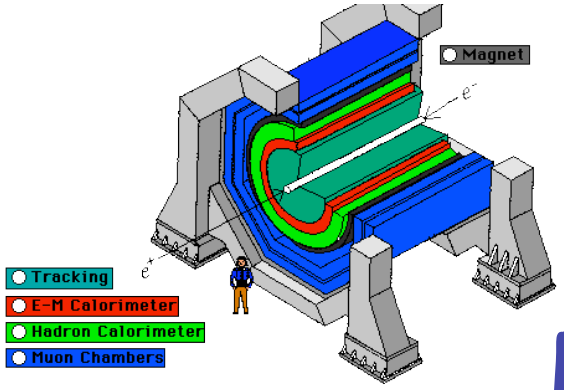
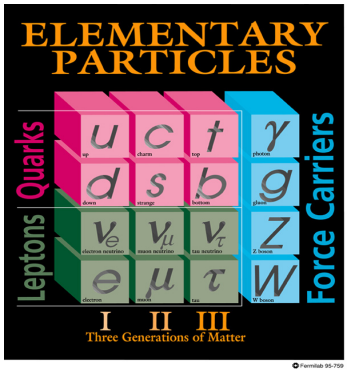




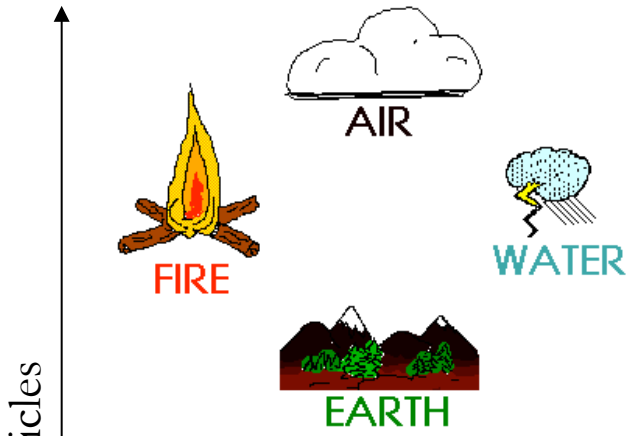
Physics at the High Energy Frontier

Eva Halkiadakis
Rutgers University

New Jersey Science Convention
October 14, 2008

Deep thoughts of a particle physicist

What are the Building Blocks of Nature?

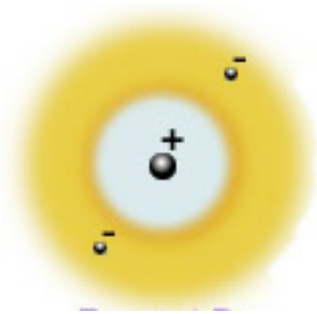


"Fundamental" Particles

Time

The term "atom" is a misnomer!

Are protons and neutrons fundamental?

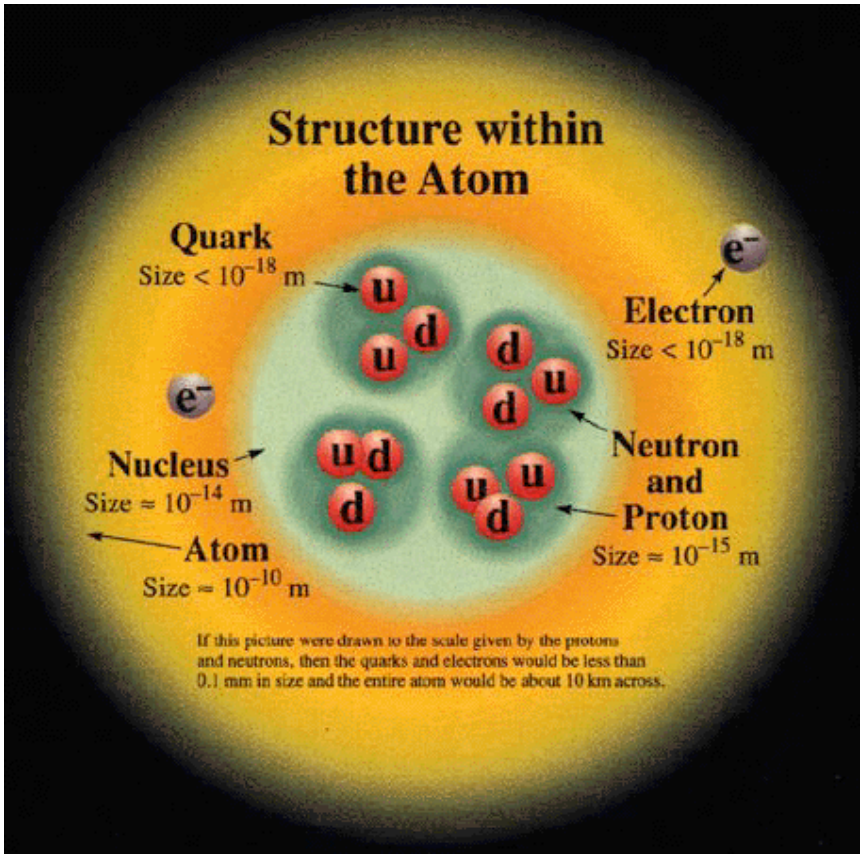


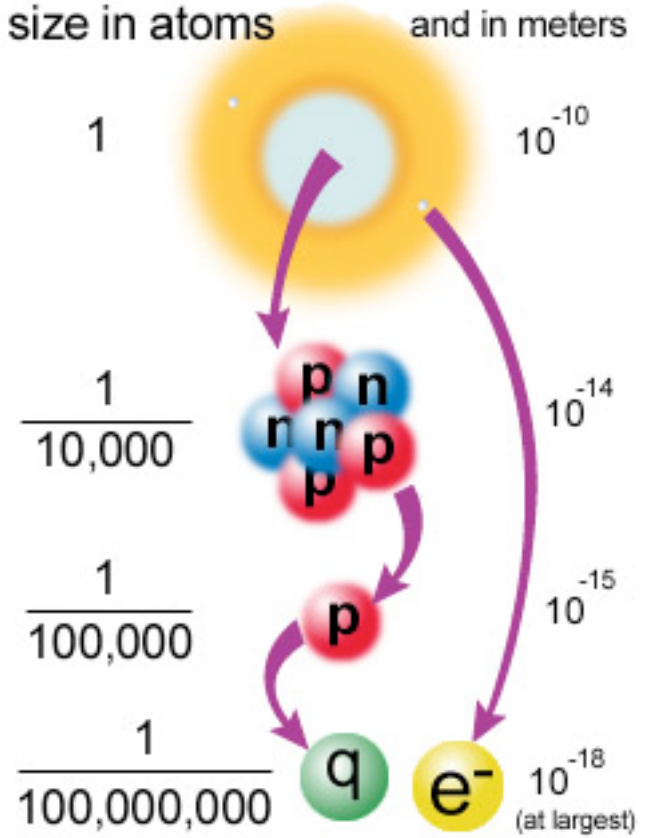
Fundamental Particles

- Physicists have discovered that protons and neutrons are composed of even smaller particles called ***quarks***.

- As far as we know, quarks are like points in geometry. They're not made up of anything else.
- After extensively testing this theory, we now suspect that quarks and the electron (and a few other things) are fundamental.

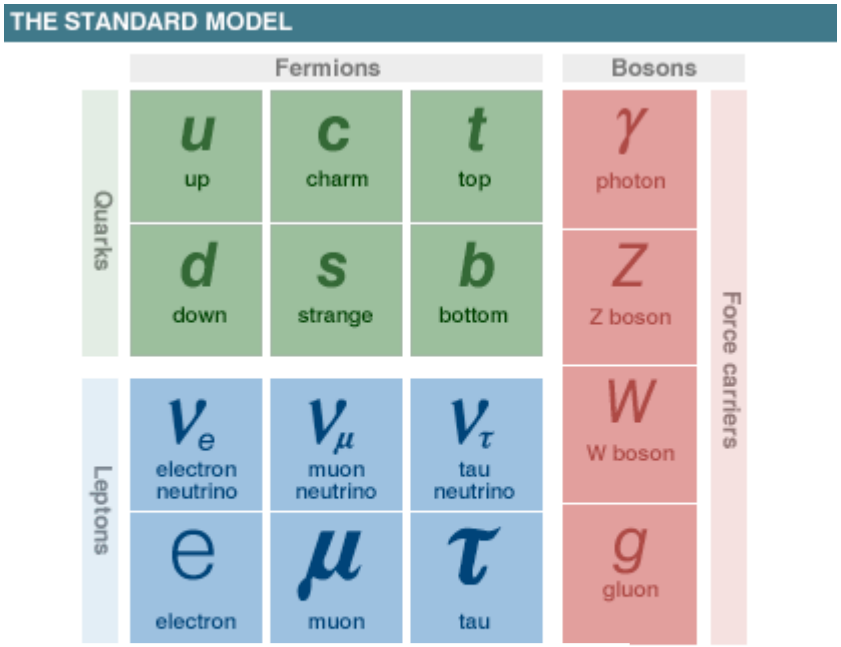
Scale of the atom





The Standard Model

- The Standard Model explains what the world is and what holds it together.
- It is a simple and comprehensive "theory" that explains all the hundreds of particles and complex interactions with:
  - 6 quarks
  - 6 leptons (The best-known lepton is the electron)
  - Force carrier particles (like the photon!)
- All the known matter particles are composites of quarks and leptons, and they interact by exchanging force carrier particles.
- Experiments have verified predictions of the Standard Model to incredible precision, and all the particles predicted by this theory have been found.
  - But it does not explain everything. For example, gravity is not included in the Standard Model.



