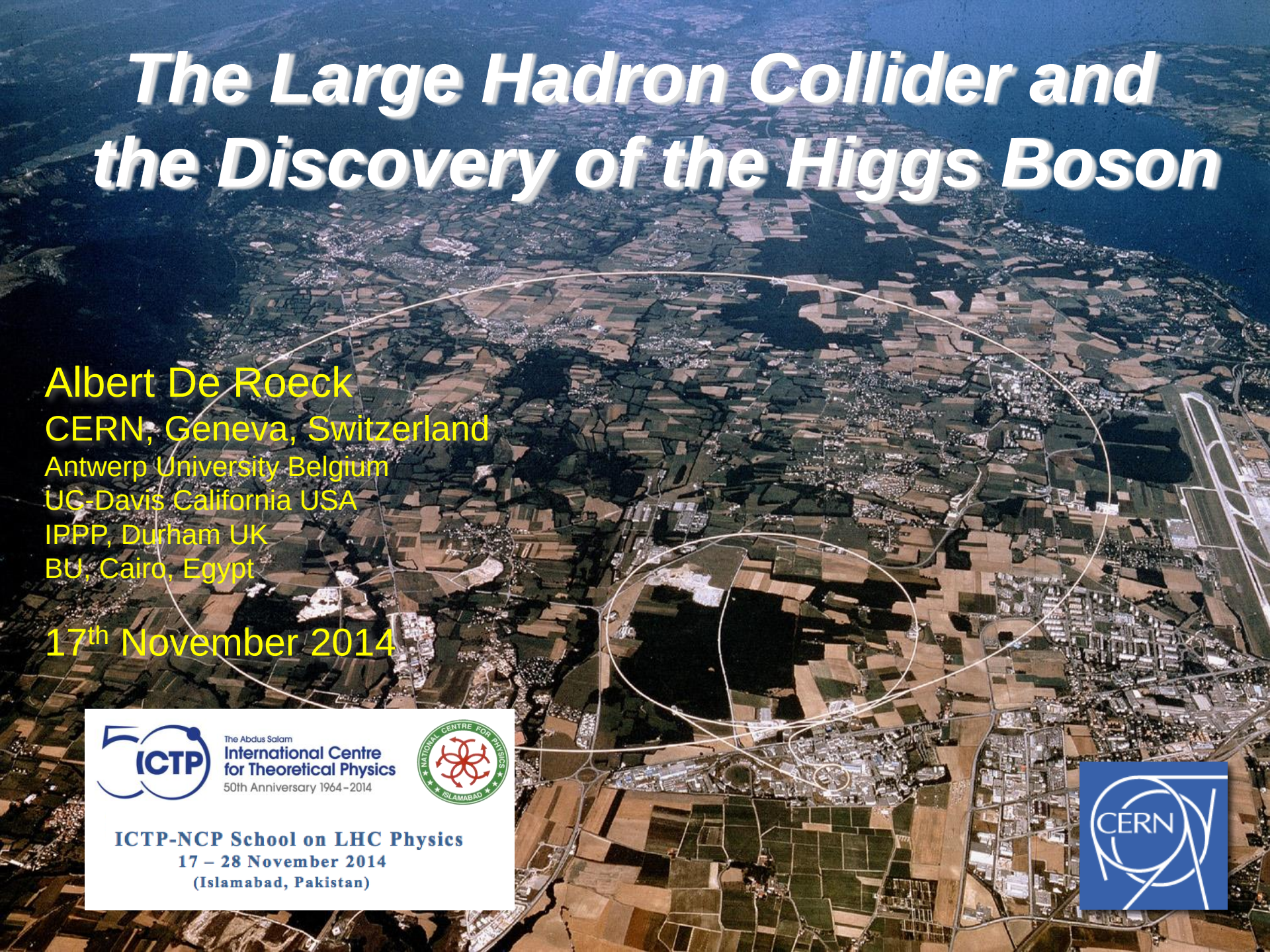
The Large Hadron Collider and the Discovery of the Higgs Boson

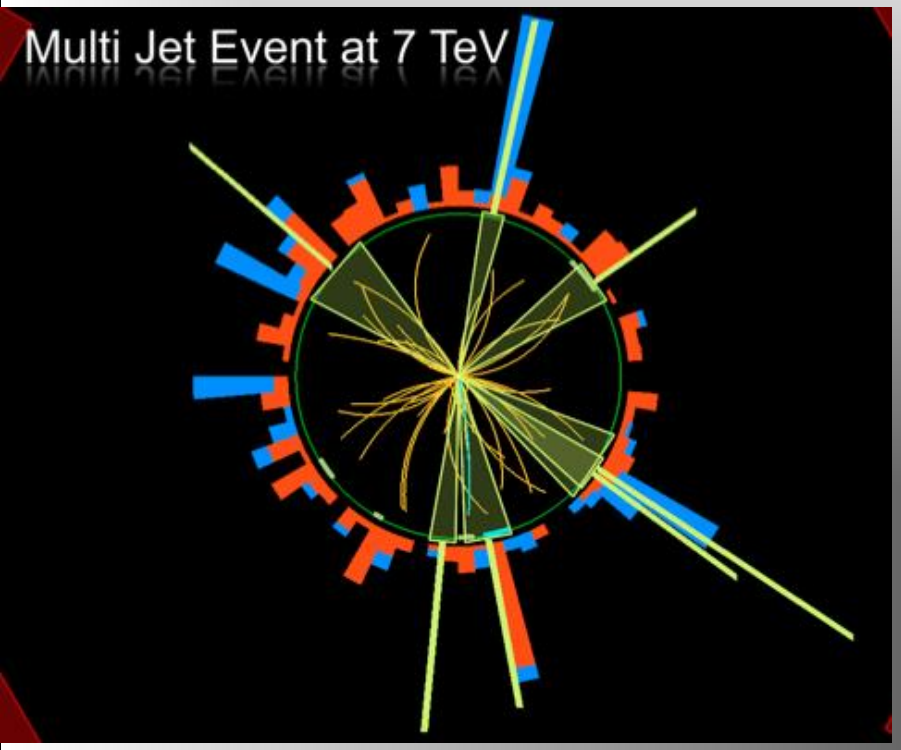


Albert De Roeck
CERN, Geneva, Switzerland
Antwerp University Belgium
UC-Davis California USA
IPPP, Durham UK
BU, Cairo, Egypt

17th November 2014

The Abdus Salam International Centre for Theoretical Physics
50th Anniversary 1964–2014

ICTP-NCP School on LHC Physics
17 – 28 November 2014
(Islamabad, Pakistan)

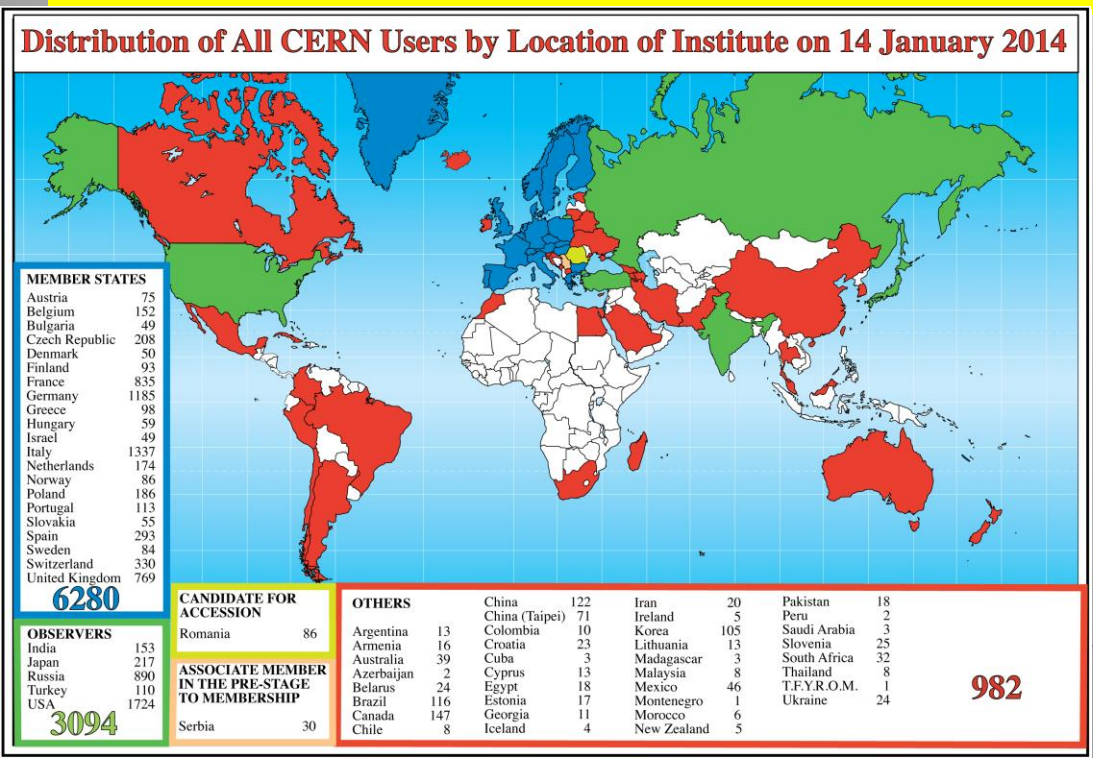


Outline

- Introduction
- The Large Hadron Collider and the Experiments
- The physics program of the Large Hadron Collider
- The Higgs discovery
- Status of the Higgs Boson
- Summary & Outlook

CERN: The European Laboratory for Particle Physics

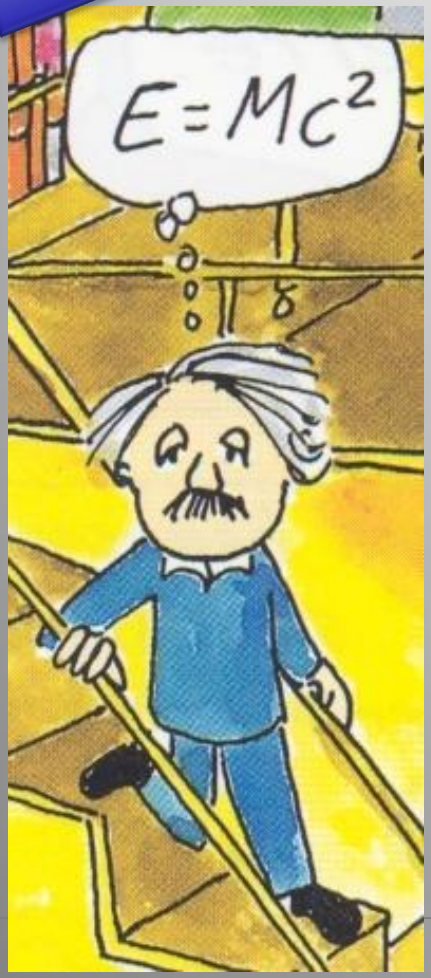
- CERN is the European Organization for Nuclear Research, the world's largest Particle Physics Centre, near Geneva, Switzerland
- It is now commonly referred to as European Laboratory for Particle Physics
- It was founded in 1954 and has 21 member states + several observer states.
- CERN employees ~4000 people + hosts ~11000 visitors from >500 universities.
- Annual budget ~ 1000 MCHF/year (2014)

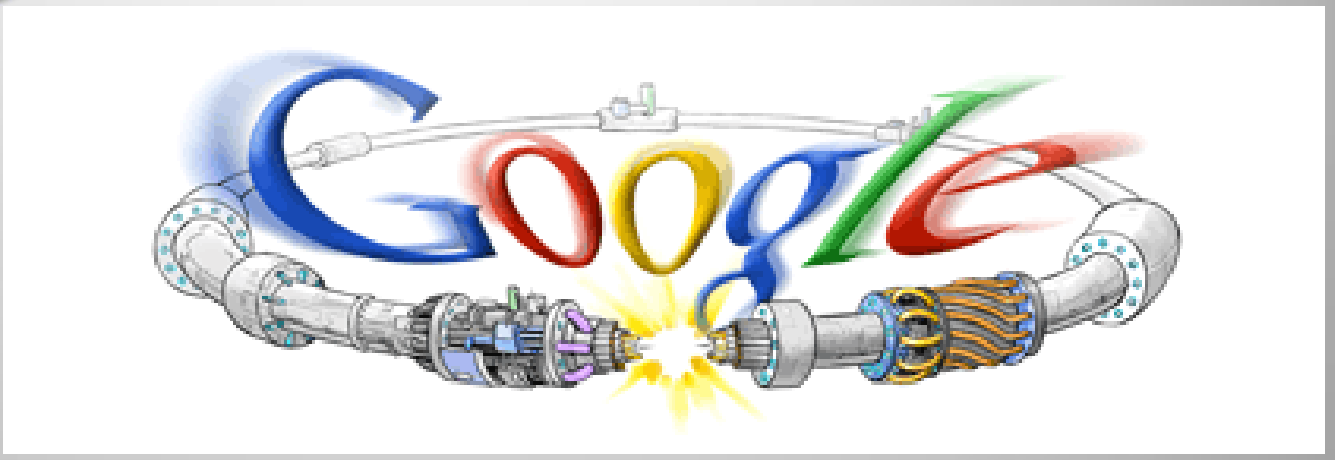


Where the World Wide Web was born...


