

# *The Discovery of a Higgs Boson at the Large Hadron Collider*

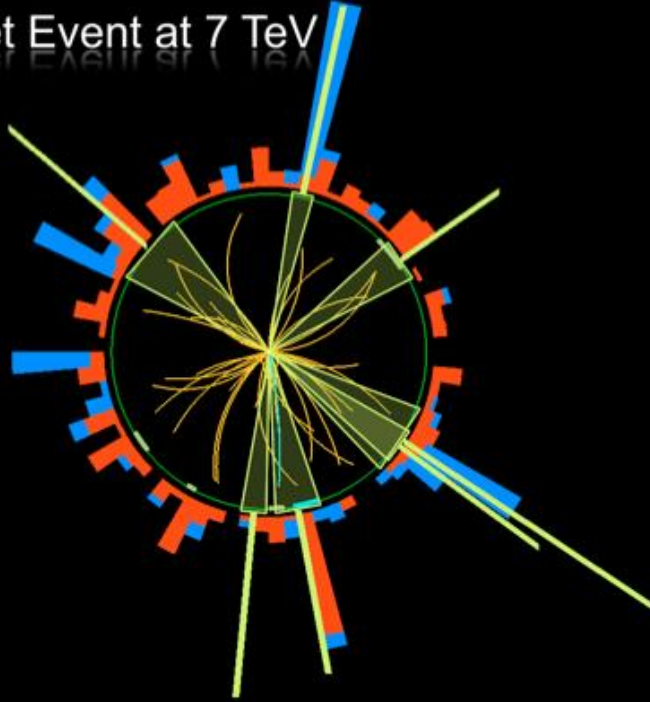
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CERN, Geneva, Switzerland  
Antwerp University Belgium  
UC-Davis California USA  
IPPP, Durham UK  
BU, Cairo, Egypt

20 September 2013



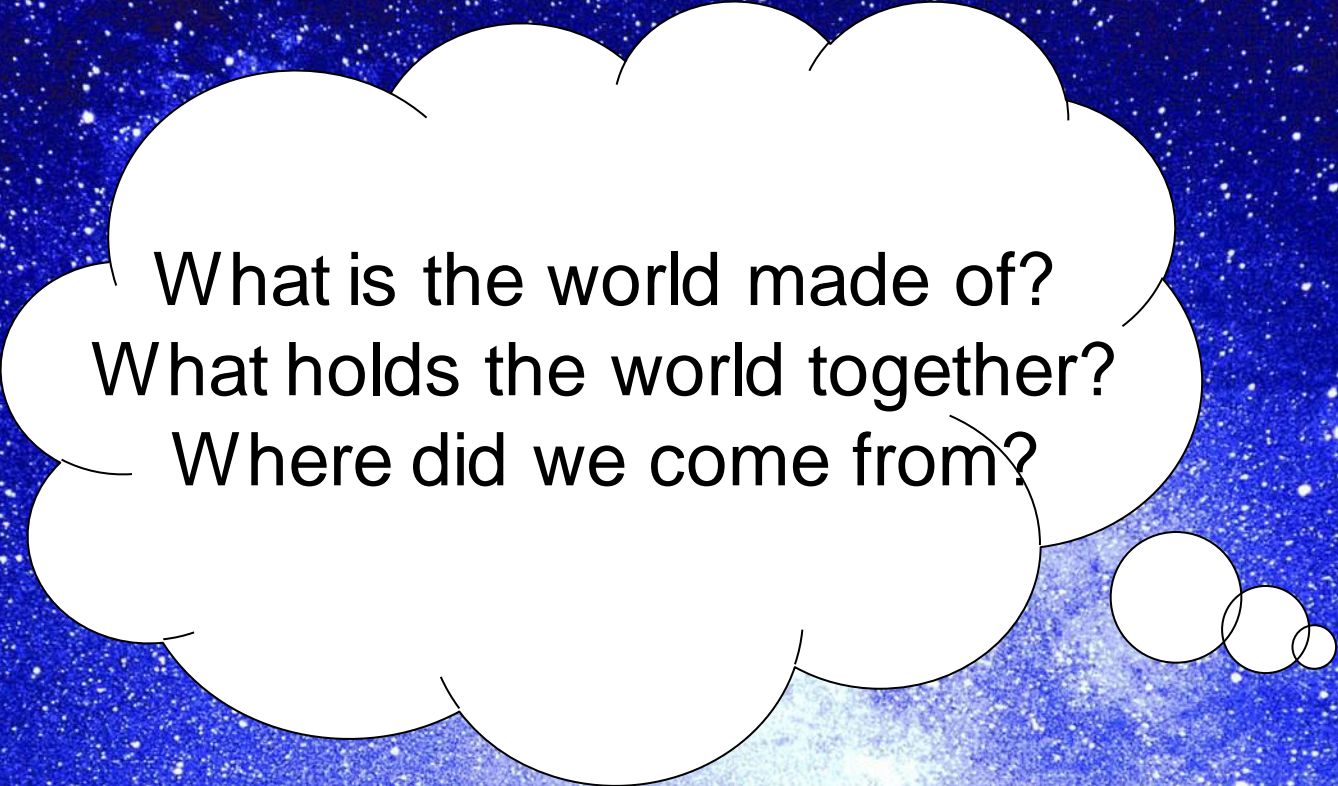


Multi Jet Event at 7 TeV



# Outline

- Introduction: The LHC and the Higgs hunter experiments
- Higgs searches
- The birth of a new particle
- Studies of Higgs properties
- What is next?
- Summary



What is the world made of?  
What holds the world together?  
Where did we come from?

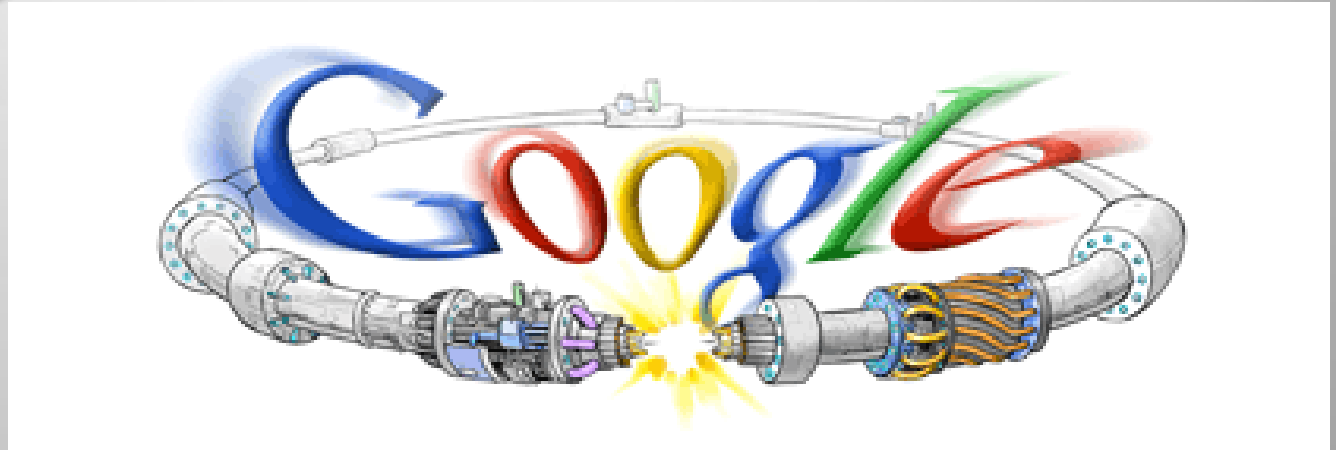
**Particle physics is a modern name for centuries old  
effort to understand the laws of Nature**

**E. Witten (String Theorist)**





We can create particles  
from energy



- Two beams of protons collide and generate, in a very tiny space, temperatures over a billion times higher than those prevailing at the center of the Sun.
- Produce particles that may have existed at the beginning of the Universe, right after the Big Bang



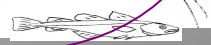
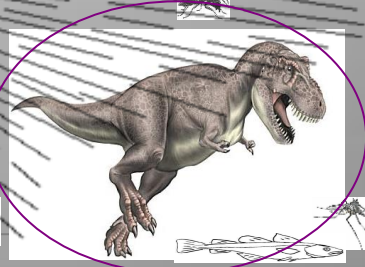
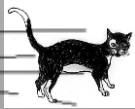
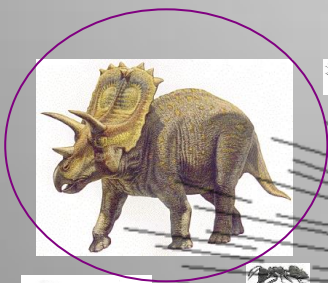
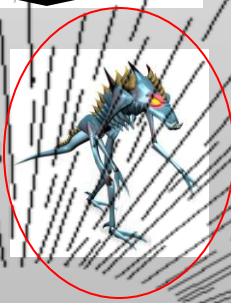
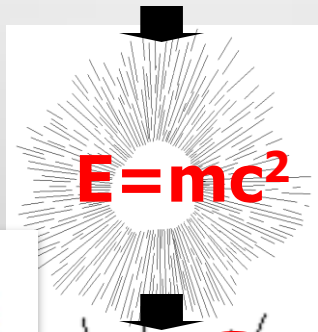
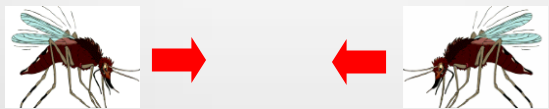
Illustrating the experiment

Highly Expected

Hypothetical

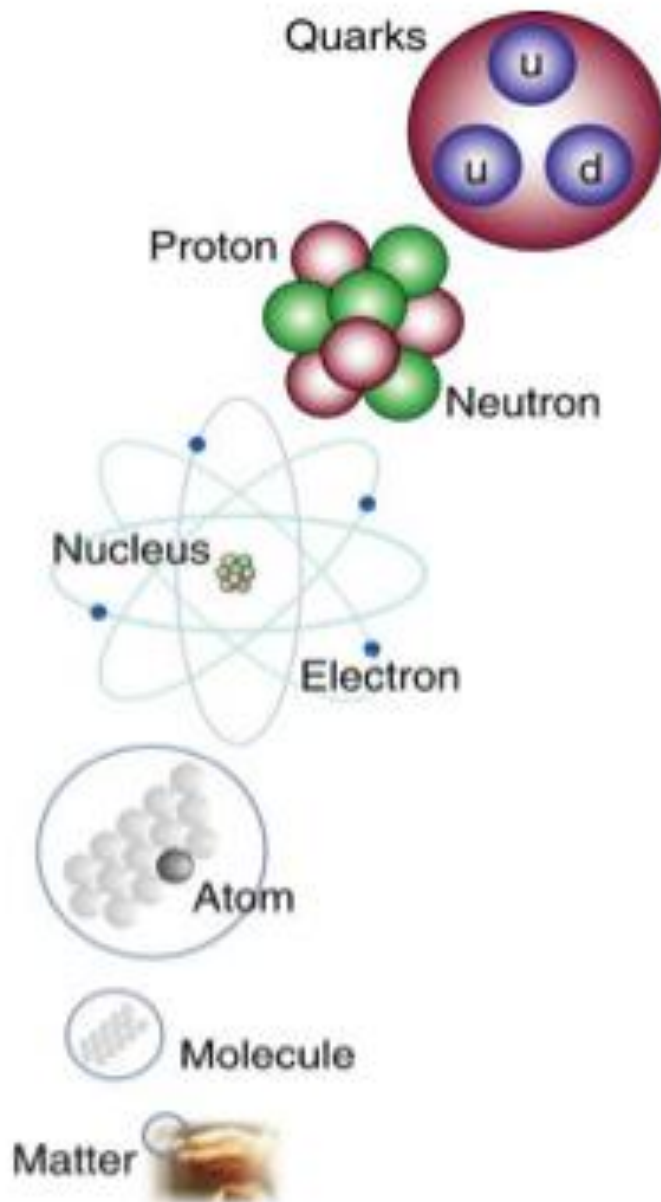
Unsuspected ?

'extinct' since Big Bang





# The Structure of Matter



Quarks and electrons are the smallest building blocks of matter that we know of today

Are there still smaller particles?

The Large Hadron Collider will address this question!

