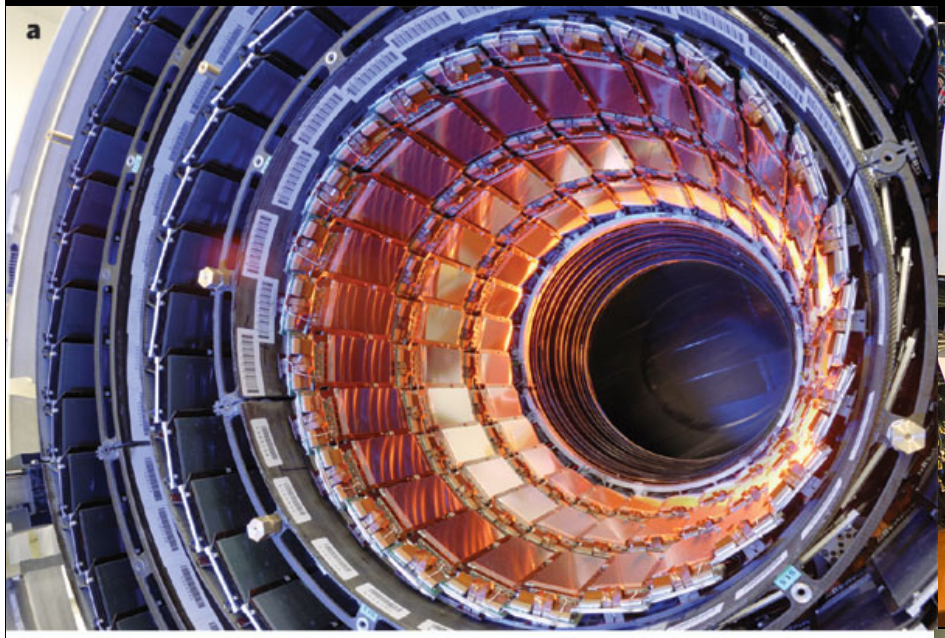
(including 1000 students)
+ many technician and engineers

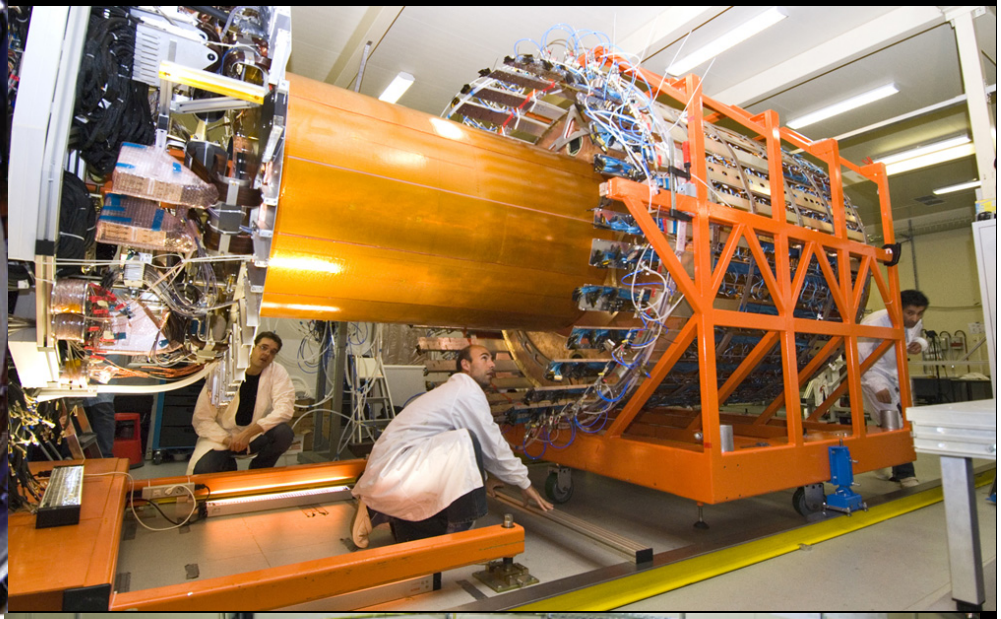
Particle Identification

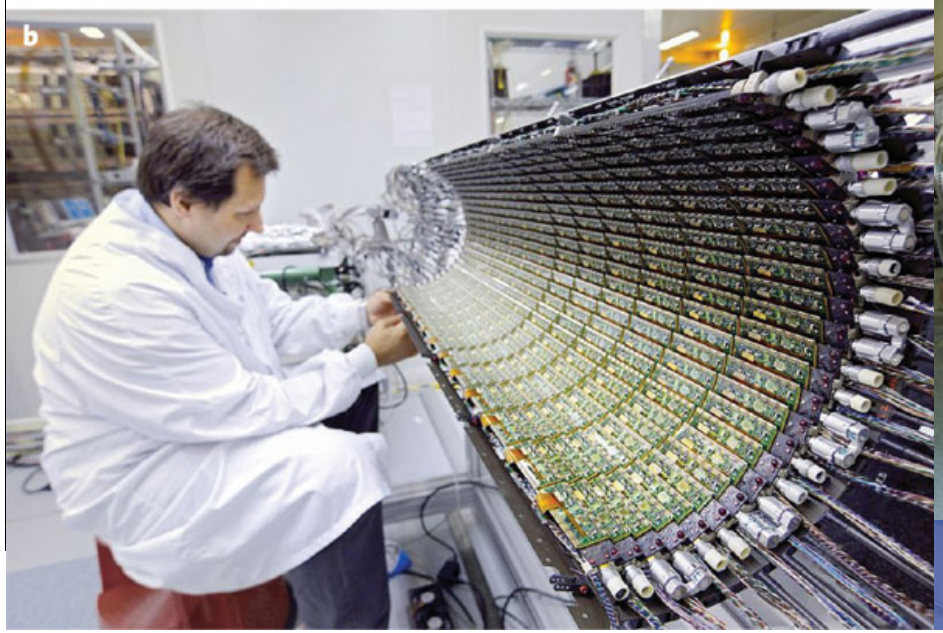
- Collisions enclosed by layers of different detectors (like an onion):
  - separate particle types
  - measure their energies



