The Discovery of a Higgs Boson at the Large Hadron Collider

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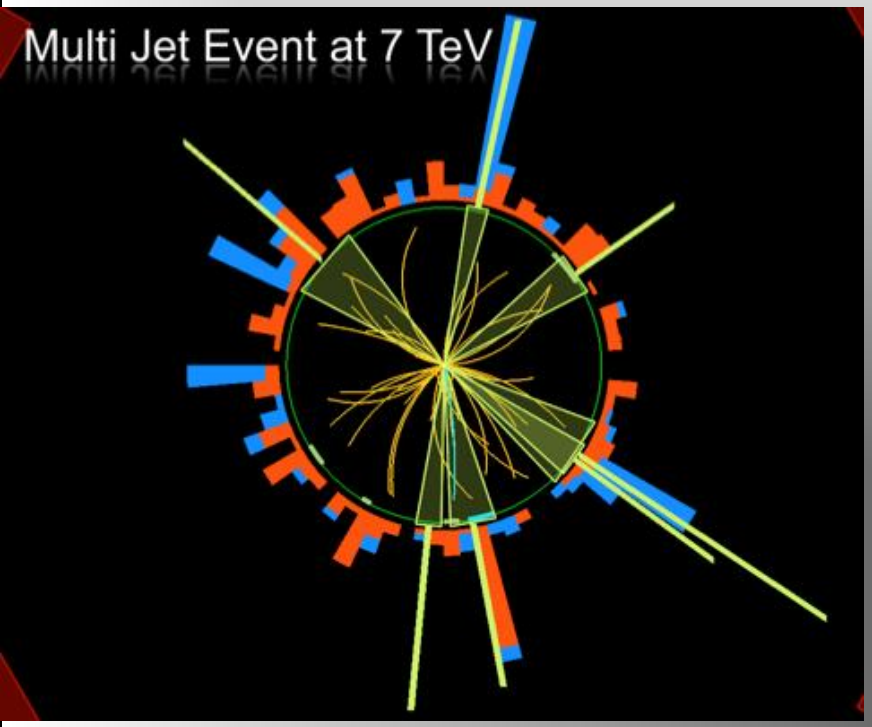
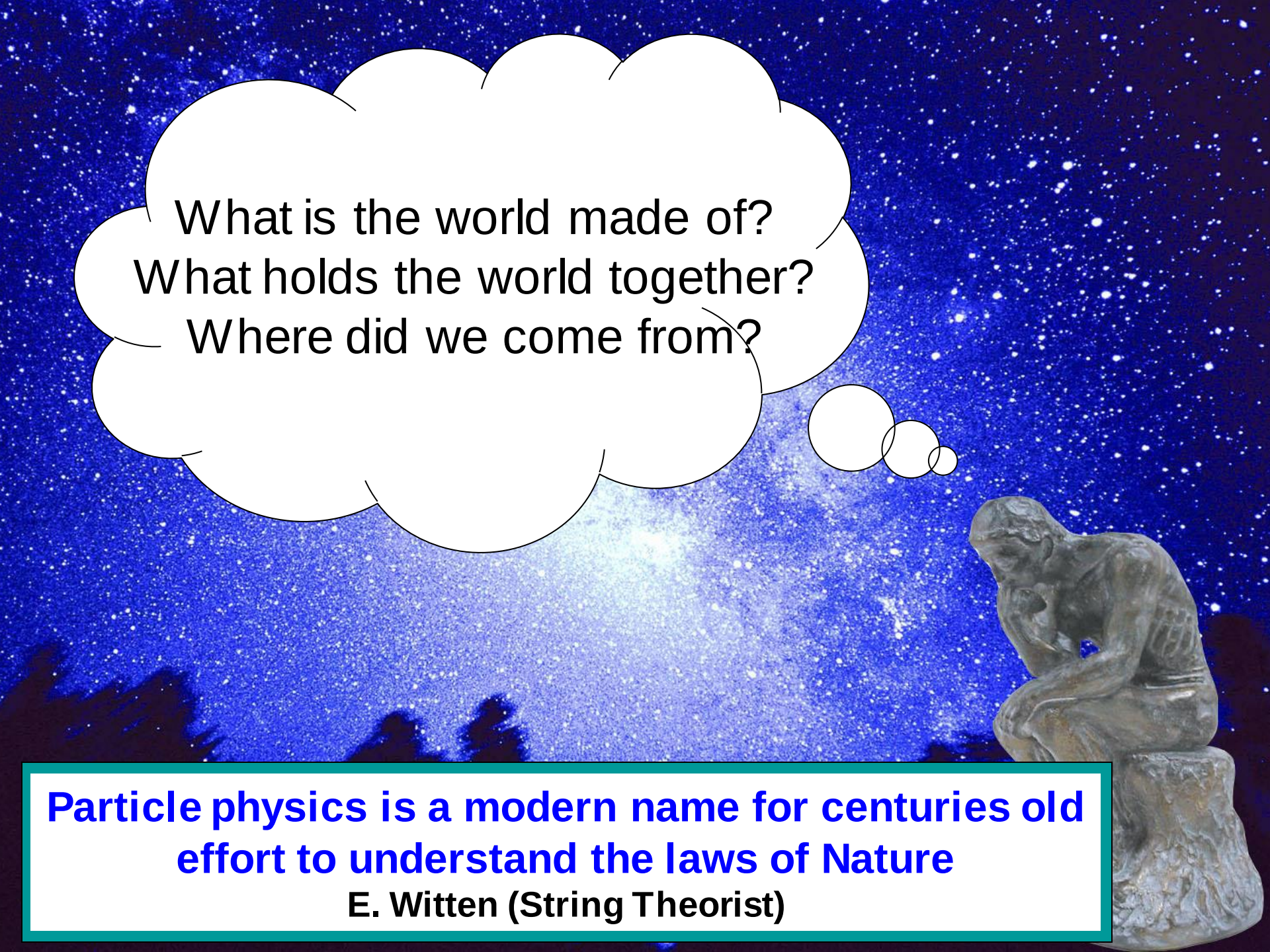
1 October 2015



Outline

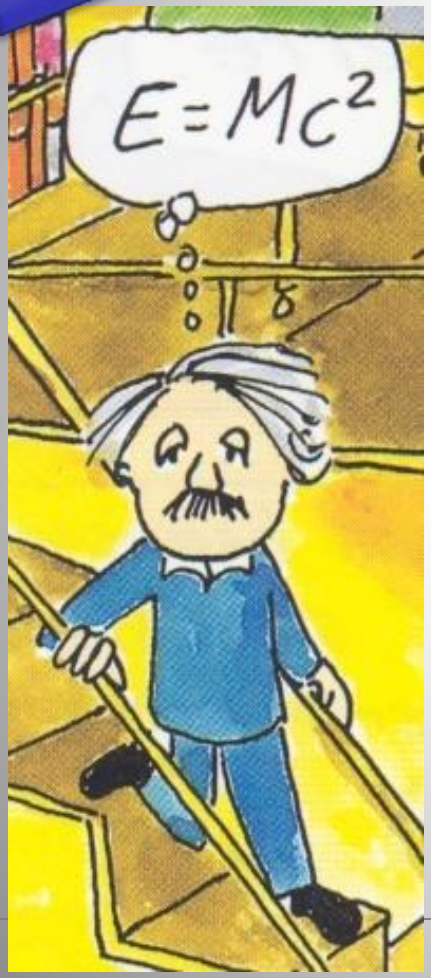
- Introduction: The LHC and the Higgs hunter experiments
- Higgs searches
- The birth of a new particle
- Studies of Higgs properties
- What is next? The next run!!
- Summary



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

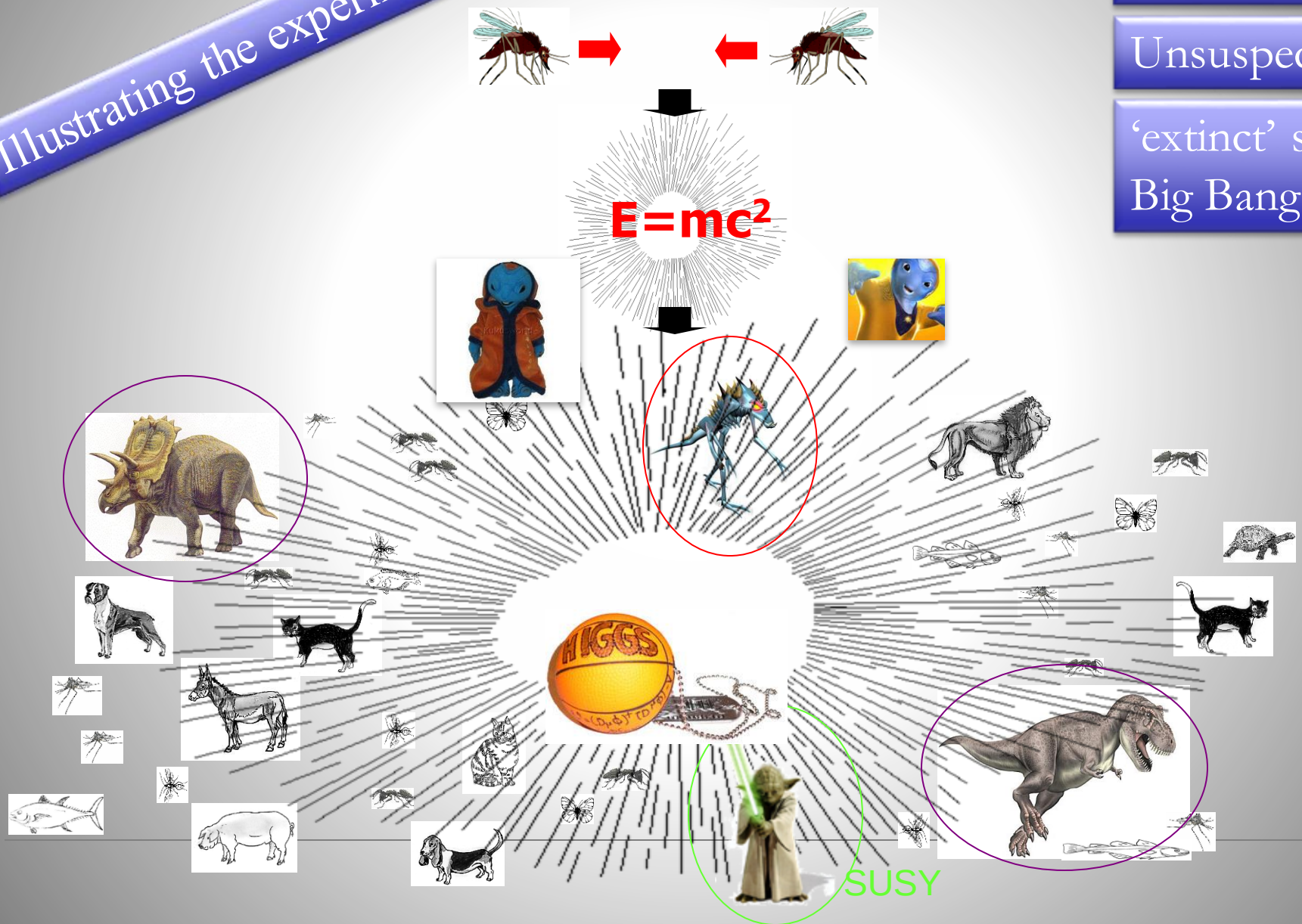
Illustrating the experiment

Highly Expected

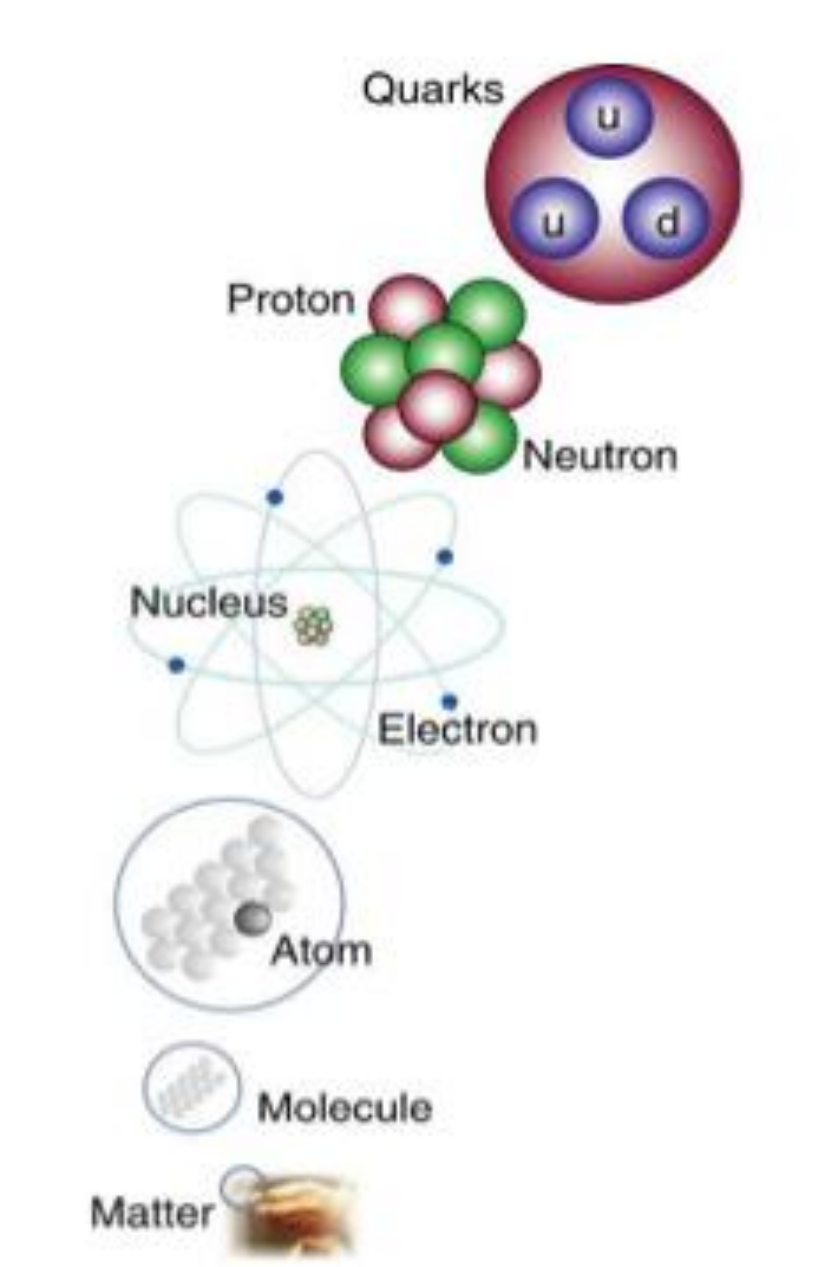
Hypothetical

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?

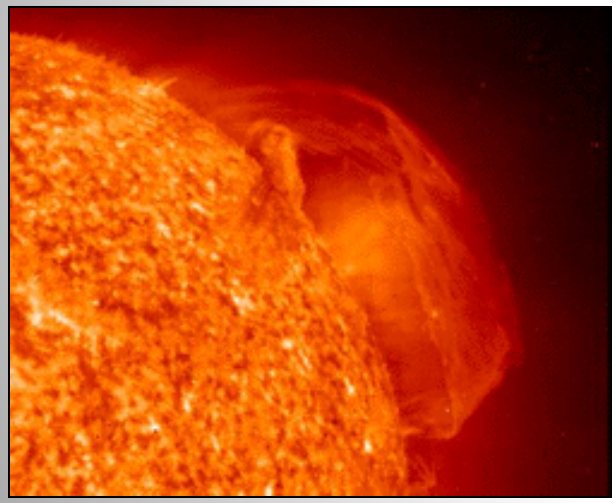
The Large Hadron Collider will address this question!

