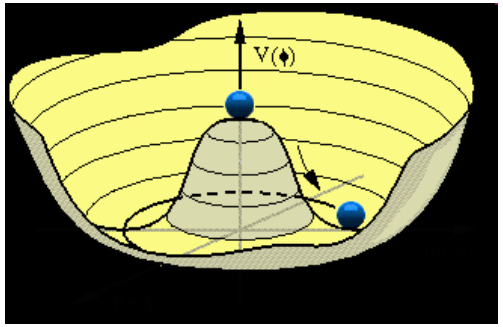
The Long Search for the Higgs

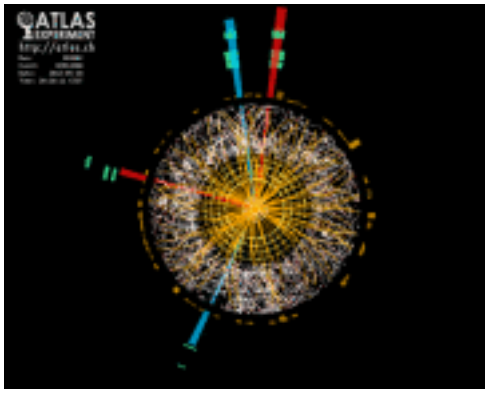
A Higgs-like particle…..

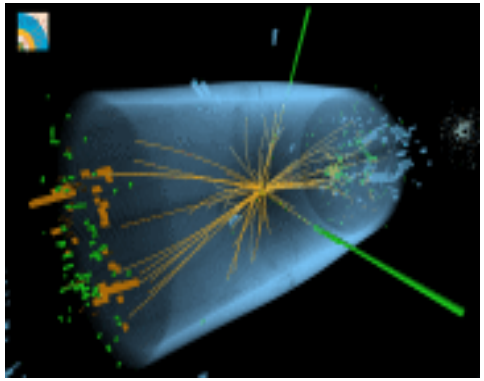
What is it and why should you care?



S. Dawson, BNL

Jan. 21, 2013





New York Times, July 5, 2012

Physicists Find Elusive Particle Seen as Key to Universe

POOL PHOTO BY DENIS BALIBOUSE

Scientists in Geneva on Wednesday applauded the discovery of a subatomic particle that looks like the Higgs boson.

History in the making

A Higgs particle predicted in 1964

Peter Higgs in the LHC tunnel in 2012

A Long Journey

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

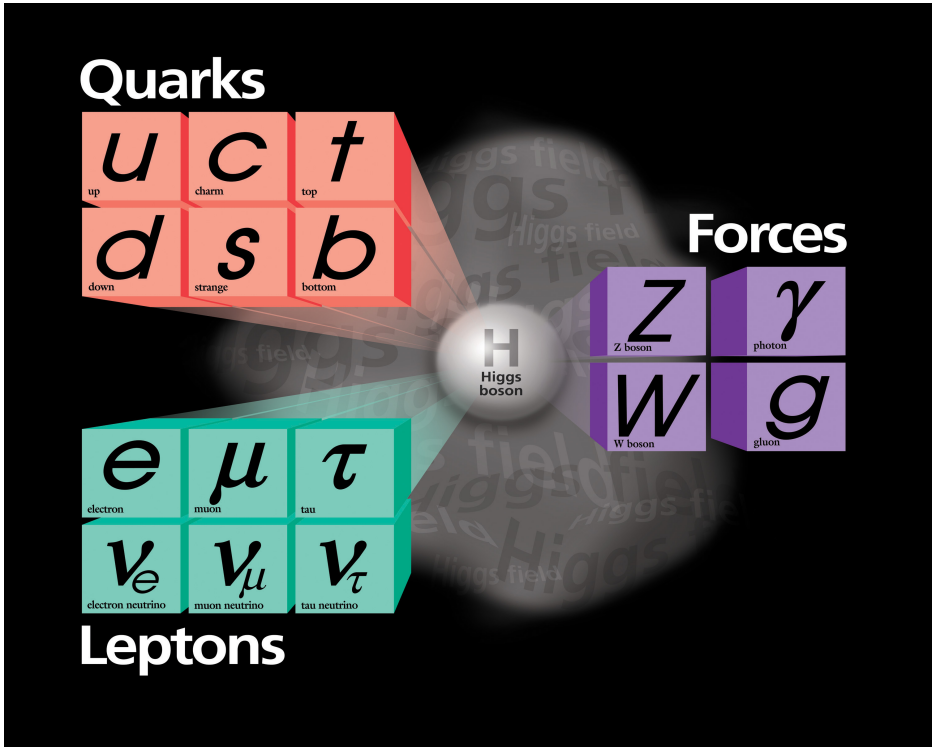
G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

Higgs particle solves many problems

- Symmetry:
  - Why do particles have different masses?
  - Why do particles have mass at all?
- An essential part of the theory
  - Without it the theory doesn't make sense
  - Without the Higgs you can't make predictions

Standard Model

- Particle physics has a "Standard Model" of particles and their interactions



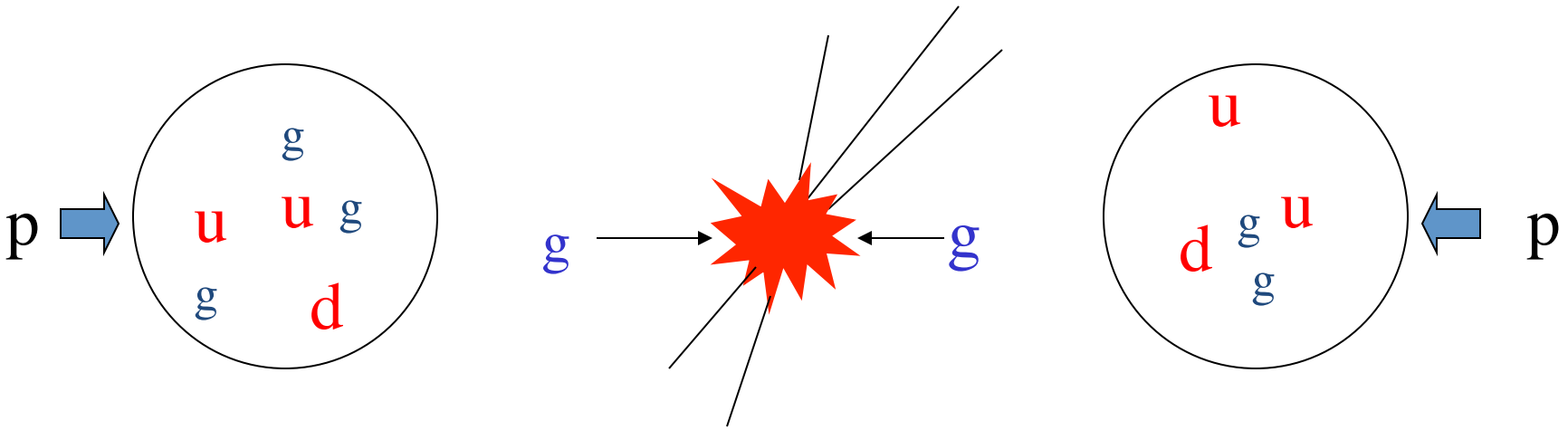
Point-like particles

Force carriers communicate between particles

The Higgs particle completes the Standard Model

The particles

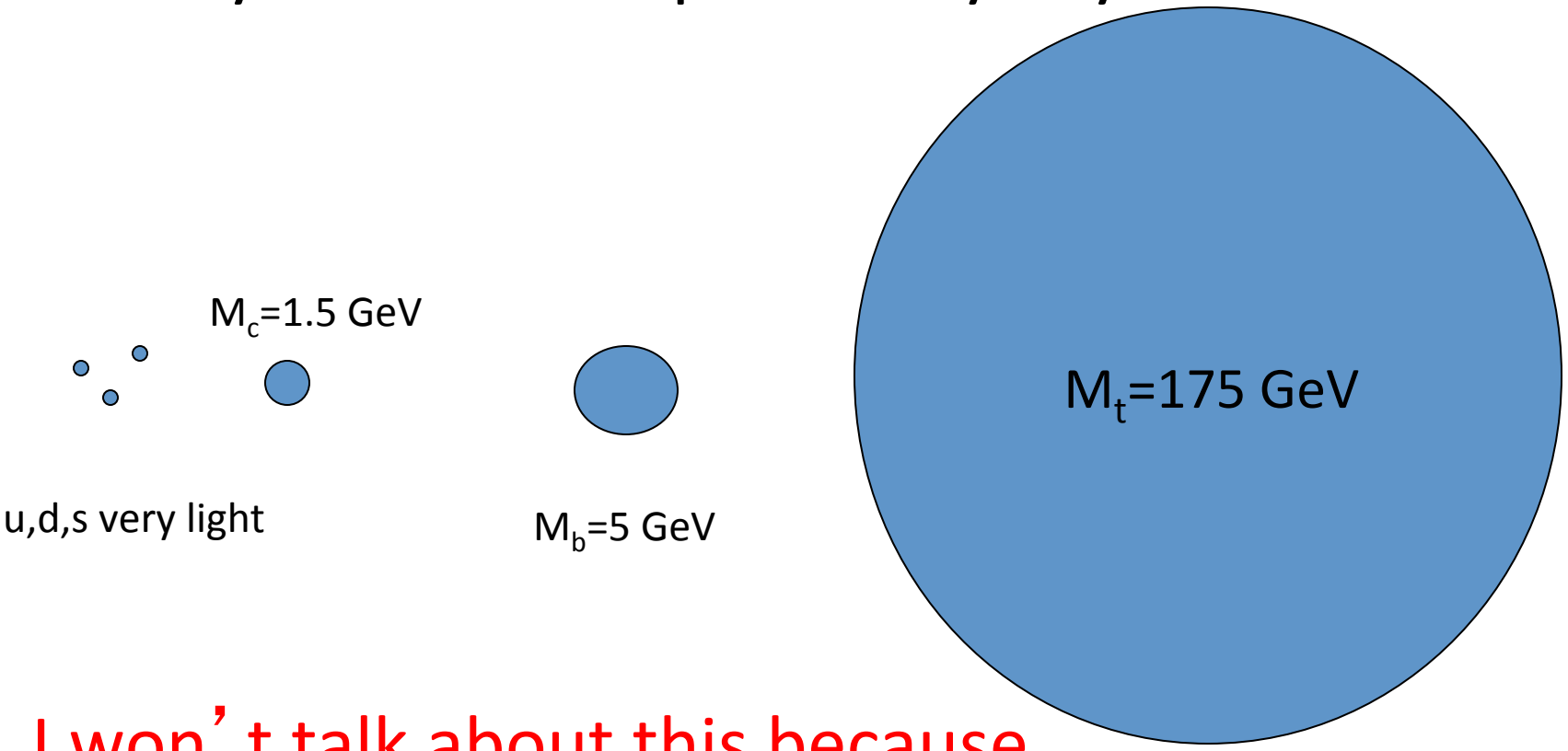
- Leptons (e, μ, τ,ν) and quarks are point-like
- No free quarks
- Proton p = uud + (infinite number of $q\bar{q}$ pairs and gluons)



Typical interaction energy at LHC ~ 1 TeV

Particles have very different masses

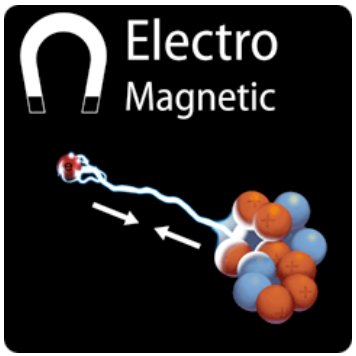
- Why are there 6 quarks anyways?