Tracking Detectors

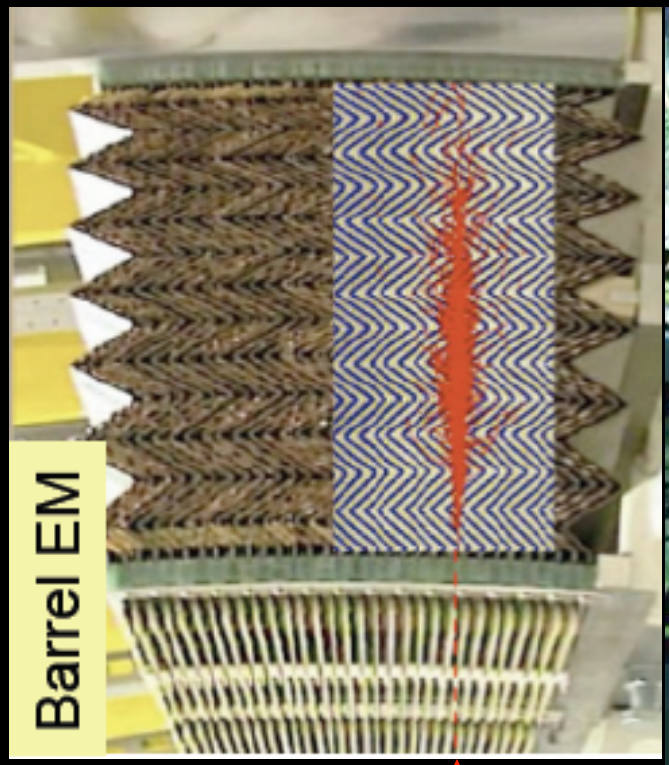


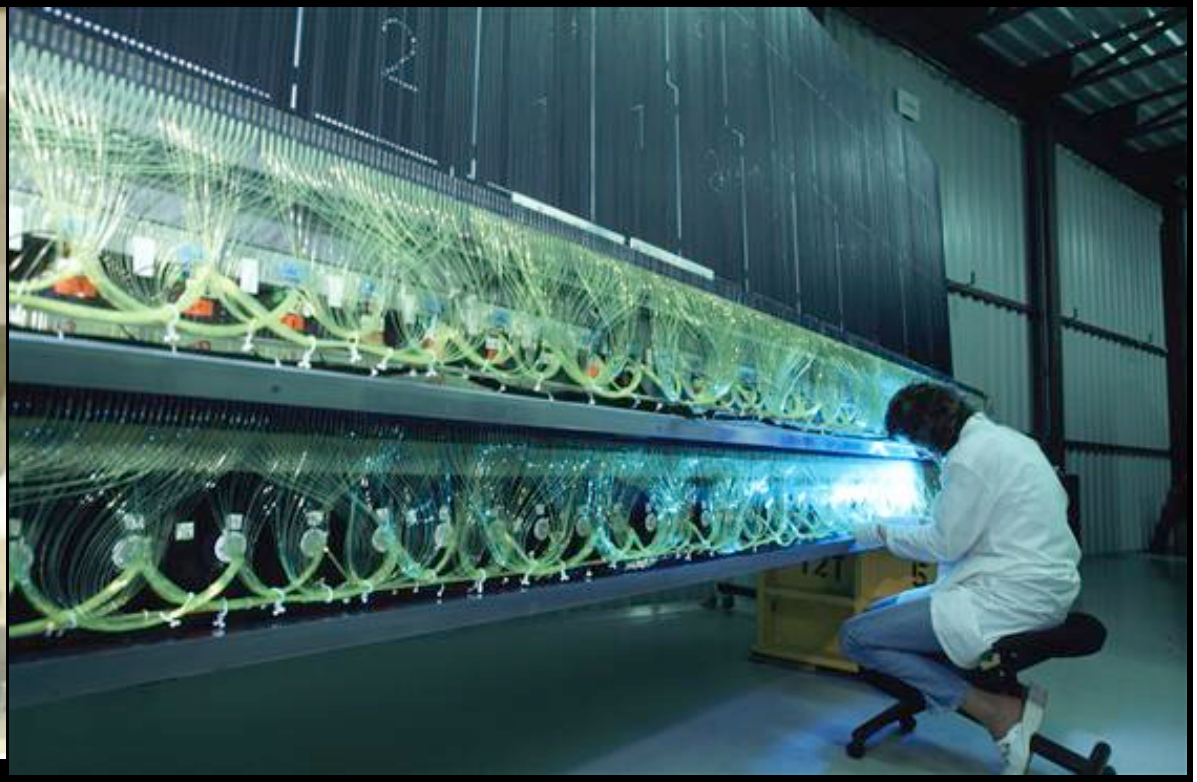




Berkeley's crew 2007

Calorimeters



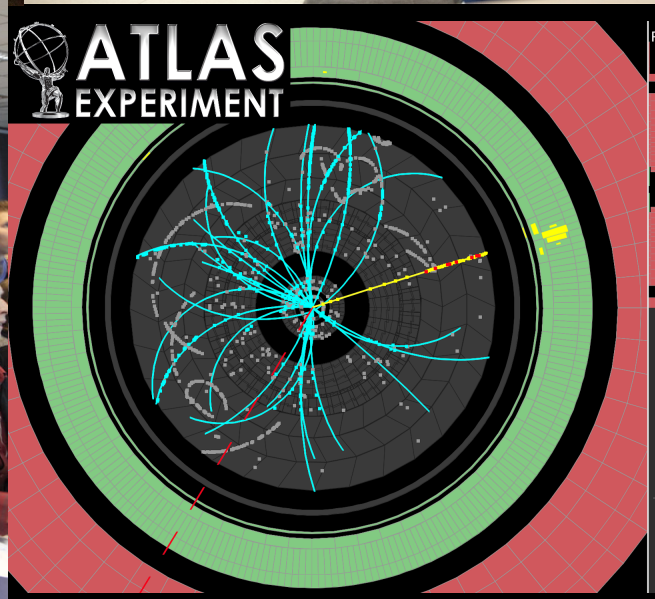


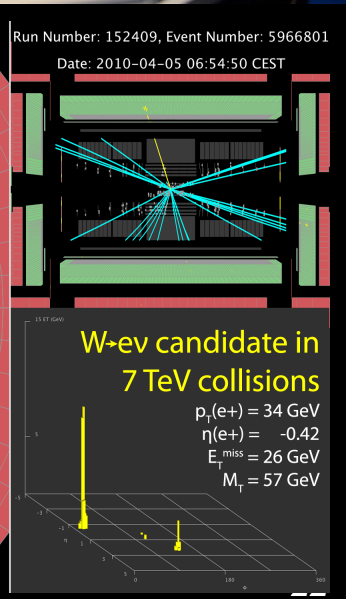
e or γ

- Measure energy and position of electrically charged and neutral particles
  - Electrons and photons
  - Hadrons (protons, pions,…)

Current Results from LHC Data

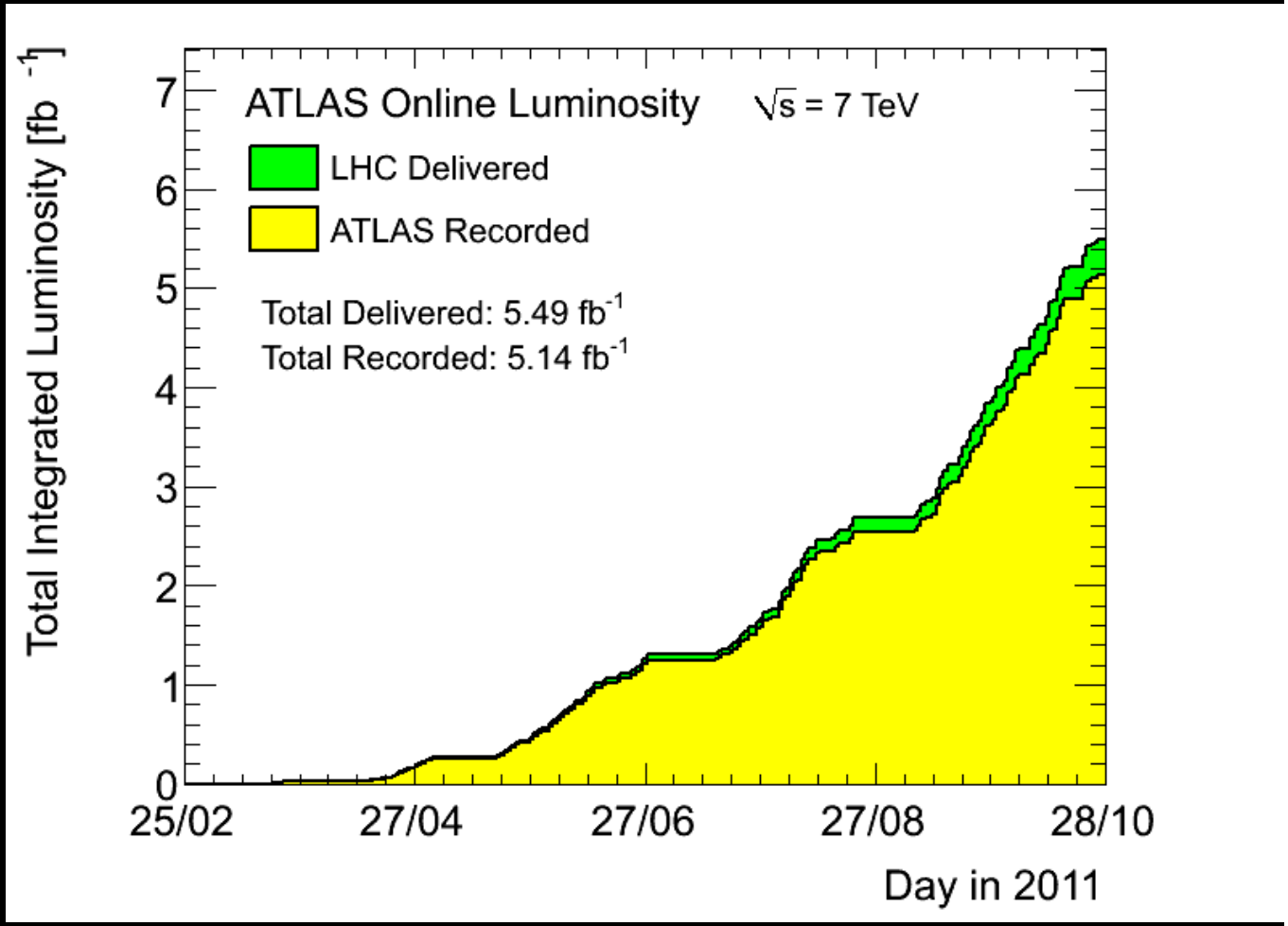
Happiness when LHC turned on!





Luminosity

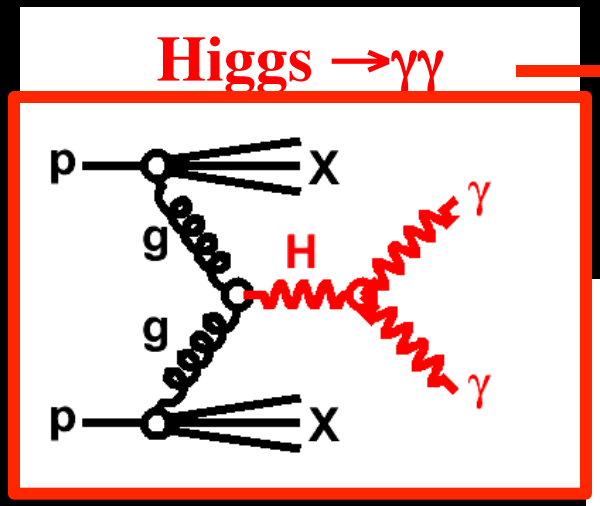
24/7
operation

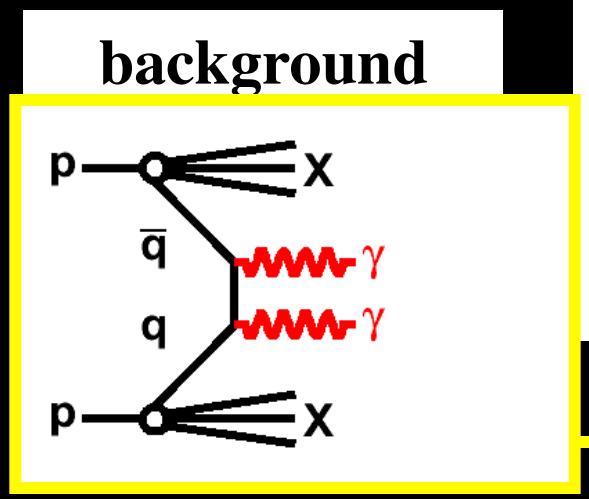


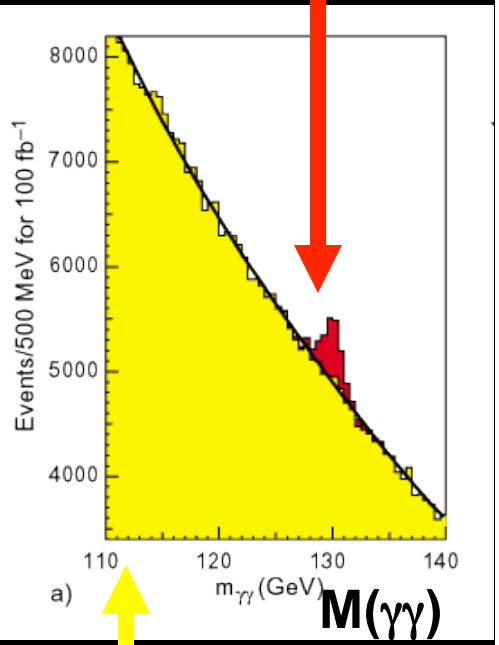
- **Delivered ”luminosity” L=5.5 fb^{-1}**
  - Number of events = Luminosity x cross section
  - Corresponds to 4x10^{20} proton-proton interactions
  - Corresponds to ~70 Higgs bosons (in diphoton decay)
    - But need to find them in all the background!