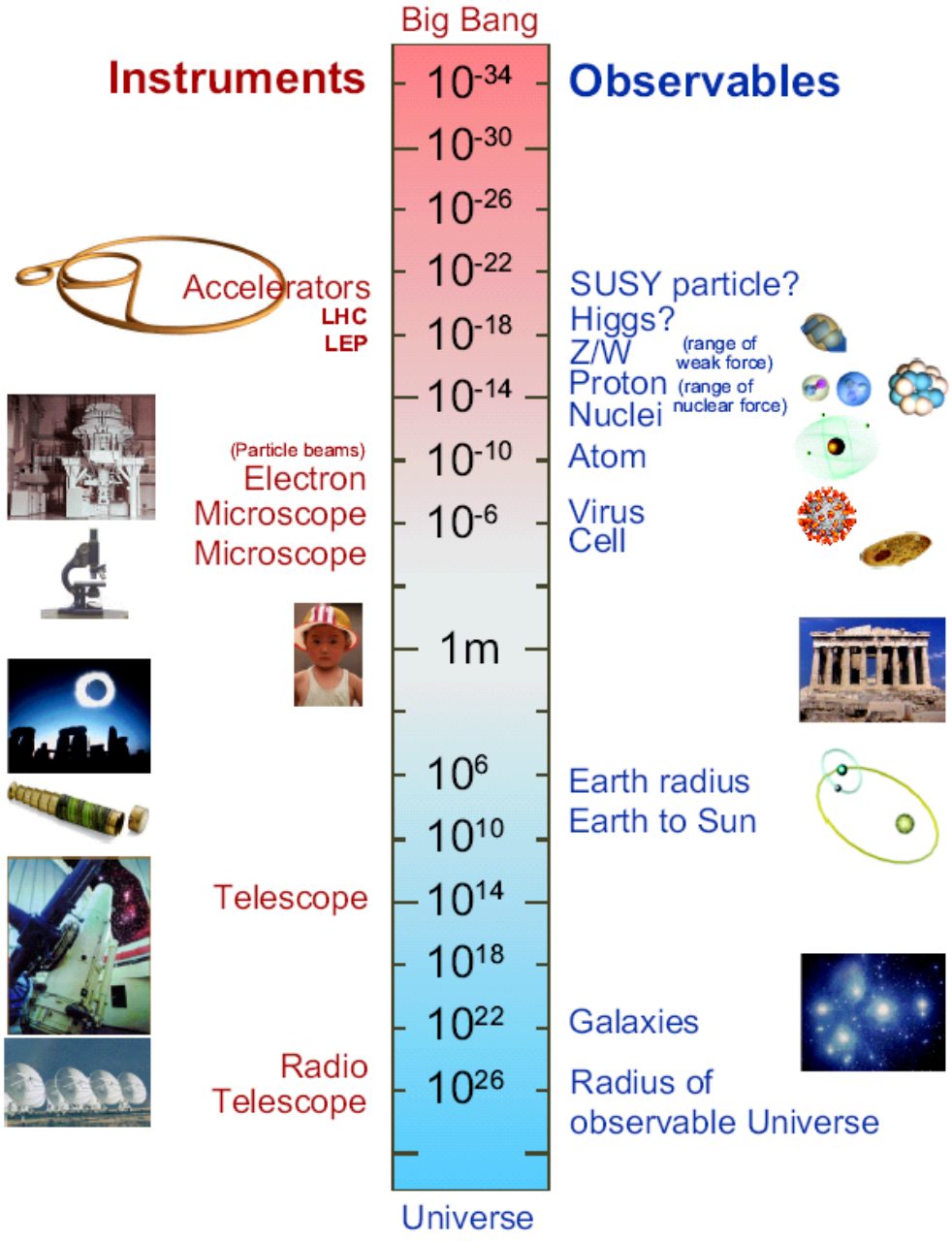
Plus all the anti-matter

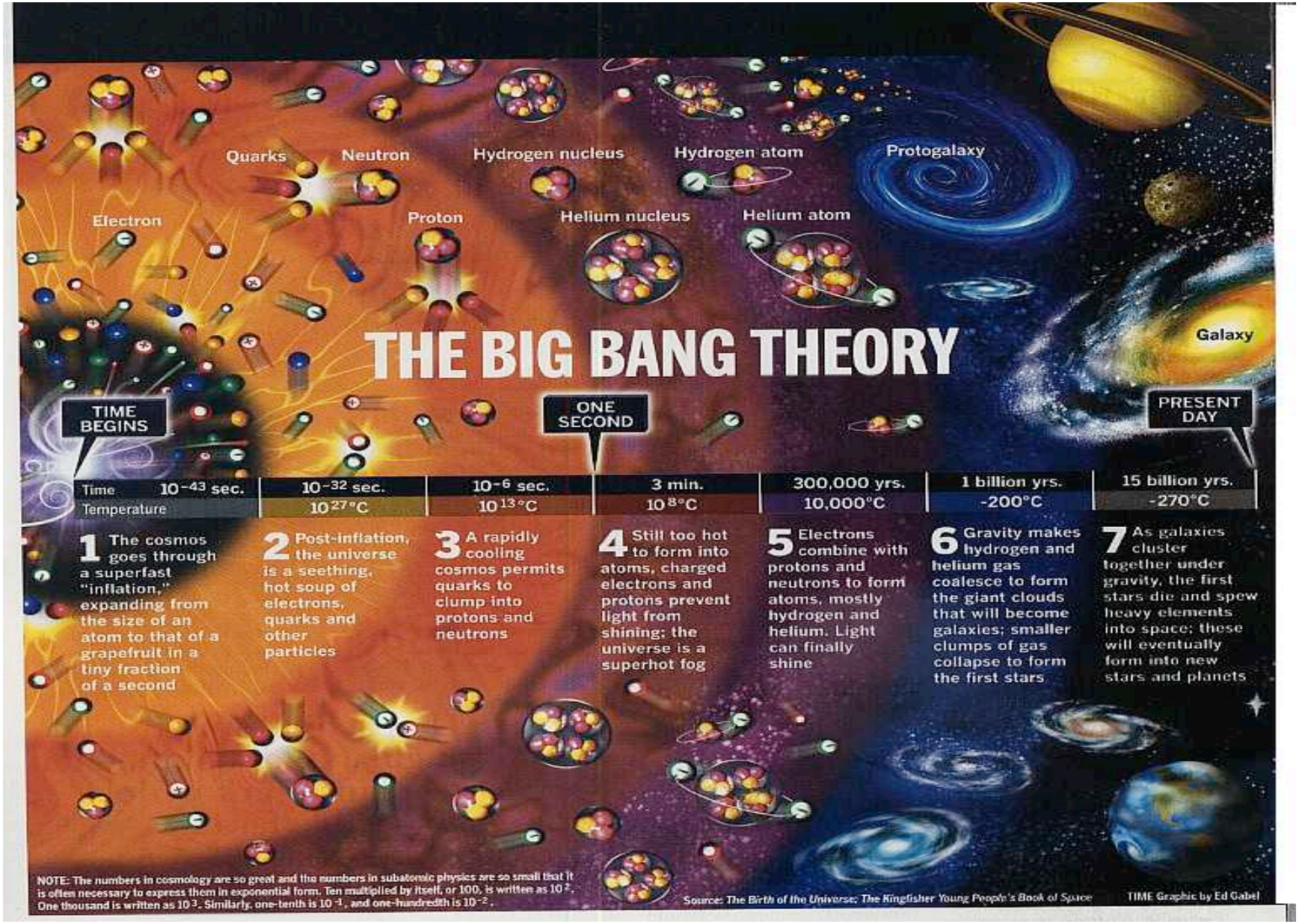
Source: AAAS

We need large tools to see small things!

In collisions involving high energy particles, some of the incoming energy can be used to create new particles.

$E=mc^2$ means energy can be transformed into mass.





Time (or higher and higher energies)

Remember this guy …

The Primitive thinker

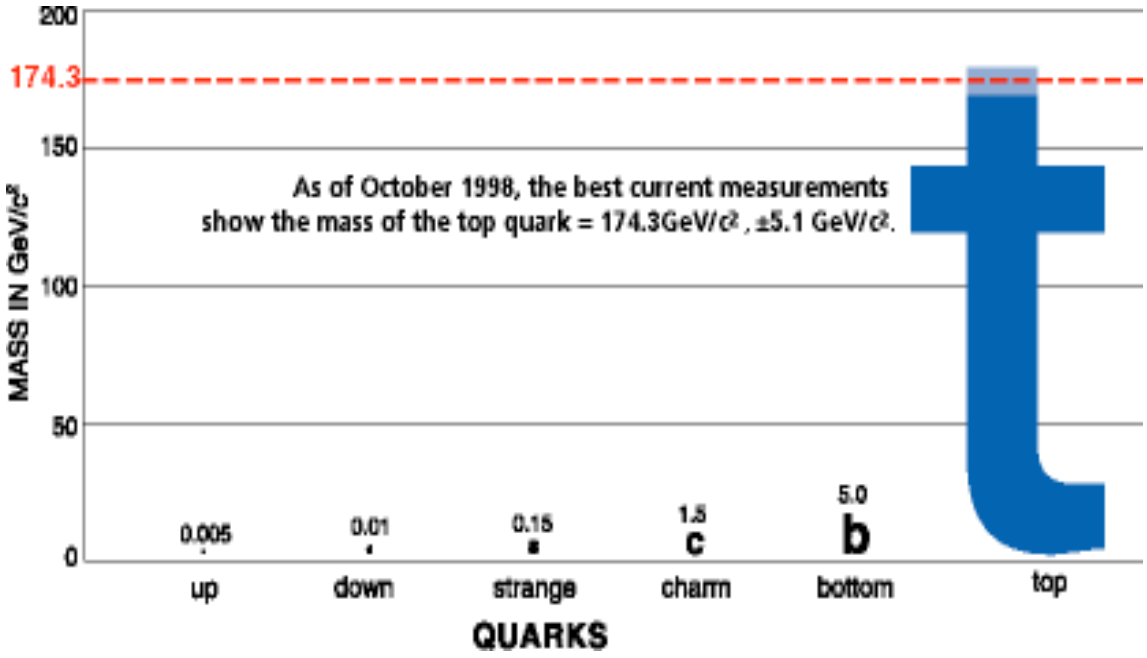
Unsolved Mysteries

- Why are there exactly three generations?
- Are quarks and leptons actually fundamental?
- Why is there a large variation in masses?
- Why is there almost no anti-matter in the universe?
- How does gravity fit into all of this?
- What is this invisible dark matter?