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

We can create particles from energy

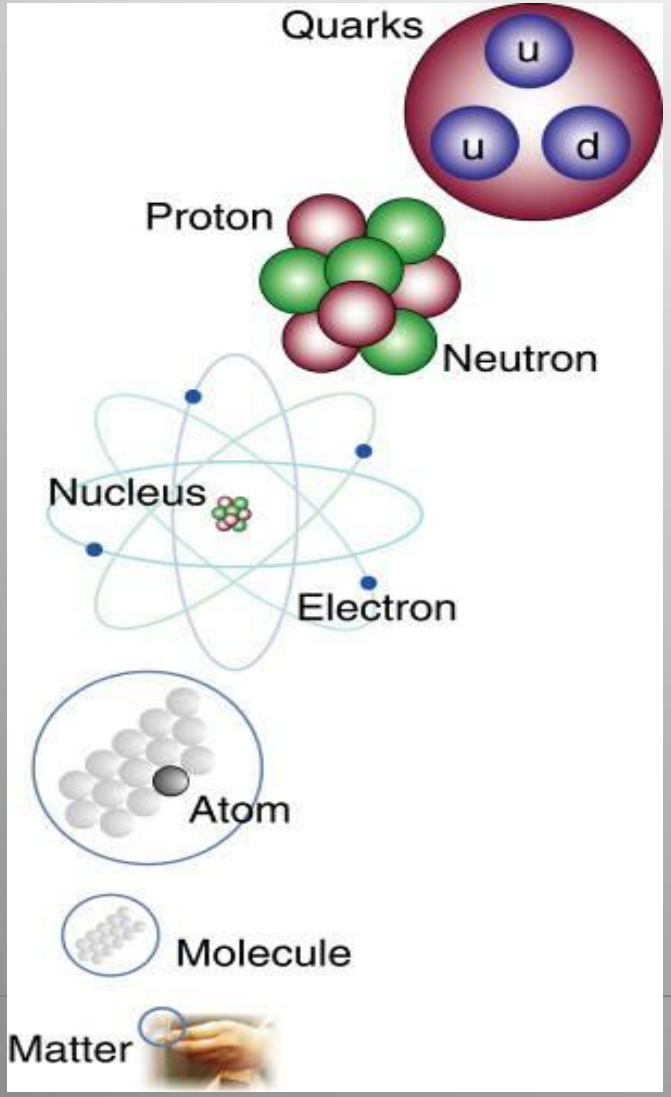




- Two beams of protons collide and generate, in a very tiny space, temperatures over a billion times higher than those prevailing at the center of the Sun.
- Produce particles that may have existed at the beginning of the Universe, right after the Big Bang

The Structure of Matter

Matter



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

Are there still smaller particles?

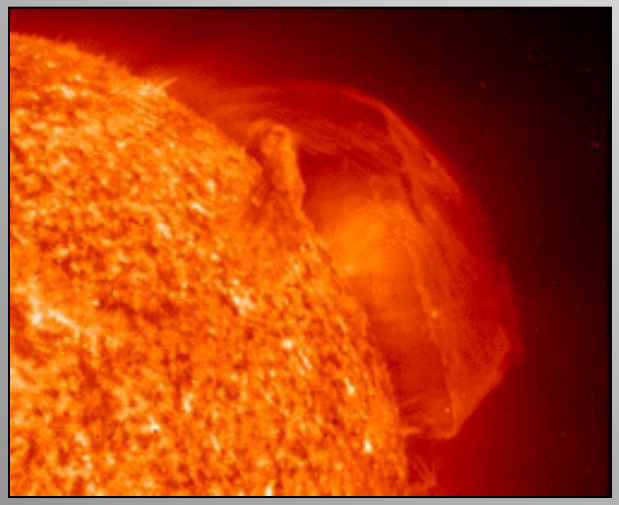
The Large Hadron Collider will address this question!

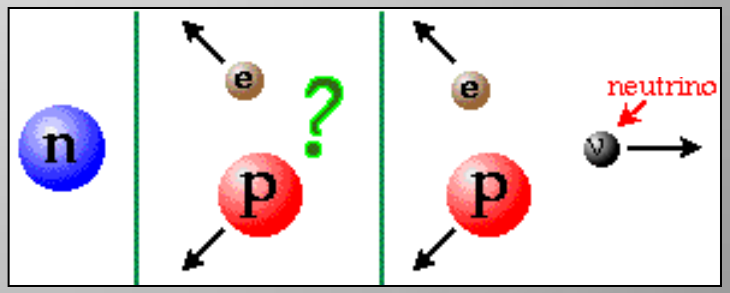
The Fundamental Forces of Nature

Electromagnetism:
gives light, radio, holds atoms together

Strong Nuclear Force:
holds nuclei together

Weak Nuclear Force:
gives radioactivity





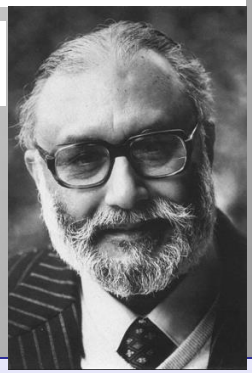
together they make the Sun shine

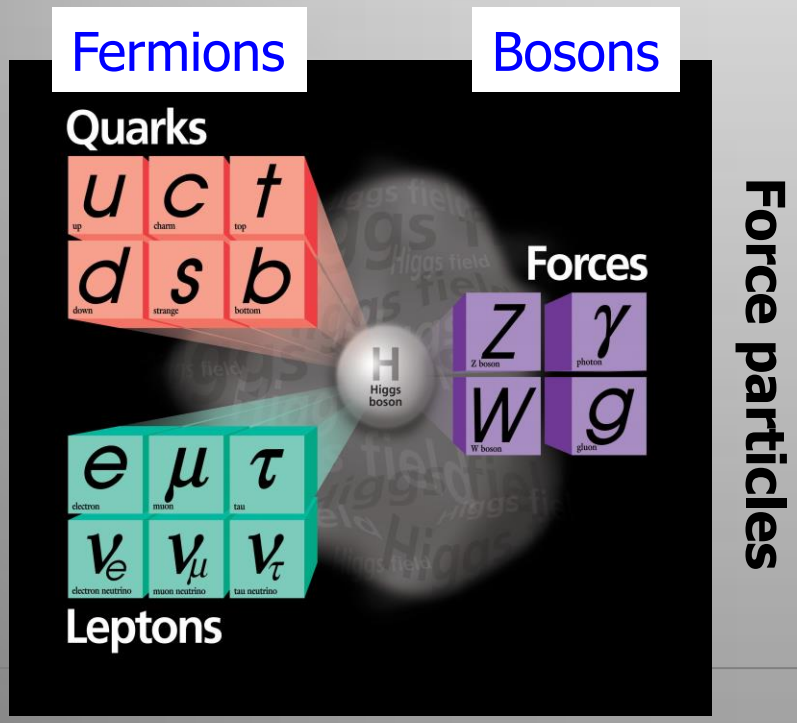
Gravity: holds planets and stars together

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

=>Work of Abdus Salam and others





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 Hunt for the Higgs

Where do the masses of elementary particles come from?

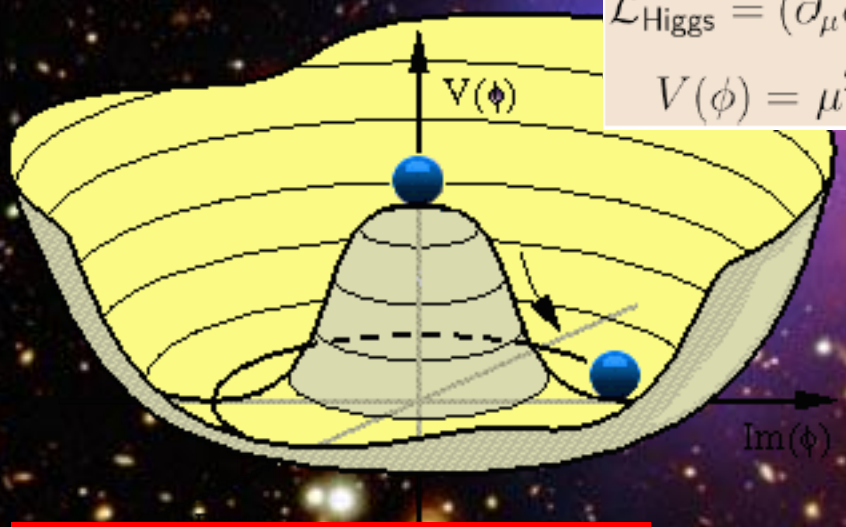
The key question (pre-2012): Does the Higgs particle exist? If so, where is the Higgs?

Massless particles move at the speed of light -> 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

Note: NOT the mass of protons and neutrons

It could be anywhere from 114 to ~700 GeV

The Higgs Field and the Cocktail Party

By David Miller

Imagine a cocktail party

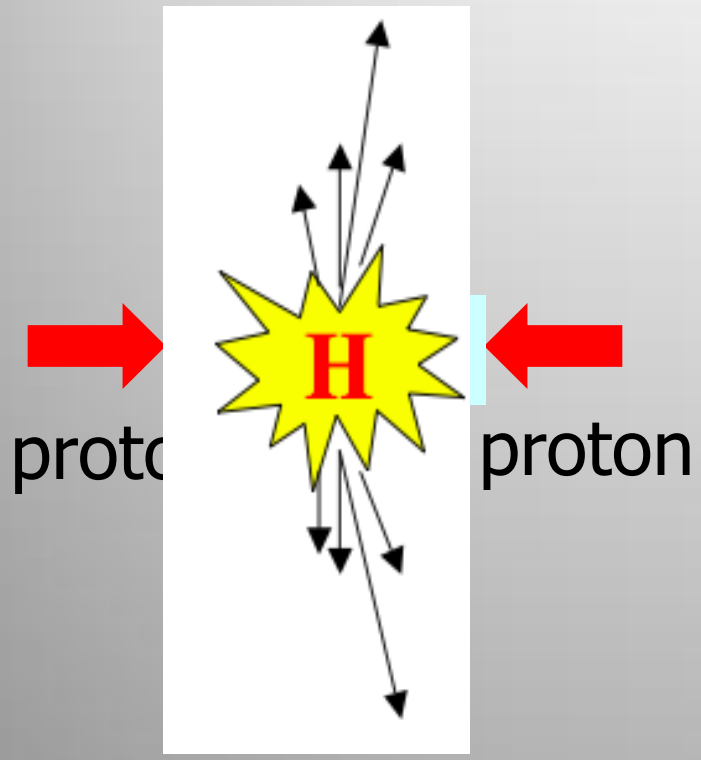
This is the Higgs field

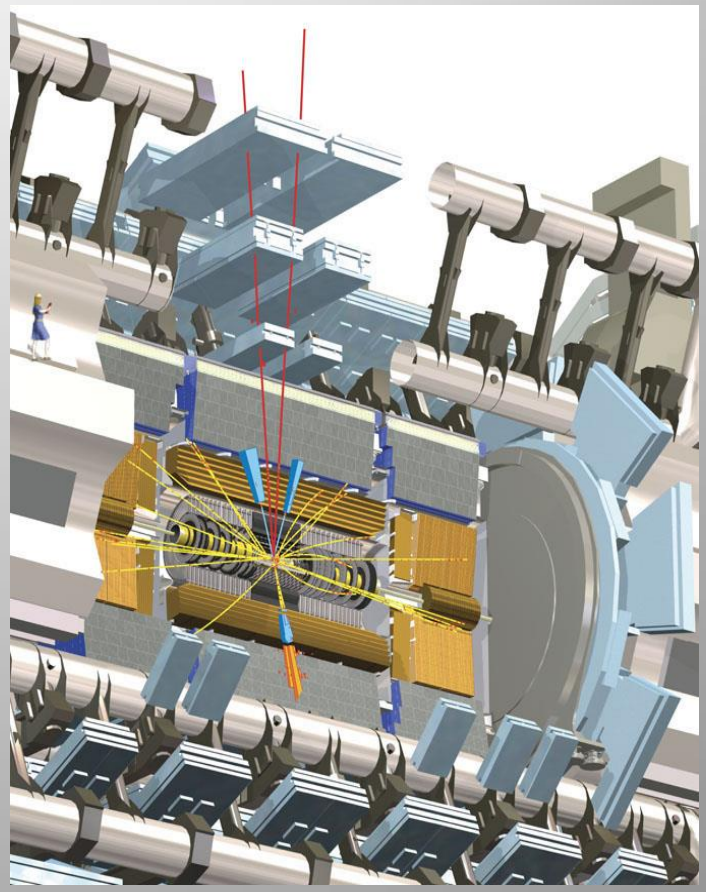
Enters a famous person…

He is slowed down on his way to the drinks!!