The Fundamental Forces of Nature

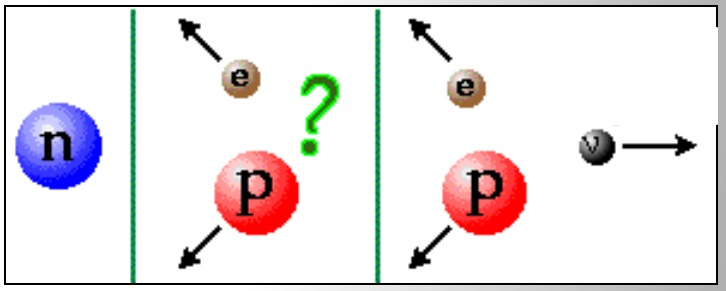
Electromagnetism:
gives light, radio, holds atoms together

Strong Nuclear Force:
holds nuclei together

Weak Nuclear Force:
gives radioactivity



together they make the Sun shine

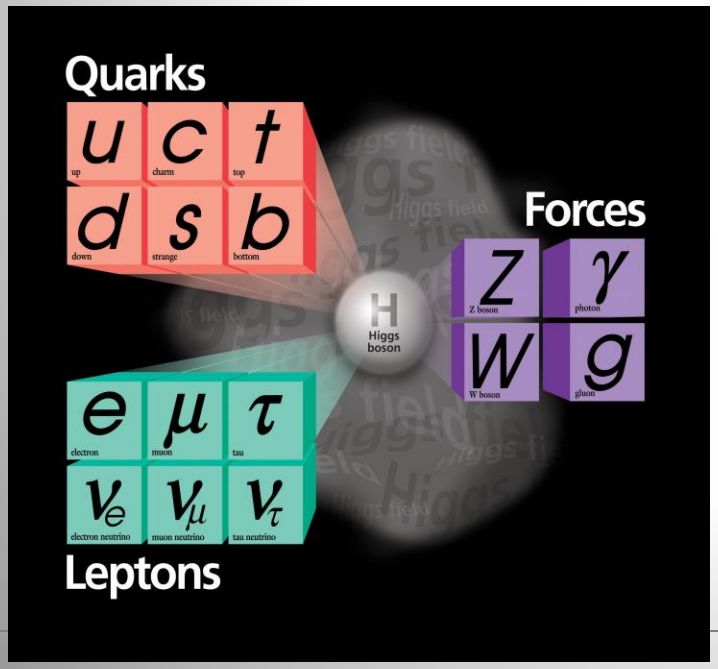


Gravity: holds planets and stars together

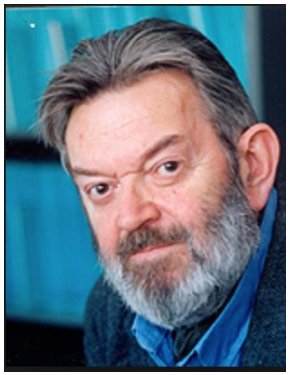
The "Standard Model"

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

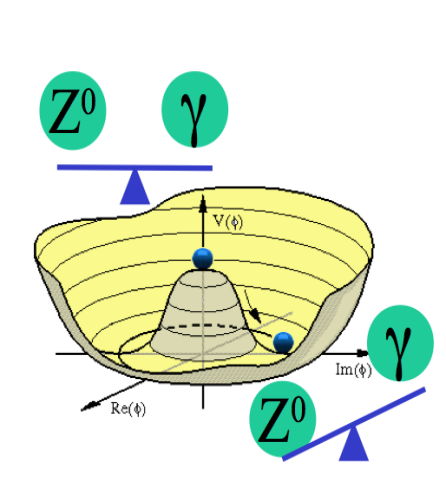


Veltman &
't Hooft

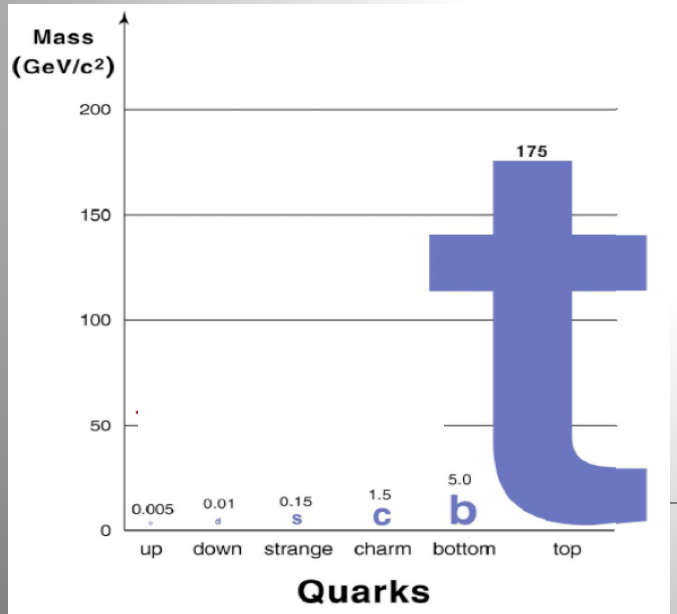
The most basic mechanism of the SM, that of granting mass to particles remained a mystery for a long time
A major step forward was made in July 2012 with the discovery of what could be the long-sought Higgs boson!!

The Origin of Particle Masses

- At 'low' energy the Weak force is much weaker than the Electromagnetic force: Electroweak Symmetry Breaking: ESB
- The W an Z bosons are very massive (~ 100 proton masses) while the photon is massless.
- The proposed mechanism(*) 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…

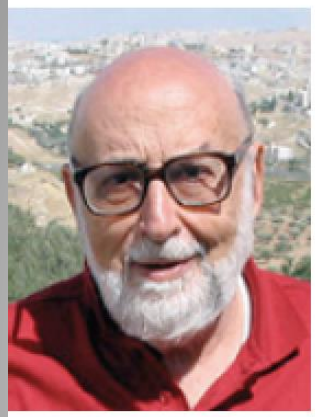


The Higgs (H) particle is the quantum of the new postulated field and has been searched for since decades at other particle colliders such as LEP and the Tevatron, and now at the large hadron collider @ CERN

Electro-weak Symmetry Breaking

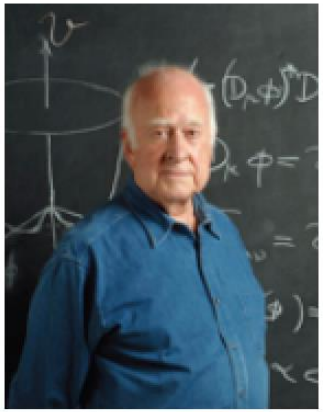
The year is 1964

Electroweak Symmetry Breaking



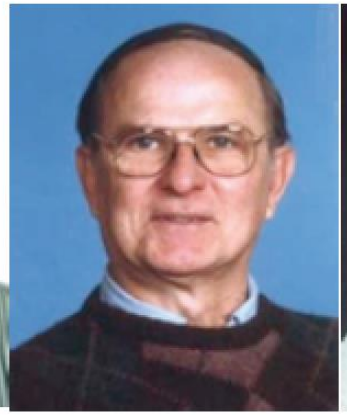
François Englert

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,† C. R. Hagen,‡ 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 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)

+ others could be mentioned that have inspired the above

The Hunt for the Higgs

Where do the masses of elementary particles come from?

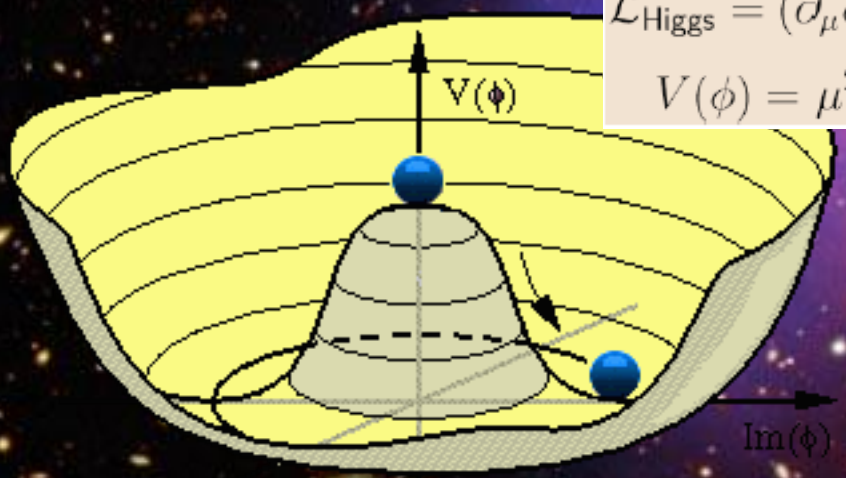
The key question (pre-2012): Does the Higgs particle exist? If so, where is the Higgs?

Massless particles move at the speed of light -> 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 ~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!!

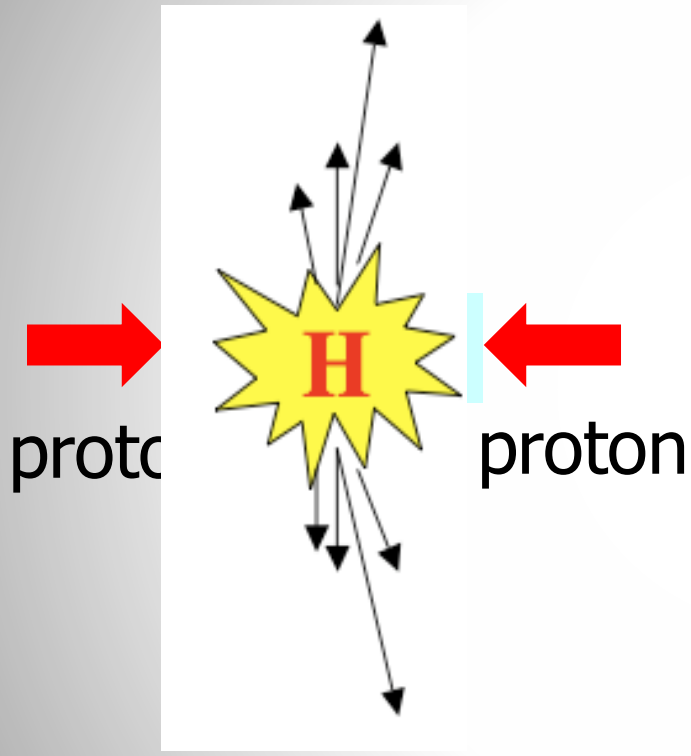
In Nederland…

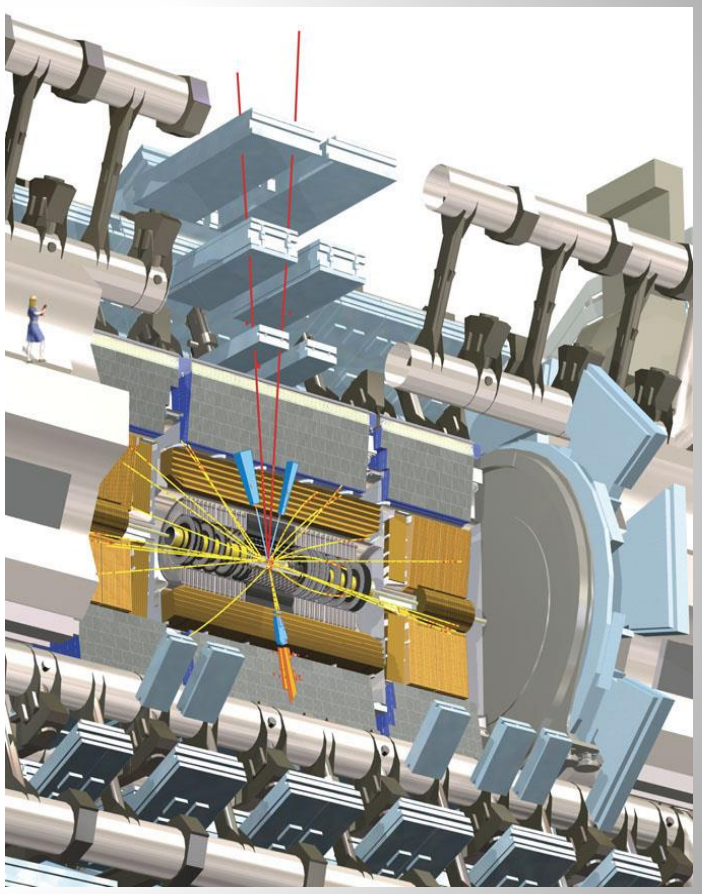
…a film on the Higgs
just before the discovery

…Now also a theatre play in Belgium and Holland

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…….

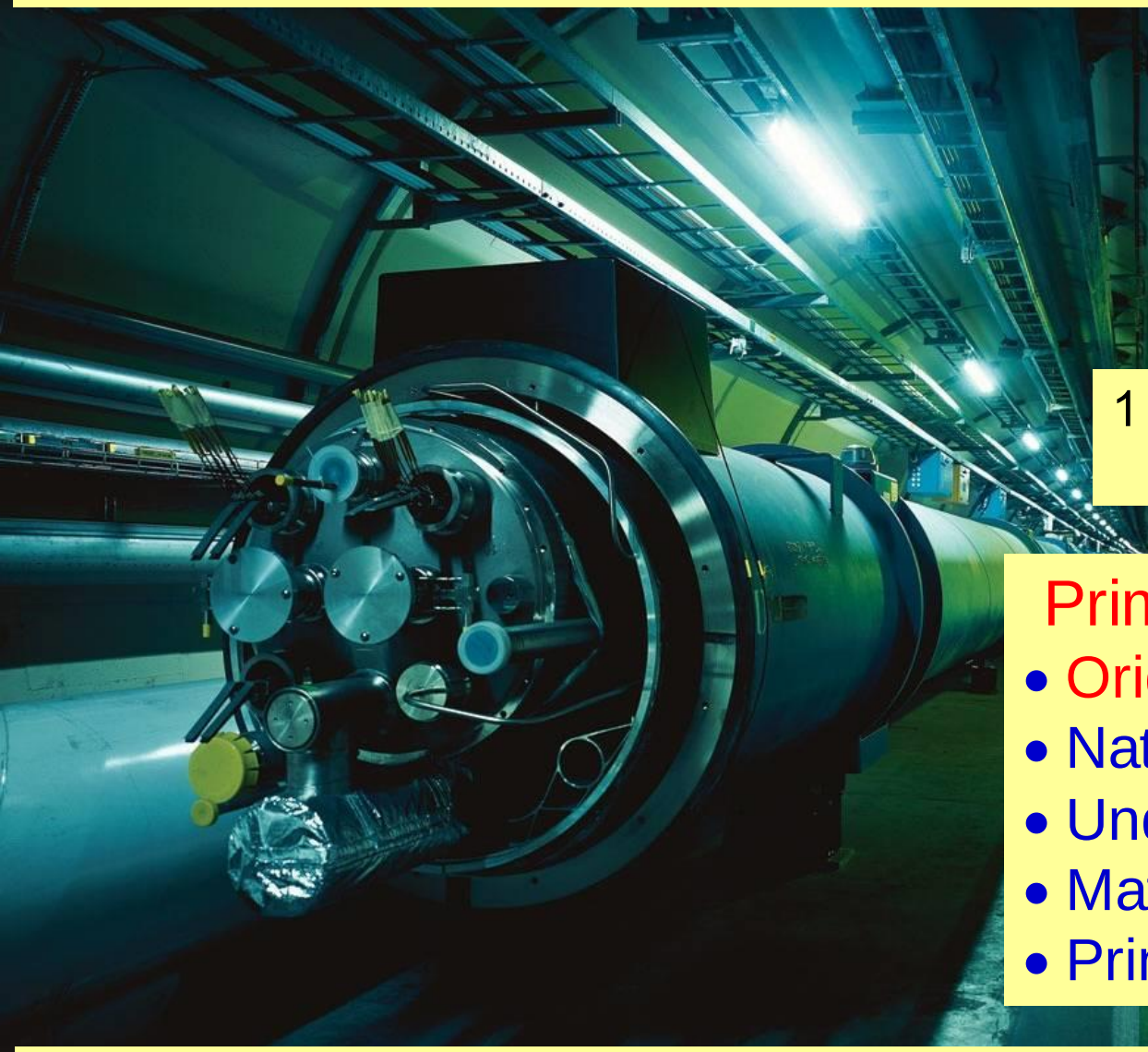
1. Accelerators : powerful machines that accelerate particles to extremely high energies and bring them into collision with other particles