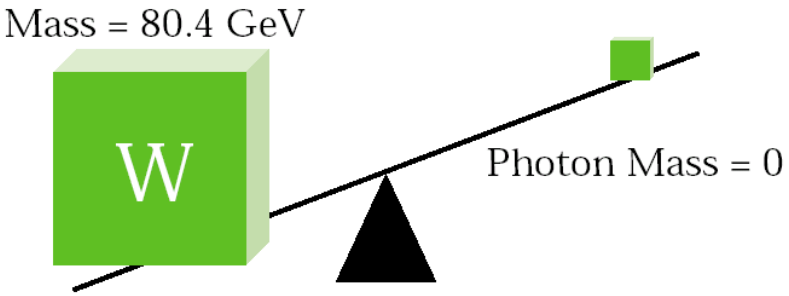
The Evolved thinker …..

The Riddle of Mass

Why is there a hierarchy of masses?



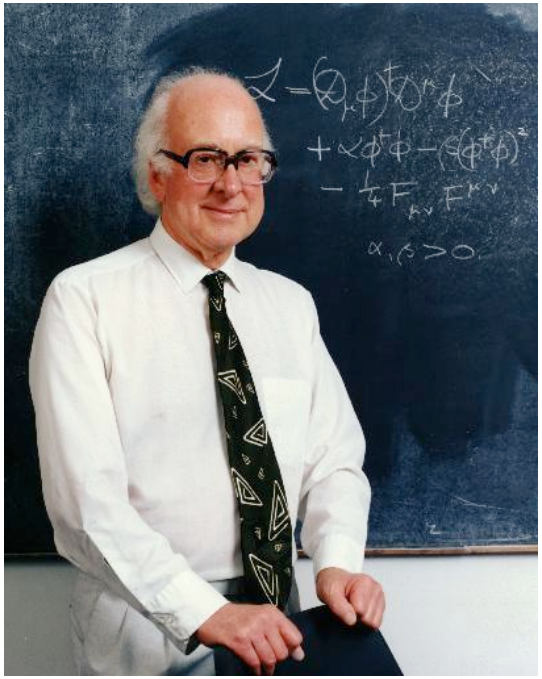
5 orders of magnitude between quark masses!



The Higgs Mechanism

Physicists have theorized the existence of the so-called ***Higgs field***, which in theory interacts with other particles to give them mass.

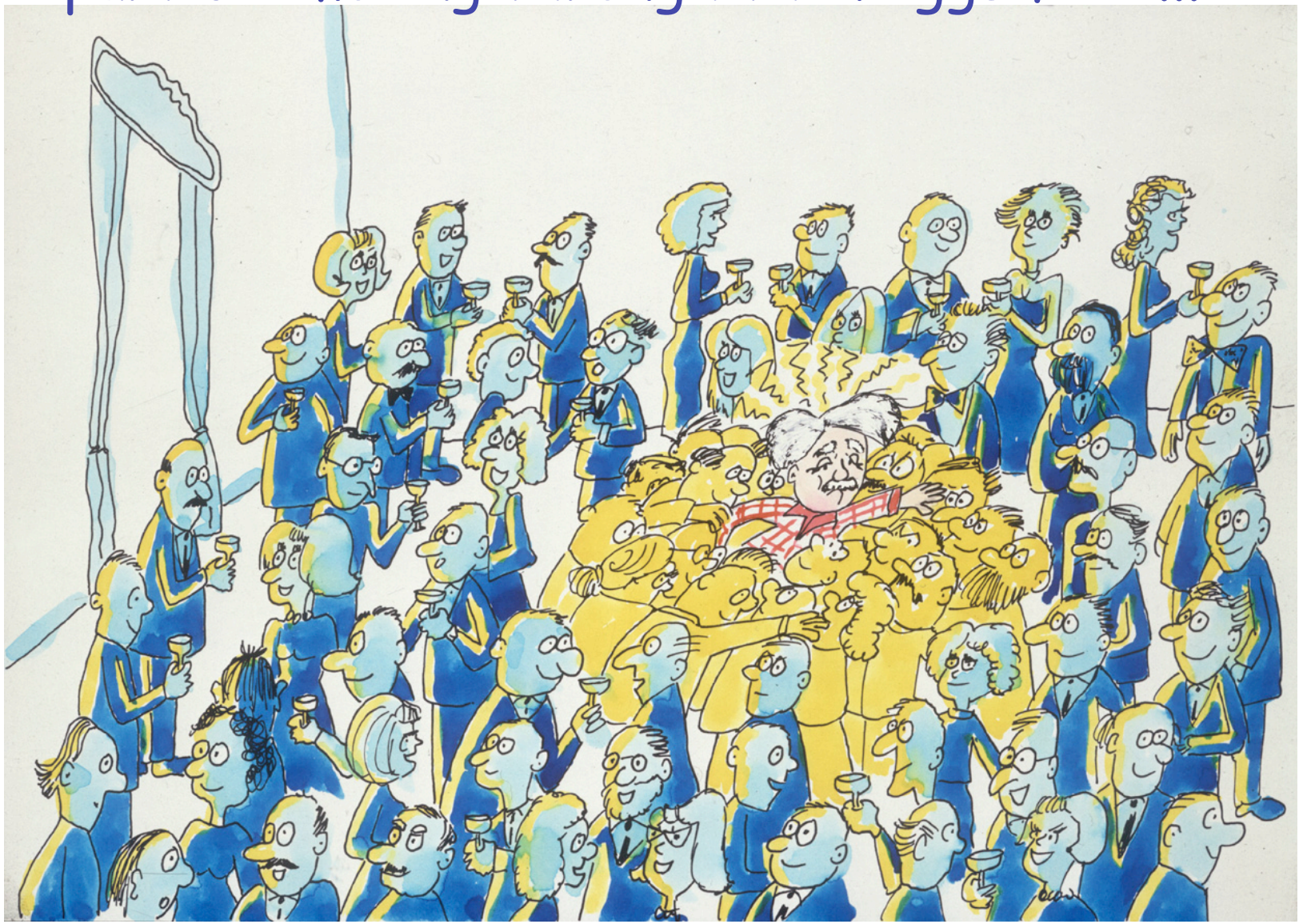
The Higgs field requires a particle, the ***Higgs boson***.



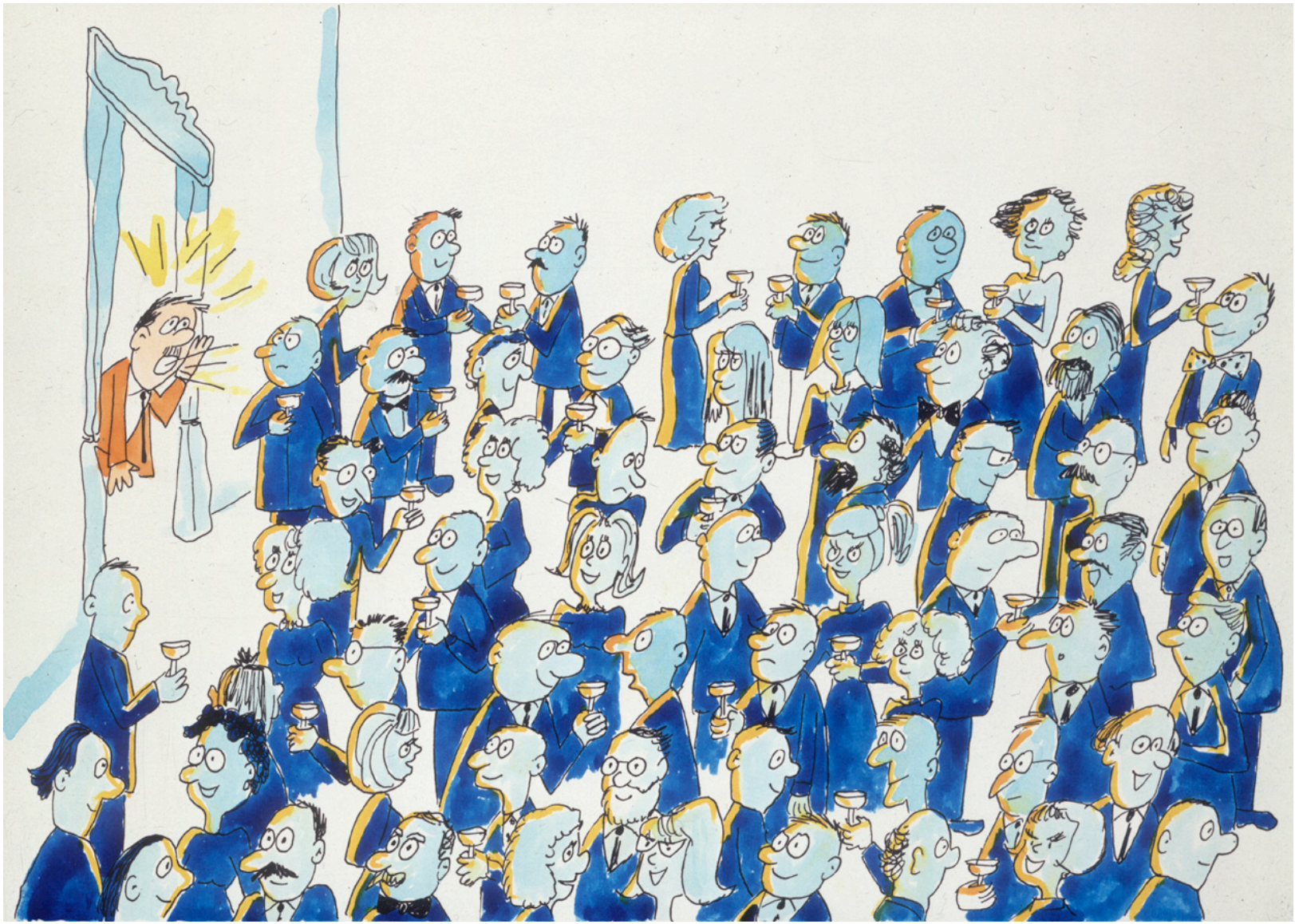
To understand Higgs mechanism, imagine that a room full of physicists chattering quietly is like space filled with the Higgs field ...

