Higgs Hunting at the Large Hadron Collider

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Saturday Morning Physics
Texas A&M University
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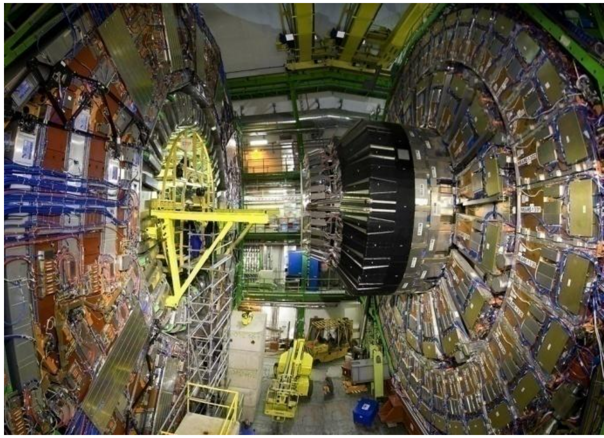
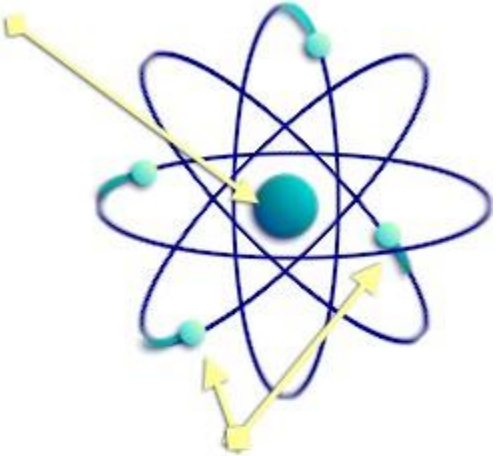


Outline

- Introduction to the Standard Model
- What is the Higgs really?
- Hunting grounds: LHC and the detectors
- How do we hunt for particles?
- How would we know we see a Higgs?
- What have we found so far?
- What's next?

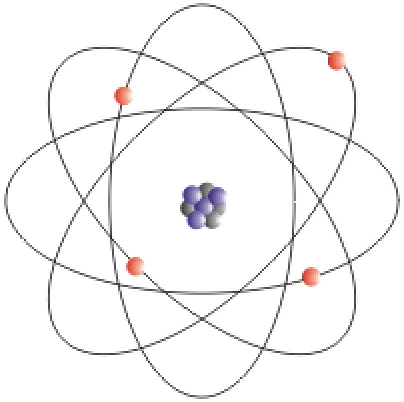
A Brief History of Particles

- The idea that all matter is composed of elementary particles dates as far back as the 6th century BC.
  - Most of these were philosophical ideas
  - 'atomos' is a Greek word meaning indivisible
- 19th century: modern atomic theory was postulated
  - Each element is composed of a unique type of particle
- 1897: the electron was discovered
  - Plum pudding model of the atom
- 1909: Rutherford's experiment with a gold foil and alpha rays
  - Atoms have a nucleus and electrons



The nucleus

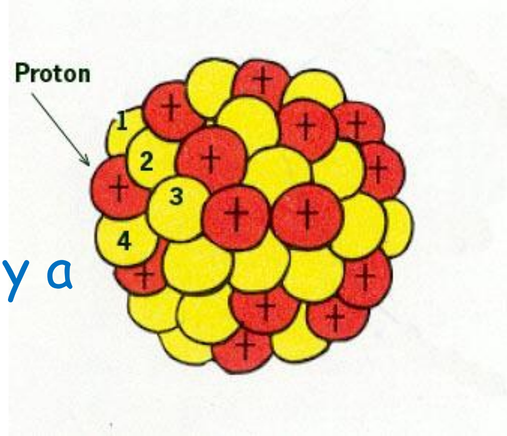
More than 99% of the mass of an atom is in the nucleus, which is more than 10,000 times smaller than the atom, about 1 – 10 fm (Fermi).
1 fm = 10^{-5} Angstrom = 10^{-15} m.



A cloud of electrons orbits the nucleus, held in place by the mutual attraction of the electric charges.

Most of the atom is just empty space!
But with a strong electromagnetic field present.

Nuclei are made up of two particles:
Protons p: positive charge +e, mass ≈ 1u
Neutrons n: neutral, roughly the same mass as p



Protons and neutrons are kept together by a new force: the **strong force**.

Sub-atomic Particles

What do we distinguish particles by?

participate in strong interactions ?
YES: they are called **hadrons**
ex: proton, neutron
NO: they are called **leptons**
ex: electron

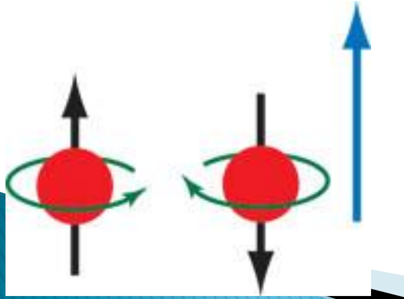
electric charge ?
positive or negative
usually in multiples of e

Mass ?
usually measured in electronvolts (eV)
1 u ≈ 0.939 GeV (Gigaelectronvolts,
Giga = Billion)

Spin ?
= Quantized angular momentum
Electrons, protons, neutrons: spin $\frac{1}{2}\hbar$

Particles with integer spin are called **bosons**.

Particles with half-integer spin are called **fermions**.



Electrons, protons and neutrons are fermions.

More Particles

The **muon** μ^- (and its antiparticle μ^+)

- The muon is a fermion with spin ½
- It does not participate in the strong interaction, so it is a lepton
- It behaves like a heavier brother of the electron.

Mass 0.106 GeV
(electron: 0.000511 GeV)

Neutrinos ν_e, ν_μ and their antiparticles $\bar{\nu}_e$, $\bar{\nu}_\mu$

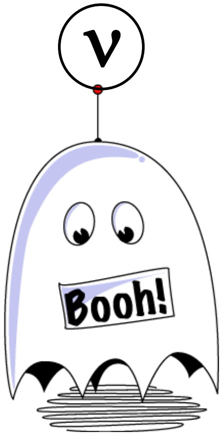
- They are fermions with spin ½.
- They don't have electric charge.
- They don't feel the strong force
- They have an extremely small mass

Most heavier particles are unstable. They decay into lighter particles, e.g. weak decay of a muon:

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

anti-electron neutrino

muon neutrino



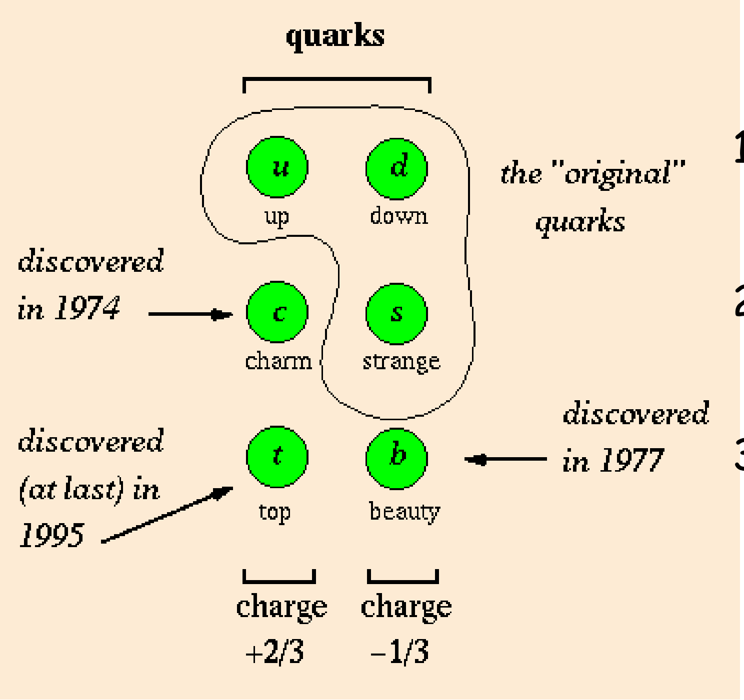
Neutrinos are 'ghost' particles.

They are almost undetectable because they only participate in the weak interaction.

Examples: muon decay, nuclear β-decay etc.

Quarks

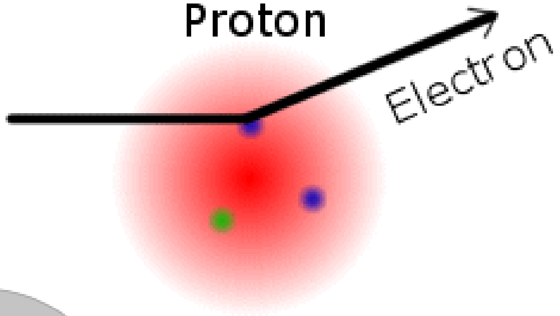
1968 a Rutherford-like experiment (deep inelastic scattering) confirmed that there are indeed quarks inside a proton.

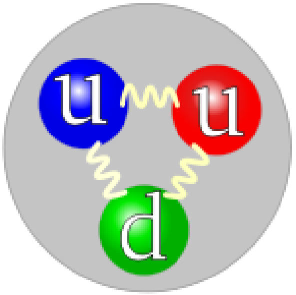


1st generation

2nd generation

3rd generation



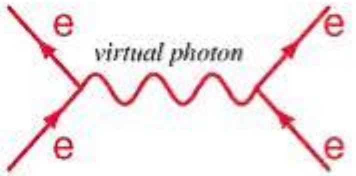


- There are 6 quarks in 3 generations + their 6 anti-quarks
- Increasing in mass from 0.002 GeV (up) to 174 GeV (top).

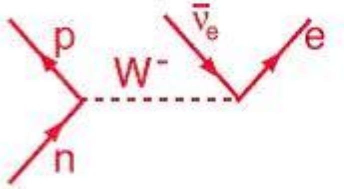
- ➢Have fractional electric charges
- ➢Can only exist in bound states
- ➢Interact via both weak and strong force

Forces of Nature

In quantum field theory forces are transmitted by force carrier particles exchanged between particles with the suitable charge.



Electromagnetic



Weak

between quarks

between nucleons

Strong Interaction

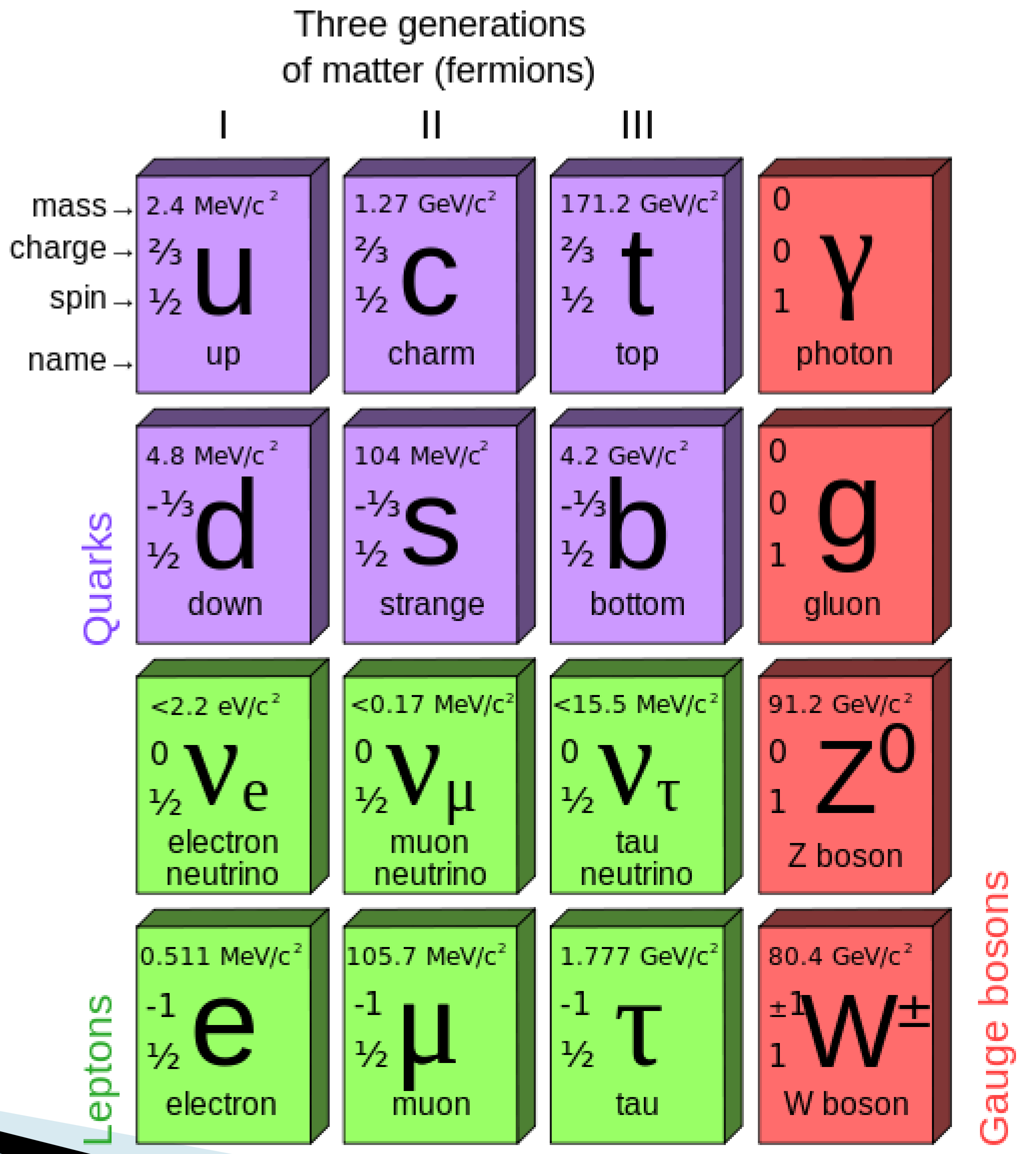
Electromagnetic force: exchange of photons between charged particles

Strong force: exchange of gluons between particles with "color charge"

Weak force: exchange of W^+, W^- and Z bosons between particles with "weak charge"

All the force carrier particles are spin-1 bosons (vector bosons) and they should have vanishing mass.