The Higgs Particle

Technique: Produce and detect Higgs Particles at Particle Colliders





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

This Search Requires……

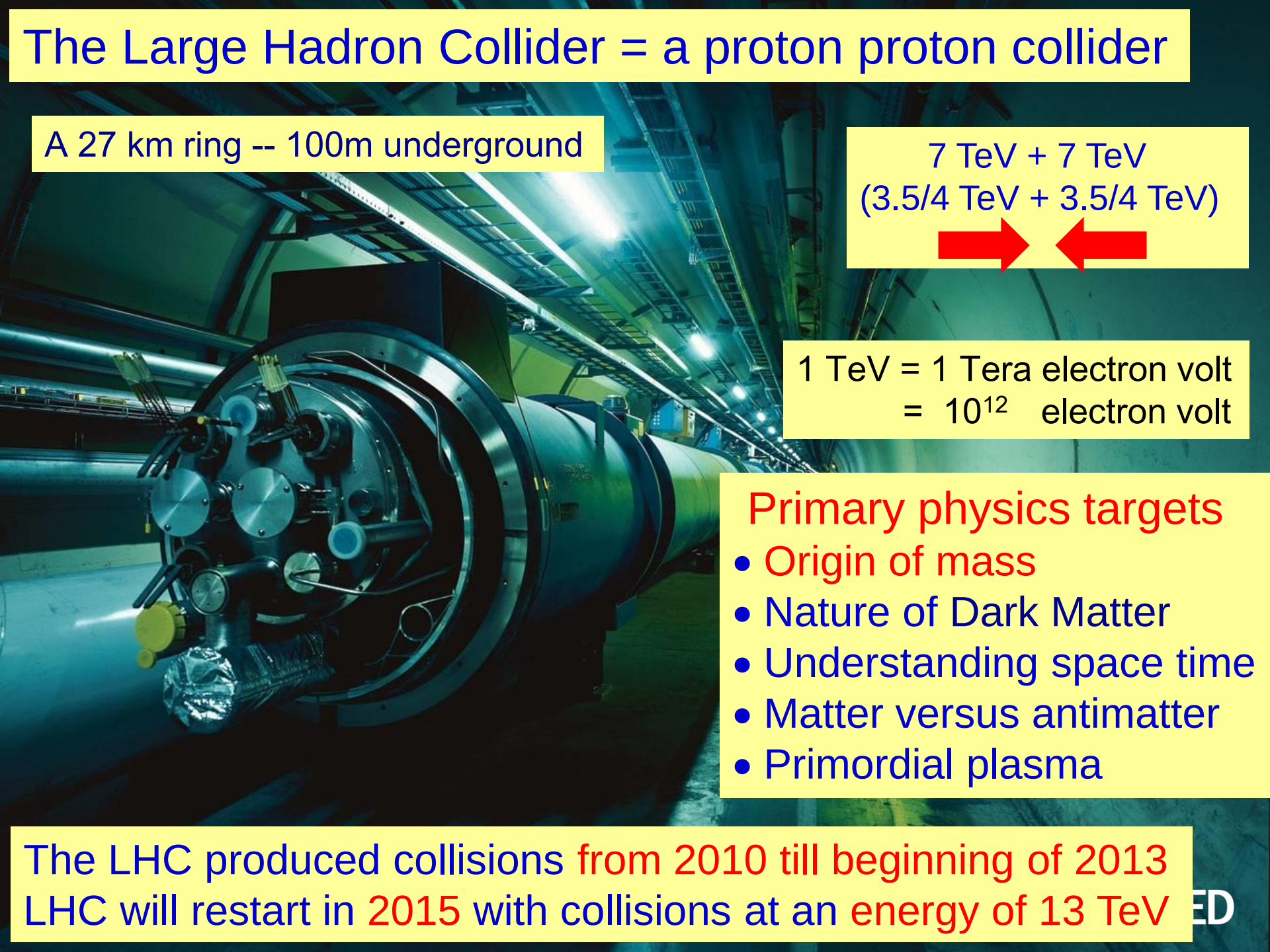
1. Accelerators : powerful machines that accelerate particles to extremely high energies and bring them into collision with other particles

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



A 27 km ring -- 100m underground

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 produced collisions from 2010 till beginning of 2013
LHC will restart in 2015 with collisions at an energy of 13 TeV

The LHC is an Extraordinary Machine

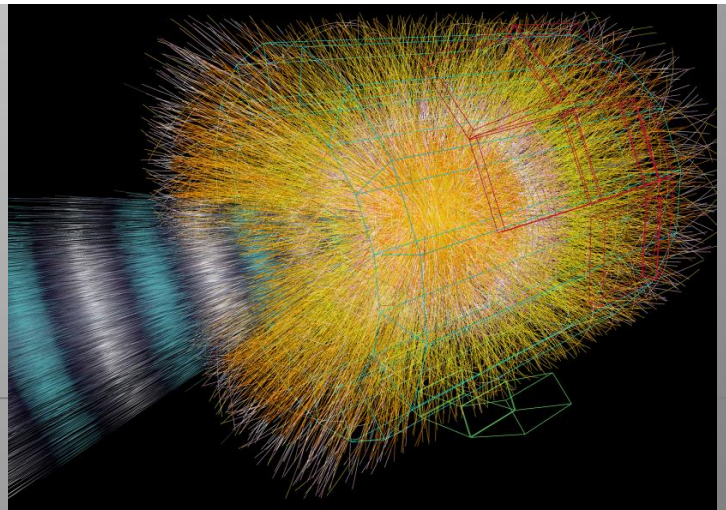
LHC facts

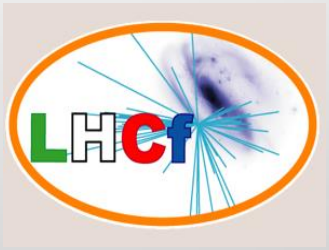
The LHC is ...

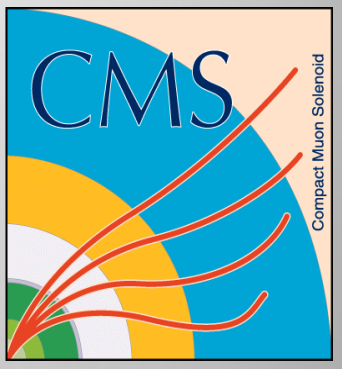
Colder than the empty space in the Universe: 1.9K ie above absolute zero

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

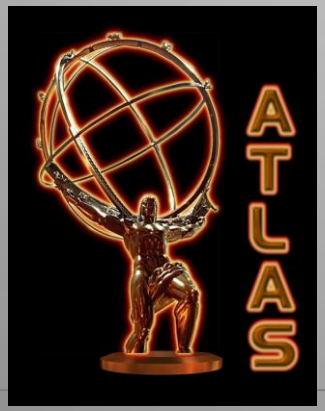
Hotter than in the sun: temperature in the collisions is a billion times the one in the centre of the sun

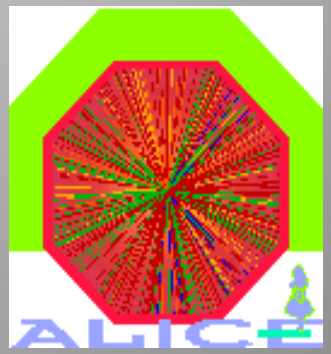






Experiments at the LHC





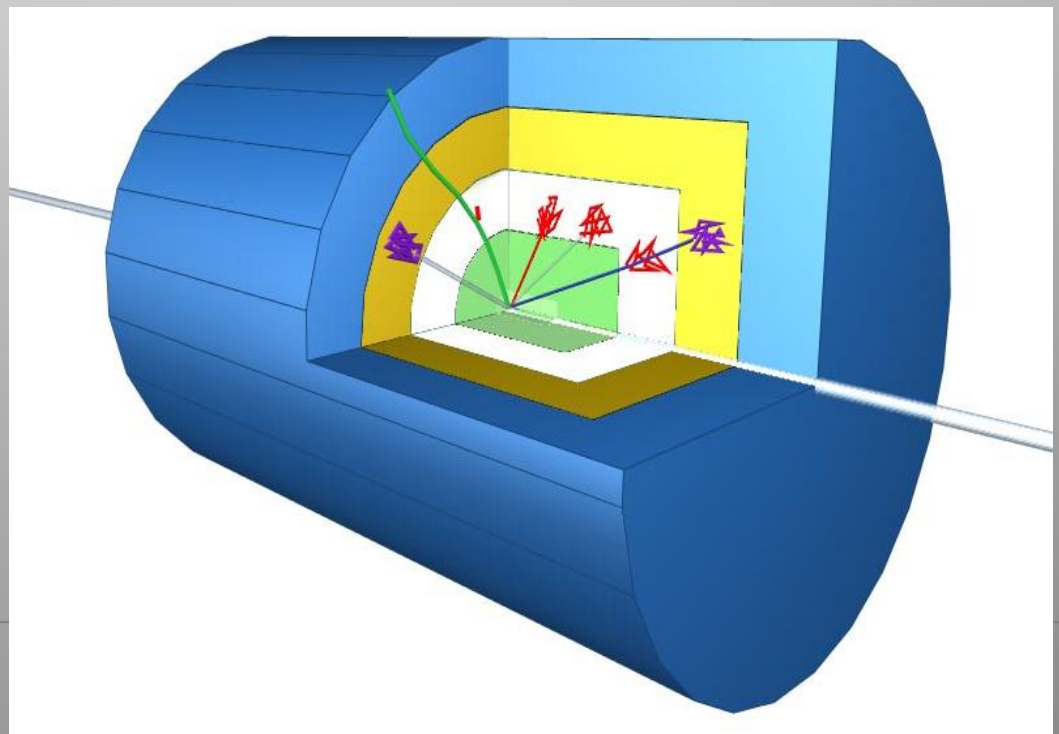
Schematic of a LHC Detector

Physics requirements drive the design!

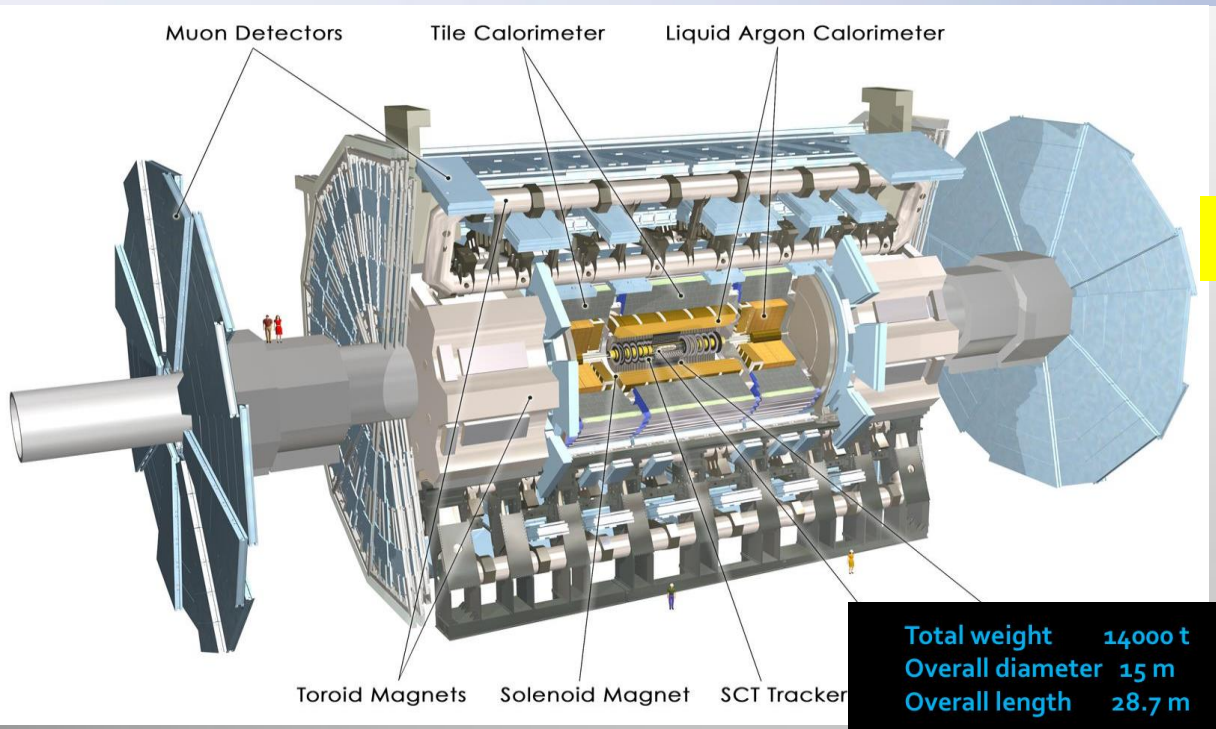
Analogy with a cylindrical onion:

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.