... a well-known scientist walks in, creating a disturbance as he moves across the room and attracting a cluster of admirers with each step...

... this increases his resistance to movement, in other words, he acquires mass, just like a particle moving through the Higgs field...



… if a rumor crosses the room, …



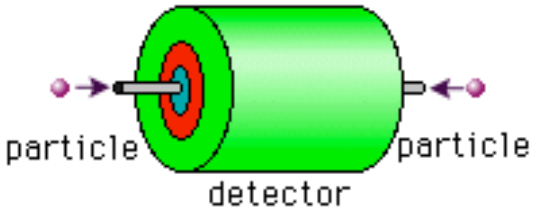
... it creates the same kind of clustering, but this time among the scientists themselves.

In this analogy, these clusters are the Higgs particles.

Now that you know what motivates particle physicists, let's learn how we do it …

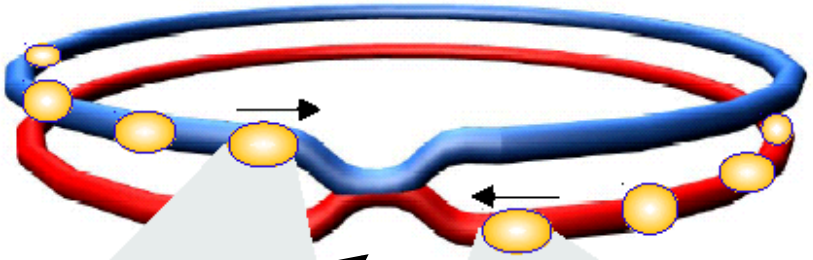
Particle Accelerators and Collisions

- Accelerators can be arranged to provide collisions of two types:
  - Fixed target: Shoot a particle at a fixed target.
  - Colliding beams: Two beams of particles are made to cross each other.



- Accelerators are shaped in one of two ways:
  - Linacs: Linear accelerators, in which the particle starts at one end and comes out the other.
  - Synchrotrons: Accelerators built in a circle, in which the particle goes around and around ...

Colliding Beams

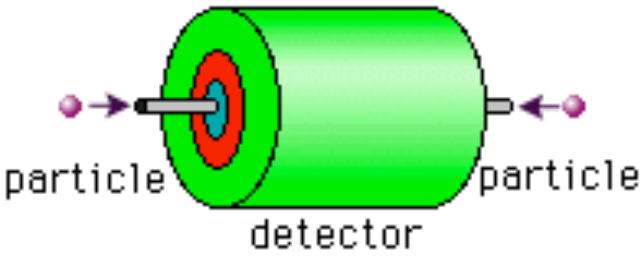


Bunch

Proton

Build your detector here

Parton
(quark, gluon)



Particle

jet

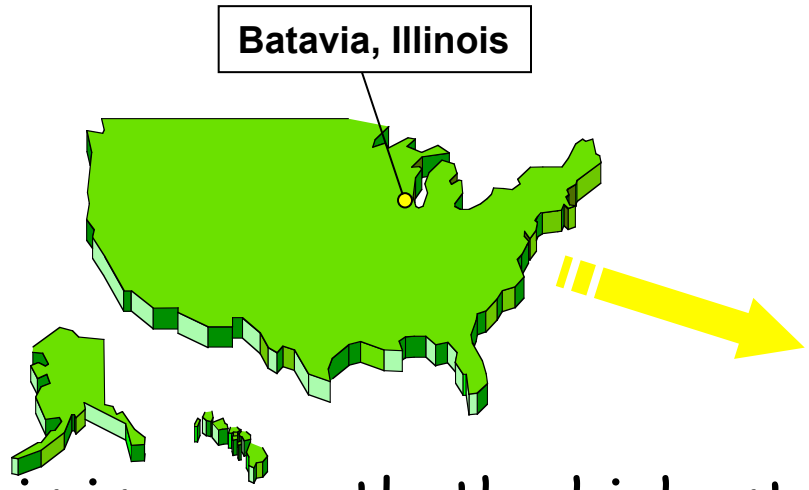
jet

The Electron-Volt

- Energies are often expressed in units of "electron-volts".
- An electron-volt (eV) is the energy acquired by a electron (or any particle with the same charge) when it is accelerated by a potential difference of 1 volt.

10^{12} eV is like having 1 battery for every star in our galaxy.

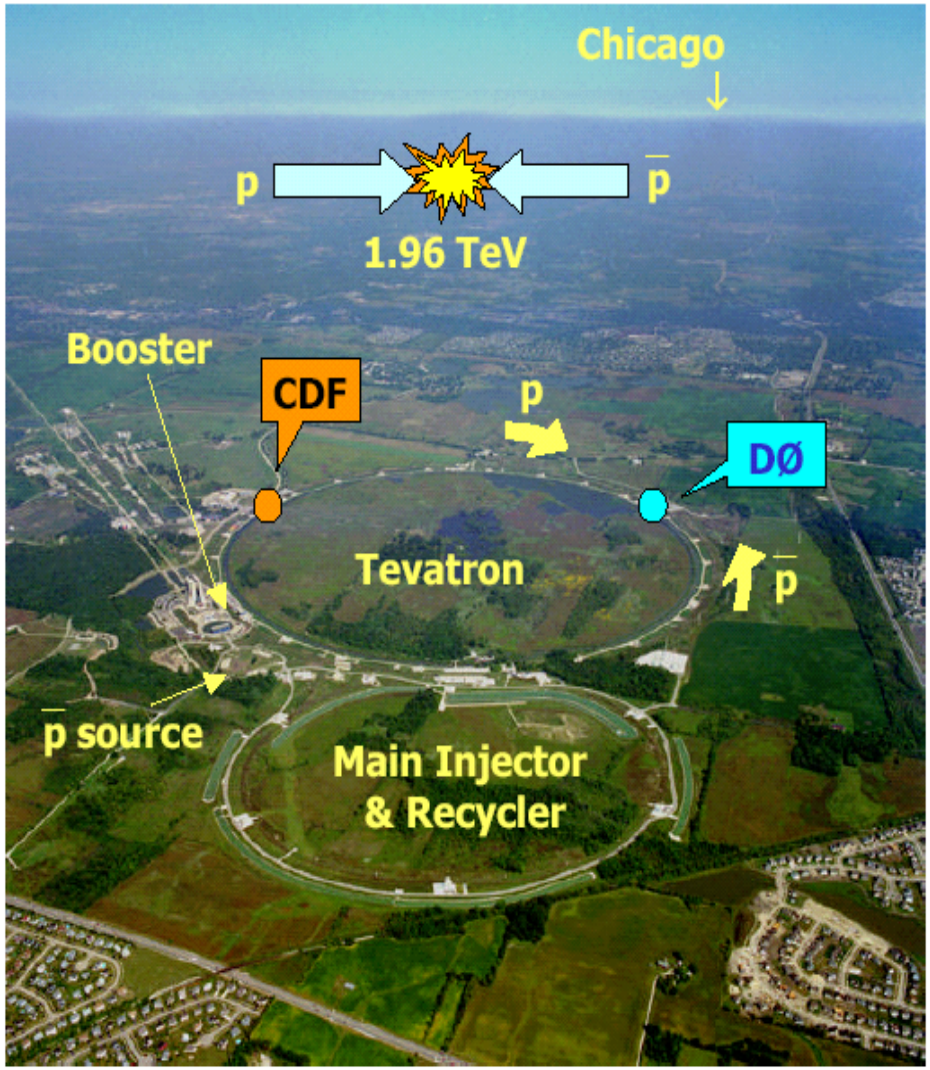
The Fermilab Tevatron



This is currently the highest energy accelerator now in operation and accelerates protons to

1 million million electron volts:

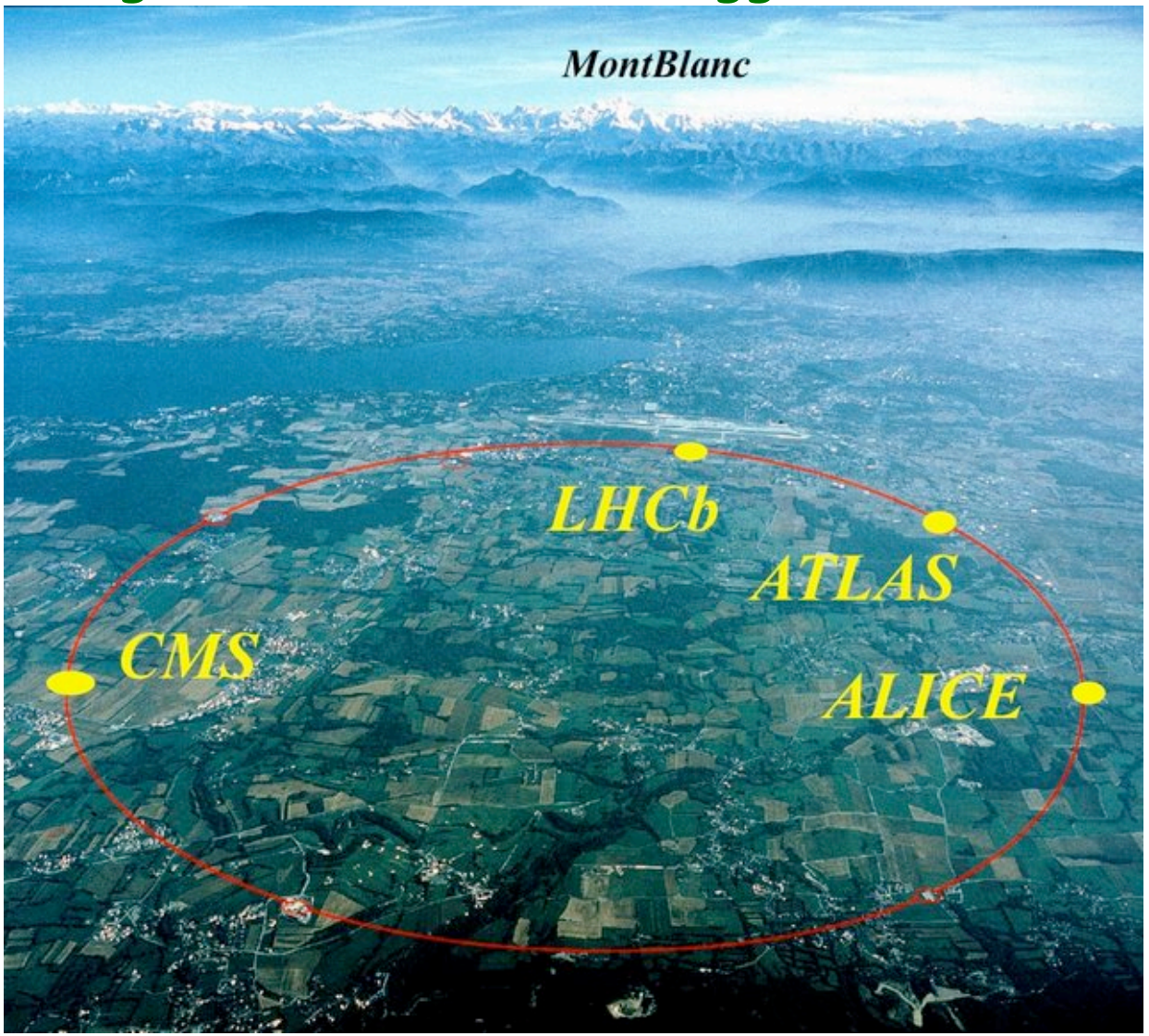
1 trillion electron volts or 1 TeV $=10^{12}$ eV



Large Hadron Collidor (LHC)

CERN laboratory near Geneva, Switzerland and the Swiss Alps!

Designed to search for Higgs and **other new discoveries**!



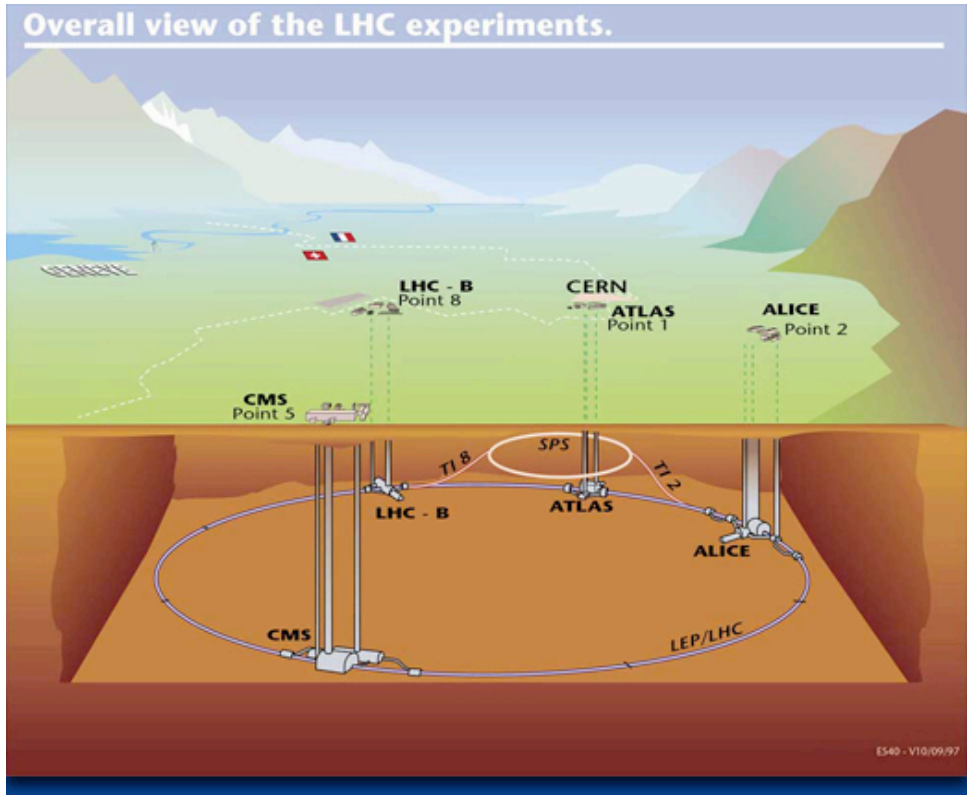
Start in spring 2009!

proton-proton collisions

Will accelerate each of two counter-rotating beams of protons to 7 TeV per proton.

The LHC

- Circular tunnel 27 km in circumference.
- The tunnel is buried around 100m underground
- The beams move around the LHC ring inside a continuous vacuum guided by superconducting magnets.
- The beams will be stored at high energy for hours. During this time collisions take place inside the four main LHC experiments.



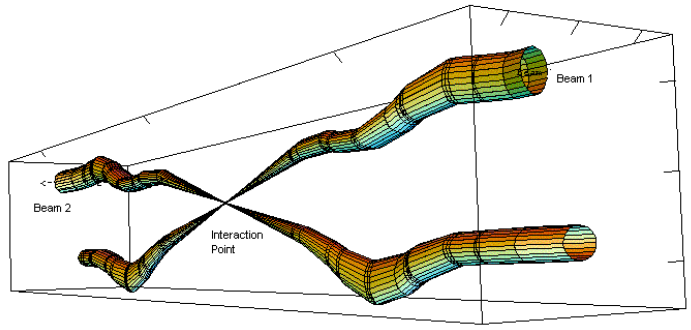
The LHC Beam

- 2808 bunches of protons per beam.
- Each bunch will contain 100 billion protons, and will be about a few cm. long
- They will travel 99.999% the speed of light
- When two beams of protons collide, they will generate temperatures more than 100,000 times hotter than the heart of the Sun, concentrated within a minuscule space.

Energy in LHC Beam

- Energy in beam is about 362 million J
  - How much energy is this?
    - The two LHC beams together could melt nearly one ton of copper.
    - Equivalent to 77.4 kg of TNT
    - Energy of an aircraft carrier traveling 11.7 knots (1knot = 1.85km/hr)
    - Equivalent to a person in a Subaru driving at 1700 km/h.

Collisions



Relative beam sizes around IP1 (Atlas) in collision

- 100,000 million protons per bunch
- Squeeze the beam size down as much as possible at the collision point to increase the chances of a collision.
  - squeeze down to 64 microns (about the width of a human hair) at the interaction point
  - only around 20 collisions per crossing.
- The bunches cross every 25 nanoseconds (10^{-9} seconds)
- Around 600 million collisions per second
- Most protons miss each other and carry on around the ring time after time. The beams will keep circulating for hours.
- To avoid colliding with gas molecules, the beams of protons will travel in an ultra-high vacuum – a cavity as empty as interplanetary space.
  - The internal pressure of the LHC is 10^{-13} atm, ten times less than the pressure on the Moon!

Superconducting Magnets

- Total of 9300 magnets inside.
- Not only is the LHC the world's largest particle accelerator, just one-eighth of its cryogenic distribution system would qualify as the world's largest fridge.
- Circulates superfluid helium around the accelerator ring, keeps the LHC at a super cool temperature of -271.3°C – even colder than outer space!
- The combined strands of the superconducting cable would go around the equator 6.8 times. If you added all the filaments of the strands together they would stretch to the sun and back 5 times with enough left over for a few trips to the moon.
- Total stored energy in magnets is 10 GigaJ or 10 Billion J!

Some Movies of Collisions …

The Modern Particle Detector

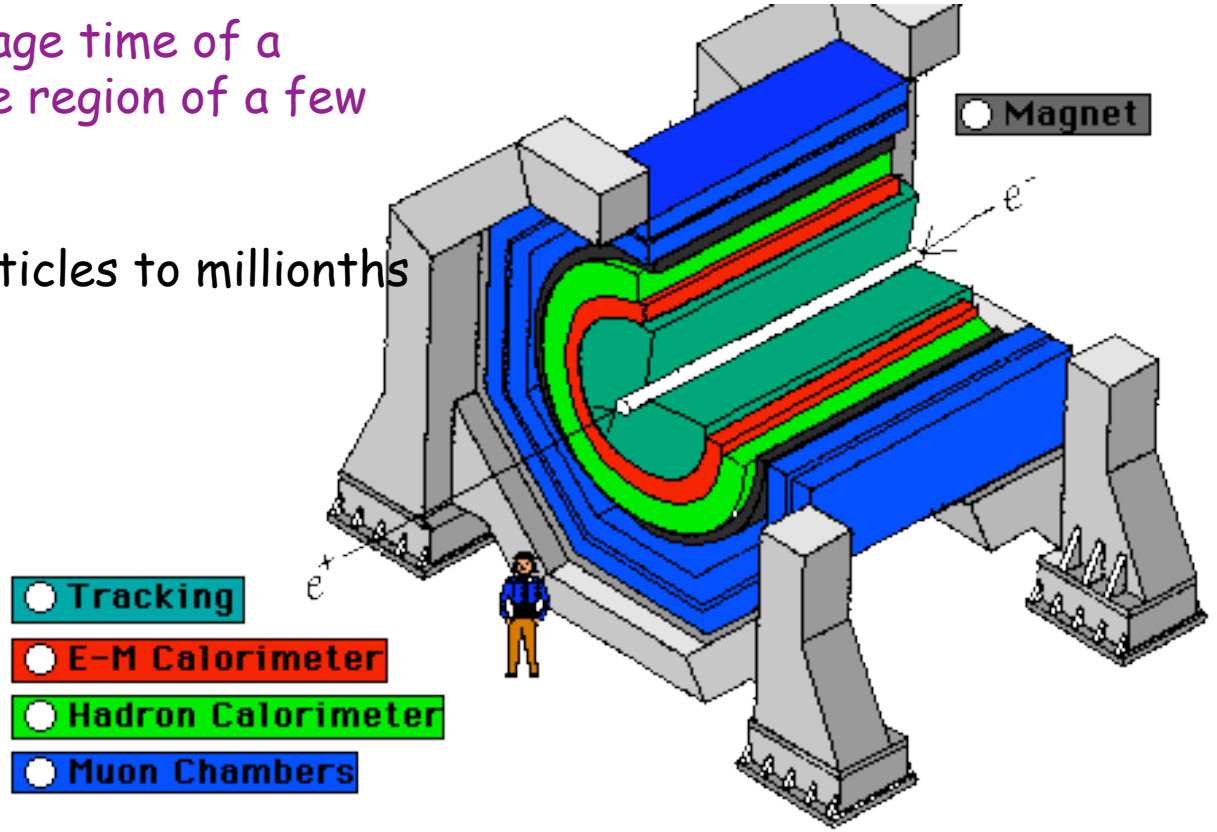
Goal is to completely surround collision.

