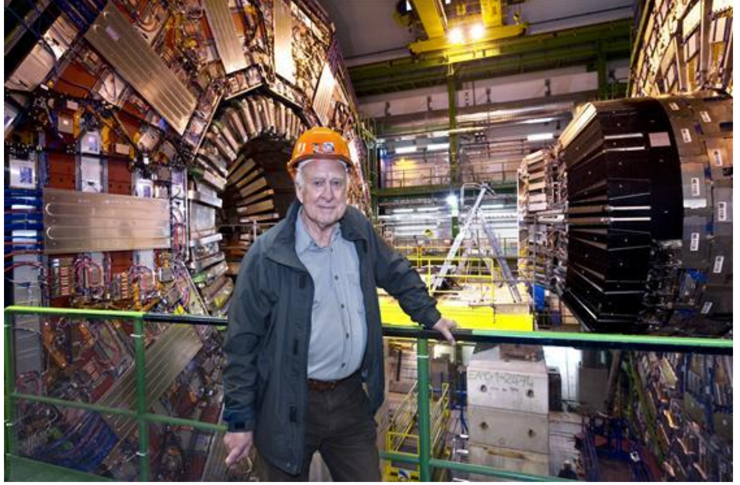
Peter Higgs
(yes he is an
actual person)

At ATLAS

At CMS



Finding the Higgs Boson on the Open Science Grid

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March 13, 2013
OSG AHM

Introduction

- A "Higgs-like" boson has finally identified to the mathematical level required for a scientific discovery.
  - Hopefully we will soon drop the "-like" soon!
  - There is a crucial meeting this week in Italy where the experiments are releasing new results to address this.
- This talk is divided into two parts:
  1. A discussion of the Higgs boson – what it is…
     - How a mathematical formalism launched a ~40 year effort involving tens of thousands of people and many billions in expense.
  2. A description of the enormous detectors and computational effort needed to measure, record, and analyze the experimental data.
     - It took an enormous number of LHC proton-proton collisions to produce the small number Higgs-like events seen at ATLAS and CMS.

Higgs Hunters

- The Higgs boson search is being carried out at CERN the world's largest particle physics lab in Geneva, Switzerland using the Large Hadronic Collider (LHC).
  - The effort is an epic international scientific collaboration.
- Two large, competitive experiments ATLAS and CMS are using the LHC beams to find the Higgs boson.
  - Fierce does not begin to describe the level of competition between the two experiments. (Think dueling pistols…)
  - But the two experiments share the computational grid fabric.
    - In the US this fabric is provided by the Open Science Grid (OSG)
- Fair disclosure: I am an ATLAS (and OSG) member.
  - I have tried to present things equally.
    - Both ATLAS and CMS have done great work!
    - In a couple of cases, I have used ATLAS information in describing how the detectors and trigger work because of familiarity.

What is a Higgs? What is a Boson? (Finding the Higgs at the LHC)

Slides describing the Higgs theory adapted from a public lecture given by Prof. Harold Ogren Indiana

What is the Higgs Boson?

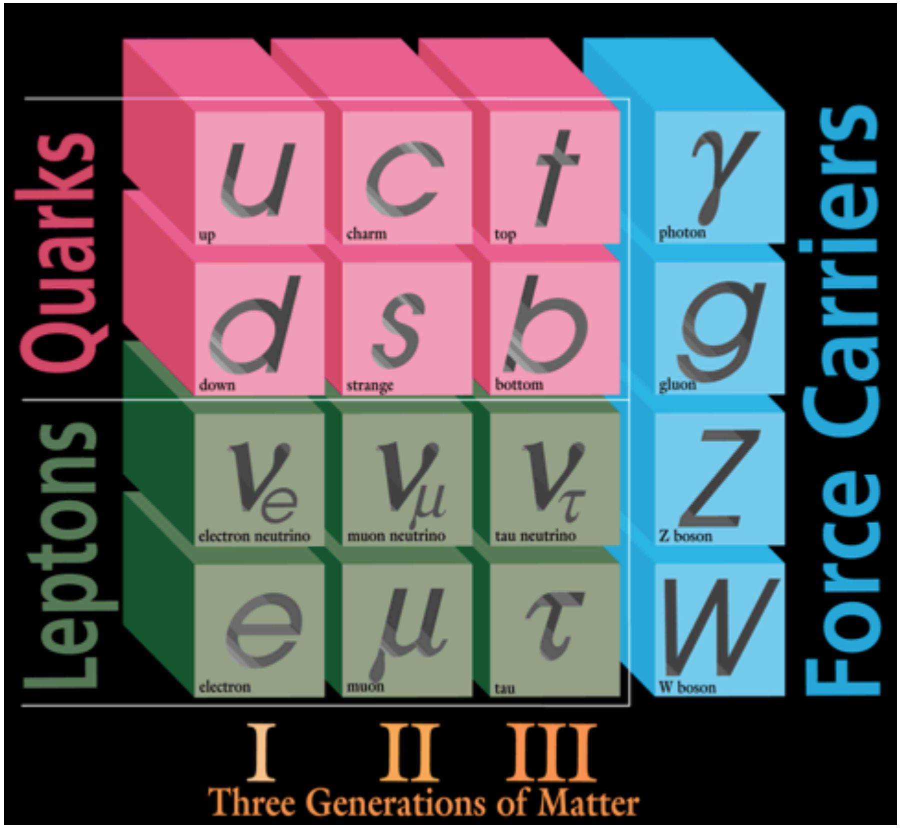
It started out as a mathematical trick to make the massless particles in a particular quantum field theory, appear to have a mass, corresponding to the particles seen in experiments.

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + i \bar{\psi} \not{D} \psi + h.c. \\
& + \psi_i y_{ij} \psi_j \phi + h.c. \\
& + |D_\mu \phi|^2 - V(\phi)
\end{aligned}
$$

To do this, you have to assume that there is a new energetic field (Higgs Field) that permeates the entire universe! A few terms in the equations allowed this to happen!

But is it true?

"Science is what we do to keep from fooling ourselves"
R. Feynman

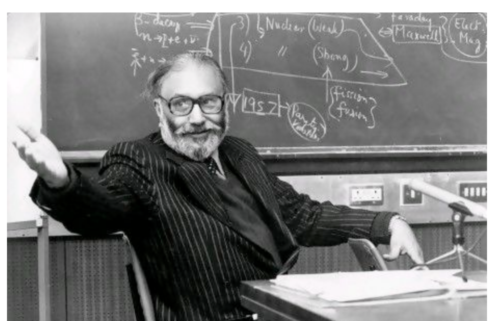


The Standard Model of particle physics was developed by Stephen Weinberg, Abdus Salam, and Sheldon Glashow in 1967. It is a quantum field theory that describes interactions of quarks and leptons (AKA Fermions). The Higgs mechanism was used to generate the masses of the Z and W gauge bosons, and the masses of the Quarks and leptons.

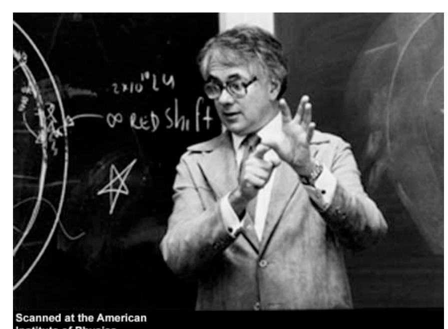
They shared the 1979 Nobel Prize.