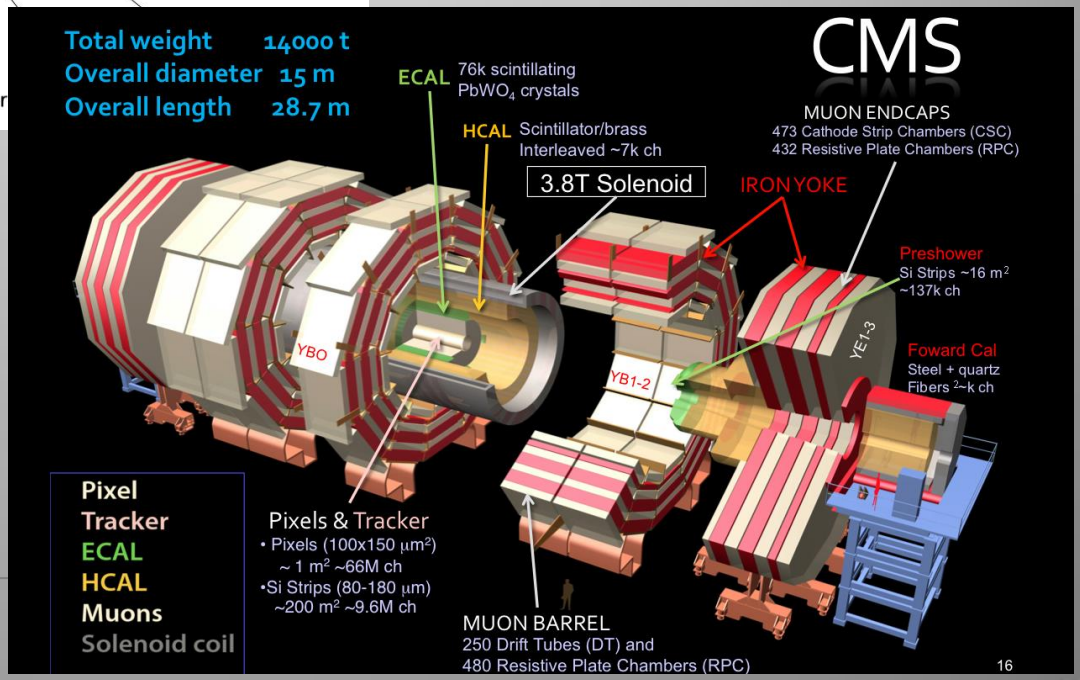
Such an experiment has ~ 100 Million read-out channels!!



The Higgs Hunters @ the LHC



The ATLAS experiment



The CMS experiment

These experiments use different technologies for their detector components

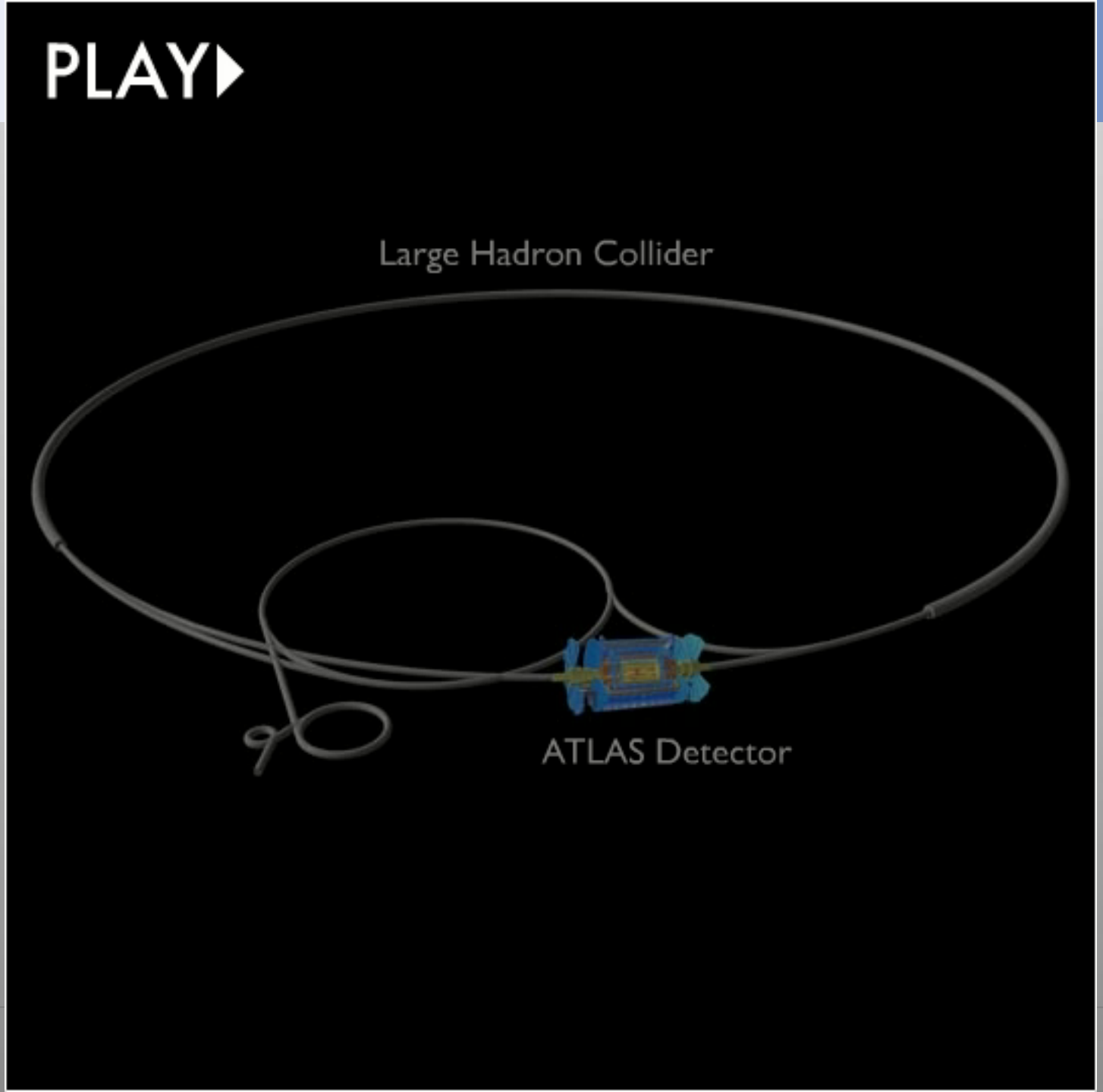

CMS before closure
ME-1/1/06
ME-1/1/05
ME-1/1/04
ME-1/1/03
ME-1/1/02
ME-1/1/01
ME-1/1/36
ME-1/1/35
HE-RBX 03
HE-RBX 02
HE-RBX 01
LIFTLUX

CMS Collaboration June 27, 2012

The CMS Collaboration: >3200 scientists and engineers, >800 students from ~190 Institutions in 42 countries .

About 1/8th of the collaboration

Pakistan is a Member of CMS


PLAY
Large Hadron Collider
ATLAS Detector

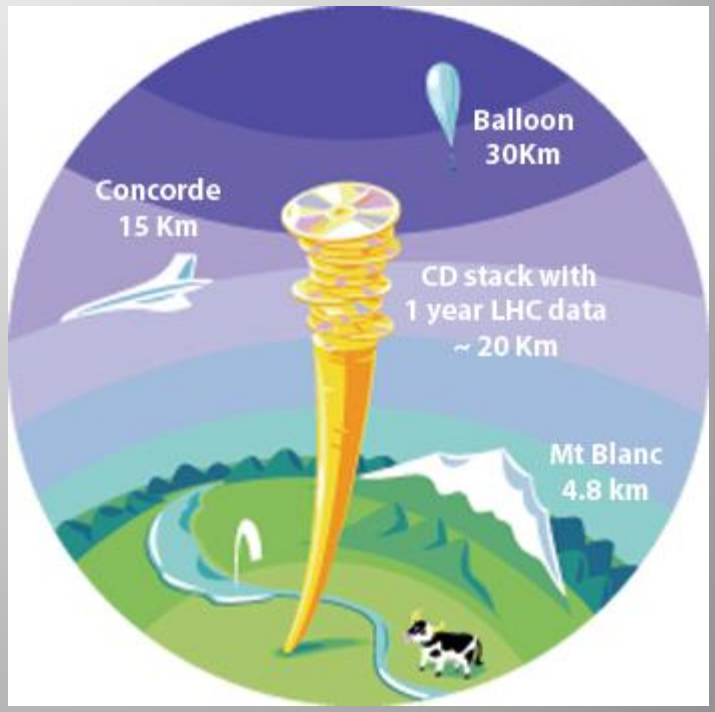
The LHC Data Challenges

Experiments were anticipated to produce about **15 Million Gigabytes** of data each year (~20 million CDs!)

The total volume in eg ATLAS is 5 billion detector events and several billion Monte Carlo events amounting to 100 Million Gigabytes of data in 3 years

LHC data analysis requires a computing power equivalent to **~100,000 of today's fastest PC processors**

=> Requires many cooperating computer centres, as CERN can only provide ~20% of the capacity



GRID Computing

The Physics Program at LHC

Data taking started in 2010

Now we have more than 300 reviewed scientific papers per experiment!

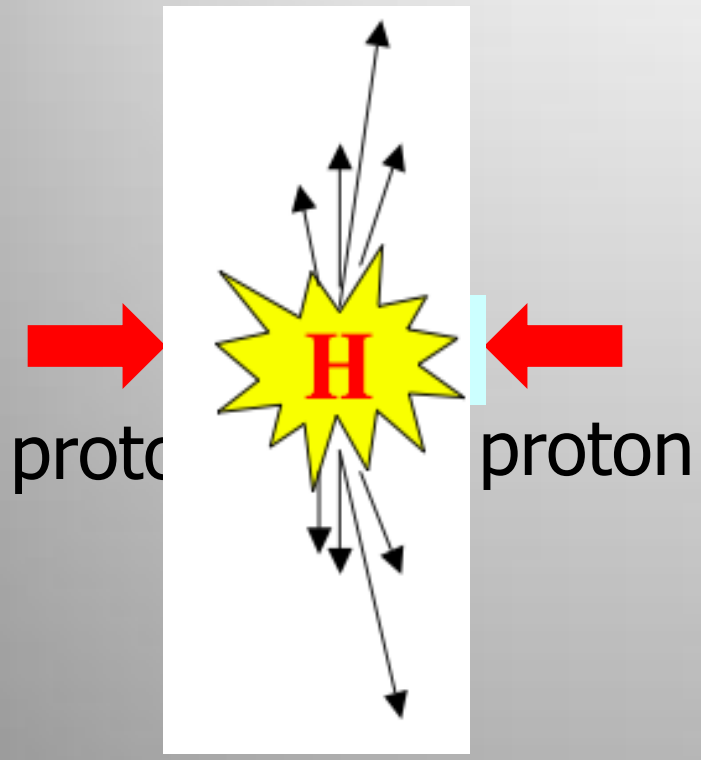
Mostly measurements of the strong and electroweak force at 7/8 TeV and Searches

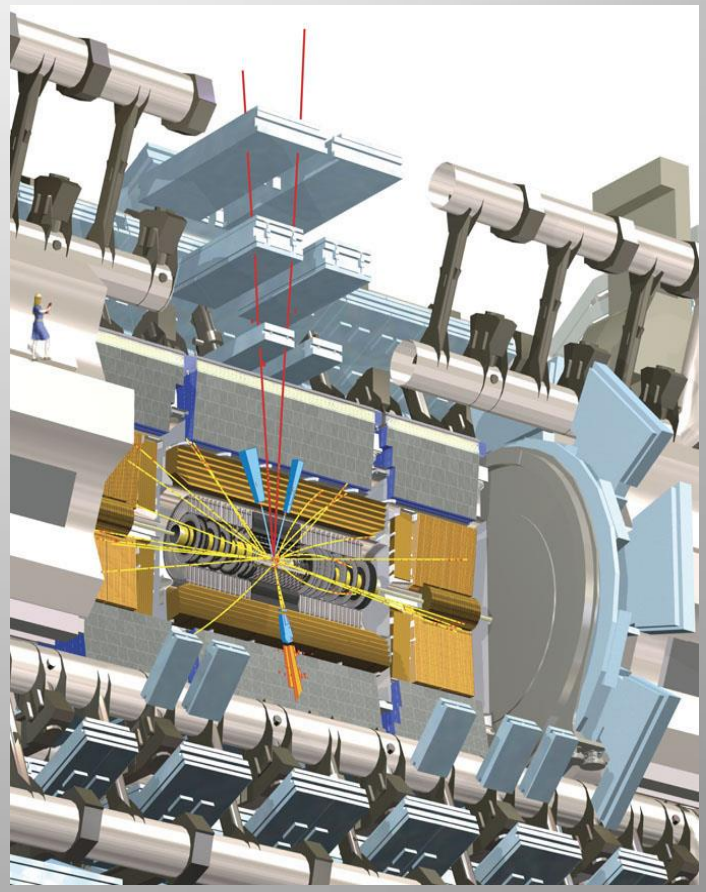
-Are quarks the elementary particles? So far yes
-Do we see supersymmetric particles? Not yet
-Do we see extra space dimensions? Not Yet
-Do we see micro-black holes? No