Arrange different types of detectors in layers.

It's like taking many very fast pictures of the collisions inside the detector

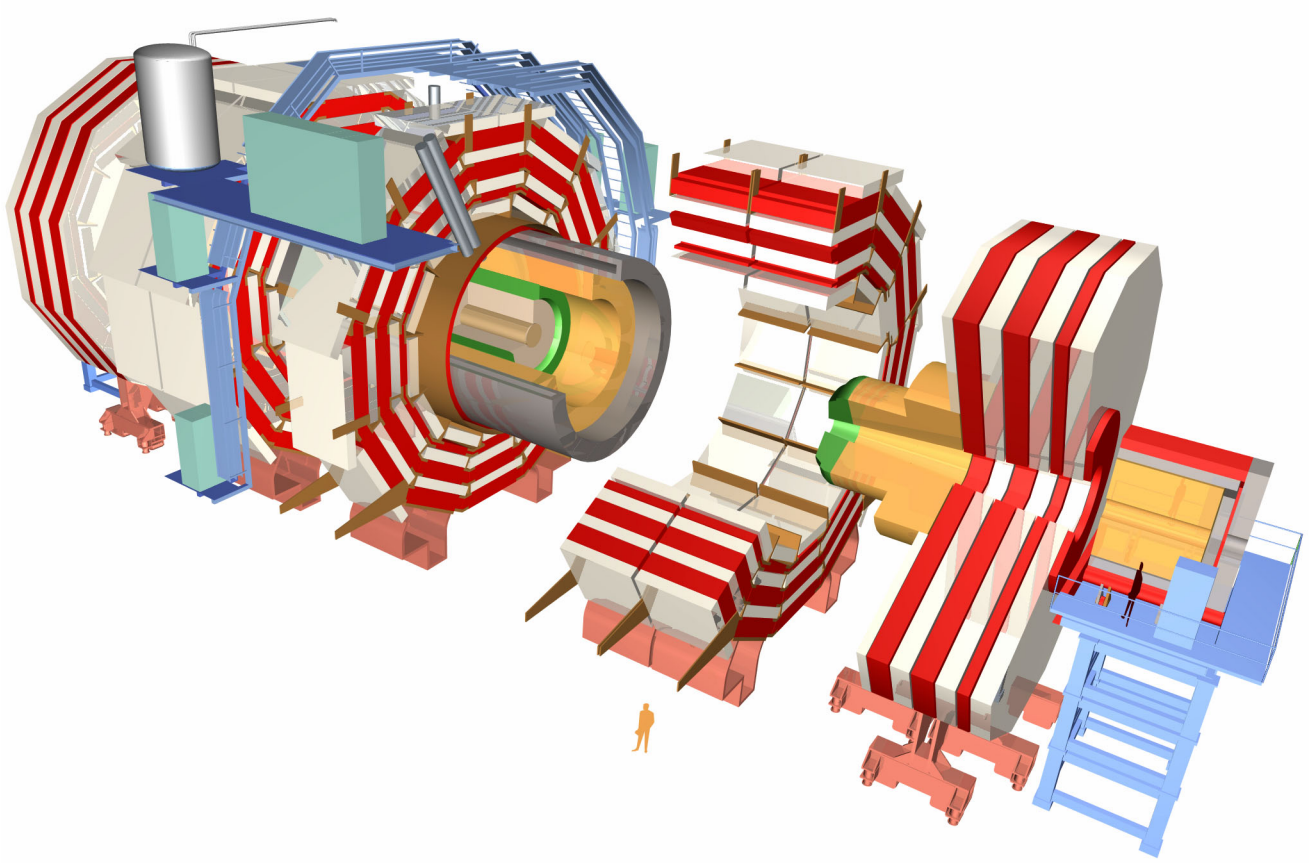
Precisely measure the passage time of a particle to accuracies in the region of a few billionths of a second.

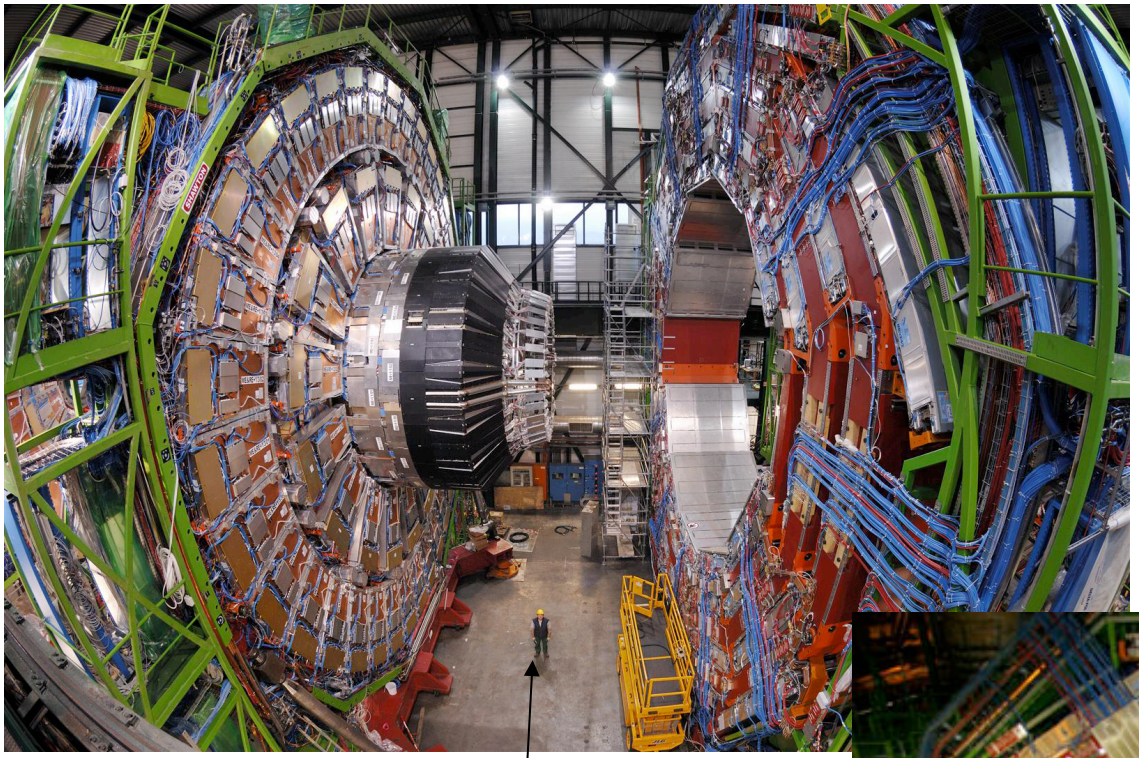
And the location of the particles to millionths of a meter.

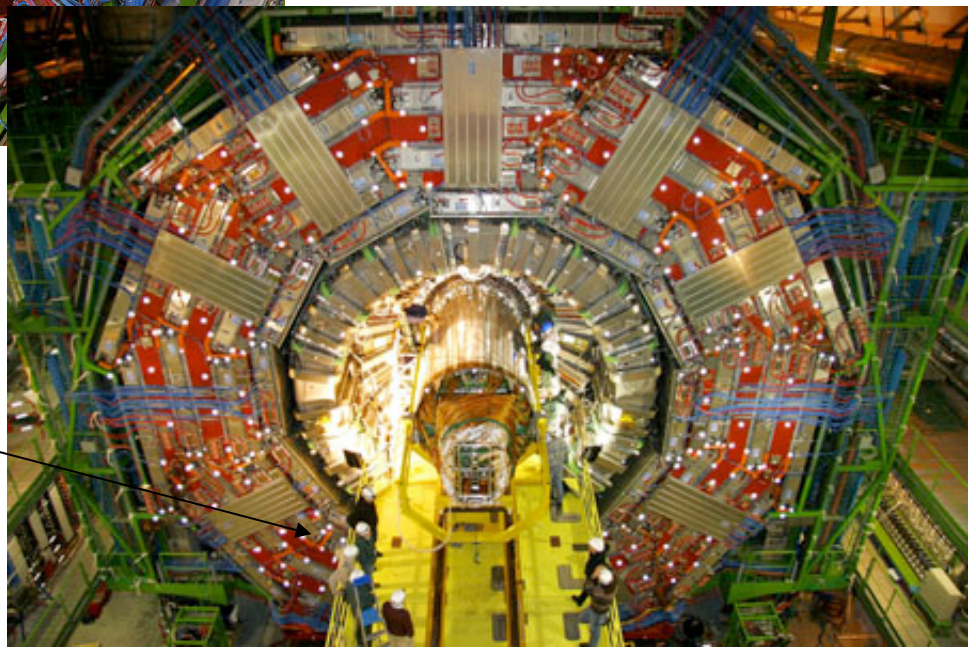


CMS Experiment

- CMS weighs around the same as 30 jumbo jets or 2,500 African elephants.