The Standard Model



Three generations of matter (fermions)

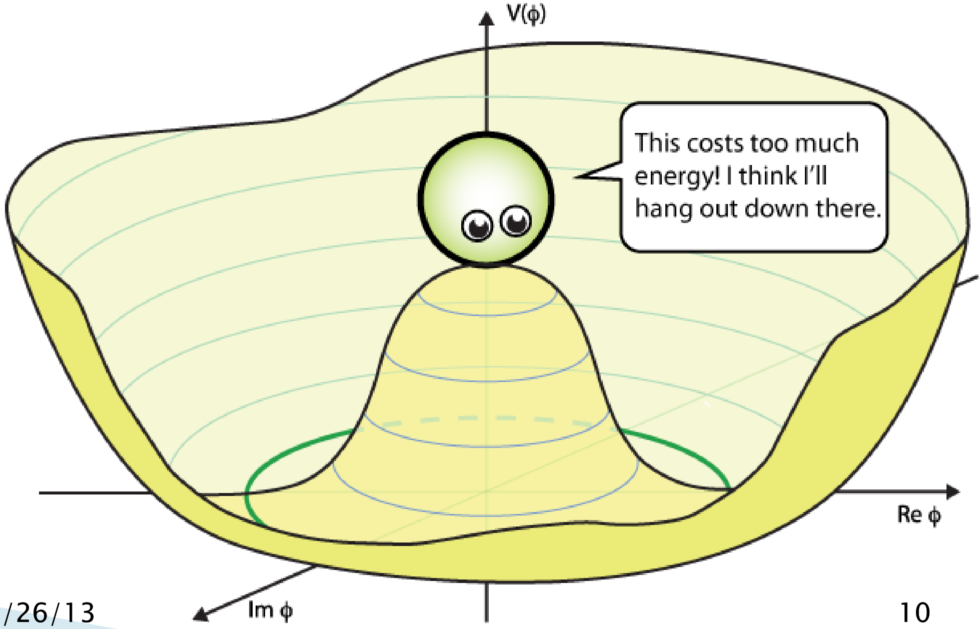
mass →
charge →
spin →
name →

	I	II	III	
Quarks	2.4 MeV/c^2 ⅔ ½ u up	1.27 GeV/c^2 ⅔ ½ c charm	171.2 GeV/c^2 ⅔ ½ t top	0 0 1 γ photon
	4.8 MeV/c^2 -⅓ ½ d down	104 MeV/c^2 -⅓ ½ s strange	4.2 GeV/c^2 -⅓ ½ b bottom	0 0 1 g gluon
Leptons	<2.2 eV/c^2 0 ½ ν_e electron neutrino	<0.17 MeV/c^2 0 ½ ν_μ muon neutrino	<15.5 MeV/c^2 0 ½ ν_τ tau neutrino	91.2 GeV/c^2 0 1 Z^0 Z boson
	0.511 MeV/c^2 -1 ½ e electron	105.7 MeV/c^2 -1 ½ μ muon	1.777 GeV/c^2 -1 ½ τ tau	80.4 GeV/c^2 ±1 1 $W^\pm$ W boson

Gauge bosons

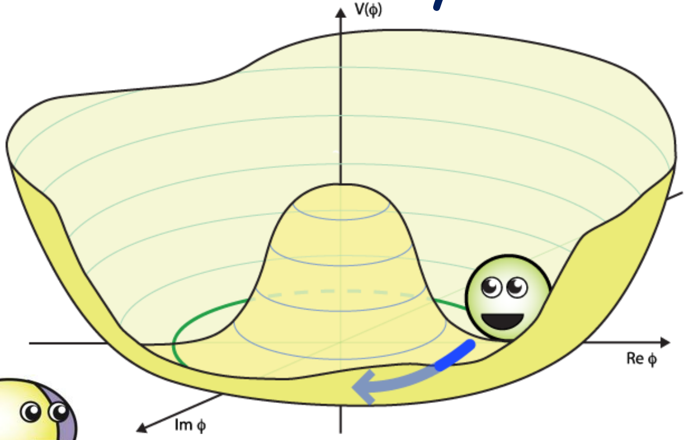
What is this “Higgs” thing?

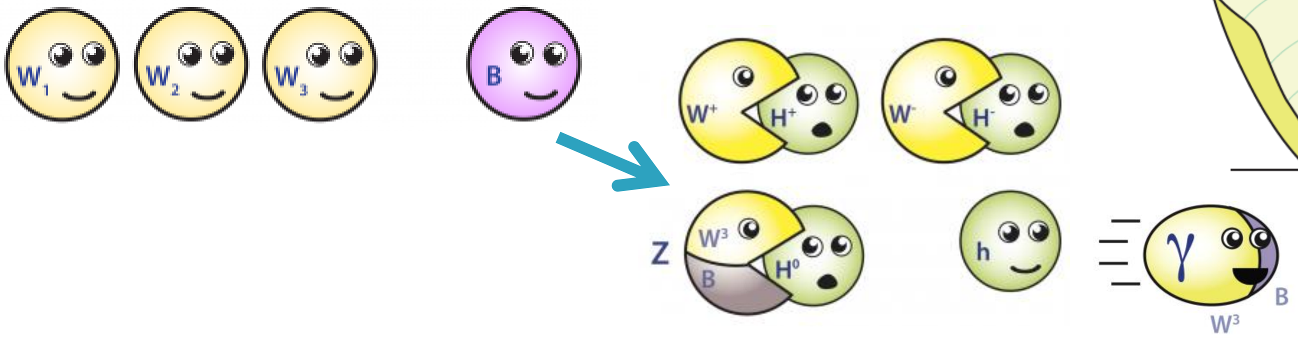
- Electroweak symmetry breaking: W and Z bosons shouldn’t have mass (like photons!); but we find they are very heavy!
- Idea: maybe W, Z couple to a field (the Higgs field!) that never vanishes, even in the vacuum (we say it has a non-zero vacuum expectation value).
- How can that happen? Imagine the Higgs field ϕ “lives” in a potential like this:
  - The preferred (lowest energy) value is at the bottom where $\phi \neq 0$.



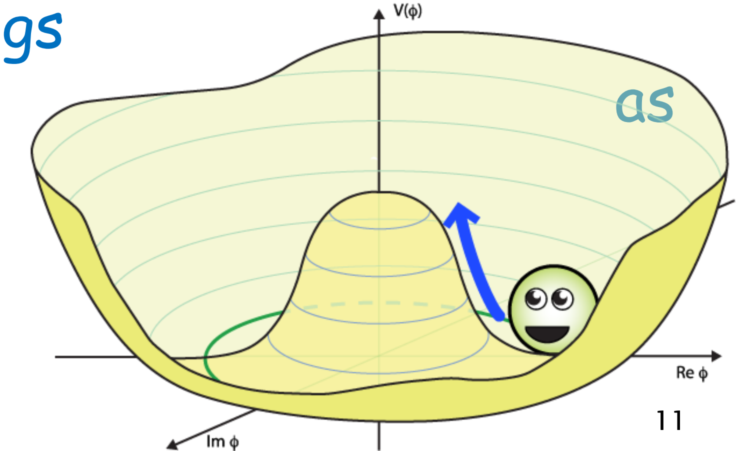
What is this “Higgs” thing?

- The vacuum expectation value of the field would not be directly visible but manifests itself in 2 ways:
  - It gives masses to W and Z as they have to move through that field.





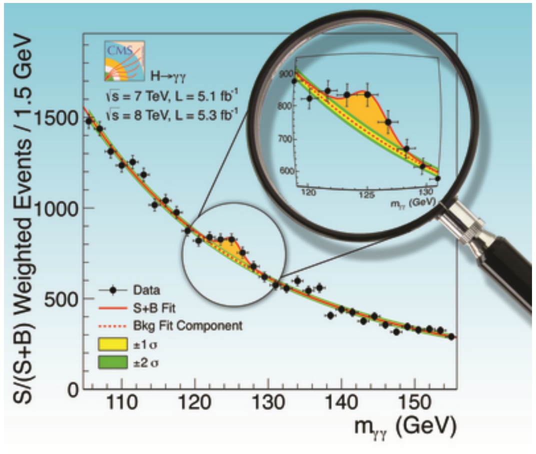
  - Excitations of the field on top of the vacuum value can be detected as a spin-0 boson (the Higgs boson!). Think of those excitations as ripples (waves) on top of a body of water.



What is this “Higgs” thing?

- Now that the Higgs field explains masses for W and Z bosons we can try to blame fermion masses on the Higgs as well.
- Postulate that all fermions couple to the Higgs field. The larger the mass the stronger the coupling.

3. Dadurch erfährt er einen Widerstand in seiner Fortbewegung, den man als Trägheit interpretieren kann, oder in anderen Worten, er erhält Masse. Genauso erhält ein Elementarteilchen Masse, da es sich durch das Higgsfeld bewegen muss.