Finding the Higgs Boson (with photons)

- Higgs boson decays to two high energy photons
  - Higgs mass can be determined from energies and directions of photons
- Background process looks identical
  - 50 times larger at given mass

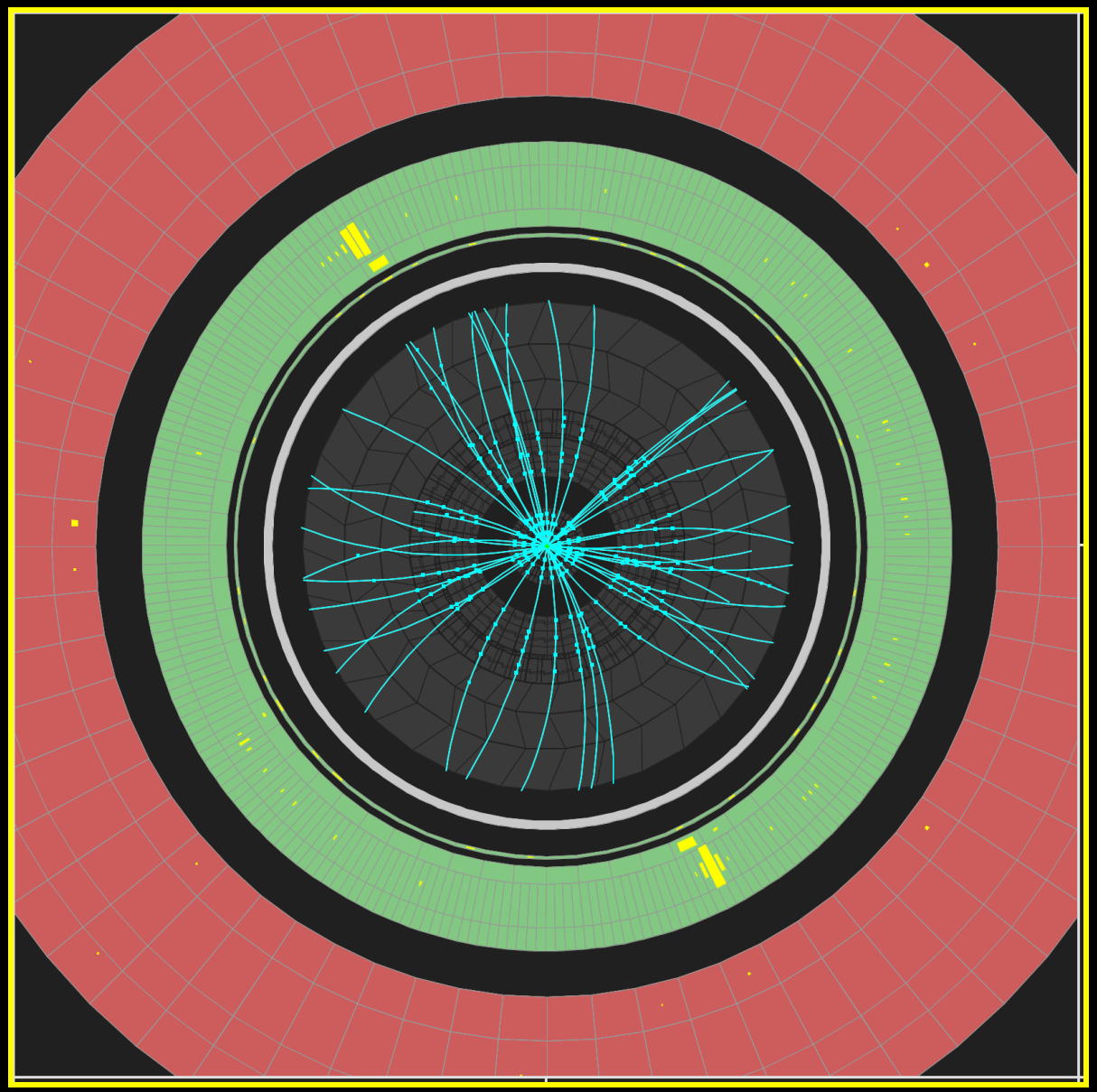


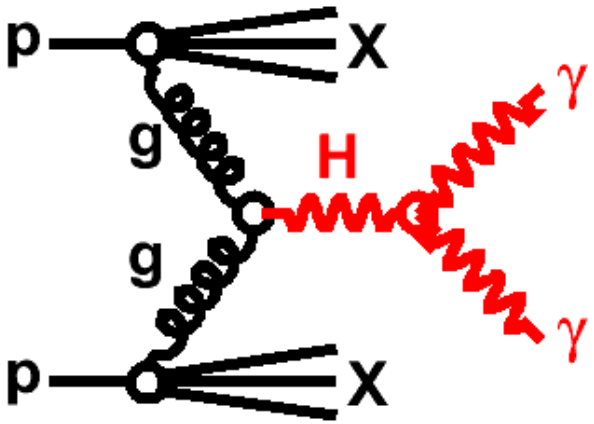




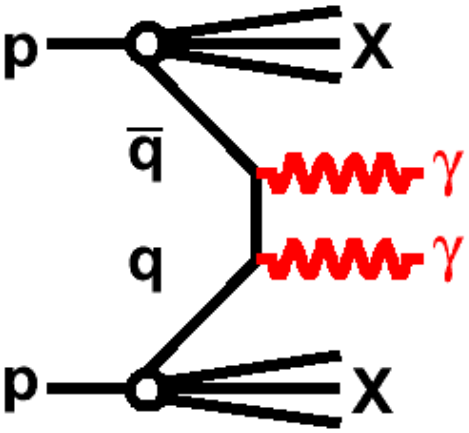
$$M_{Higgs}=M(\gamma\gamma)=\sqrt{[(E_1+E_2)^2-(p_1+p_2)^2]}$$