Weinberg

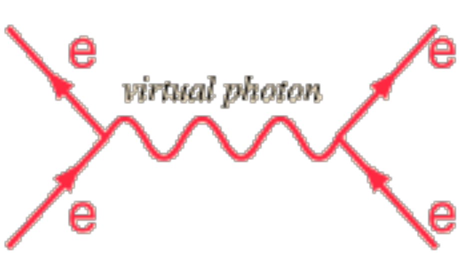
Salam



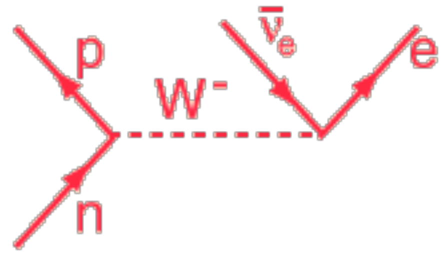
Glashow



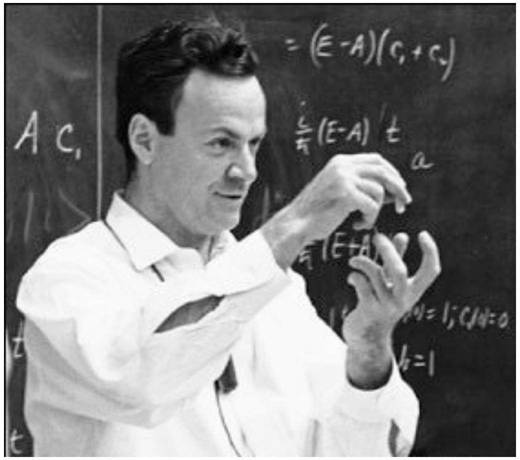
According to the Standard Model all known forces are due to the exchange of bosons - the photon, gluino, W, Z , or the Higgs. Richard Feynman showed how interactions represented in a quantum field theory could be drawn as an (infinite) series of diagrams where matter (fermions) interacts via bosons.

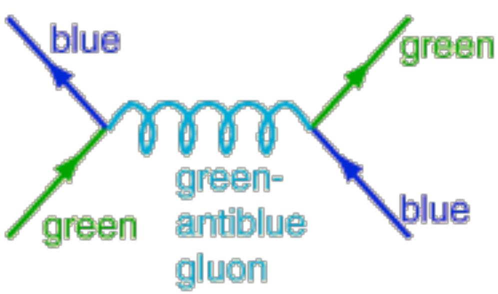


Electromagnetic

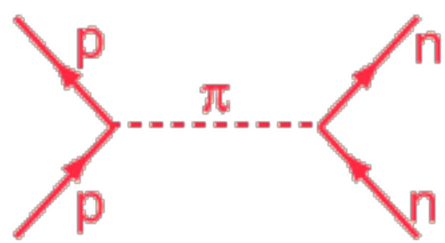


Weak





between quarks



between nucleons

Strong Interaction

Feynman received the Nobel Prize in 1965.

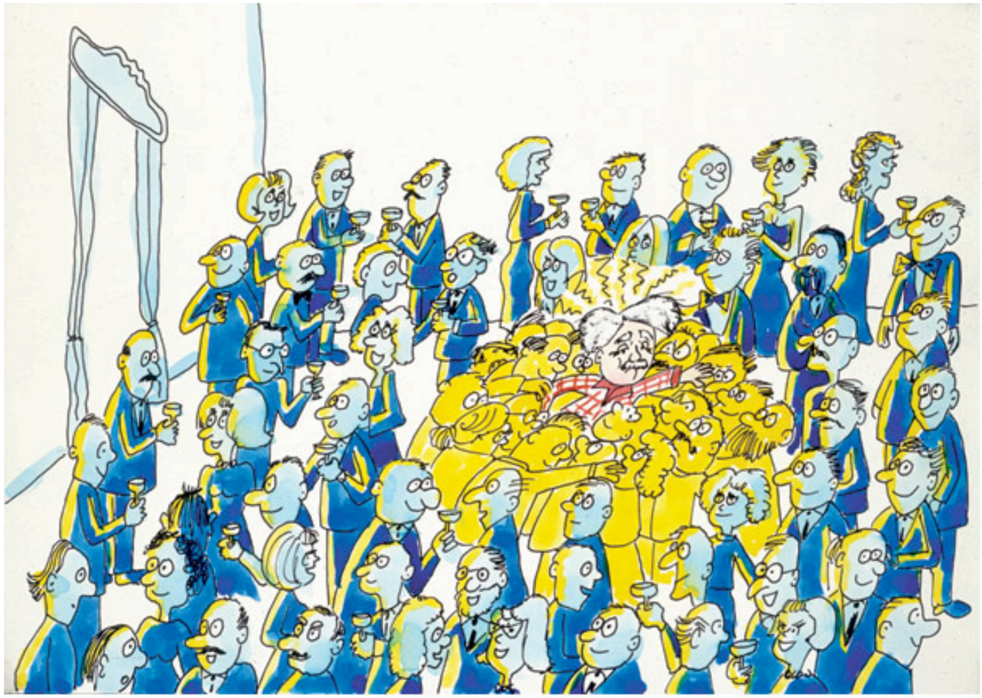
Who proposed the Higgs boson?

Although Peter Higgs name is associated with the addition of a scalar field, there were several others who came up with the same idea about the same time.

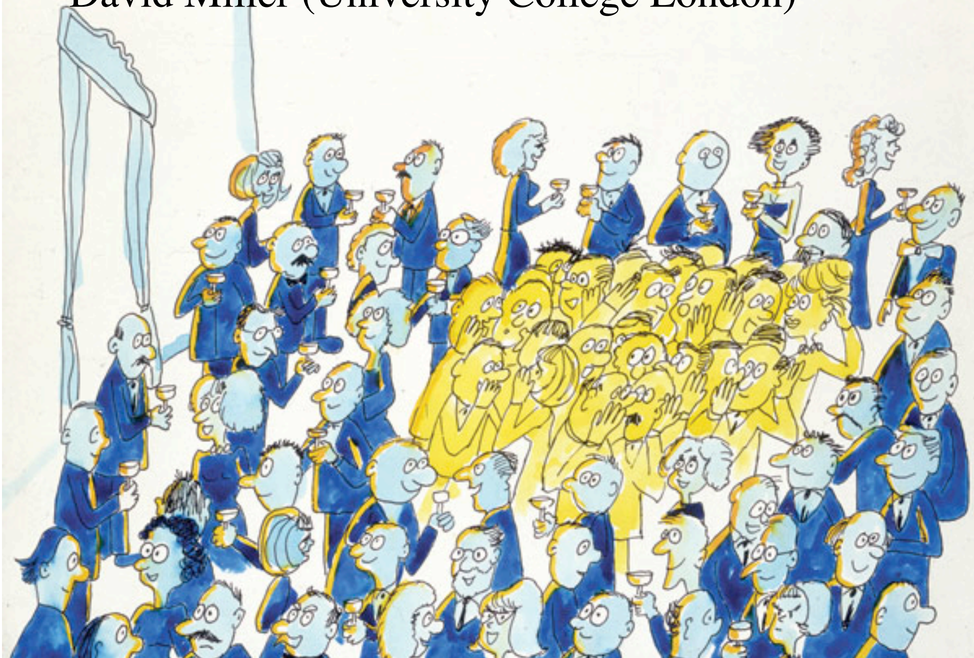
The basic method of adding a scalar field was proposed in 1962 by Philip Warren Anderson, a solid state theorist.
A relativistic model was developed in 1964 by three independent groups: Robert Brout and Francois Englert; Peter Higgs; and Gerald Guralnik, C. R. Hagen, and Tom Kibble.