Collider Detectors

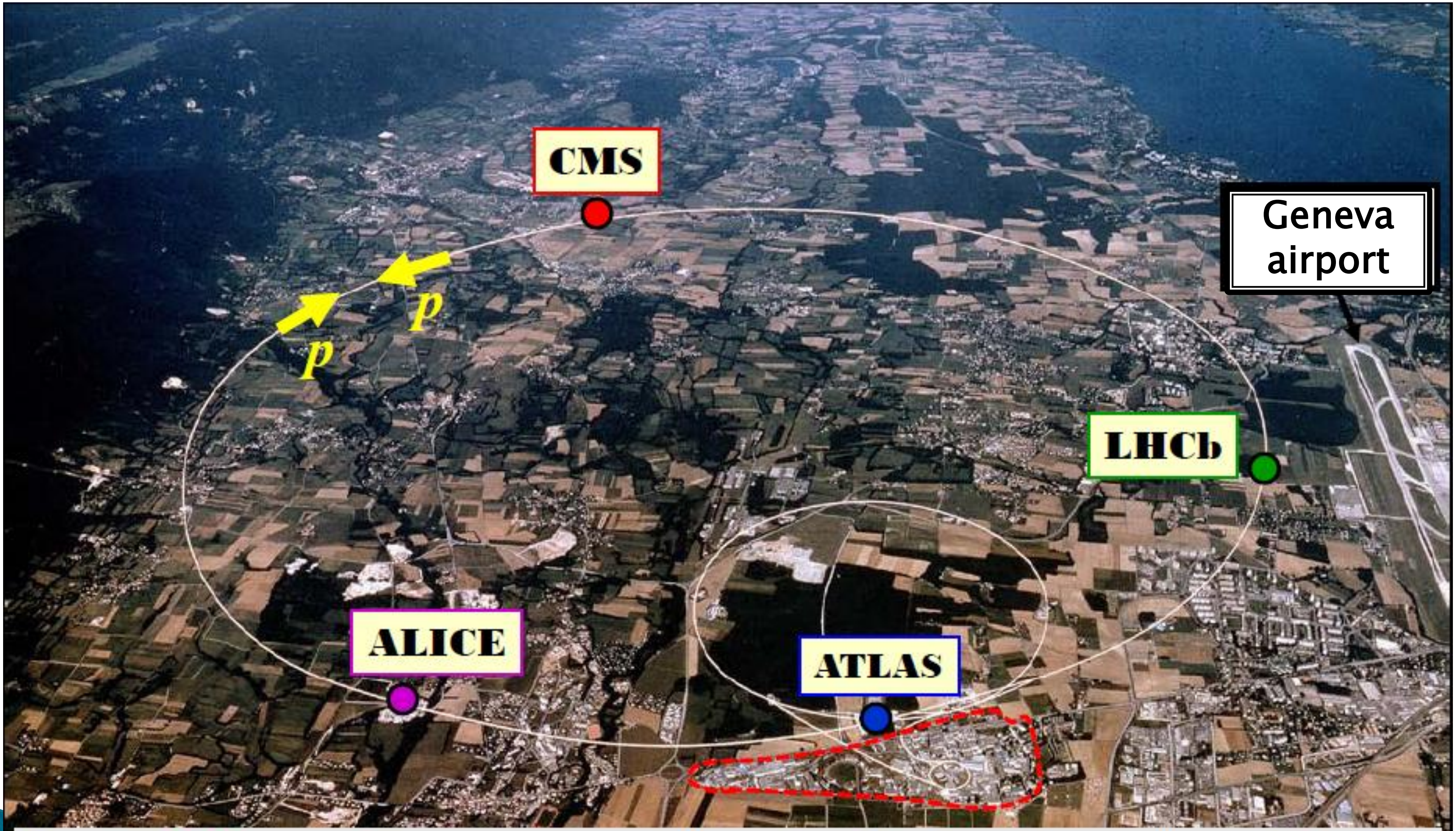
Use detectors to search for particles

Higher the energy, the more new particles can be created

And, take lots and lots and lots (!) of data

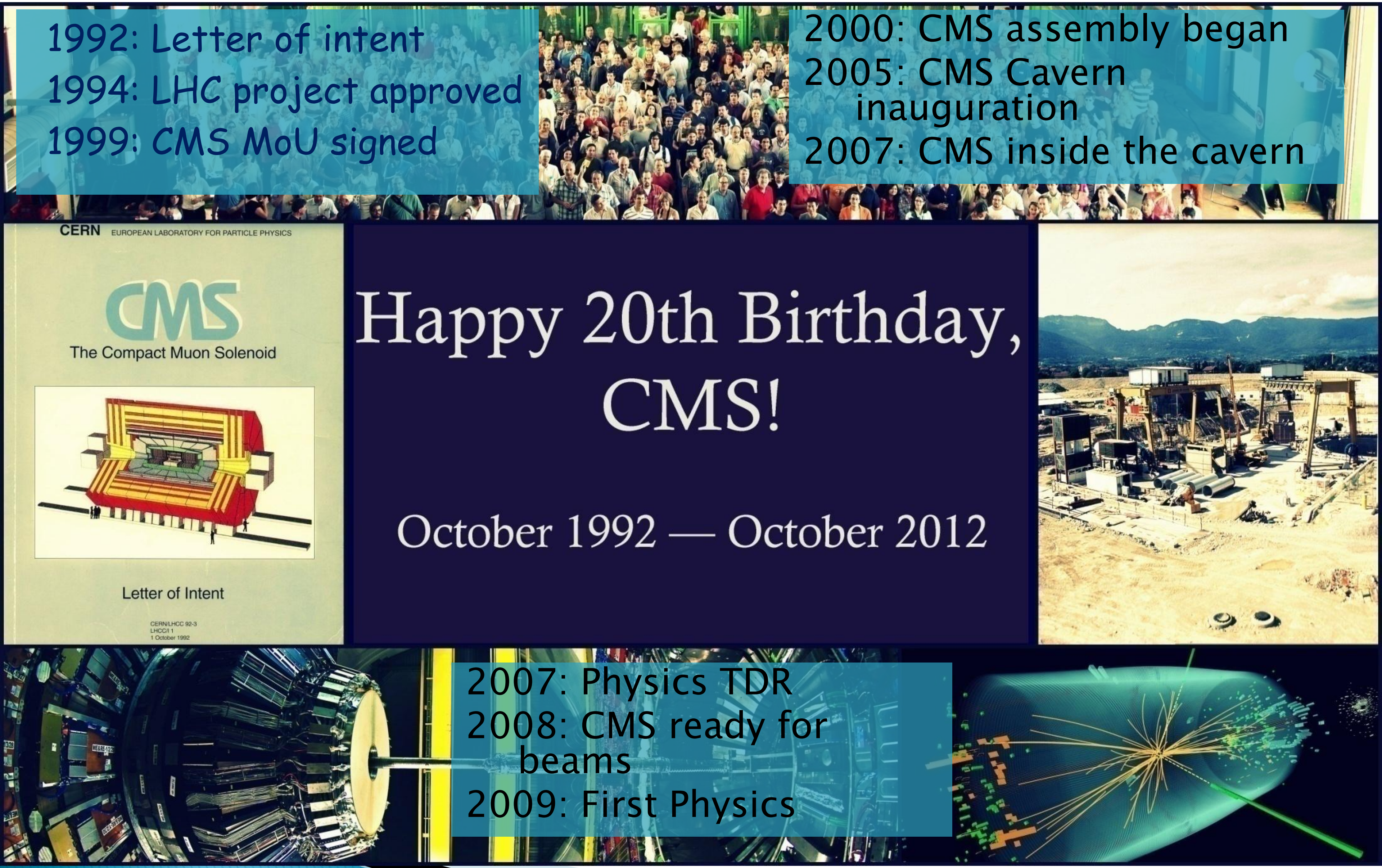
	LEP	TeVatron	LHC
Collisions	e^+e^-	$p\bar{p}$	pp
Years	1989-2000	1987-2011	2009-2018
Max E, GeV	208	2000	14000
Integrated lumi.	0.5fb^{-1}	12fb^{-1}	$5(300)\text{fb}^{-1}$
Higgs reach	0-115	100-180?	120-600

The Large Hadron Collider



The LHC at CERN (known as European Organization for Nuclear Research in Geneva, Switzerland) provides the proton-proton (pp) collisions. The smashing power is 3.5 times larger than that of the Tevatron at Fermilab (Batavia, IL, USA).

Compact Muon Solenoid Detector



1992: Letter of intent
1994: LHC project approved
1999: CMS MoU signed

2000: CMS assembly began
2005: CMS Cavern inauguration
2007: CMS inside the cavern

CERN EUROPEAN LABORATORY FOR PARTICLE PHYSICS

CMS
The Compact Muon Solenoid

Letter of Intent

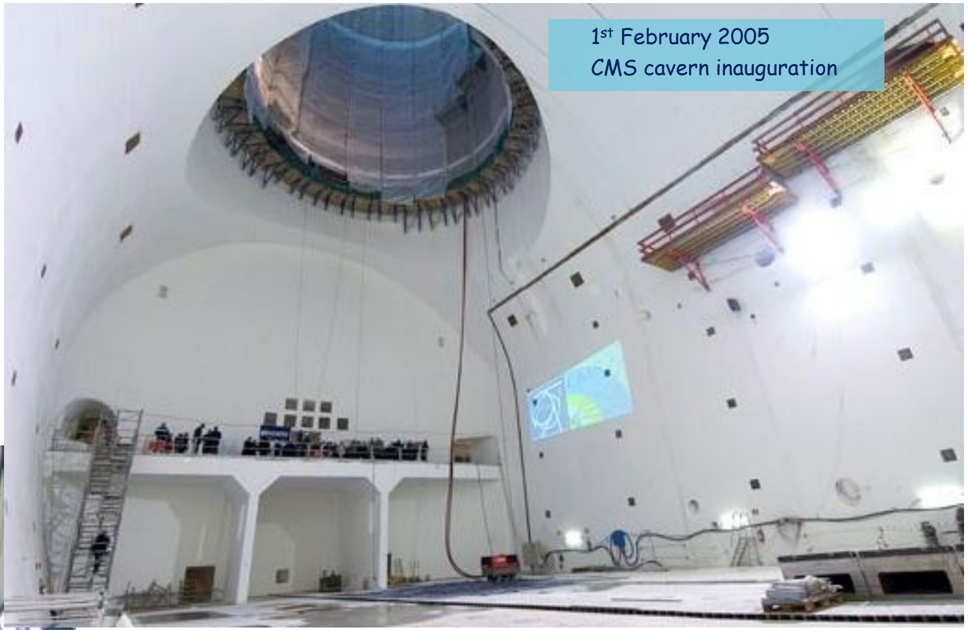
CERN/LHCC 92-3
LHCC/I 1
1 October 1992

Happy 20th Birthday, CMS!