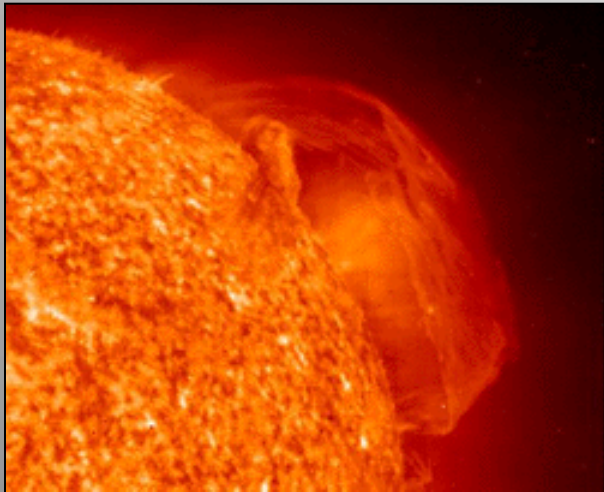


# The Fundamental Forces of Nature

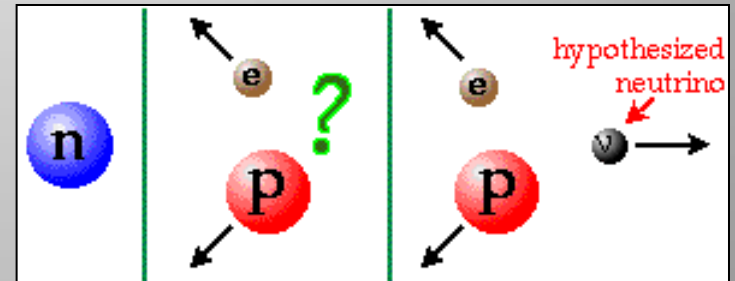
**Electromagnetism:**  
gives light, radio, holds atoms together

**Strong Nuclear Force:**  
holds nuclei together

**Weak Nuclear Force:**  
gives radioactivity



together  
they make  
the Sun  
shine



**Gravity:** holds planets and stars together



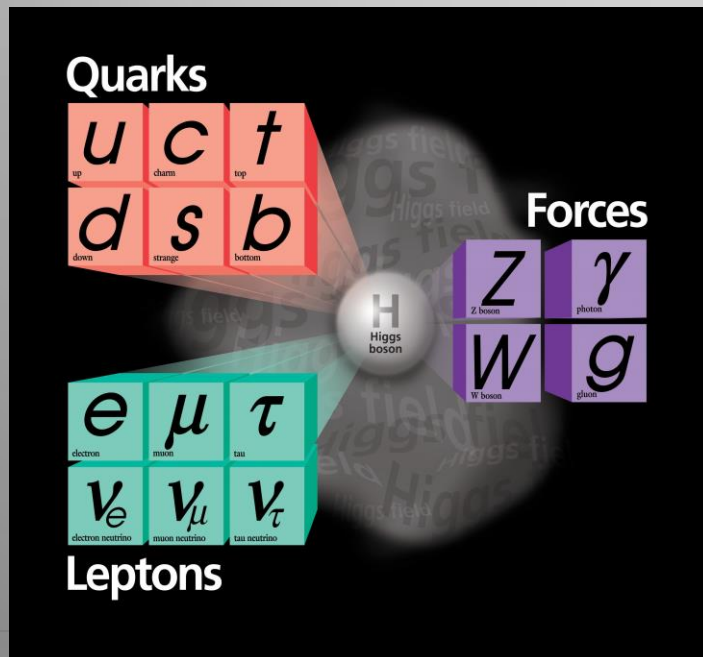


# The “Standard Model”

Over the last 100 years: combination of **Quantum Mechanics and Special Theory of relativity** along with all new particles discovered has led to the **Standard Model of Particle Physics.**

**The new (final?) “Periodic Table” of fundamental elements:**

Matter particles

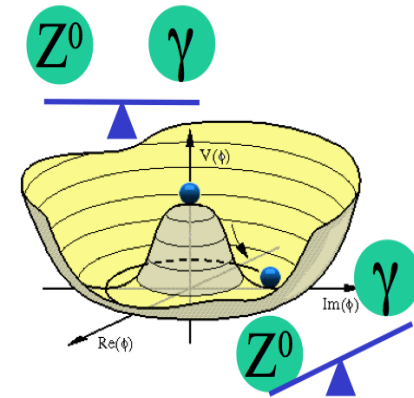


Force particles

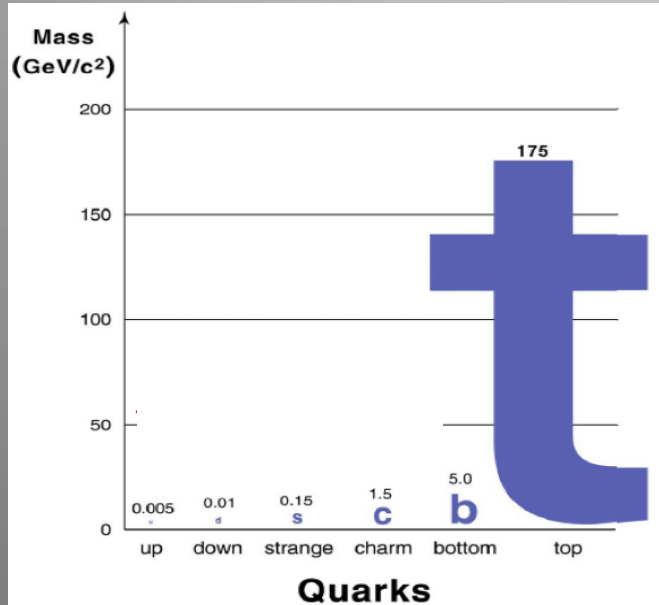
The most basic mechanism of the SM, that of granting mass to particles remained a mystery for a long time **A major step forward was made in July 2012 with the discovery of what could be the long-sought Higgs boson!!**

# The Origin of Particle Masses

- At 'low' energy the Weak force is much weaker than the Electromagnetic force: **Electroweak Symmetry Breaking: ESB**
- The W and Z bosons are very massive ( $\sim 100$  proton masses) while the photon is massless.
- The proposed mechanism<sup>(\*)</sup> in 1964 gives mass to W and Z bosons and predicts the existence of a new elementary 'Higgs' particle,. Extend the mechanism to give mass to the Fermions via Yukawa couplings.



(\*) Higgs, Brout Englert, Kibble, Hagen and Guralnik, and...



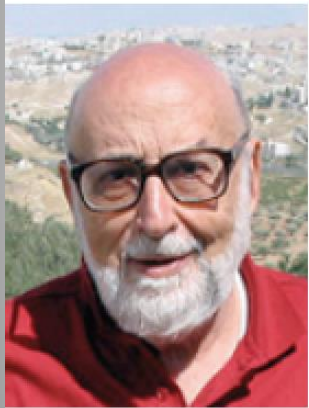
The Higgs (H) particle is the quantum of the new postulated field and has been searched for since decades at other particle colliders such as **LEP** and the **Tevatron**, and now at the **large hadron collider @ CERN**



# ESB Heroics

The year is 1964

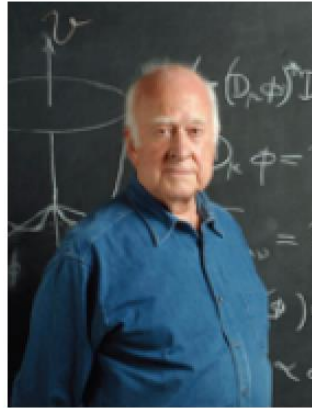
Electroweak Symmetry Breaking



François Englert



Robert Brout



Peter Higgs



Gerald Guralnik



Carl Hagen



Tom Kibble

**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)

**GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES\***

G. S. Guralnik,<sup>†</sup> C. R. Hagen,<sup>‡</sup> and T. W. B. Kibble

Department of Physics, Imperial College, London, England

(Received 12 October 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 15, 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)

+ others could be mentioned that have inspired the above

# The Hunt for the Higgs

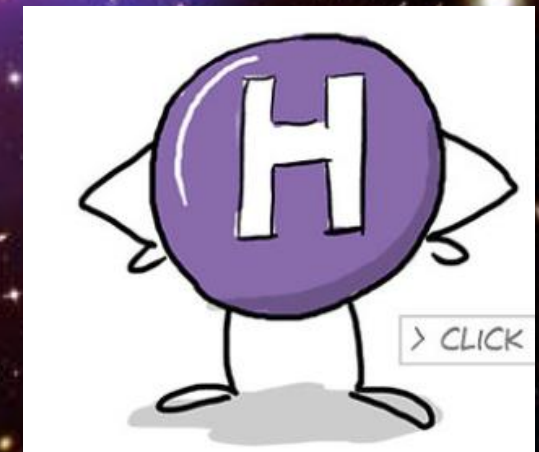
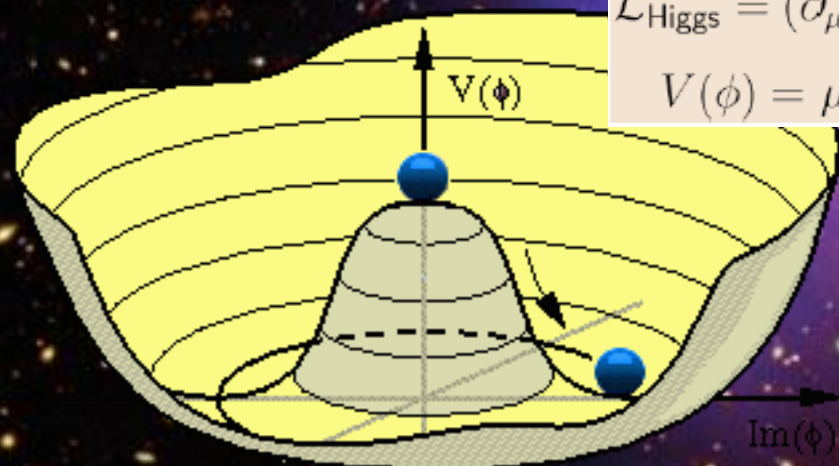
Where do the masses of elementary particles come from?

The key question (pre-2012):  
Does the Higgs particle exist?  
If so, where is the Higgs?

Massless particles move at the speed of light  $\rightarrow$  no atom formation!!

We do not know the mass of the Higgs Boson

$$\mathcal{L}_{\text{Higgs}} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi)$$
$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$



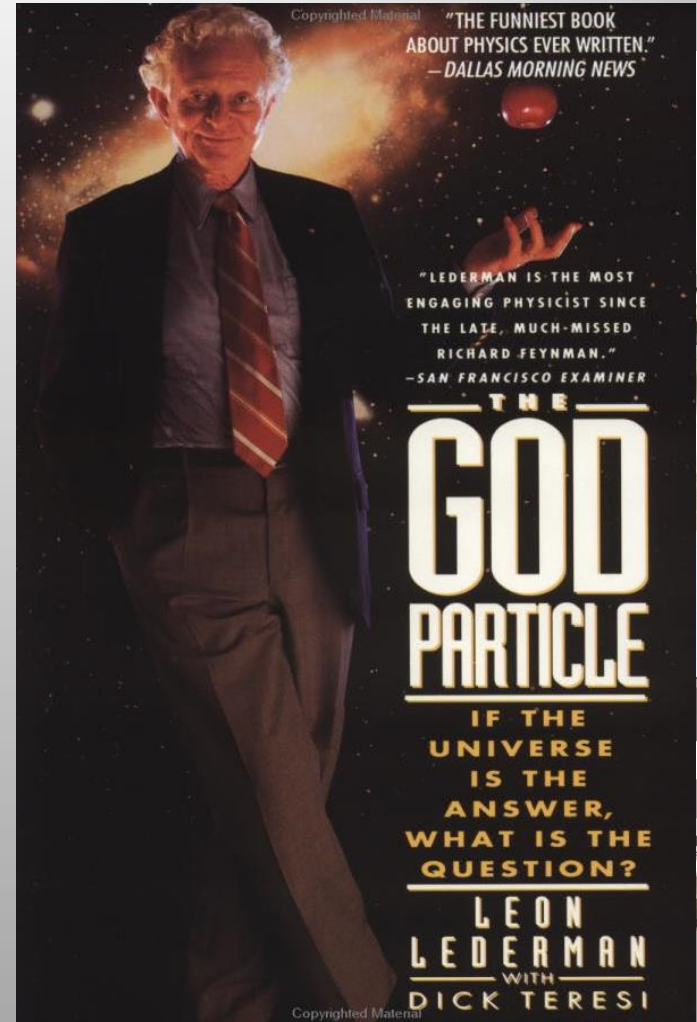
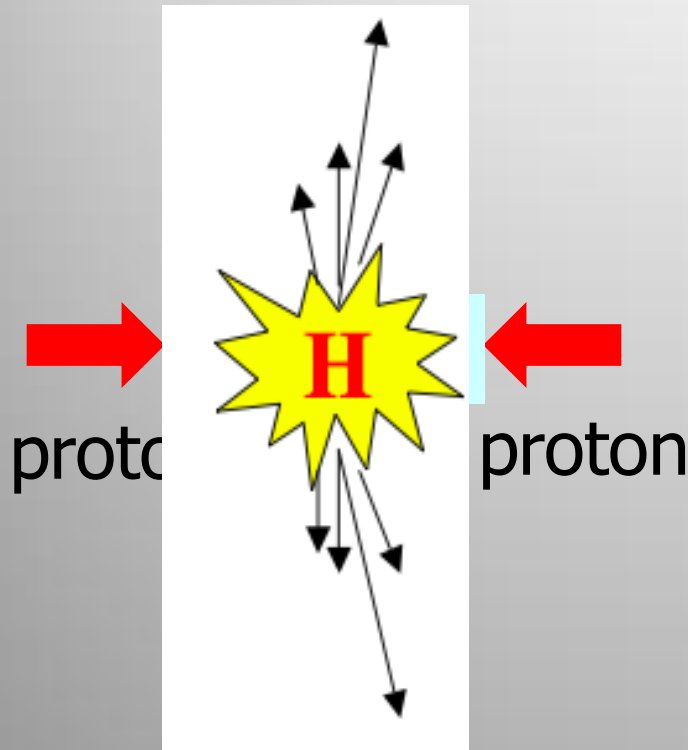
Scalar field with at least one scalar particle

It could be anywhere from 114 to  $\sim 700$  GeV



# The Higgs Particle

Technique: Produce and detect **Higgs** Particles at Particle Colliders



The Higgs particle is the last missing particle in the Standard Model

# In Nederland...

...a film on the Higgs  
just before the discovery

info: [doc@viewpointdocs.com](mailto:doc@viewpointdocs.com)



# HIGGS

*into the heart of imagination*

A FILM BY

Hannie van den Bergh  
Jan van den Berg



# This Search Requires.....



**1. Accelerators :** powerful machines that accelerate particles to extremely high energies and bring them into collision with other particles

**2. Detectors :** gigantic instruments that record the resulting particles as they “stream” out from the point of collision.