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

The Higgs Particle

Technique: Produce and detect Higgs Particles at Particle Colliders





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

Higgs Hunters

Higgs Hunting Basics

Needle-in-the-hay-stack problem

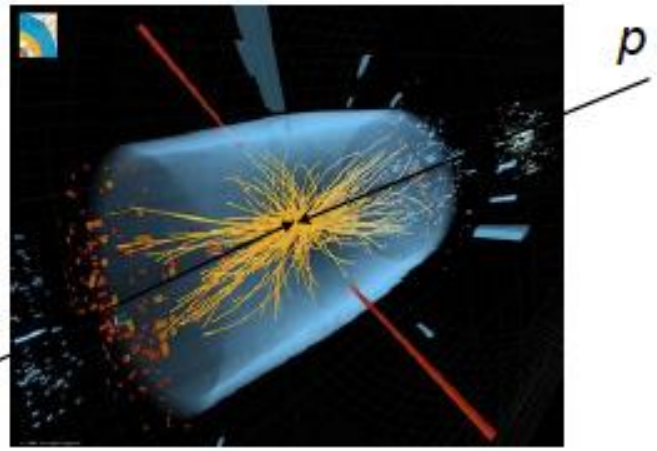
- need high energy:

  $E = mc^2$

- need lots of data

non-deterministic and very rare

order 1 in 10^{10}



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

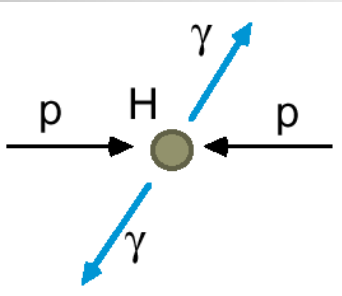
Higgs Boson Searches (simulation)