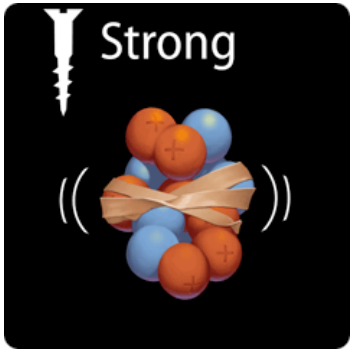


I won't talk about this because nobody has any good ideas

Understanding Forces

- Electromagnetism explains electricity and magnetism
- Weak force explains radioactivity
- Strong force explains why quarks are bound in protons
- Gravity seems simple…..





Forces associated with particles

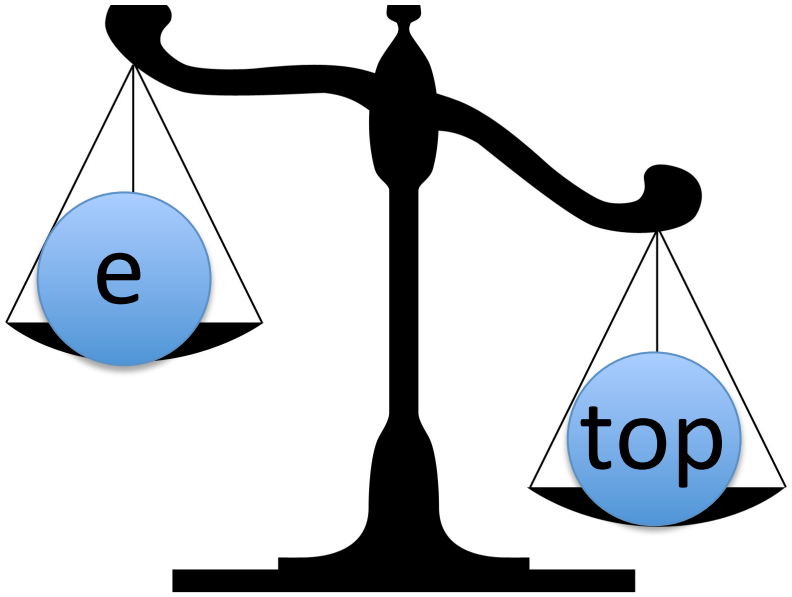
- Force carriers: gluon, W and Z bosons, photon
- Gluon and photon are massless
- W and Z are very heavy…..***WHY?????***
- We say that the symmetry is broken

The Higgs boson was invented to explain why the W and Z boson are heavy

What is this thing?????

- A particle (The Higgs boson)
  - All of its properties except for its mass are predicted
  - It is a real particle which we can study
- A field (The Higgs field)
  - When other particles (like the W and Z bosons) interact with the Higgs field they become massive

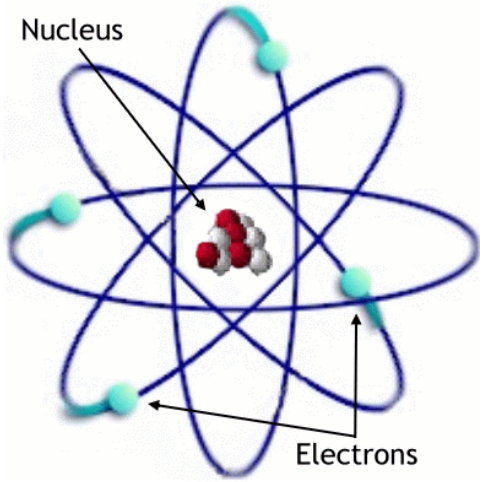
Masses for particles



- The more a particle interacts with the Higgs boson, the heavier it is
- Higgs particle explains quark and electron masses

If there were no Higgs Boson

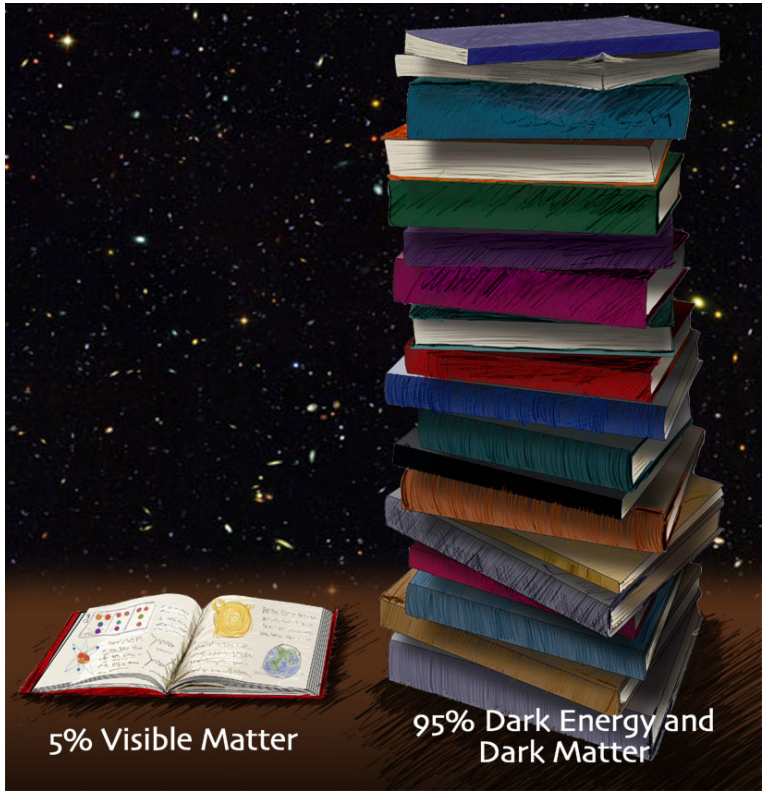
- Higgs boson explains why electron has mass
- Radius of nuclei depend on electron mass



Radius is proportional to 1/mass(electron)

- Atoms wouldn't form without the Higgs boson!

Explaining Mass

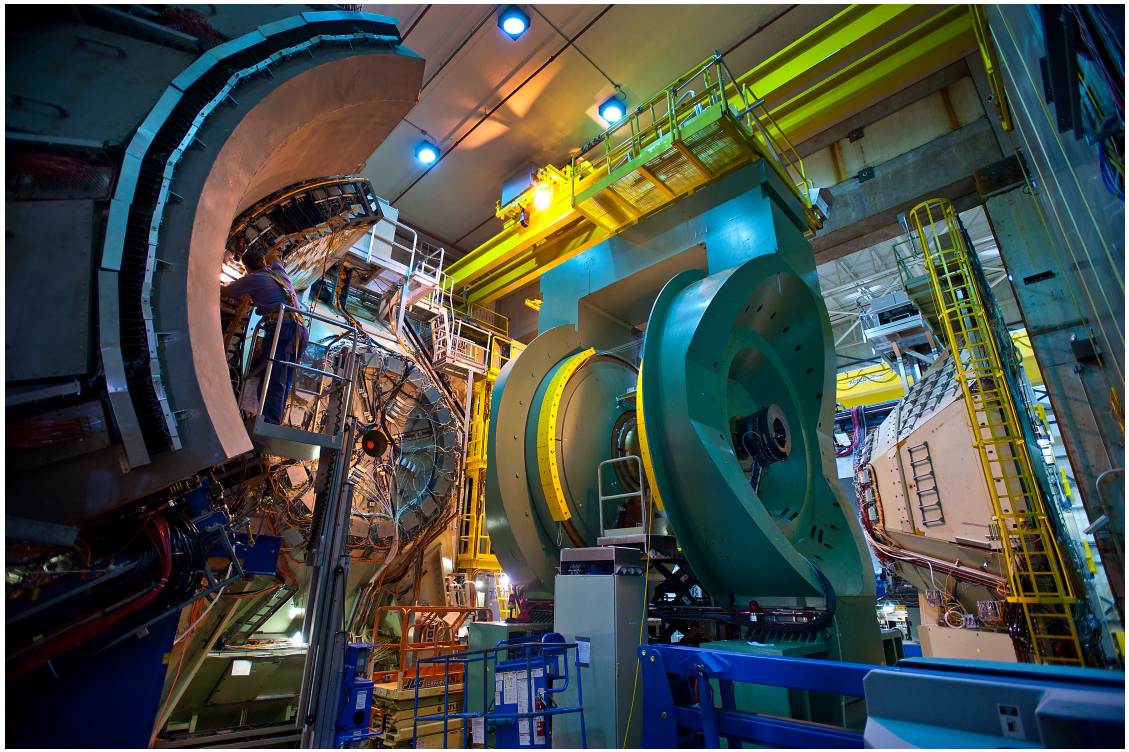


95% of the mass of the universe is dark matter and dark energy which is not explained by the Higgs boson

Explaining Mass

- Mass of a proton comes from the interactions of the gluons within the proton (not from the Higgs mechanism)

PHENIX experiment at RHIC



Why is Mass a Problem?

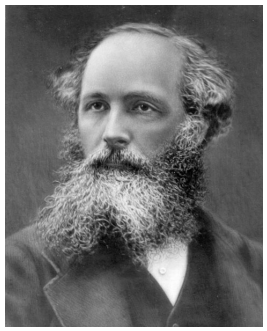
- Interactions of photon (A) unchanged if:

$$A \rightarrow A + (anything)$$

- Mass term for gauge boson

$$\frac{1}{2} M^2 A^2$$

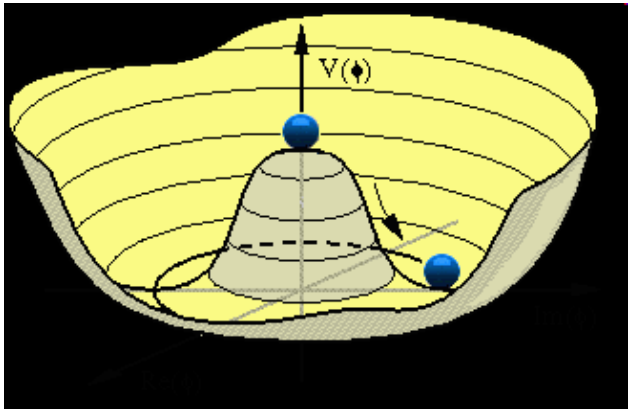
- Violates *gauge invariance*
- So we understand why photon is massless



James Maxwell, 1831-1879

Wanted

- Wanted….gauge invariant way to give mass to W and Z
- Solution is "Higgs Mechanism"
- Relies on broken symmetry of scalar field



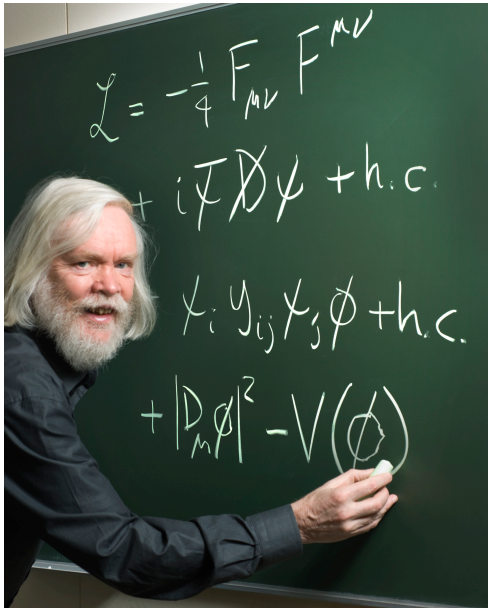
Choice of minimum breaks symmetry

What is a theory????