A Higgs Boson Candidate Event



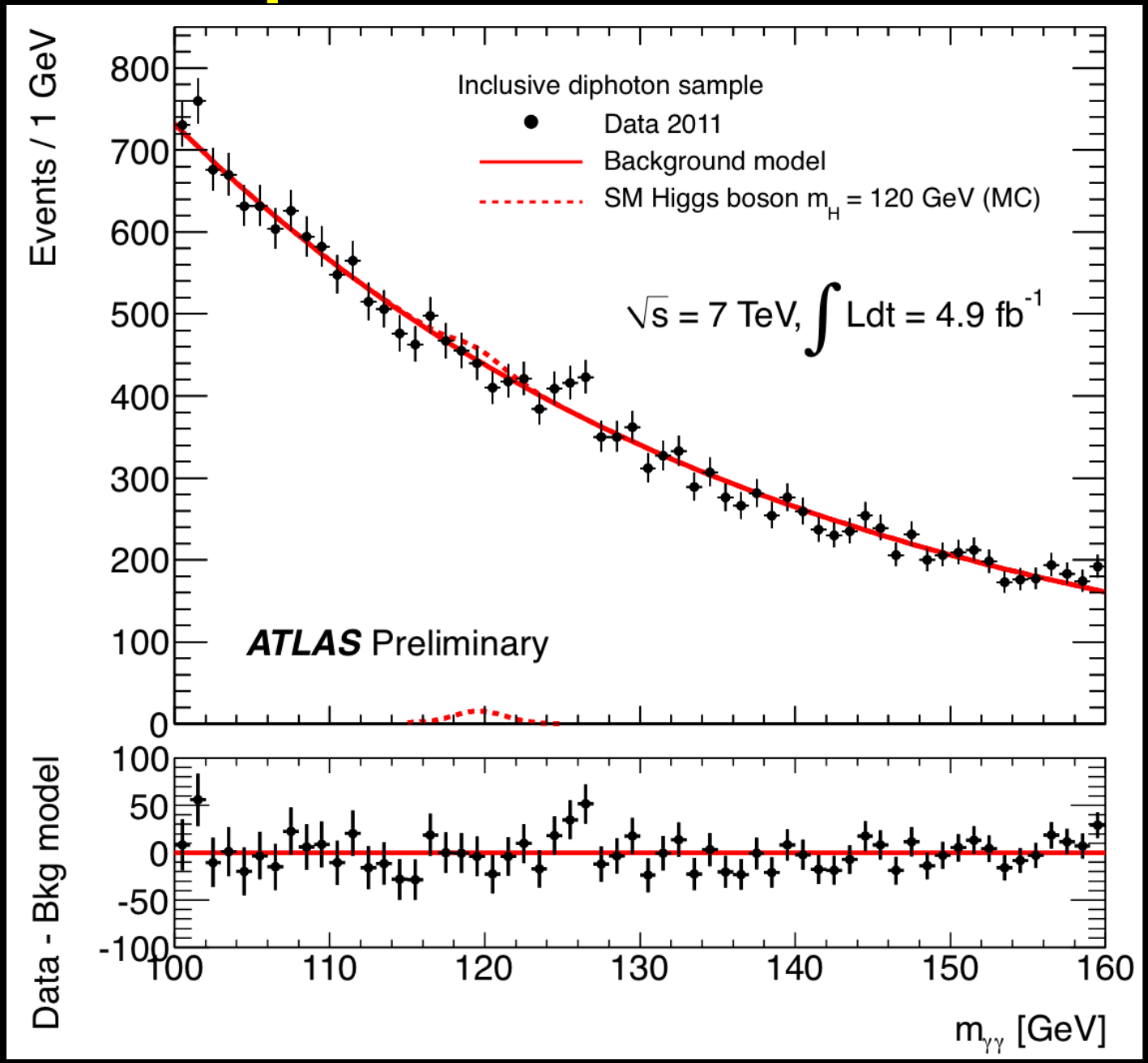


or

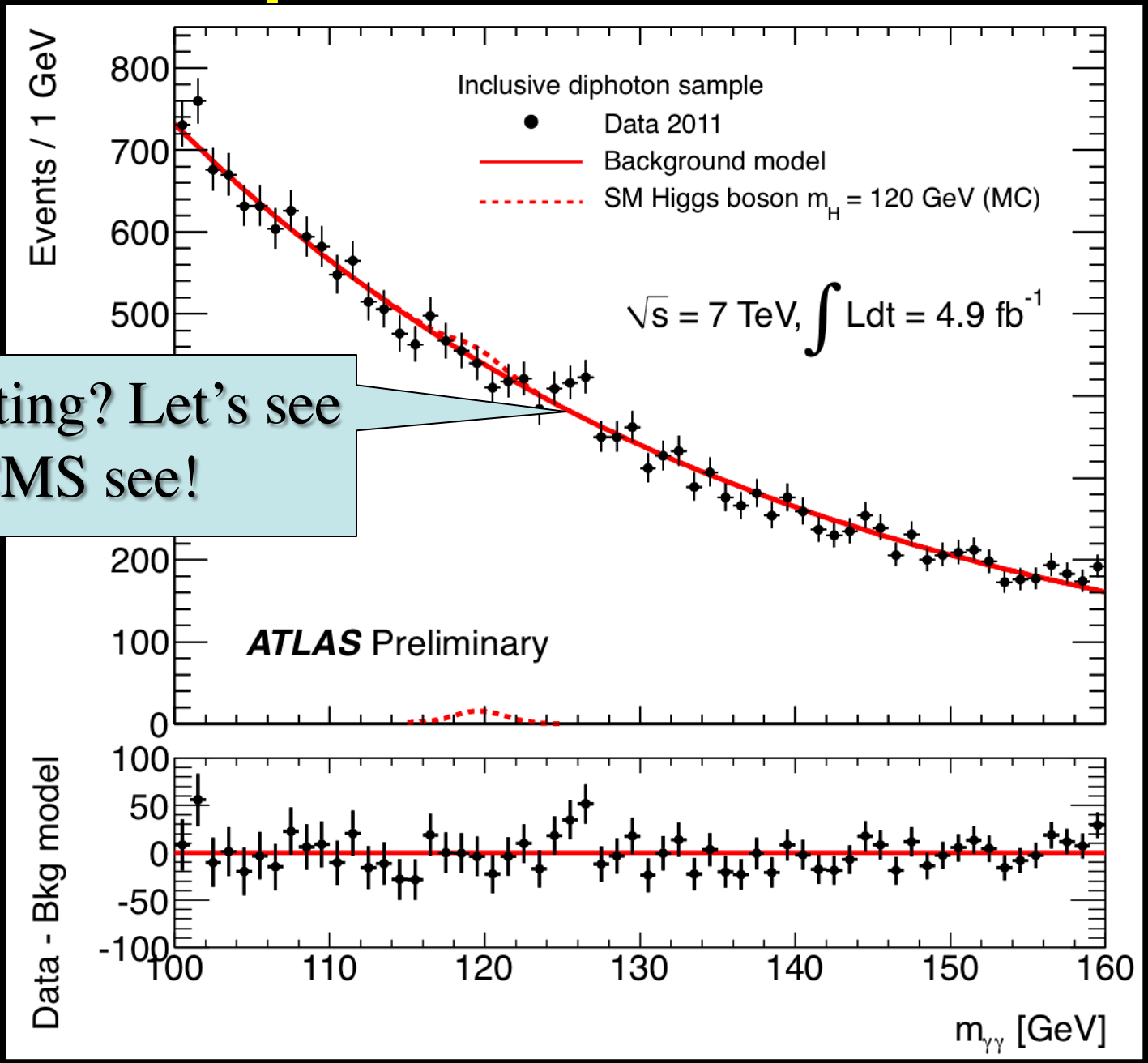


?