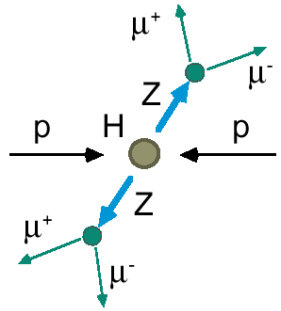
Low M_H < 140 GeV/c²

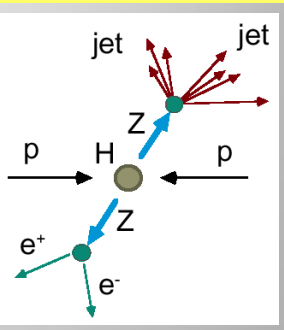
Medium 130<M_H<500 GeV/c²

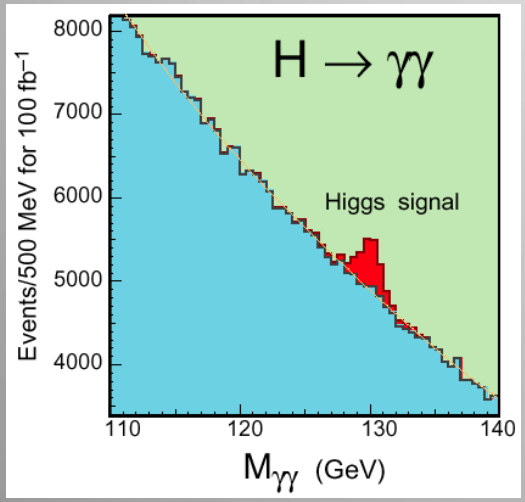
High M_H > 500 GeV/c²

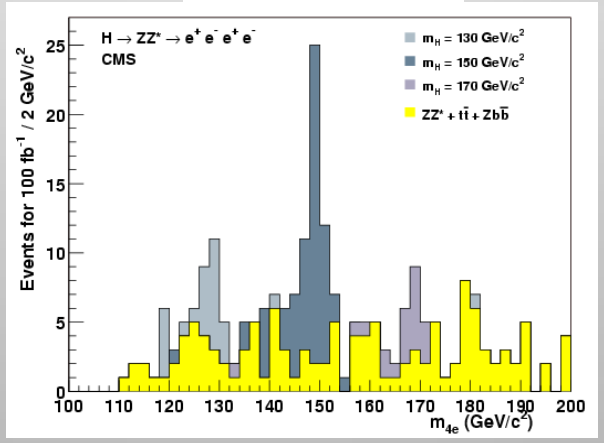
simulation

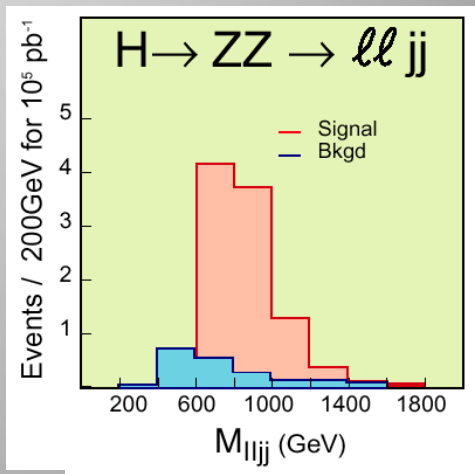


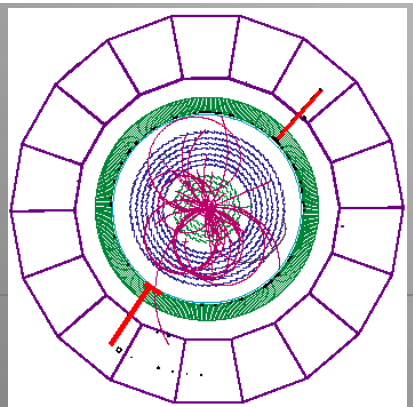


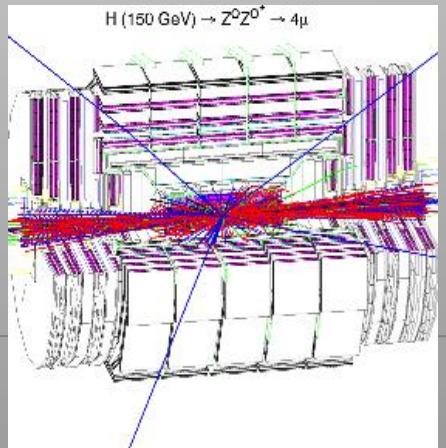


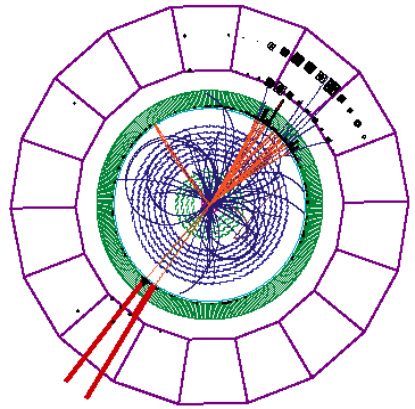




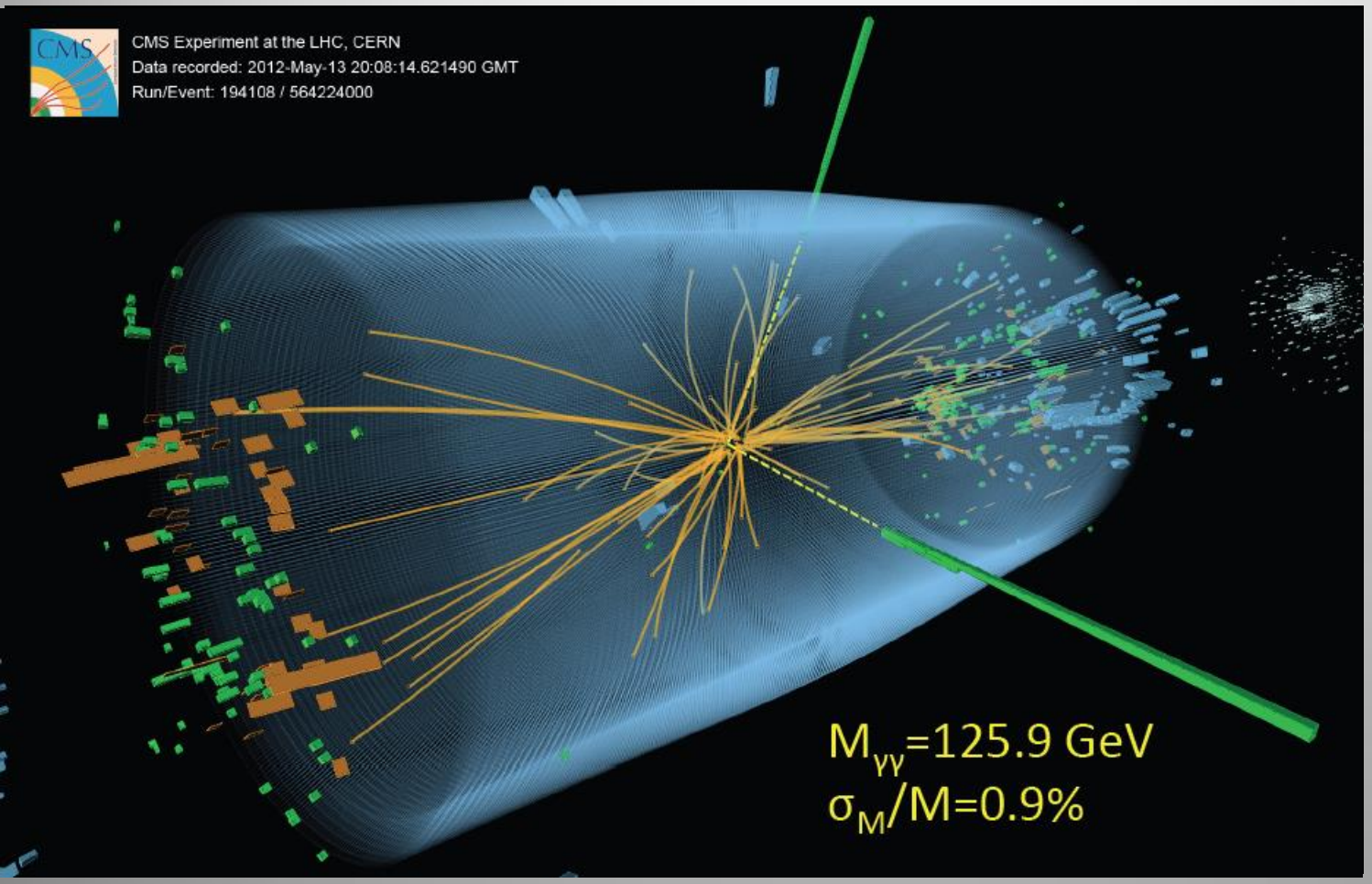


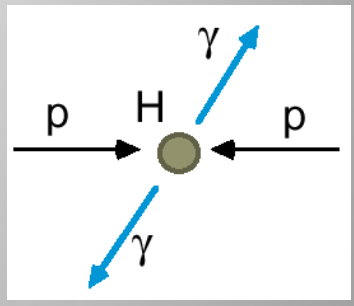






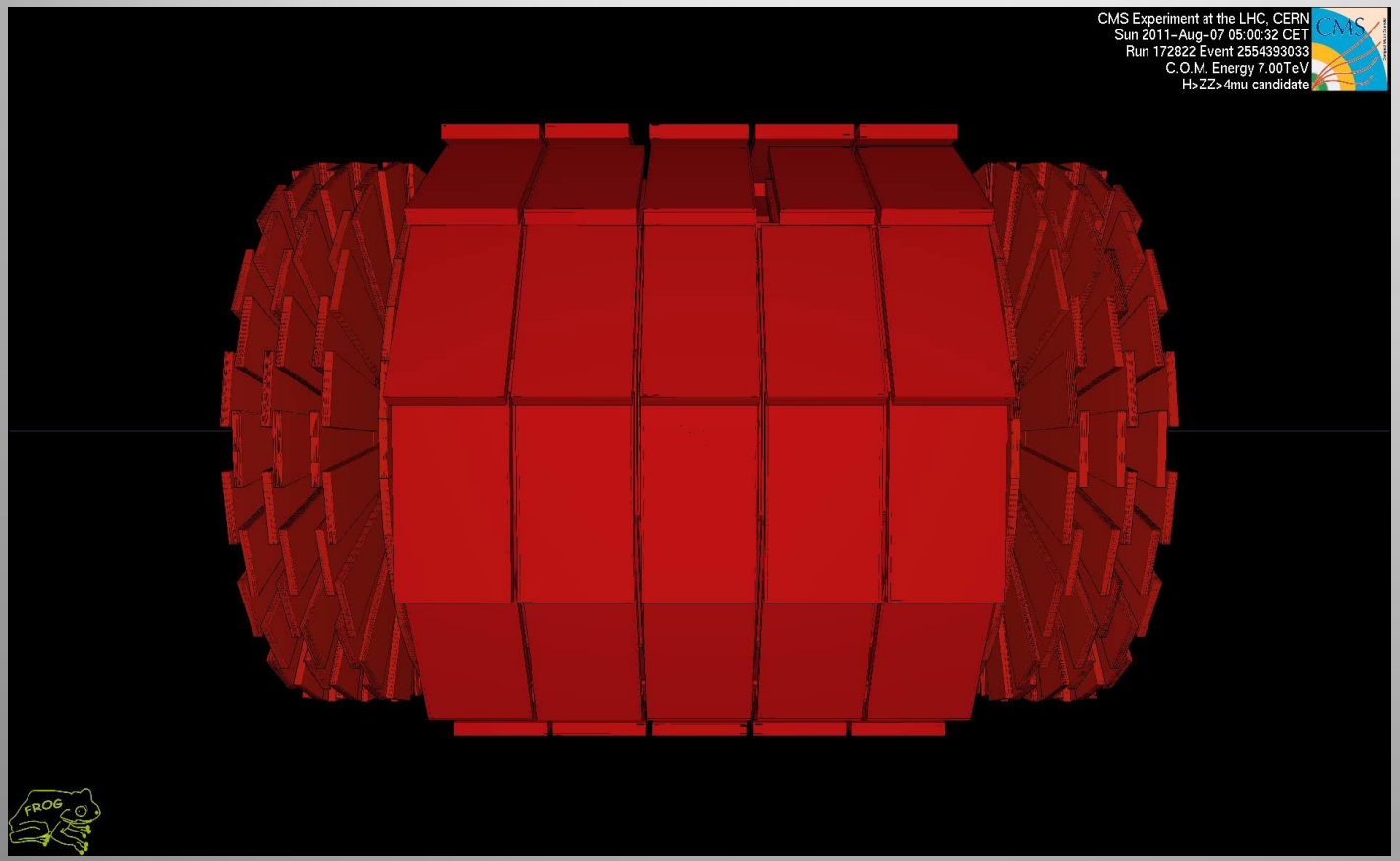
A Collision with two Photons

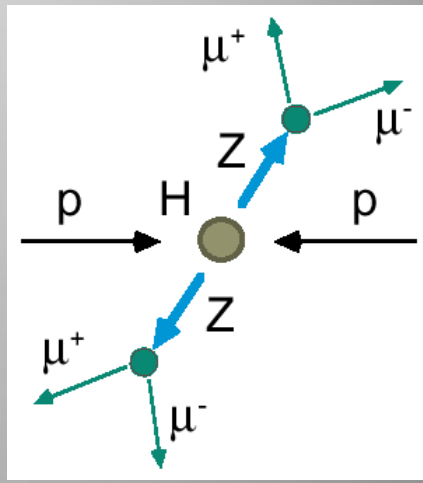




A Higgs or
a 'background'
process without
a Higgs?

A real collisions: ZZ-> 4 muons





July 4th 2012

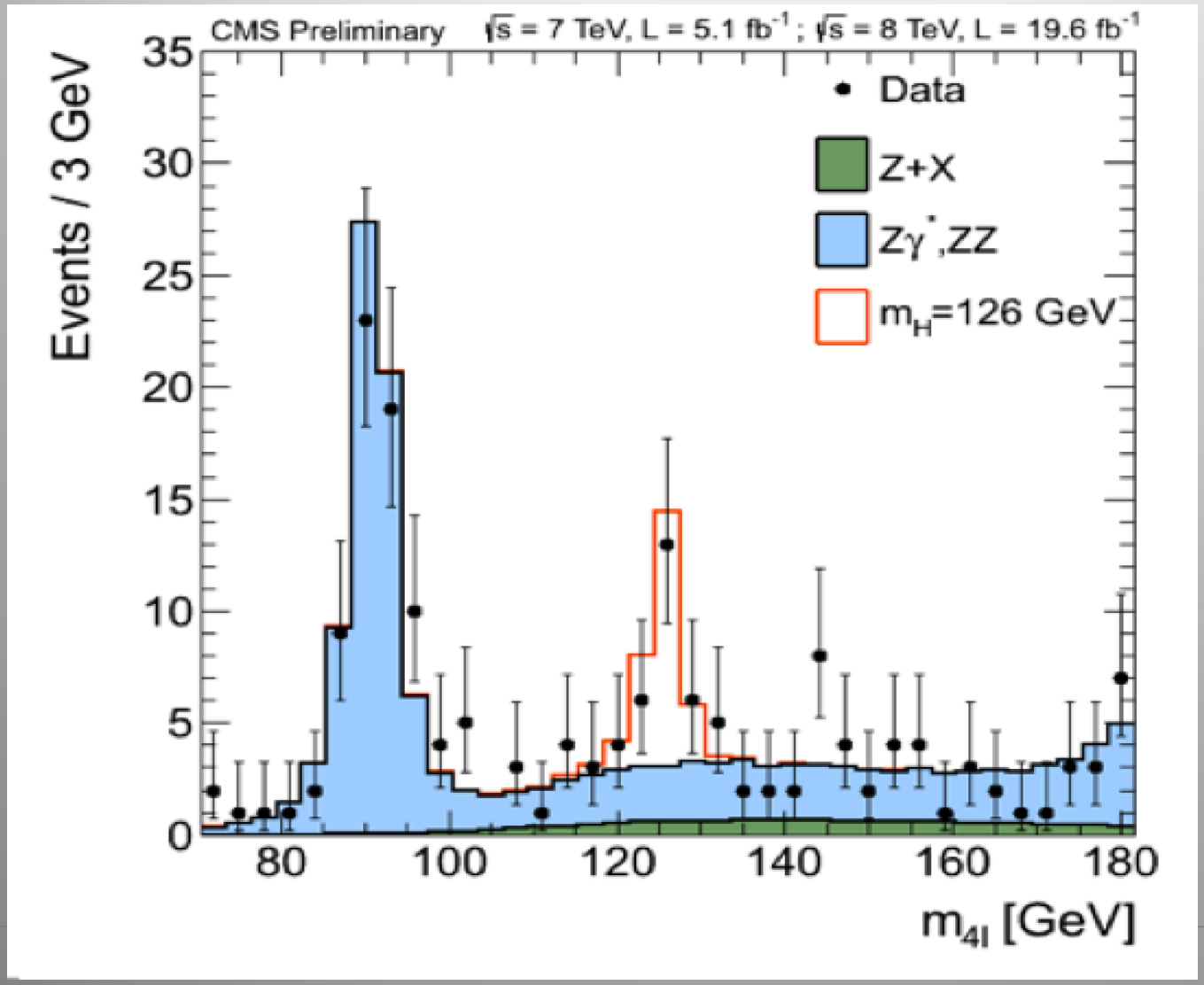
- Official announcement of the discovery of a Higgs-like particle with mass of 125-126 GeV by CMS and ATLAS.
- Historic seminar at CERN with simultaneous transmission and live link at the large particle physics conference of 2012 in Melbourne, Australia

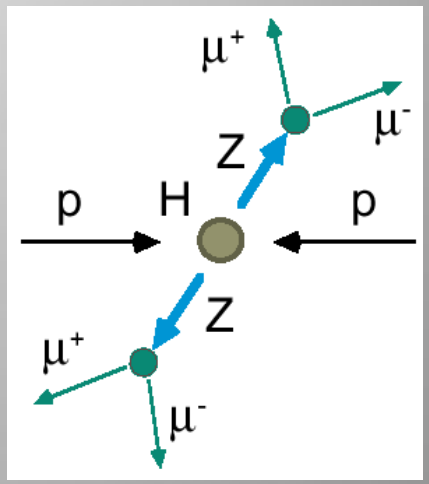
CERN

Melbourne

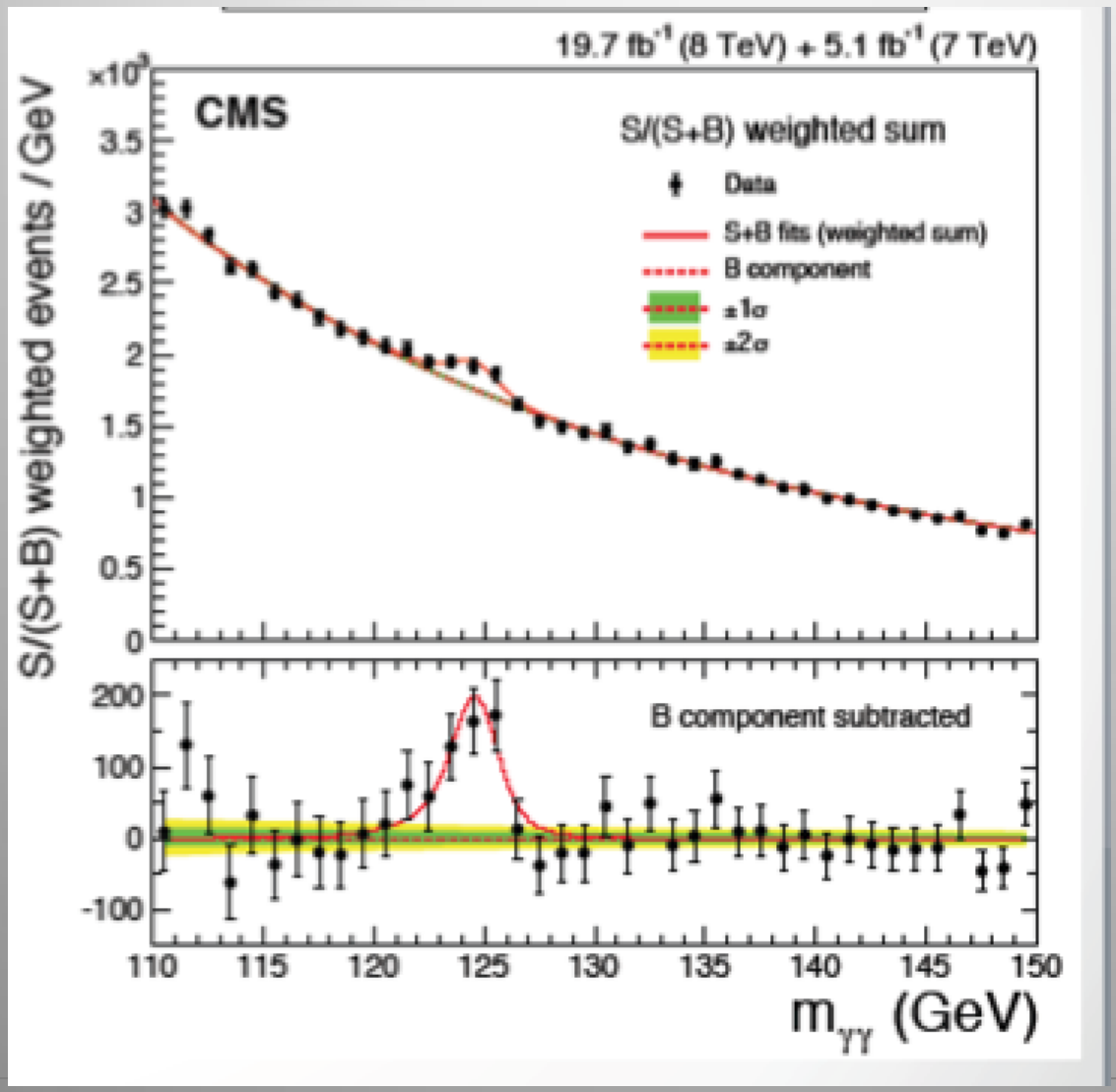
Followed live around the world…

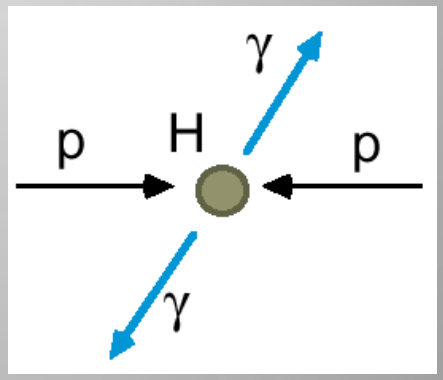
Discovery of the Higgs Boson...





Discovery of the Higgs Boson...