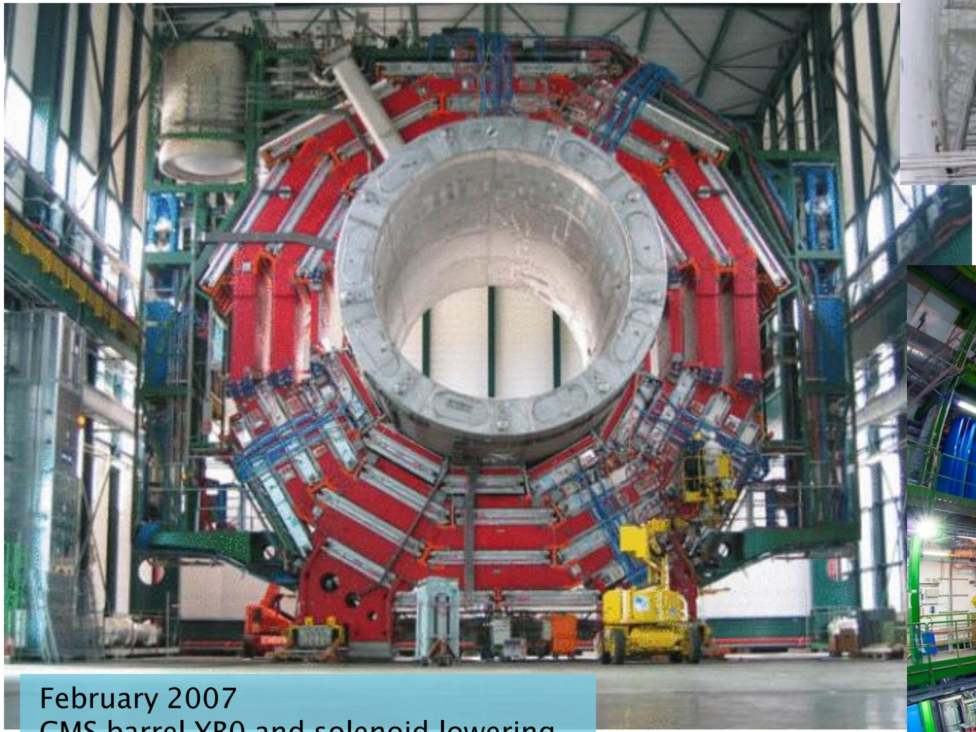
October 1992 — October 2012

2007: Physics TDR
2008: CMS ready for beams
2009: First Physics

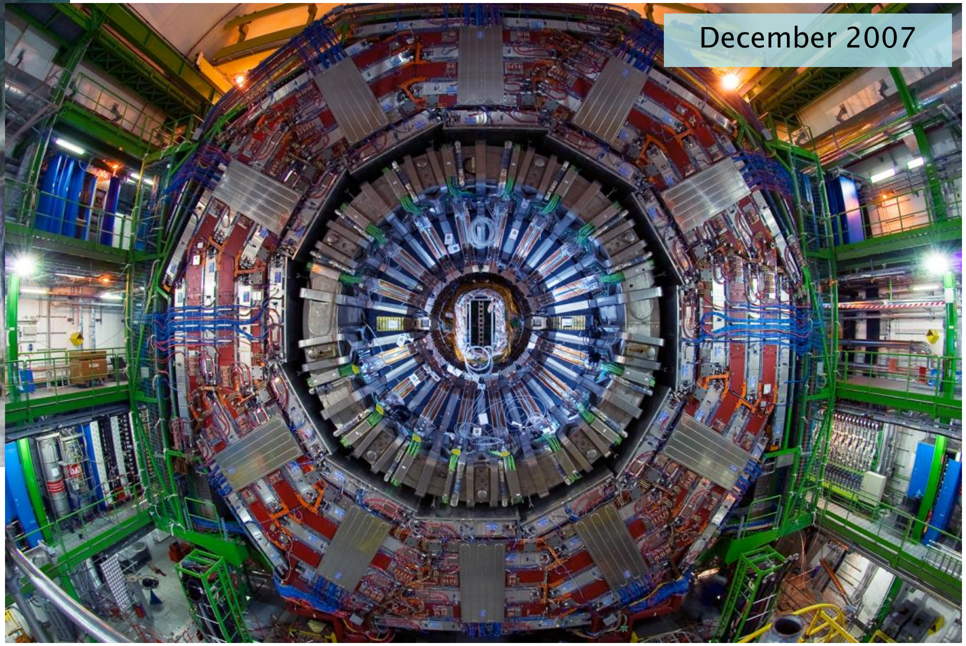
CMS construction timeline



1st February 2005
CMS cavern inauguration

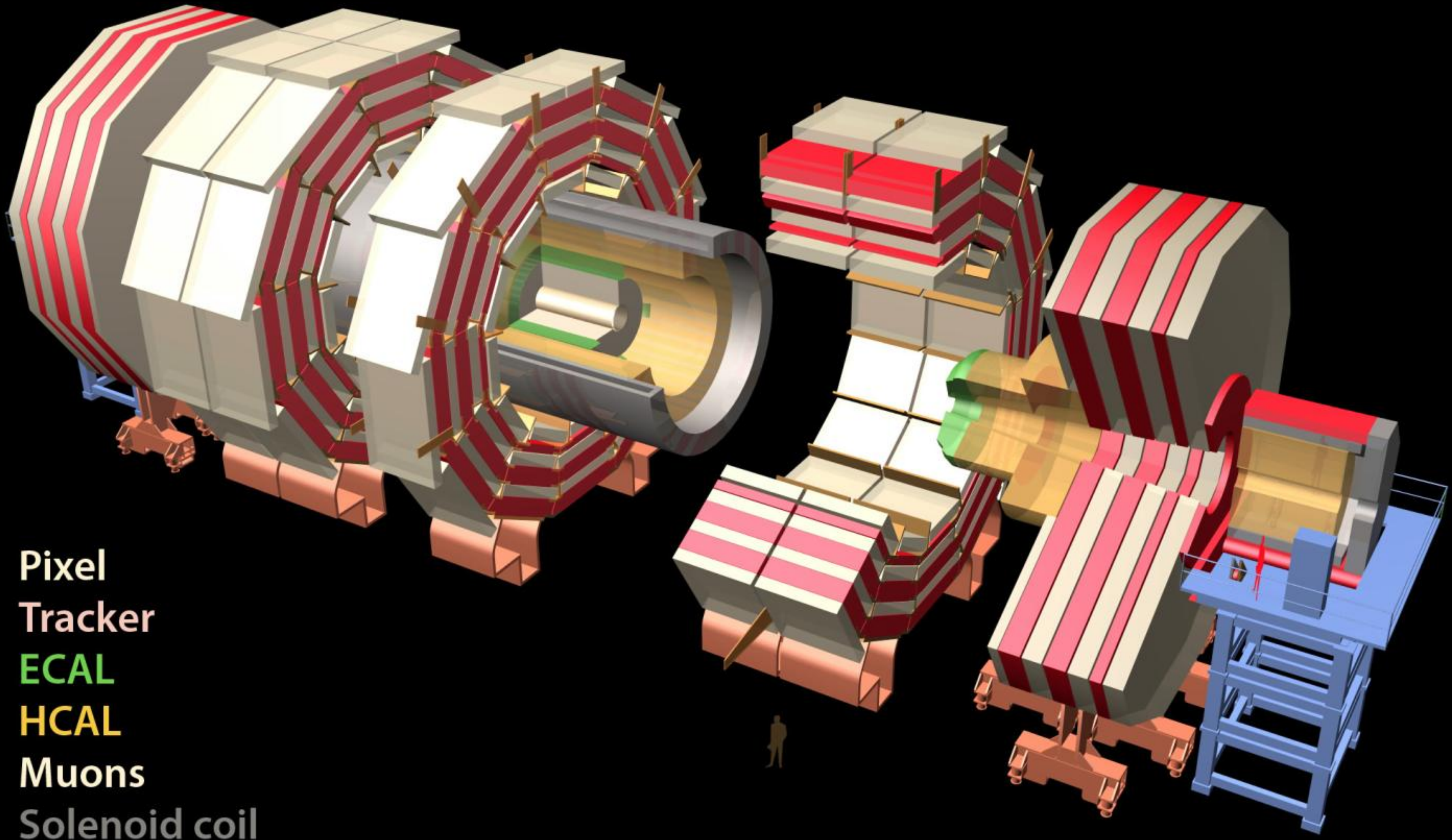


February 2007
CMS barrel YB0 and solenoid lowering



December 2007

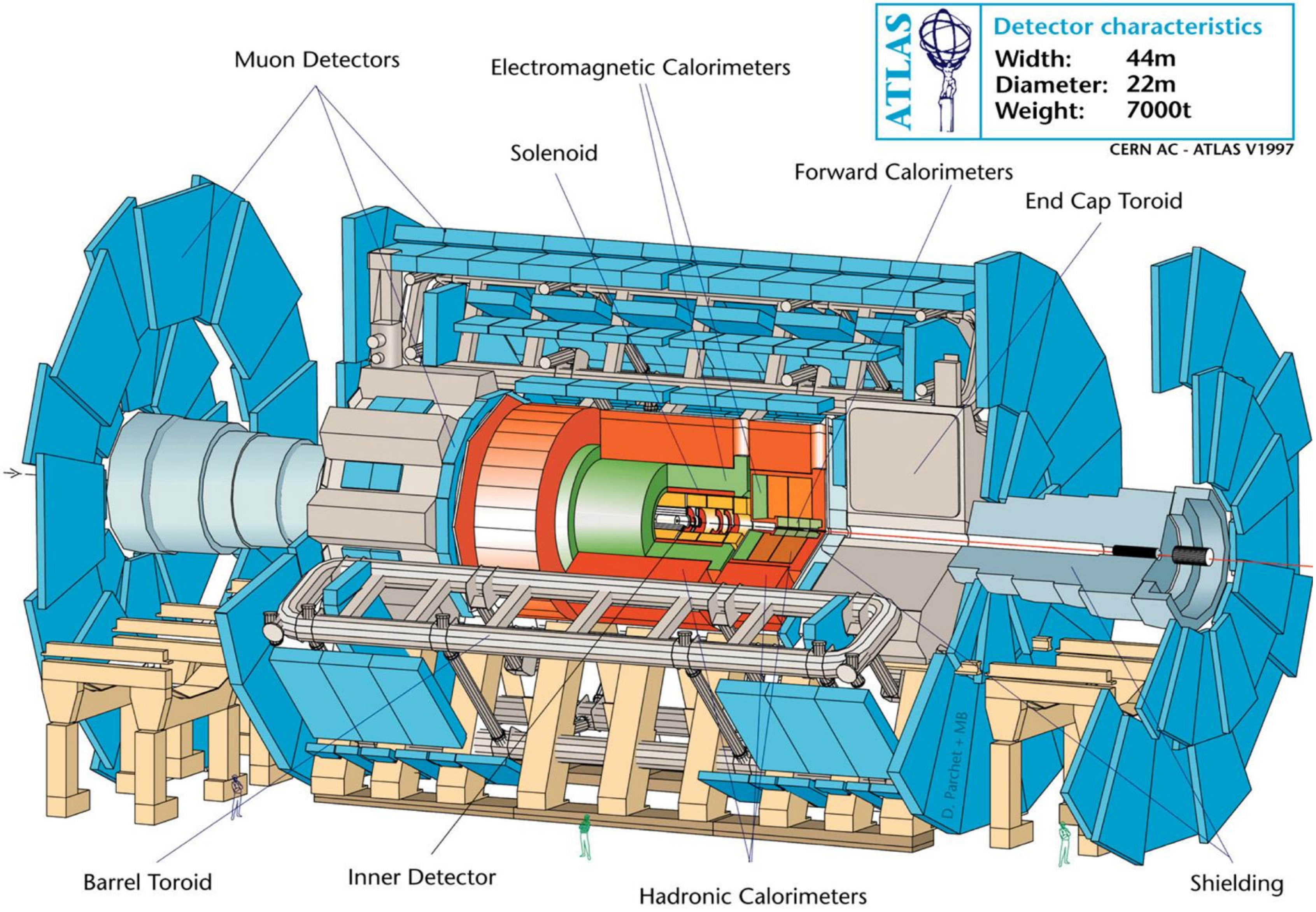
The CMS Detector



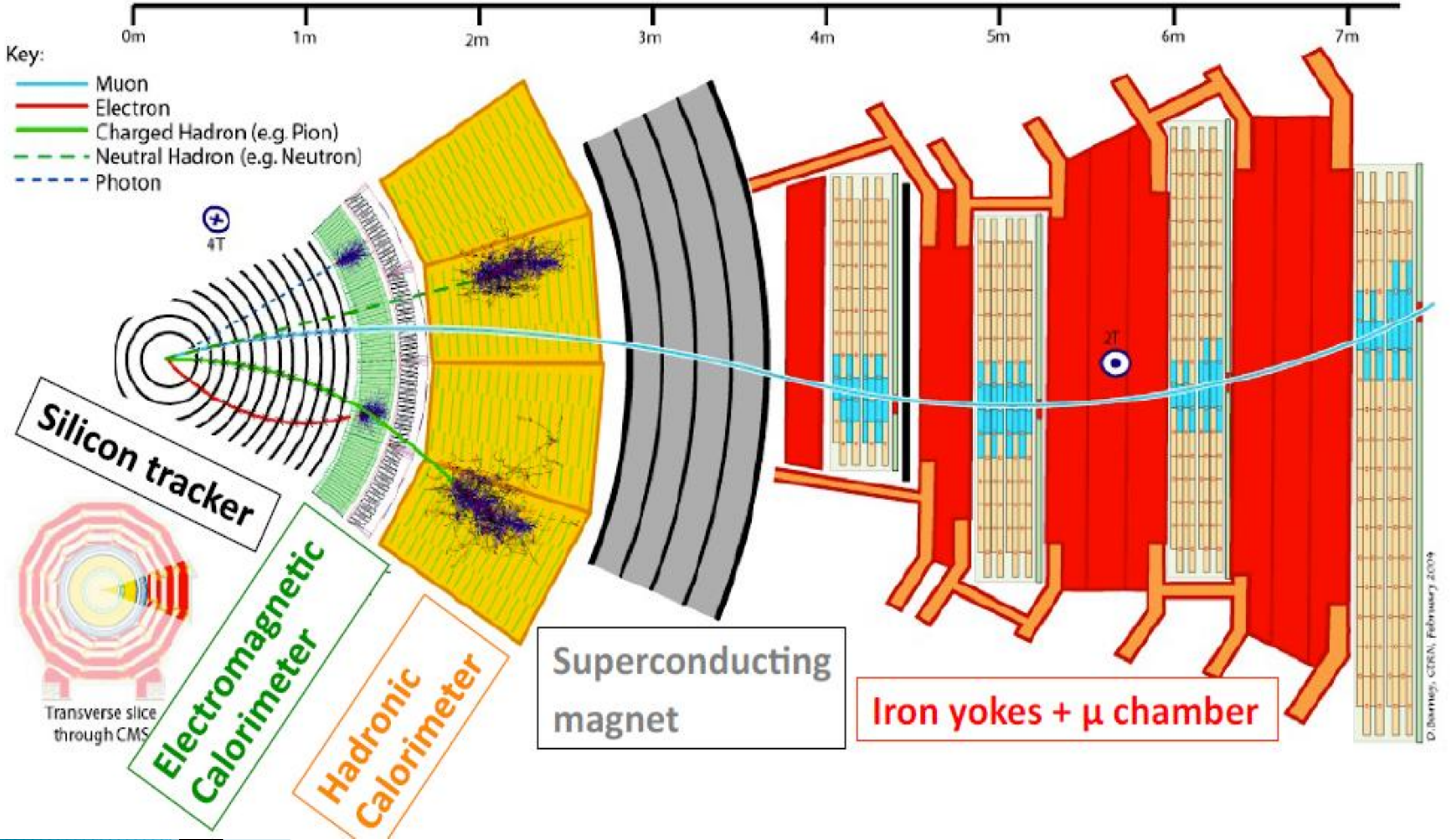
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil

Total weight 12500 t, Overall diameter 15 m, Overall length 21.6 m, Magnetic field 4 Tesla

The ATLAS detector



How are particles detected?



So how do we detect a “Z” Boson?

Can we detect it directly?

NO! Most particles will decay very soon after being produced.
What we really observe (measure) are the end products.

So what does the Z decay into?
$Z \rightarrow l^+ l^-$ where l = e, μ, τ, υ

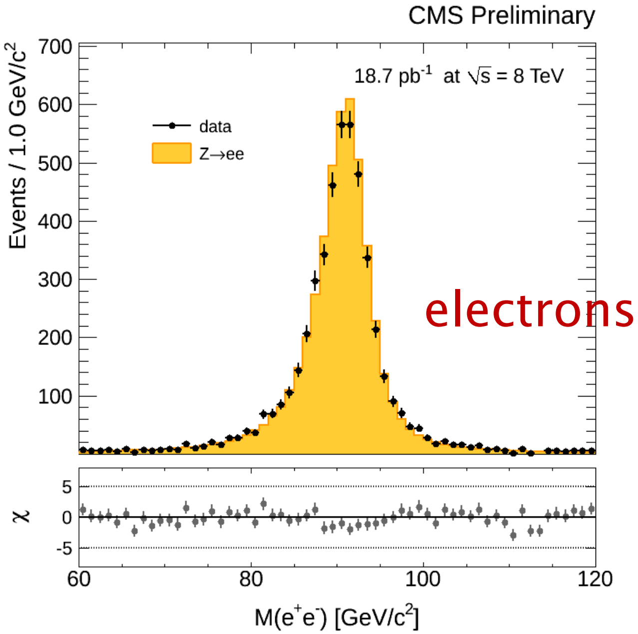
Z invariant mass

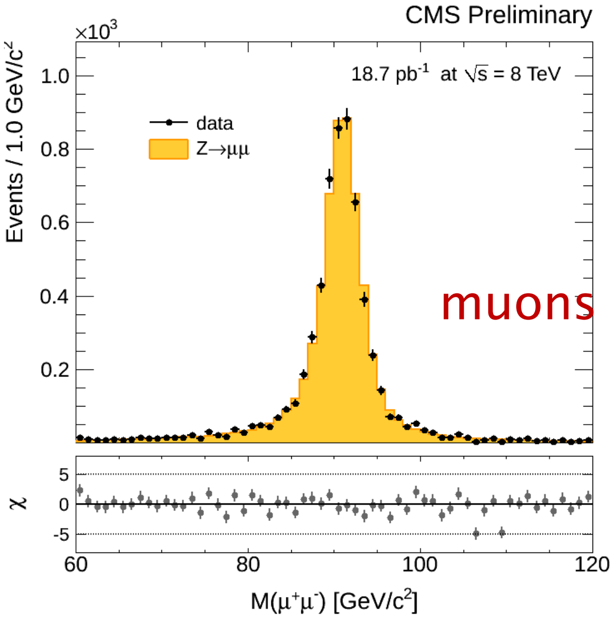
$$m_0^{(Z)} = \sqrt{\left(m_0^{(1)}\right)^2 + \left(m_0^{(2)}\right)^2 + 2\left(\frac{1}{c^4}\cdot E_1\cdot E_2 - \frac{1}{c^2}\cdot \vec{p}_1\cdot \vec{p}_2\right)}$$

