Exploring the Universe with the "Big Bang Machine"

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Fundamental Particles of the Standard Model

- The fundamental constituents of the universe are 3 generations of fermions (and their corresponding anti-particles) of two types:

Quarks

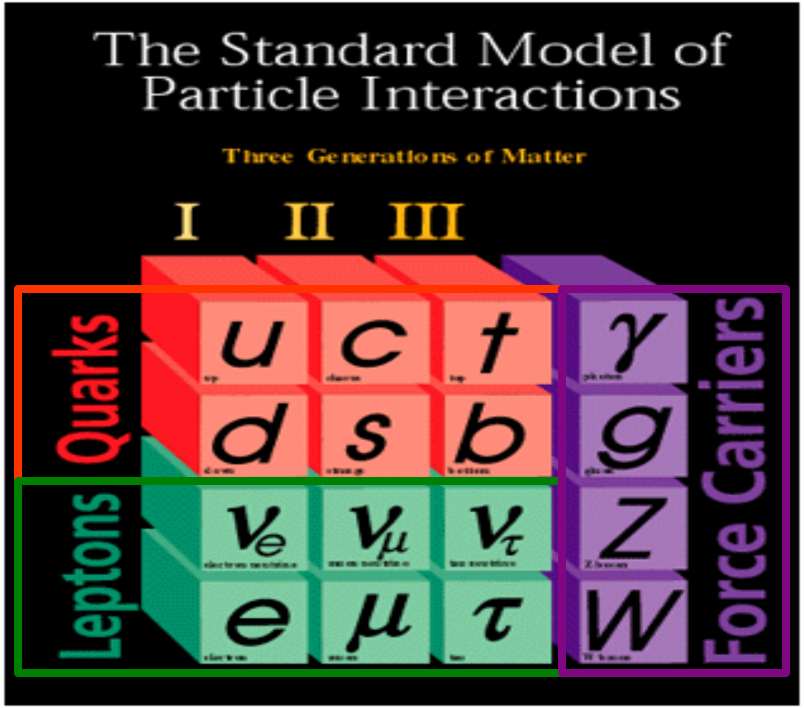
- for example, the up and down quark of which protons and neutrons are made:

proton = uud

neutron = udd

Leptons

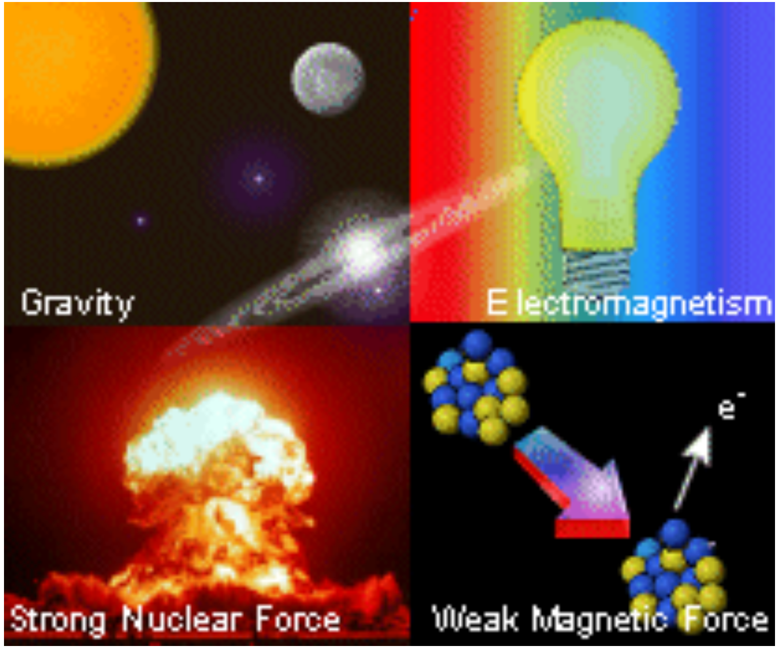
- for example the electron, and neutrinos



- These particles interact with one another via 4 fundamental forces, which are mediated by the exchange of force carrier bosons

Fundamental Forces

- The 4 fundamental forces are
  - Electromagnetism
    - eg. Coulomb's law keeping electrons bound inside atoms
  - Weak force
    - eg. responsible for certain radioactive decays (eg. β-decay)
  - Strong (nuclear) force
    - eg. holds nucleus together, overcoming Coulomb repulsion of the protons
  - Gravity
    - eg. keeps Moon in orbit around Earth, Earth in orbit around Sun, …



(actually, gravity is not included in the SM, but more about that later)

Problems with the SM

Success of the SM

- SM describes our experimental data very well, at typically % level
  - So, why are most physicists convinced it is NOT the final answer??
- For one thing, the SM has 19 free parameters which cannot be calculated, the values of which must be provided by experiment
  - This demonstrates that the SM is incomplete, but there are more problems:
- We do not understand the matter-antimatter asymmetry in the universe
- Gravity is not included in the SM
- We have not (fully) verified the SM explanation of particle masses

  (ie. does mass arise due to the Higgs boson, as proposed in the SM?)
- We do not know what makes up Dark Matter
- We do not know the nature of Dark Energy

Cosmological Connections

- Einstein's famous equation from Special Relativity

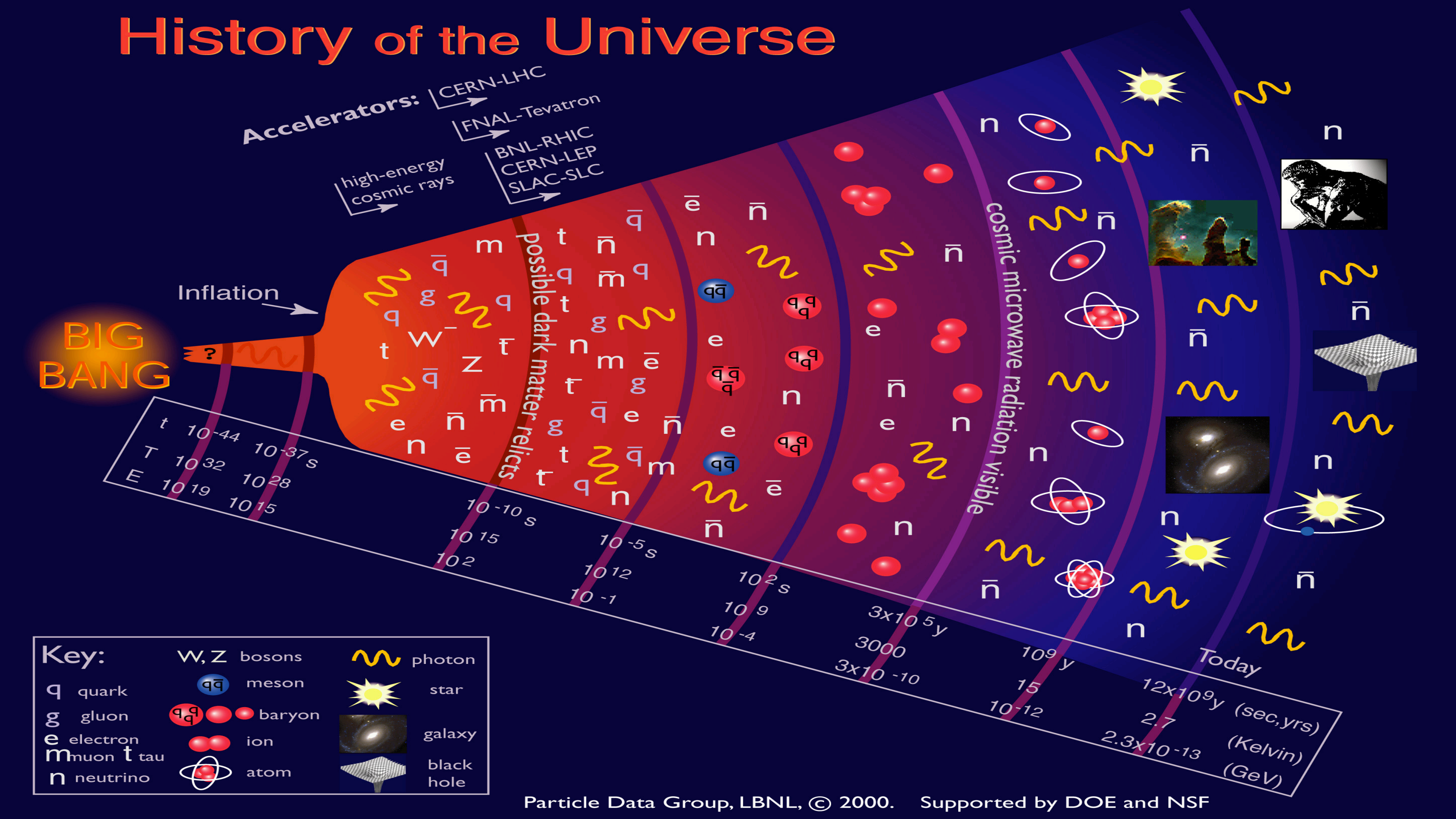
$$E = mc^2$$

tells us the mass (m) than can be created given a certain available energy (E)

- We know the universe started with the Big Bang, almost 14 billion years ago, and has been expanding (and cooling) ever since

- If we "run the film backwards", we see that the universe was hotter and hotter (more energetic) as we look back in time closer and closer to the Big Bang

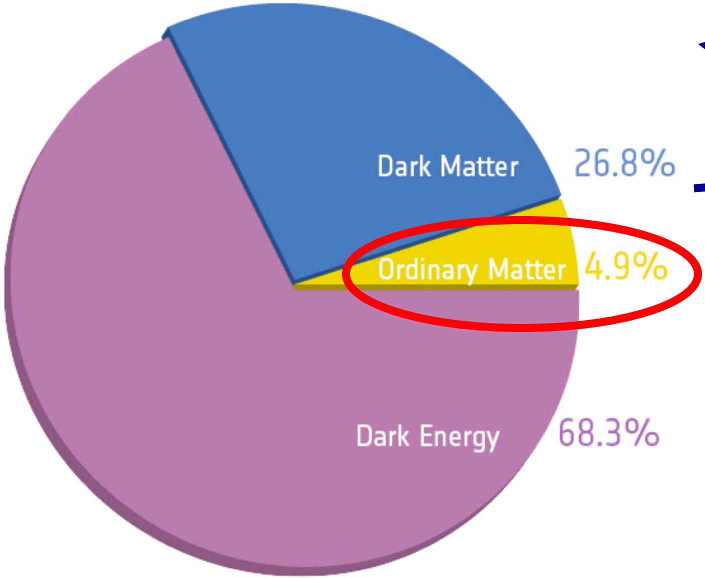
- The Big Bang was the ultimate particle accelerator!!
  - Studies of the entire universe as a whole and of its smallest building blocks are inextricably connected !!