ATLAS Diphoton Mass Distribution

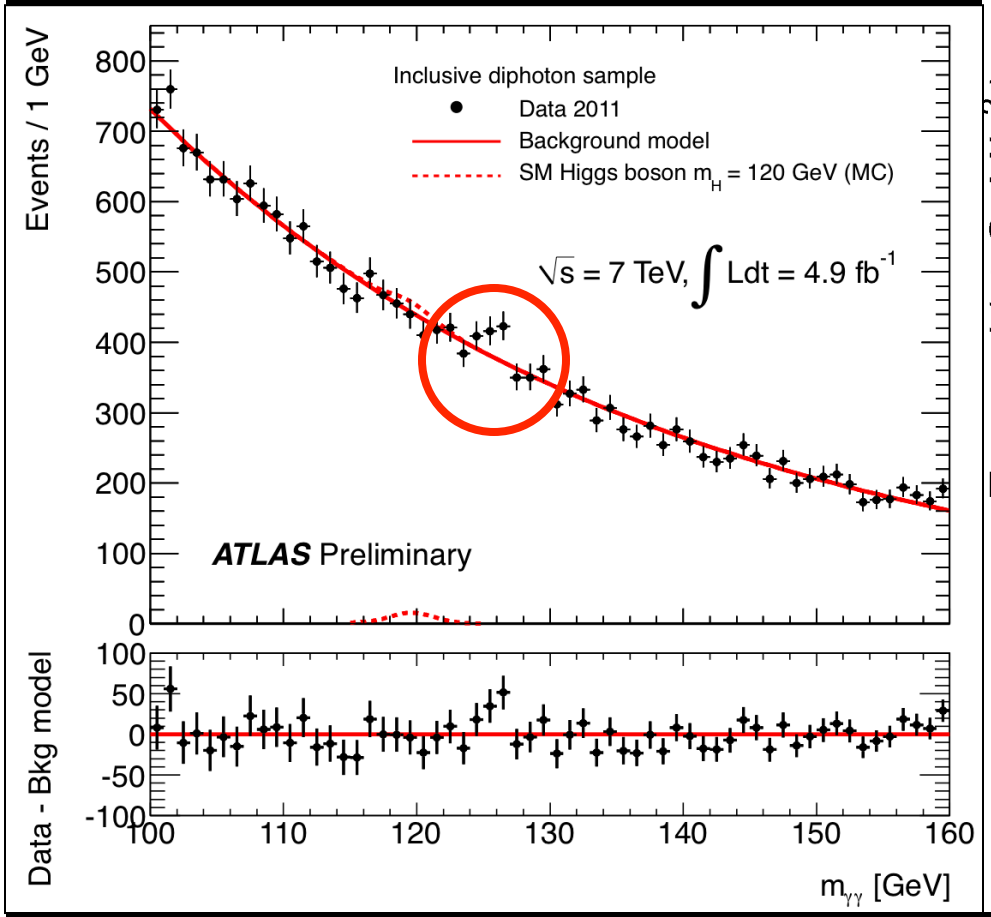


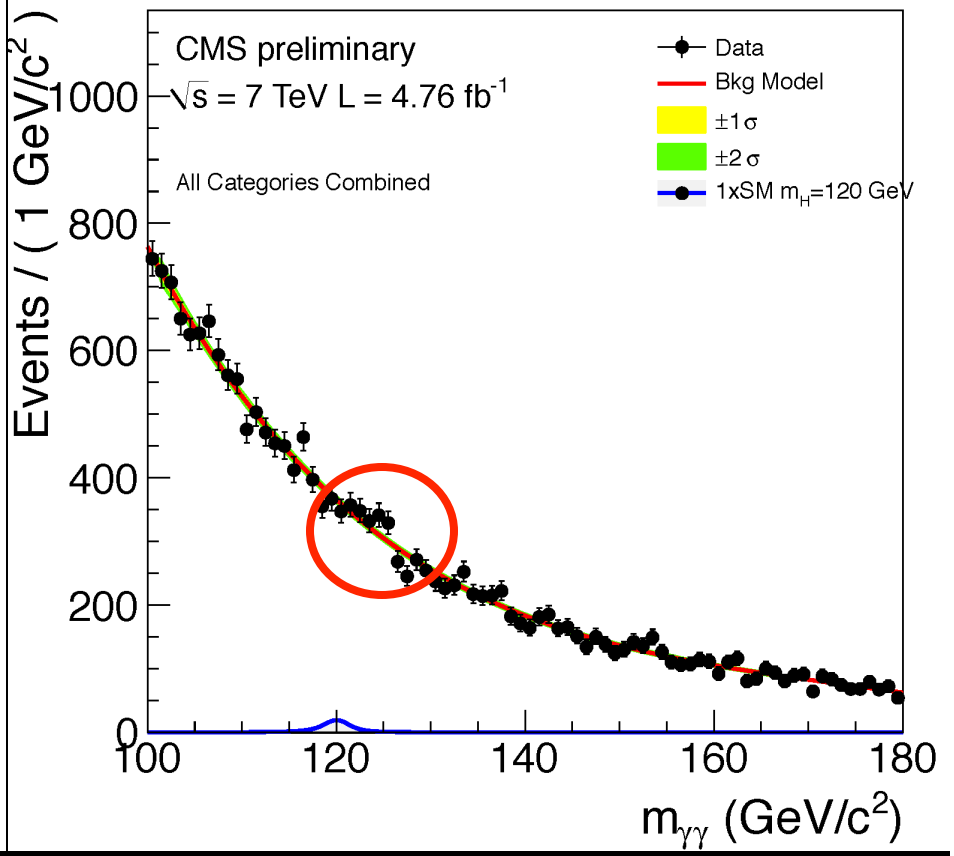
ATLAS Diphoton Mass Distribution



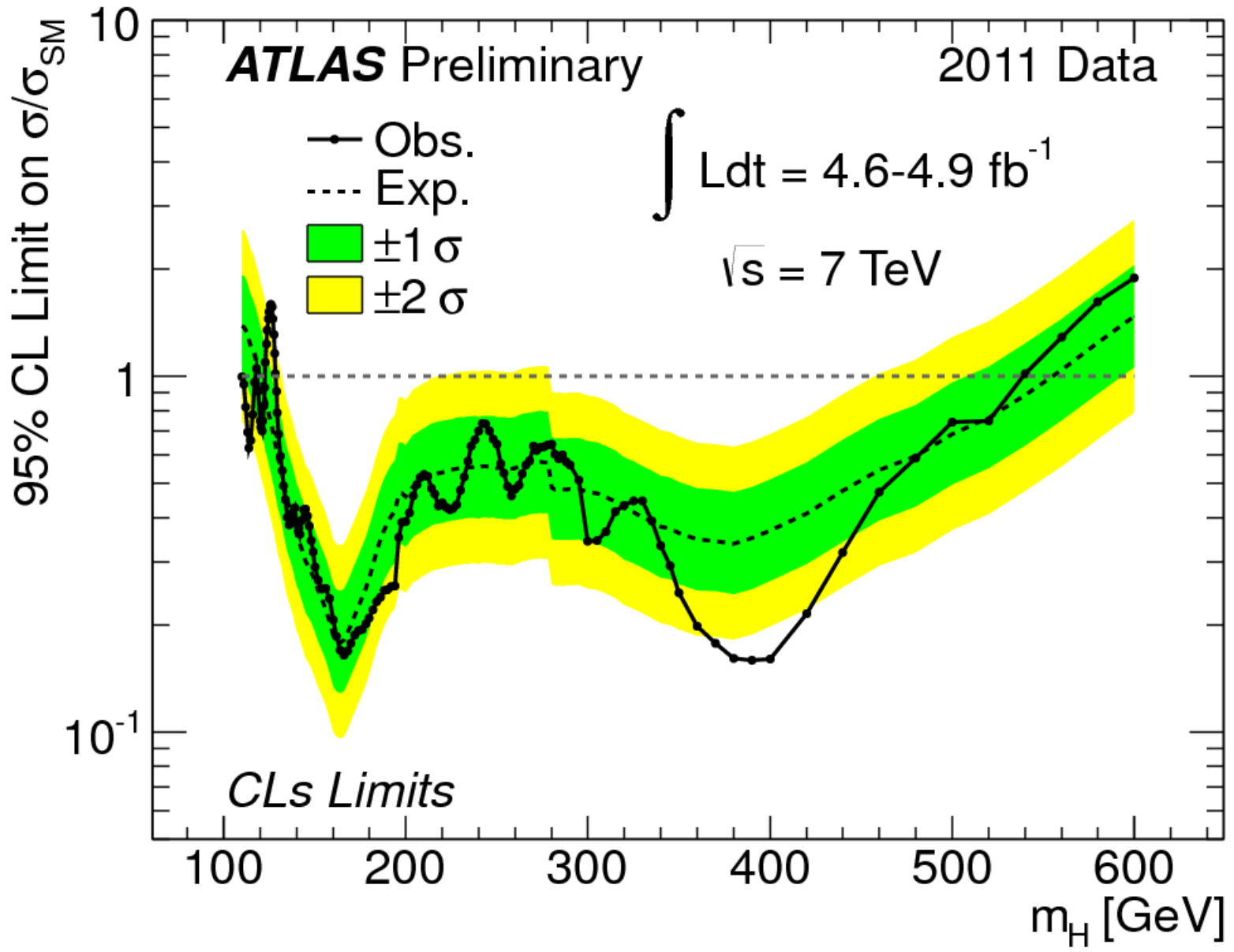
Interesting? Let's see what CMS see!