Higgs's original article describing the model was rejected by Physics Letters. When revising the article before resubmitting it (August 31, 1964), he added a sentence at the end of the paper mentioning that this scalar field implies the existence of one or more new, massive spin 0 bosons, which are excitations of the Higgs fields: These are the now called Higgs bosons.

All six theorists received the 2010 Sakurai prize, but only three are allowed to share the Nobel Prize! (maybe in 2013?)



David Miller (University College London)



An elementary particle
gets a mass from
the Higgs field

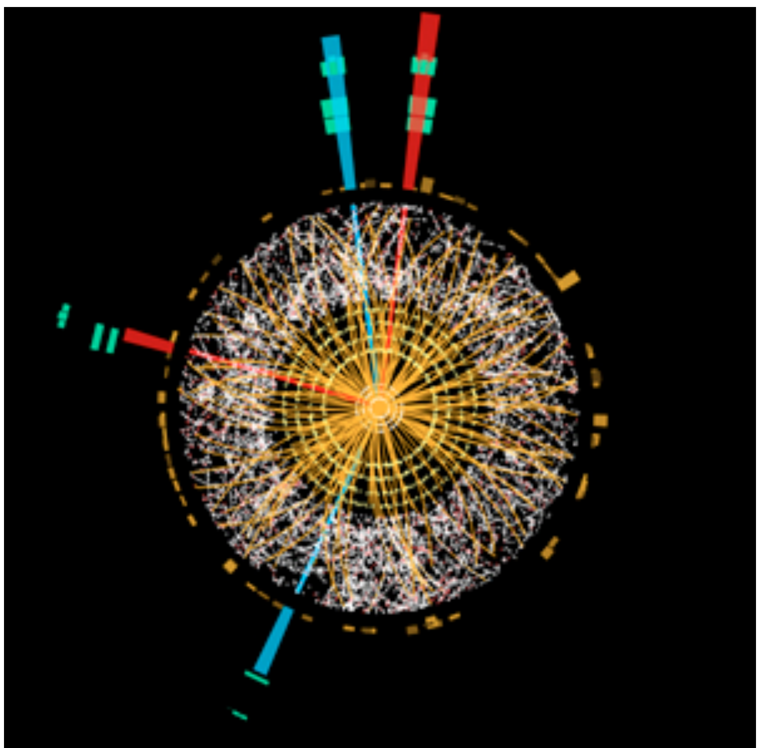
Each type of particle has a
different interaction strength
for giving it a mass.

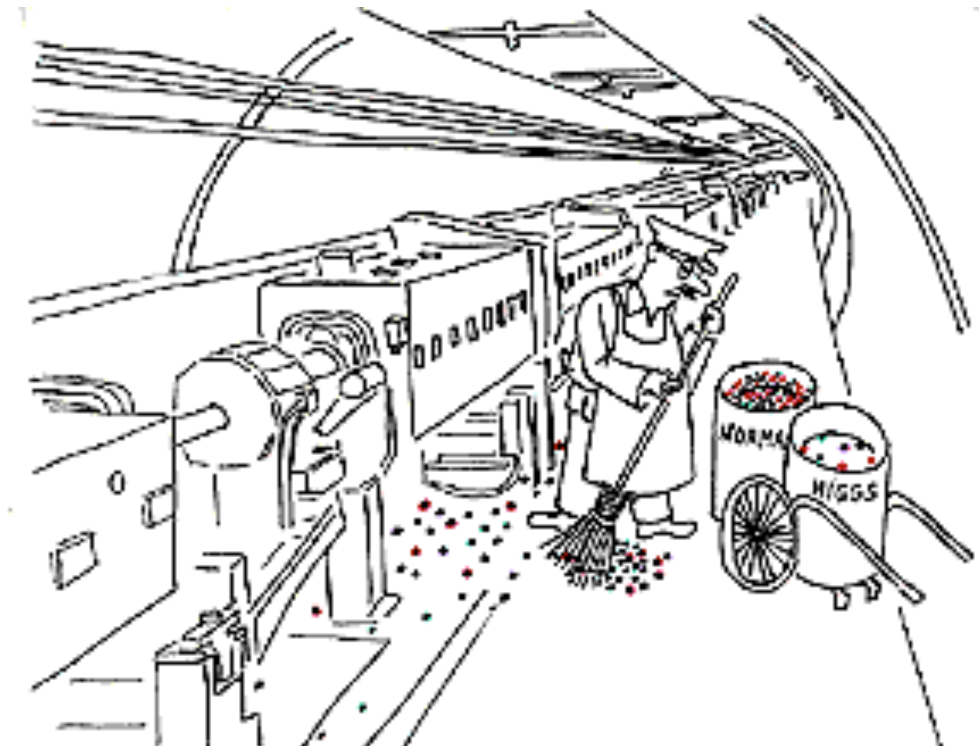
An excitation of the
Higgs Field generates
A Higgs Boson

Just like the excitation
of the electromagnetic
field creating photons!

How do we look for the Higgs?