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Our Universe

- Measurements of the cosmos tell us our universe is expanding and is 13.7 billion years old
  - Recent measurements tell us that the expansion of the universe is accelerating!!! (2011 Nobel Prize in Physics awarded for this discovery)

- The resultant picture of the energy content of the universe shows that it is DOMINATED by "Dark Energy"



Dark Energy: Something new and not understood, driving the accelerating expansion

Dark Matter: Some new form of (non-SM) matter

The "stuff" we (and everything we understand) is made of!

The “Dark Side”

- Dark Matter/Dark Energy contribute ~ 95% of the universe!
  - We understand VERY LITTLE about MOST of the energy of the universe!!

Dark Matter

- We have known for ~ 80 yrs that DM exists, but we still don’t know what it is
- DM is some new form of matter, NOT made of SM particles
- More speculative theories of particle physics, and in particular Supersymmetry (SUSY), include an ideal DM candidate, a Weakly Interacting Massive Particle (WIMP) with a mass of typically ~ 100-150 GeV
- By reproducing conditions of the early universe, we hope to be able to create and study DM particles in our experiment at the LHC

Dark Energy

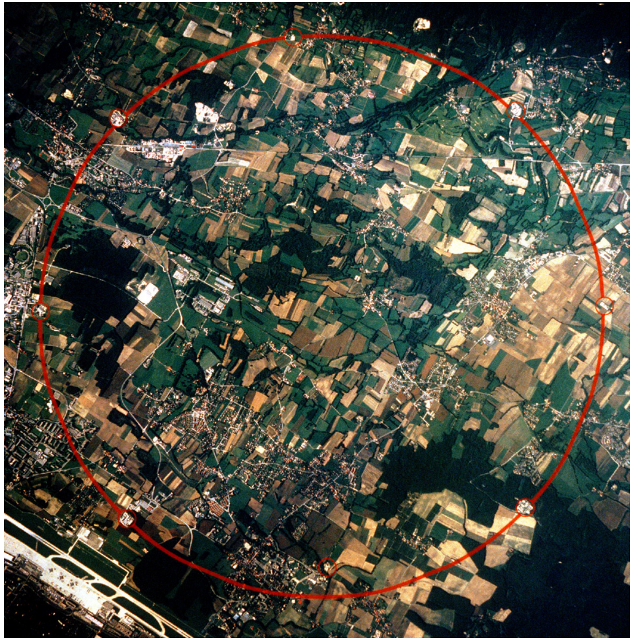
- Operates like a “pressure” to drive the accelerating expansion of the universe
- The SM gives an estimate of the amount of Dark Energy which is wrong by about 120 powers of 10 !!!! (ie. 10^{120})

The Origin of Mass

- During the development of the SM, a problem was encountered:
  - While experiments show that most fundamental particles (eg. electron) have non-zero masses, the theory seemed to work only for <u>massless particles</u>
- In 1964, a theoretical solution was found: the "Higgs Mechanism", which postulates existence of a "Higgs field" that permeates all of space
  - A necessary consequence of this <u>theoretical proposal</u> is the existence of an additional **particle**, the Higgs Boson
  - As with the other particles, the SM cannot predict the Higgs' mass
- For the past several decades, successive generations of experiments have sought evidence for the existence of the Higgs boson
  - For almost 50 years, expts succeeded only to rule out certain values of the Higgs' mass
  - The LHC (and ATLAS) were designed to be finally be able to either discover the Higgs boson, or to definitively rule out its existence

The Large Hadron Collider

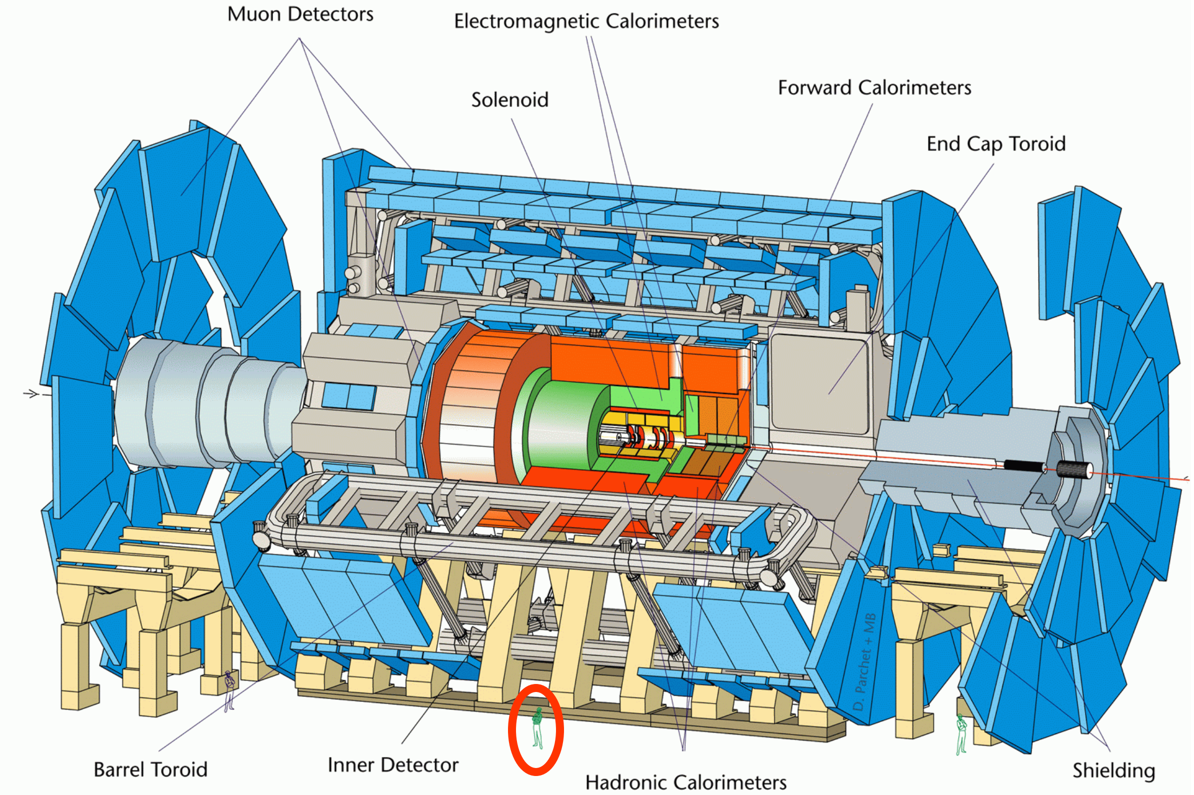
- The LHC at CERN is the world's most powerful particle accelerator
  - proton-proton collisions, with design CM energy of 14 TeV
- Built in a tunnel 17 miles around, about 100 yards underground, near Geneva, Switzerland
- Protons travel around ring 11,245 times per sec (with a speed of about 99.999999% x c)
- The counter-circulating proton beams are so intense that they produce ~ 1 billion pp collisions per second!



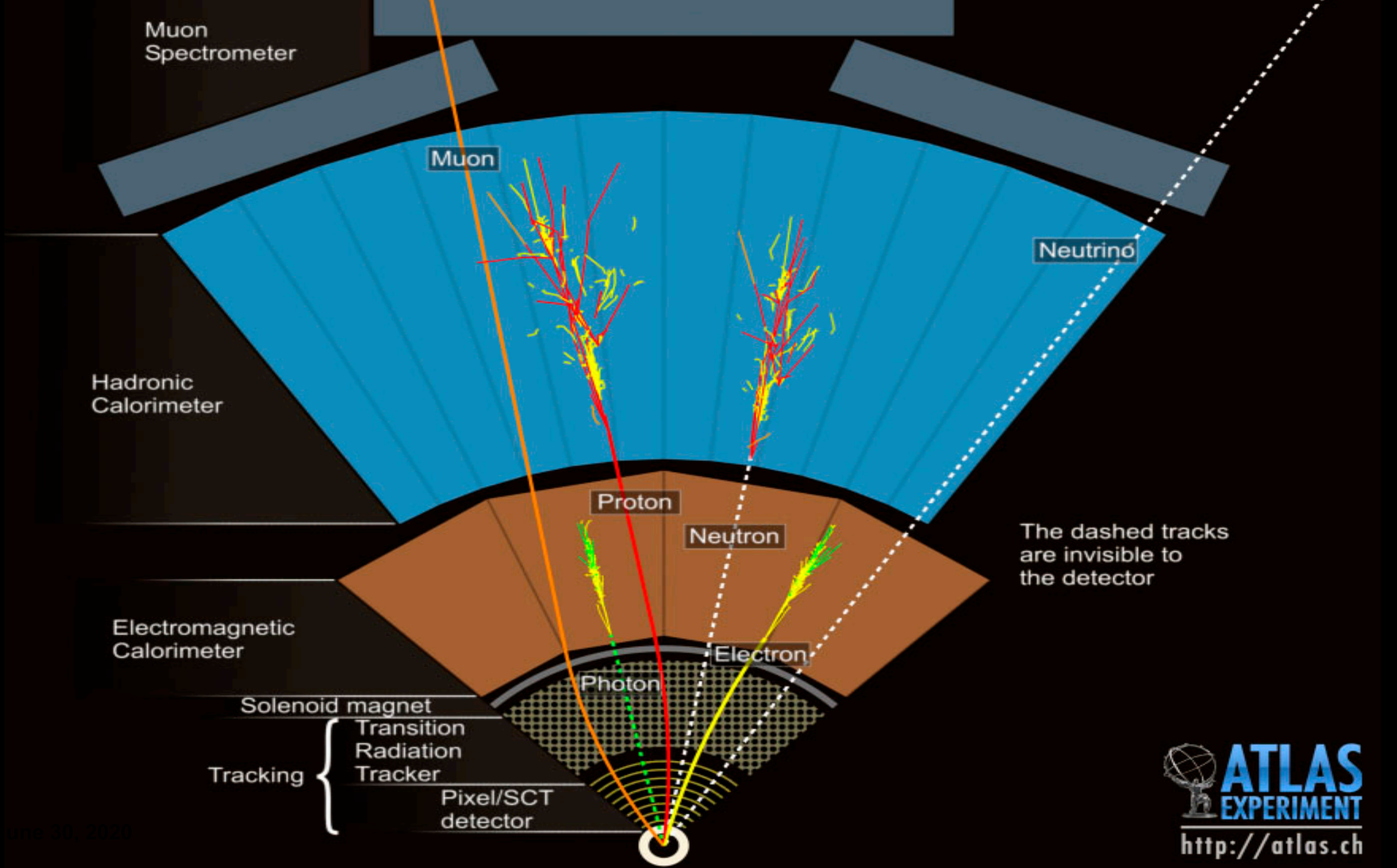
- Run 1 at LHC was 2010-2012, with operation at 7 and 8 TeV
- Run 2 of LHC was 2015-2018, with operation at 13 TeV
- Run 3 will start in 2021, after ongoing 2-year period of maintenance and upgrade