ATLAS and CMS Diphoton Mass Distributions

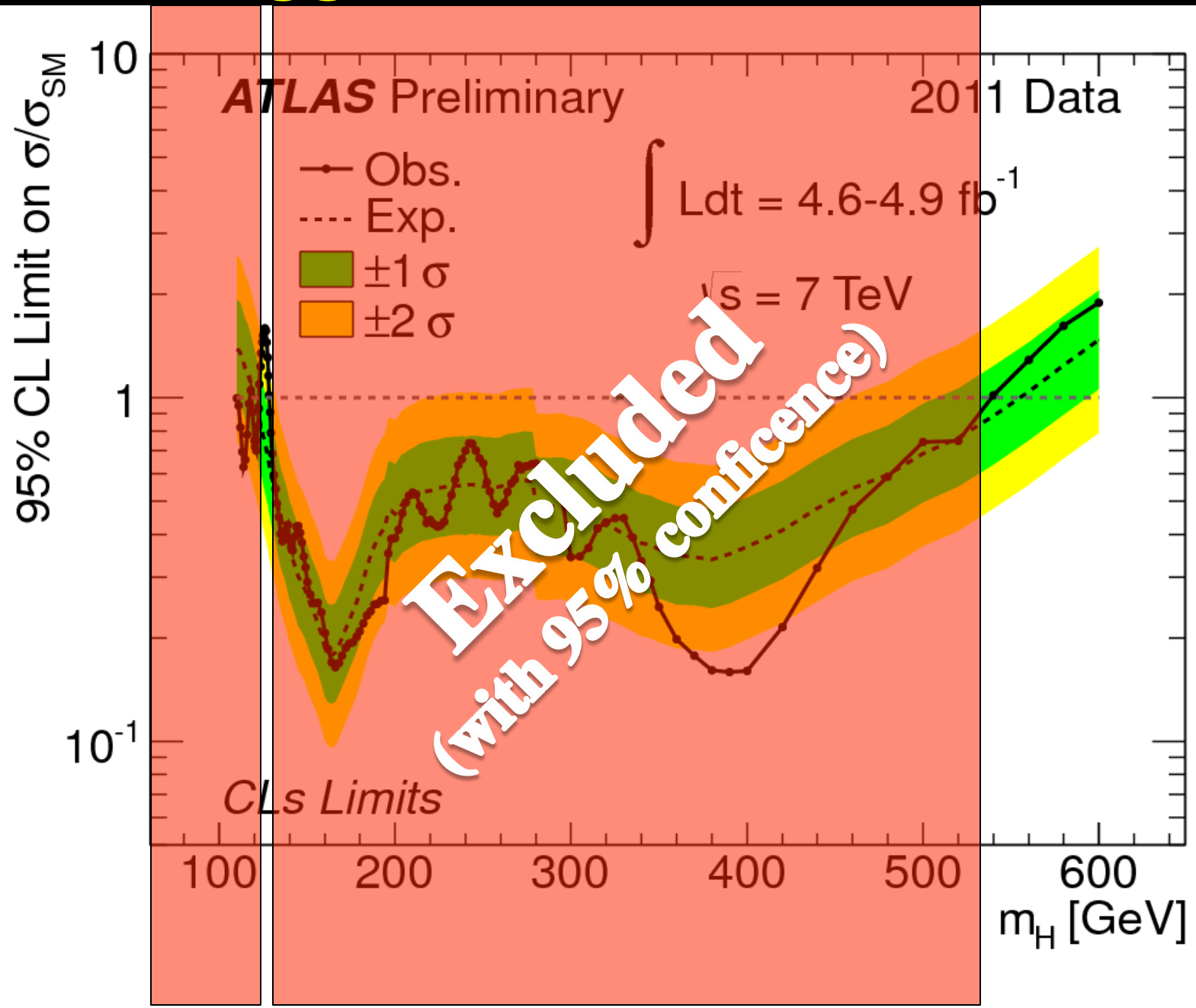




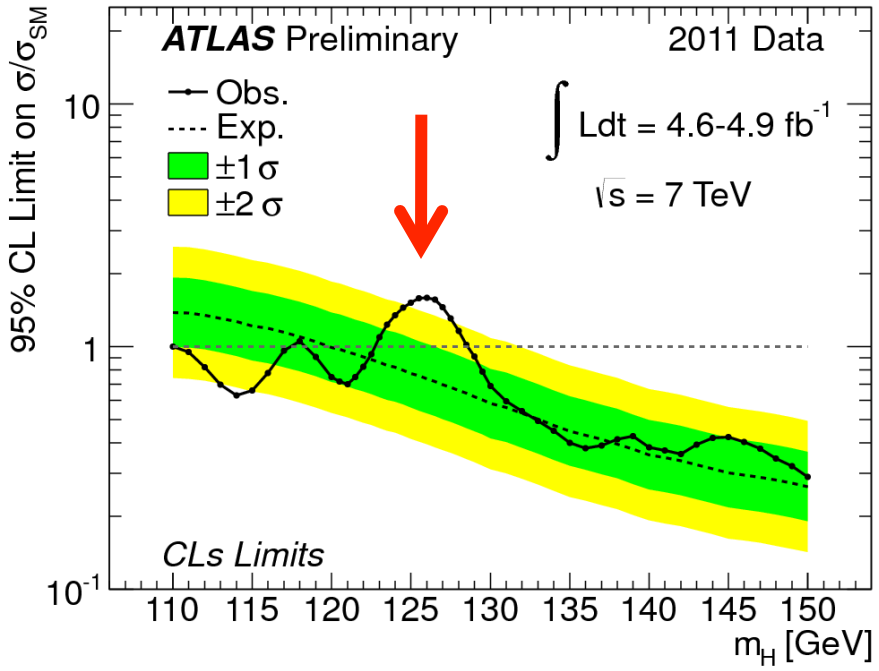
Higgs Boson Constraints

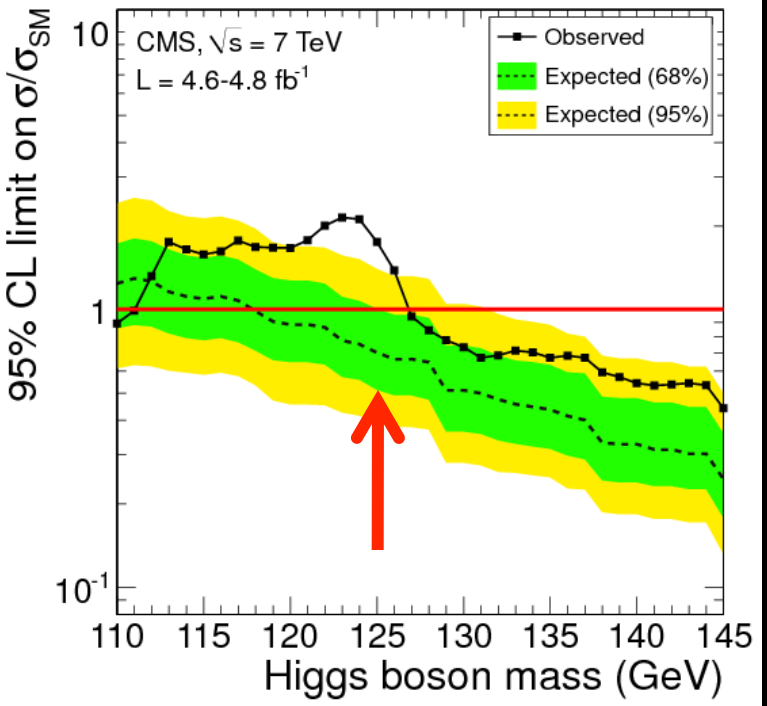


Higgs Boson Constraints



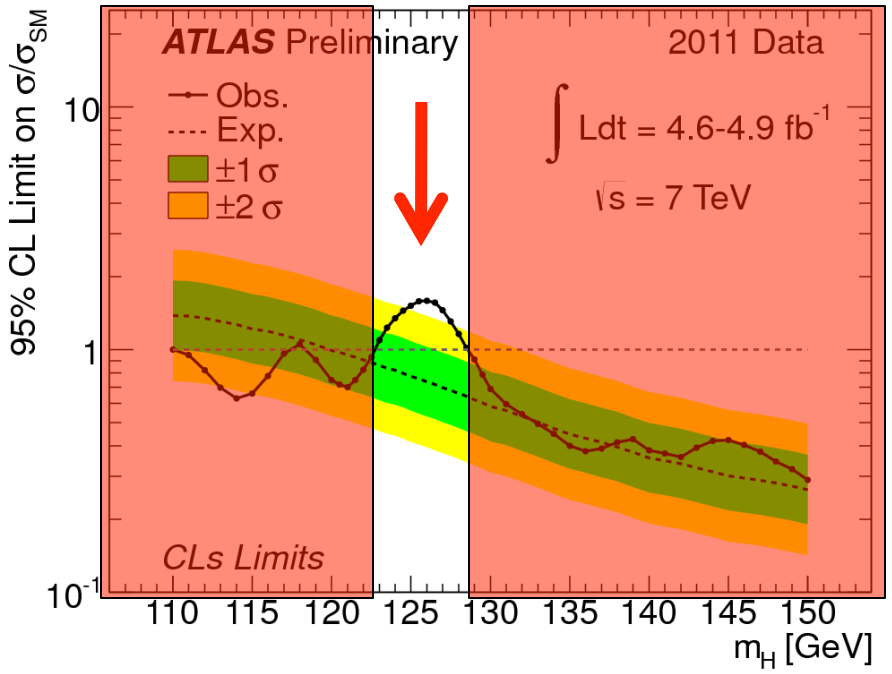
Zoom into remaining allowed range

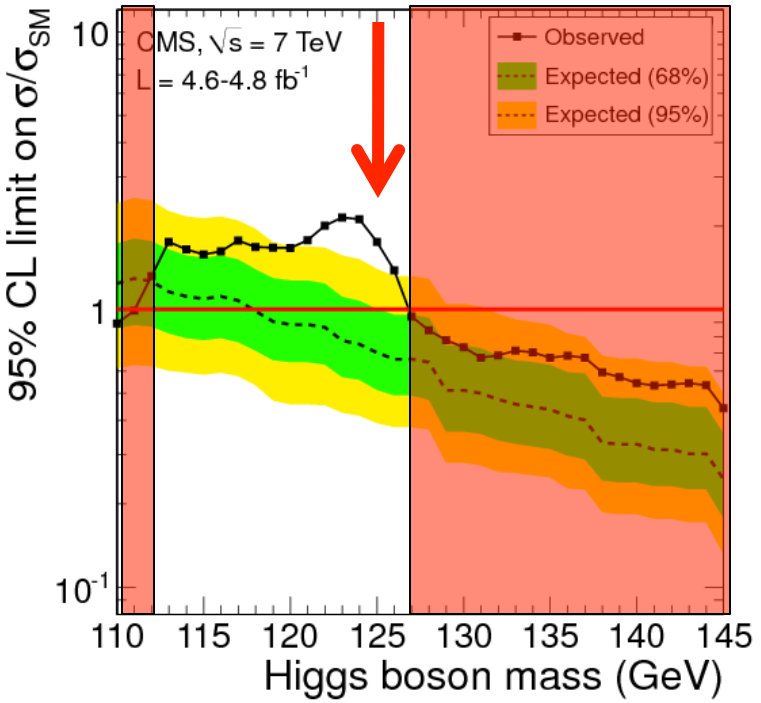




- Both experiments see more events than expected from background at ~125 GeV
  - This could be the first hint for the Higgs boson
  - But only more data can tell if this is it!
- Remaining allowed range is 122.5-129 GeV

Zoom into remaining allowed range





- Both experiments see more events than expected from background at ~125 GeV
  - This could be the first hint for the Higgs boson
  - But only more data can tell if this is it!
- Remaining allowed range is 122.5-127 GeV

Conclusions and Outlook

- After a more than 20 year design and construction phase the LHC experiments are taking data and produce exciting scientific results
  - Largest scientific experiments ever built
  - 6000 scientists work on analyzing LHC data: ~25% from US
  - UC Berkeley and Lawrence Berkeley National Lab playing major roles

- Higgs mechanism and particle was first invented in 1964
  - Most likely mass value now is 125 x proton mass
    - But “excess” could still be a “fluke” (statistical fluctuation) with a few % probability
  - At the end of 2012 we will have 4 times more data and then can tell if the Higgs boson exists (in it’s most simple form)

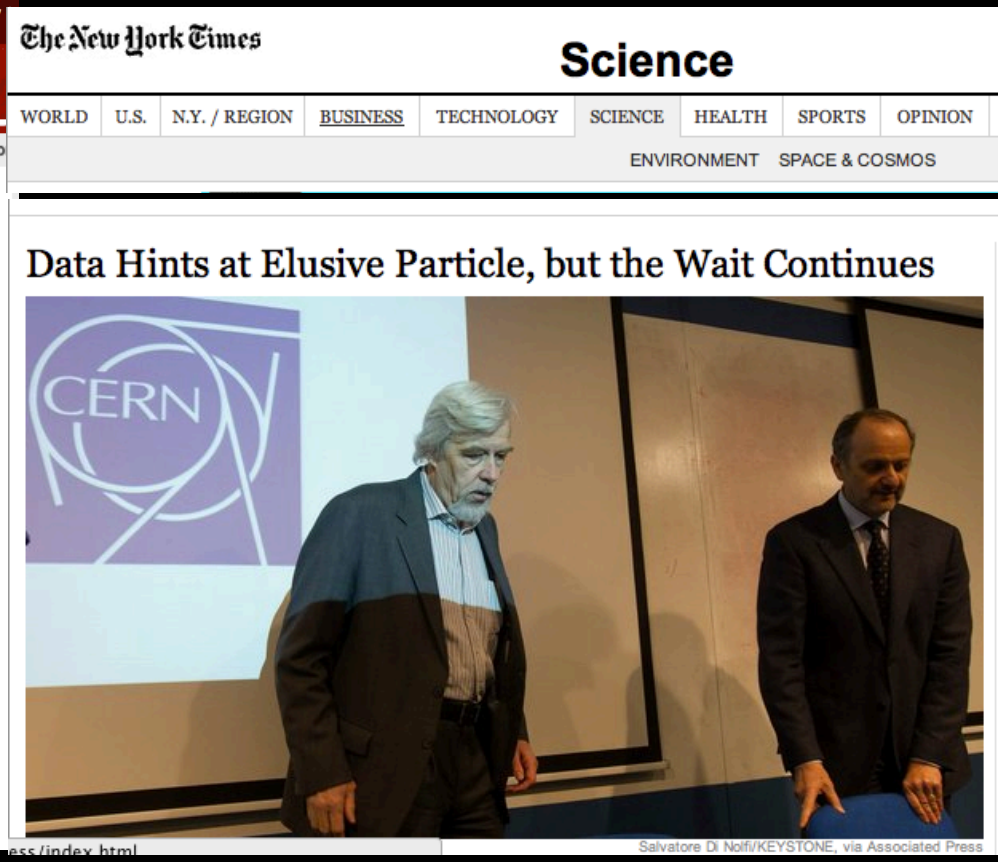
- Many other important studies and searches ongoing
  - E.g. searches for Dark Matter, extra spacial dimensions, new types of quarks, more Higgs bosons, …
  - See http://public.web.cern.ch, http://atlas.ch and http://cmsinfo.cern.ch/outreach/ for explanations, articles, movies, images, …

Thank you for your interest and attention!

Backup Slides

Many Other Possibilities at the LHC …

News Stories: what are they about??