We know the mass of the leptons

We can measure their energy and momenta from the detector

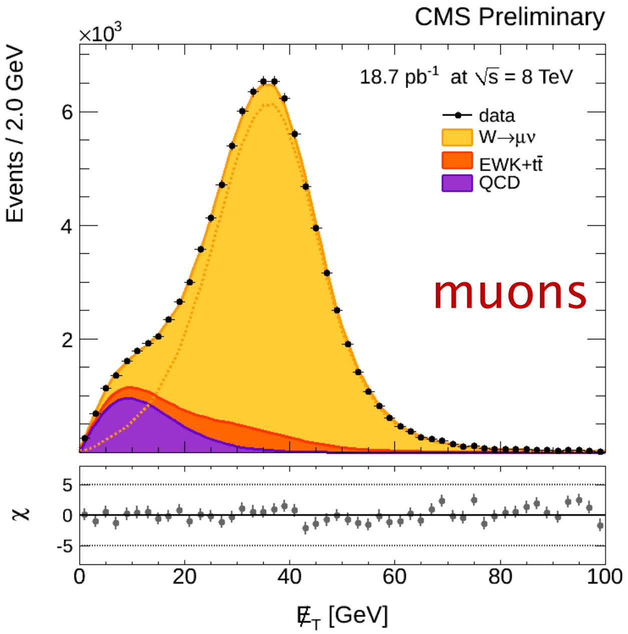
Choose events with with 2 clean leptons

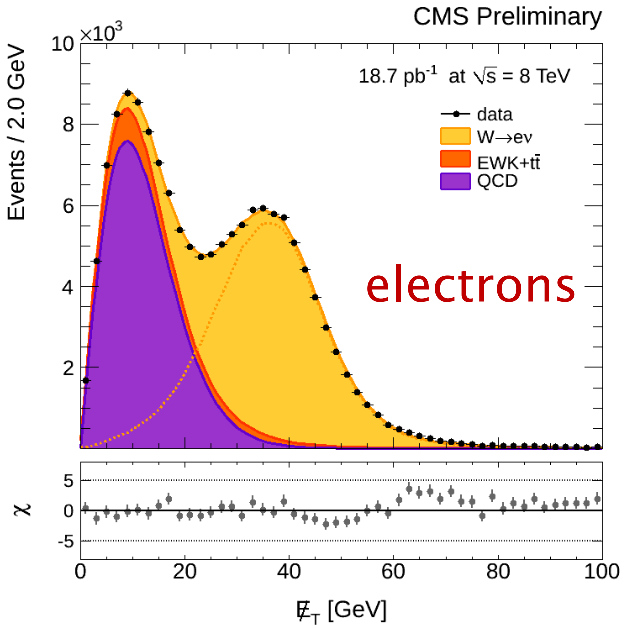




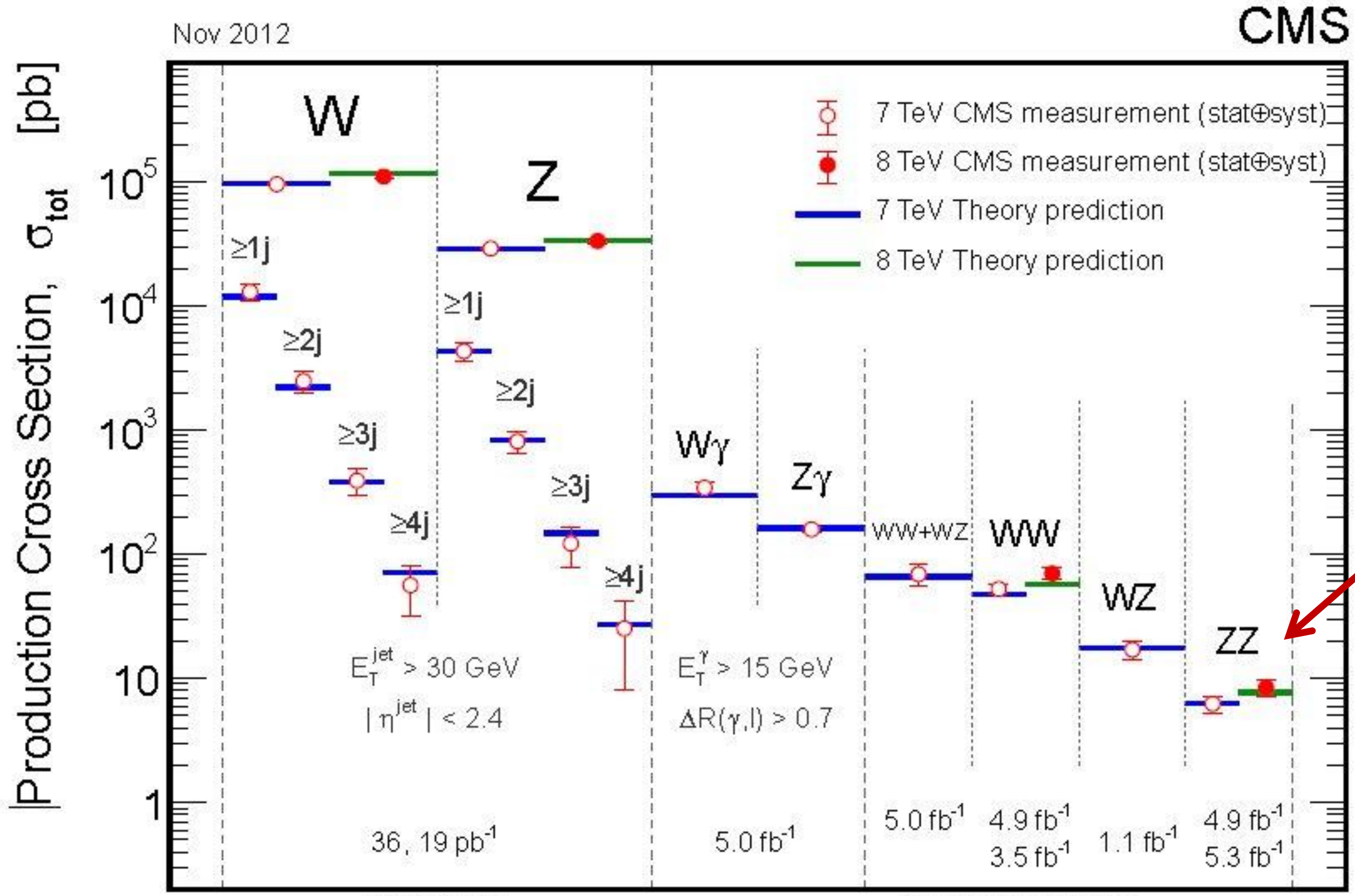
How about the “W” Boson?

- We need to know what the W decays into
  - W → lυ where the lepton can be an electron or a muon
  - We can measure the momentum of the lepton
  - Negative of the vector sum of the energies of all the particles in the event gives the “missing energy” in the event → this is my neutrino.
  - Compare distributions with what is expected from theory





How often can we spot a Higgs?



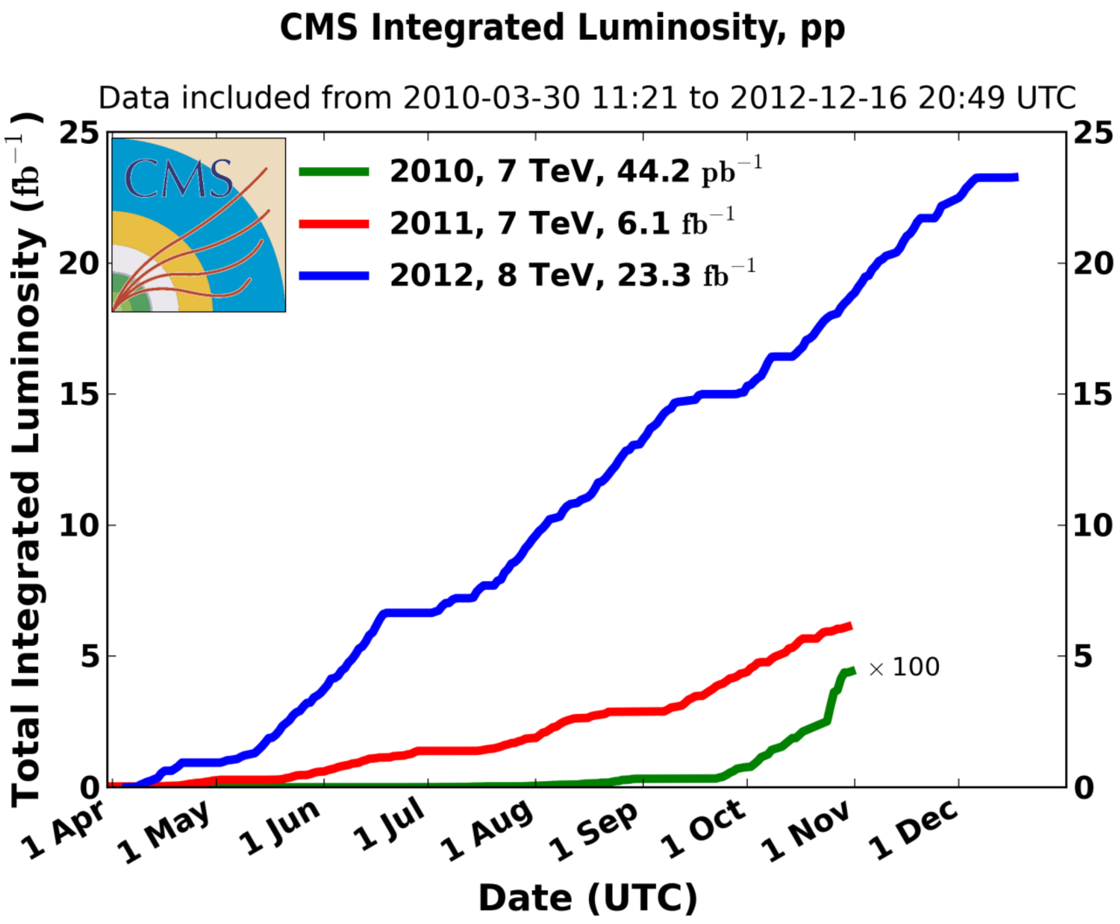
JHEP10(2011)132
JHEP01(2012)010
CMS-PAS-SMP-12-011 (W/Z 8 TeV)

CMS EWK-11-009

CMS-PAS-EWK-11-010 (WZ)
CMS-PAS-SMP-12-005 (WW7),
007(ZZ7), 013(WW8), 014(ZZ8), 015(WV)

Higgs is way down here

How much data do we have?



December 2012

Integrated Luminosity
2012 8 TeV

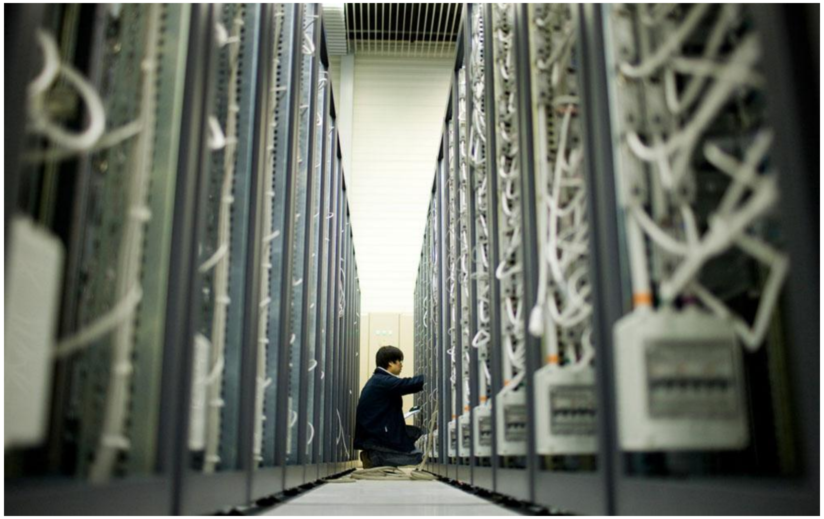
Delivered 23.3 fb^{-1}
Recorded 21.8 fb^{-1}

Integrated Luminosity
2011 7 TeV

Delivered 6.13 fb^{-1}
Recorded 5.55 fb^{-1}

How do we sort through all this data?

- We generate much more data than we record
  - cant control what we generate
  - limited by readout (electronics)
  - limited by computing (CPU)
  - limited by hardware (storage)
  - not all events are interesting

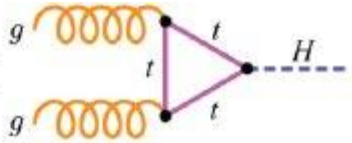


- So we filter the data
  - We use "Triggers" to do this
  - CMS has a 2 level trigger system
    - The L1 trigger and the High Level Trigger
    - Triggers are based in hardware as well as software
    - Of 40 MHz of incoming data 100 Hz is stored to tape.

How do we find the Higgs?

How is the Higgs Produced?

1)



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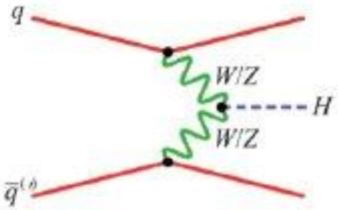

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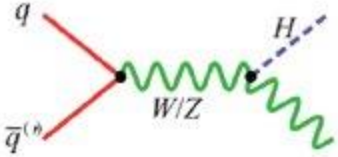
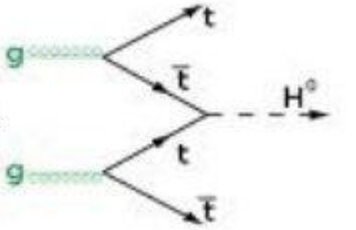
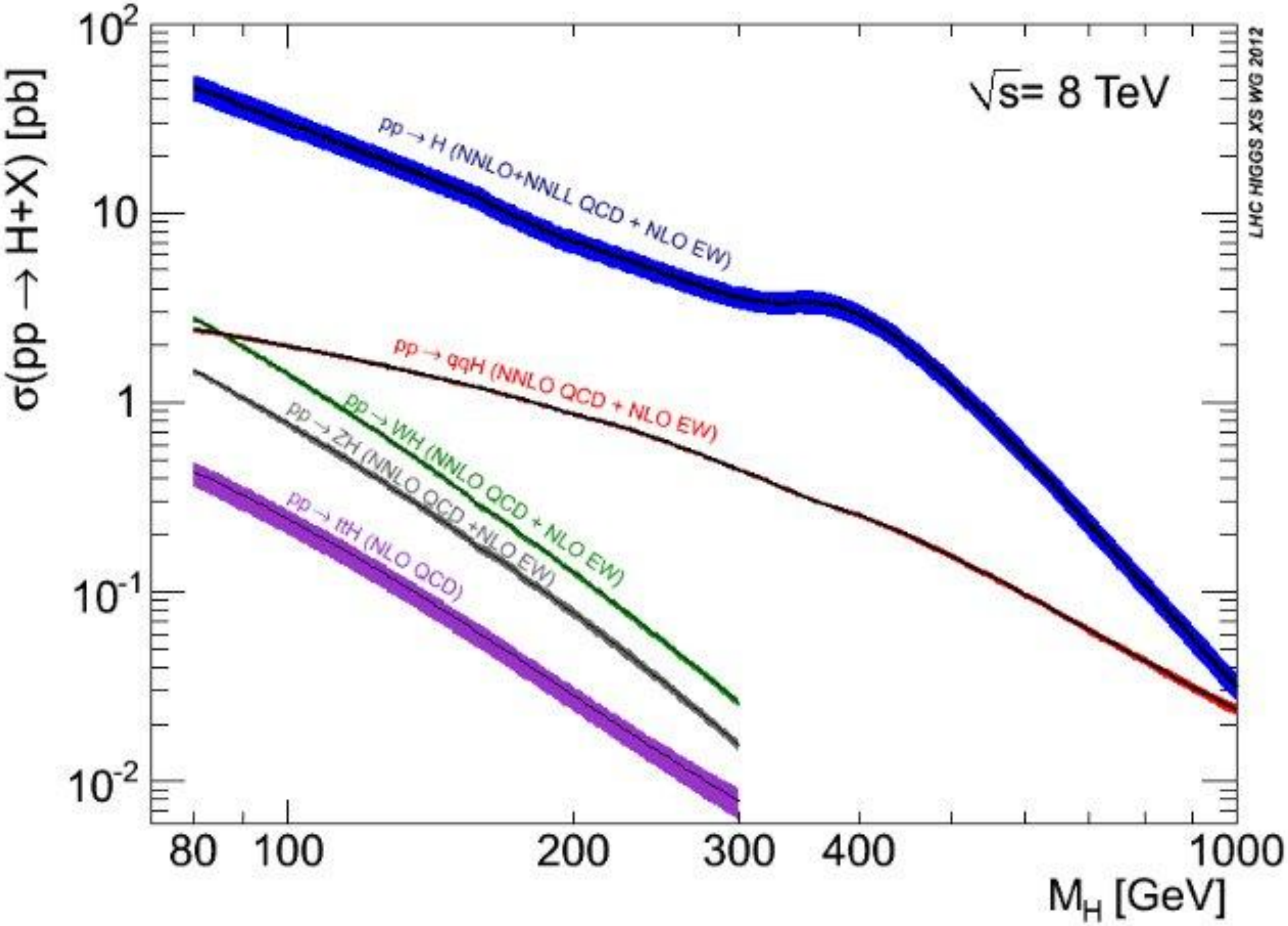


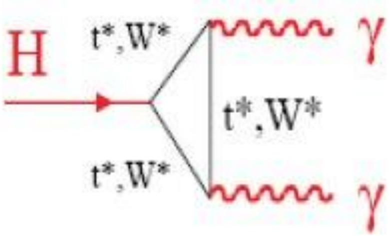
4)



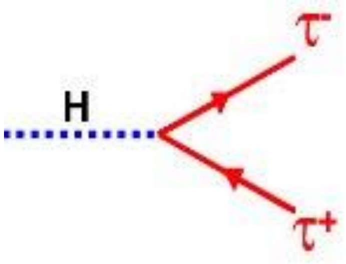


How does the Higgs Decay?