38 Countries
174 Institutions
3000 Scientists
1000 Students
ATLAS
Collaboration

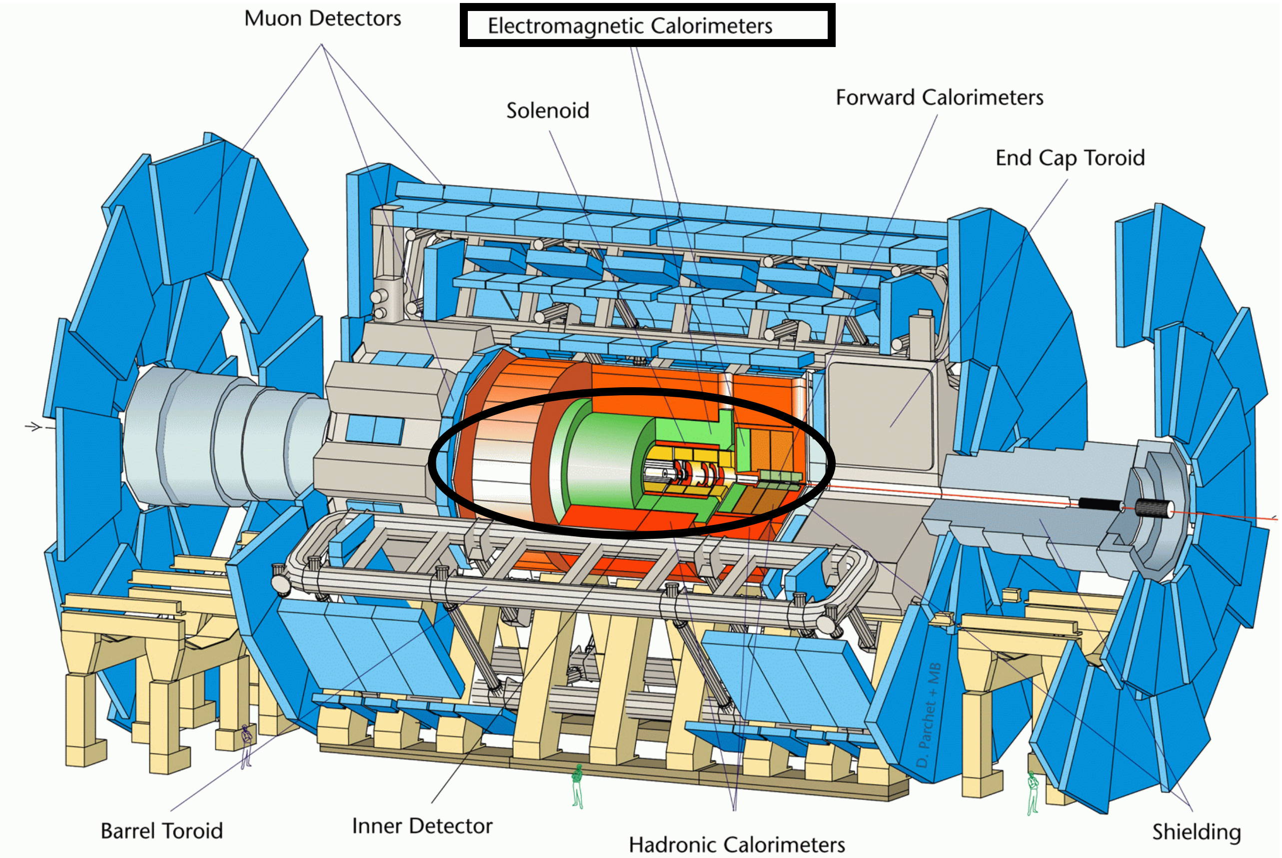
The ATLAS Detector



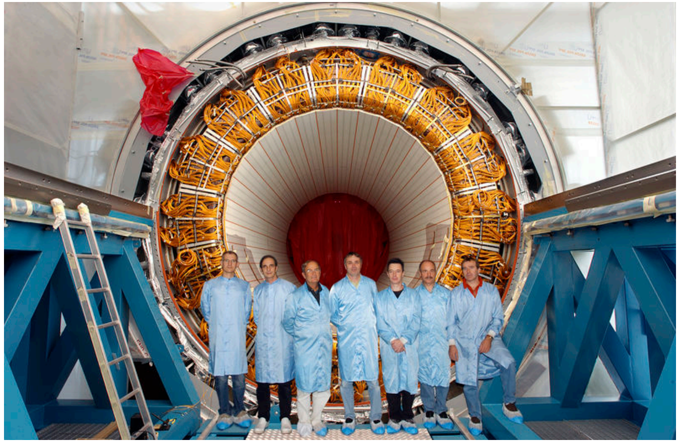
- **Overall length = 143 ft, diameter = 81 ft, weight = 7000 tons**

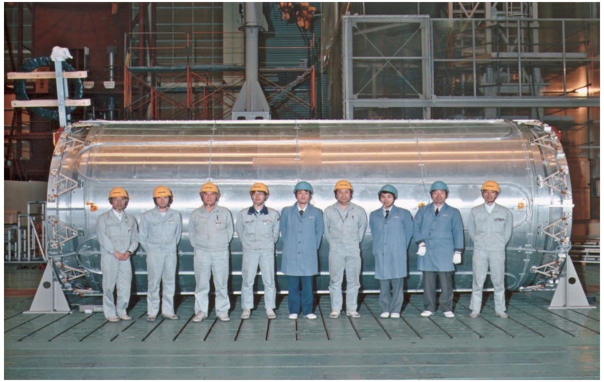

Muon
Spectrometer
Hadronic
Calorimeter
Electromagnetic
Calorimeter
Solenoid magnet
Tracking
Transition
Radiation
Tracker
Pixel/SCT
detector
Muon
Neutrino
Proton
Neutron
Electron
Photon
The dashed tracks
are invisible to
the detector
ATLAS
EXPERIMENT
http://atlas.ch

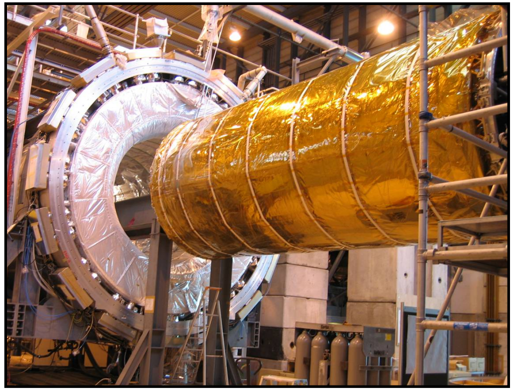
The ATLAS Detector



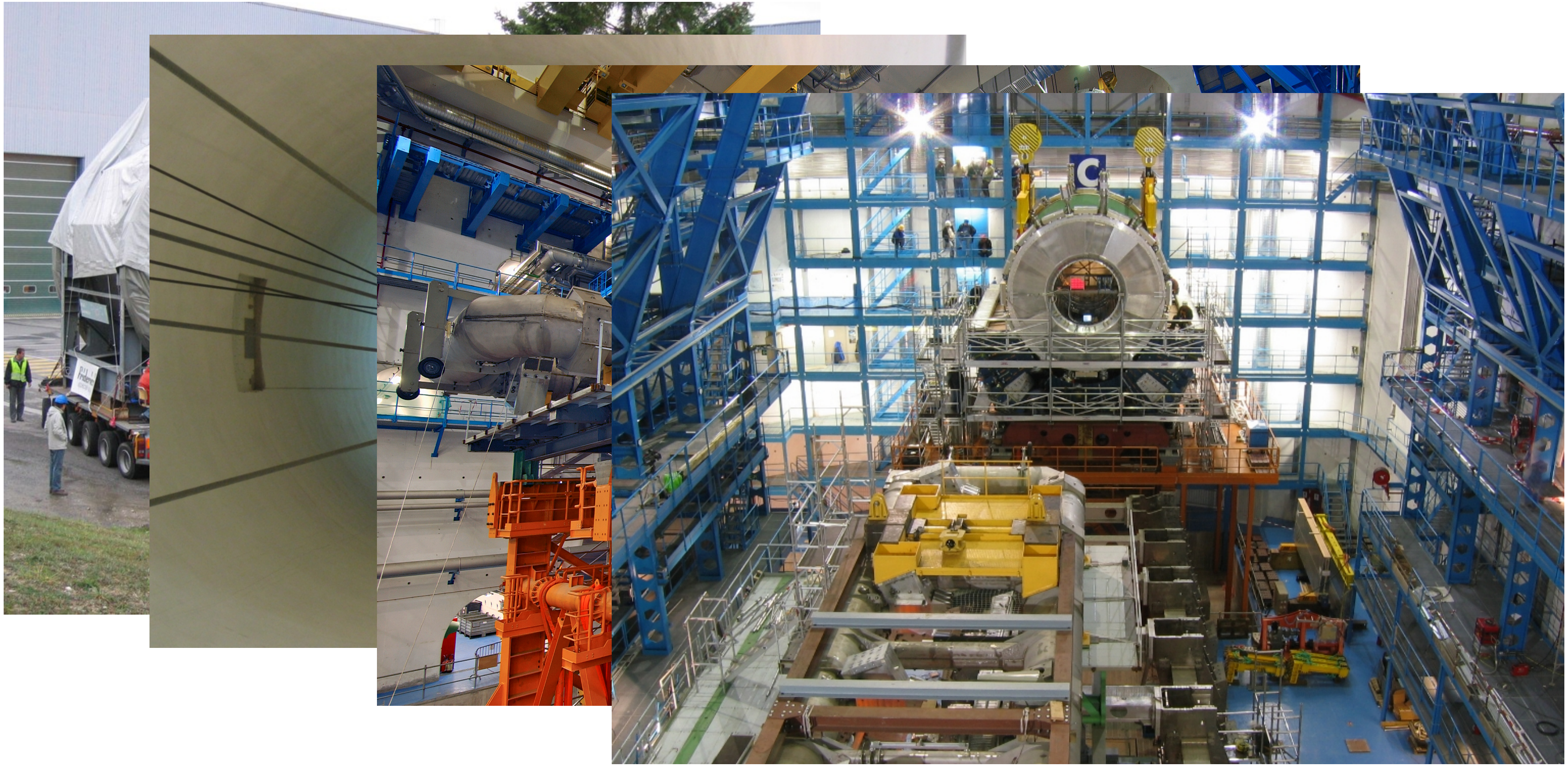
ATLAS Barrel Cryostat and Superconducting Solenoid