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



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

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

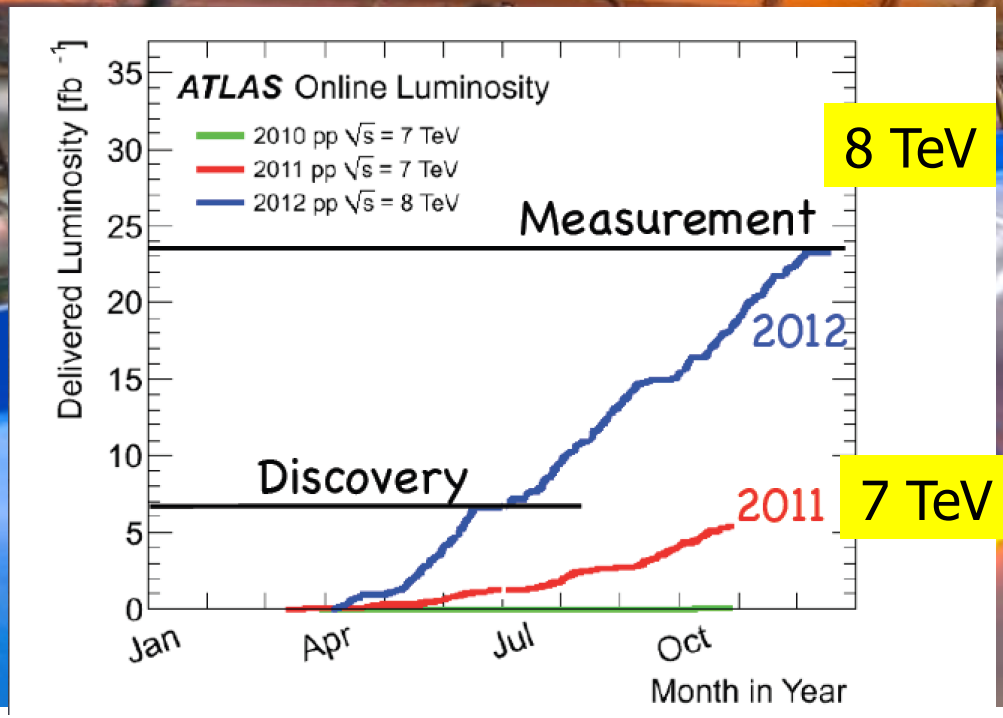
Primary physics targets

- 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



Luminosity = # events/cross section/time

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

100 meter underground

The LHC is an Extraordinary Machine

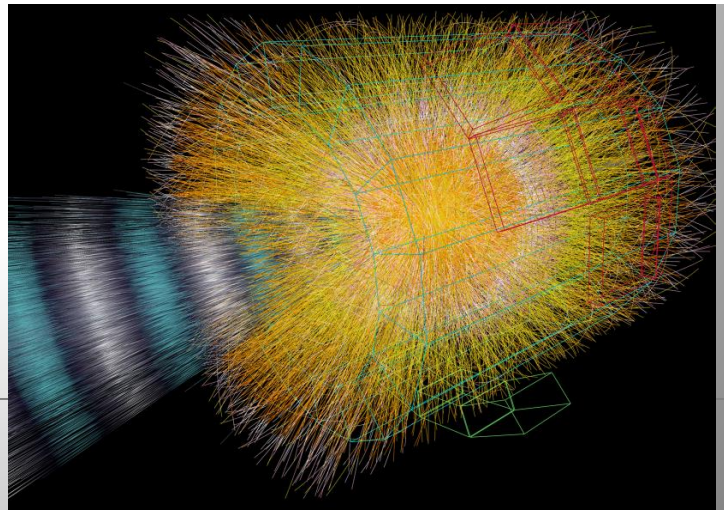
LHC facts

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

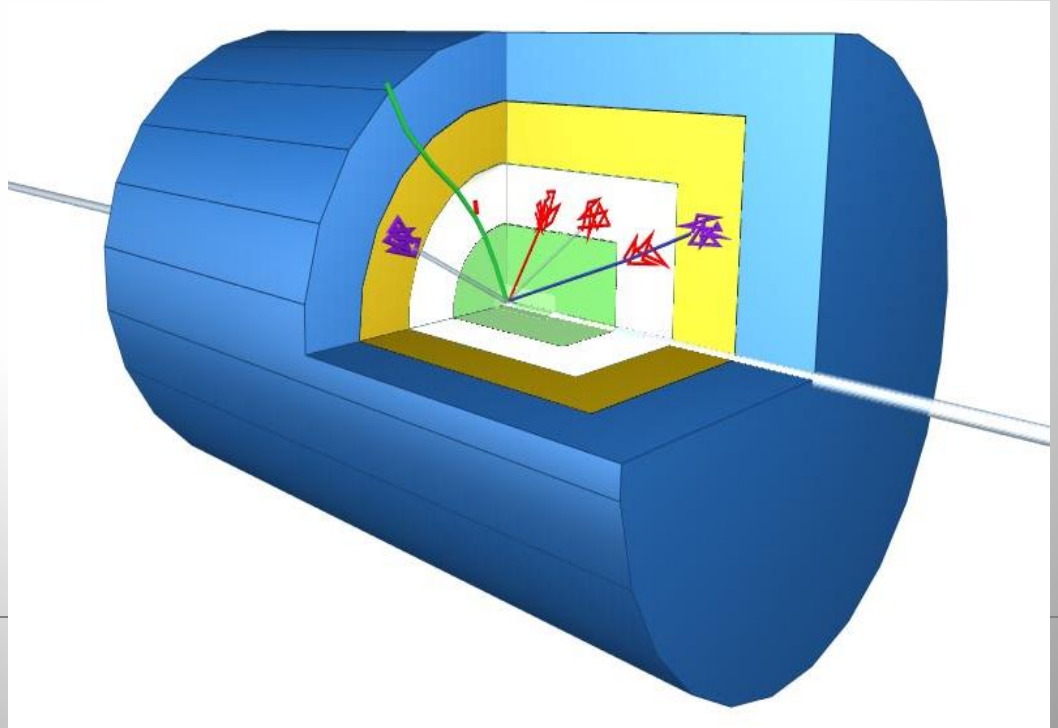
Schematic of a LHC Detector

Physics requirements drive the design!

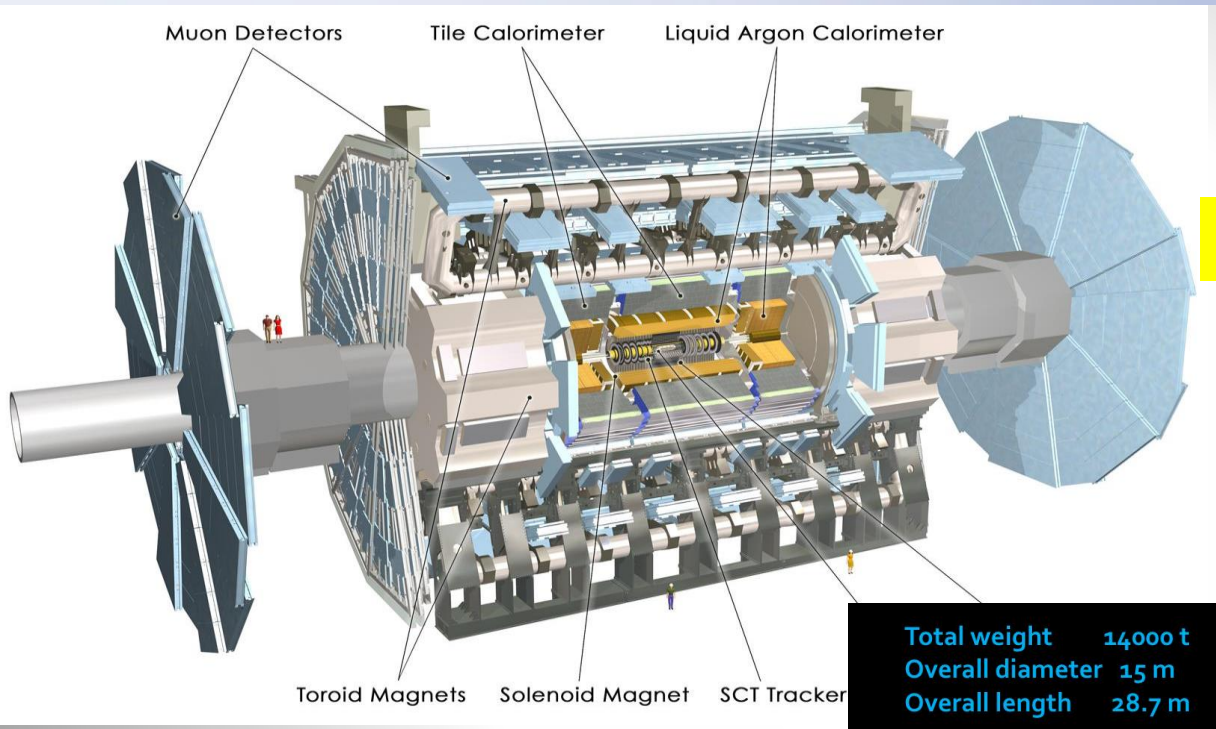
Analogy with a cylindrical onion:

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.

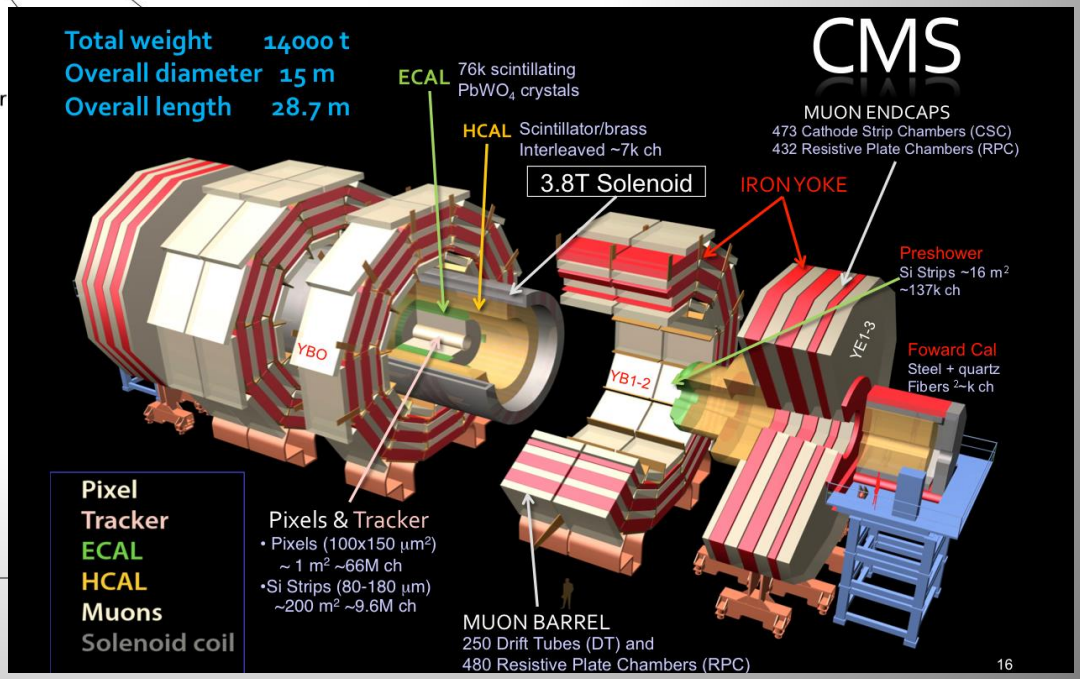
Such an experiment has ~ 100 Million read-out channels!!



The Higgs Hunters @ the LHC



The ATLAS experiment



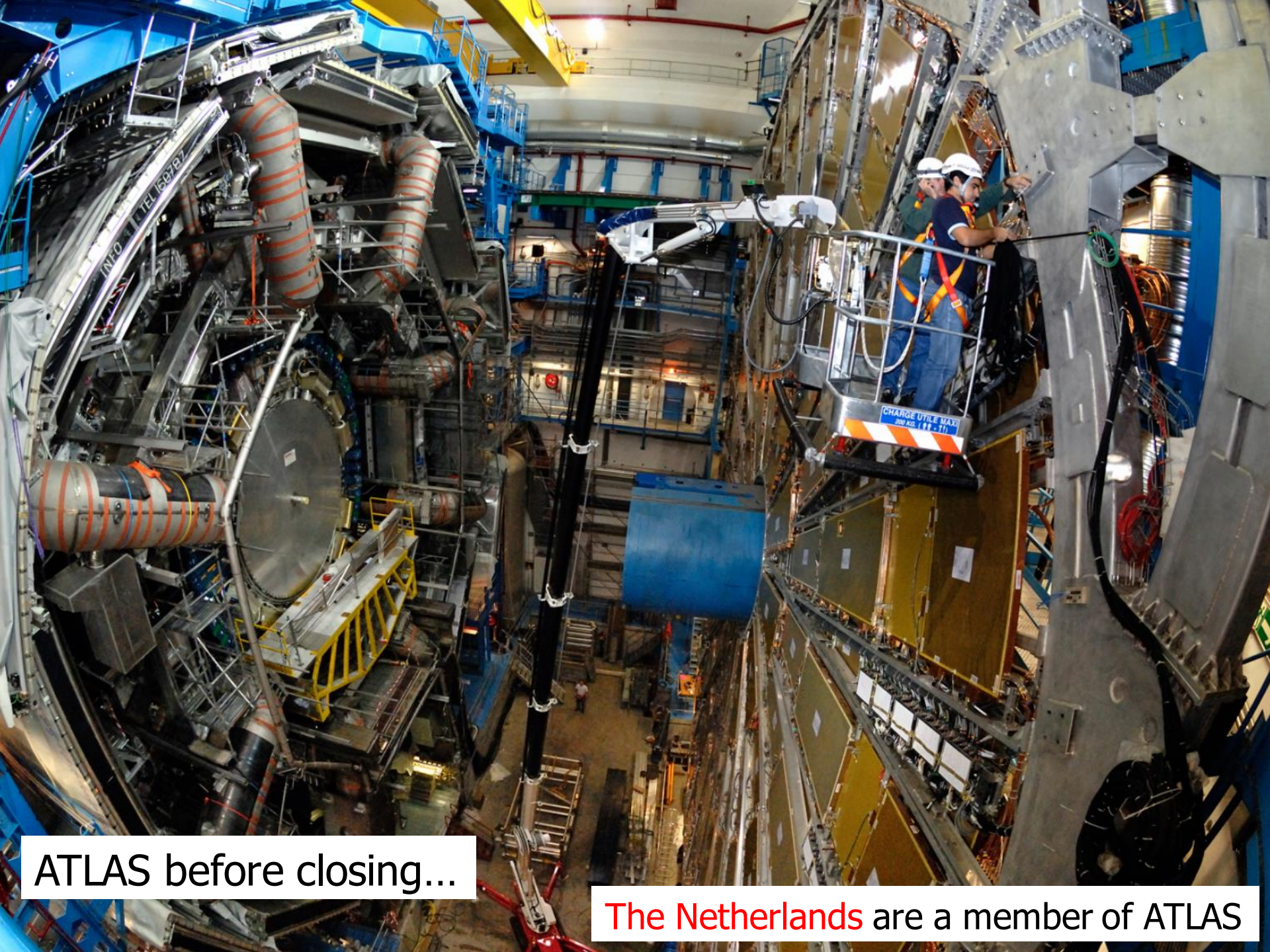
The CMS experiment

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 .