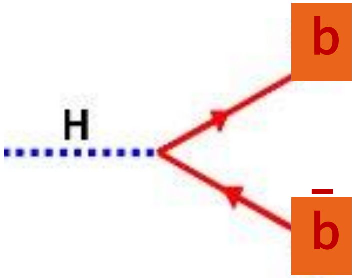
$H \rightarrow \gamma\gamma$



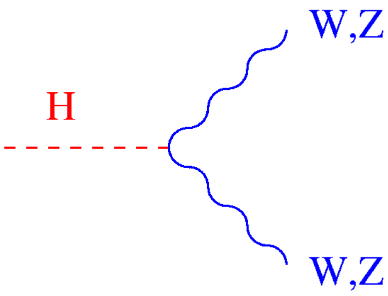
$H \rightarrow \tau\tau$

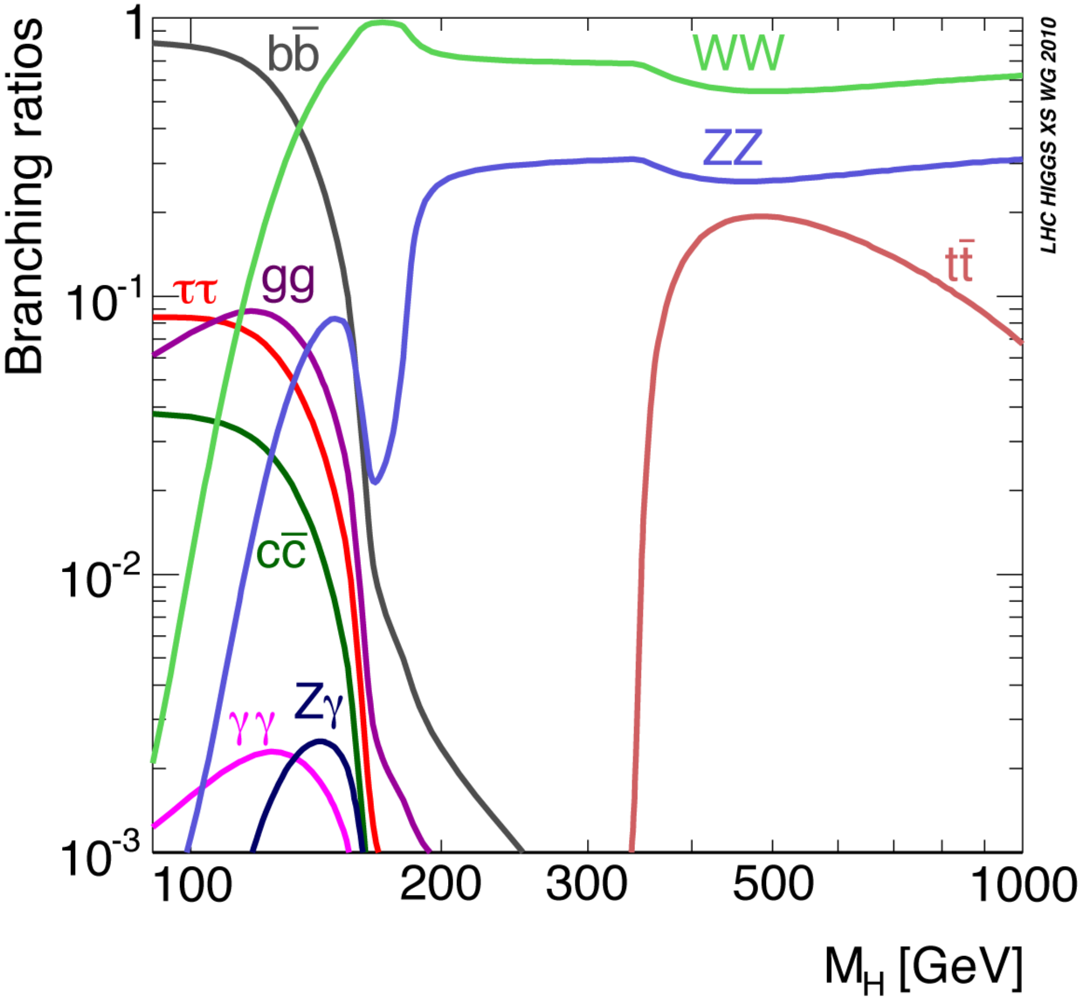


$H \rightarrow bb$



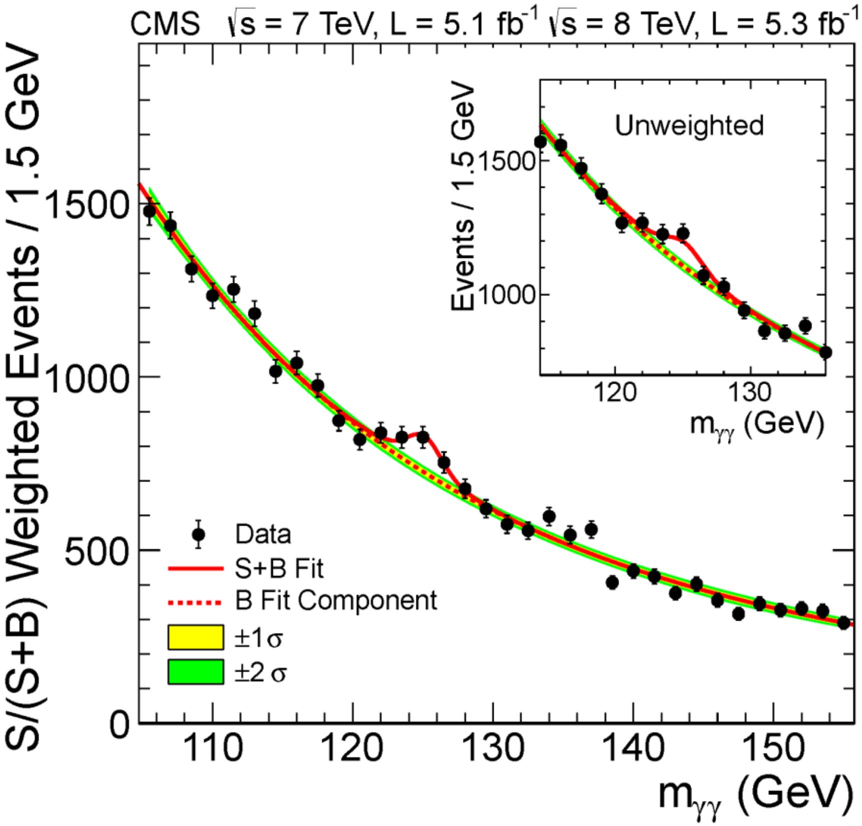
$H \rightarrow WW$, $H \rightarrow ZZ$



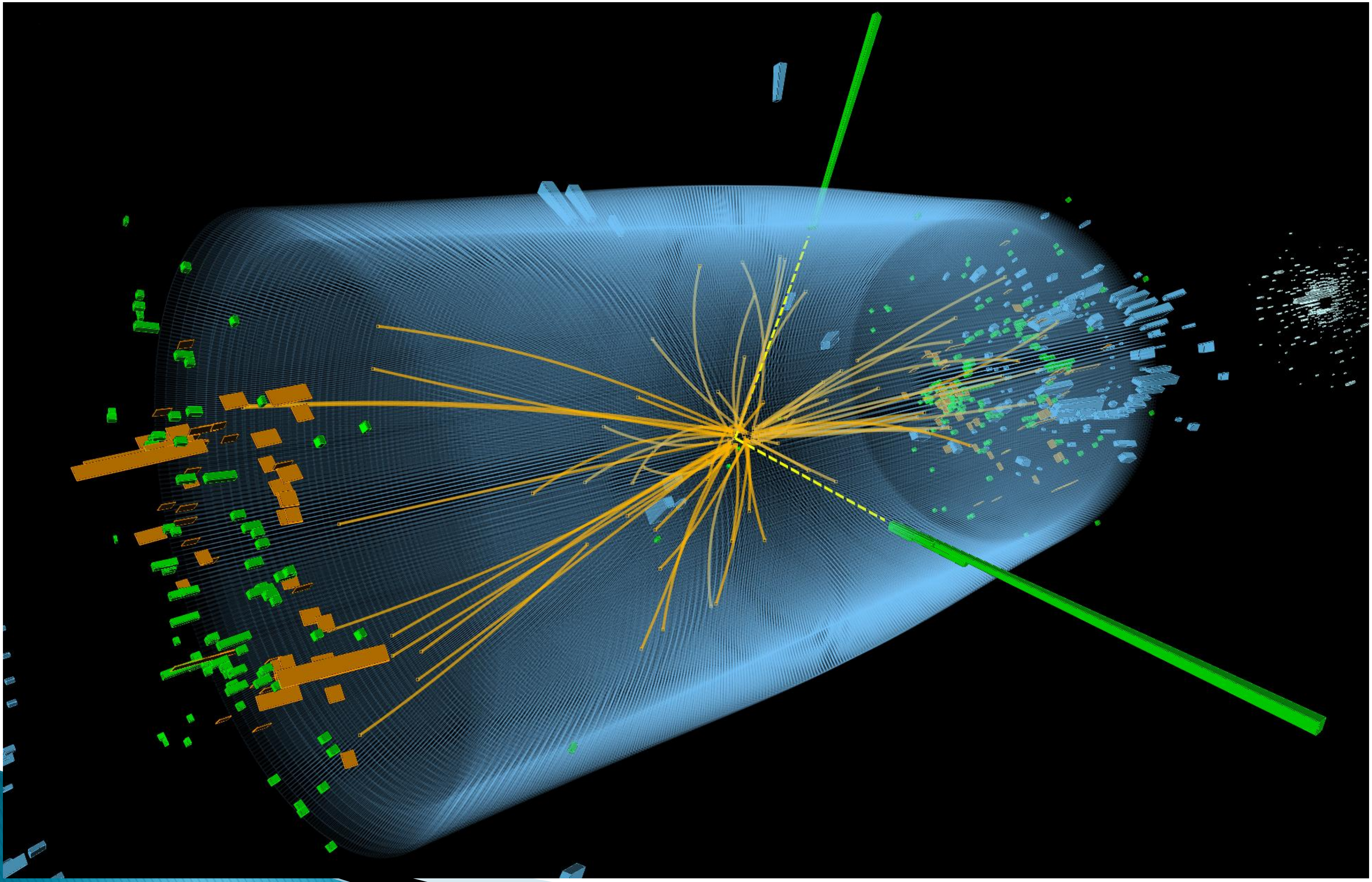


Higgs decaying to 2 photons

- $H \rightarrow \gamma\gamma$ is the fundamental decay channel for the discovery and mass measurement of the Higgs
- We have a nice final state with 2 well identified photons – thanks to ECAL
- We get a clean peak for the diphoton invariant mass
- Backgrounds can be dealt with easily