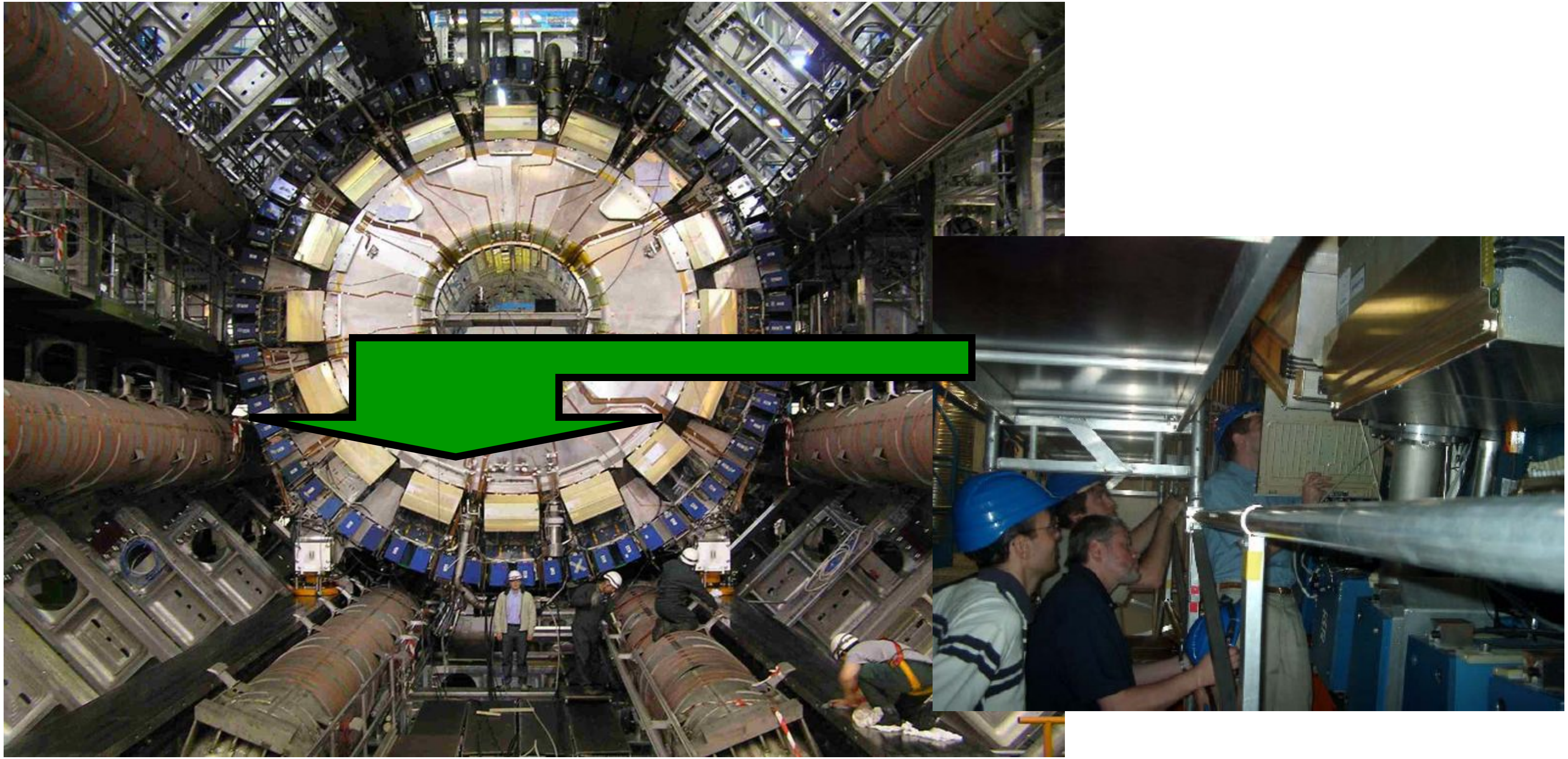




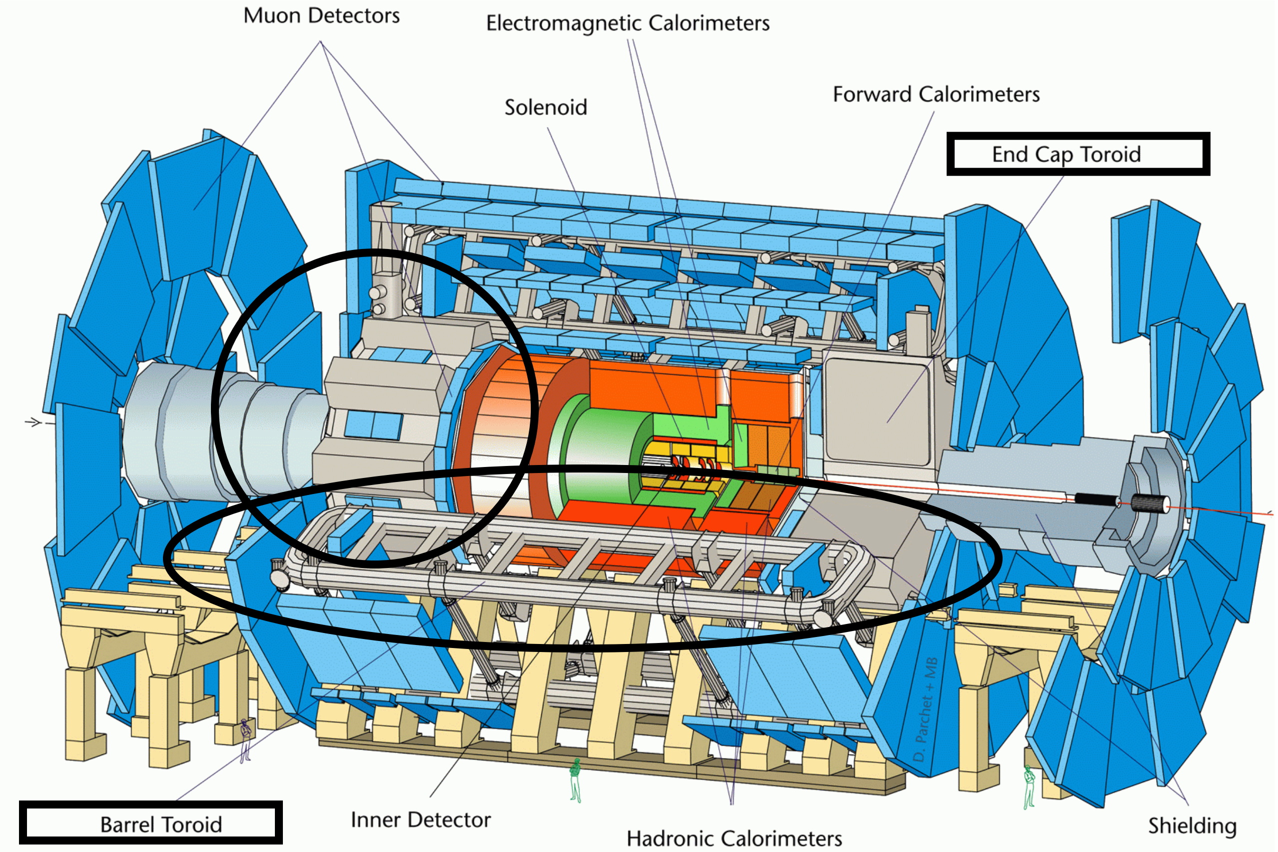
ATLAS Barrel Calorimeter Installation



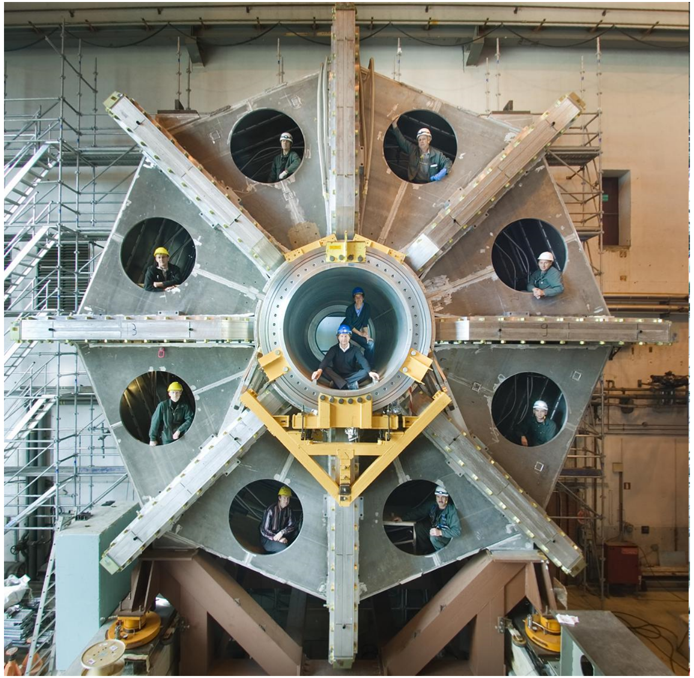
ATLAS Barrel Calorimeter Installation



The ATLAS Detector



ATLAS Toroidal Magnet System

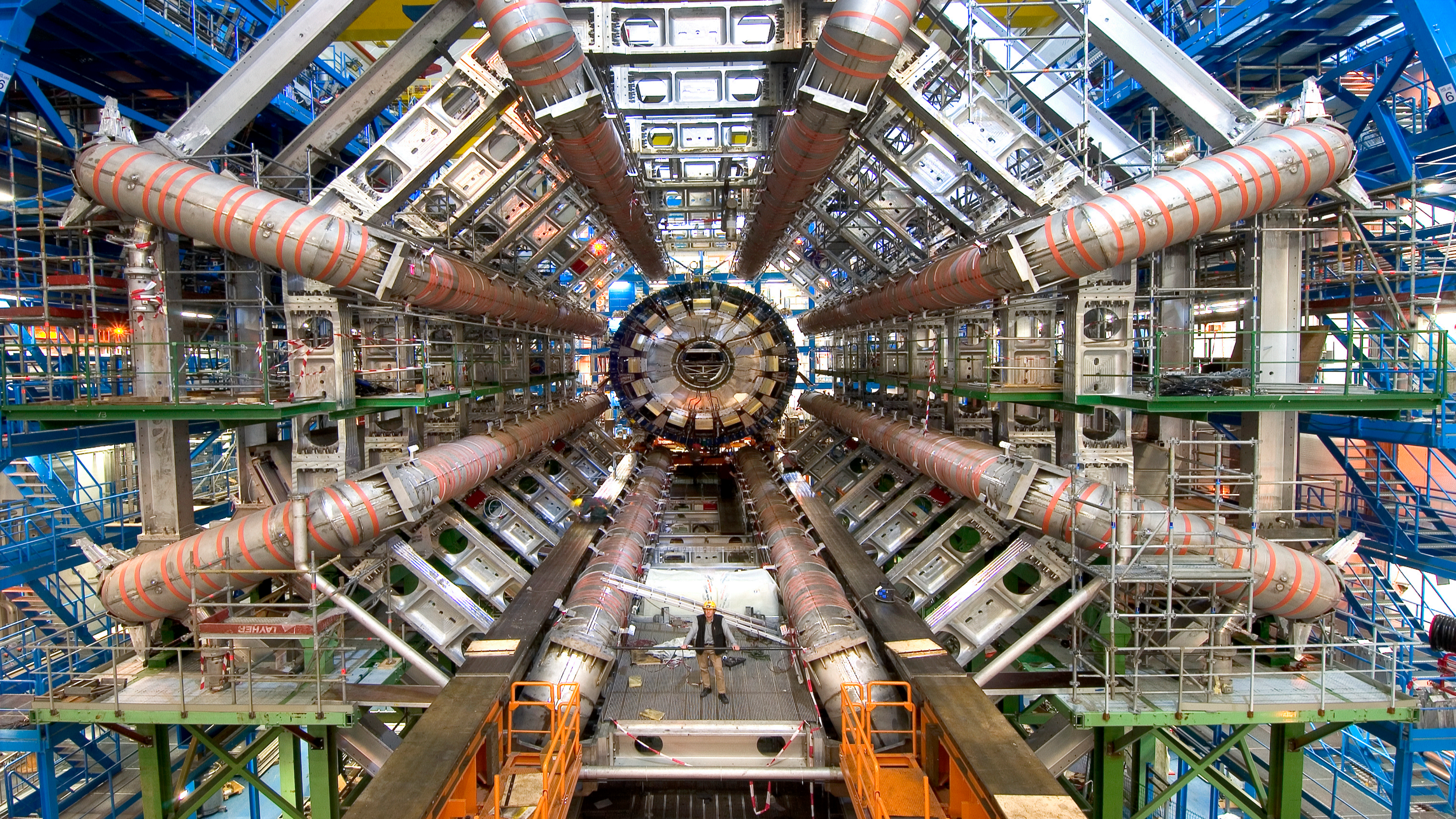