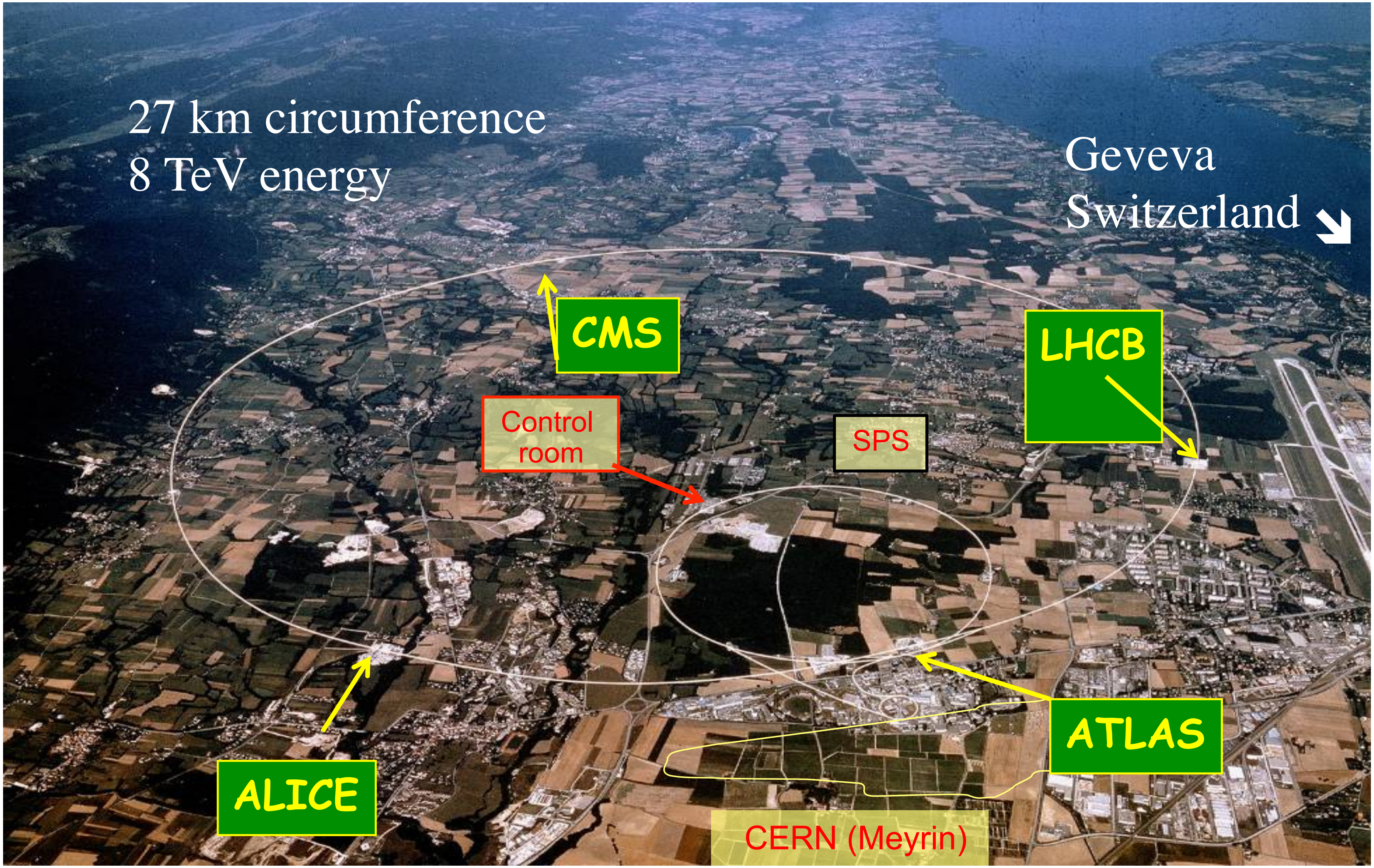
The standard model indicates that the Higgs boson will live for only ~10^{-21} sec before it decays into other particles. So we will not directly "see" the Higgs, only particles it decays into. Many possible decays are predicted by the standard model BUT the exact value of the mass of the Higgs boson is not predicted!





To find the Higgs we need to build colliding beam accelerators

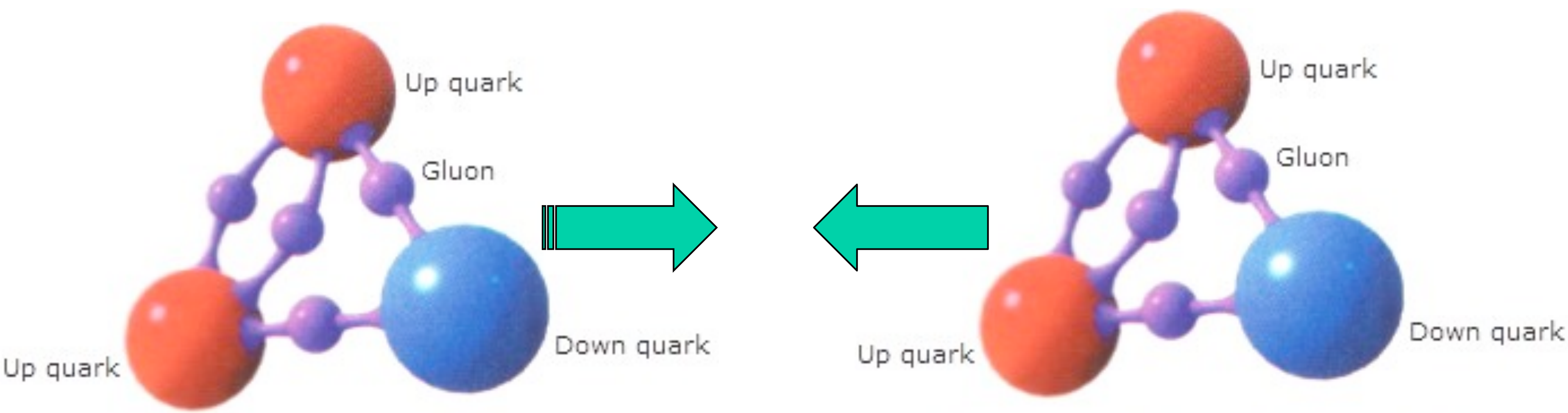
LHC - LARGE HADRON COLLIDER



(A HADRON IS ANY PARTICLE MADE OUT OF QUARKS)

What happens in a proton-proton collision at LHC?

Protons collide at the interaction points around the LHC ring, but the proton is not a fundamental particle. The quarks and gluons that make up the proton are the particles that interact. At the LHC both quark-quark and gluon-gluon interactions are very important.



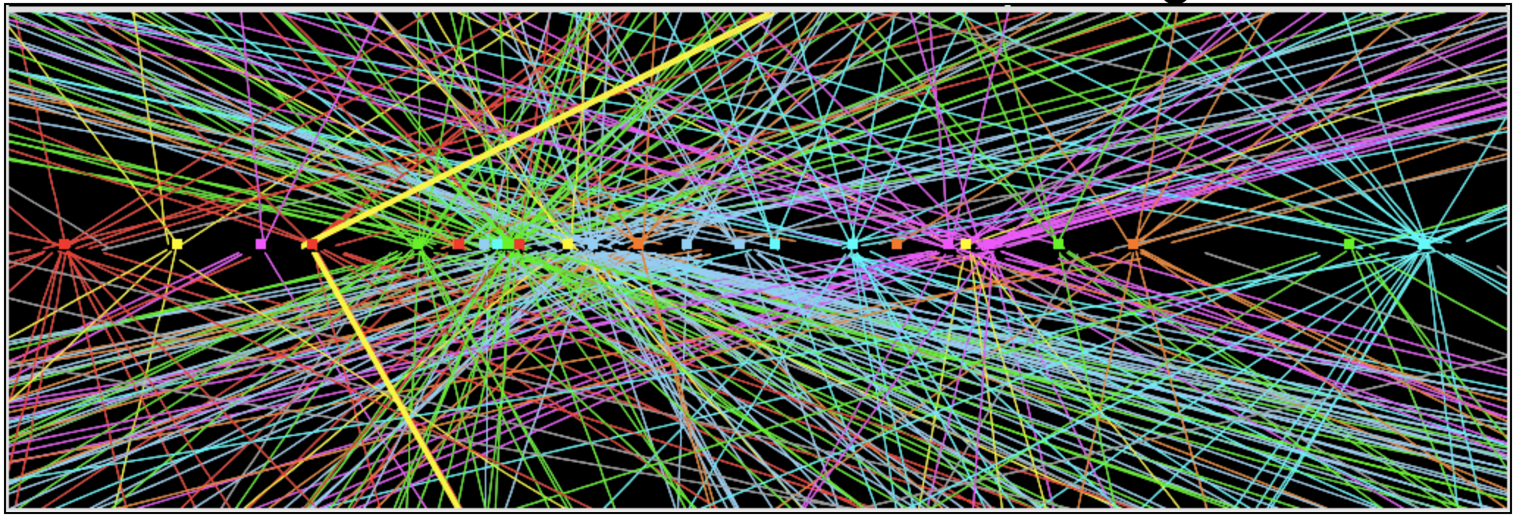
Gluons holding quarks together to form a proton (diagram from *Scientific American*)

Gluons holding quarks together to form a proton (diagram from *Scientific American*)

Proton collisions in the LHC

For the most recent running period, the LHC had two stored opposing beams of 2 x 10^{13} (20 trillion) protons with each beam16 microns in diameter (half the size of a human hair) and about 20 cm long. The protons in each beam were grouped about ~1300 bunches resulting in about 20 million bunch crossings /sec.