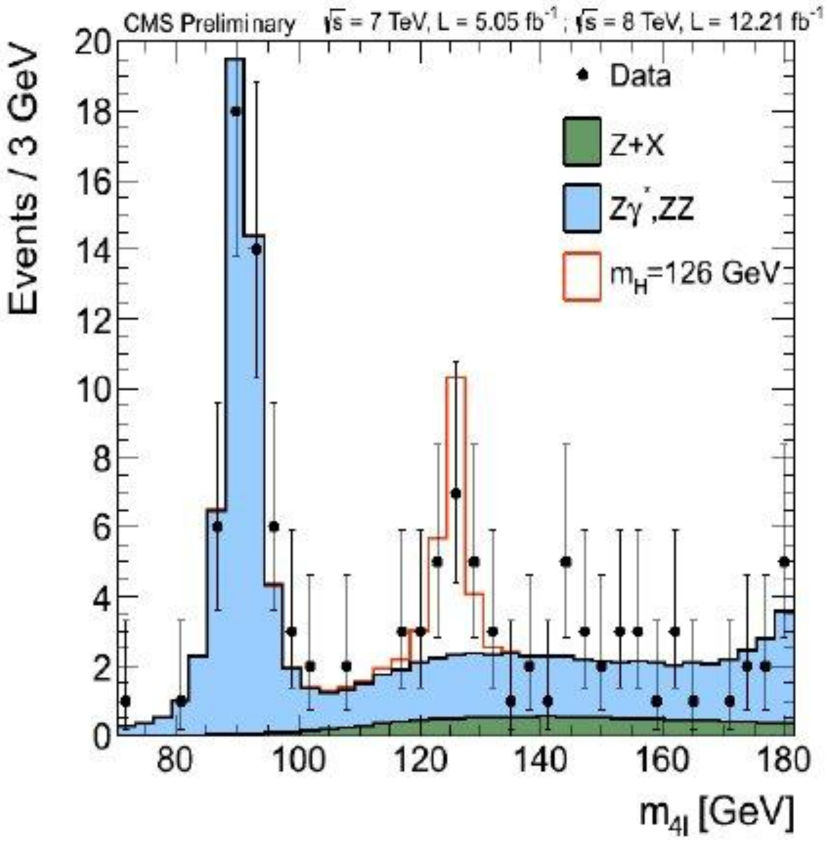


A candidate for H→$\gamma\gamma$

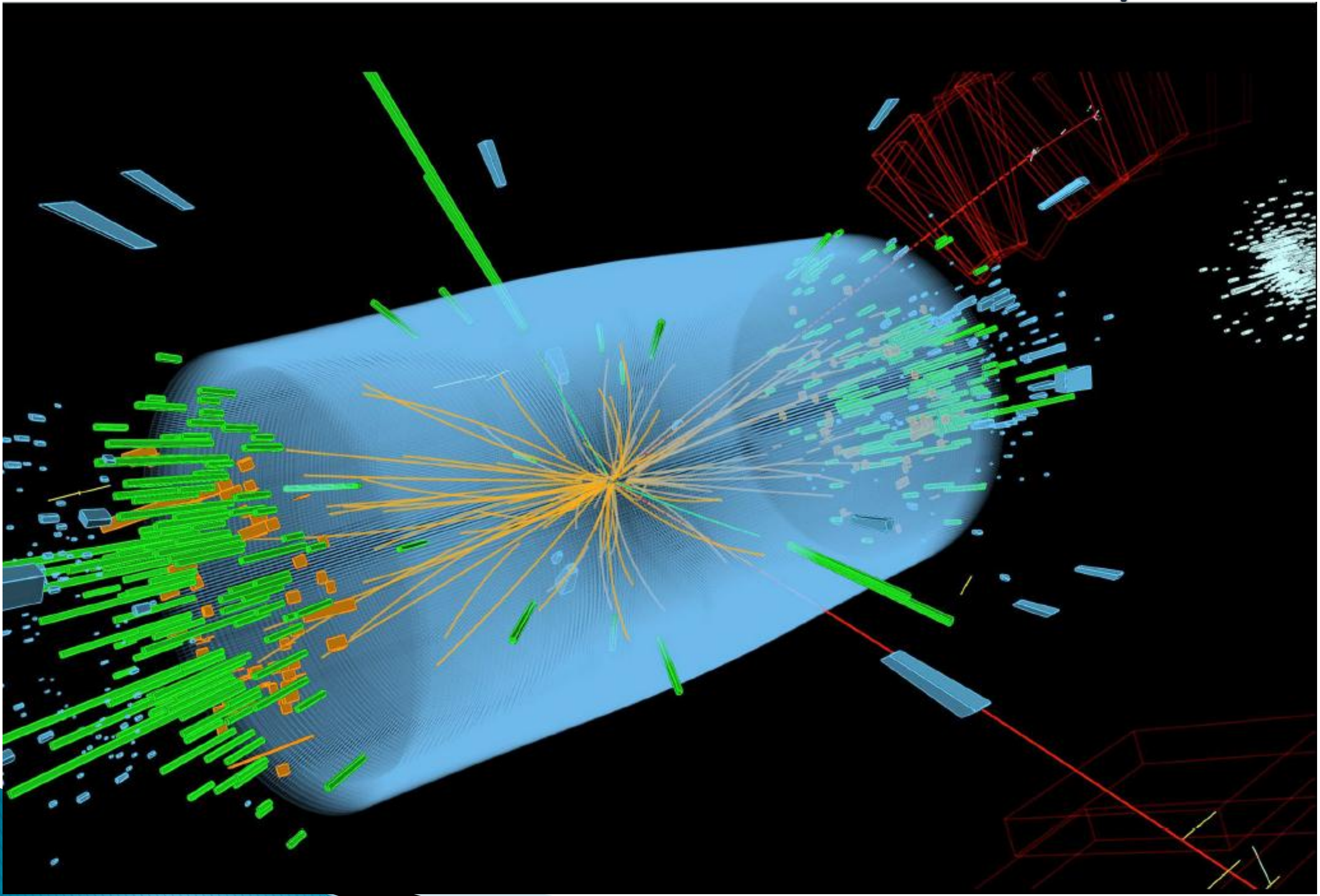


Higgs decaying to 4 leptons

- H → ZZ → 4l is a very clean signature
  - Hard to find many events with exactly 4 leptons
- There are 11 channels due to lepton flavor
- Leptons with large transverse momentum can be identified and measured very precisely
  - so also the Higgs mass can be calculated very precisely
- We can model the main backgrounds well using our knowledge of theory
- Can use this channel to measure spin and parity of the Higgs Boson



A candidate for $H \rightarrow ZZ \rightarrow 2e2\mu$



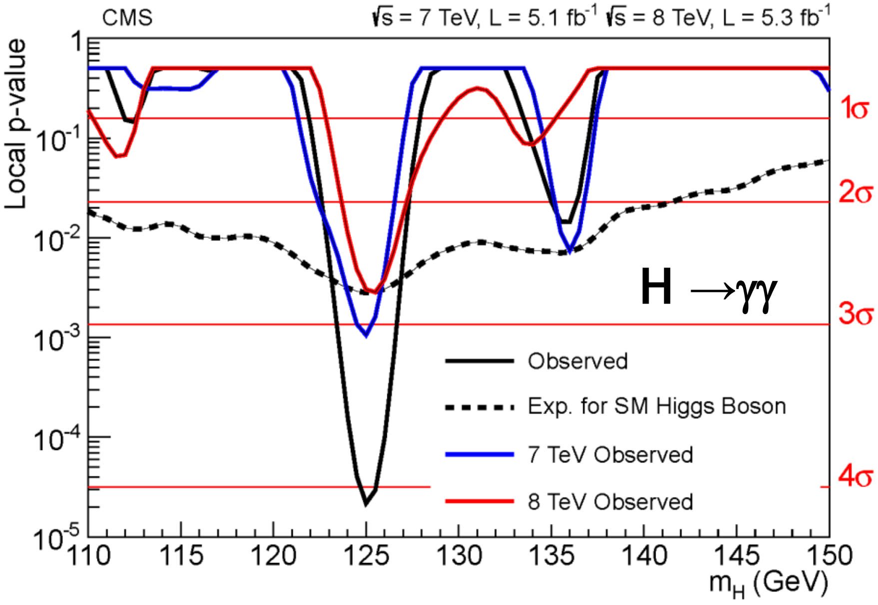
What about the other decay channels?

- We also have measurements from the other channels but these are more challenging

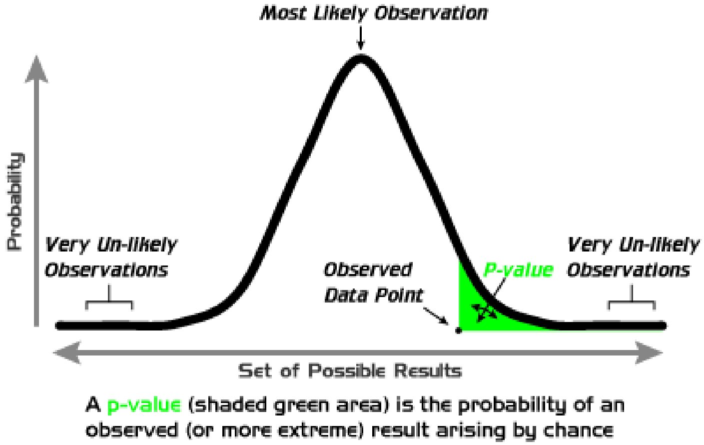
- H → WW →2l2υ
  - Need to know our backgrounds very precisely
  - Having 2 neutrinos makes it hard to reconstruct mass

- H → ττ and H → bb
  - Both have high Branching ratios but are rather challenging experimentally

Combined channel results



The observed local p-values



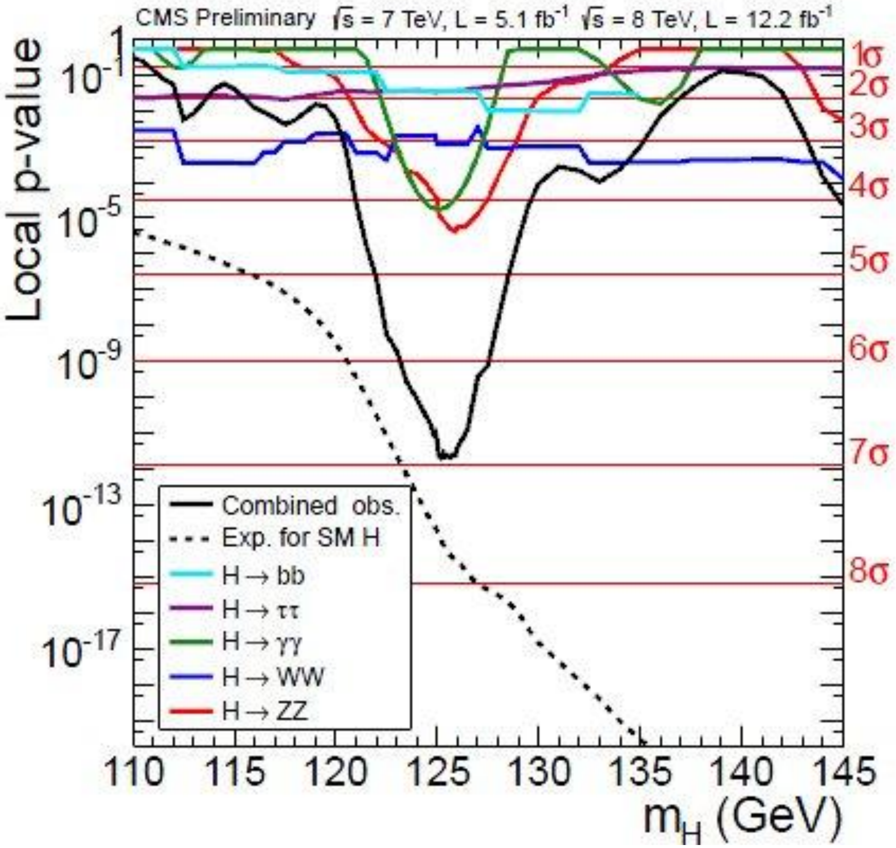
A p-value (shaded green area) is the probability of an observed (or more extreme) result arising by chance

The mass m_H is determined using the $\gamma\gamma$ and ZZ decay modes. The best fit gives us this value:

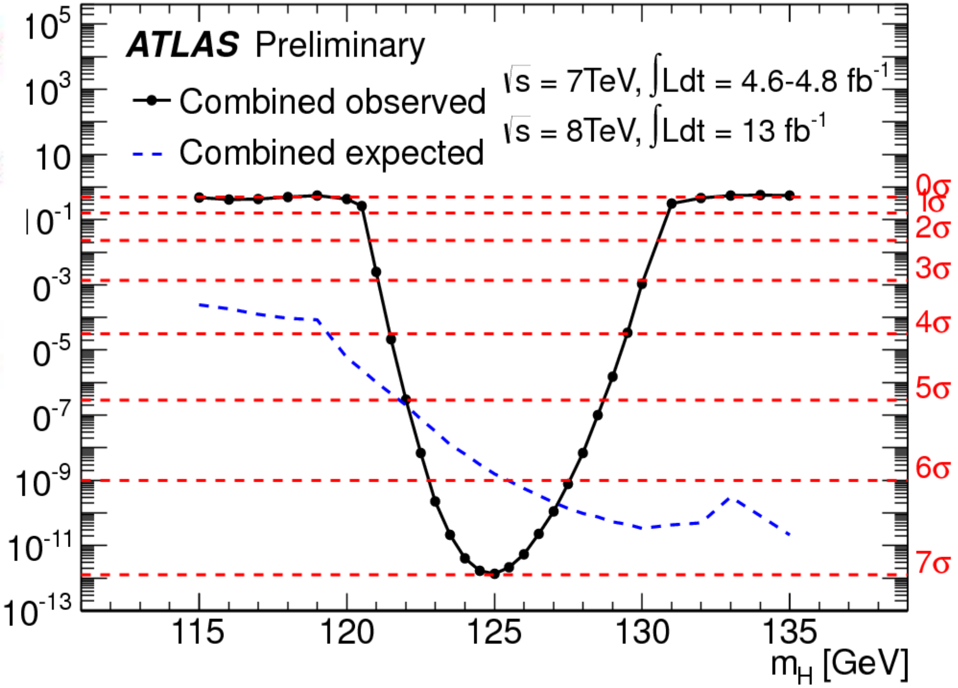
m_H = 125.3 ± 0.4 (stat.) ± 0.5 (syst.) GeV → July 2012

m_H = 125.8 ± 0.4 (stat.) ± 0.4 (syst.) GeV → Nov. 2012

Latest Results from CMS and ATLAS

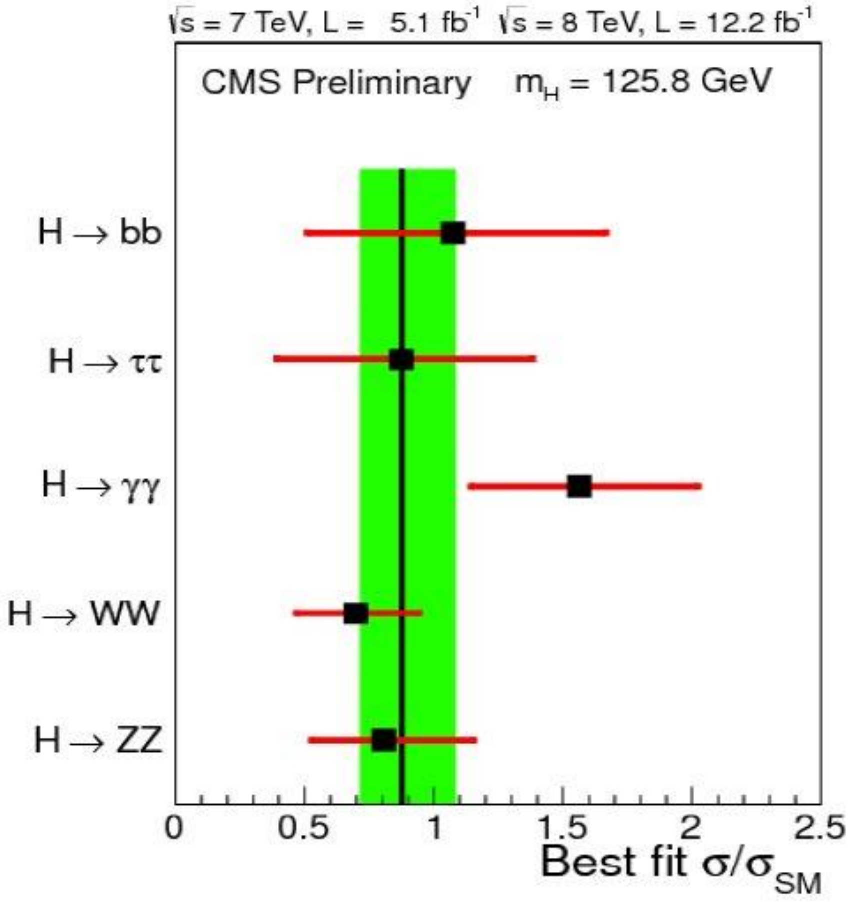


Both experiments independently see a Higgs like Boson with a mass of about 125 GeV @ 7σ



What's next?

- What we have so far seems to indicate that we have found a SM Higgs
  - Need to further verify that
  - Analyze full collected data
  - Make sure there are no other Higgs lurking out there
  - Measure the mass and other properties of the Higgs Boson more precisely
  - Measure the coupling constants
  - Try to come up with a new theory to explain what is still unknown!!