Endcap toroid

Barrel toroid

- 90 km of superconductor, 700 ton cold mass
- Total energy stored in magnetic field: 1.55 GJ

(equiv. to ~ 15 million light bulbs!)



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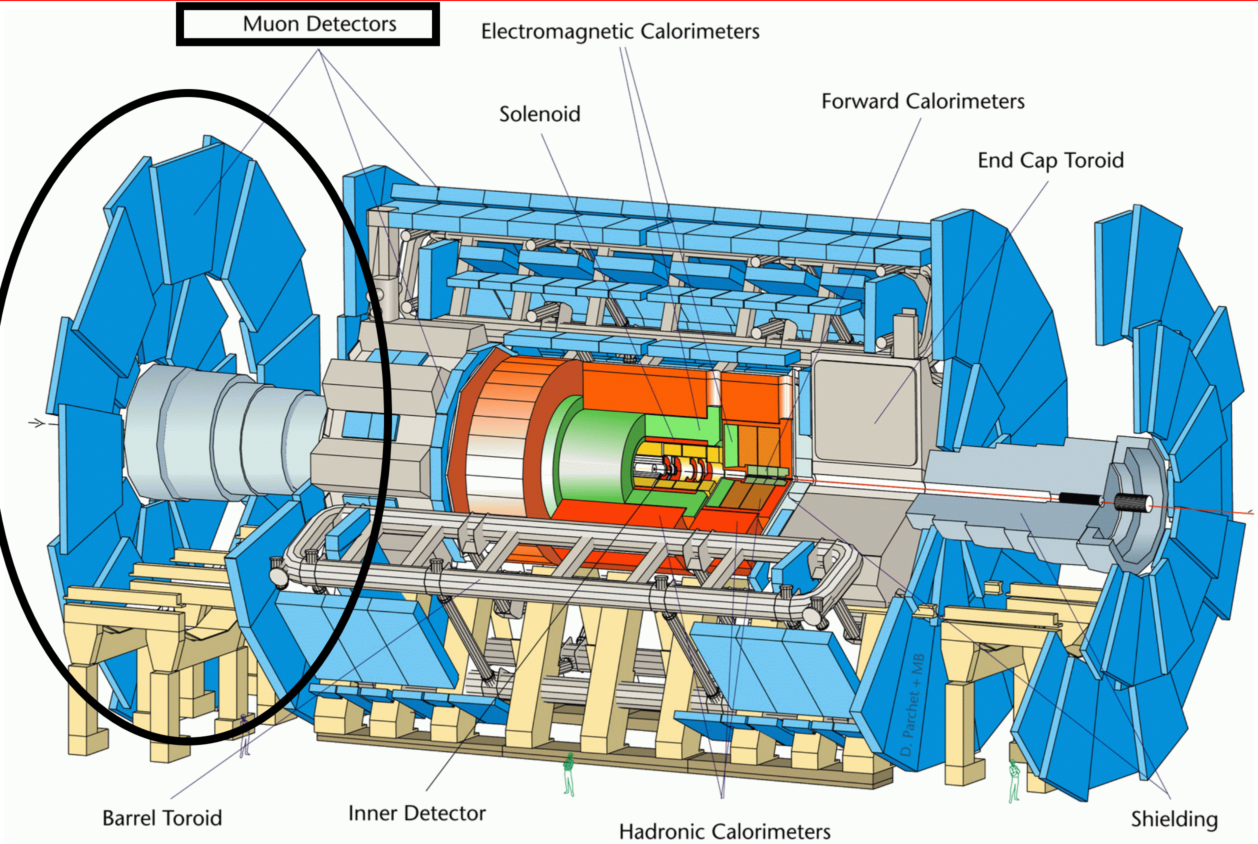
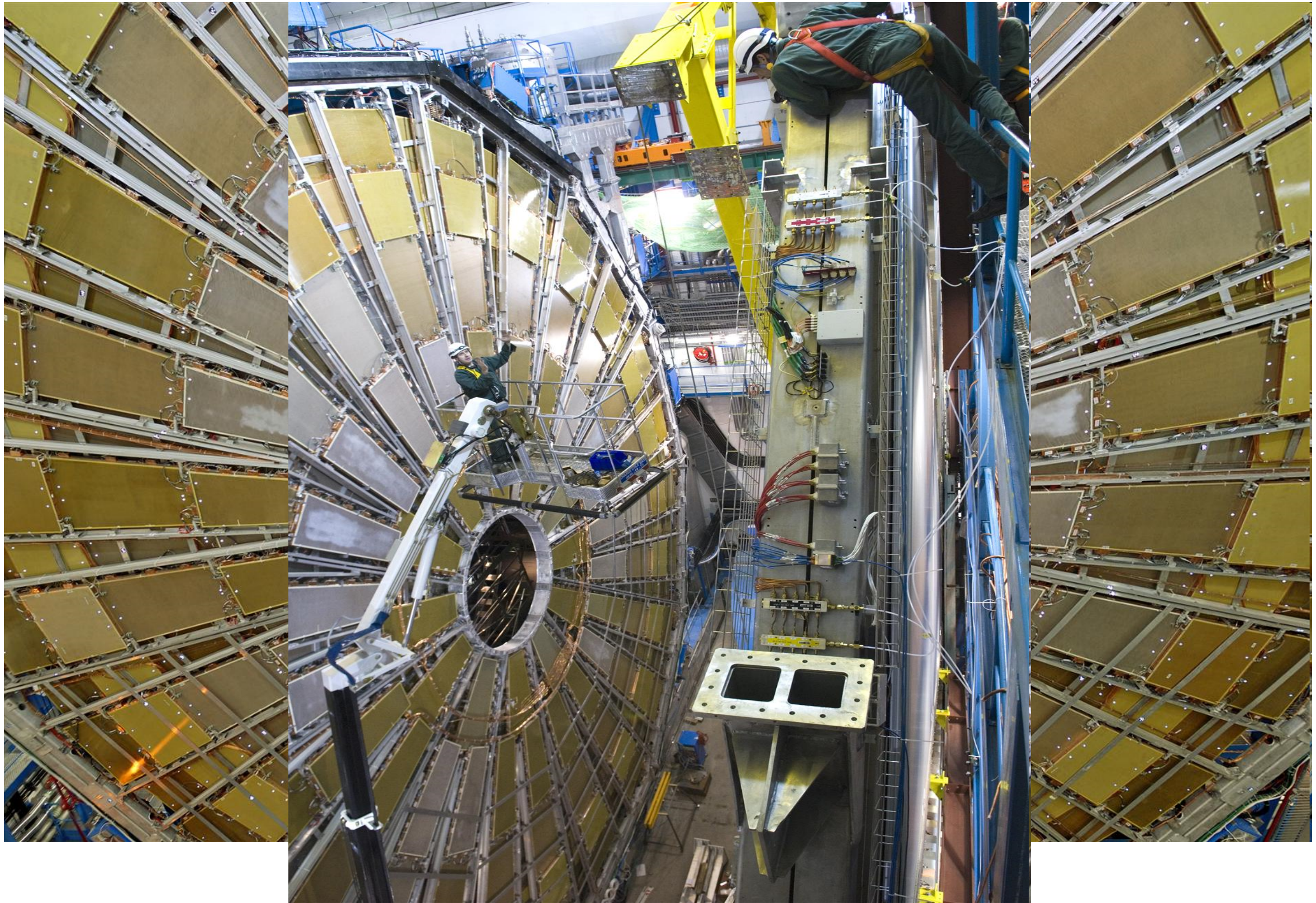