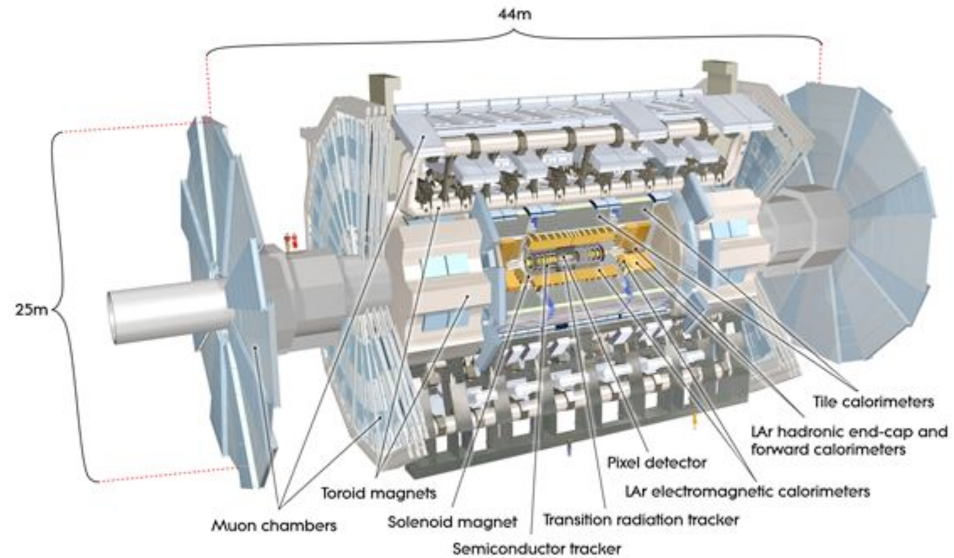
As the two thin bunches passed through each, up to 30 proton-proton collisions resulted. The bunch crossing are ~ head-on.

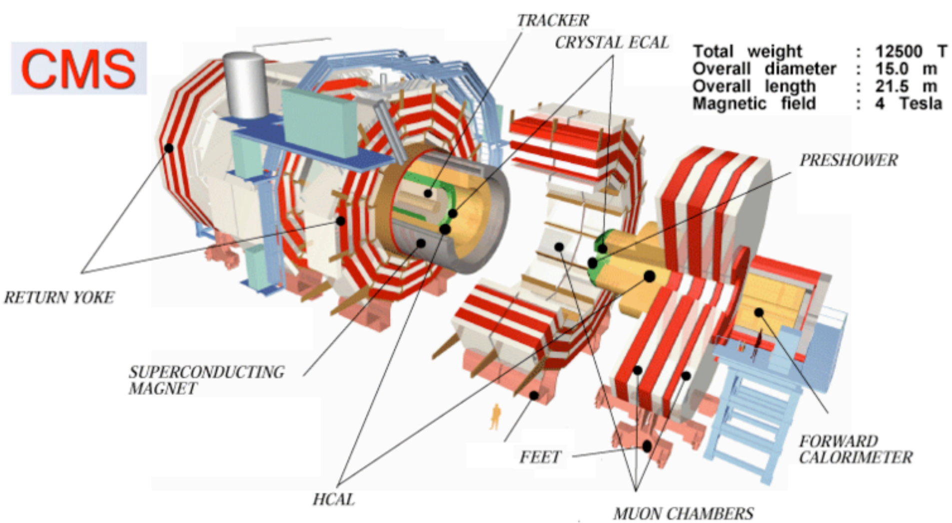


Higgs Finders: ATLAS and CMS

ATLAS is about 25 m in diameter and 44 m long while CMS being compact is “only” 15 m in diameter and 21.5 m long.

ATLAS





The experiment names are:

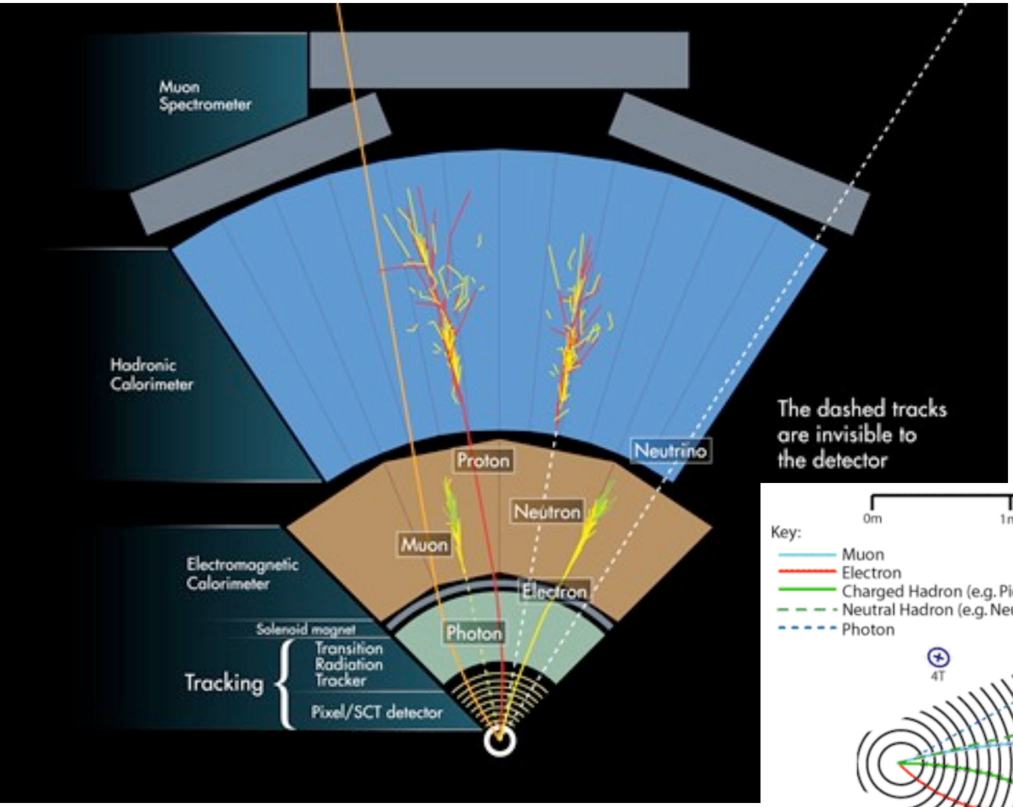
ATLAS - A Toroidal LHC ApparatuS

CMS - Compact Muon Solenoid

The Detector Layers

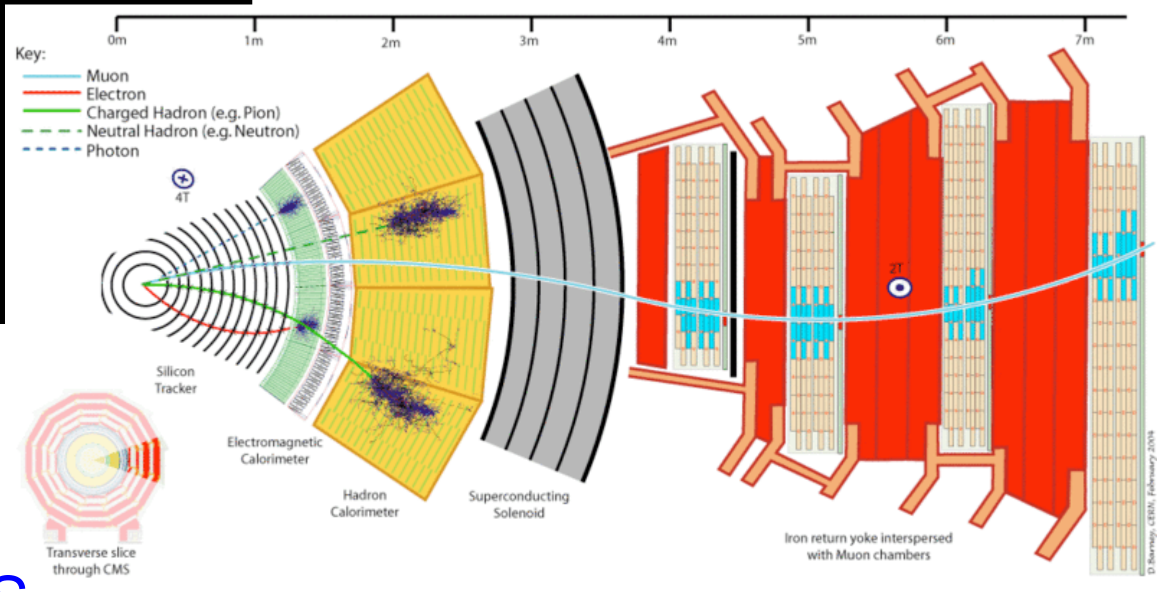
- Charged Particle Tracking (inner layer)
  - measures the trajectory of longer-lived particles: electrons/ positrons, muons, and pions
  - Also finds decay vertices from short-lived particles
  - Use bend in magnetic field to measure momentum
- Calorimeters (middle layer)
  - Electromagnetic Calorimeters measure electrons and photons by absorbing (nearly) all of their energy
  - Hadronic Calorimeters measure pions using absorption.
- Muon System (outer layer)
  - Measures the muons which normally pass through the calorimeters without being absorbed.
- Missing Transverse Energy
  - Measures energy carried off by neutrinos.

Detector Parts



Particle physics detectors are built in layers that detect different particles.

ATLAS

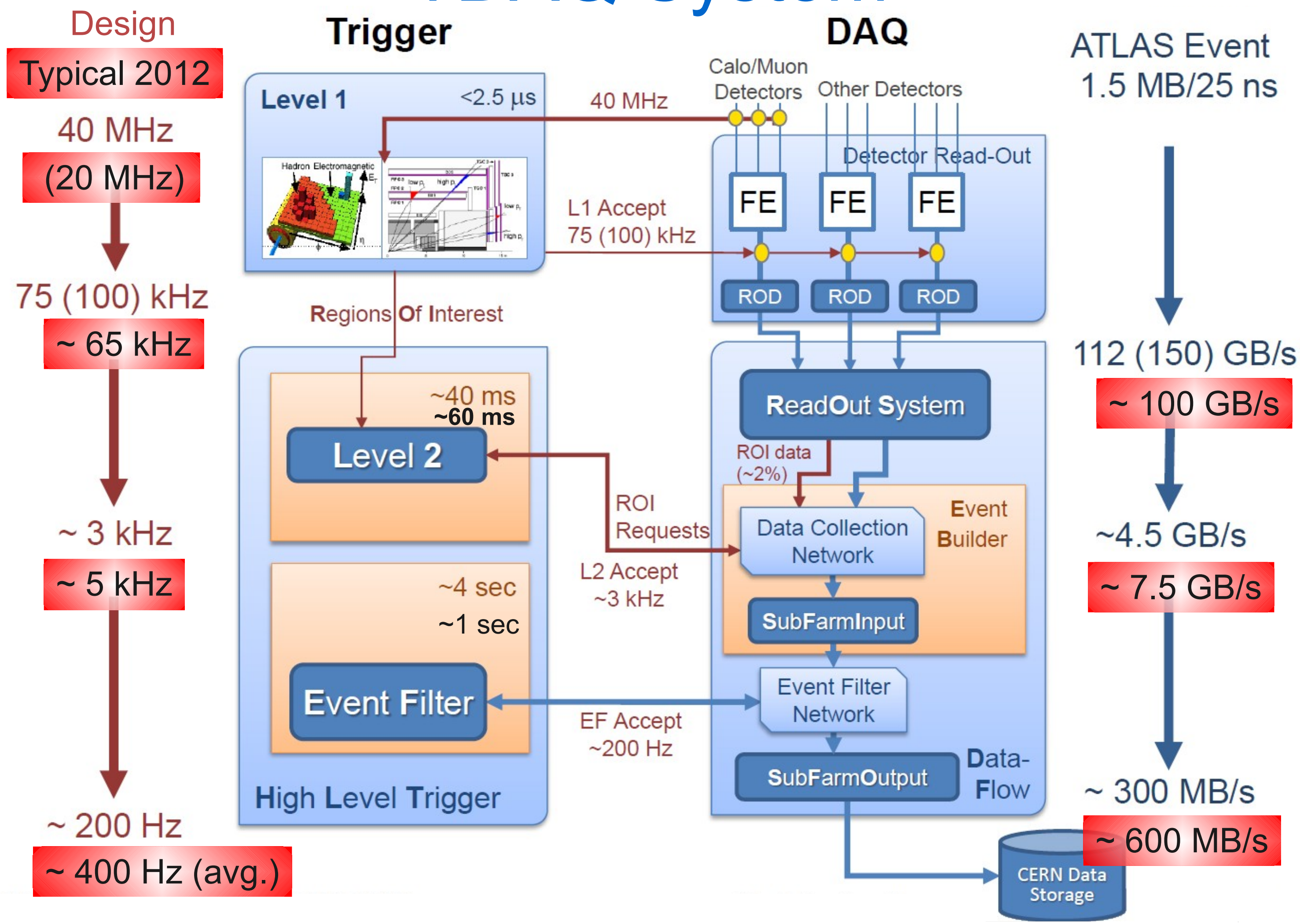


CMS

Trigger and Data Acquisition

- In 2012, the LHC proton beams crossed 20 million times a second producing an average of 10-20 proton-proton collisions.
  - Each crossing generates ~1.5 MB of data.
  - Almost all interactions are caused by well measured processes and generate previously observed particles.
  - ATLAS and CMS could write to permanent storage data from ~200-400 crossings per second. This results in an enormous data storage requirement (10s of PB - more if one includes simulated data needed to understand the detector).
  - The trigger system makes several layers of processing to select in real time the events that are saved.
  - The data acquisition system writes these events to storage.
- Mistakes in TDAQ are generally unrecoverable.