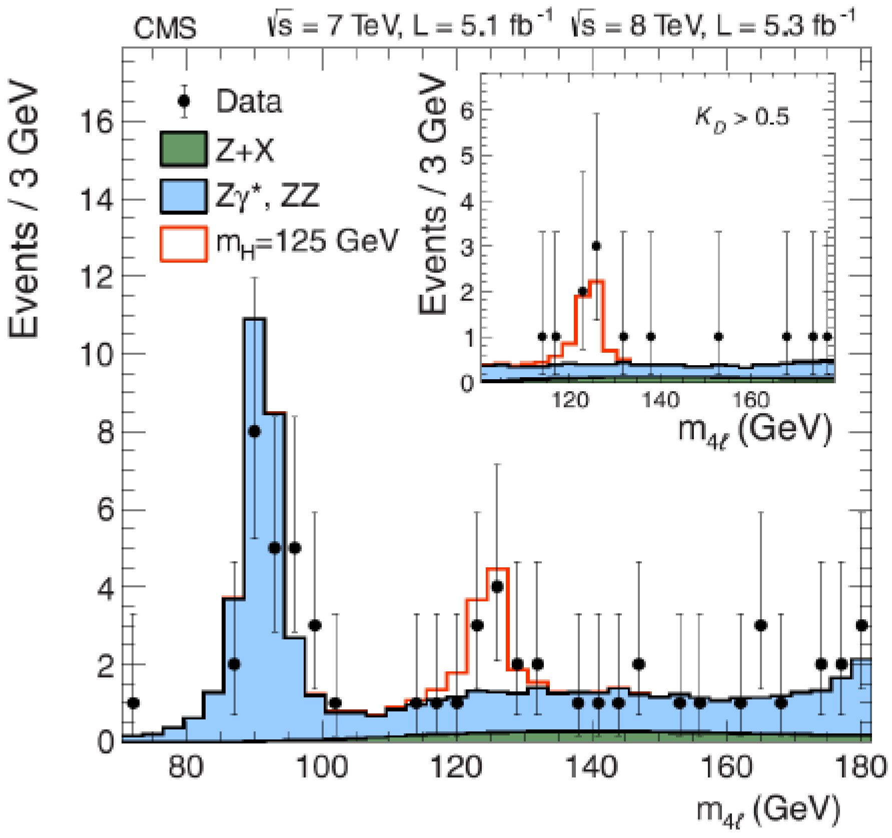
Peter Higgs

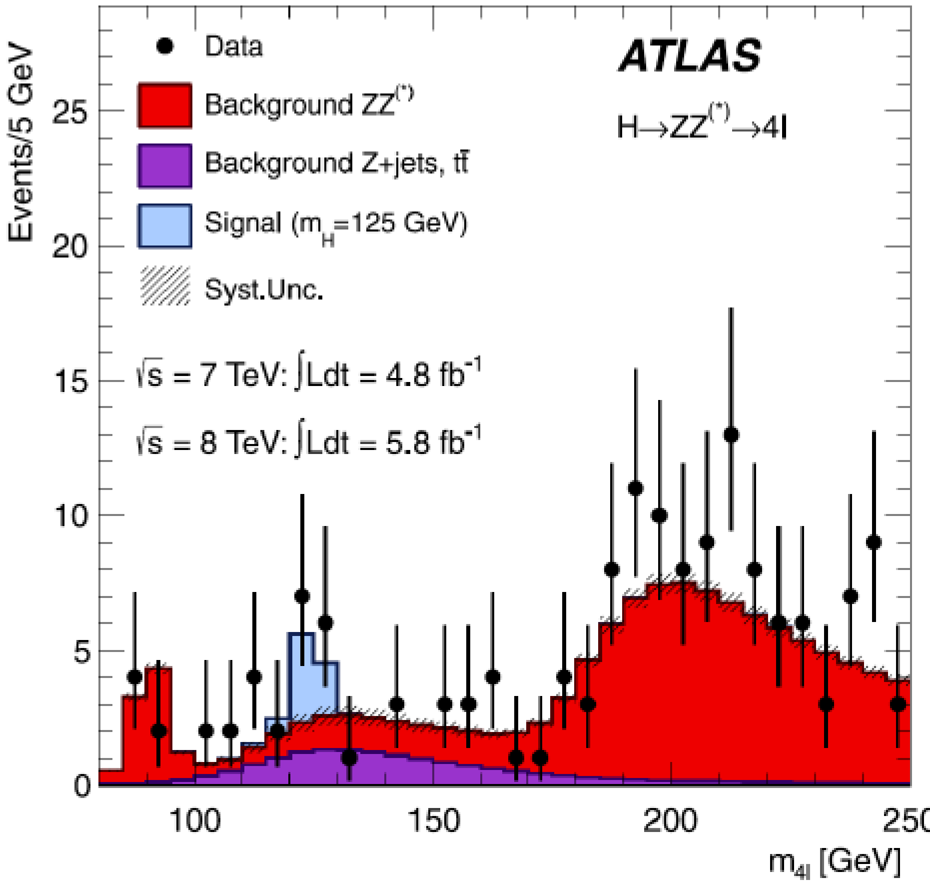
At CMS in April 2008

At CERN for the Higgs discovery announcement in July 2012

Backup Slides

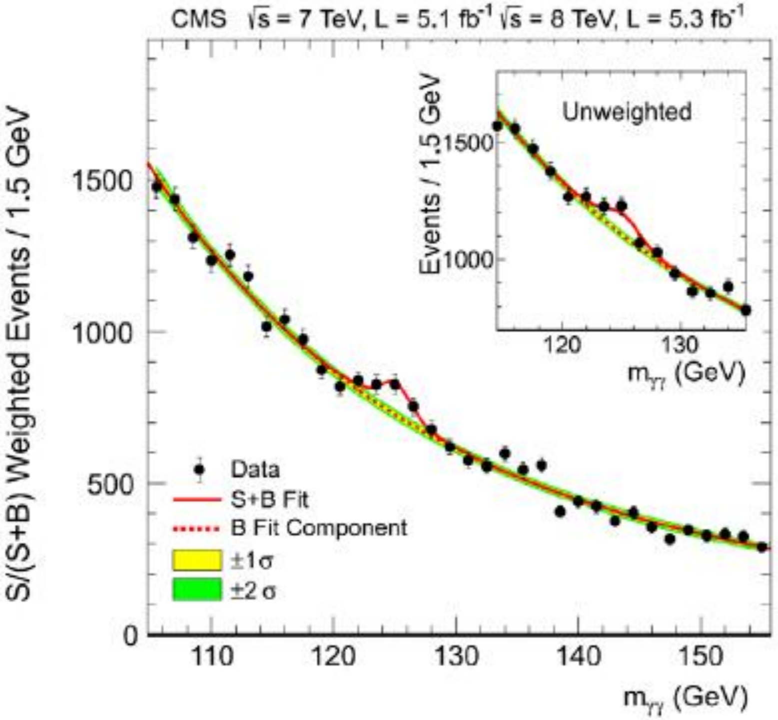
July 4:
We show frequency of invariant mass for each four-lepton event.

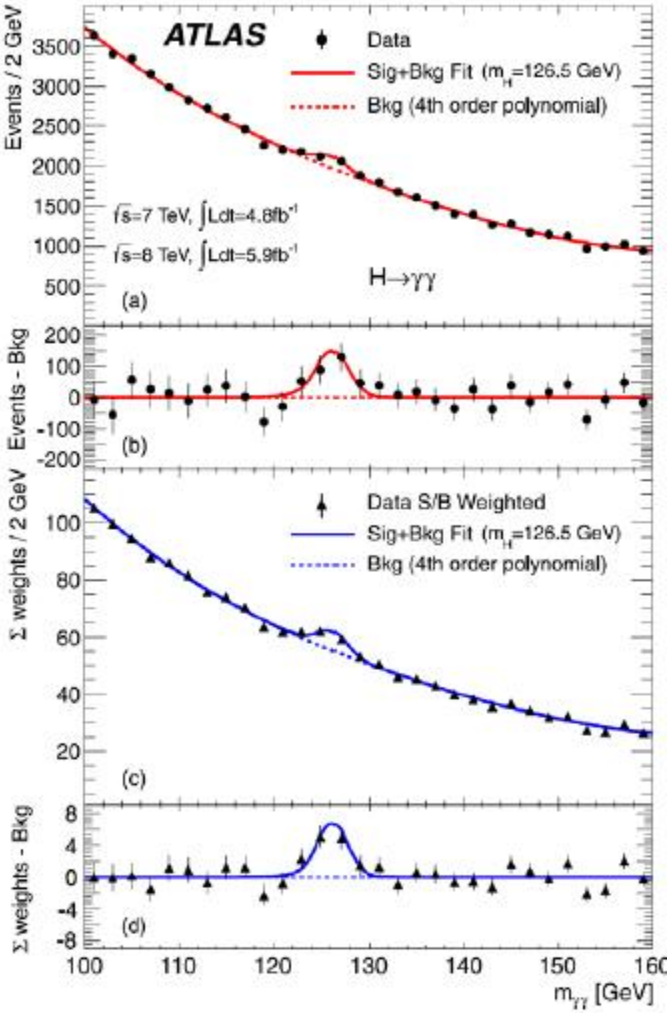




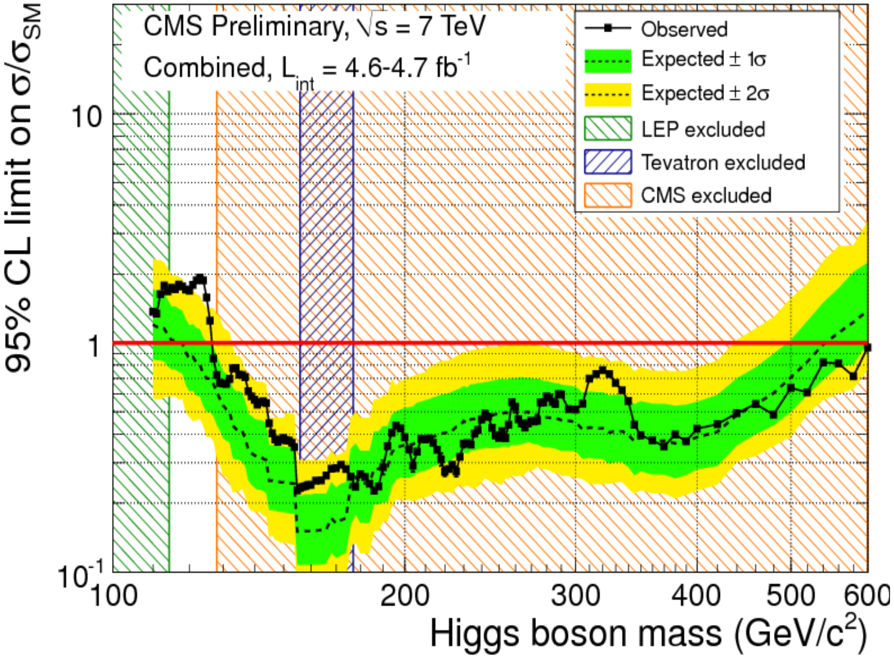
CMS, ATLAS both see excess near 125 GeV!

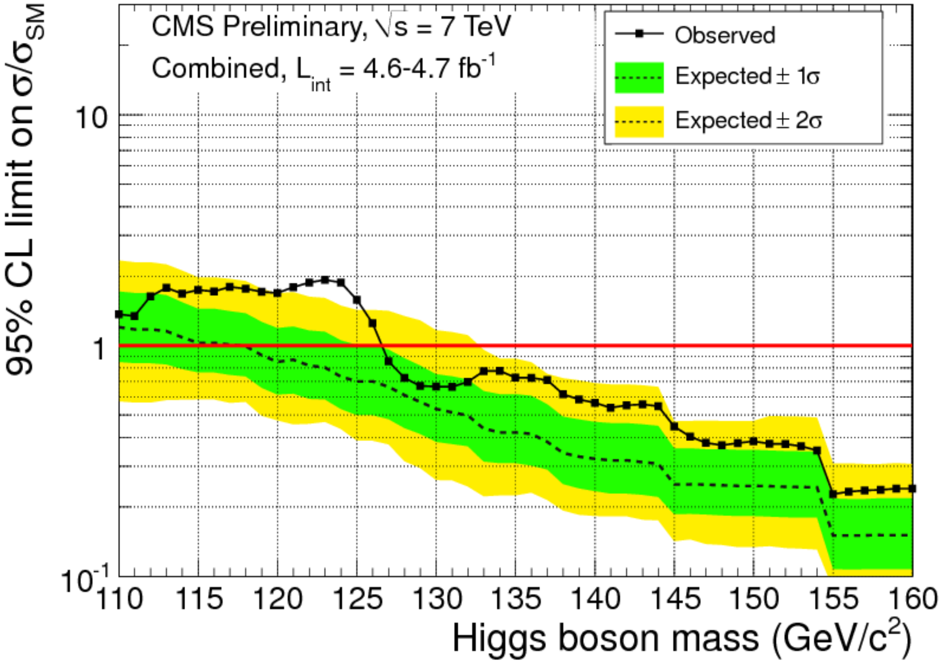
July 4:
CMS, ATLAS both see excess near 125 GeV!





CMS and ATLAS each conclude “observation” of a new particle!
CERN announces discovery.


CMS Preliminary, $\sqrt{s}$ = 7 TeV
Combined, L_{int} = 4.6-4.7 fb^{-1}
Observed
Expected ± 1σ
Expected ± 2σ
LEP excluded
Tevatron excluded
CMS excluded
95% CL limit on σ/σ_{SM}
10^{-1}
1
10
100
200
300
400
500
600
Higgs boson mass (GeV/c^2)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10^{-1}
1
10
110
115
120
125
130
135
140
145
150
155
160
Higgs boson mass (GeV/c^2)

Think of the Higgs this way….

- All particles in Physics (photons, electrons, quarks) are viewed as a sort of quantum field.
- Most have a zero “vacuum expectation value”
  - In empty space we expect no photons, no electrons etc

- The Higgs is a special sort of quantum field.
- It has a non-zero “vacuum expectation value”
  - The Higgs field permeates all of space – it is everywhere
  - All particles acquire mass due to their interactions with this field.
  - The Higgs boson is a manifestation of the Higgs field