ATLAS Muon Spectrometer



Some Quick Facts About ATLAS

- ATLAS weighs 7000 tons
  - About same as the Eiffel Tower or 100 empty 747 Jumbo Jets
- The ATLAS detector includes ~ 100 million channels

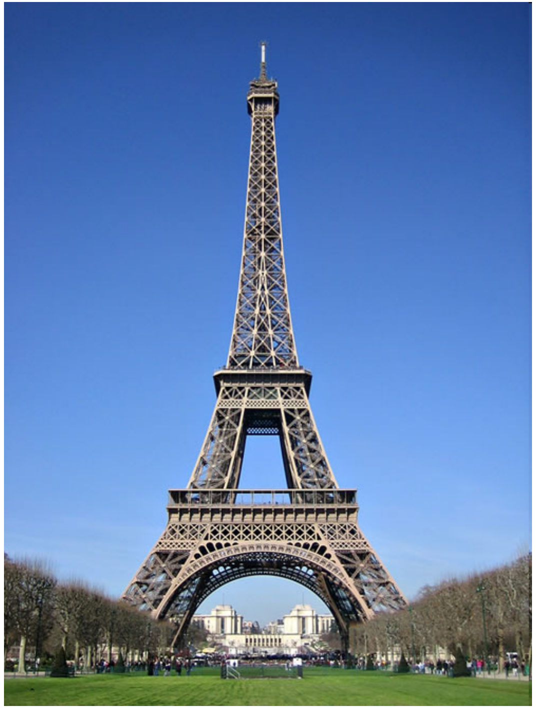
of readout electronics

- ATLAS records what happens in each of

  40 million bunch crossings per second

- The raw data from ATLAS is equivalent to 50 billion simultaneous telephone calls
  - We record only a fraction of the data, but still equivalent to approximately

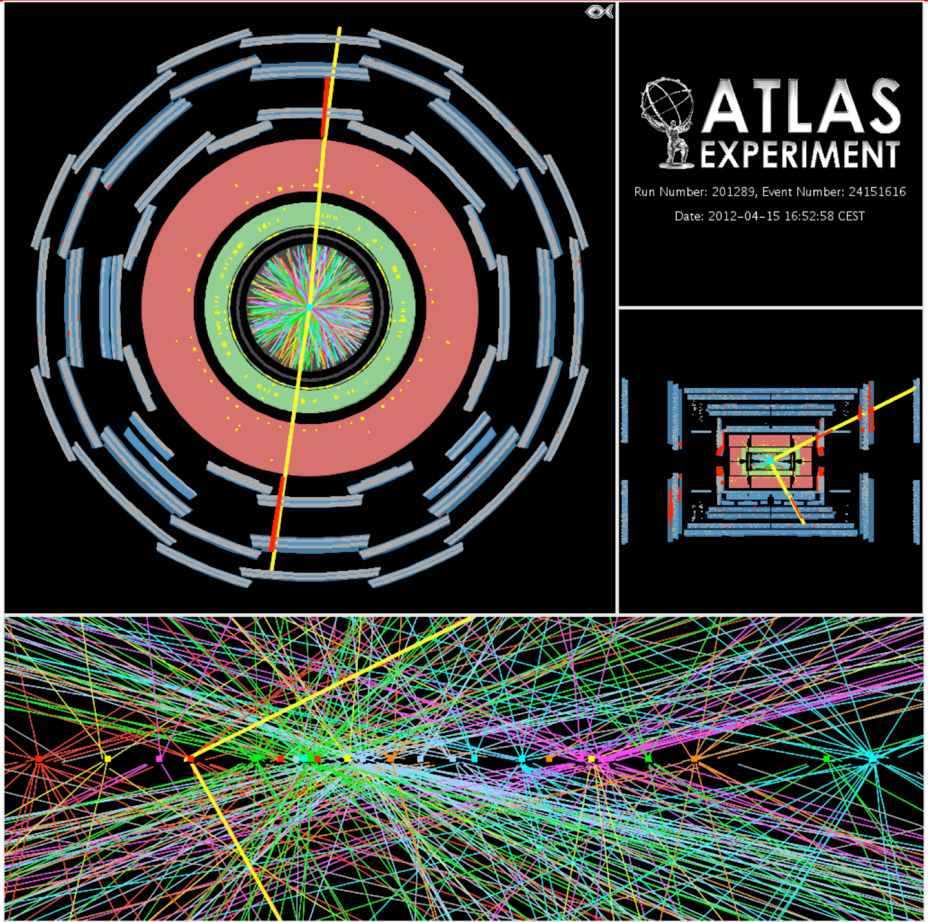
    27 CDs per minute (~ 100 km stack per year)

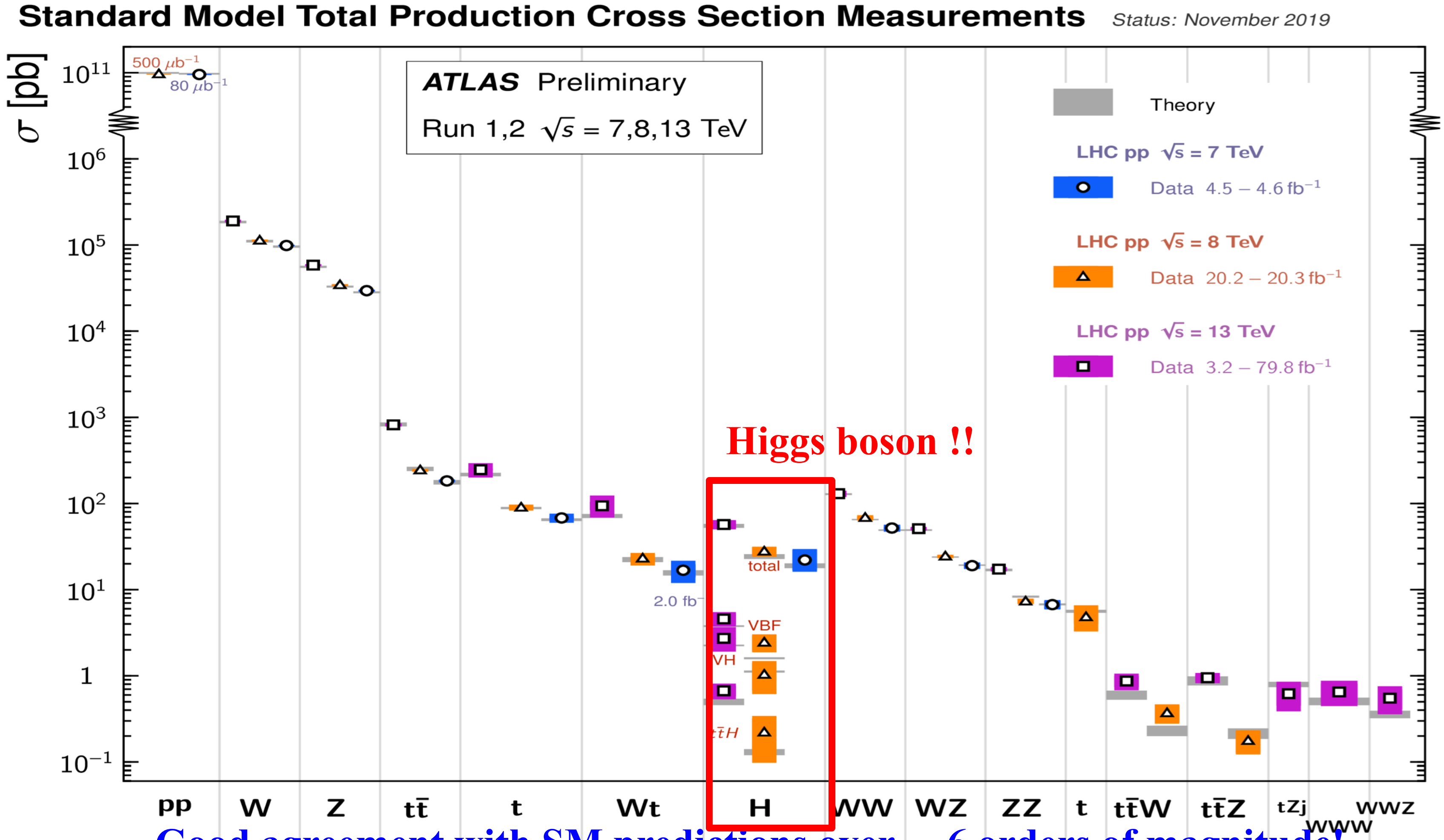


- In the Si tracker, ATLAS measures the position of passing charged particles with a precision equivalent to ~ 1/10 of the width of a human hair

Pileup in 2011/2012 Data!