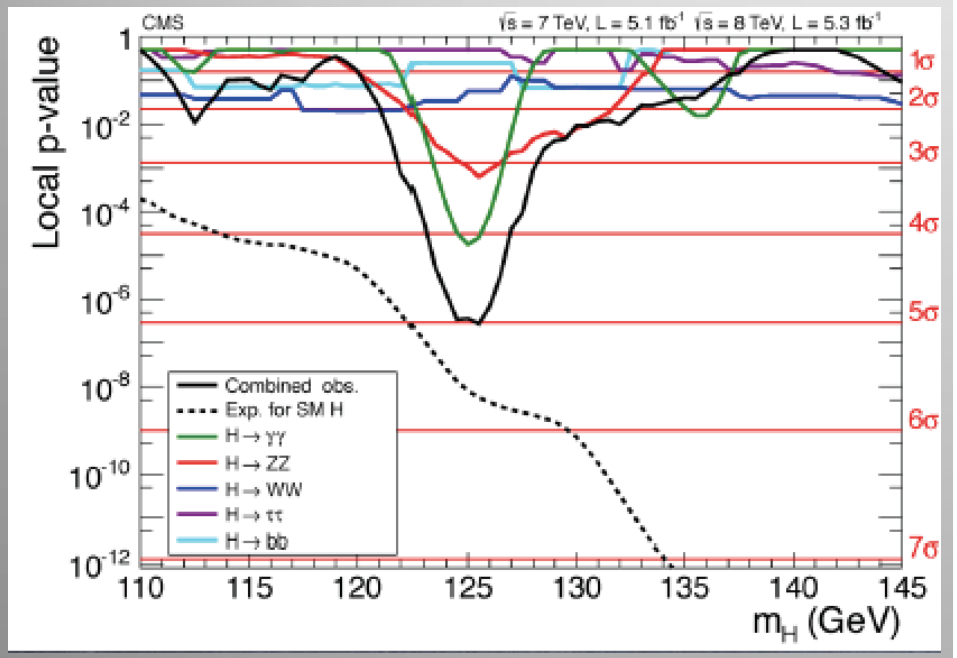
July 2012: Results

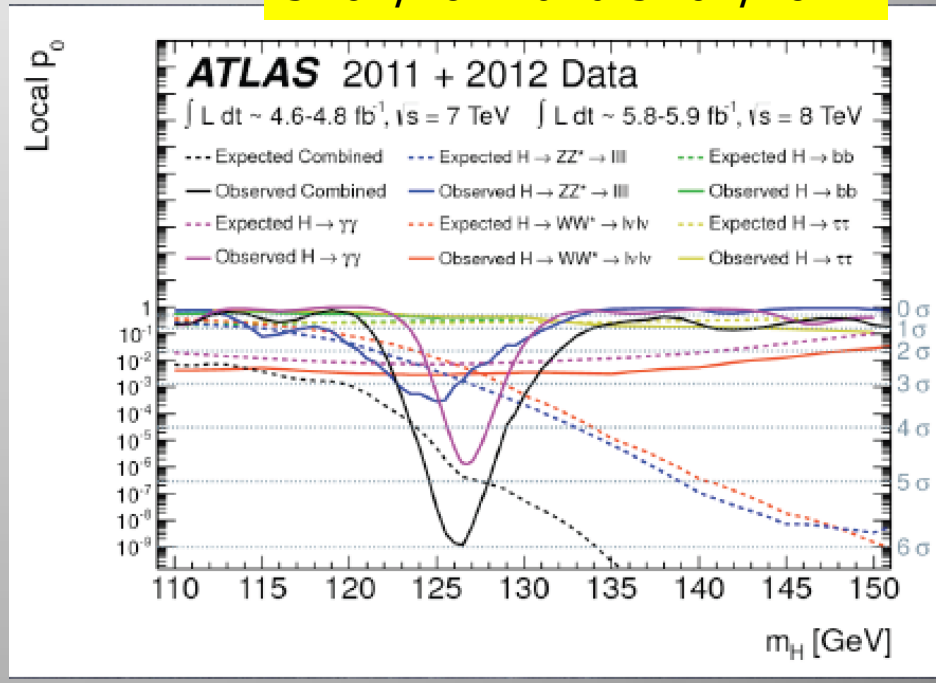
Both experiments see an excess ~125 GeV in the γγ, ZZ and WW channel

→Final result by adding up al the channels

Shown is the compatibility with a 'background only hypothesis"

5 fb^{-1}/2011 and 5 fb^{-1}/2012



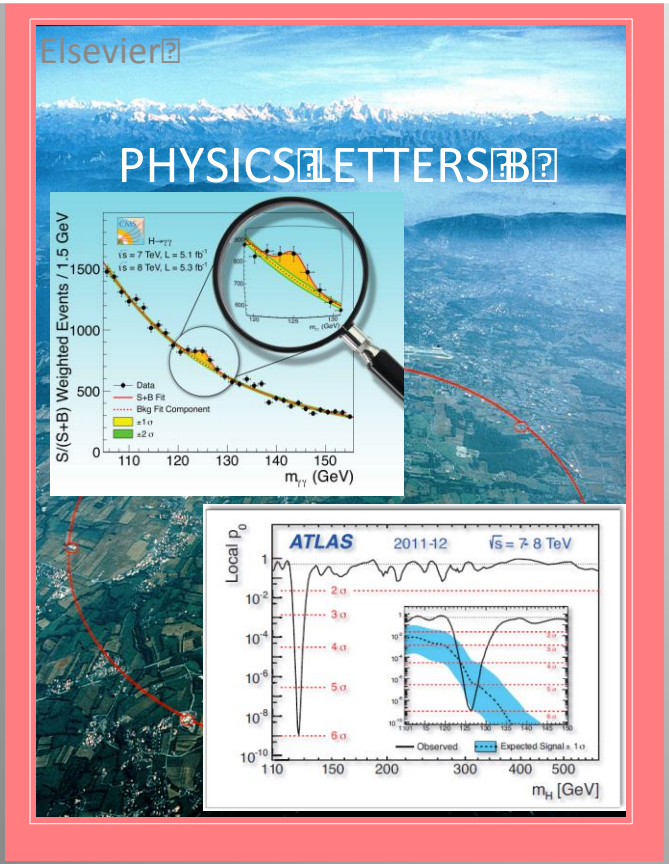


CMS and ATLAS observe a new boson with a significance of about 5 sigma (1 chance in 3 million to be wrong!!!)

July 4th 2012
The discovery of a new particle

Higgs Publications...

Special Physics Letters B edition with the ATLAS and CMS papers



Also...

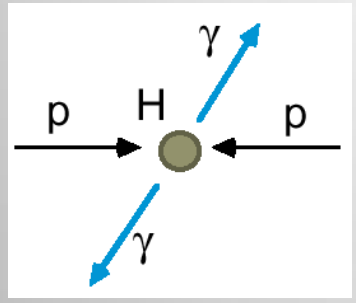
We called the new particle a "higgs-like" particle

The News Since July 2012

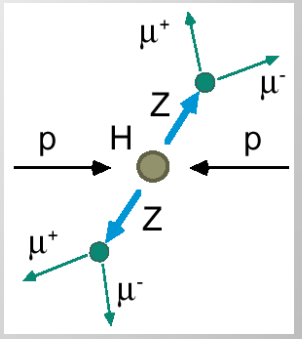
- The discovery of the new particle has been confirmed with more added collisions in 2012 (like 10σ now…)
- Signals in the fermion-channels start building up. In total we see these with a significance of ~ 4σ/exp.
- We tested the spin: it is compatible with a 0^+ state and not with a 0^- or spin 2 states
- The mass is measured better with time, now in the around 125 GeV.
- The couplings to Bosons and Fermions are consistent with the SM predictions (but these are not very precise yet; Surprises possible…)

March 2013: We call it now “a Higgs particle”

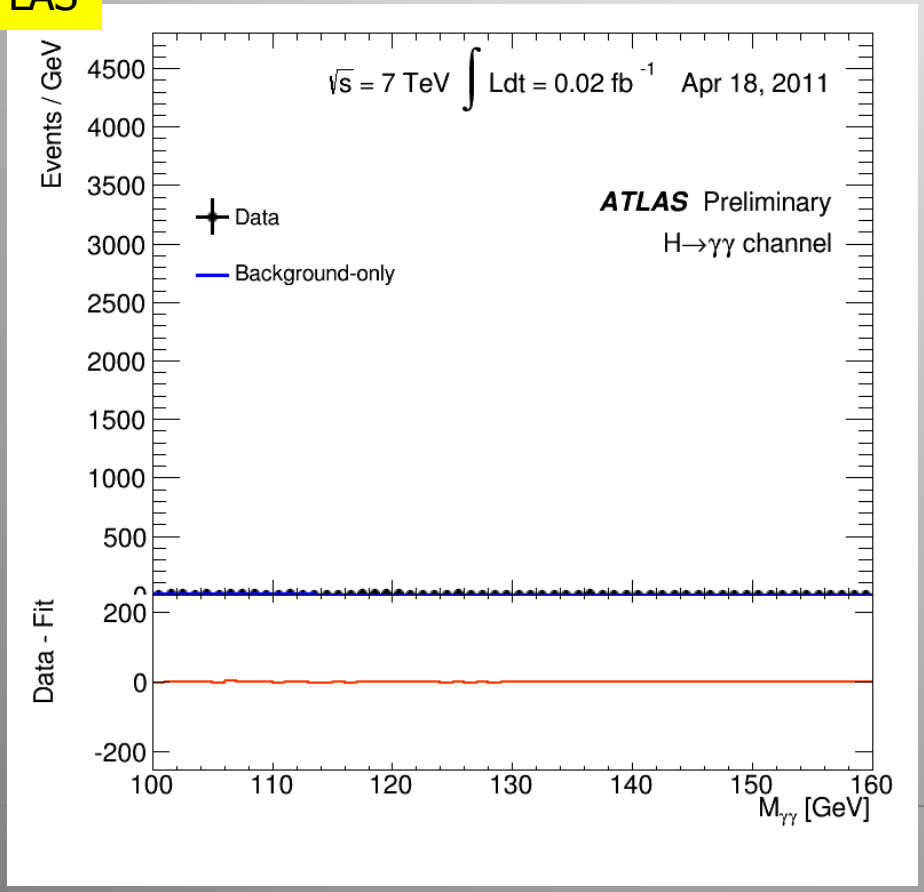
The Birth of a Particle



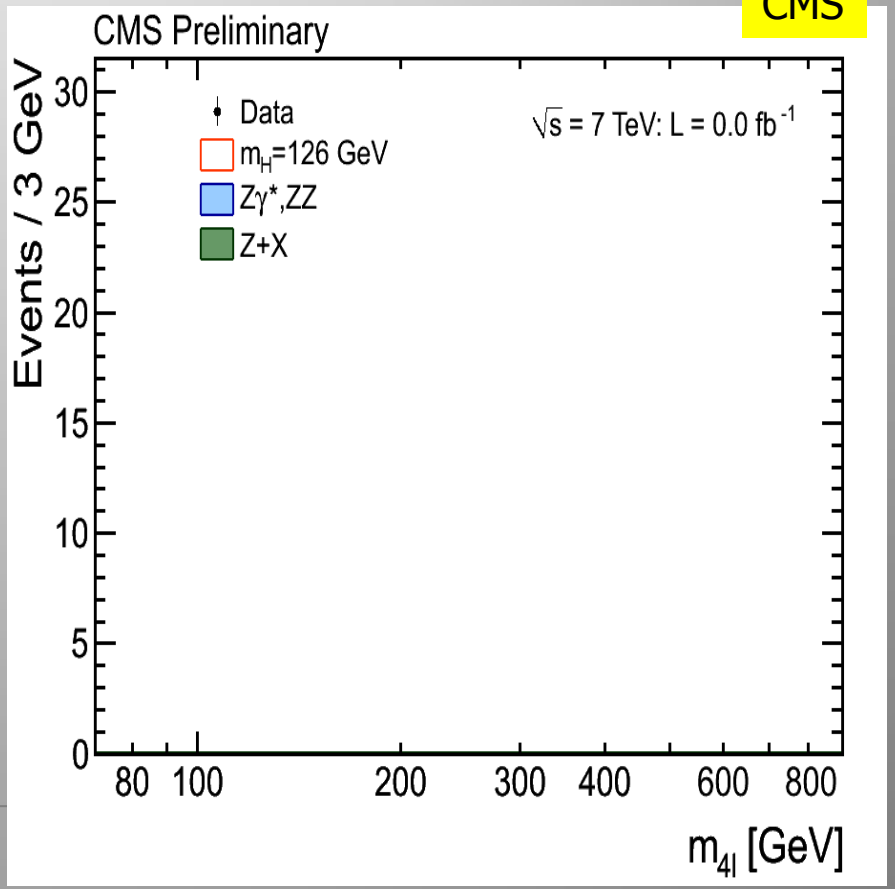
"History" of the data accumulation during the last two years