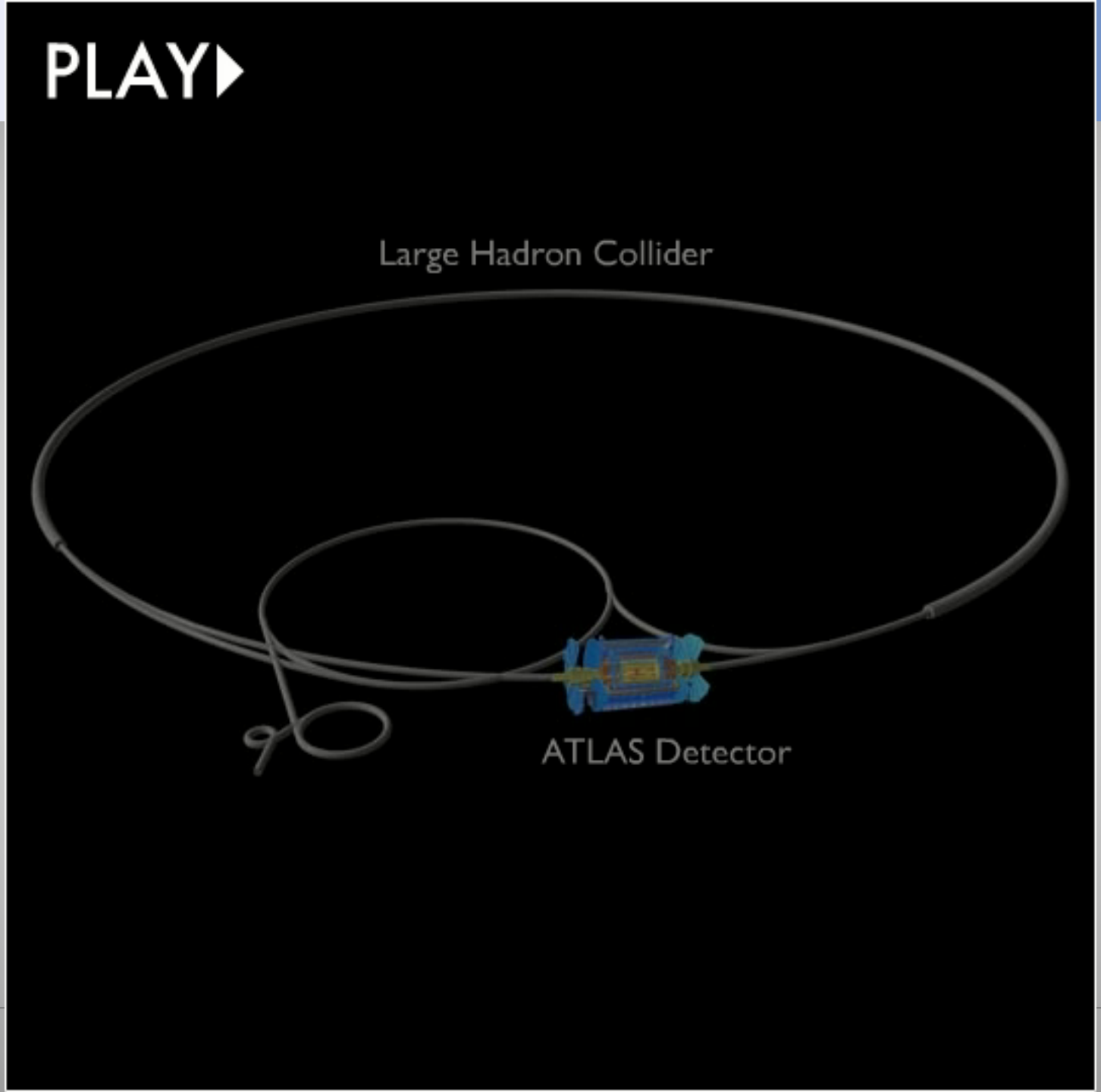
About 1/8th of the collaboration



ATLAS before closing…

The Netherlands are a member of ATLAS

CMS before closure


PLAY
Large Hadron Collider
ATLAS Detector

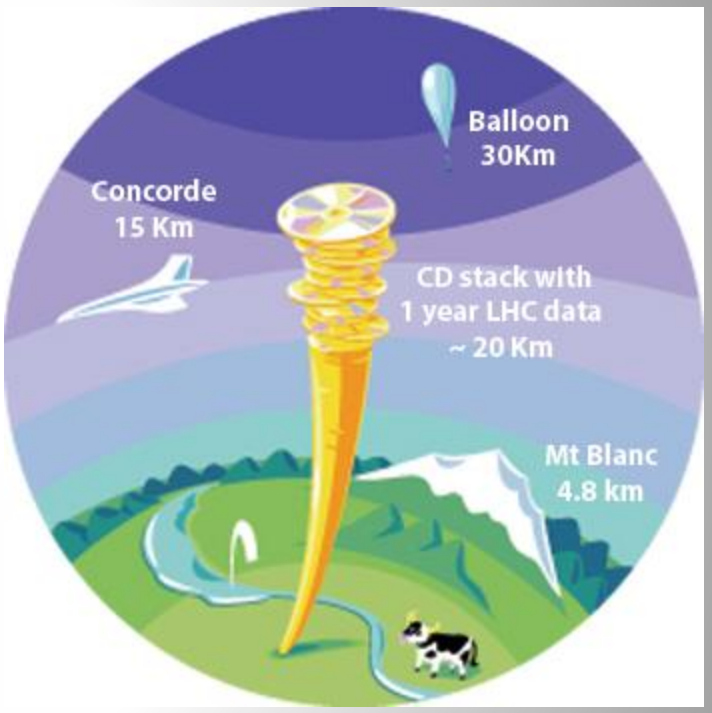
The LHC Data Challenges

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

The total volume in eg ATLAS alone has been 100 Million Gigabytes of data in 3 years. So we wrong by a factor ~5!!!

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!!

Higgs Hunters

Higgs Hunting Basics

Needle-in-the-hay-stack problem

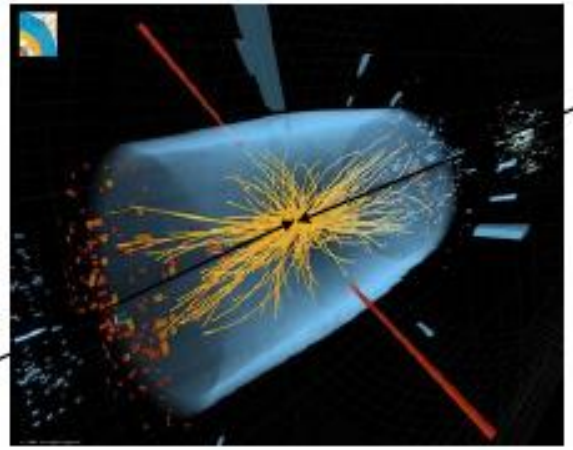
- need high energy:

  $E = mc^2$

- 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

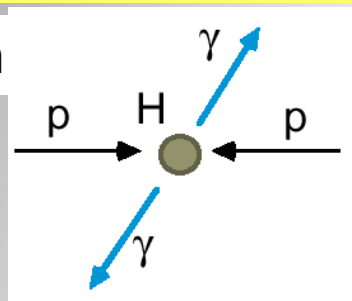
Higgs Boson Searches (simulation)

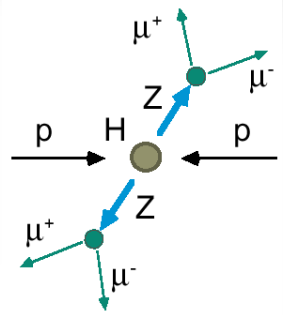
Low M_H < 140 GeV/c²

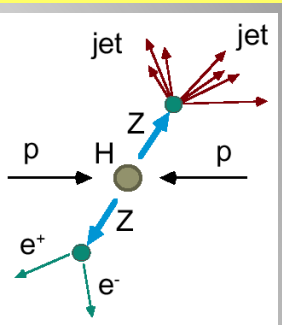
Medium 130<M_H<500 GeV/c²

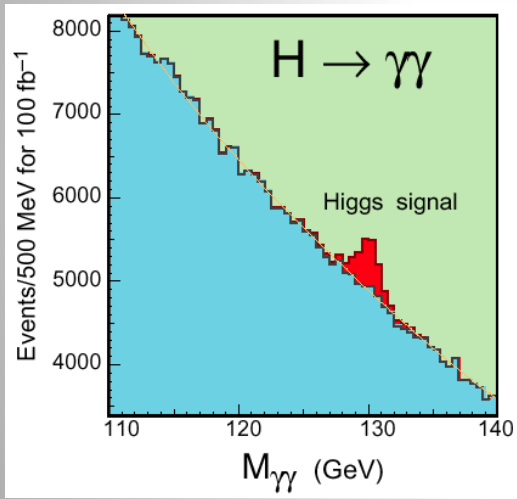
High M_H > ~500 GeV/c²

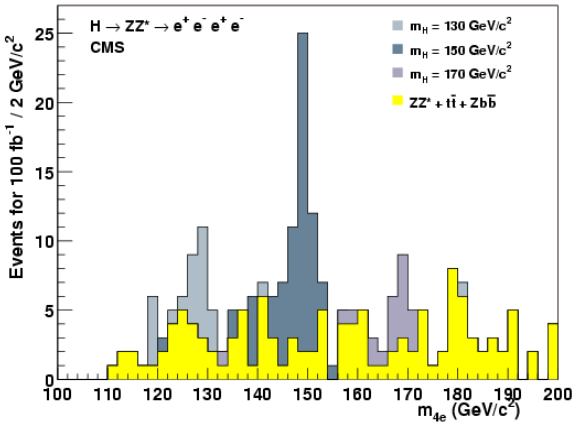
simulation

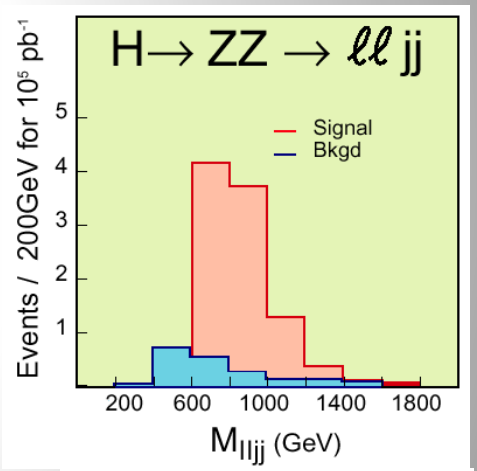


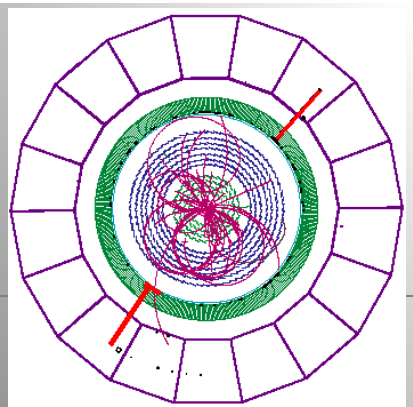


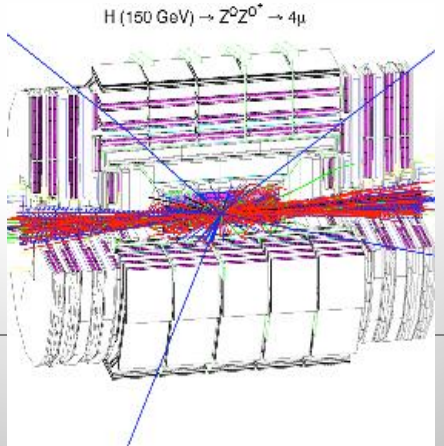


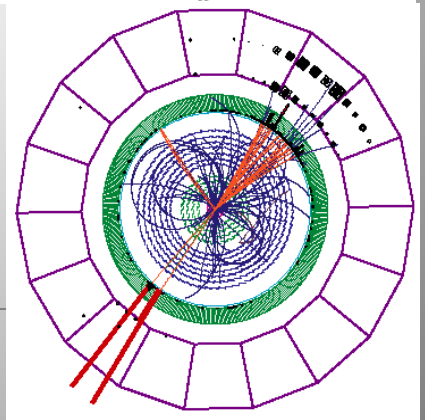










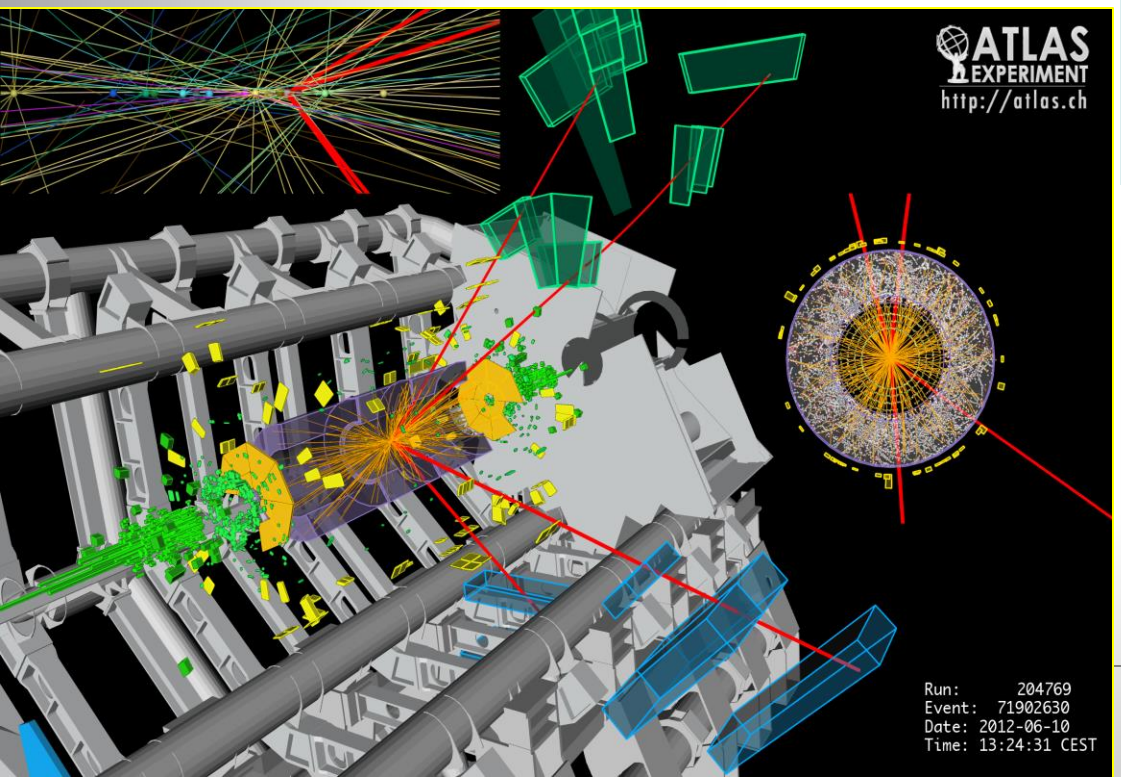


Searches for the Higgs Particle

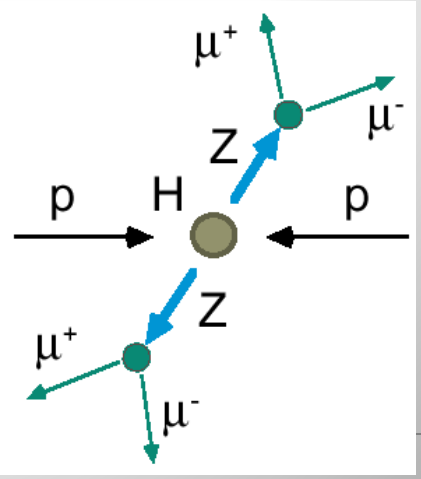
A Higgs particle will decay immediately, eg in two heavy quarks or two heavy (W,Z) bosons

Example: Higgs(?) decays into ZZ and each Z boson decays into μμ

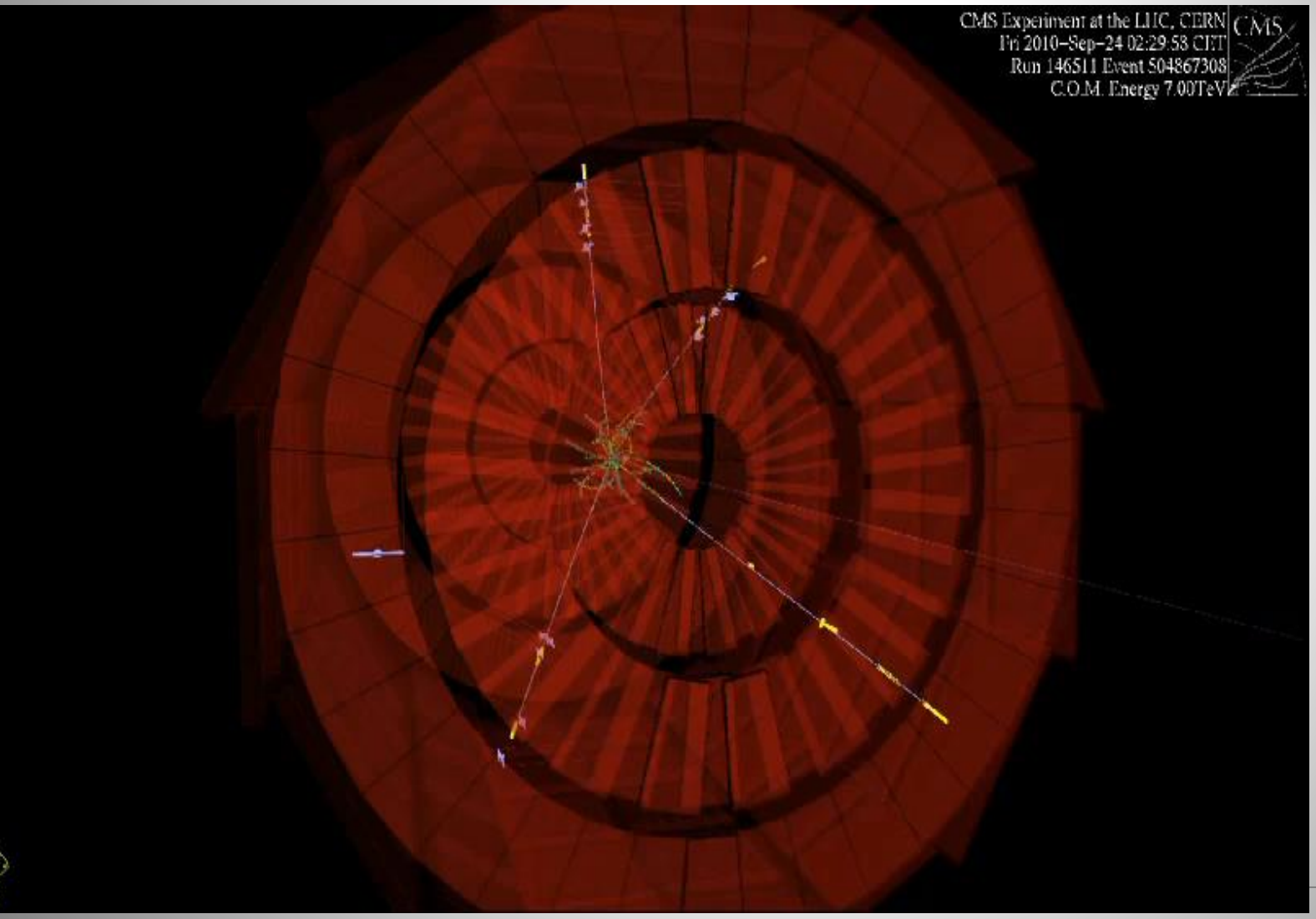
So we look for 4 muons in the detector

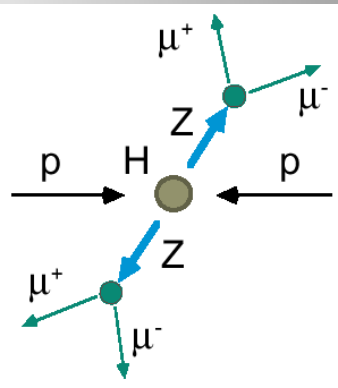


But two Z bosons can also be produced in LHC collisions, without involving a Higgs!
We cannot say for on event by event (we can reconstruct the total mass with the 4 muons)