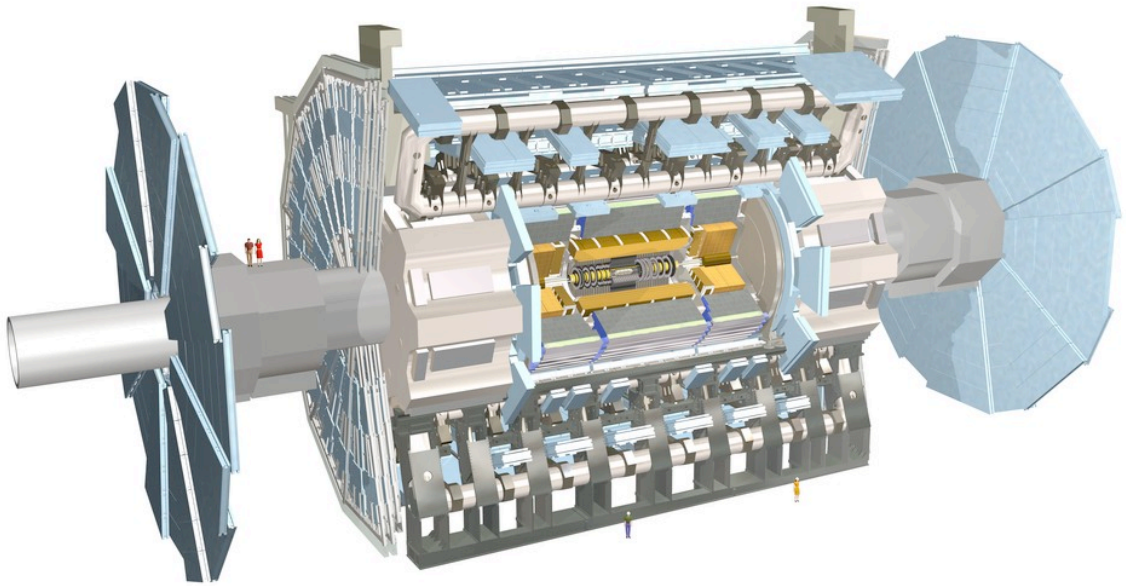


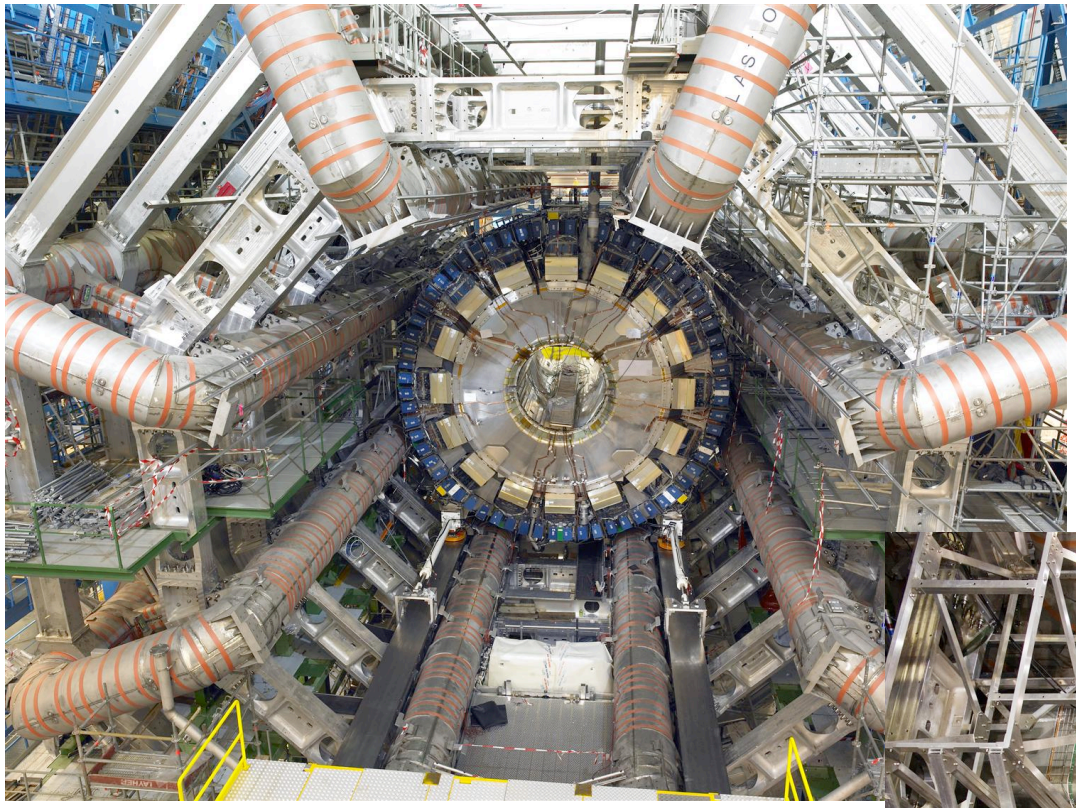


People!

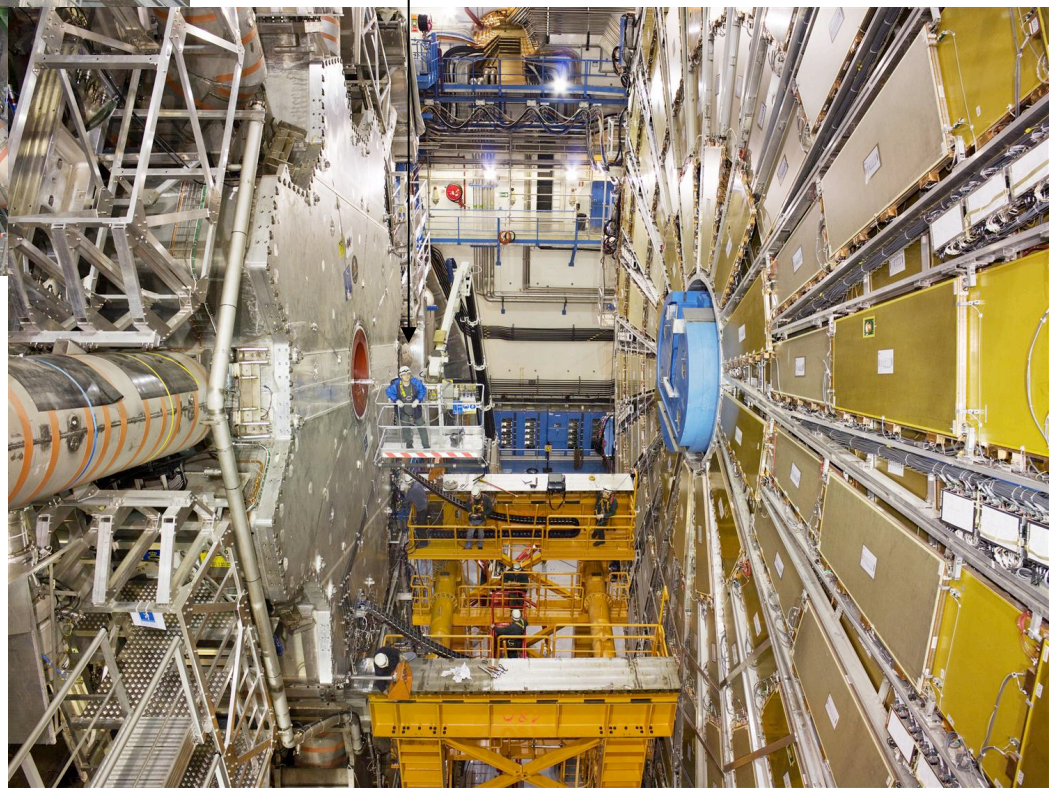
ATLAS

- The ATLAS cavern could hold the nave of Notre Dam cathedral.