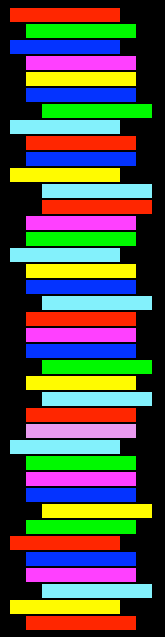
- Mid December many news stories appeared about the elusive Higgs boson
  - aka the “God Particle” (Leon Lederman)
- Will try to explain what this is all about

LHC milestones

- March 2007: last dipole magnet installed
- September 2008: first beam but major accident prevents LHC startup in 2008
- Nov. 2009: first collisions at injection energy (900 GeV)
- March 2010: first collisions at 7 TeV
  - 3.5 time higher energy than Tevatron
- End of 2010: L=40 pb^{-1} of data recorded
  - Sufficient to make many tests of Standard Model and to test supersymmetry beyond Tevatron
  - Not enough to test the Higgs
- End of 2011: L=5 fb^{-1} of data recorded
  - nearly 100 times more than 2010
  - Sufficient to probe Higgs boson over much of the mass range

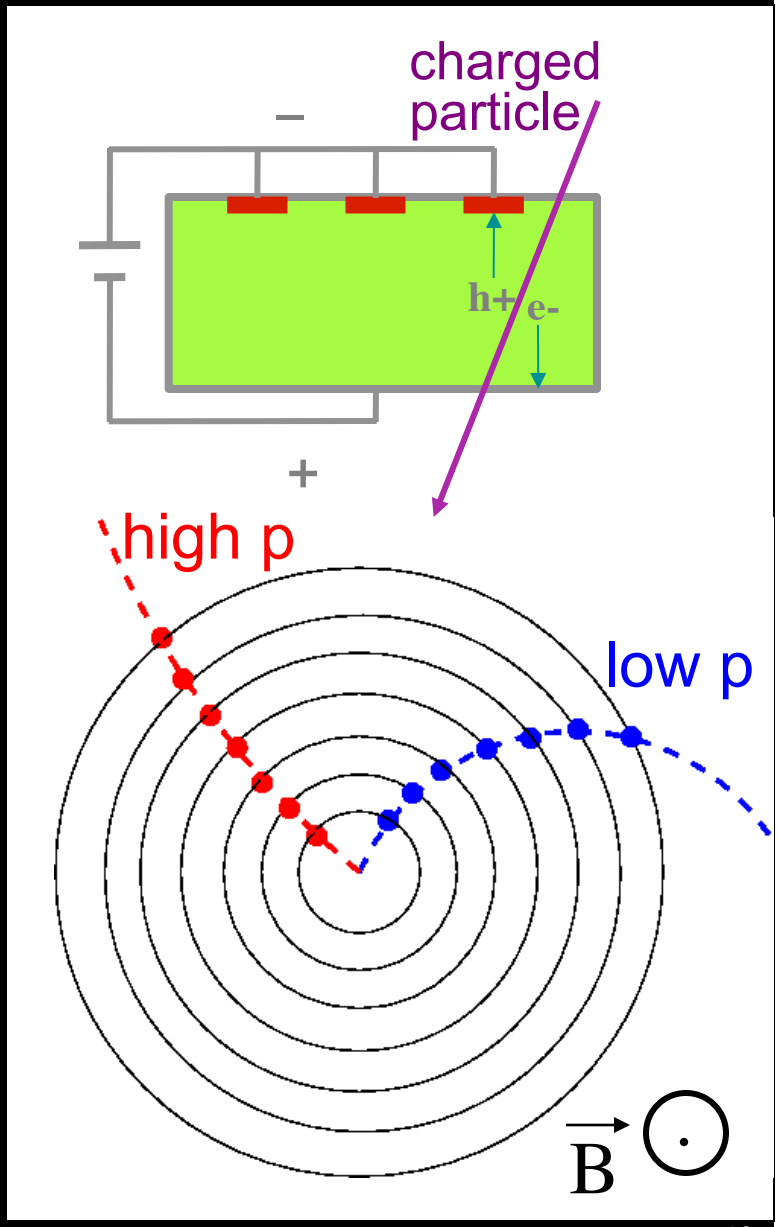
Enormous Data Volumes

- **Pushing the computing limits!**
  - 1 second of LHC data: 1000 GigaBytes
    - **10,000 sets of the Encyclopedia Britannica**
  - 1 year of of LHC data: 10,000,000 GB
    - **25 km tower of CD's (~2 x earth diameter)**
  - 10 years of LHC data:
    - **All the words spoken by humankind since its appearance on earth**
- **Solution: the "Grid"**
  - Global distribution of CPU power
    - More than 100 CPU farms worldwide share computing power
    - Arranged in clouds

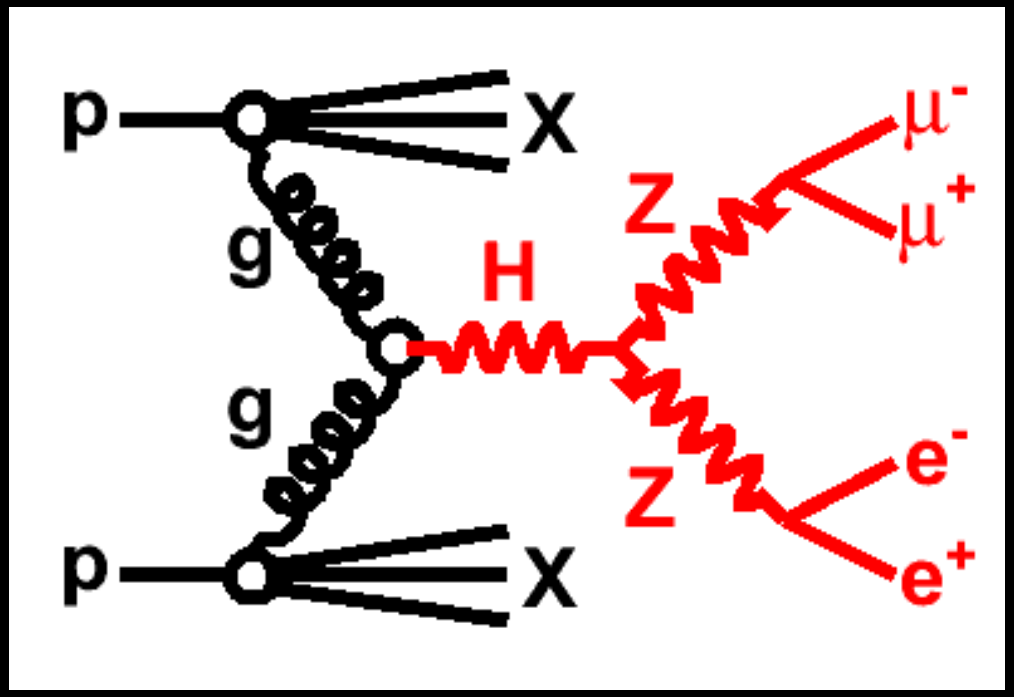


Silicon Tracking Detectors

- Charged particle traverses gas or silicon
  - Sets free electrons
    - Measured charge gets collected at electrodes
  - Thus we find out position of particle
    - Resolution typically 15 μm
- Detector placed inside magnetic field:
  - Lorentz force: $\mathbf{F}_L \sim q\,\mathbf{v} \times \mathbf{B}$
- Hits along trajectory are fit to form a track
  - deviation from straight line proportional to momentum (**p~v**)
  - Direction of curvature tells us the electric charge



Higgs decaying to two Z bosons



Proceedings of LHC Workshop (Aachen, 1990): H→ 4l signals
m_H=130, 150, 170 GeV
√s = 16 TeV, 100 fb^{-1}