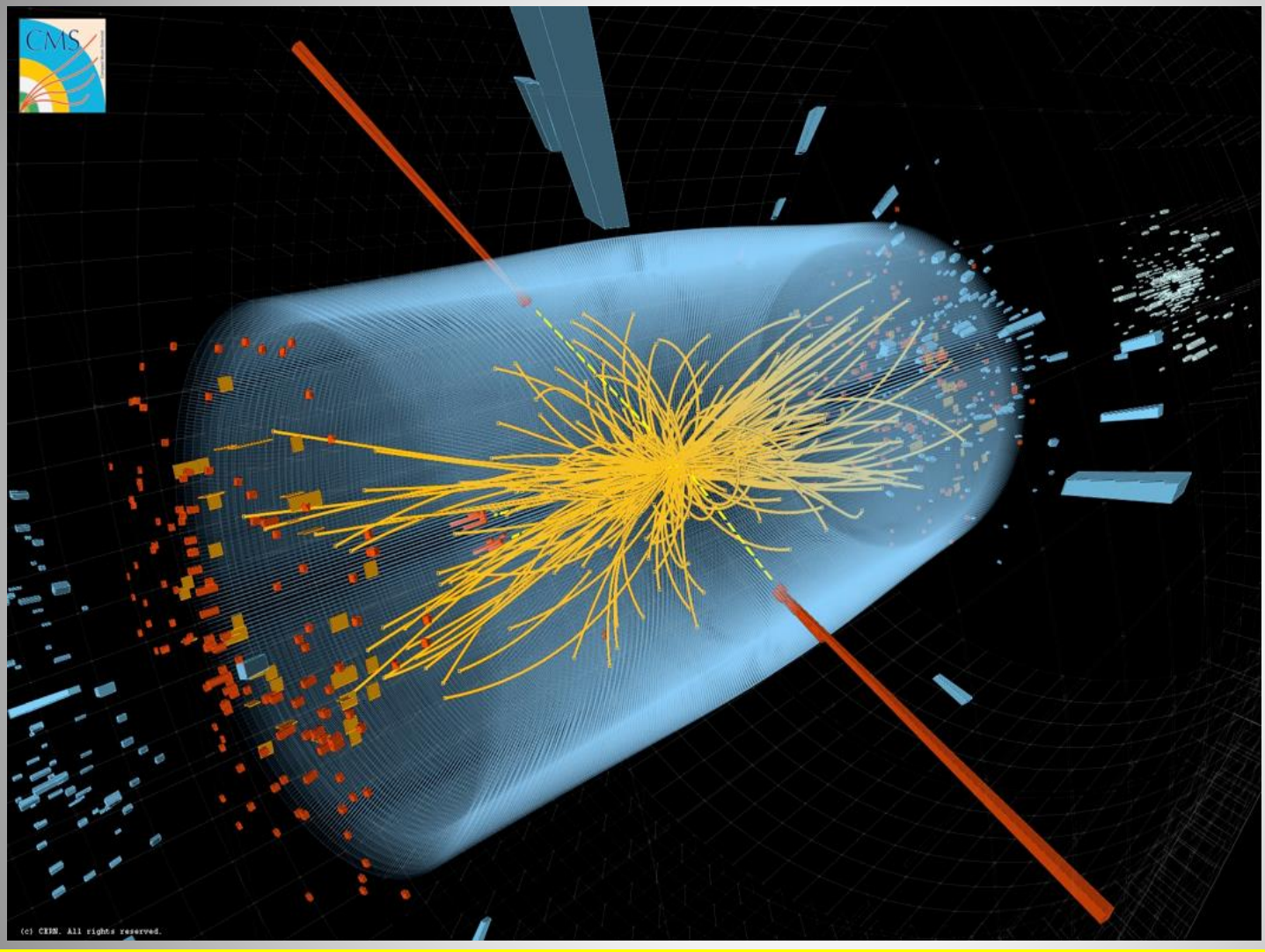


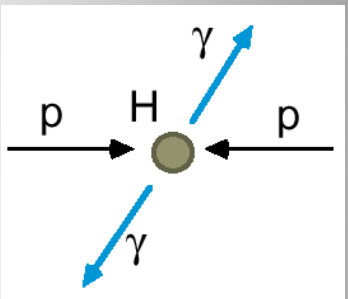
A real collisions: ZZ-> 4 muons





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

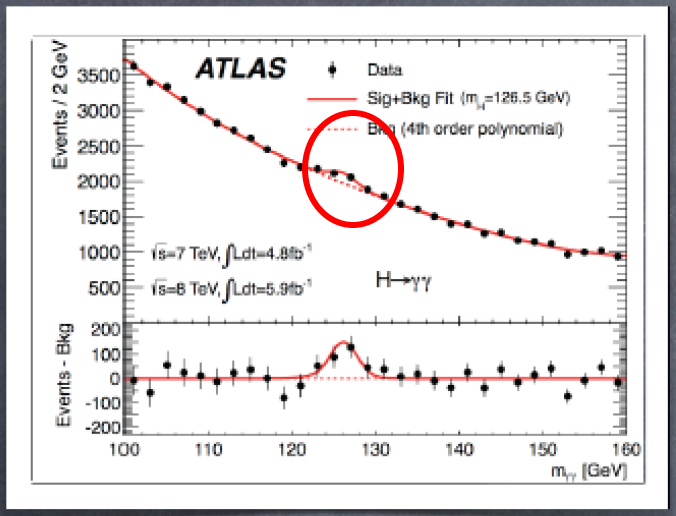
Physicists hope to find the Higgs boson, key to unified field theory, this year

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.

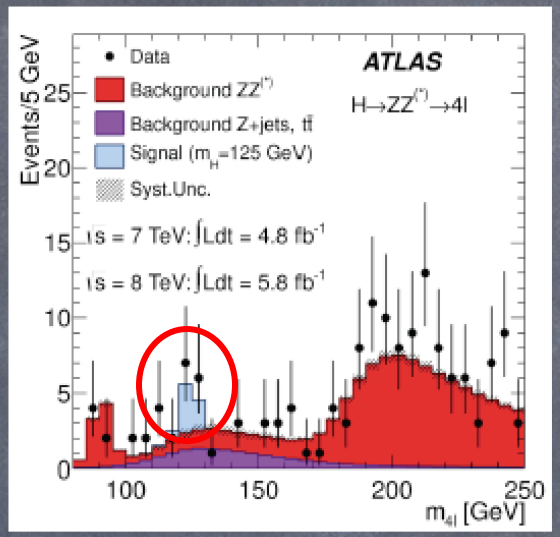
The suspense was building up…

Summer 2012: Results

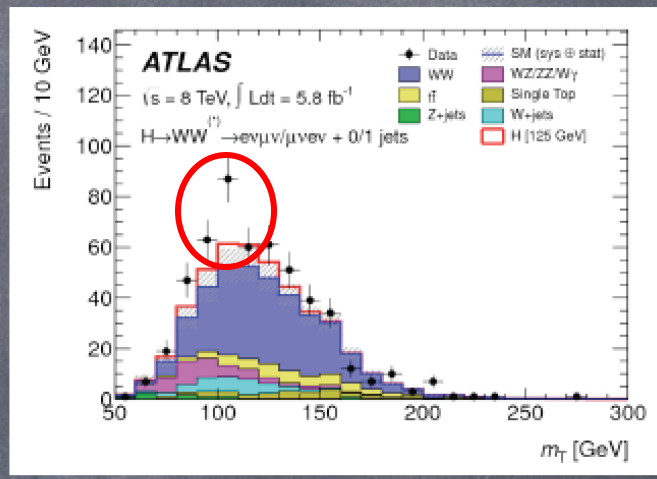
Higgs → 2 photons!!

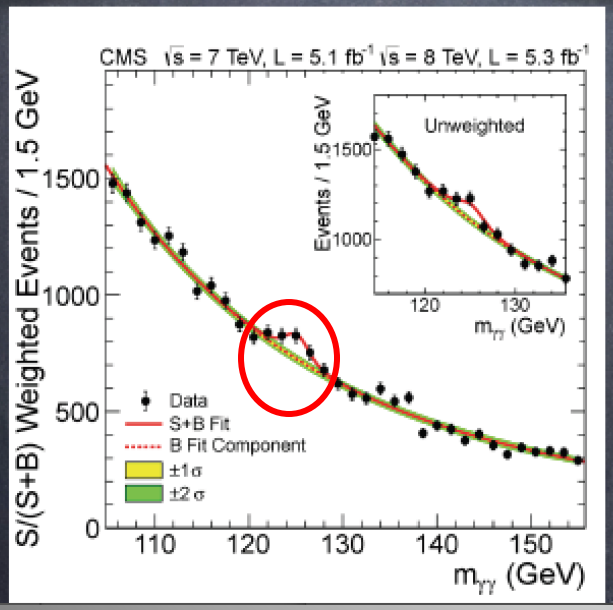


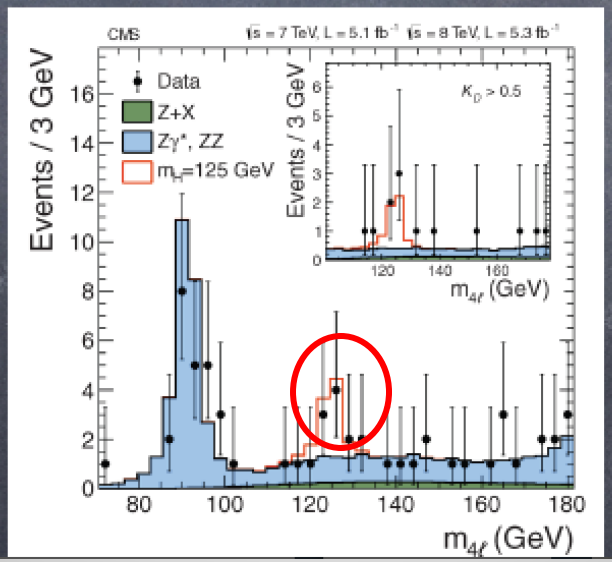
Higgs → 2Z →4 leptons!!

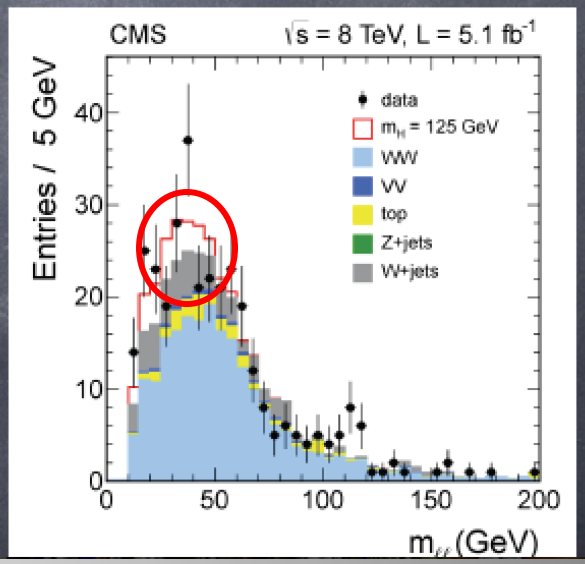


Higgs → 2W →2l2v!!









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…

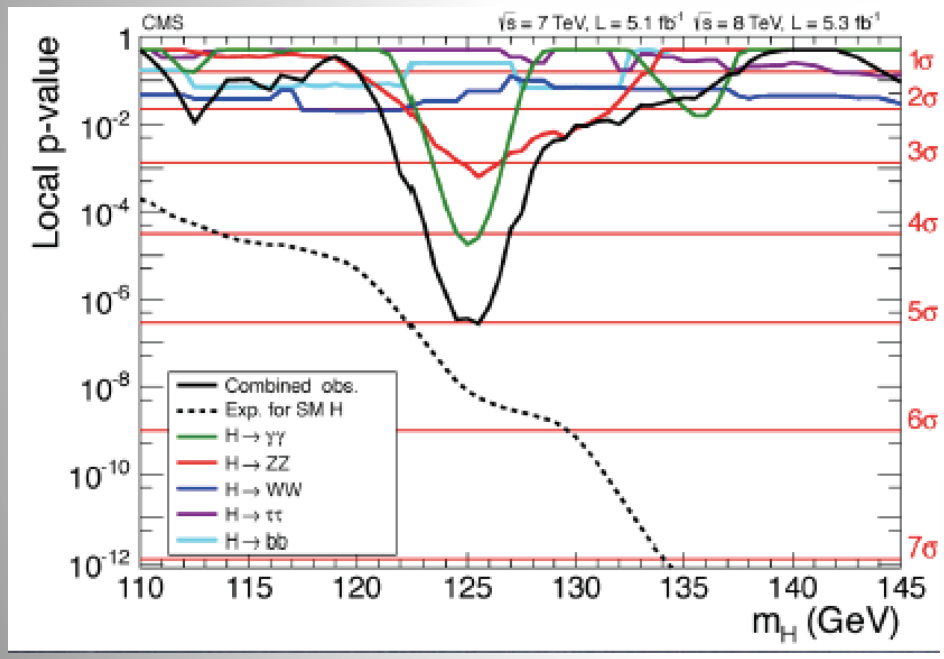
Summer 2012: Results

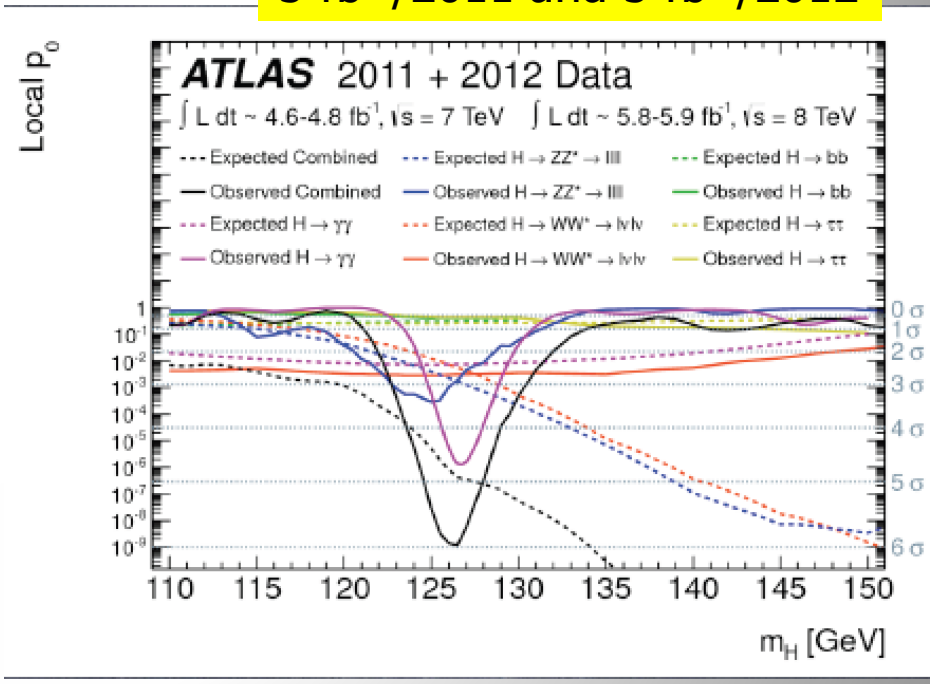
Both experiments see an excess ~125 GeV in the γγ, ZZ and WW channel

→Adding up al the channels gives the following combination

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!!!)