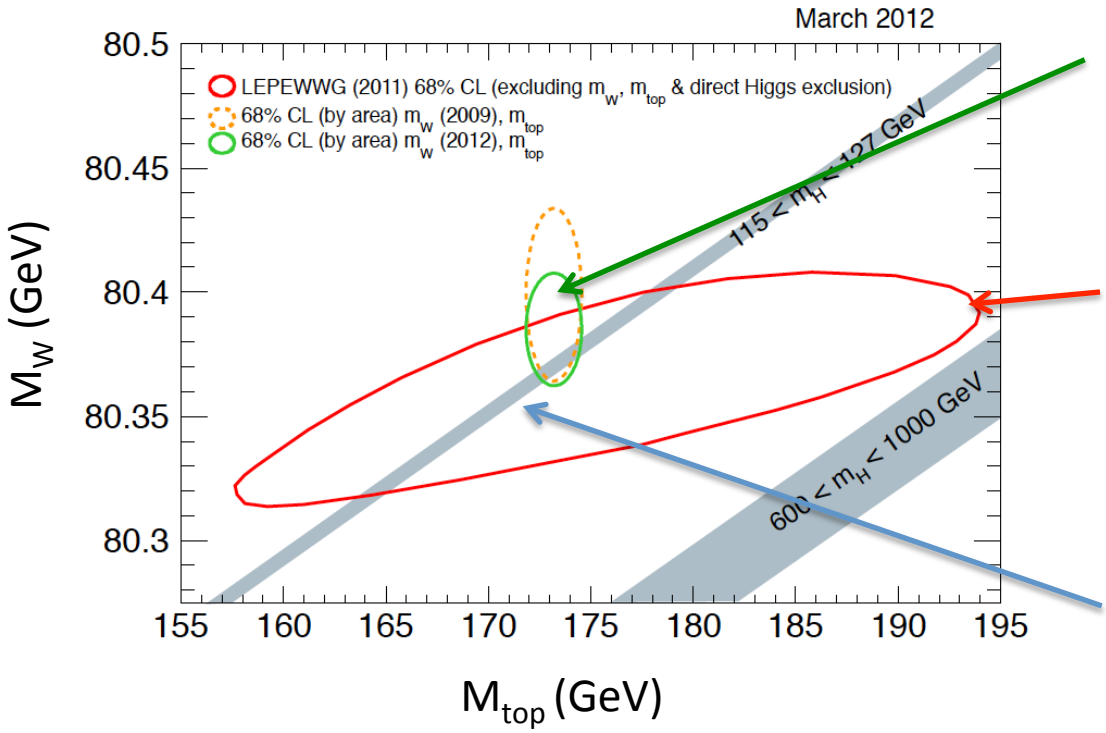
- We have the "Standard Model"
  - Calculate and make predictions
- Without something like a Higgs boson, results are infinite
- Predict: M_W=82 GeV + infinity

  OOPS!
- Better:

M_W=82 GeV + logarithm (M_{Higgs}) +….



The 6 billion dollar plot



Experimental measurements from Fermilab

Inferred values of M_W and M_t from other experiments

Theory predictions

Self-consistency of the theory told us the Higgs couldn't be too heavy

String Theory and the Higgs

- Calculate how often an accelerator will make a Higgs particle:

$$Rate = \alpha_s^2(\dots) + \alpha_s^3(\dots) + \alpha_s^4(\dots) + \dots$$

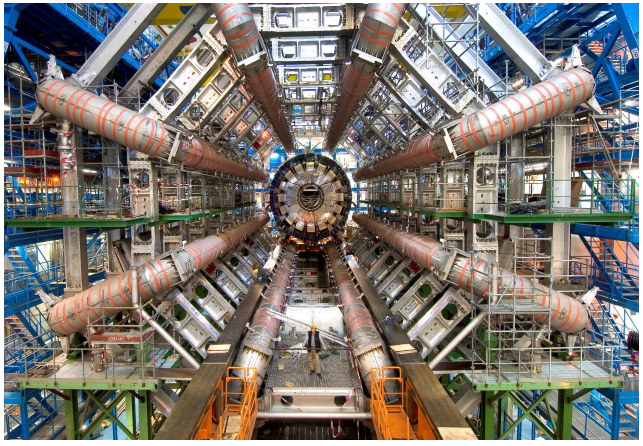
Easy **Hard**

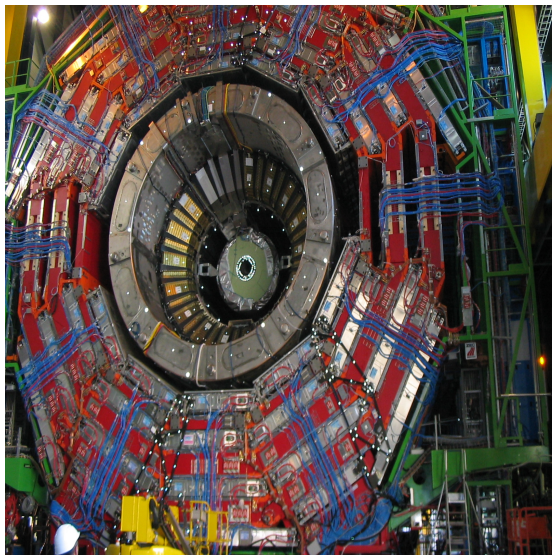
- $\alpha_s = .118$ describes gluon interactions

- Mathematical techniques from string theory allow us to calculate terms in the series that were unimaginably hard 20 years ago

How to find the Higgs

- Need the tools
  - Theory: pointing the way to look
  - Accelerator: Large Hadron Collider
  - Detectors: ATLAS and CMS





30 Years of Experiments

- If….the Standard Model with a Higgs boson is the whole story….
- We infer from many measurements:

$$\mathbf{M_H < 145\ GeV}$$

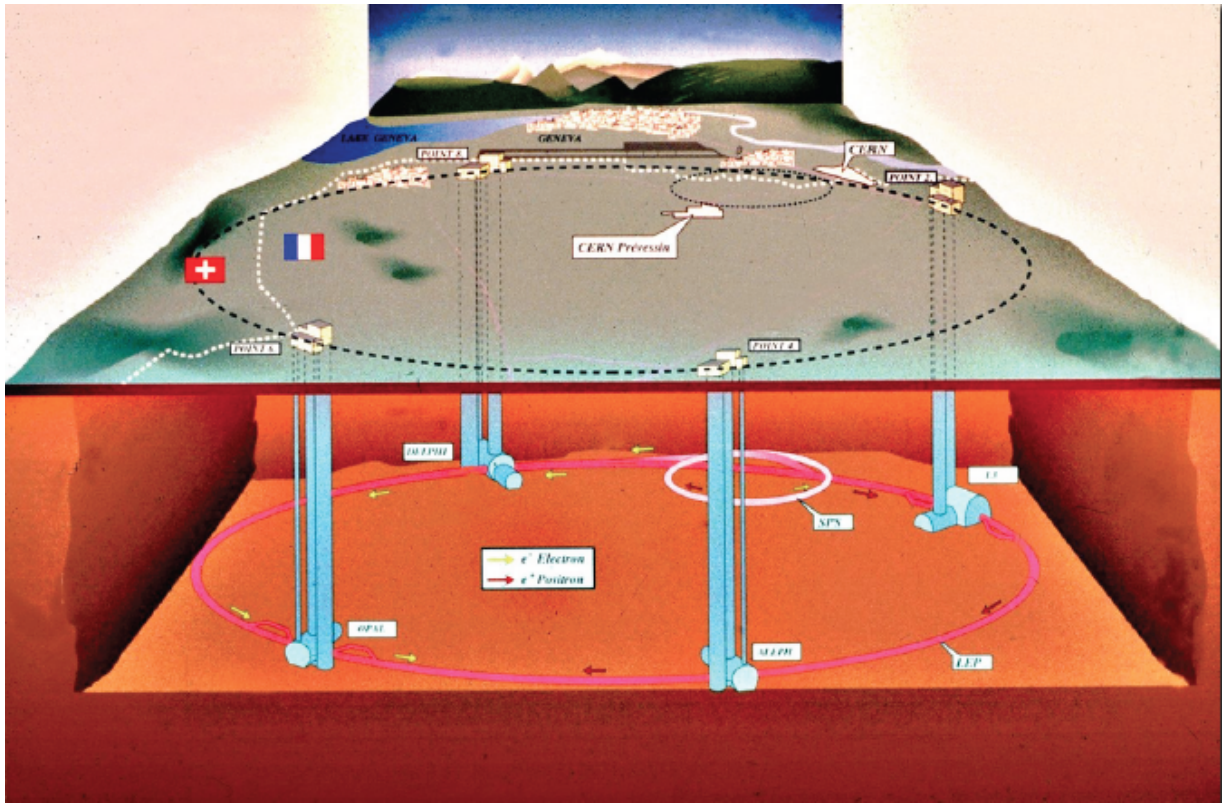
  - *Discovery of a 125 GeV Higgs boson is consistent with our Standard Model expectations*

Higgs Hunting over the Years

Accelerator	type, laboratory	energy $\sqrt{s}$	years of operation
LEP-I	e^+e^- collider, CERN	91 GeV	1989 - 1994
LEP-II	e^+e^- collider, CERN	209 GeV	1995 - 2000
HERA-I	ep collider, DESY	27 + 800 GeV	1992 - 2000
HERA-II	ep collider, DESY	27 + 920 GeV	2002 - 2007
TeVatron Run I	ppbar collider, Fermilab	1.8 TeV	1987 - 1996
TeVatron Run II	ppbar collider, Fermilab	1.96 TeV	2002 - 2011
LHC, phase I	pp collider, CERN	7 TeV	2010- 2012
LHC, phase II	pp collider, CERN	14 TeV	2014- .....

The Search Started With e^+e^- Machines

- At LEP (Geneva, Switzerland)
- Physics point: Nothing inside electrons
  - Use conservation of energy in Higgs search



Looking for the Higgs with e^+e^-

- In 1990, there were 185,000 Z's at LEP
  - No Higgs: $M_H > 48$ GeV
- Raise the energy to 200 GeV
  - Look for Higgs made in association with Z's
  - No Higgs: $M_H > 114$ GeV
  - Machine turned off in 2000 to make room for LHC

We expected to find the Higgs in these experiments!