**3. Computing :** to collect, store, distribute and analyse the vast amount of data produced by these detectors

**4. Collaborative Science on Worldwide scale :** thousands of scientists, engineers, technicians and support staff to design, build and operate these complex “machines”.

# The Large Hadron Collider = a proton proton collider

7 TeV + 7 TeV  
(3.5/4 TeV + 3.5/4 TeV)



1 TeV = 1 Tera electron volt  
=  $10^{12}$  electron volt

## Primary physics targets

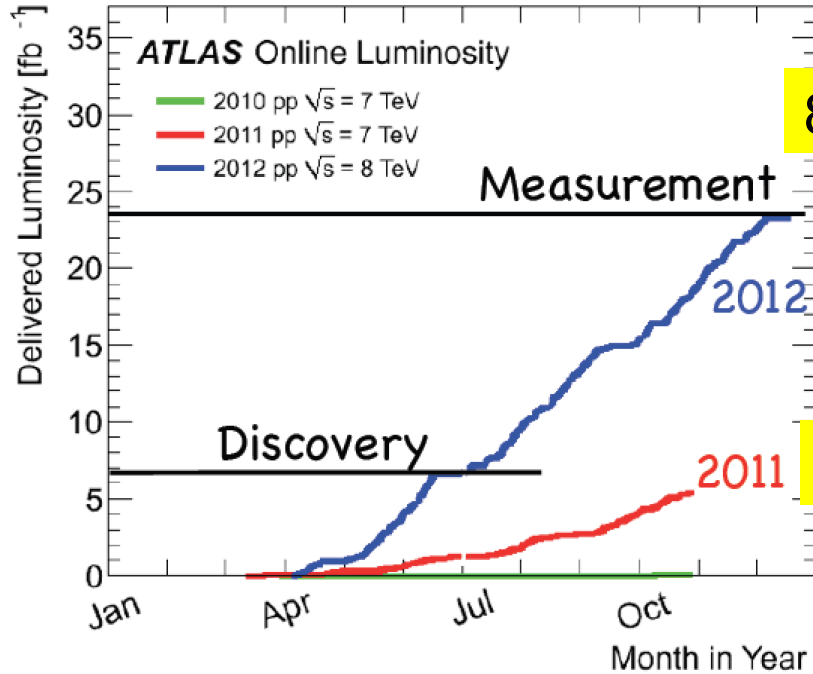
- Origin of mass
- Nature of Dark Matter
- Understanding space time
- Matter versus antimatter
- Primordial plasma

The LHC is a **Discovery Machine**

The LHC will determine the Future course of High Energy Physics



- Several thousand billion protons
- Each with the energy of a fly
- 99.9999991% of light speed
- They orbit a 27km ring 11 000 times/second
- A billion collisions a second in the experiments



8 TeV

LHC operation is now stopped for 2 years, and the machine is being prepared for running at 13-14 TeV from 2015 onwards

7 TeV

Luminosity = # events/cross section/time

100 meter underground

# The LHC is an Extraordinary Machine

LHC facts

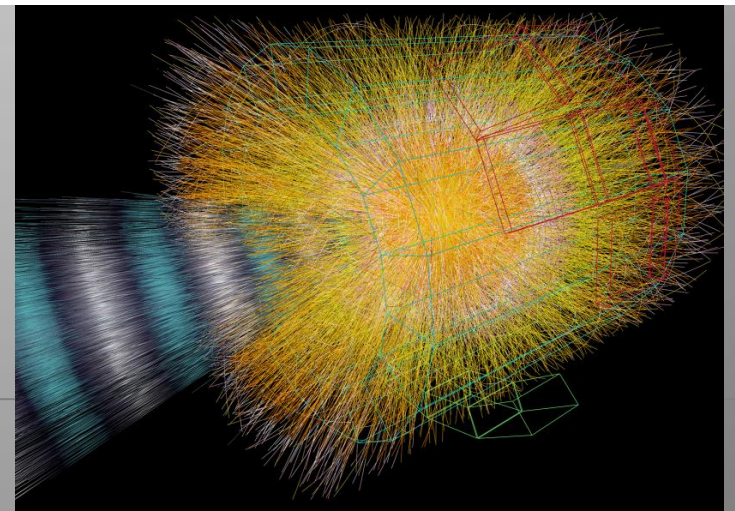
The LHC is ...

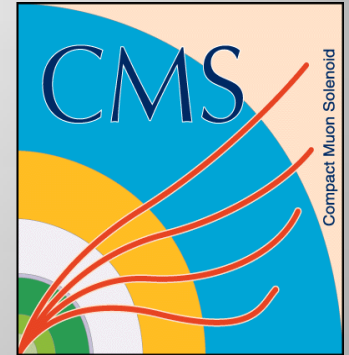
Colder than the empty  
Space in the Universe: 1.9K  
ie above absolute zero

The emptiest place in our solar  
system. The vacuum is better  
than on the moon

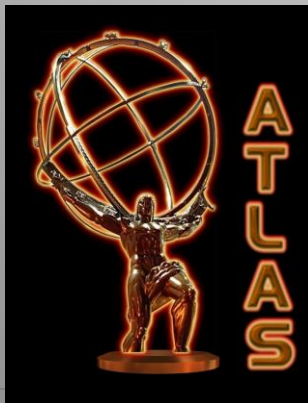


Hotter than in the sun: temperature  
in the collisions is a billion times  
the one in the centre of the sun





# Experiments at the LHC





# Schematic of a LHC Detector

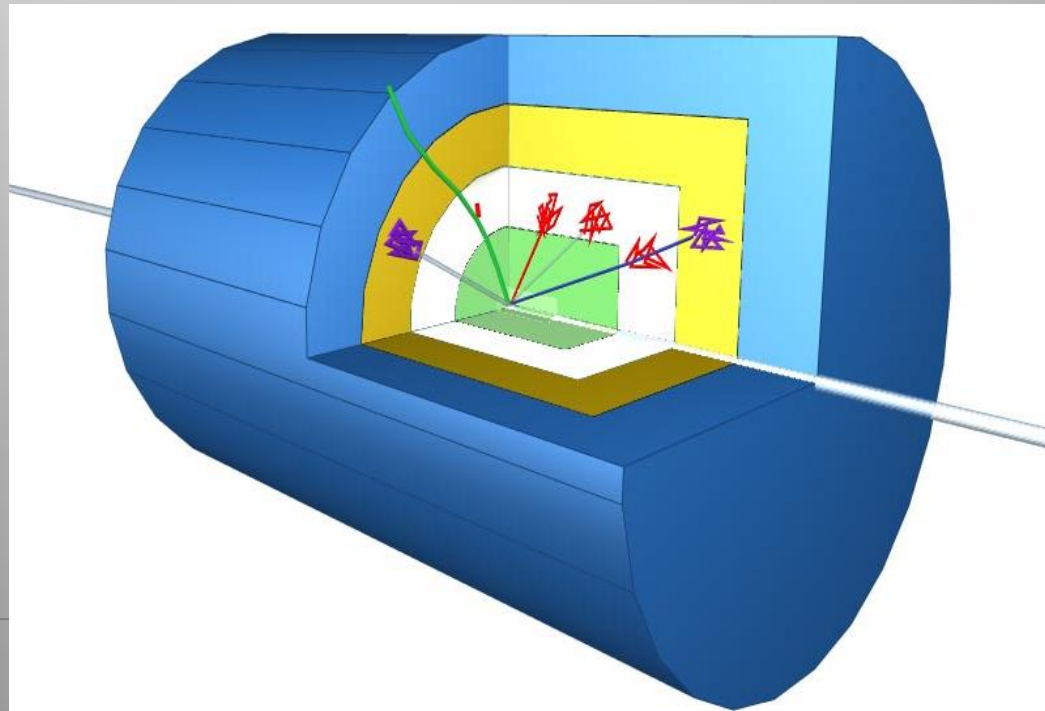
**Physics requirements drive the design!**

**Analogy with a cylindrical onion:**

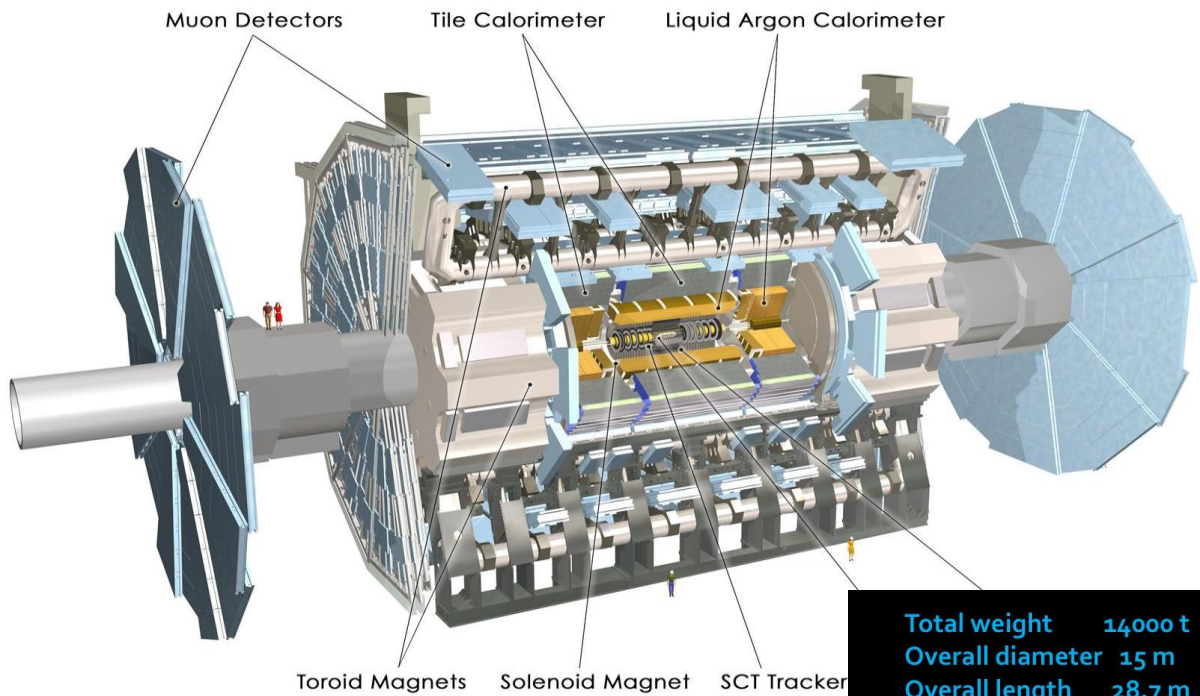
Technologically advanced detectors comprising many layers, each designed to perform a specific task.

Together these layers allow us to identify and precisely measure the energies and directions of all the particles produced in collisions.

Such an experiment has ~ 100 Million read-out channels!!