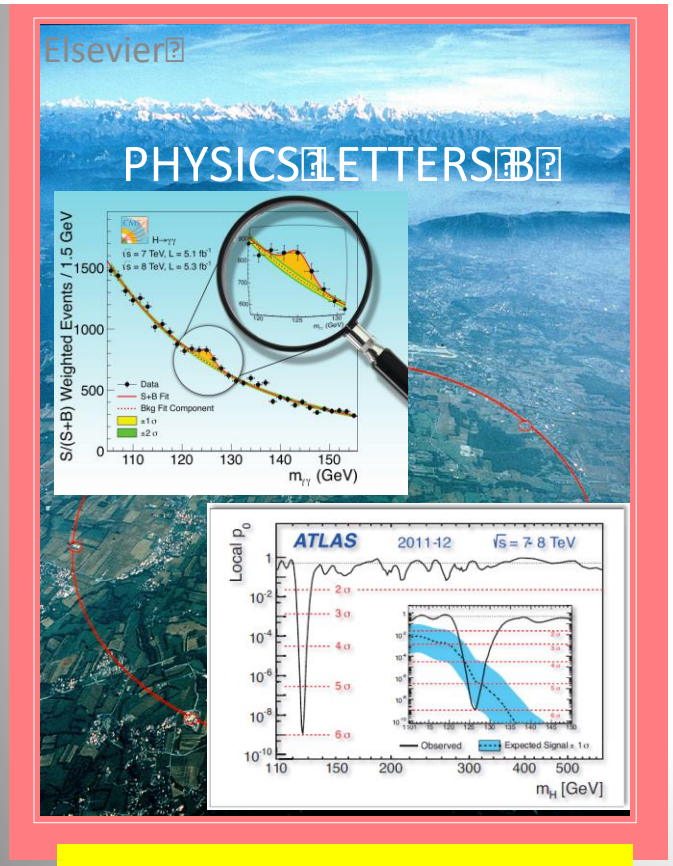
Since then: 4th of July is…

July 4th 2012

The discovery of a new particle

Most cited LHC papers so far...

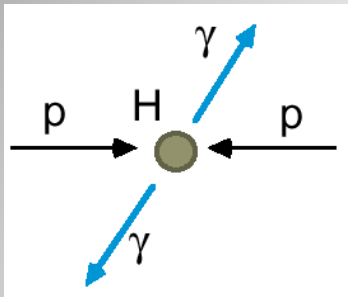
Special Physics Letters B edition with the ATLAS and CMS CMS papers on the Higgs Discovery



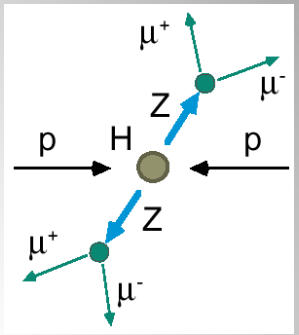
More than 4800 times cited so far...

Also...

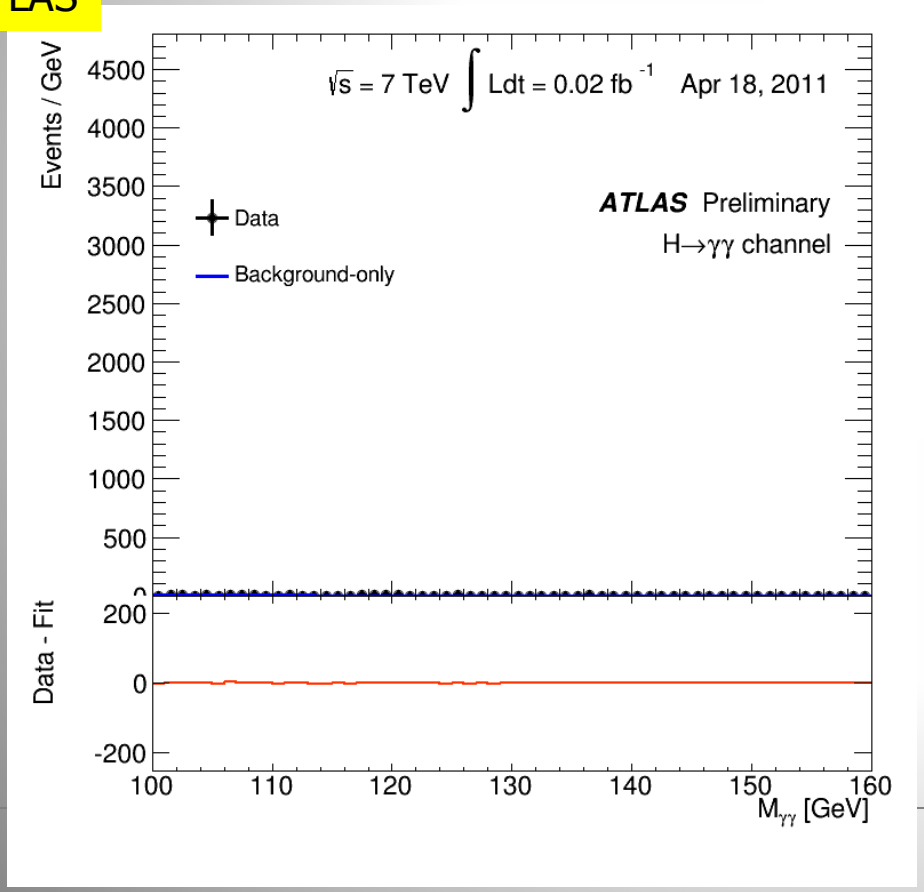
The Birth of a Particle



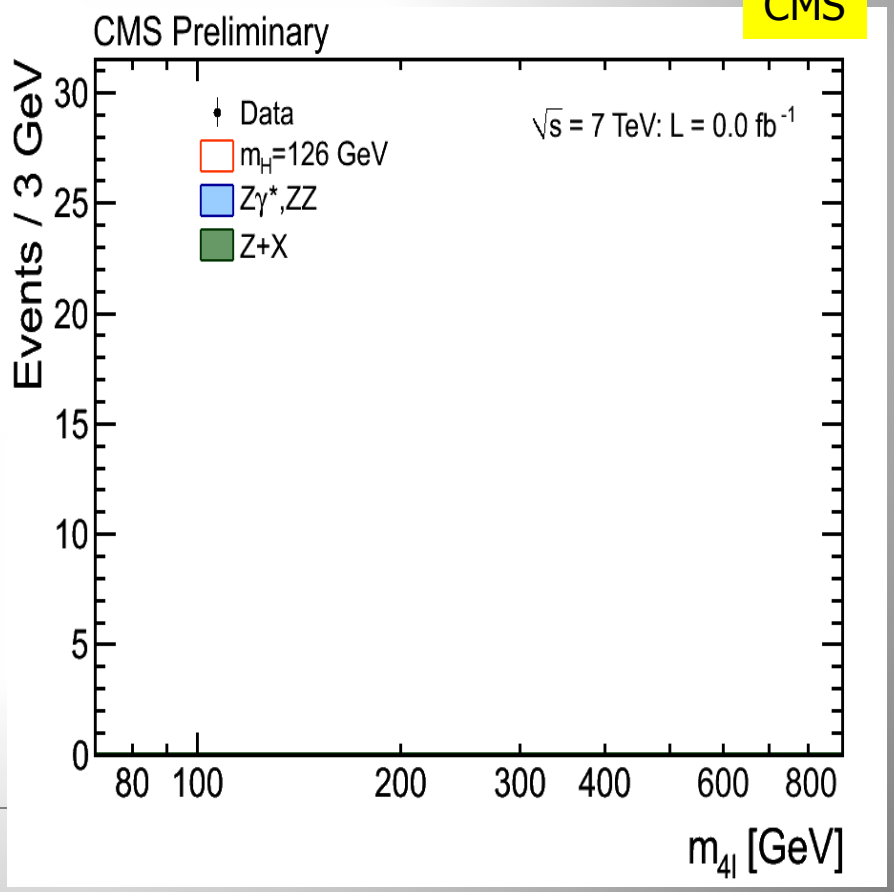
"History" of the data accumulation during the last two years



ATLAS



CMS



Higgs Discovery Status

- In summer 2012 we called it a "Higgs-like" particle
- In spring 2013 (with 3x more data) we called it a Higgs particle

Spin/parity 0^+ favored, couplings roughly as in SM for Bosons

What happened Next?

- More detailed analyses of the 125 GeV particle, in particular the search for direct decays into fermions, ttH channel,...
- More precise measurements of the "signal strength σ/σ_{SM}" and of the mass of the particle, and the spin, couplings
- Searches for Higgs like particles at higher masses
- Searches for exotic, non-SM decays (none found so far)
- Searches for di-Higgs events (in BSM scenarios, none found so far)
- Differential distributions + fiducial volume cross sections

→The Experiments have published Run-I legacy papers

The Higgs is the new playground: Room for new experimental/theoretical ideas!!

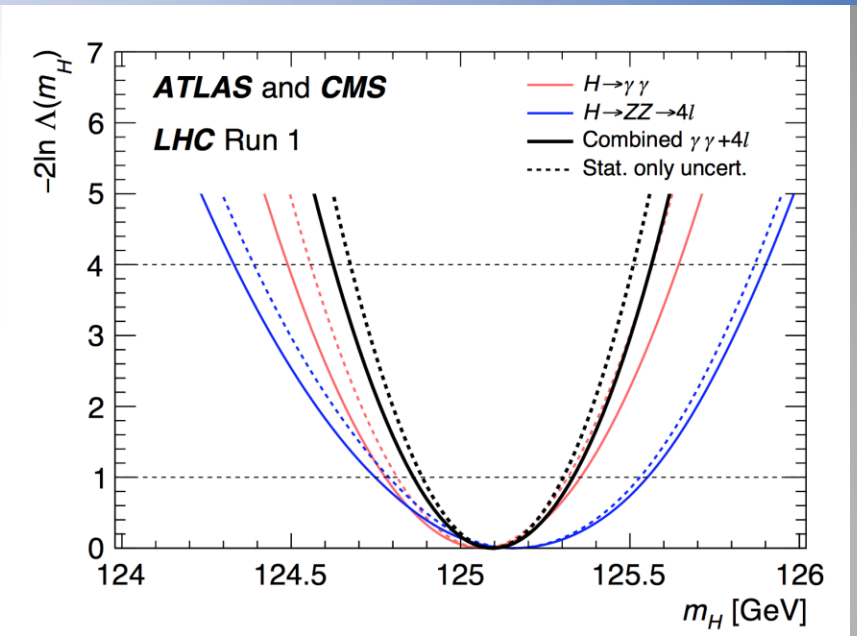
Remember: we have already ~1 Million Higgses produced at the LHC

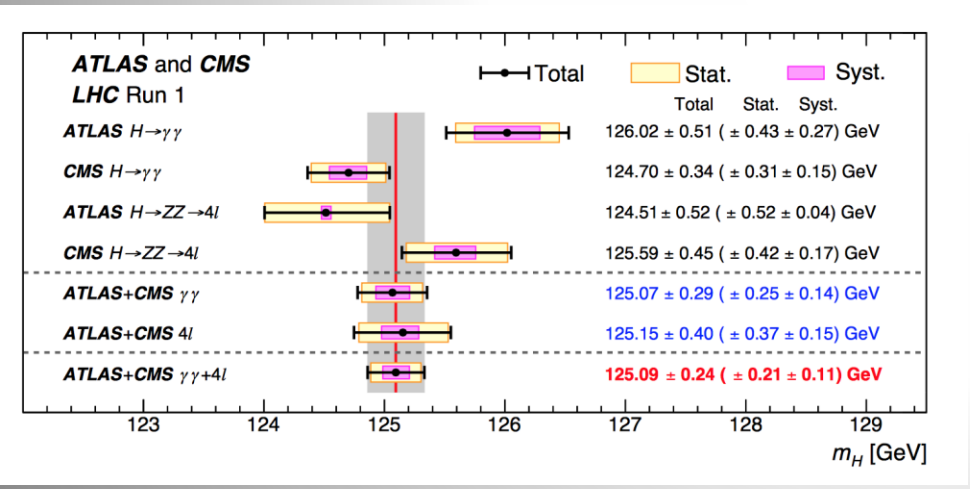
Mass of the Higgs

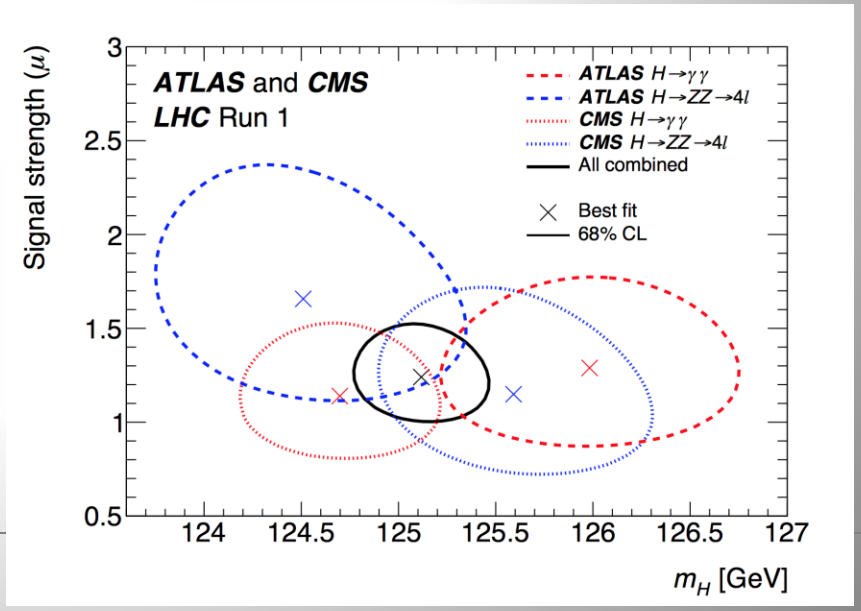
Combined result from CMS and ATLAS
Mass precision ~ 0.2%

$$m_H = 125.09 \pm 0.21\,(\text{stat.}) \pm 0.11\,(\text{syst.})\ \text{GeV}$$

arXiv:1503.07589







CMS+ATLAS Mass Paper

First common paper CMS+ATLAS!!

For the record

- 5153 authors.
  - One duplicate, 2×10^{-4} effect.
- Found that there are two:
  - Archana Sharma (both CMS)
  - **Andrea Bocci (one CMS, one ATLAS)**
  - Muhammad Ahmad (ditto)
  - F. M. Giorgi (ditto)

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NATURE | NEWS

Physics paper sets record with more than 5,000 authors

Detector teams at the Large Hadron Collider collaborated for a more precise estimate of the size of the Higgs boson.

Davide Castelvecchi

15 May 2015

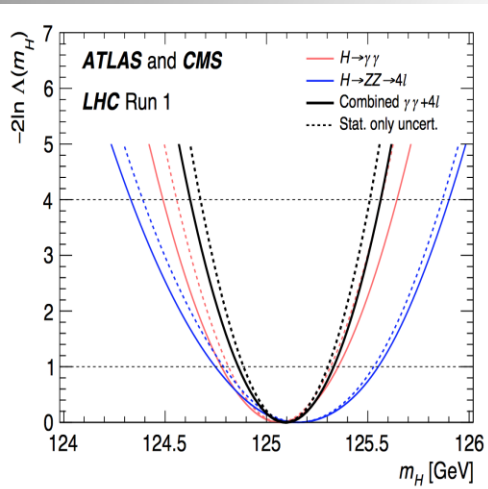
CERN

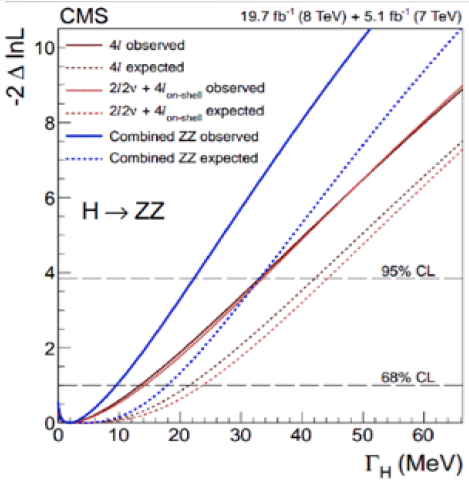
Thousands of scientists and engineers have worked on the Large Hadron Collider at CERN.