Next Hunting Ground

- Superconducting super collider (SSC)
  - To be built in Texas with 3X's LHC energy
  - Cancelled in 1993
  - Would have discovered the Higgs

15 miles of tunnel dug

Tevatron (Chicago, Illinois)

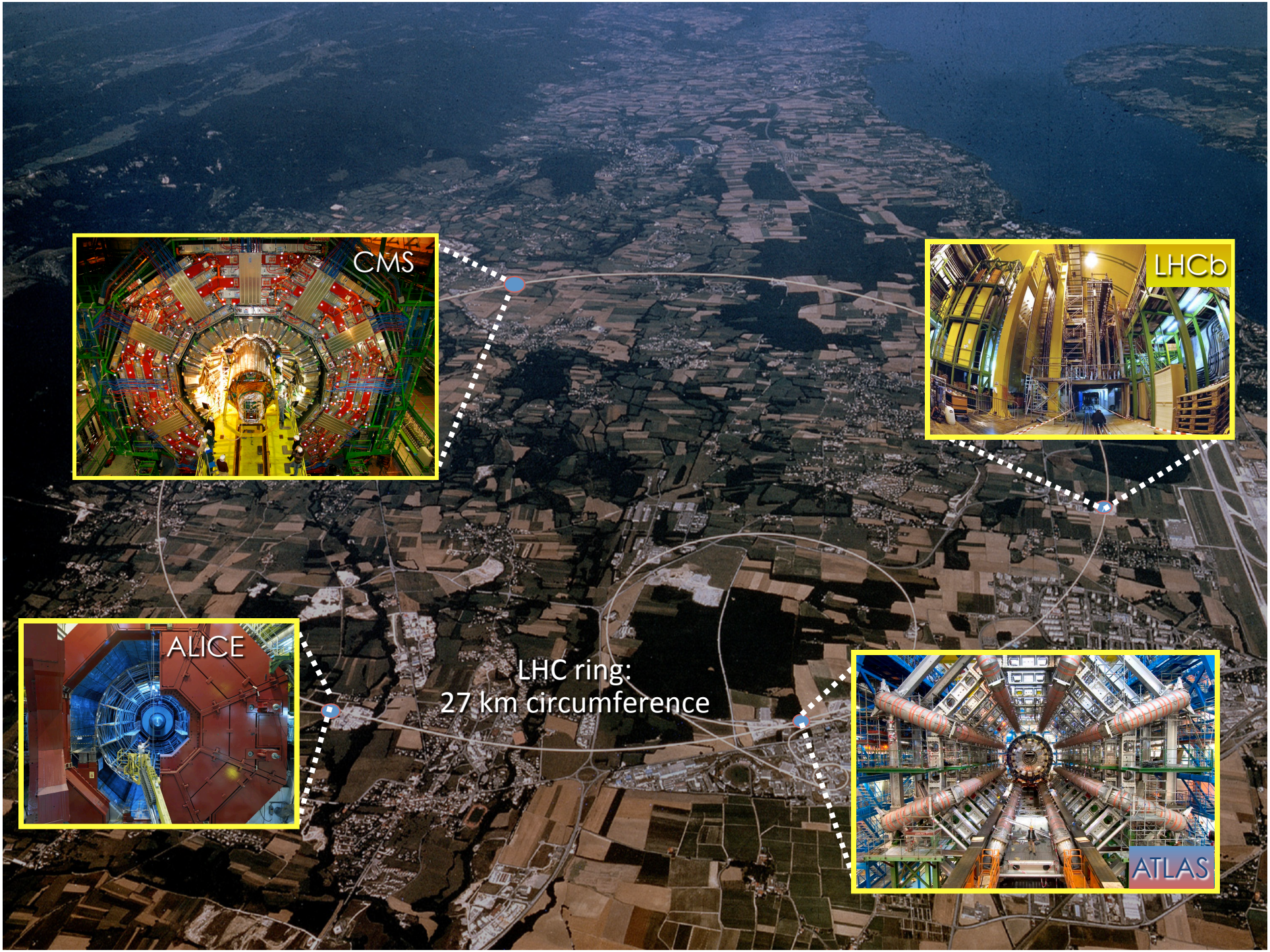
- $p\bar{p}$ collisions at energy = 1960 GeV
- Closed at end of 2011

Still no Higgs

Large Hadron Collider (LHC)

- proton-proton collider at CERN
  - First collisions, March 30, 2010!
- Goal: 14 TeV energy
  - 7 mph slower than the speed of light
  - *cf*. 2 TeV @ Fermilab

  (307 mph slower than the speed of light)
- Typical energy of quarks and gluons 1-2 TeV


CMS
LHCb
ALICE
LHC ring:
27 km circumference
ATLAS

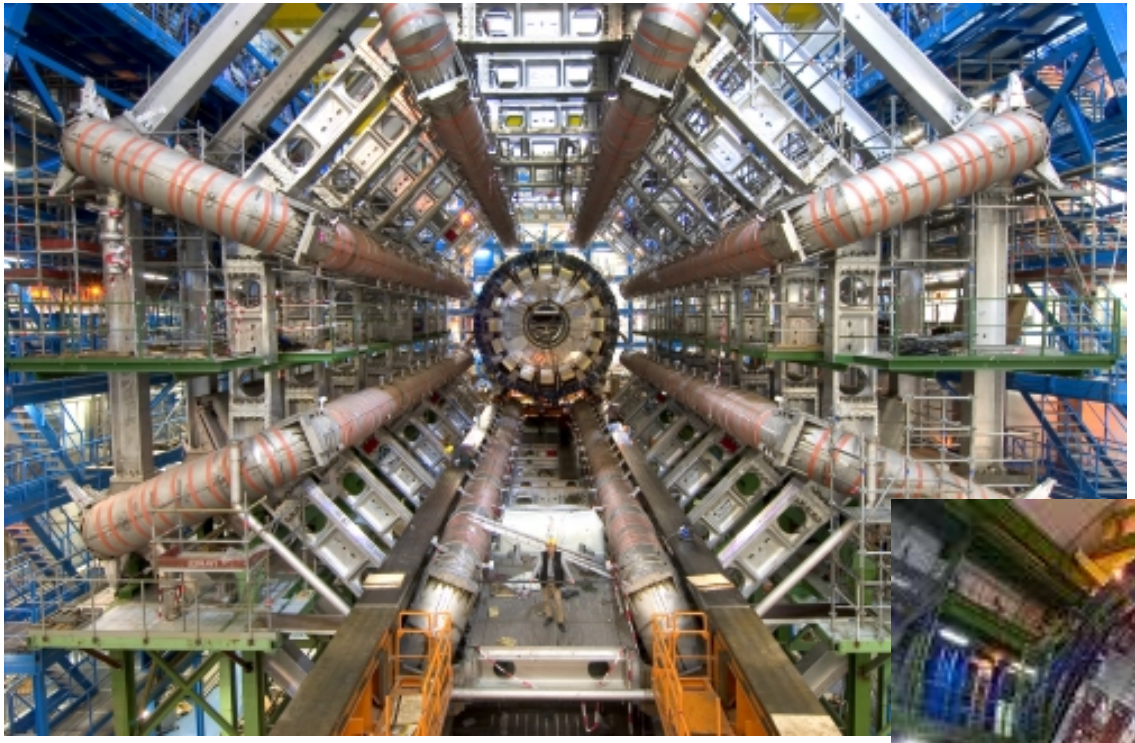
Stored Energy of Beams

- E_{beam}=1.5 Giga Joule
- LHC beams at 7 TeV have same kinetic energy as aircraft carrier at 15 knots!
- Largest scientific project ever completed

Two Detector Collaborations

- ATLAS and CMS (~3000 members each from 41 countries)

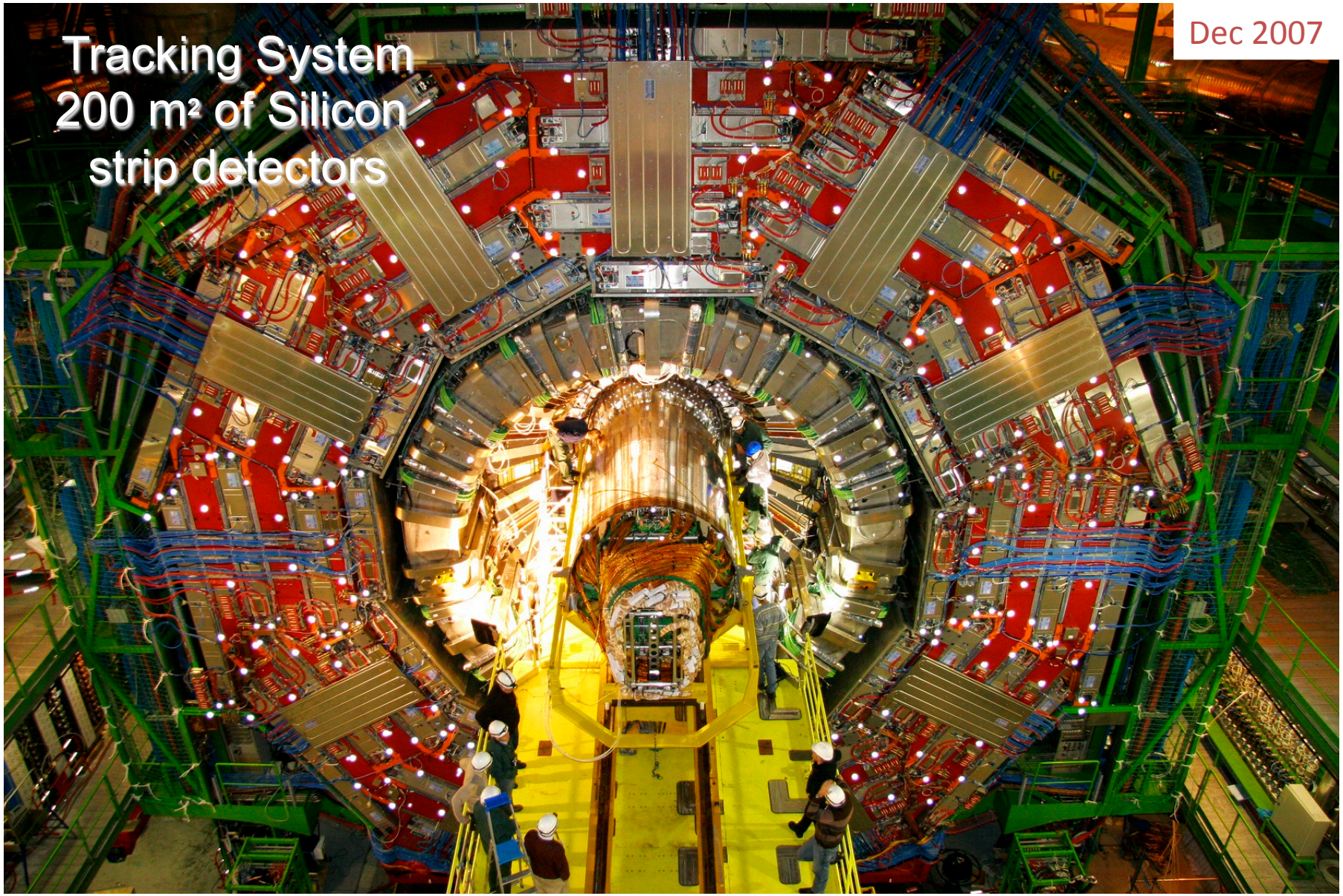
Two Detectors



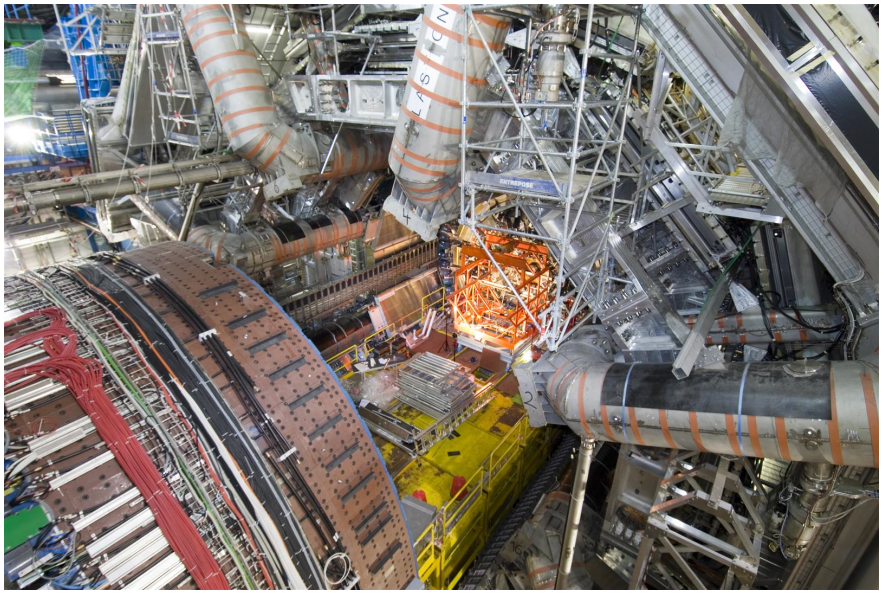
LHC Requires Detectors of Unprecedented Scale