TDAQ System

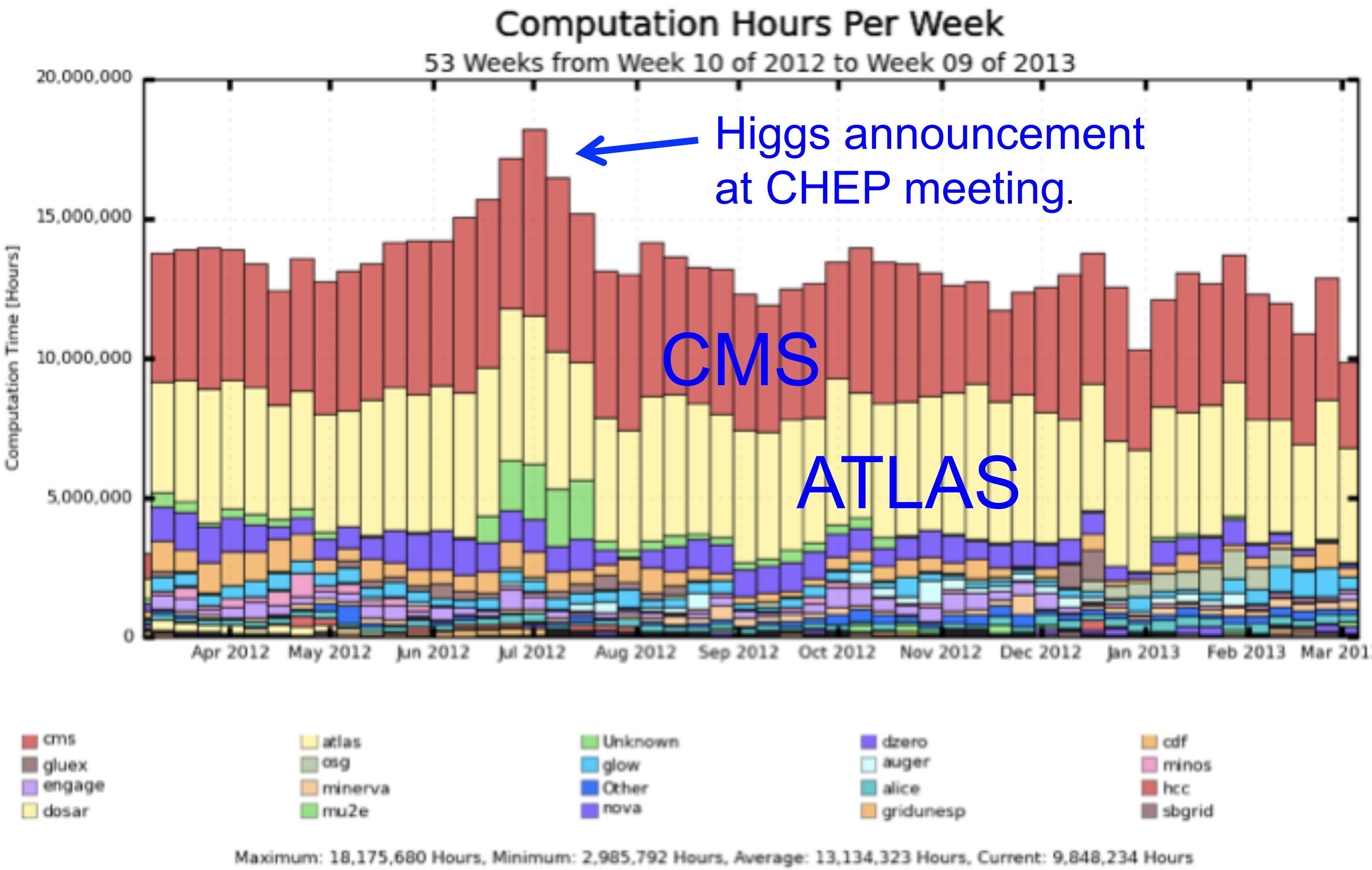


This diagram is from an ATLAS talk given in conjunction with the July 2012 Higgs announcement. CMS has a similar multi-level Trigger/Data Acquisition scheme. From B. Petersen / N. Garelli.

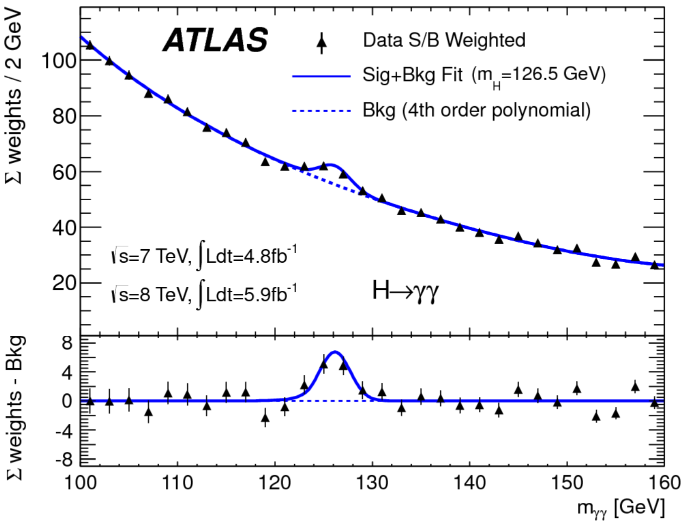
Offline Processing (the Grid)

- The recorded data is processed to find Higgs bosons.
  - As previously mentioned, the data is many petabytes of recorded data and simulated events.
  - Hundreds of analyses look for different kinds of new physics.
    - Analyses also check carefully and improve known results.
- Since the offline processing does not occur in real time, more CPU time can be spent than in the trigger.
  - The offline processing uses servers located at hundreds of sites and many PB of storage located throughout the world.
- This is where OSG /the Grid enters the picture
  - OSG provides access to part of the servers and storage.
  - At the July announcement both the ATLAS and CMS spokespersons and the CERN director general gave credit to the huge contribution that the grid made to the discovery.

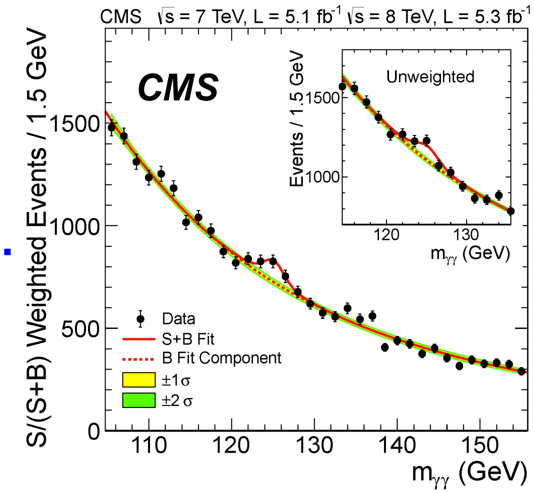
ATLAS and CMS Compute Hours

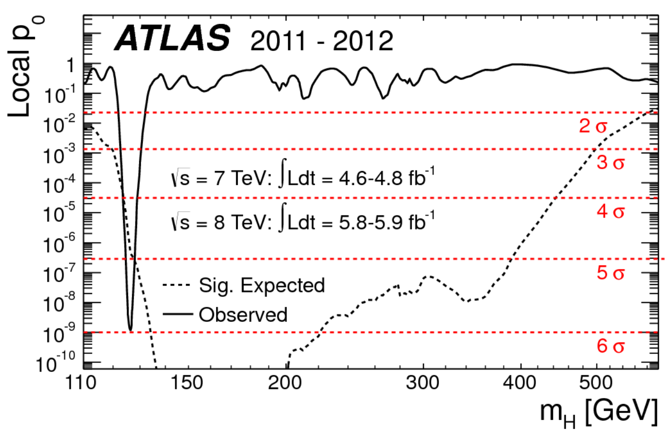


The Final Result



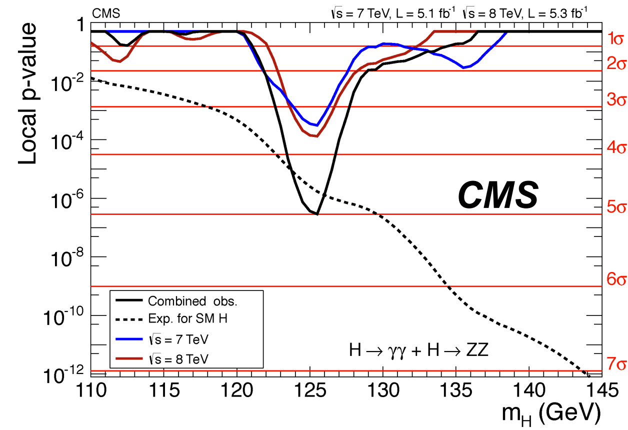
A small bump but…





Totally unlikely to be chance!