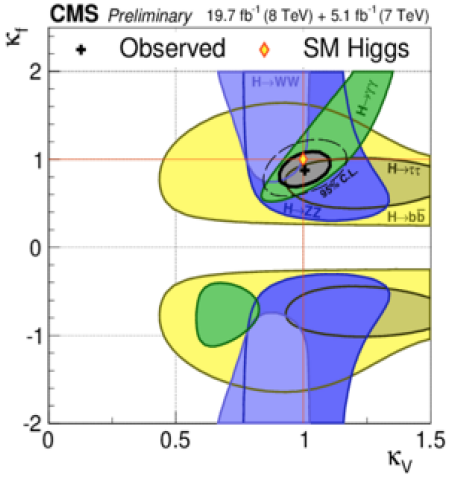
A physics paper with 5,154 authors has — as far as anyone knows — broken the record for the largest number of

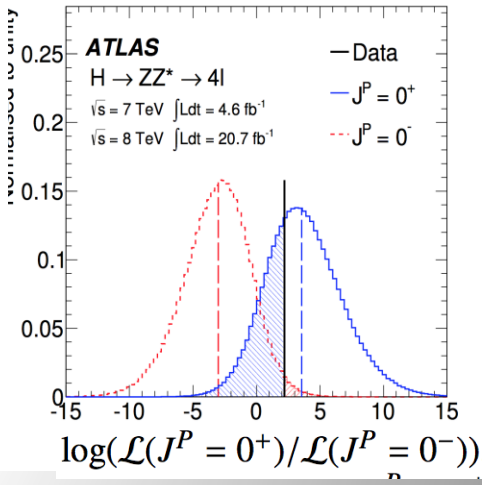
Brief Higgs Summary

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









Mass = CMS+ATLAS
125.09 ±0.21(stat)
±0.11(syst) GeV

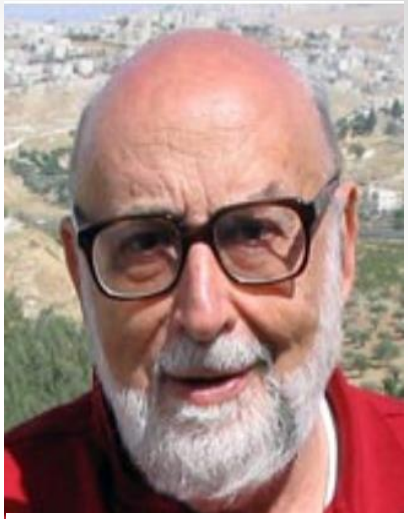
Width =
A: < 24 MeV
C: < 22 MeV
(95%CL)

Couplings are within 20% of the SM values

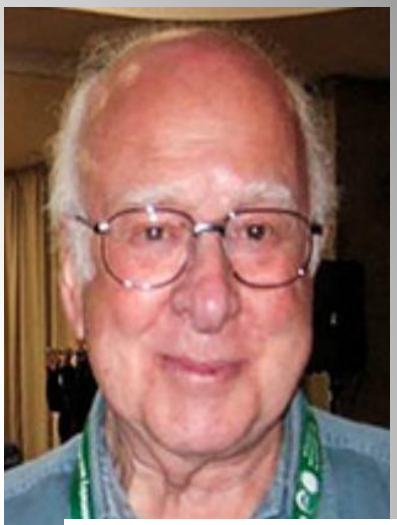
Spin =
$0^{+(+)}$ preferred over 0^-,1,2

SM-like behaviour for most properties, but continue to look for anomalies, i.e. unexpected decay modes or couplings, multi-Higgs production…

Tuesday 8 October 2013

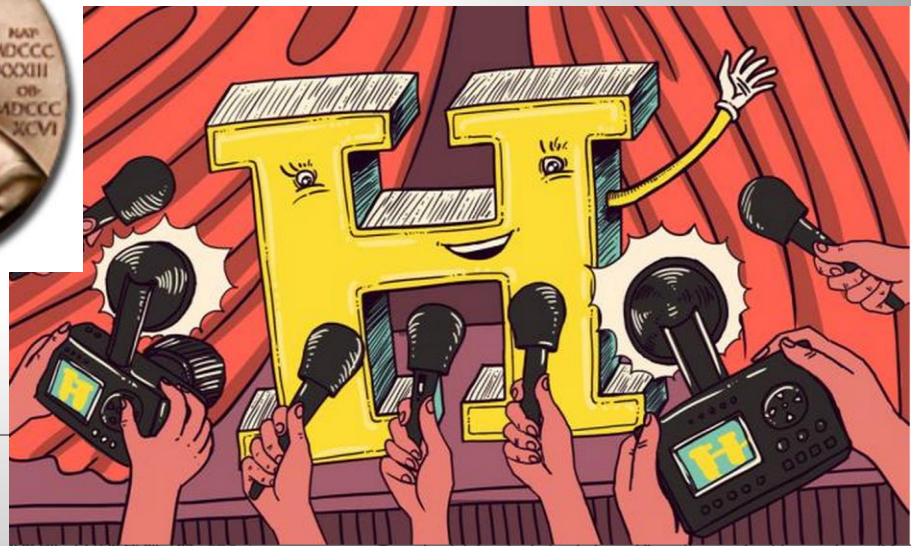


Francois Englert



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 Future: Studying the Higgs…

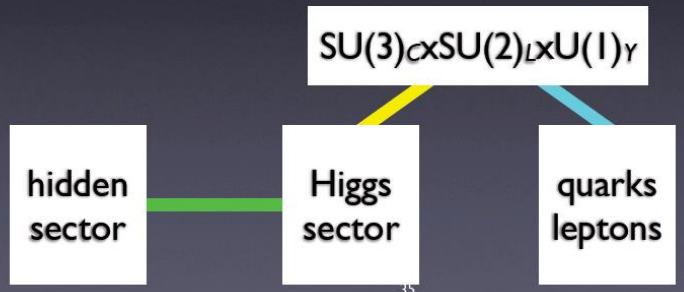
Higher Energy in 2015!
LHC lumi upgrade !
Experiment upgrades!!
(Other/new machines?)

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

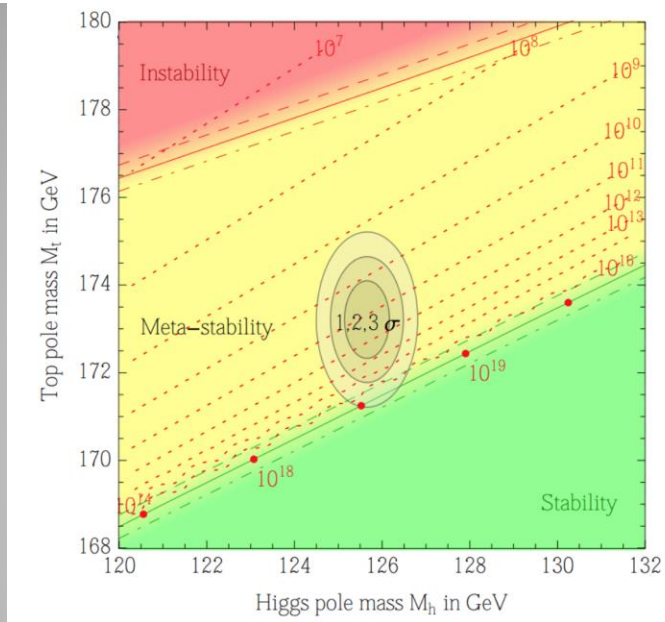
Higgs as a portal

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



Searches for New Physics

Important SM parameter → stability of EW vacuum

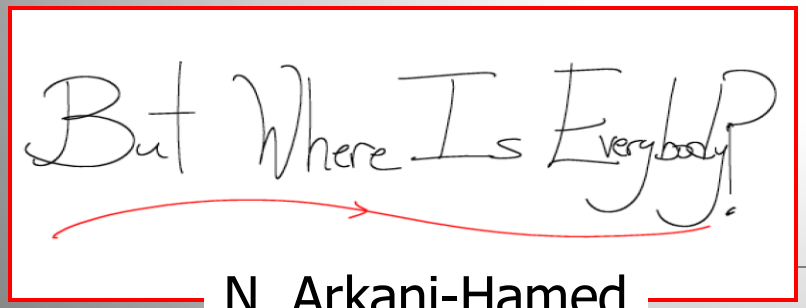


arXiv:1205.6497

arXiv:1403.6535

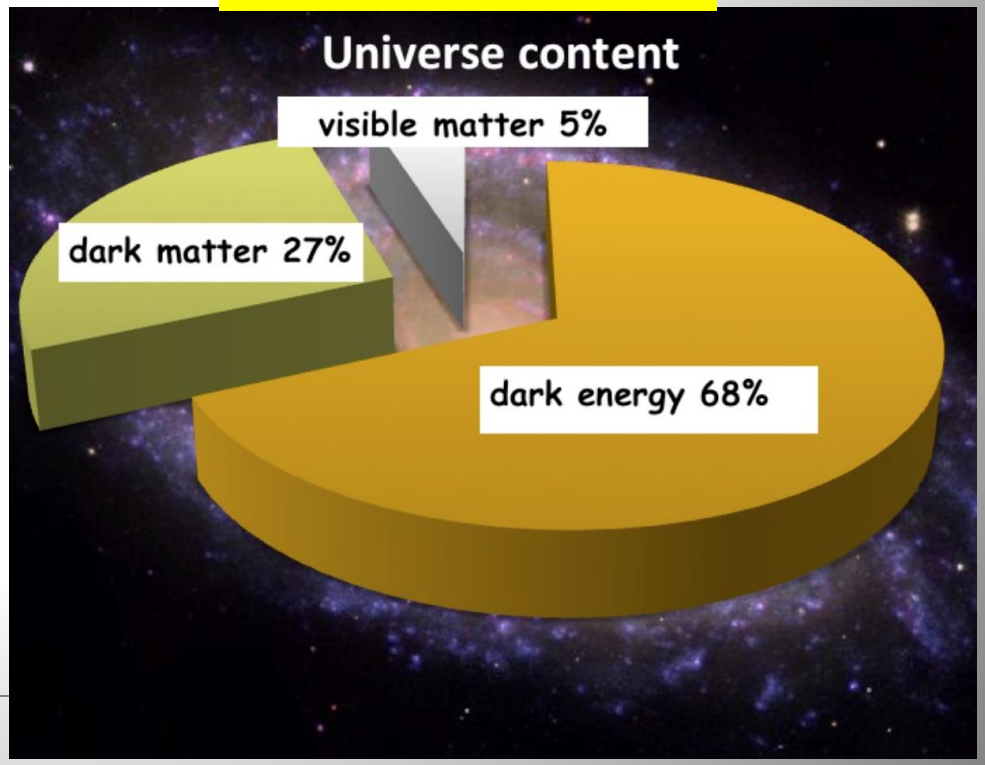
Precise measurements of the top quark and first measurements of the Higgs mass

New Physics inevitable!
Supersymmetric Particles??



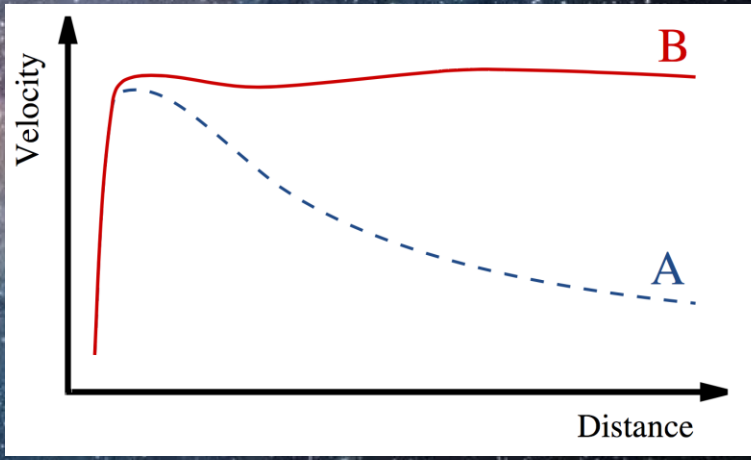
N. Arkani-Hamed

We also know that:



Dark Matter: The Next Challenge !?!

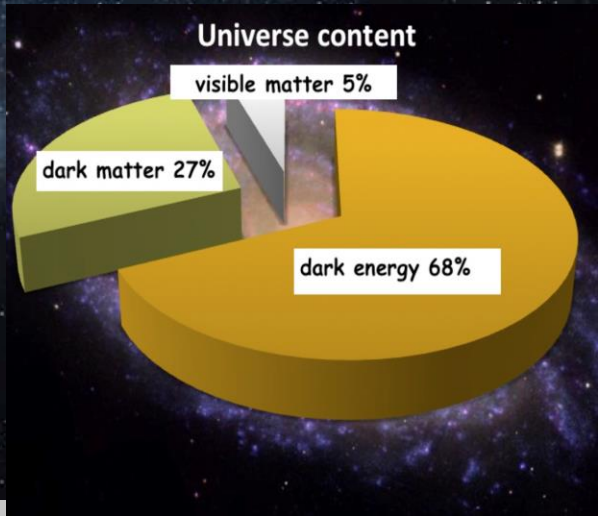
Astronomers found that most of the matter in the Universe must be invisible Dark Matter



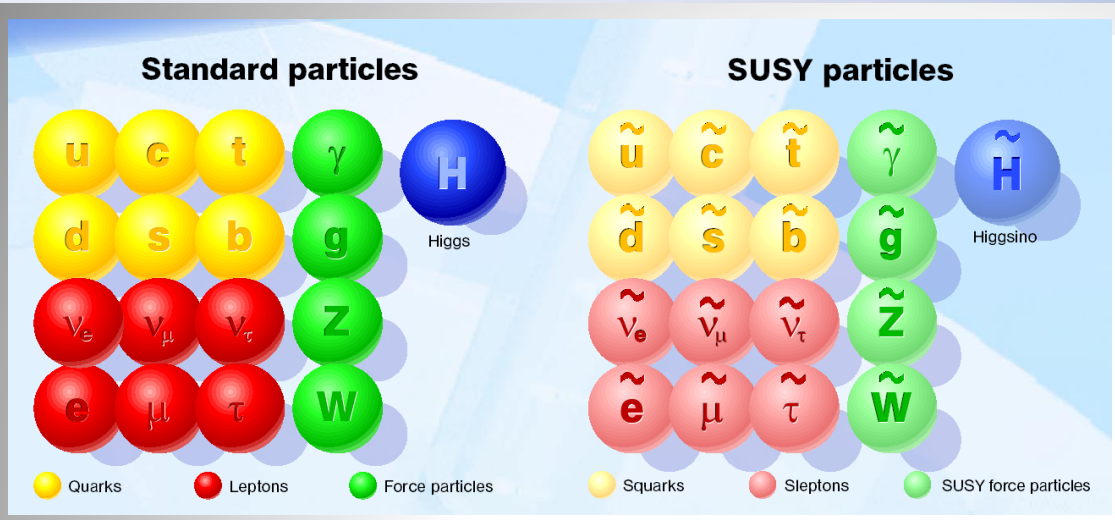
'Supersymmetric' particles ?