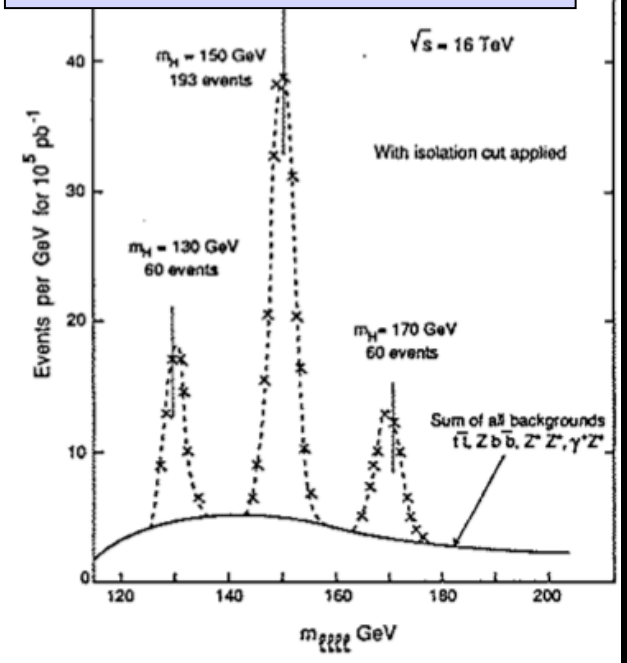
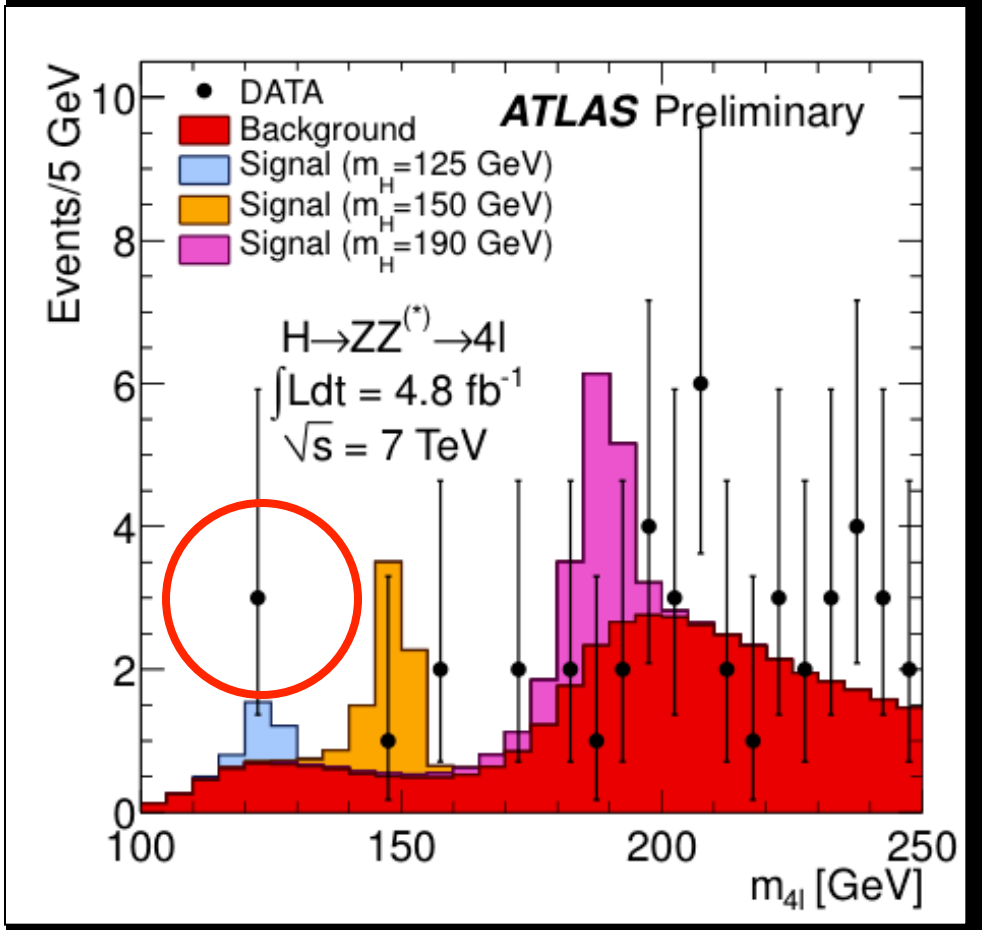
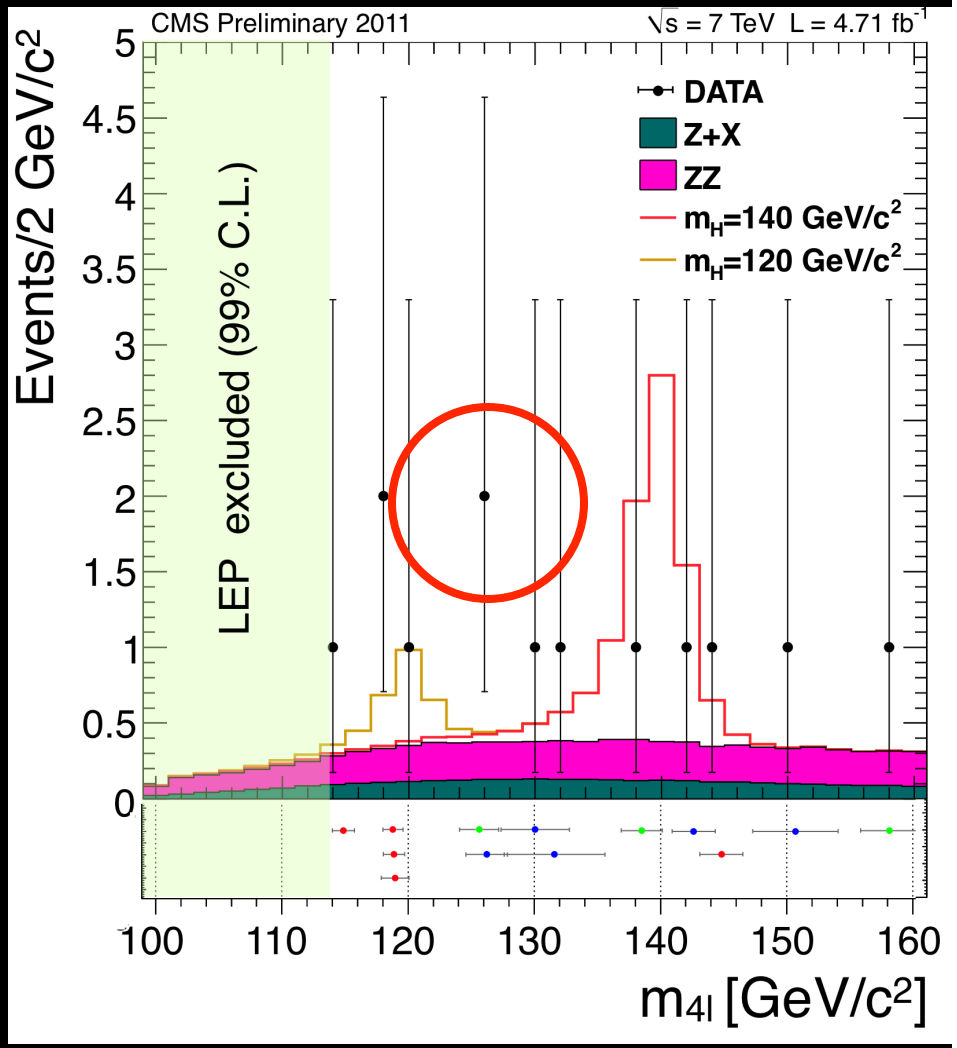


Fig. 10

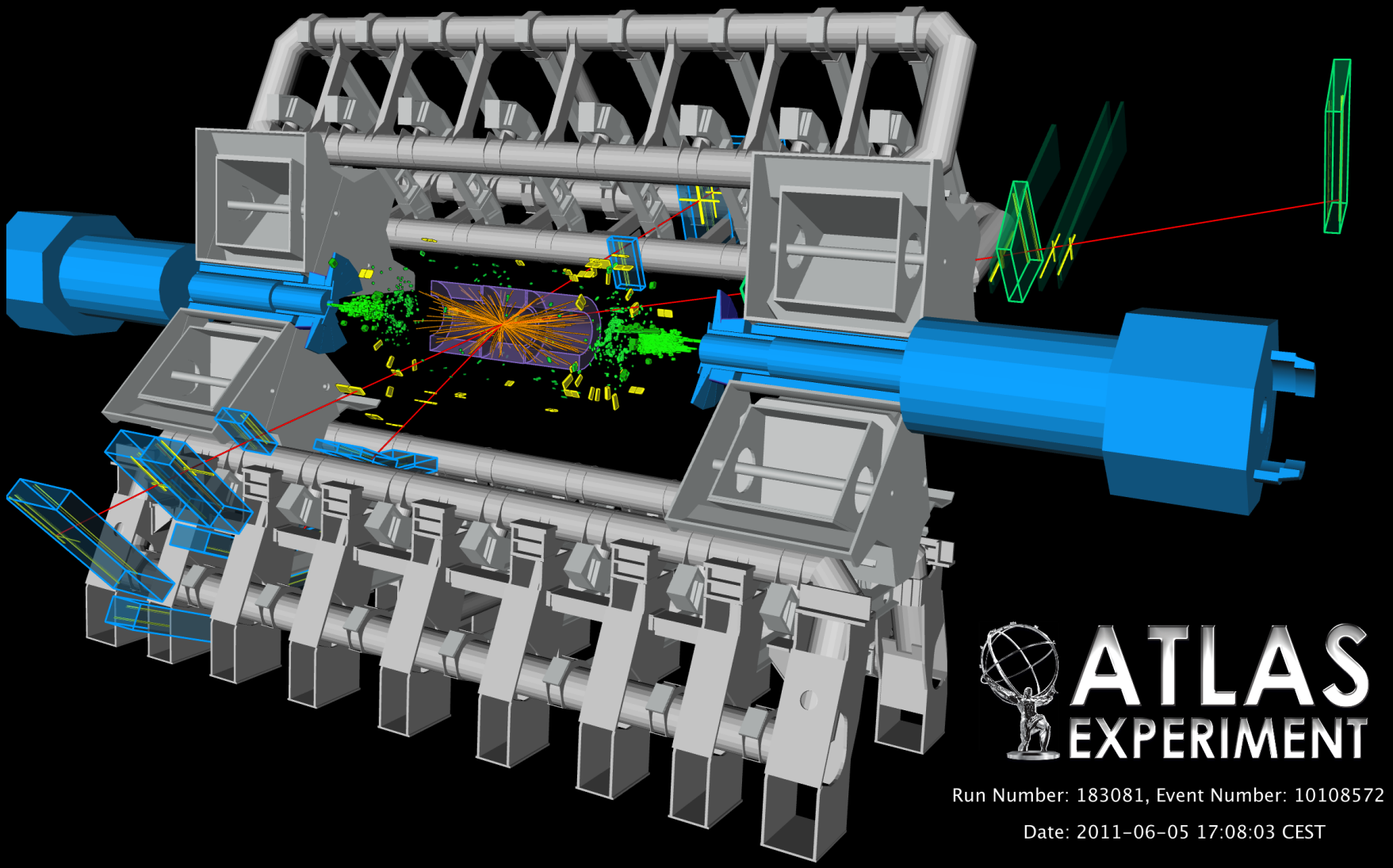
- Expect about 2.5 events in current dataset
- Number of background events about 1.7

4 lepton Mass Spectrum





Another Higgs Boson Candidate Event



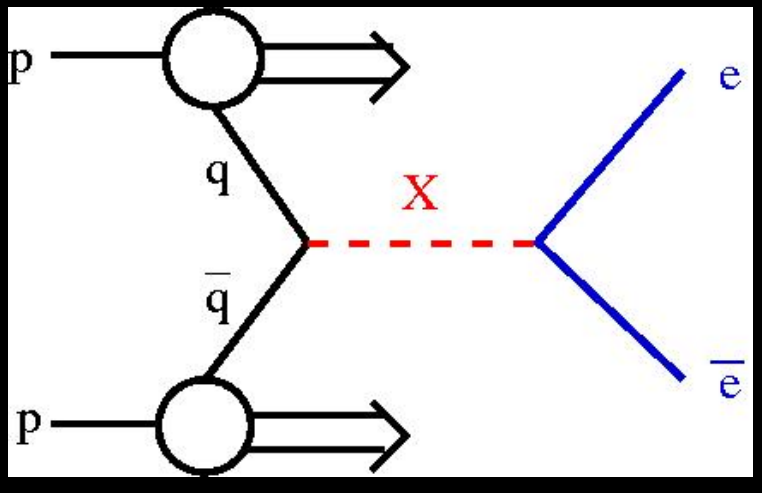
Units and Numbers

- Mass is measured in electronVolt/c^2 where c = speed of light
  - *1 eV/c^2 = 1.8 x 10^{-36} kg*
  - *m_{proton} = 1 GeV/c^2 = 2 x10^{-27} kg*

We will mostly use the unit “GeV”= Gigaelectronvolt = proton mass

Energy and mass are equivalent: $E=mc^2$

- Einstein's famous formula: **$E=mc^2$**
  - c = speed of light, m = particle mass, E = particle energy
- Collide 2 protons with E=3,500 GeV
  - Total energy: E=7,000 GeV
  - Can create particle X with mass $m_X < 7{,}000\ GeV/c^2$
  - Most particles we create live only for a very short fraction of a second and then decay, e.g.X decays to electron and anti-electron



A real LHC Z boson Event