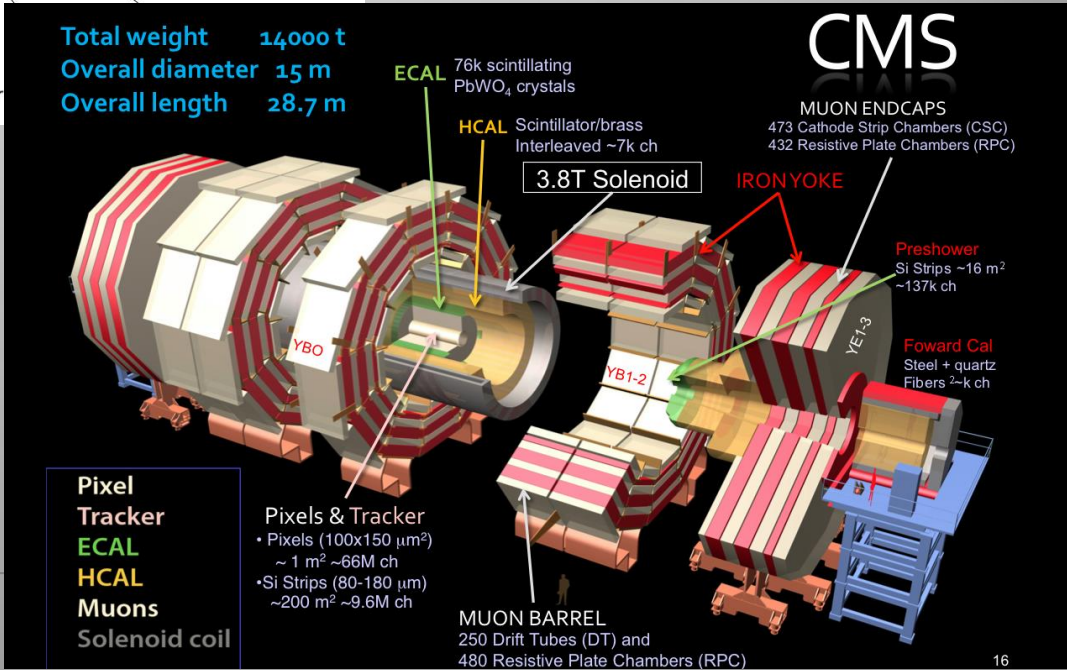


# The Higgs Hunters @ the LHC

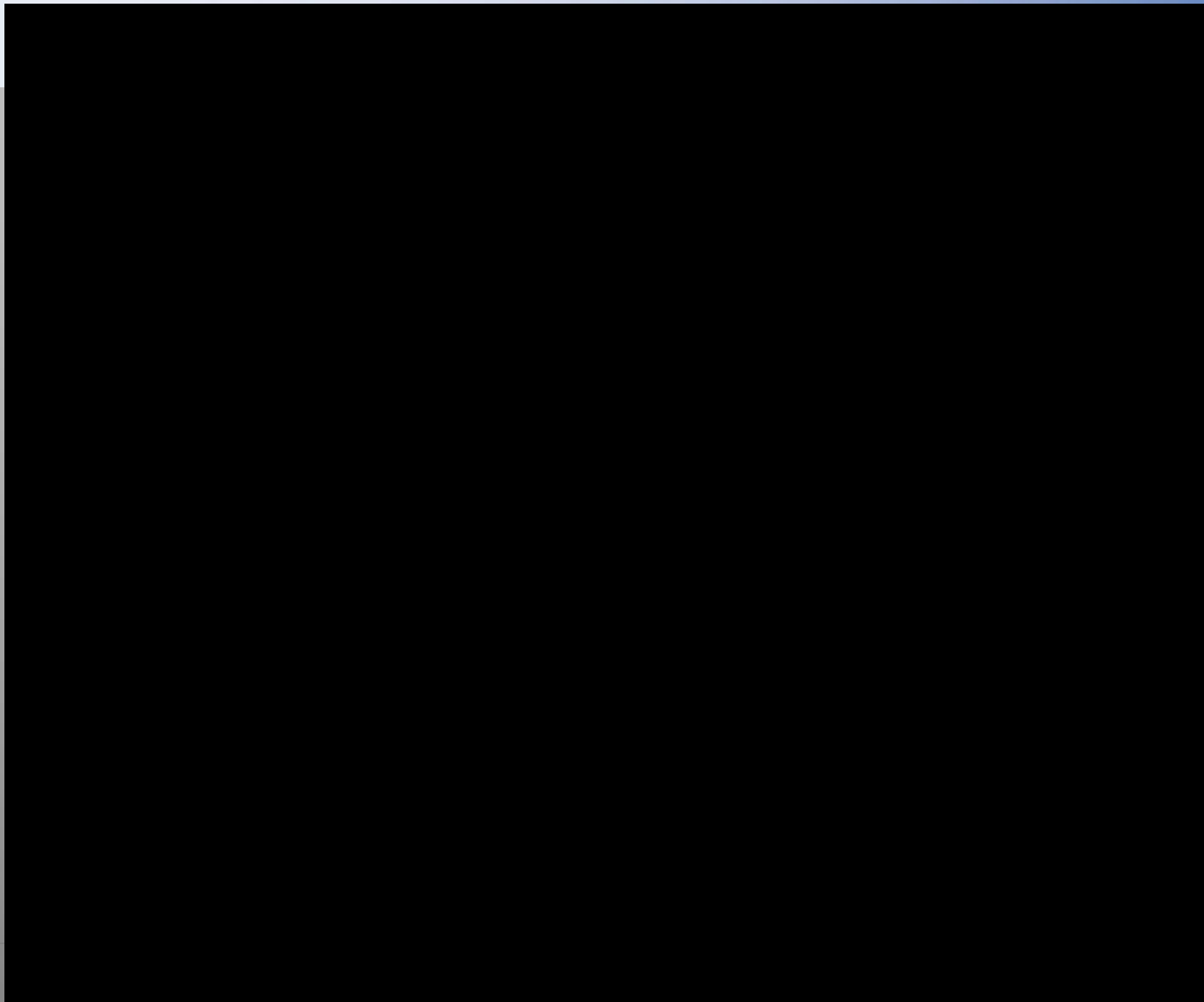


The ATLAS experiment

The CMS experiment



These experiments use different technologies for their detector components





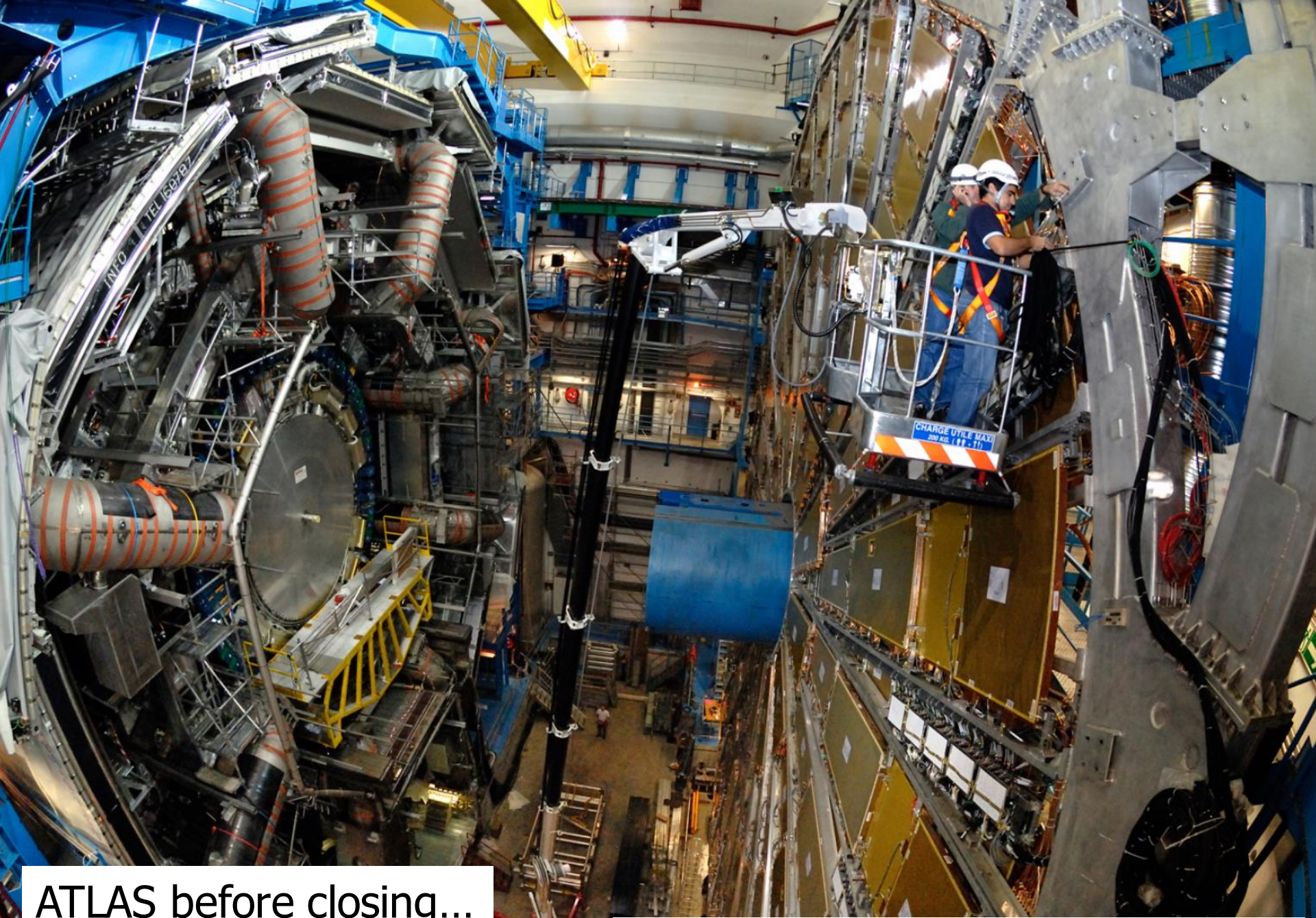
# CMS Collaboration June 27, 2012

The CMS Collaboration: >3300 scientists and engineers,  
>800 PhD students from ~181 Institutions in 42 countries .

About 1/8th of the  
collaboration







ATLAS before closing...

The Netherlands are a member of ATLAS



***CMS before closure***





# The Physics Program at LHC

**Data taking started in 2010**

**Now we have more than 250 reviewed scientific papers per experiment!**

**Mostly measurements of the strong and electroweak force at 7/8 TeV and Searches**

- |  |                   |
|--|-------------------|
| <b>-Are quarks the elementary particles?</b> | <b>So far yes</b> |
| <b>-Do we see supersymmetric particles?</b>  | <b>Not yet</b>    |
| <b>-Do we see extra space dimensions?</b>    | <b>Not Yet</b>    |
| <b>-Do we see micro-black holes?</b>         | <b>No</b>         |

**->The Discovery of a Higgs-like particle!!**

# Higgs Hunters

## *Higgs Hunting Basics*

Needle-in-the-hay-stack problem

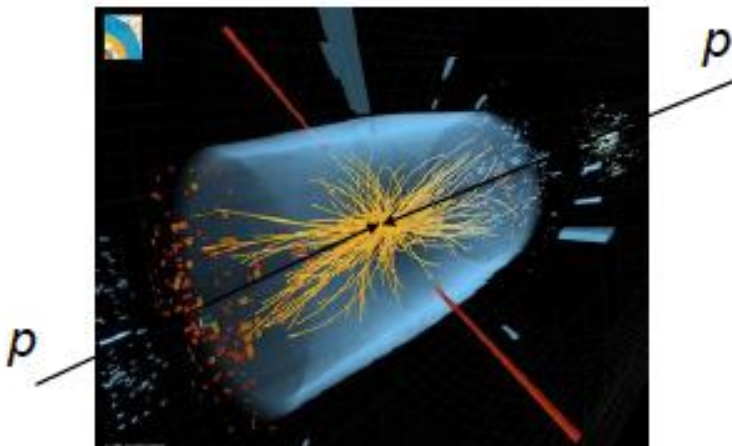
- need high energy:

$$E = mc^2$$

- need lots of data

non-deterministic and very rare

order 1 in  $10^{11}$

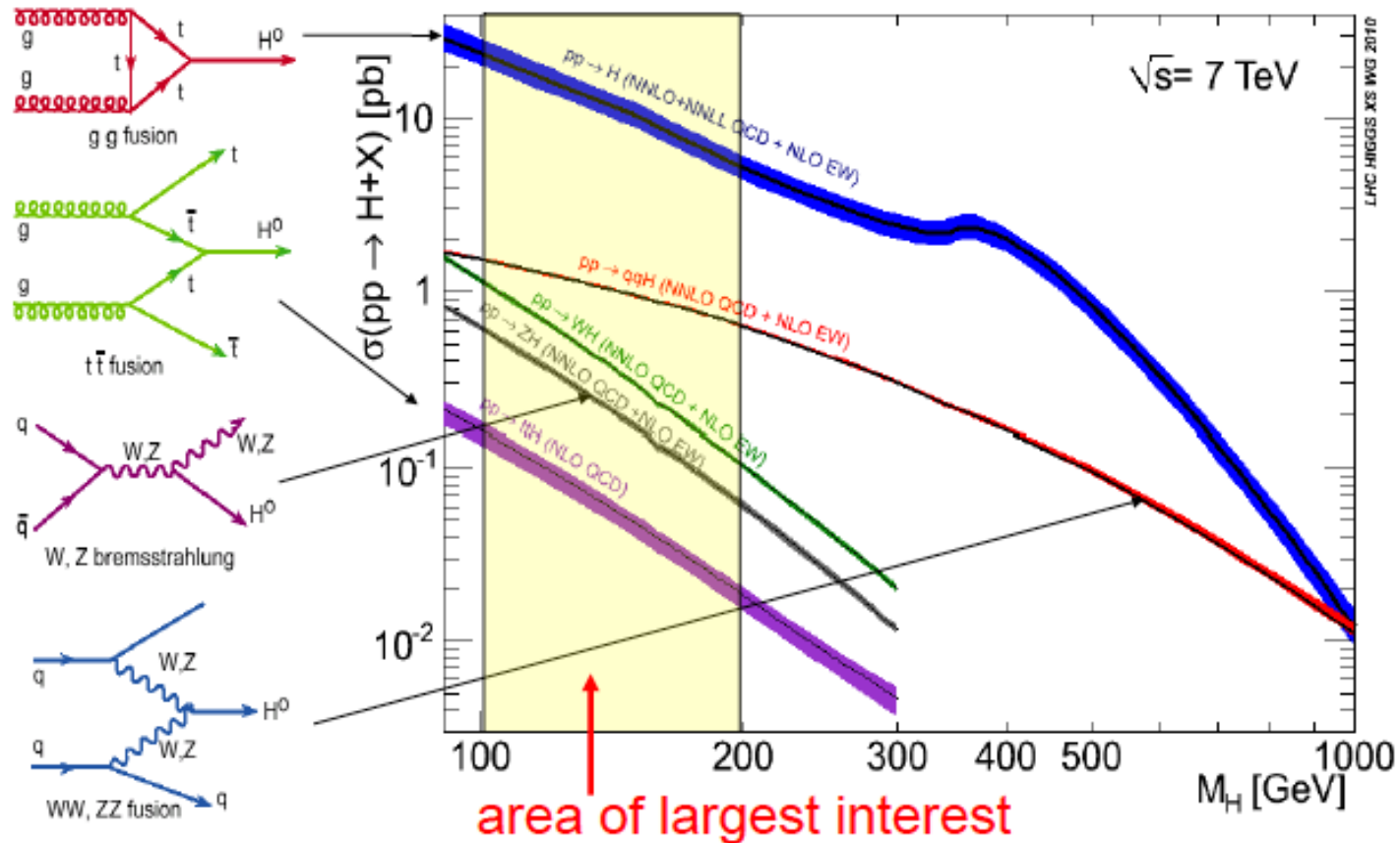


\* for us finding the Higgs it was  
48 years = 1,513,728,000 sec

# Higgs Production Channels vs Mass

## Higgs Production at the LHC

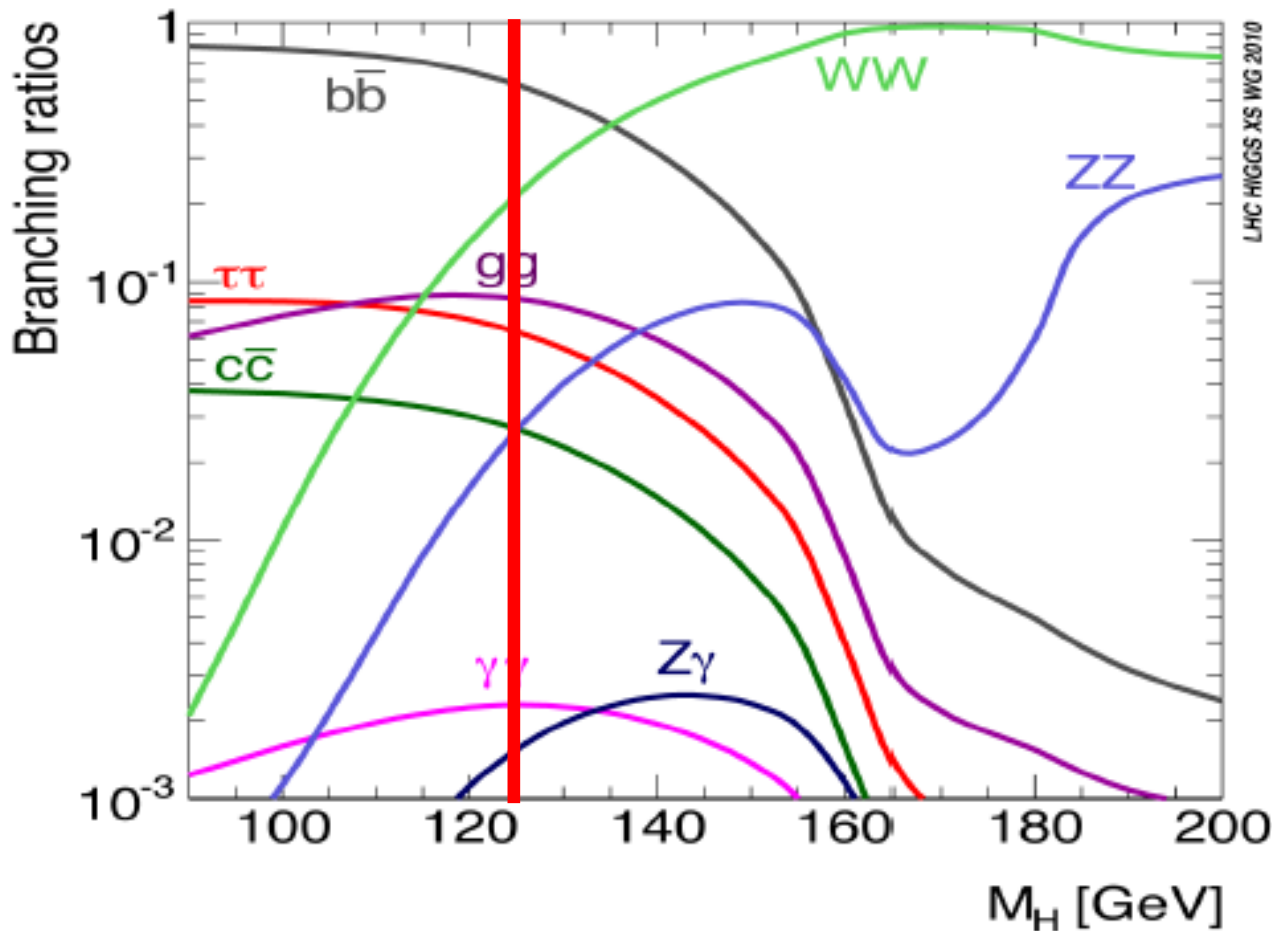
Higgs production in proton-proton collisions



We now start to have data on all production channels



# Higgs Decay Channel vs. Mass



Higgs boson couples to mass

$$\Gamma_{Hff} \sim m_f^2$$

Messy: many channels, many subsequent decays etc. etc.

- common: leptons/photons essential for any search
- 5 channels are most promising

# Higgs Hunting at the LHC

*Higgs Hunting – The big five*



The big five are the five most sensitive search channels at the LHC

# Higgs Hunting at the LHC

## *Overview – The big five*

Channel	$m_H$ range (GeV/c <sup>2</sup> )	Data used 7+8 TeV (fb <sup>-1</sup> )	$m_H$ resolution
H -> $\gamma\gamma$	110-150	5.1+19.6	1-2%
H -> tautau	110-145	4.9+19.6	15%
H -> bb	110-135	5.0+19.0	10%
H -> WW -> l $\nu$ l $\nu$	110-600	4.9+19.5	20%
H -> ZZ -> 4l	110-1000	5.1+19.6	1-2%

Many more channels studied eg also “invisible Higgs decays”

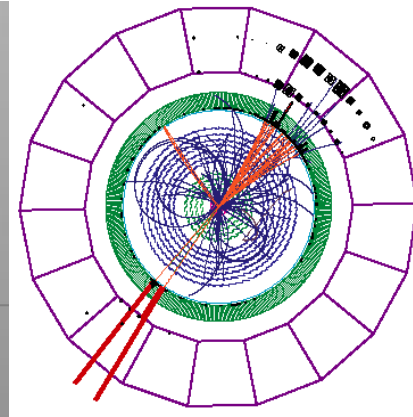
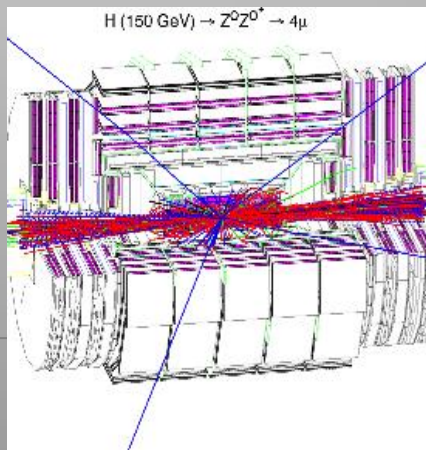
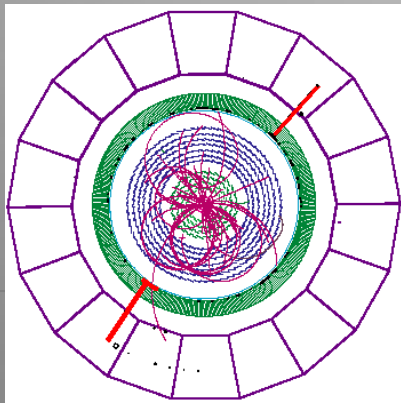
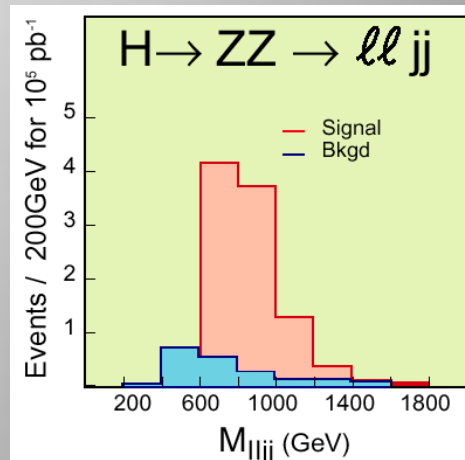
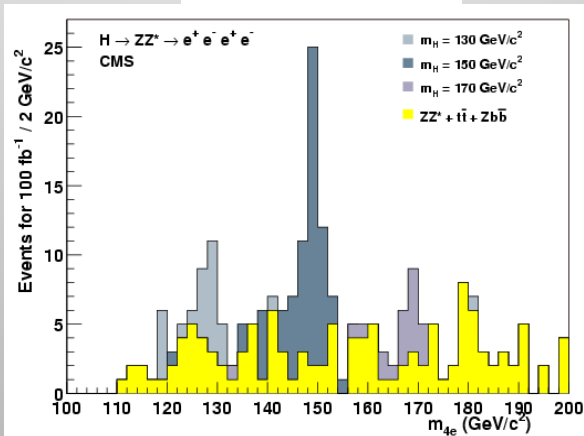
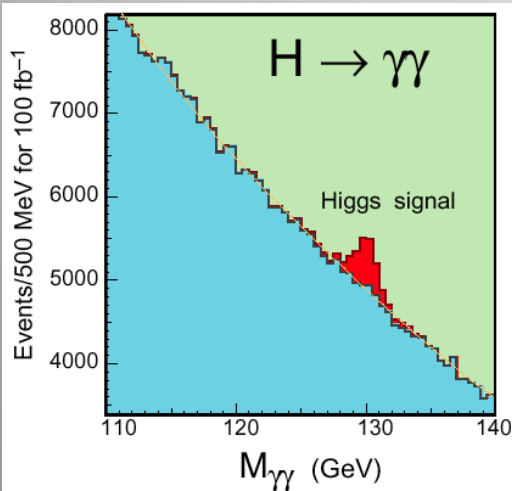
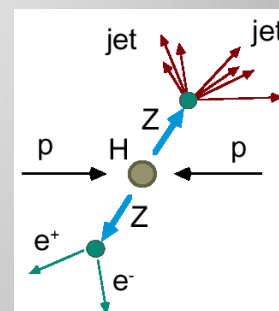
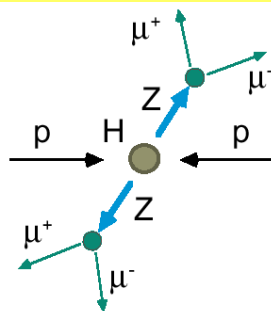
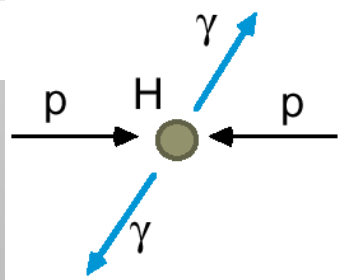


# Higgs Boson Searches (simulation)

Low  $M_H < 140 \text{ GeV}/c^2$

Medium  $130 < M_H < 500 \text{ GeV}/c^2$  High  $M_H > \sim 500 \text{ GeV}/c^2$

simulation



# Searches for the Higgs Particle

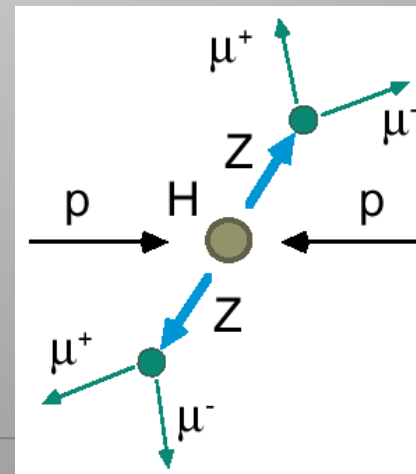
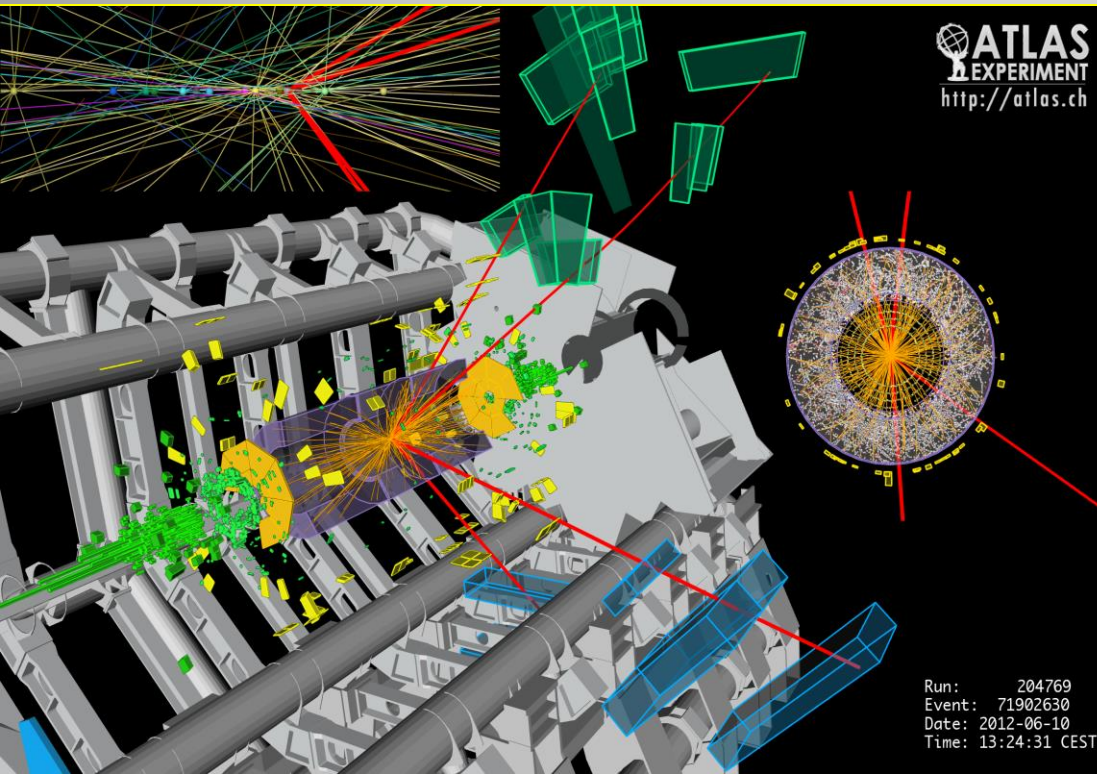
A Higgs particle will decay immediately, eg in two heavy quarks or two heavy (W,Z) bosons

Example: Higgs(?) decays into ZZ and each Z boson decays into  $\mu\mu$

So we look for 4 muons in the detector

But two Z bosons can also be produced in LHC collisions, without involving a Higgs!