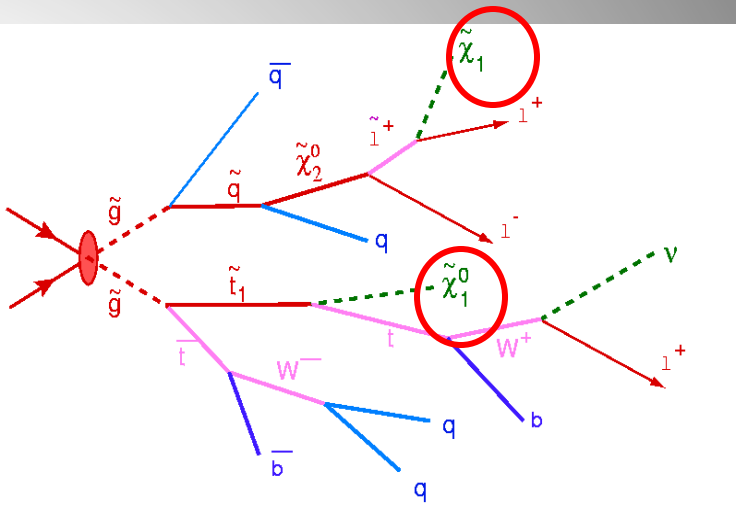
F. Zwicky 1898-1974

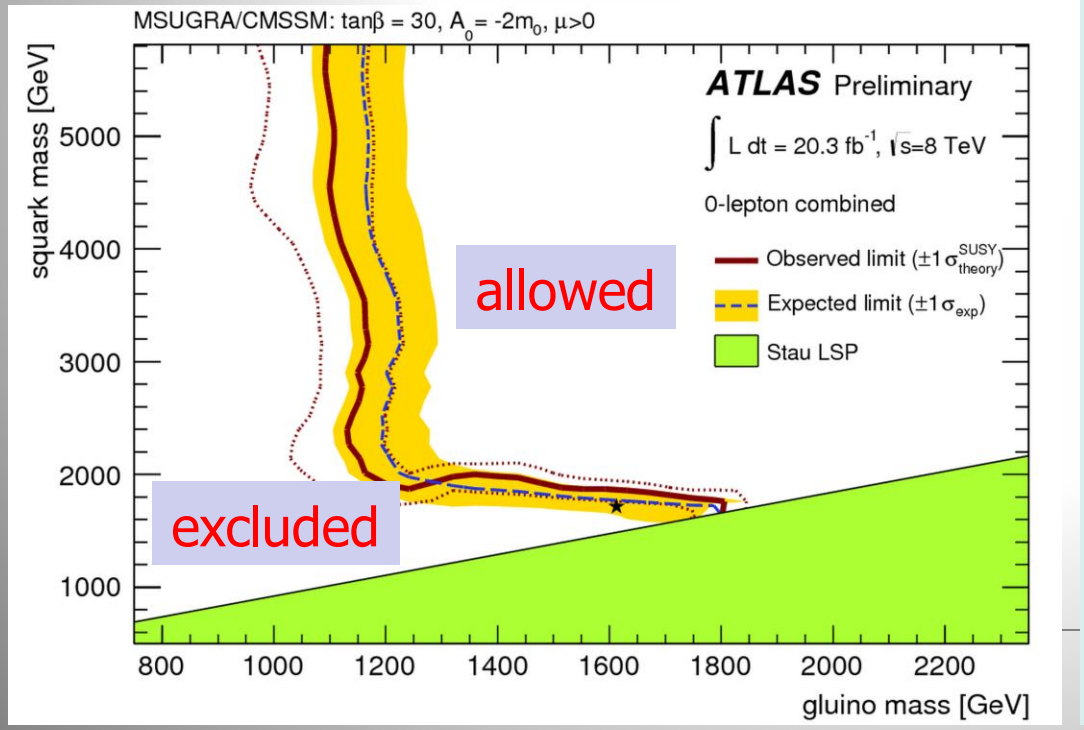
Vera Rubin ~ 1970



SUSY Searches: No signal yet to date…



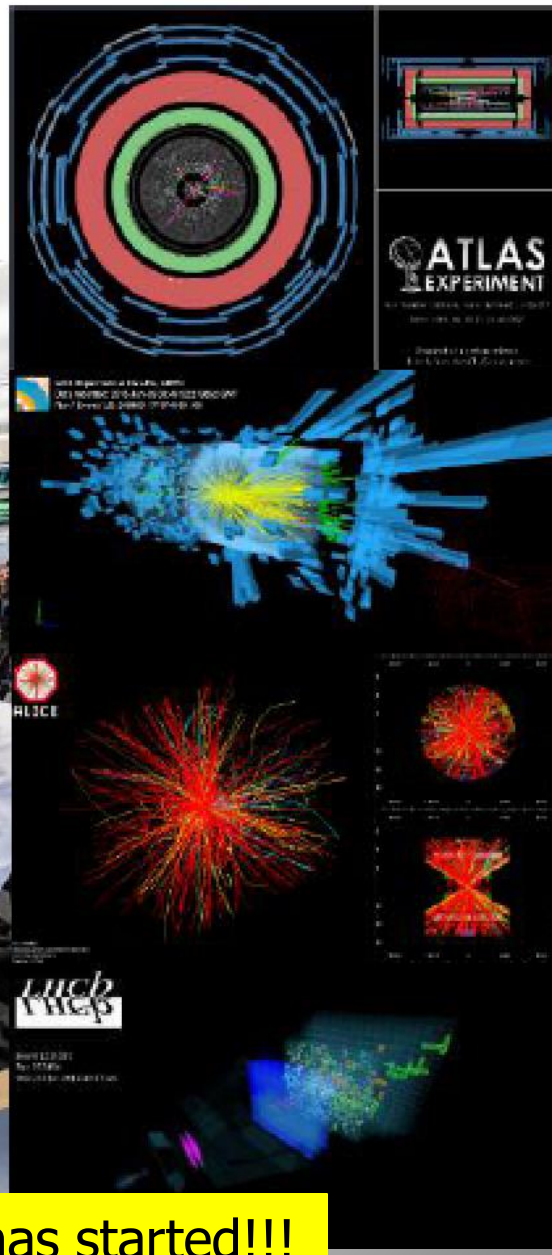




- So far NO clear signal of supersymmetric particles has been found so far SUSY particles must be heavier than 1000 GeV
- We can exclude regions where the new particles could exist.
- Searches will continue for the with the higher LHC energy

LHC experiments are back in business at a new record energy 13 TeV

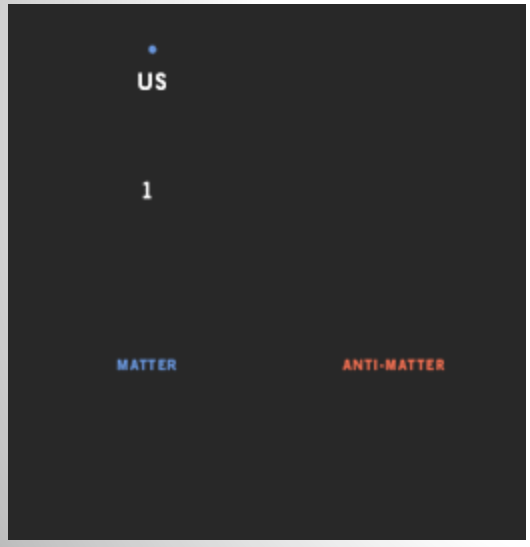
3rd June 2015

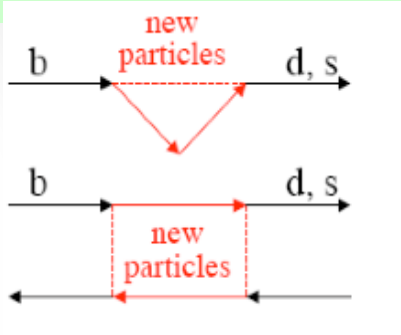


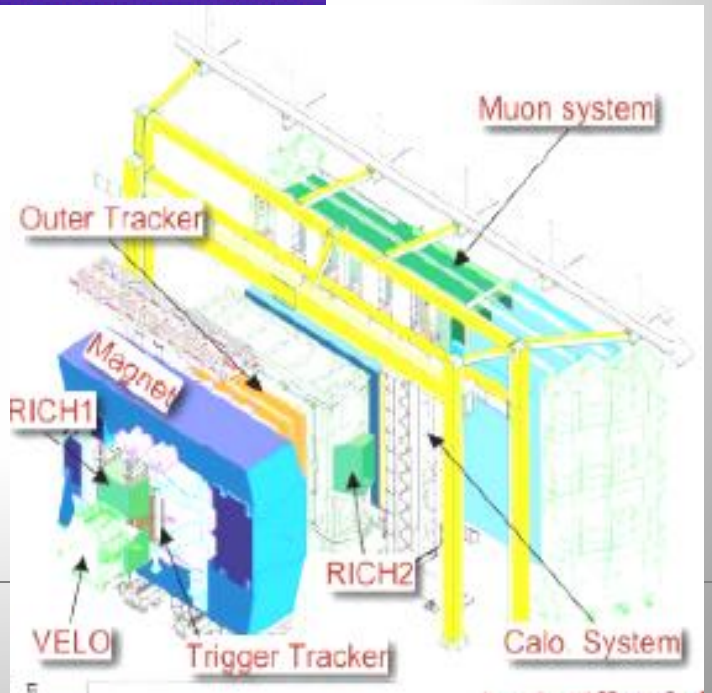
The hunt for supersymmetric particles and dark matter has started!!!

Matter-Antimatter

The properties and subtle differences of matter and anti-matter using mesons containing the beauty quark, will be studied further in the LHCb experiment

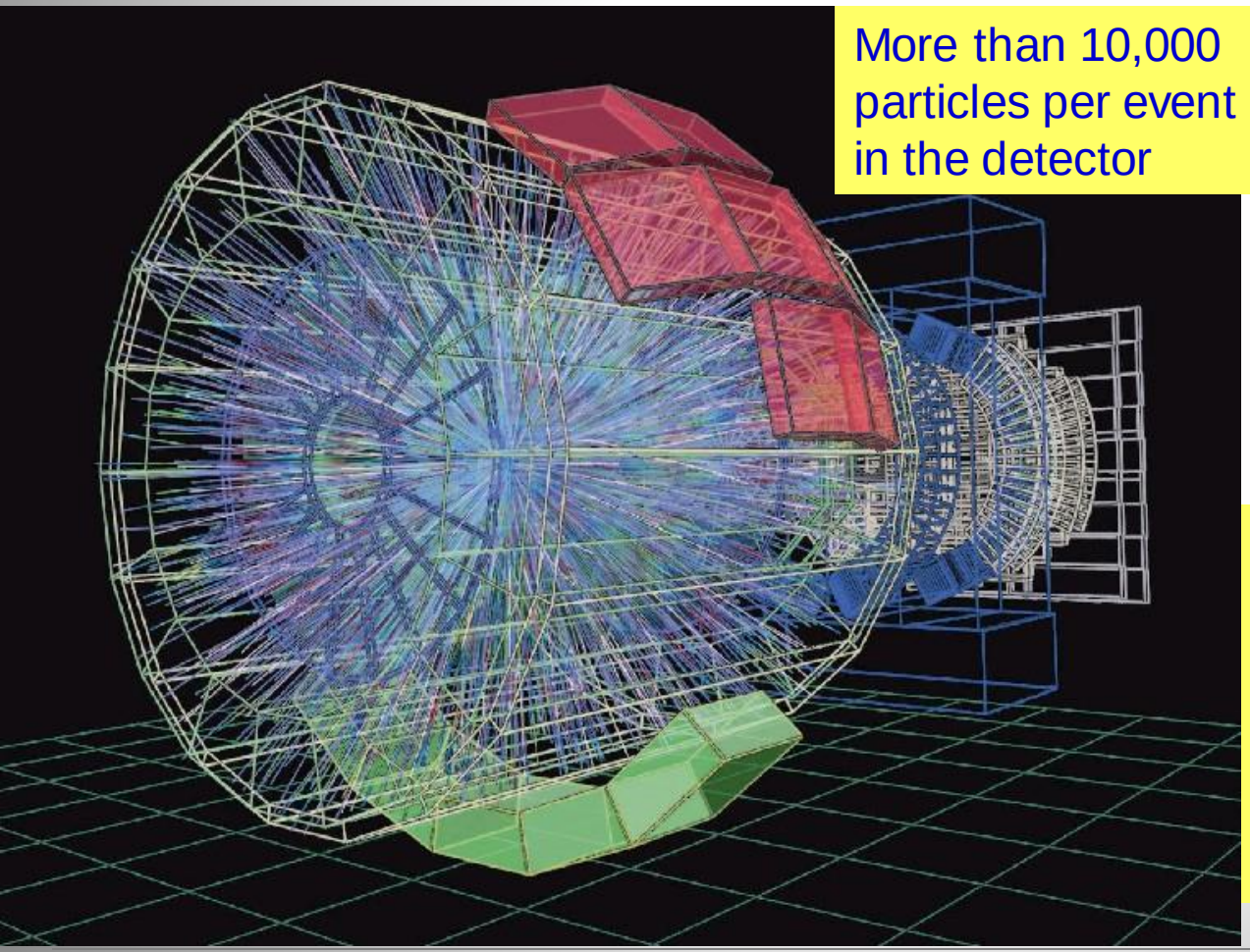




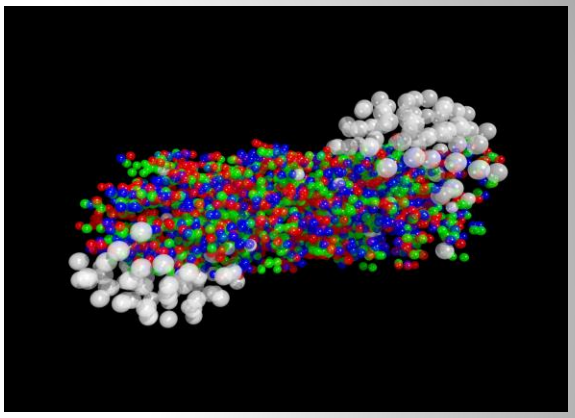


Primordial Plasma

Lead-lead collisions at the LHC to study the primordial plasma, a state of matter in the early moments of the Universe

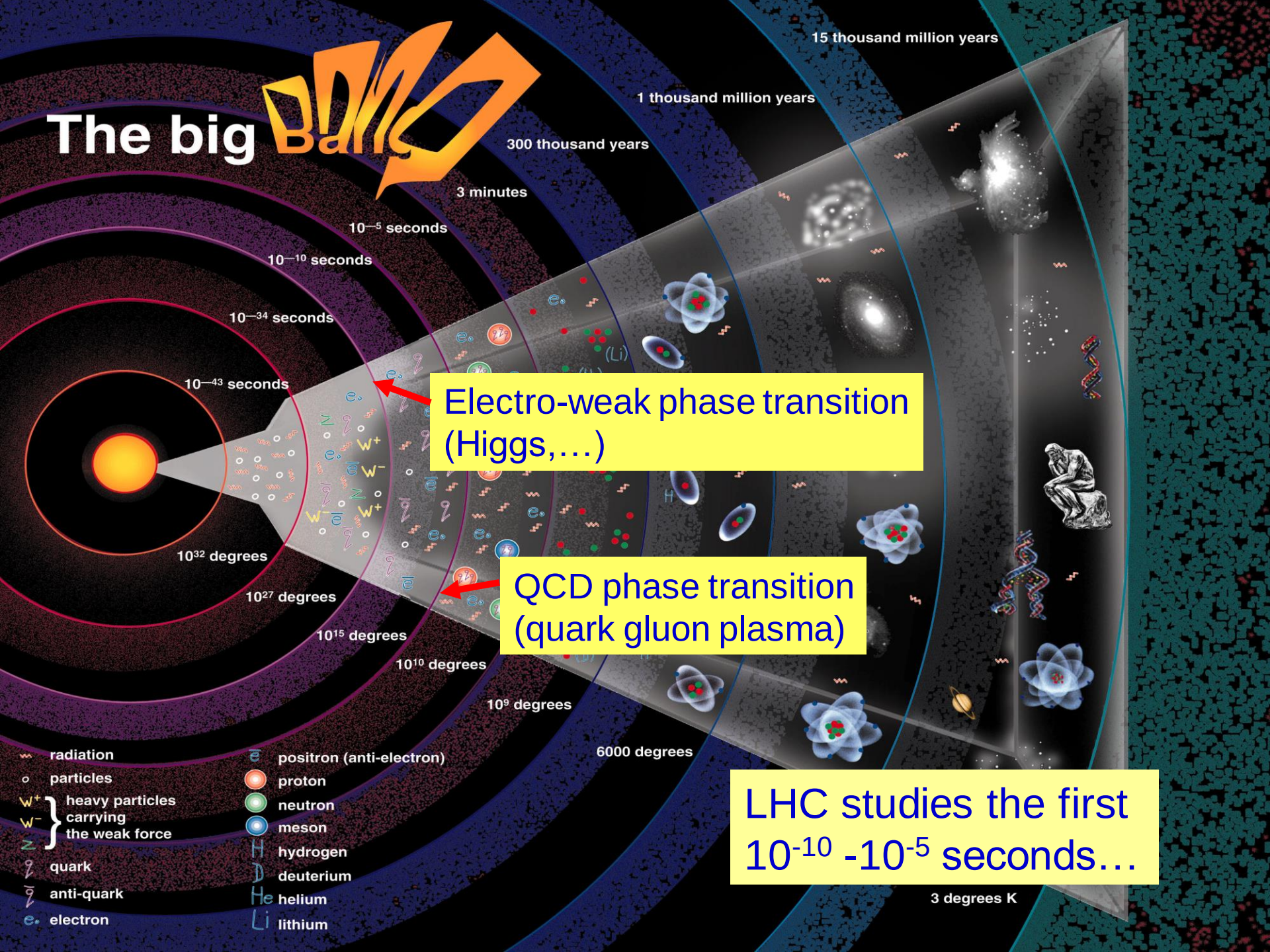


More than 10,000 particles per event in the detector



Study the phase transition of a state of quark gluon plasma created at the time of the early Universe to the baryonic matter we observe today

A lead lead collision in the ALICE detector


The big Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
10⁻⁵ seconds
10⁻¹⁰ seconds
10⁻³⁴ seconds
10⁻⁴³ seconds
10³² degrees
10²⁷ degrees
10¹⁵ degrees
10¹⁰ degrees
10⁹ degrees
6000 degrees
3 degrees K
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium
Electro-weak phase transition (Higgs,…)
QCD phase transition (quark gluon plasma)
LHC studies the first 10-10 -10-5 seconds…

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.

The spin and couplings to W and Z bosons are consistent with the expectation for a Higgs boson. Hence we call it from now "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.

Will the run starting now at 13 TeV reveal the long awaited SUSY particles or a different surprise?? Dark Matter Particles???

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

This is only the beginning!!!