Z → μμ event with the vertices of 25 separate and simultaneous pp collisions reconstructed !!

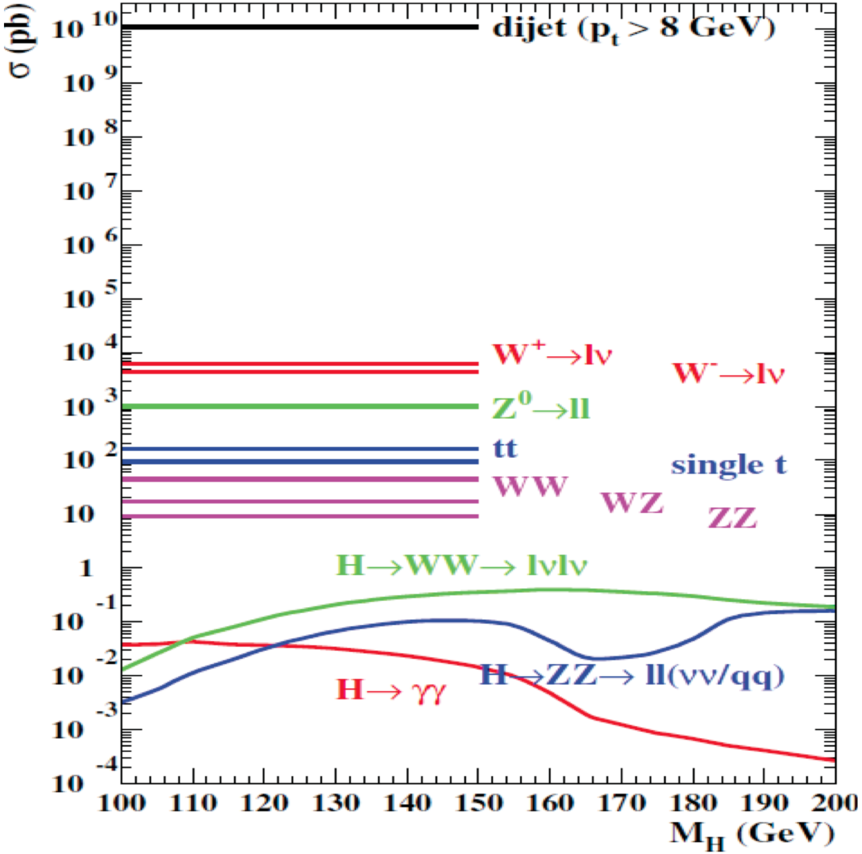




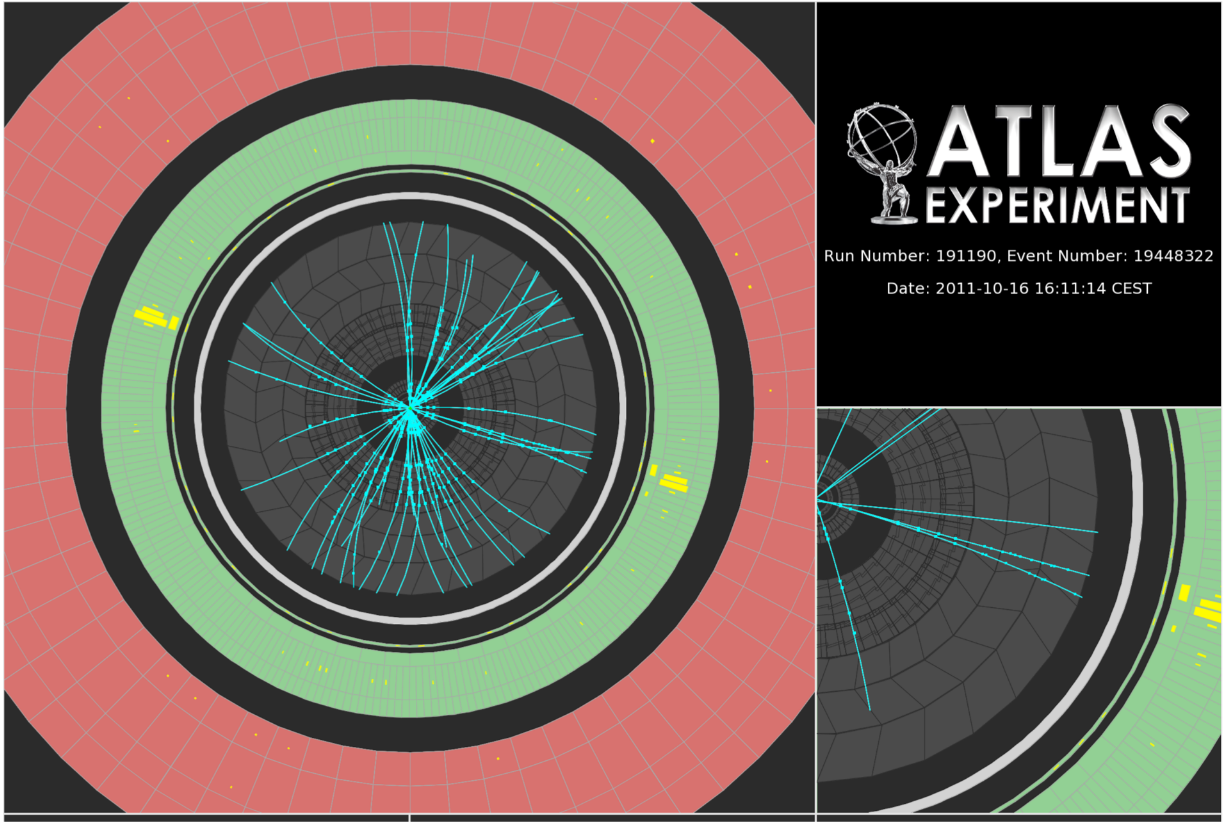
Good agreement with SM predictions over ~ 6 orders of magnitude!

The SM Higgs Challenge !

< 1 detectable Higgs boson
per 10^{12} collisions !