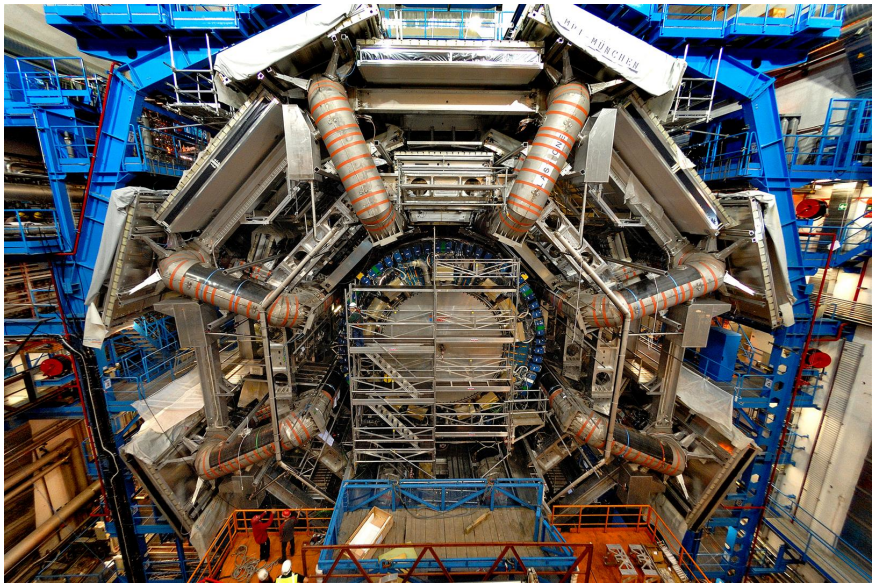
- CMS is 12,000 tons (2 x's ATLAS)
- ATLAS has 8 times the volume of CMS

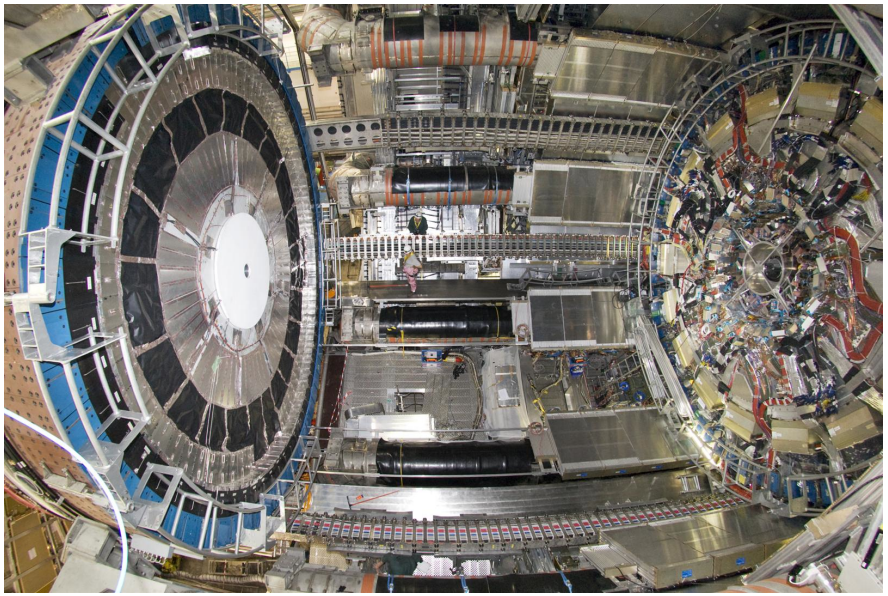
CMS

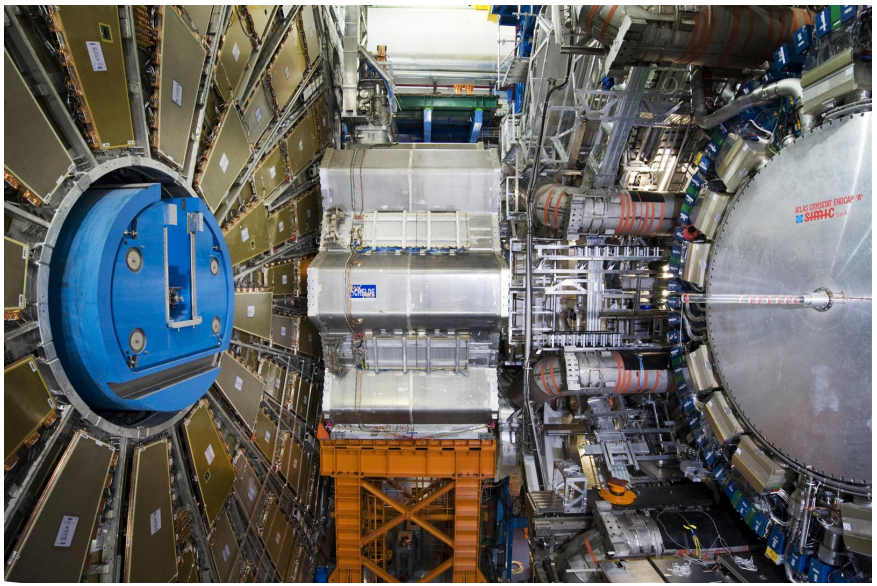


ATLAS



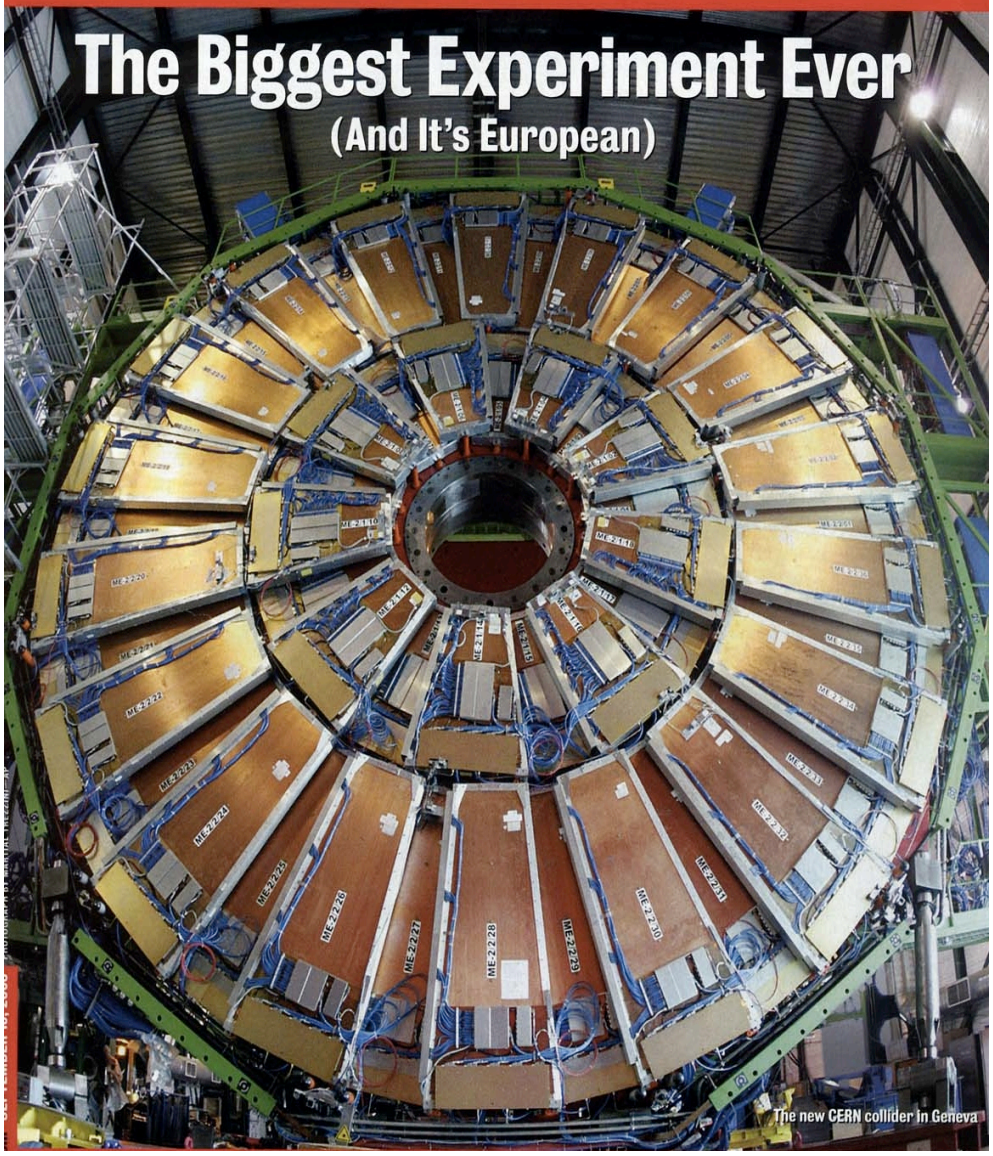






Newsweek

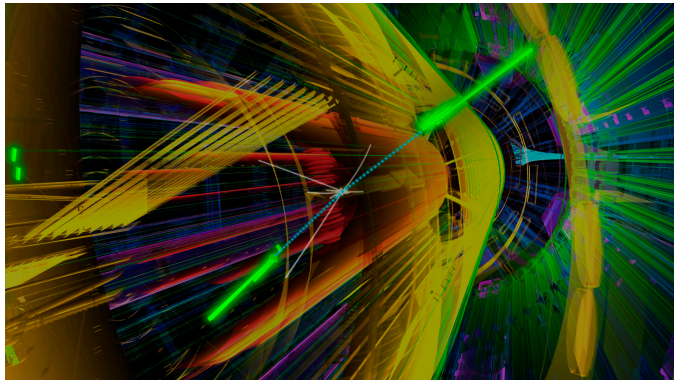
The Biggest Experiment Ever
(And It's European)



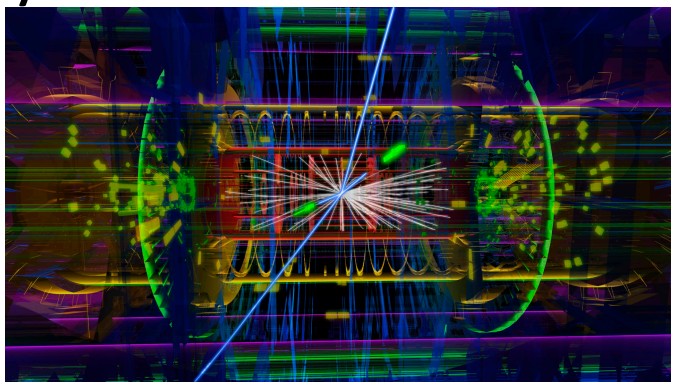
The new CERN collider in Geneva

Making a Higgs boson

- At the LHC, protons collide at 99% of the speed of light
  - Most of the time no Higgs boson is made
  - Very (!) rarely, out comes a Higgs boson which decays in 10^{-22} seconds
  - We can calculate how many Higgs bosons are made and what they decay to