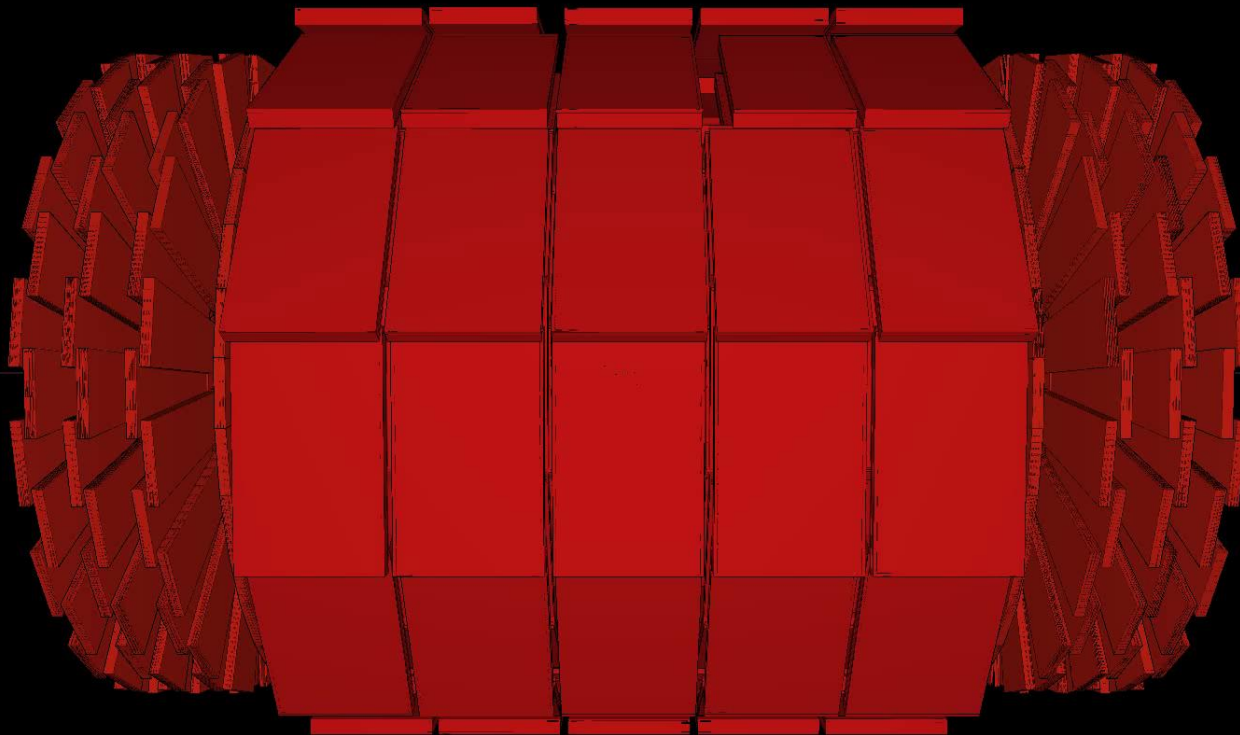
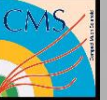
We cannot say for one event by event (we can reconstruct the total mass with the 4 muons)



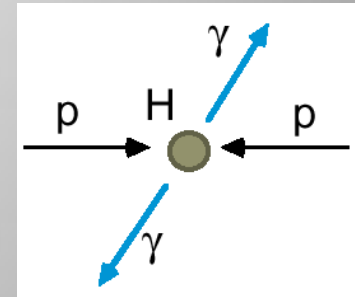
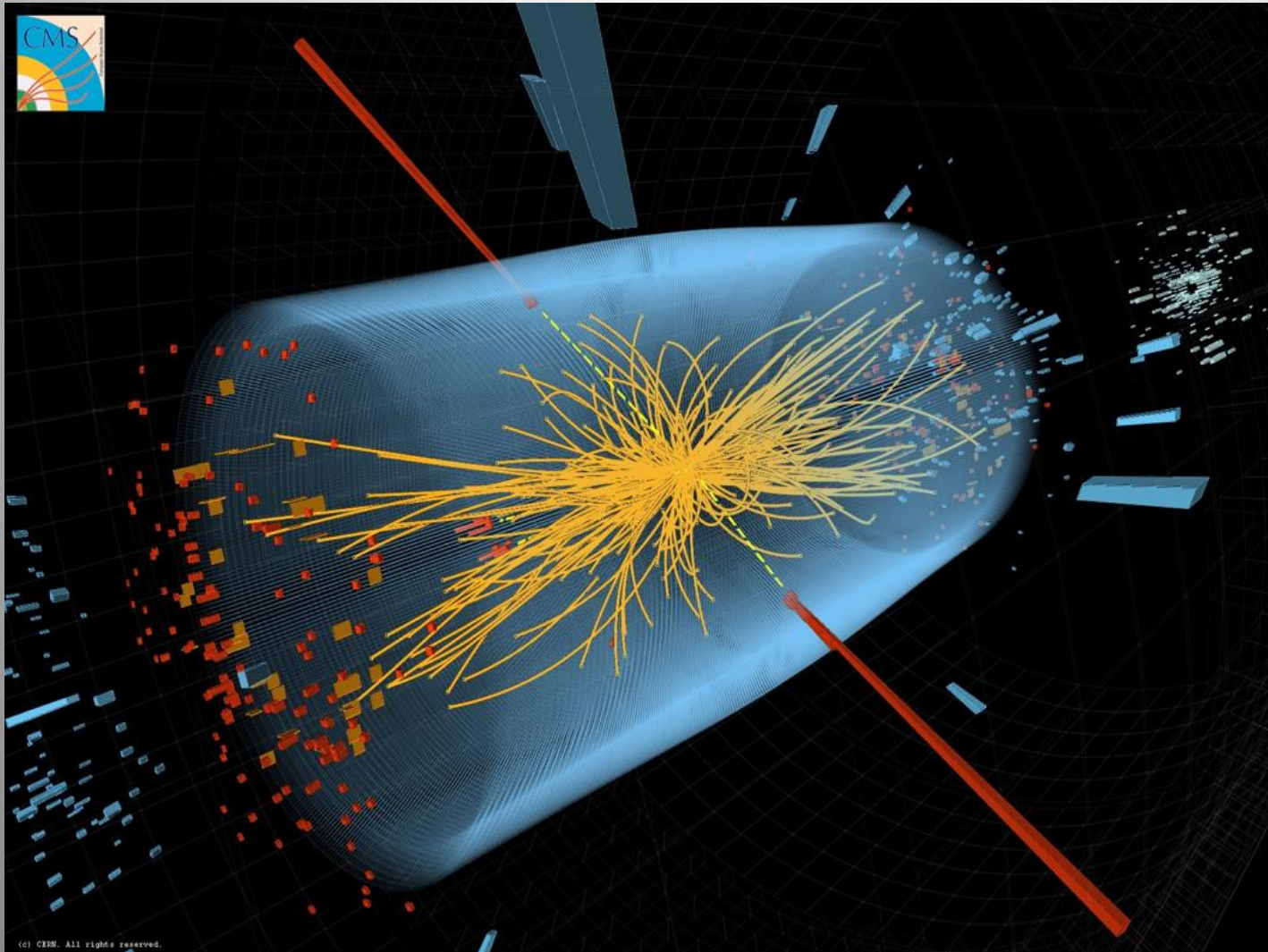


# A real collisions: ZZ-> 4 muons

CMS Experiment at the LHC, CERN  
Sun 2011-Aug-07 05:00:32 CET  
Run 172822 Event 2554393033  
C.O.M. Energy 7.00TeV  
H>ZZ>4mu candidate



# A Collision with two Photons



A Higgs or  
a 'background'  
process without  
a Higgs?

Note: the LHC is a Higgs Factory: 1 Million Higgses already produced  
15 Higgses/minute with present luminosity



# The Higgs Boson

The Washington Post

**NATIONAL**

Spring 2012

**Physicists hope to find the Higgs boson, key to unified field theory, this year**



Fabrice Coffrini/Agence France-Presse via Getty Images - A superconducting solenoid magnet, the largest of its kind, is part of the Large Hadron Collider, which is searching for the Higgs boson.

The suspense was building up...

# July 4<sup>th</sup> 2012

- Official announcement of the discovery of a Higgs-like particle with mass of 125-126 GeV by CMS and ATLAS.
- Historic seminar at CERN with simultaneous transmission and live link at the large particle physics conference of 2012 in Melbourne, Australia

CERN



Melbourne

Followed live around  
the world...

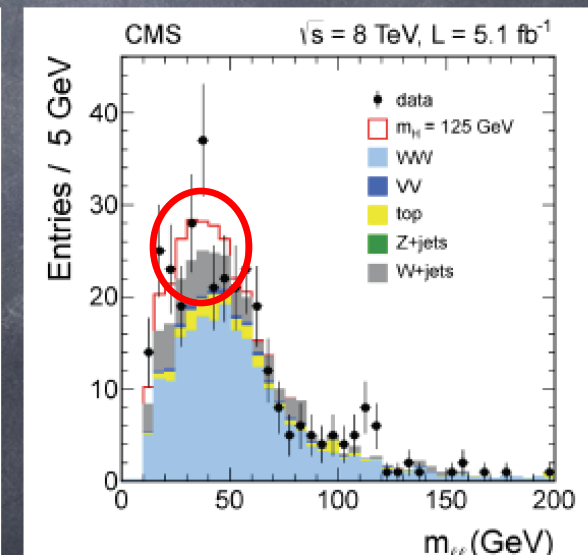
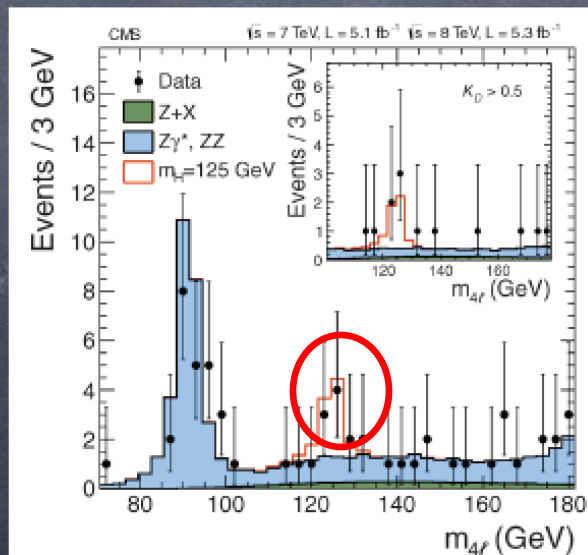
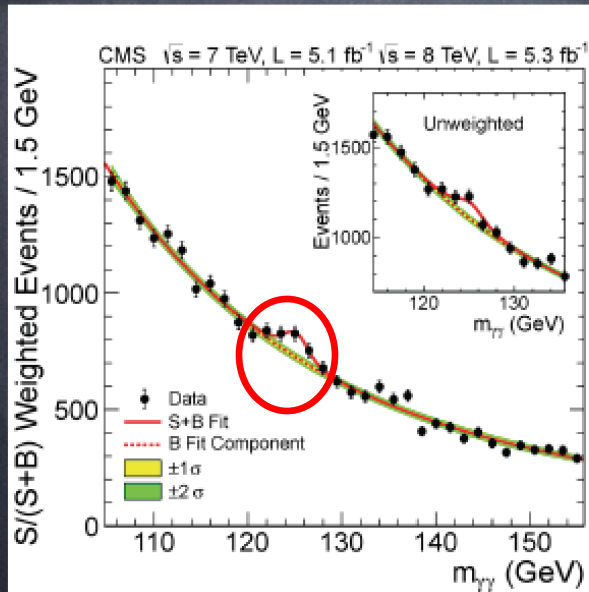
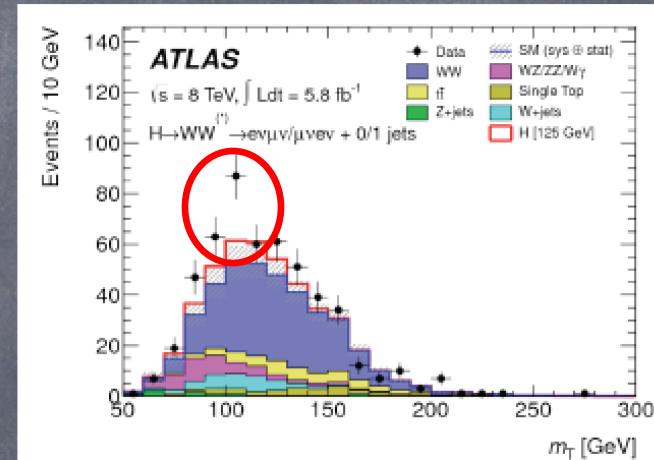
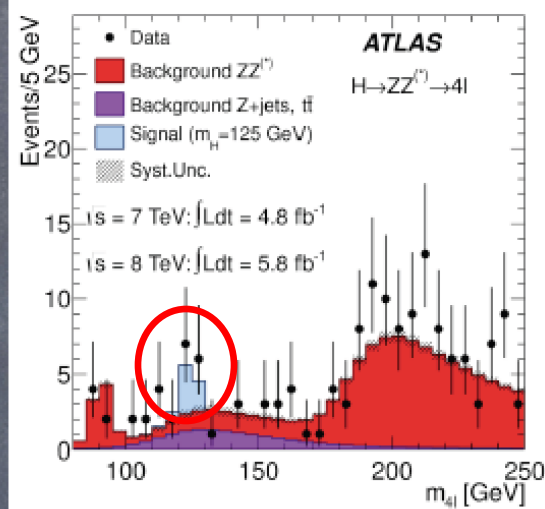
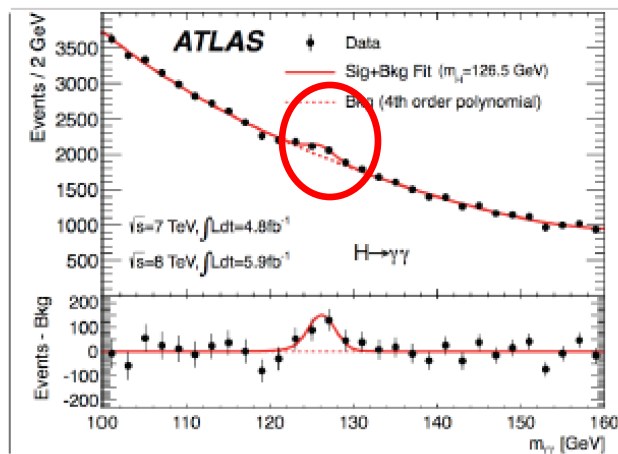


# Summer 2012: Results

Higgs  $\rightarrow$  2 photons!!