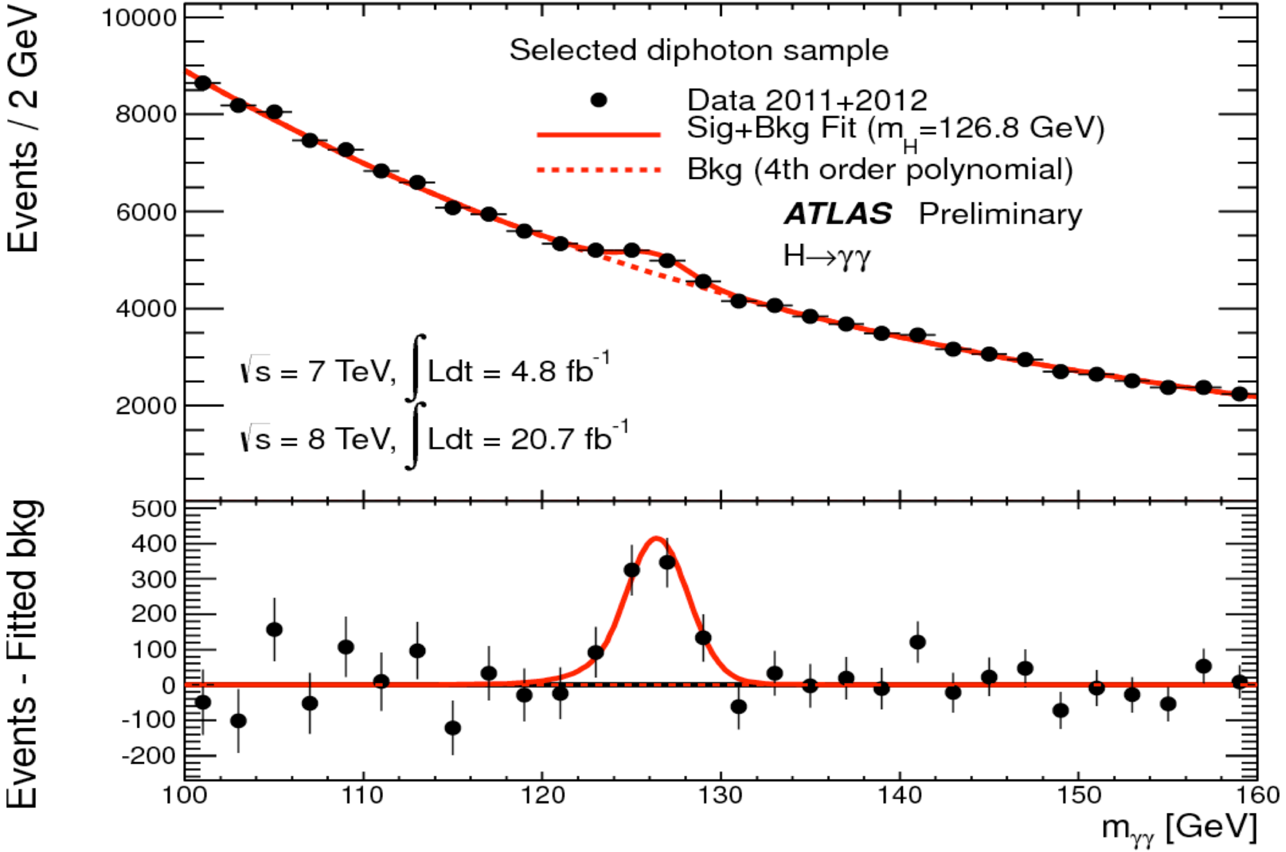
One H→ γγ Candidate Event



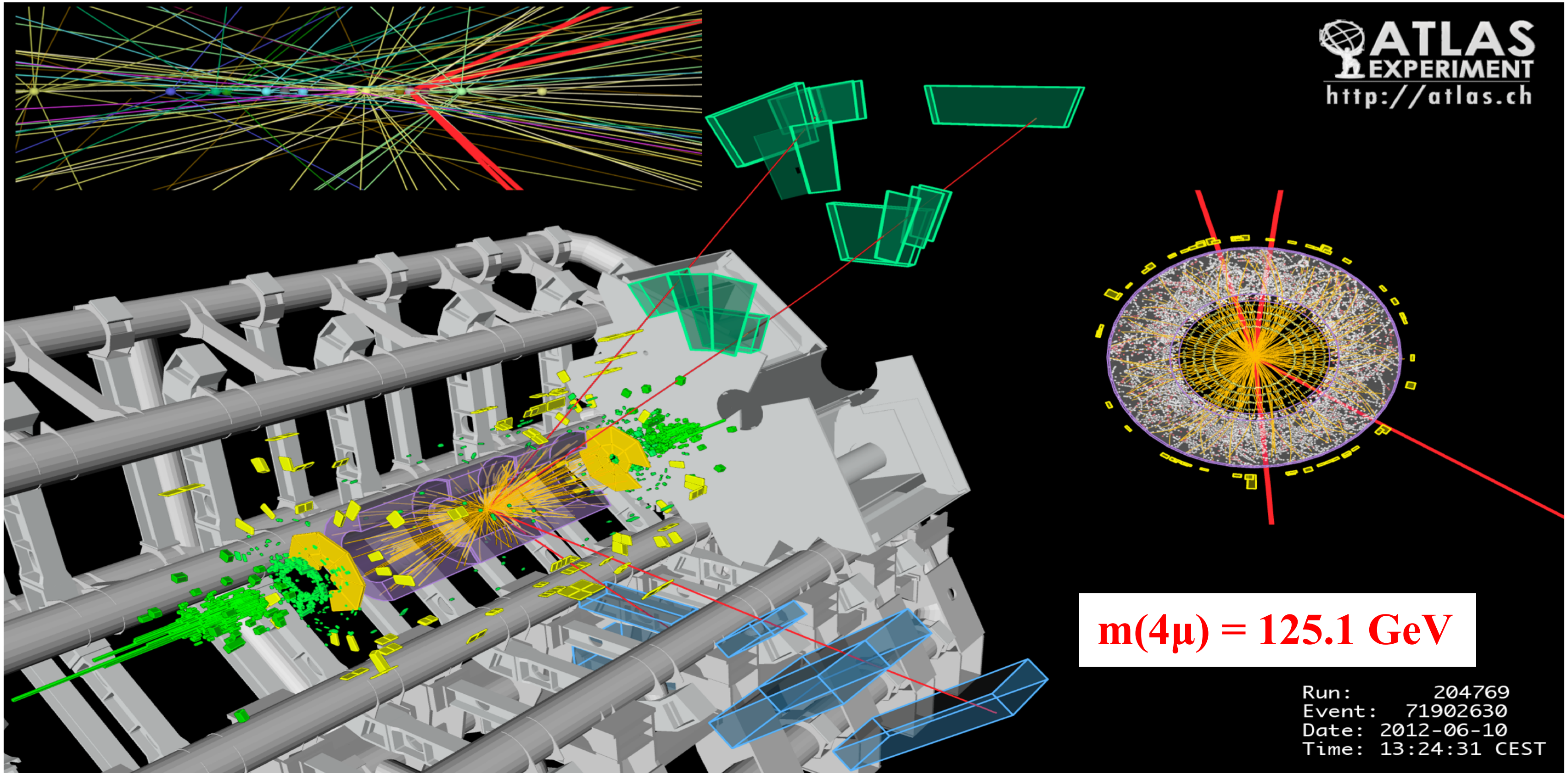
1 converted photon and 1 unconverted photon, with

m(γγ) = 125.8 GeV

$H \rightarrow \gamma\gamma$ Mass Spectrum

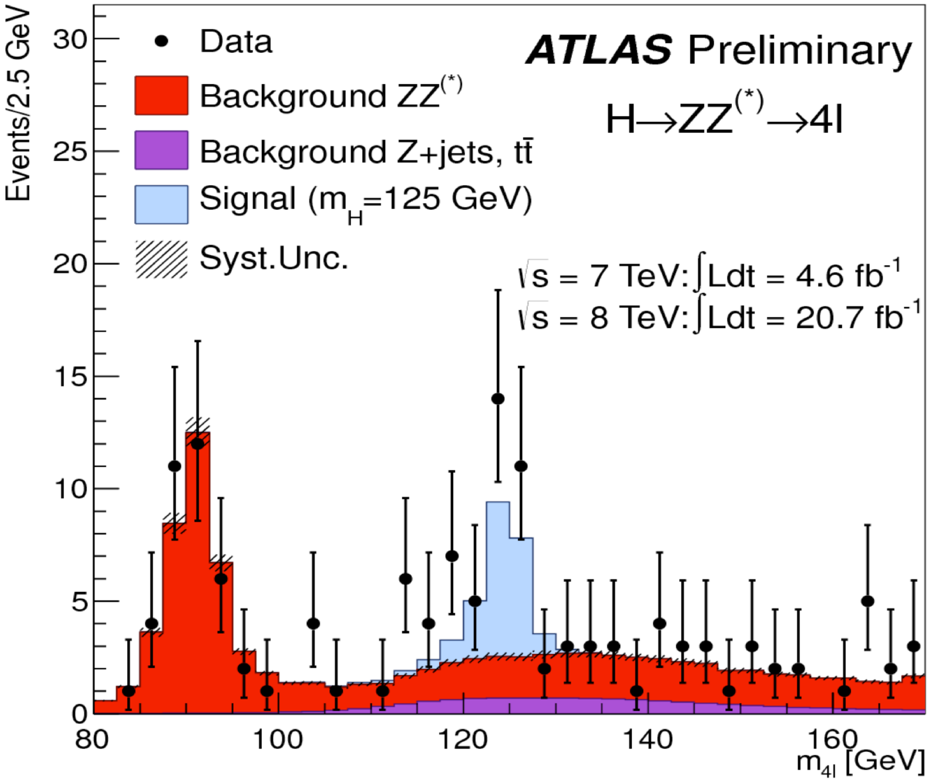


$H \rightarrow ZZ^* \rightarrow \mu\mu\mu\mu$ Candidate



$H \rightarrow ZZ^{(*)} \rightarrow ll\ ll$

- Very clean, “golden channel”
  - Has very low backgrounds, but signal statistics is also low

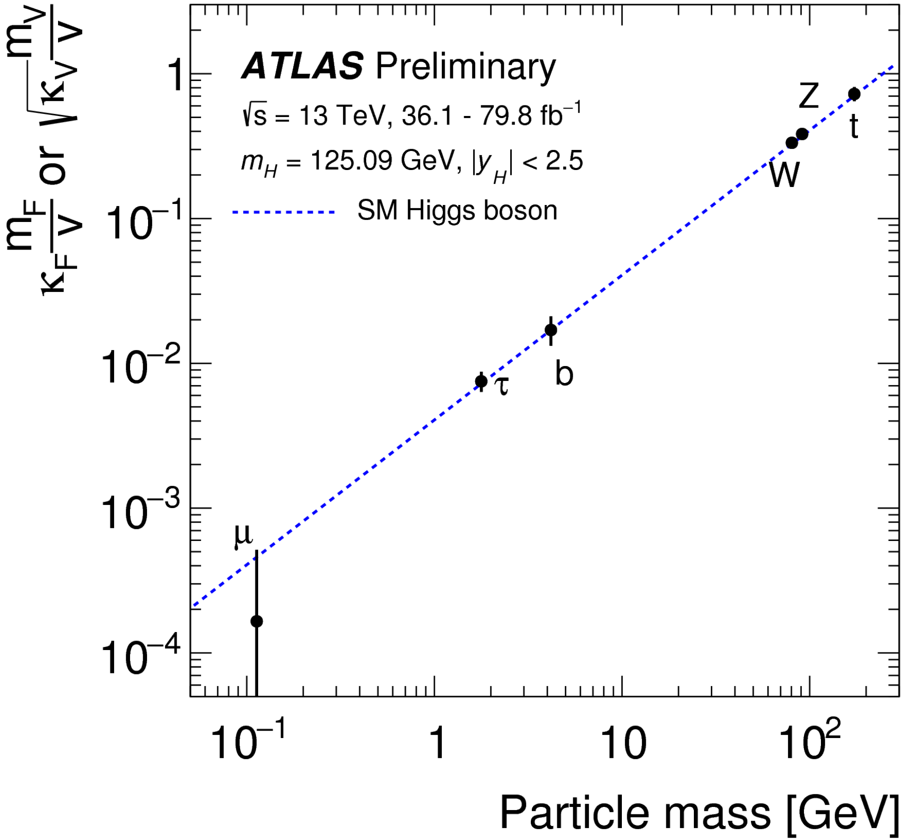


2013 Nobel Prize in Physics

- **Higgs boson discovery was announced at CERN on July 4, 2012 by ATLAS and CMS expts**
- **Subsequently, 2013 Nobel Prize in Physics was awarded to Peter Higgs and Francois Englert**

"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"

Higgs Boson Connection to Particle Mass



Searches for Beyond SM Physics

- Need to measure more precisely the properties of the new particle, and check if it behaves (exactly) as predicted for the SM Higgs boson
  - We can use the Higgs boson as a new window on possible BSM physics
- In addition, while the Higgs boson answers one very important question (the origin of mass), the SM (even with the Higgs boson), leaves MANY other questions unanswered:
  - What is Dark Energy?
  - What makes up Dark Matter?
  - How to include gravity? (string theory??)
  - What explains the matter-antimatter asymmetry of the universe?
  - etc.
- Answering these questions will require discovery of something new
  - We continue to search for direct evidence of BSM physics
    - New particles? New forces? Additional spacetime dimensions? …

Summary and Outlook

- LHC Run 1 (2010-2012), with center-of-mass energies of 7-8 TeV was VERY successful!
  - Discovery of a Higgs Boson (leading to awarding of 2013 Nobel Prize in Physics)
  - Huge extensions of explored regions for BSM physics, placing significant constraints on a enormous variety of models
- Analysis is ongoing of large data set from LHC Run 2 (6/2015 – end 2018), operating at record energy of 13 TeV!
  - We are entering the era of "precision" Higgs boson measurements, looking for discrepancies wrt SM prediction that could shed light on new physics
  - In addition, we are extending to higher mass scales the search for BSM physics
- Plans for future LHC upgrades will extend dataset by an additional factor > 20 !
  - We hope to make further discoveries to enable a deeper understanding of profound mysteries about the nature, history and future of the universe

Get more info (and watch for updates) at http://atlas.ch