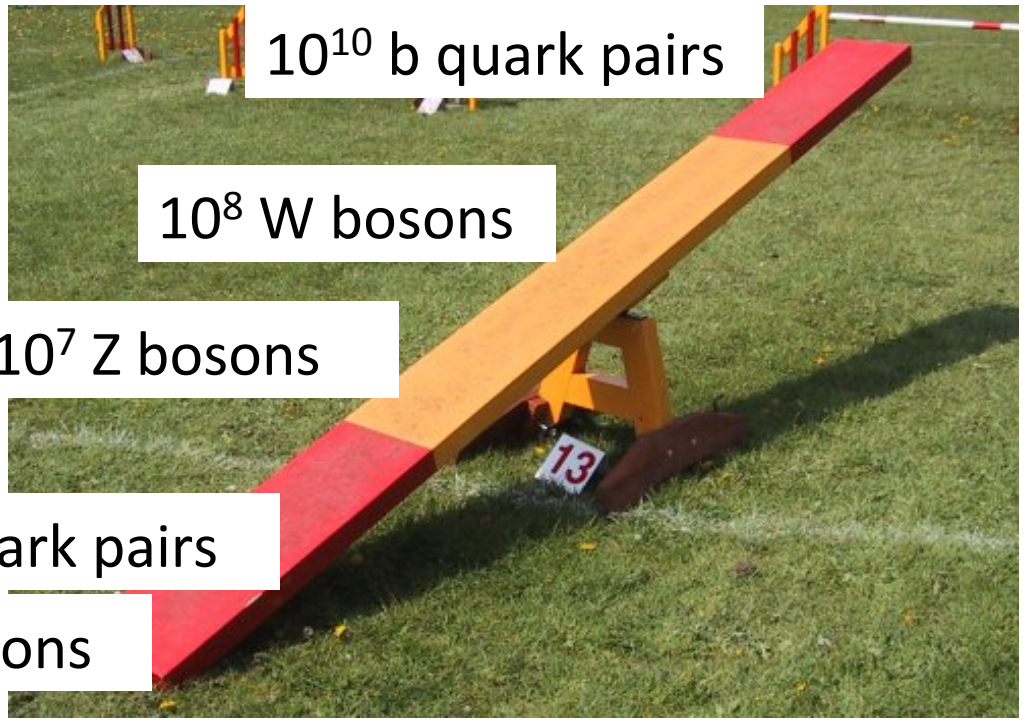
Higgs decaying to two photons



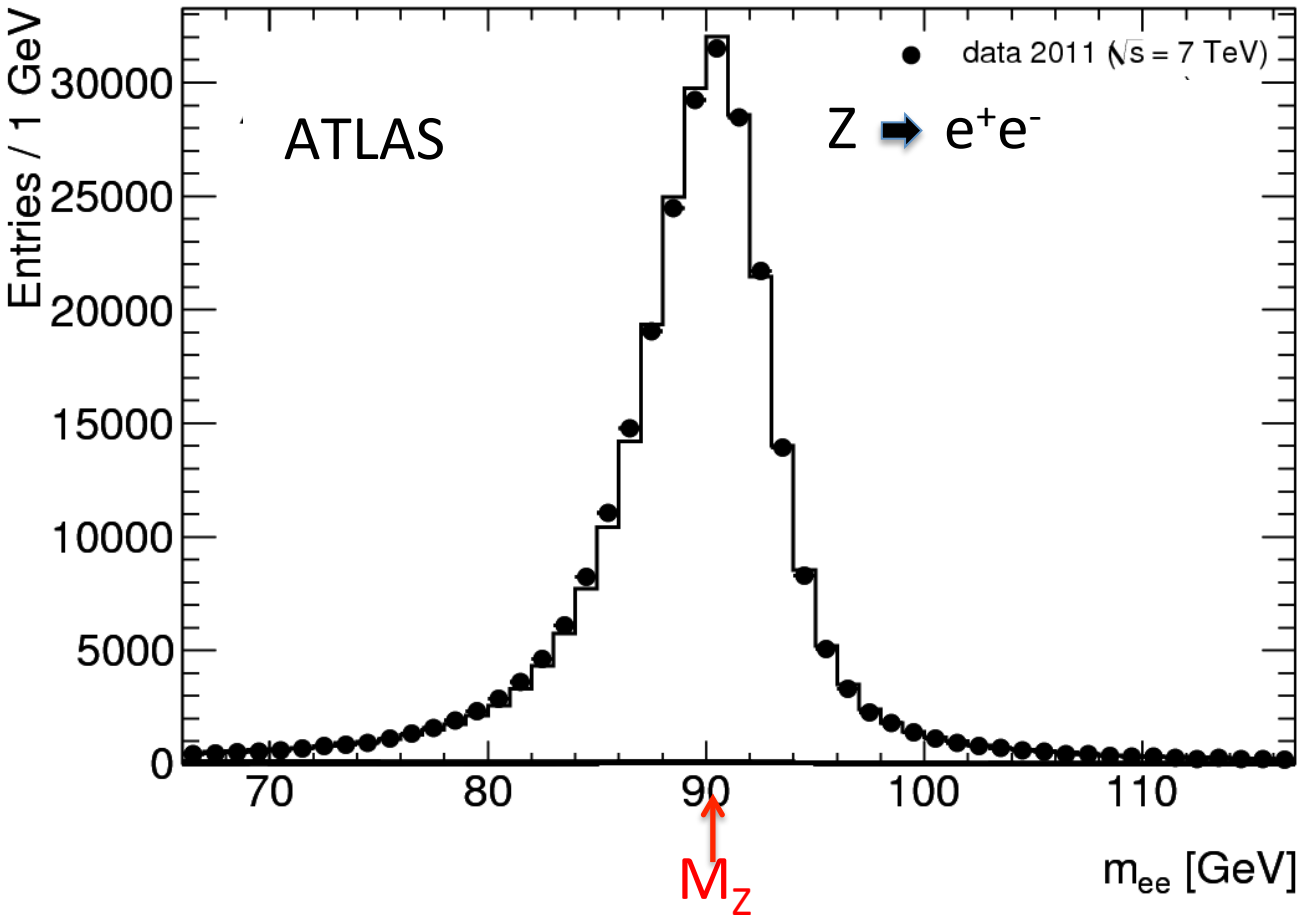
Higgs decaying to 2 electrons and 2 muons

How Rare is a Higgs?

- The LHC has made:



Discovery by Bump Hunting



$(M_Z c^{2)2} = (E_+ + E_-)^2 - (p_+ + p_-)^2 c^2$

Bump Hunting the Higgs

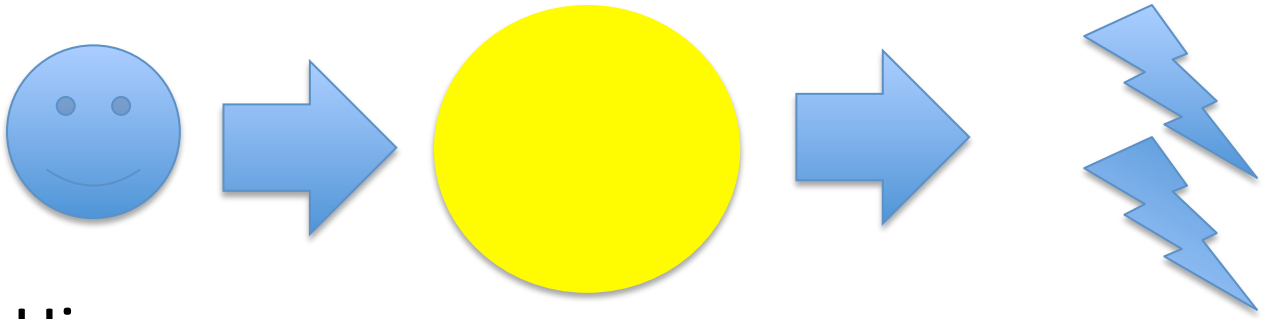
- To start look for:

$$pp \to Higgs \to \gamma\gamma$$
$$pp \to Higgs \to ZZ \to e^+e^-\mu^+\mu^-$$

- Detectors designed to be very good at measuring photons, electrons, and muons

Wait a minute

- Question: How does the Higgs interact with a massless photon?
- Answer: Indirectly



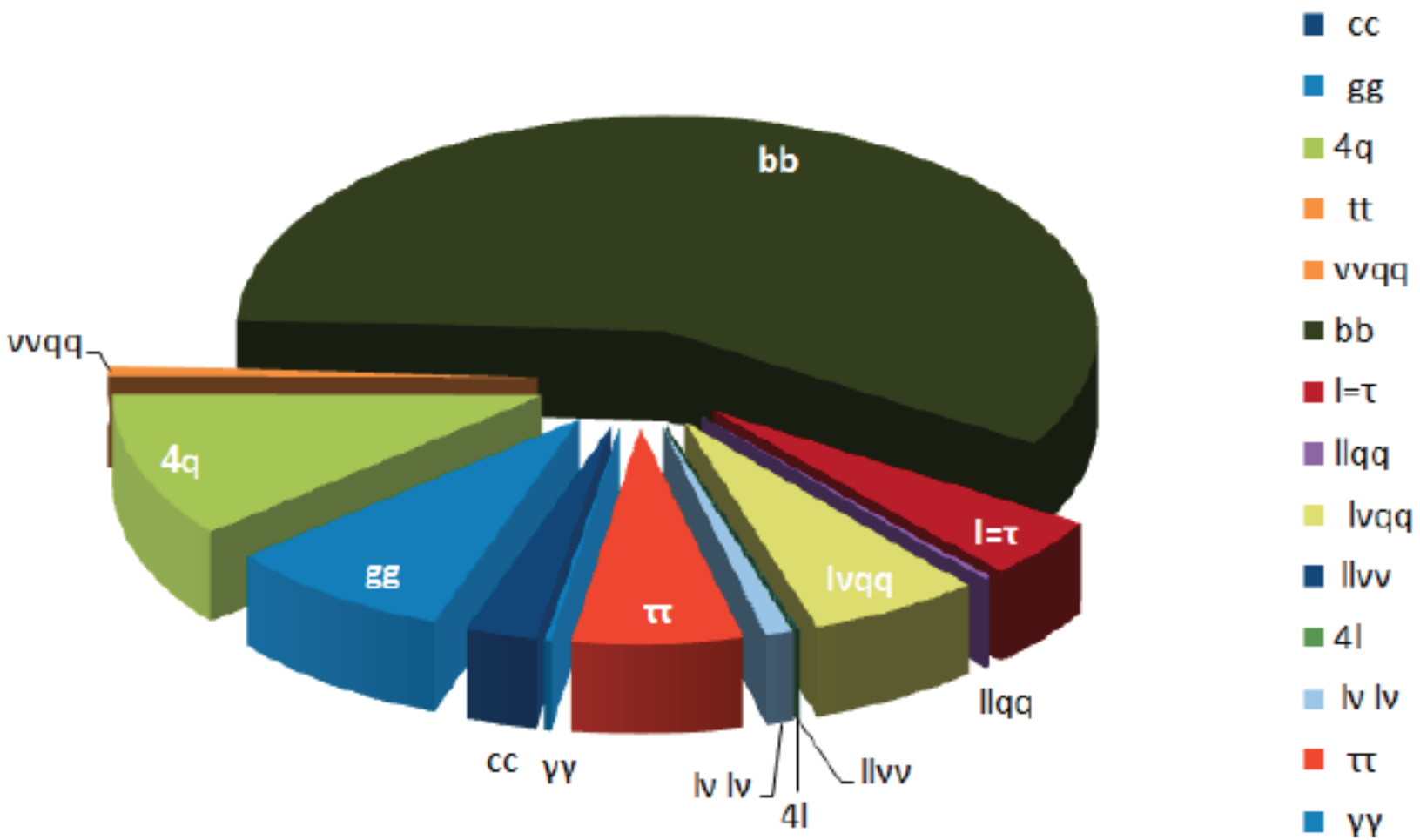
Predictions:

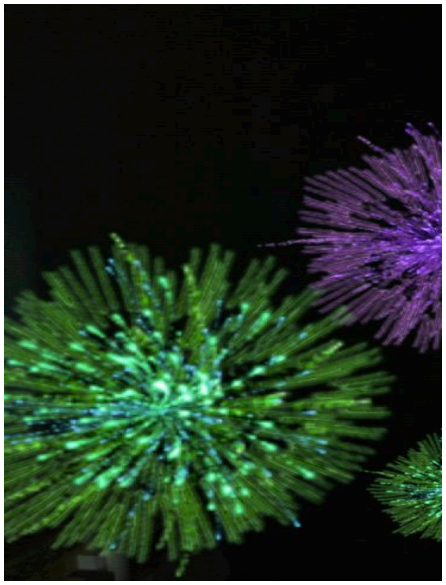
- 174,000 Higgs made
  - 397 decayed to 2γ
  - 10 decayed to 2 Z's which then decayed to $e^+e^-\mu^+\mu^-$ pairs
  - 60% of the Higgs bosons decay to b quarks

"Always the last place you look"

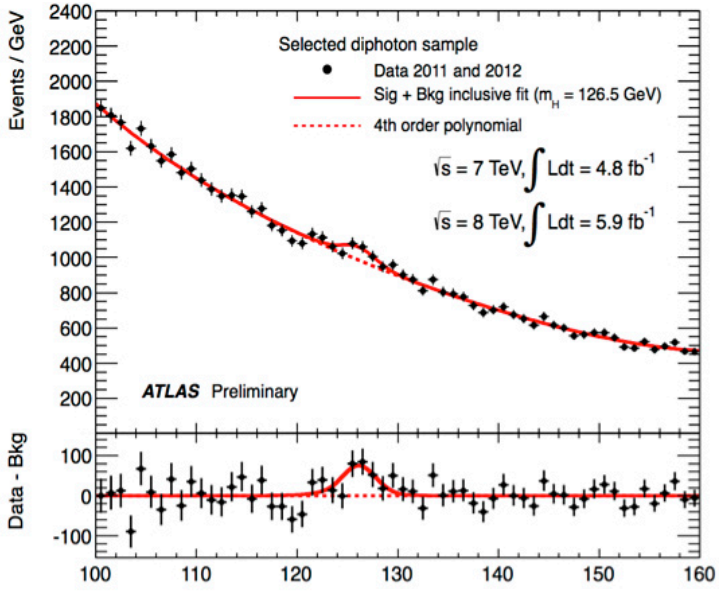
* As of July 4 announcement. Now have 3 times more data

Where does the Higgs go?

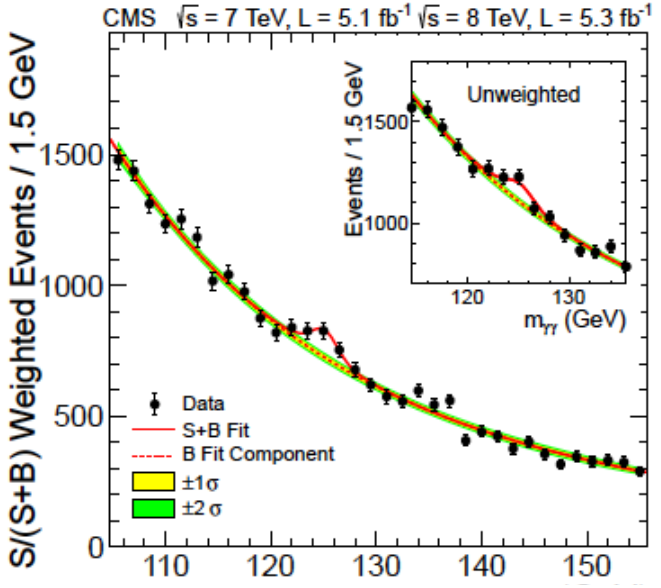




The 4th of July!

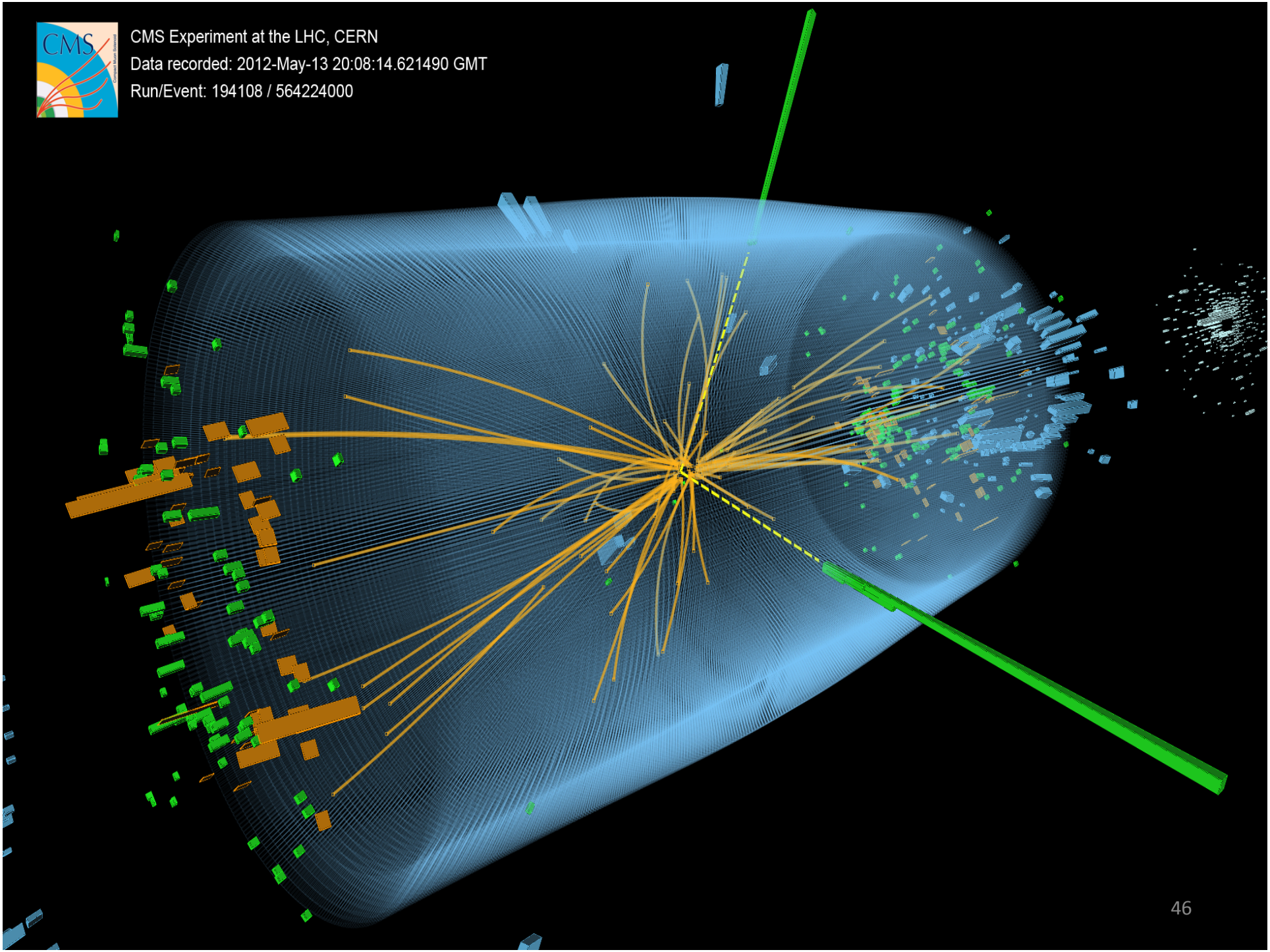


$M_{\gamma\gamma}$ (GeV)

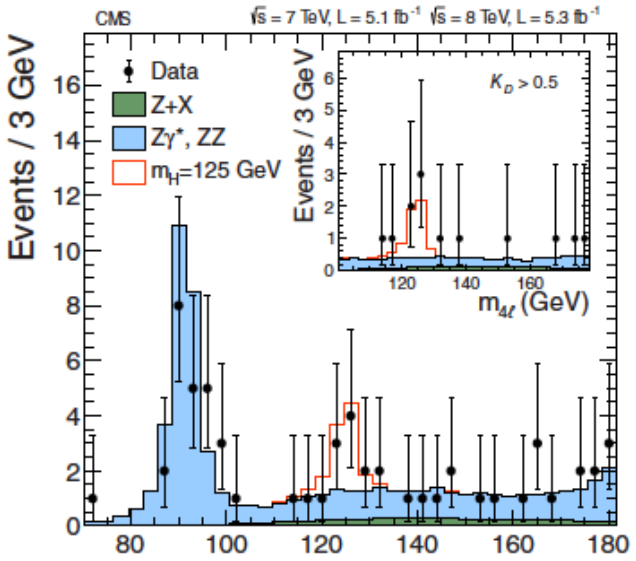


$M_{\gamma\gamma}$ (GeV)

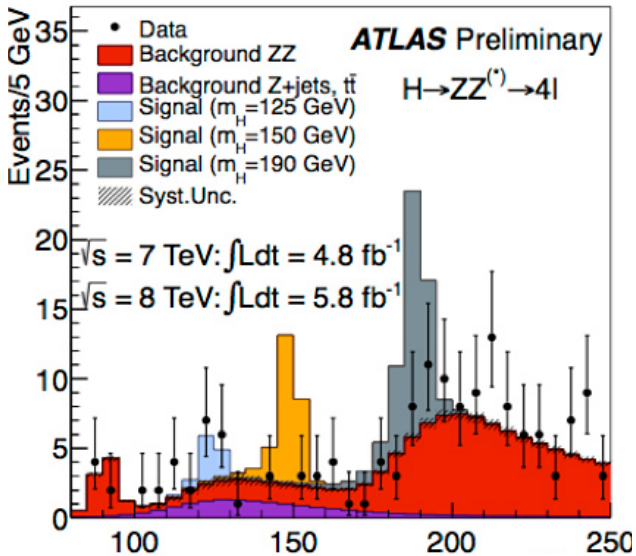
$H \rightarrow \gamma\gamma$


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000

Also saw H → ZZ



M_{4l} (GeV)