Higgs  $\rightarrow$  2Z  $\rightarrow$  4 leptons!!

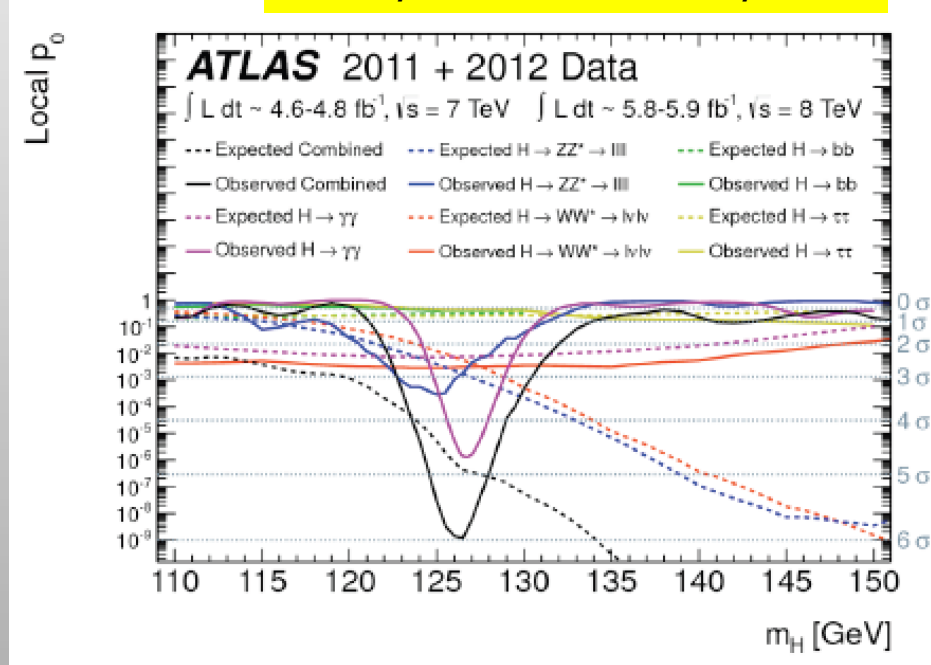
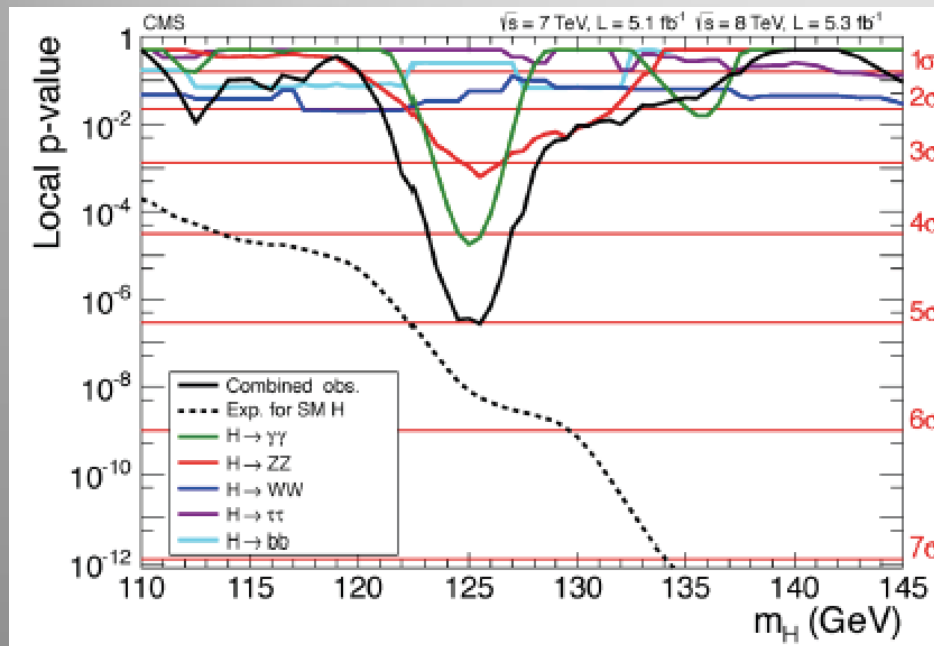
Higgs  $\rightarrow$  2W  $\rightarrow$  2l2v!!



# Summer 2012: Results

Both experiments see an excess  $\sim 125$  GeV in the  $\gamma\gamma$ , ZZ and WW channel  
→ Adding up all the channels gives the following combination  
Shown is the compatibility with a 'background only hypothesis'

5 fb<sup>-1</sup>/2011 and 5 fb<sup>-1</sup>/2012



CMS and ATLAS observe a **new boson** with a significance of **about 5 sigma** (1 chance in 3 million to be wrong!!!)



# Since then: 4<sup>th</sup> of July is...



*Higgsdependence Day*  
July 4, 2012

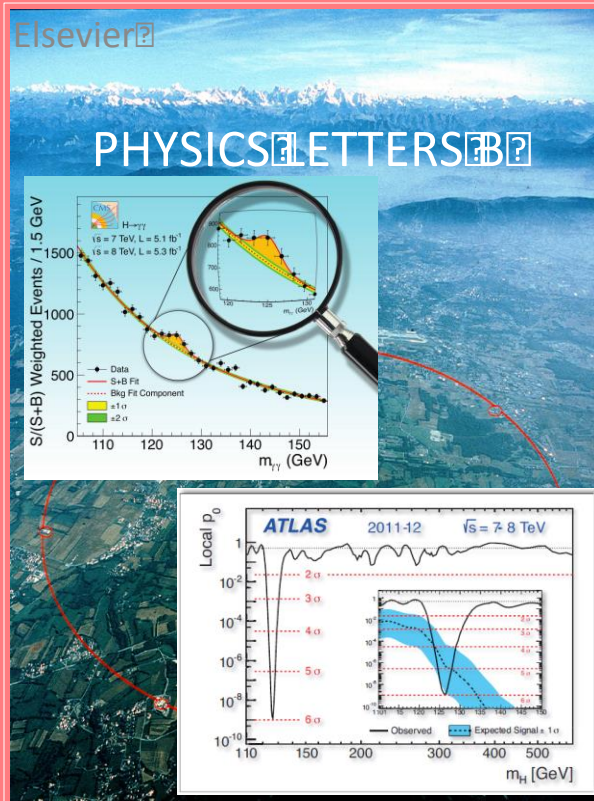
I FOUND A NEW PARTICLE



# Higgs Publications...

Special Physics Letters B  
edition with the ATLAS and  
CMS papers

Also...





# The Press... (5<sup>th</sup> July 2012)

The discovery of the Higgs made the headlines worldwide

Hawking lost \$100 bet over Higgs boson

What Comes After Higgs Boson?

*Atlantic*  
**wire** what matters now

'God Particle' 'Discovered': European Researchers Claim Discovery of Higgs Boson-Like Particle

**HOW THE HIGGS COULD BECOME ANNOYING**

Yes, the discovery of the Higgs boson is thrilling and game-changing. But it could also introduce some aggravating situations.

**Хиггс увидит бозон**

В CERN открыли бозон Хиггса

Текст

— 3.07.12 15:13 —

ТЕКСТ: АЛЕКСАНДРА БОРИСОВА  
D: SCIENCEUNSEEN.COM

Discovery of Higgs Boson Bittersweet News in Texas

Scientists Set The Higgs Boson To Music

3 Ways the Higgs Boson Discovery Will Impact Financial Services



**Higgs boson discovery could make science fiction a reality**

Discovery of the 'God particle' could make science fiction a reality, and answer one of the most basic questions of our universe: How did light become matter — and us?

**Higgs boson researchers consider move to Cloud computing**

"Within another decade the Cloud will be where grid computing is now"

# Is it really the Higgs Boson?

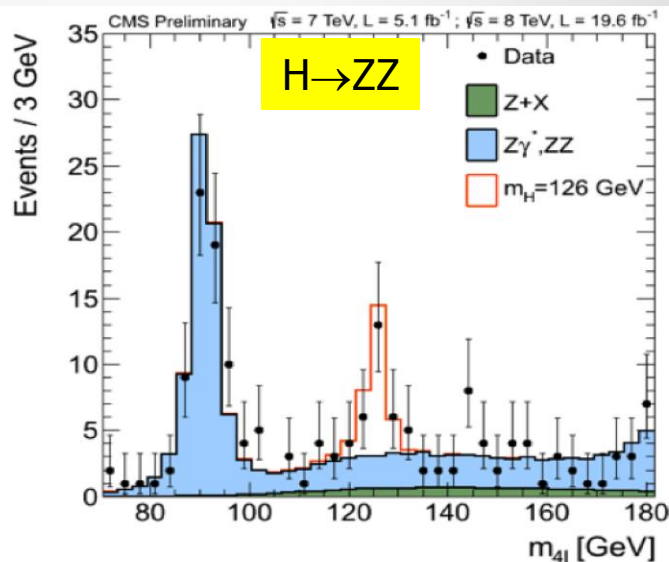
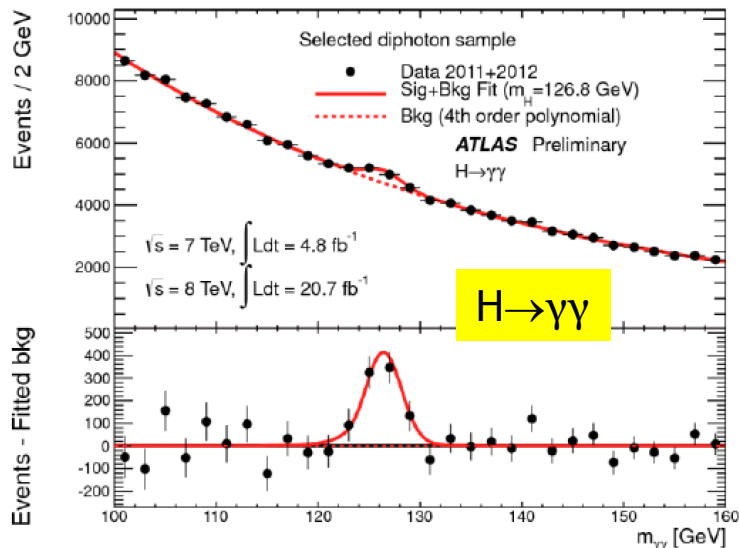
We, experimentalists, called it a “Higgs-like” particle

- Does this new particle have all the properties that we expect a Higgs Boson to have? (Summer 2012  $5+5 \text{ fb}^{-1}$ )
  - So far it seems to couple as expected to photons, heavy Z and W bosons, but at the time of the discovery it was not seen that they also couple to quarks or leptons
- What are the quantum numbers of this new particle?
  - EG Spin and Parity: for the SM Higgs we expect it to have spin = 0 and parity = +.
- Is there more than one Higgs-like particle? Some theories beyond the Standard Model predict these...
- Does it have ‘exotic’ properties?

Still a lot of questions to be answered in summer 2012!!  
Let's look at the new updates with full 2012 data ( $\sim 25 \text{ fb}^{-1}$ )

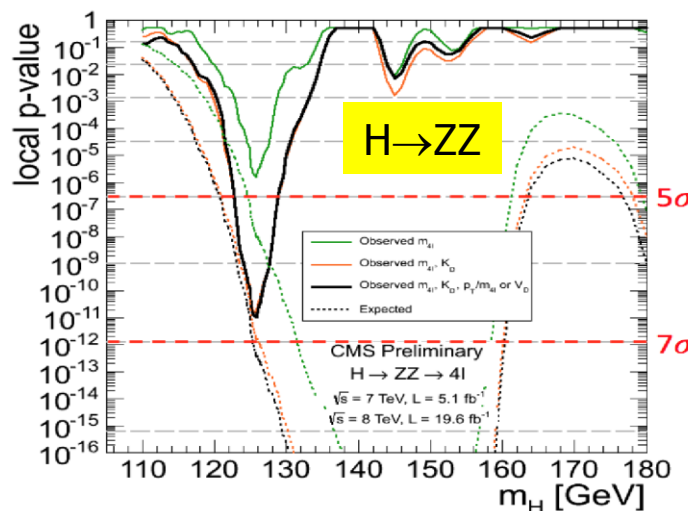
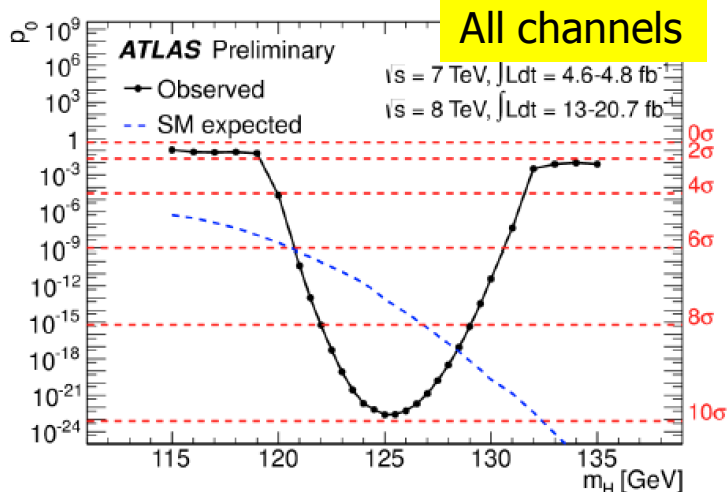


# Update with the Full 2012 Data Sample



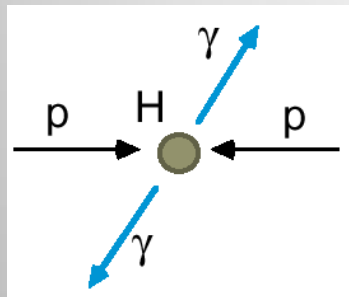
Increased data sample with a factor of  $\sim 3$

The particle is clearly still with us, now with a significance of  $> 10\sigma$  !!