ATLAS & CMS get the same result



Note: ATLAS and CMS probability plots have somewhat different definitions.

Global Effort → Global Success

After ATLAS and CMS gave their talks announcing discovery of a Higgs-like particle, Rolf-Dieter Heuer summed up on this single slide… 04-Jul-2012

Results today only possible due to extraordinary performance of accelerators – experiments – Grid computing

Observation of a new particle consistent with a Higgs Boson (but which one ?)

Historic Milestone but only the beginning

Global Implications for the future

R-D Heuer

Interesting Links

- CERN:
  - http://www.quantumdiaries.org/author/cern/
  - http://home.web.cern.ch/
- The public outreach sites of the experiments:
  - http://atlas.ch/
  - http://cms.web.cern.ch/
- The public scientific results of the experiments:
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
- Wikipedia:
  - http://en.wikipedia.org/wiki/Higgs_boson
  - http://en.wikipedia.org/wiki/Standard_Model
  - Many interesting additional links found in the above 2 articles

Picture from Wikipedia article about Higgs Boson.

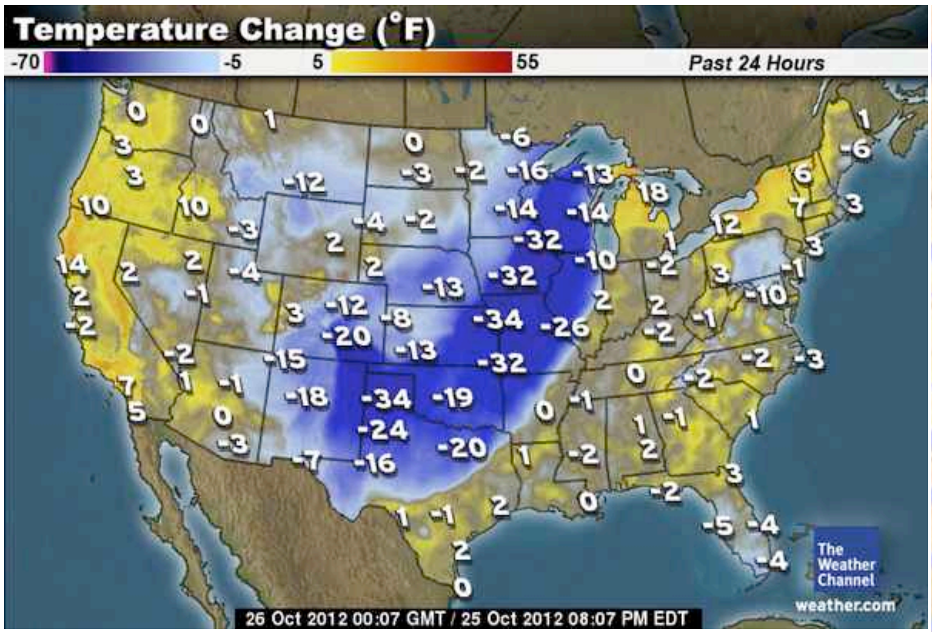
Backup Slides

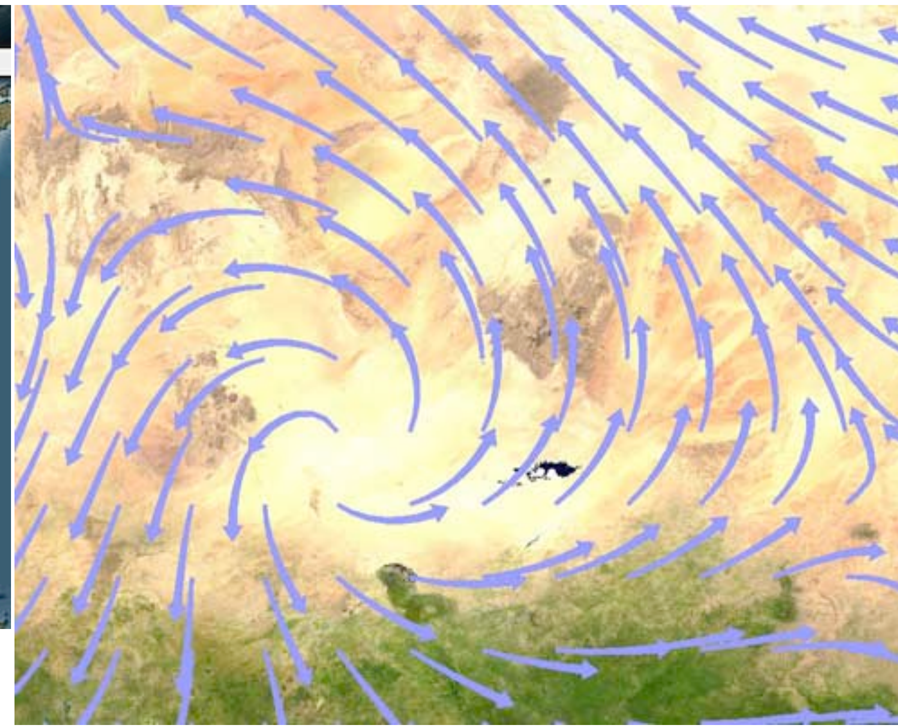
The original theorists (except Higgs) in 2010:
Kibble, Guralnik, Hagen, Englert, Brout

What is a Field?

Temperature at each point

Velocity at each point





scalar

vector

Higgs Field

“One of the consequences of the electroweak symmetry is that, if nothing new is added to the theory, then all elementary particles are massless, including quarks and leptons , which of course they are not. So, something has to be added to the electroweak theory, some new kind of matter or field, not yet observed in nature. The search for the Higgs particle has been a search for the answer to this question - what new stuff do we need to add?”

“Higgs Field implies that there are an hitherto unobserved fields that pervade empty space. These fields distinguish the weak force from the electromagnetic force, giving mass to the particles that carry weak force and other particles, but leave photons with zero mass. These fields are called ‘scalar’ fields, meaning that unlike magnetic fields they do not have directions in ordinary space.”

Steven Weinberg

(Most of) OSG

This map shows OSG resources in the US. ATLAS and CMS use many but not all of these sites. Not shown are resources in South America.

To be clear there are lots and lots of other Grid resources used by ATLAS and CMS in the rest of world that are accessed through other Grids (primarily the LHC Computing Grid).

Cumulative CPU Hours