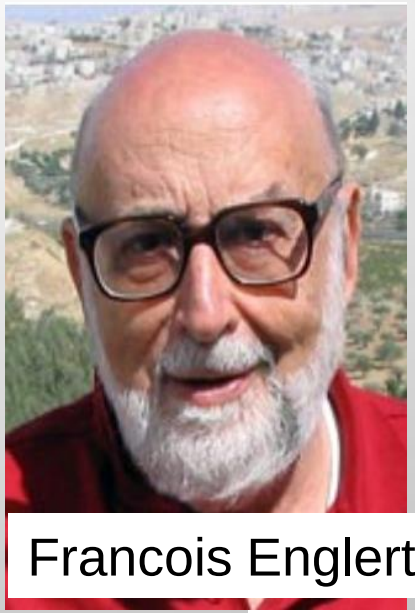
ATLAS



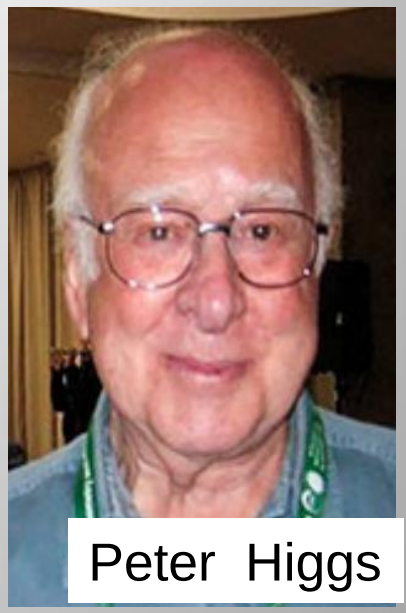
CMS



Tuesday 8 October 2013

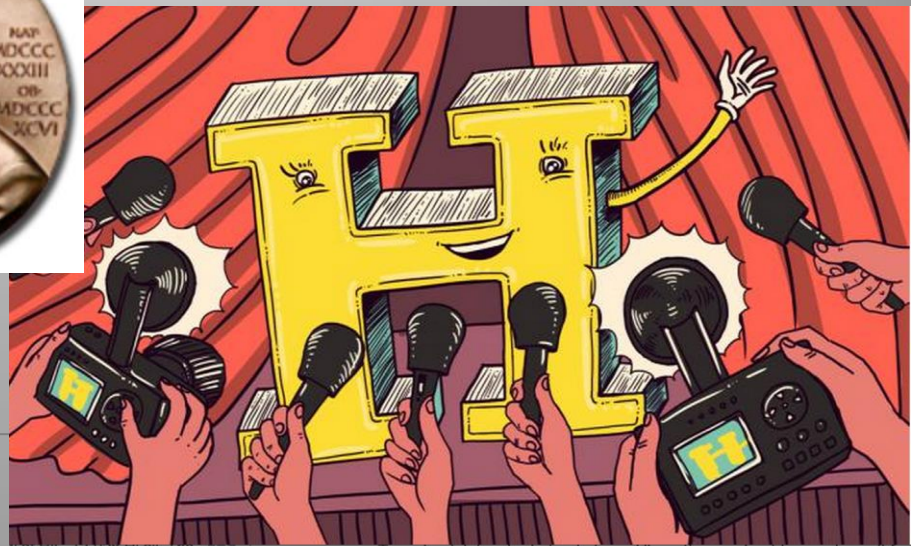


Francois Englert



Peter Higgs

Congratulations!!!!



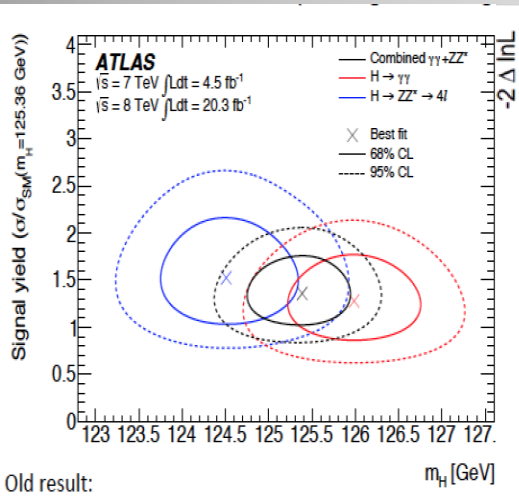
...and December 2013

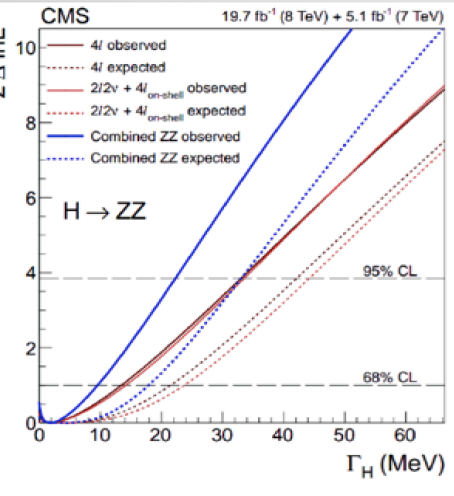
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".*

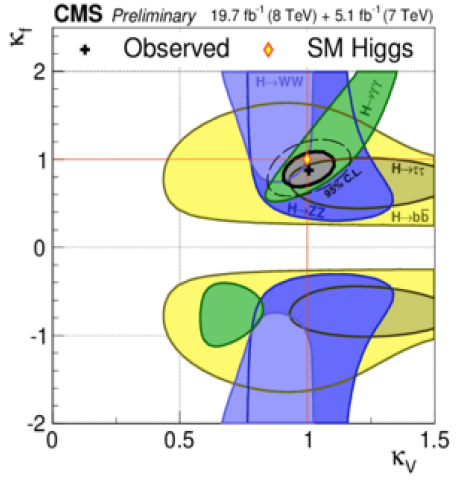
The Higgs… our New Tool!

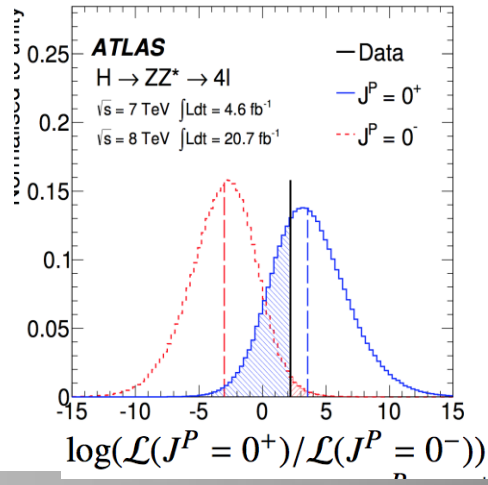
We know already a lot on this Brand New Higgs Particle!!

A= ATLAS C= CMS









Mass =
A: 125.4 ±0.4 GeV
C: 125.0 ±0.3 GeV

Width =
A: < 24 MeV
C: < 22 MeV
(95%CL)

Couplings are within 20% of the SM values

Spin =
0^+ preferred over 0^-,1,2

The Higgs is the new playground: Room for new experimental/theoretical ideas!!
We have already ~1 Million Higgses produced at the LHC (but use less than a %)

The Future: Studying the Higgs…

LHC upgrade !
Experiment upgrades!!
(Other/new machines?)

Many questions are still unanswered:

- What explain a Higgs mass ~ 126 GeV?
- What explains the particle mass pattern?
- Connection with Dark Matter?
- Where is the antimatter in the Universe?
- ⑤

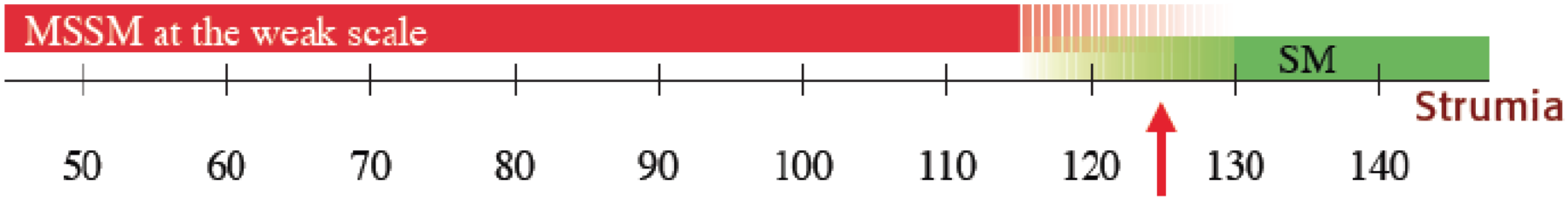
Higgs as a portal

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

A Higgs…

A malicious choice!

$m_H = 125.6 \pm 0.4$ GeV



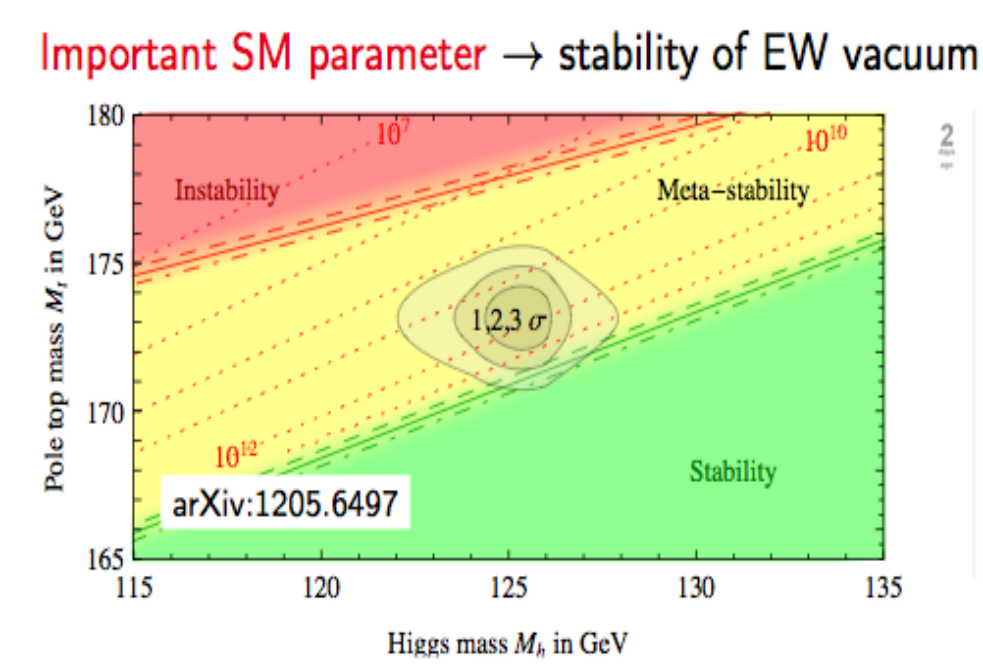
The Higgs:
so simple yet so unnatural

Guido Altarelli

Stockholm Nobel Symposium
May 2013

But there there still a lot of questions…

Consequences for our Universe?



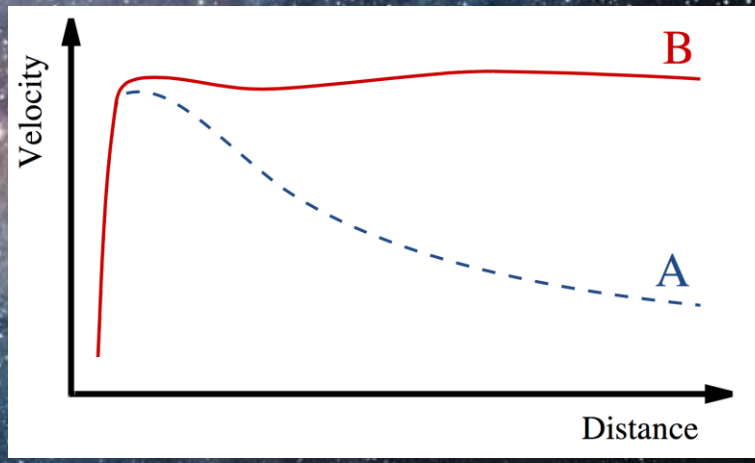
Precise measurements of the top quark and first measurements of the Higgs mass:

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

New Physics inevitable?
But at which scale/energy?

Dark Matter: The Next Challenge !?!

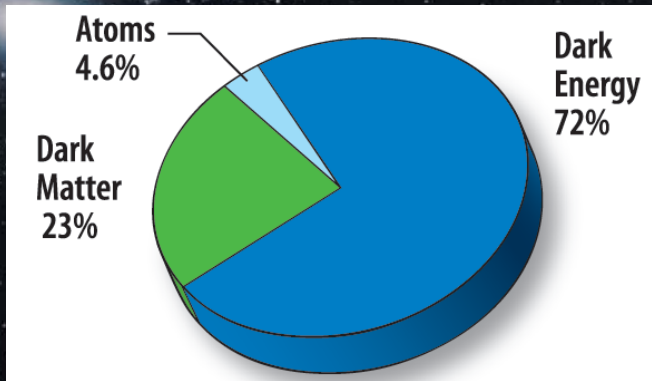
Astronomers found that most of the matter in the Universe must be invisible Dark Matter



'Supersymmetric' particles ?


F. Zwicky 1898-1974


Vera Rubin ~ 1970



Summer 2012 the CMS and ATLAS experiment found a new particle, with a mass of 125-126 GeV, which looked like the long sought fundamental scalar 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 now "a Higgs particle". This is a brand new fundamental particle, as we never seen before.

This Higgs boson is 'very light' which suggest new physics Beyond the Standard Model will be needed. Supersymmetry? Extra Dimensions? Other? The next years @ the LHC will tell…

We are on the verge of a revolution in our understanding of the Universe and our place within it. Pakistani students and scientist have the opportunity to participate in this science adventure

This is only the beginning!!!