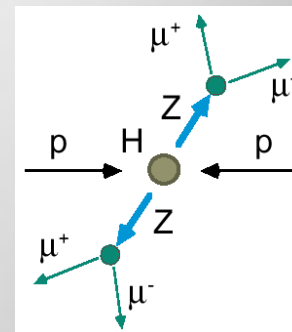


We now enter the phase of measuring the properties of the new particle

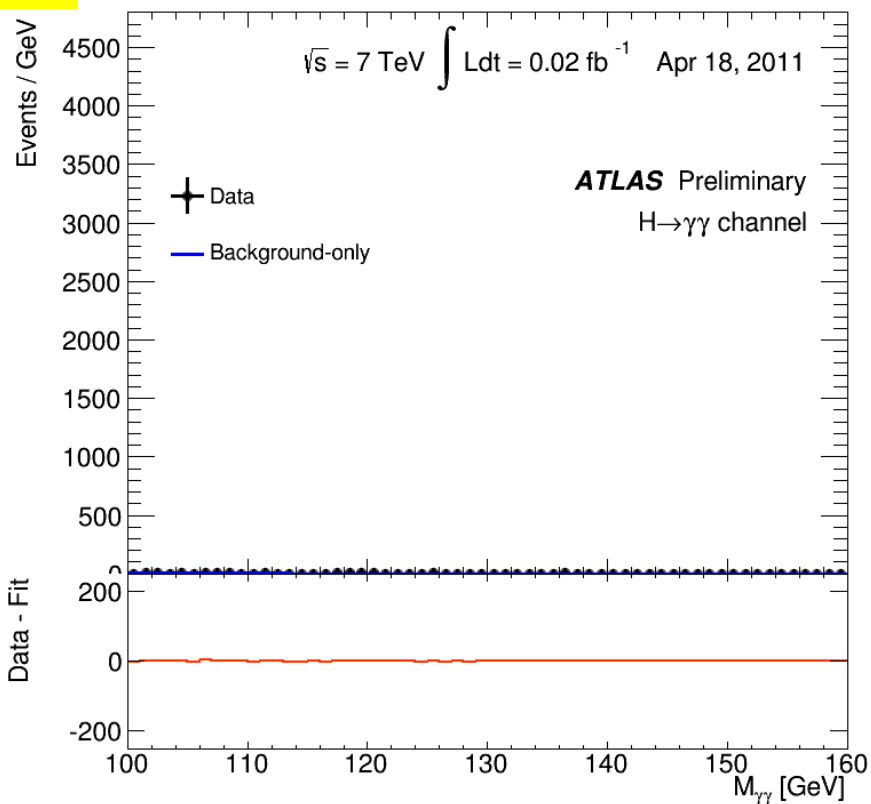
# The Birth of a Particle



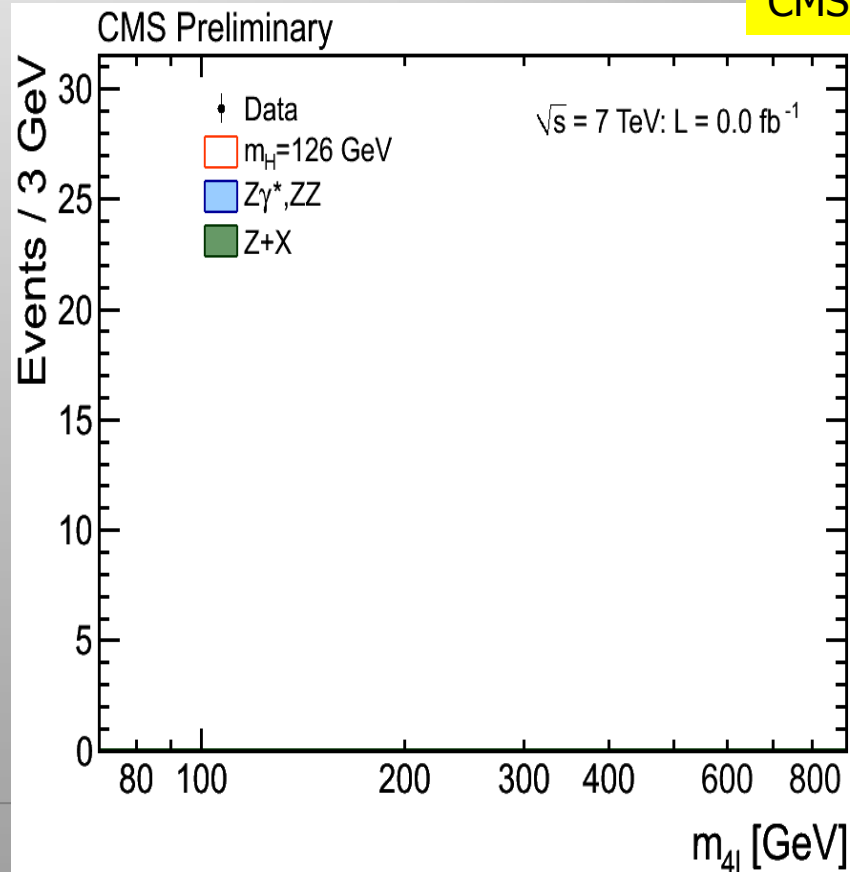
“History” of the data accumulation during the last two years



ATLAS



CMS

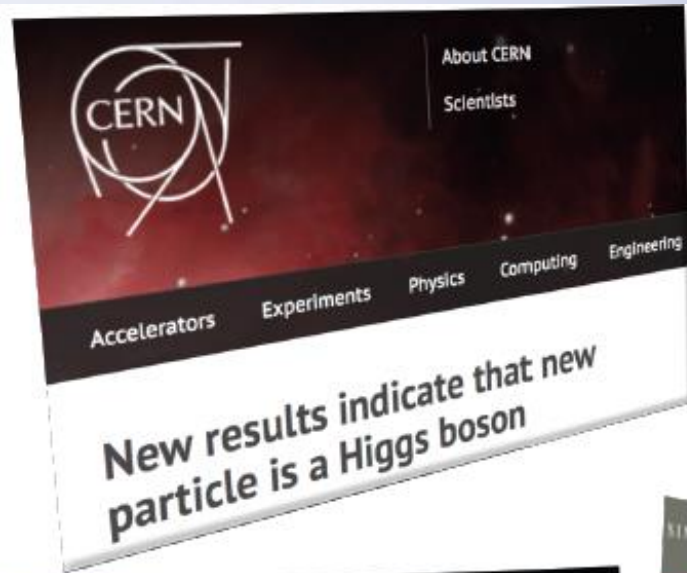




# The News Since July 2012

- Results based on the full data set of 2011-2012 have been released this spring/summer
- The discovery of the new particle has been **confirmed** with more added collisions
- Signals in the fermion-channels start building up
- We tested the spin: **it is compatible with a  $0^+$  state and not with (simple)  $0^-$  or spin 2 ( $1$ ) states**
- The mass is getting measured better with time, in the **range 125-126 GeV. A naïve average gives 125.6 GeV**
- The couplings to Bosons and Fermions are **consistent with the SM predictions** (but these are not very precise yet; Surprises possible...)

# March 2013 News



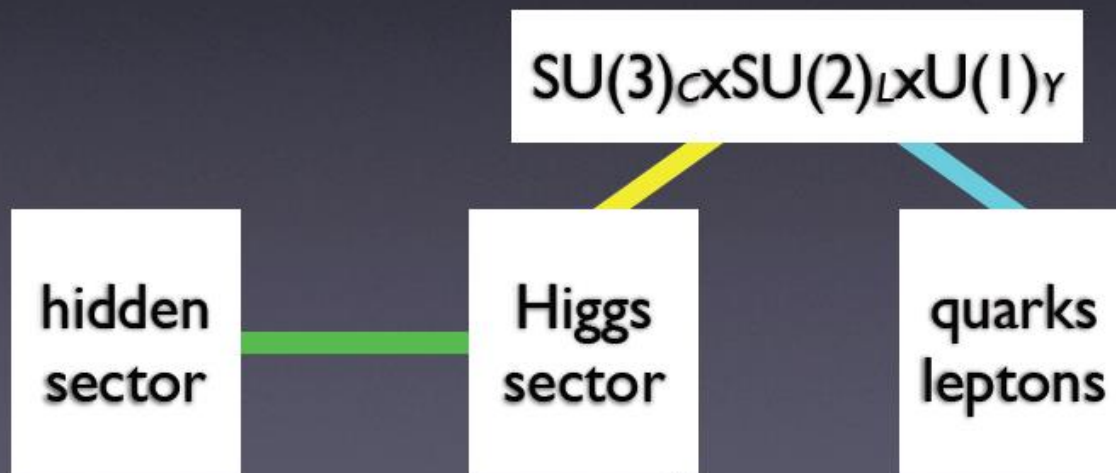
Following the data released by ATLAS and by CMS last March, we now call it a **Higgs boson** (instead of a Higgs-like boson)



# What is Next?

## Higgs as a portal

- having discovered the Higgs?
- Higgs boson may connect the Standard Model to other “sectors”



35

Need for precision measurements with  $\sim 100x$  the present statistics  
LHC upgrade ! Experiment upgrades!! (Other machines?)

Summer 2012 the CMS and ATLAS experiment found a new particle, with a mass of 125-126 GeV, which looked like the long sought Higgs boson, postulated in 1964.

March 2013: The full statistics of 2011+2012 (about a factor 3 more data) confirms the existence of the new particle.

**The spin and couplings to W and Z bosons are consistent with the expectation for a Higgs boson. Hence we call it from now onwards “a Higgs particle”. This is a brand new particle, as we never seen before.**

This Higgs boson is likely to carry the ‘genetic code’ for the physics Beyond the Standard Model. Present studies do not yet reveal any BSM signatures but have only a ~20% precision.

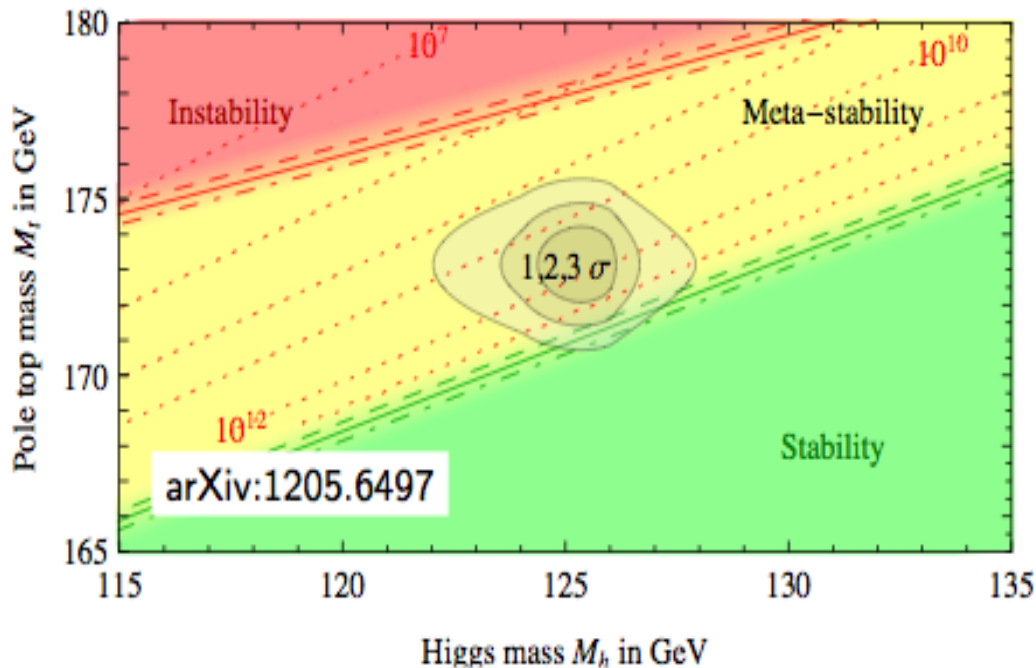
**We are on the verge of a revolution in our understanding of the Universe and our place within it.**

**This is only the beginning!!!**



# Consequences for our Universe?

Important SM parameter  $\rightarrow$  stability of EW vacuum



Precise measurements of the top quark and first measurements of the Higgs mass:

Our Universe meta-stable ?  
Will the Universe disappear in a **Big Slurp**? (NBCNEWS.com)

Will our universe end in a 'big slurp'?  
Higgs-like particle suggests it might