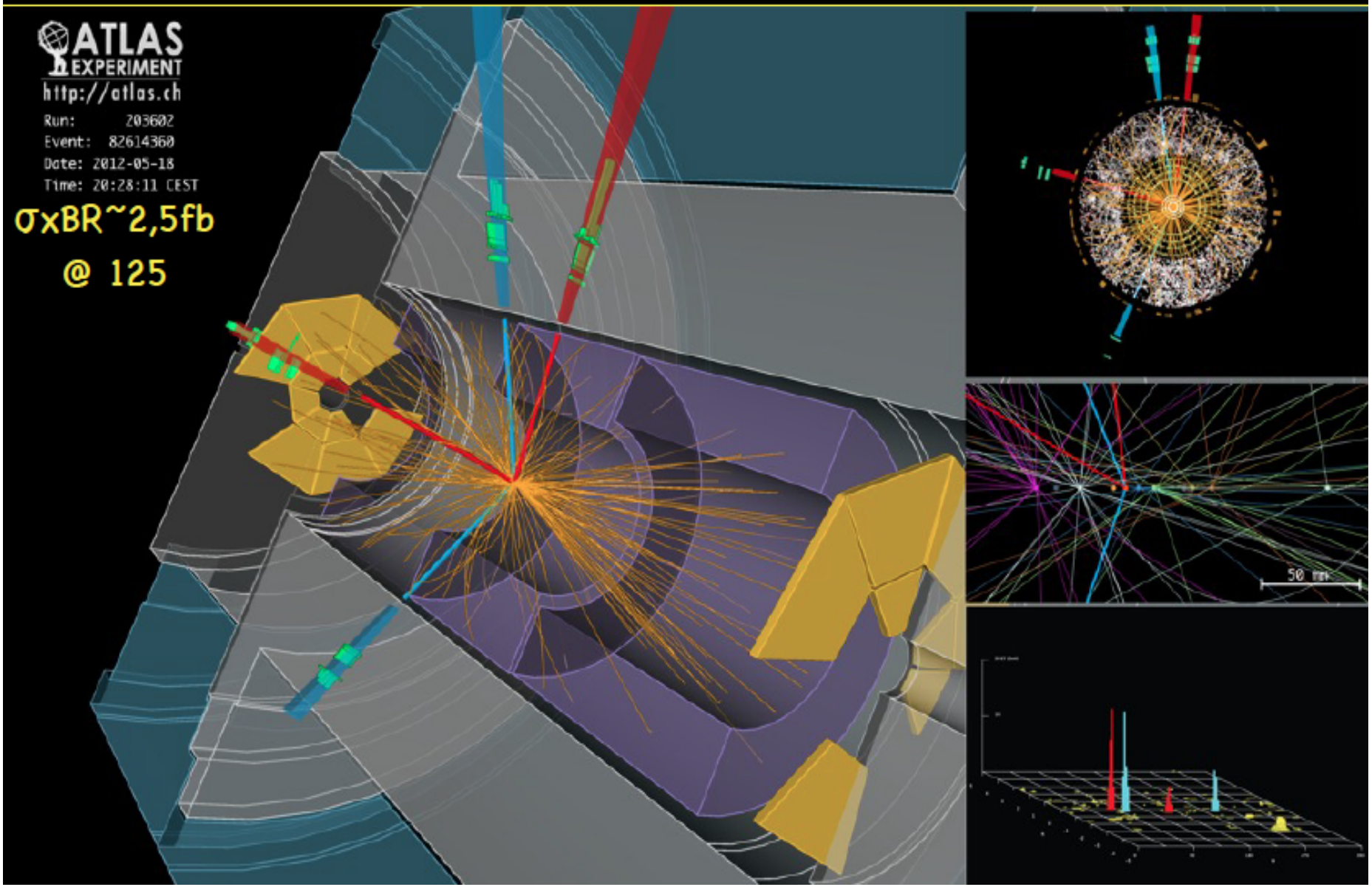


M_{4l} (GeV)

H ⟶ ZZ*⟶ 4 leptons

4 leptons

4e candidate with mass = 124.5 GeV



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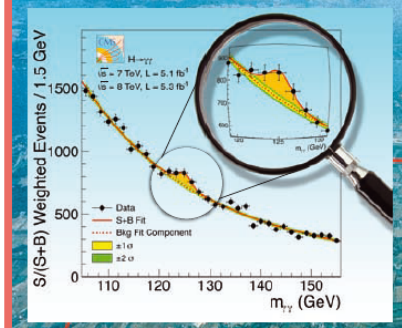
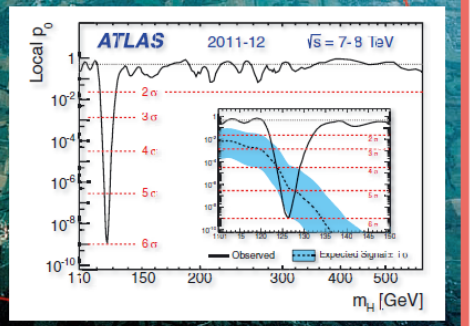
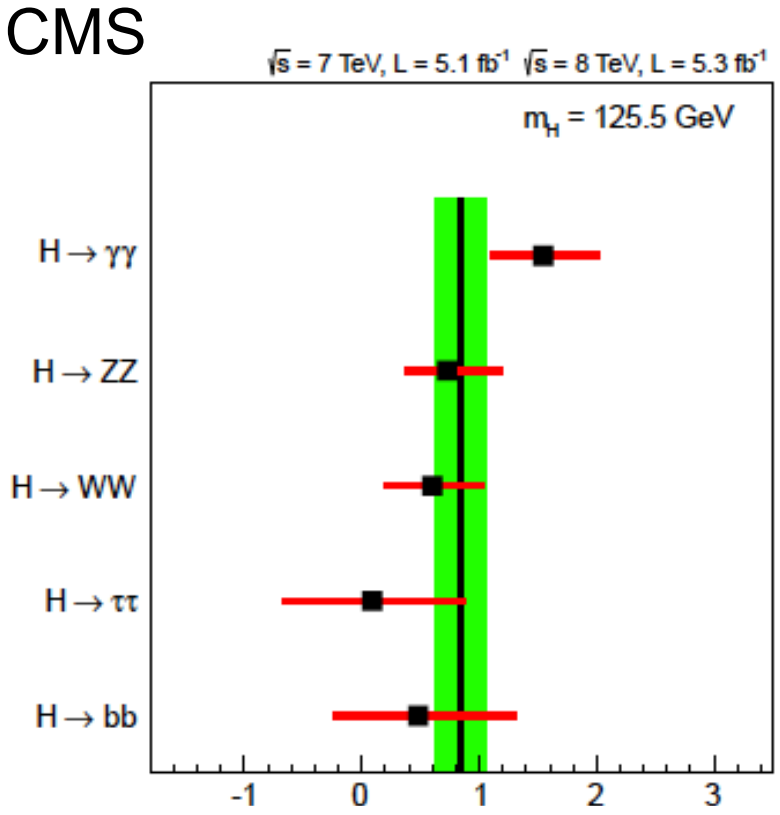




http://www.elsevier.com/locate/physletb

Higgs Candidate Looks Right



No fudge factors in theory!!!!

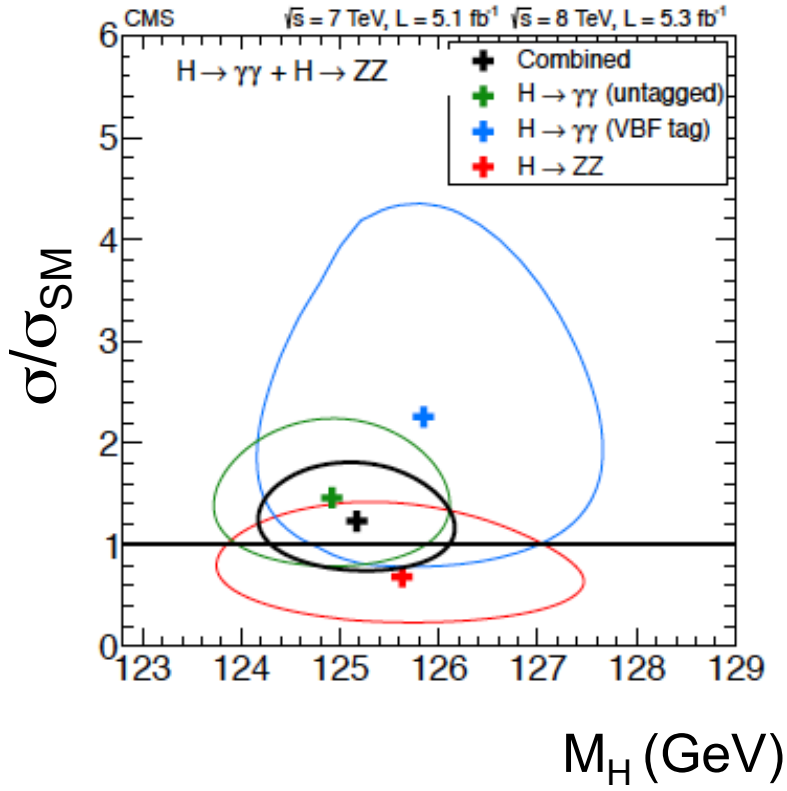
Higgs decays in predicted manner

Measured rate/predicted rate

Average = .88 ± .21

Higgs Candidate Looks Right

- Higgs masses extracted from different decays are all consistent

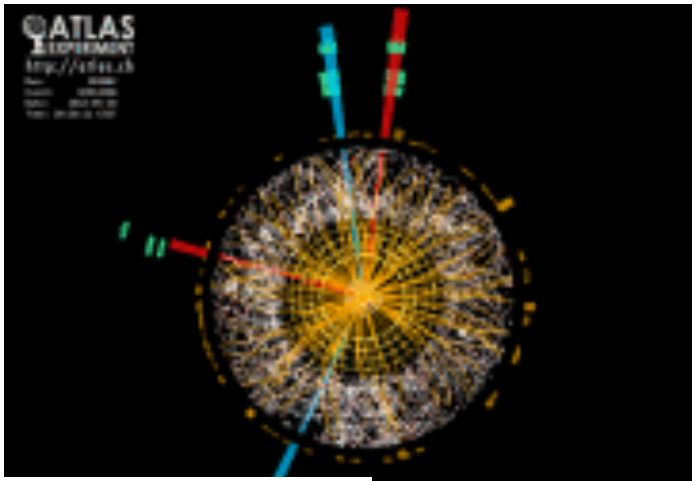


CMS

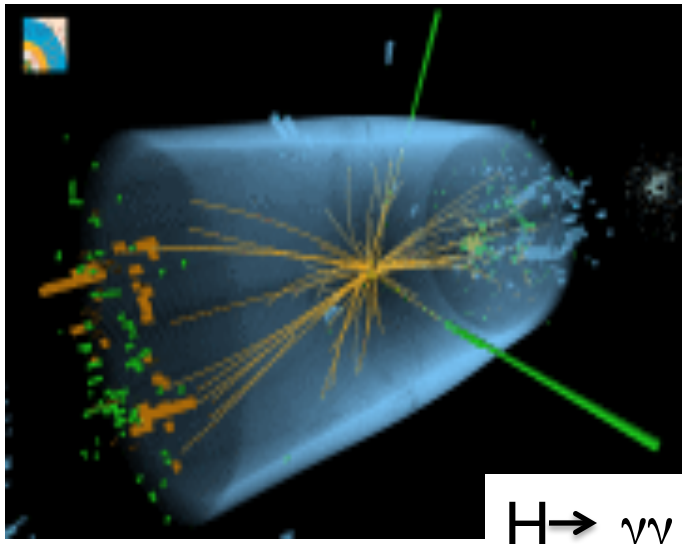
M_H=125±.4(stat)±.5(syst) GeV

What We Know

- There is something with many of the right properties to be a Higgs boson with mass ~125 GeV!
- Both CMS and ATLAS see something that looks like a Higgs in the $\gamma\gamma$ and ZZ channels; also in other decay channels
- Combined significance roughly 6σ for each experiment



$H \rightarrow e^+e^-e^+e^-$



$H \rightarrow \gamma\gamma$

Just the beginning of the story

The Detective Story

- Finding a Higgs-like particle is just the beginning
- We need to measure all its properties
  - Is it the predicted particle?
- Many unanswered questions
  - What is dark matter?
  - Why are some particles so much heavier than others?
  - We are just beginning the exploration

Pure science at its best!