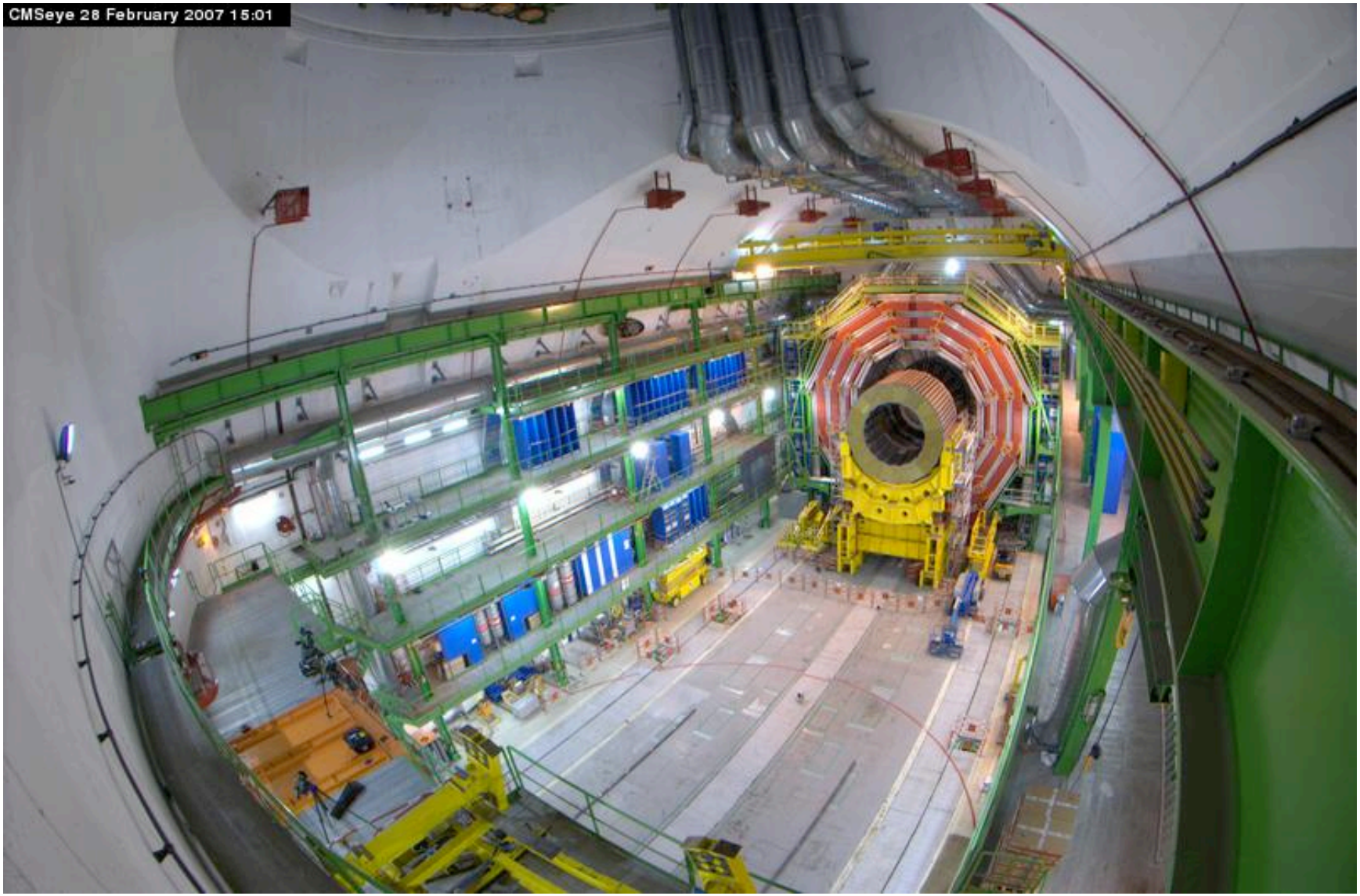


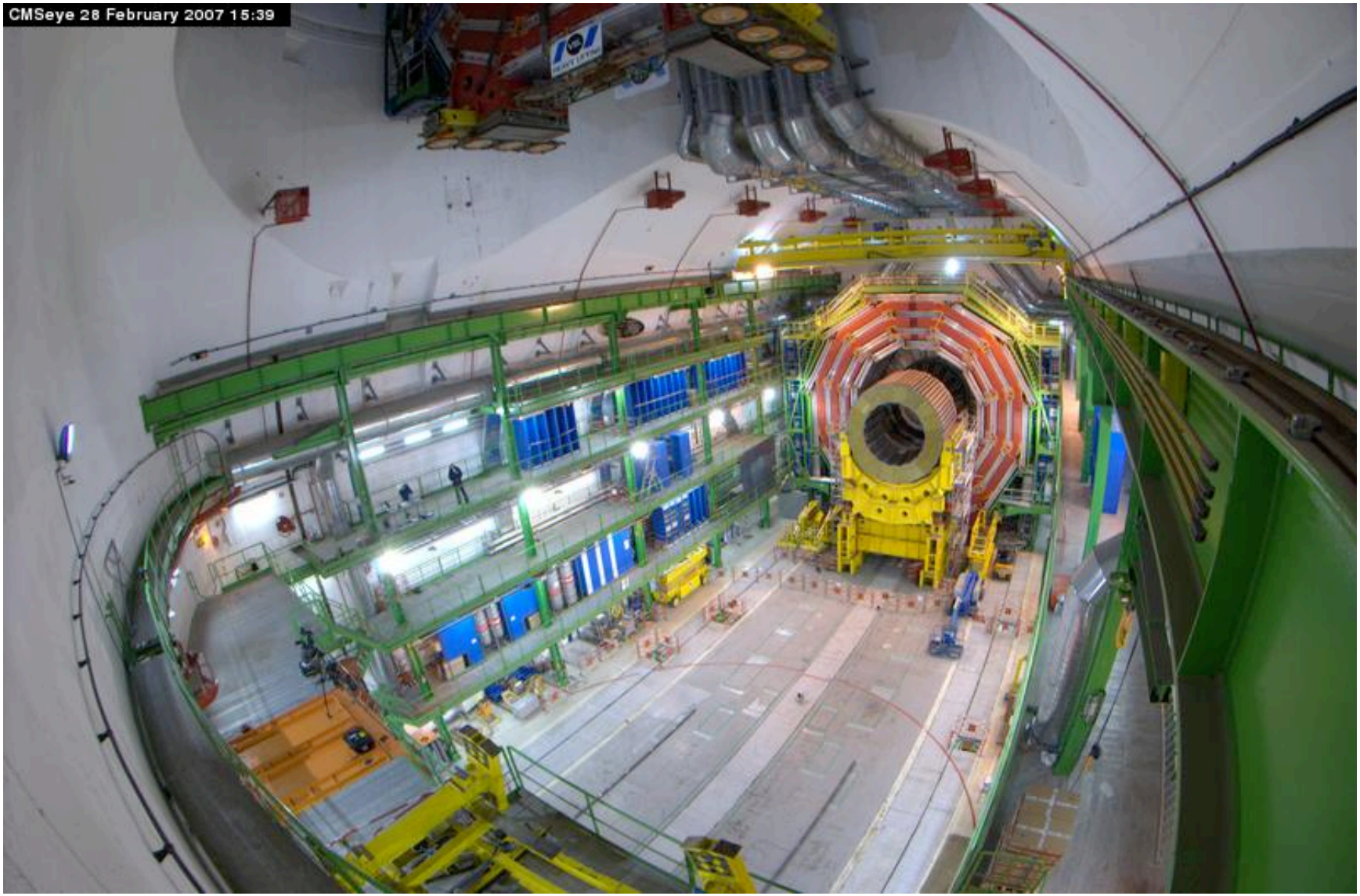
A person!

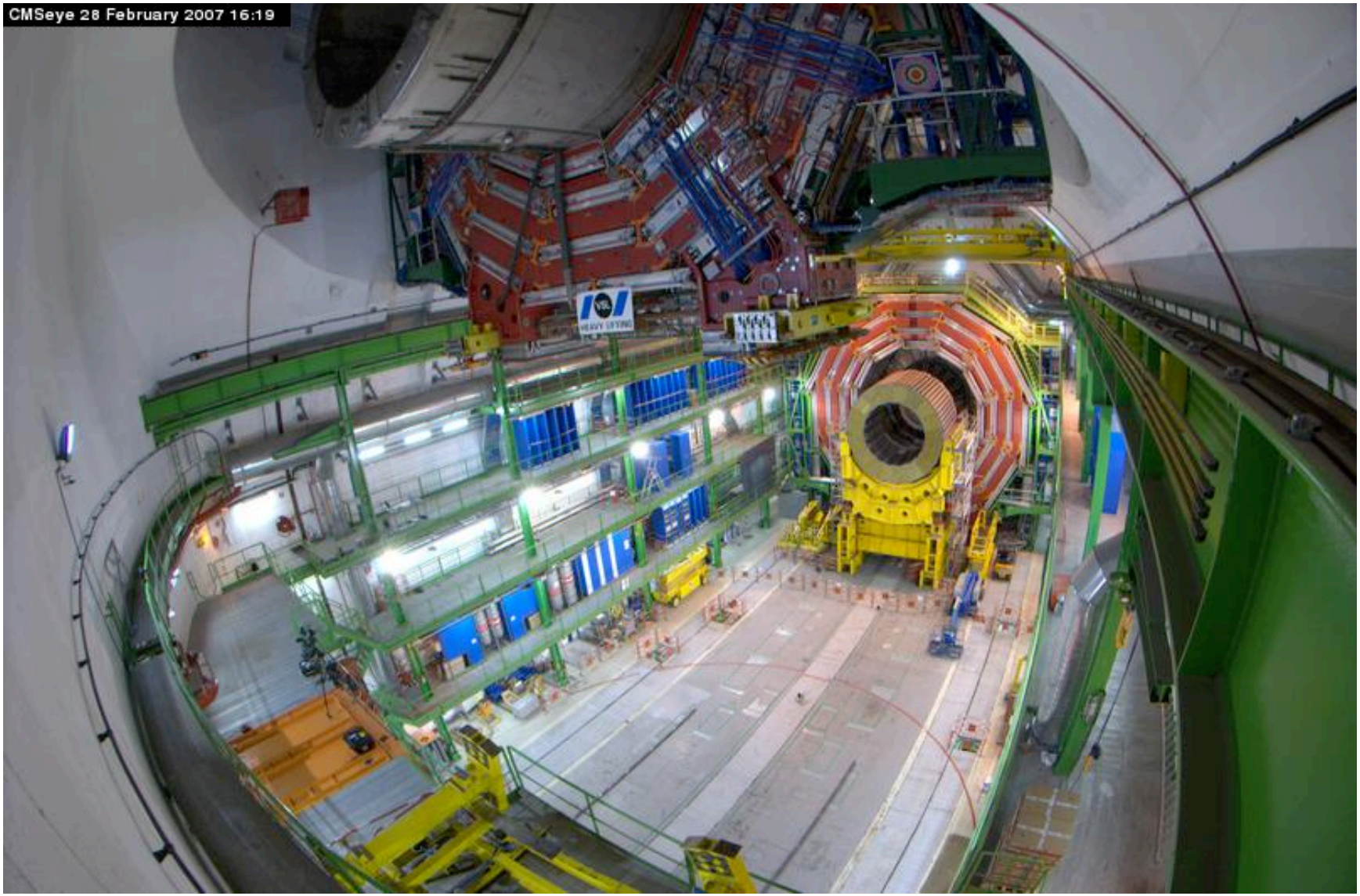


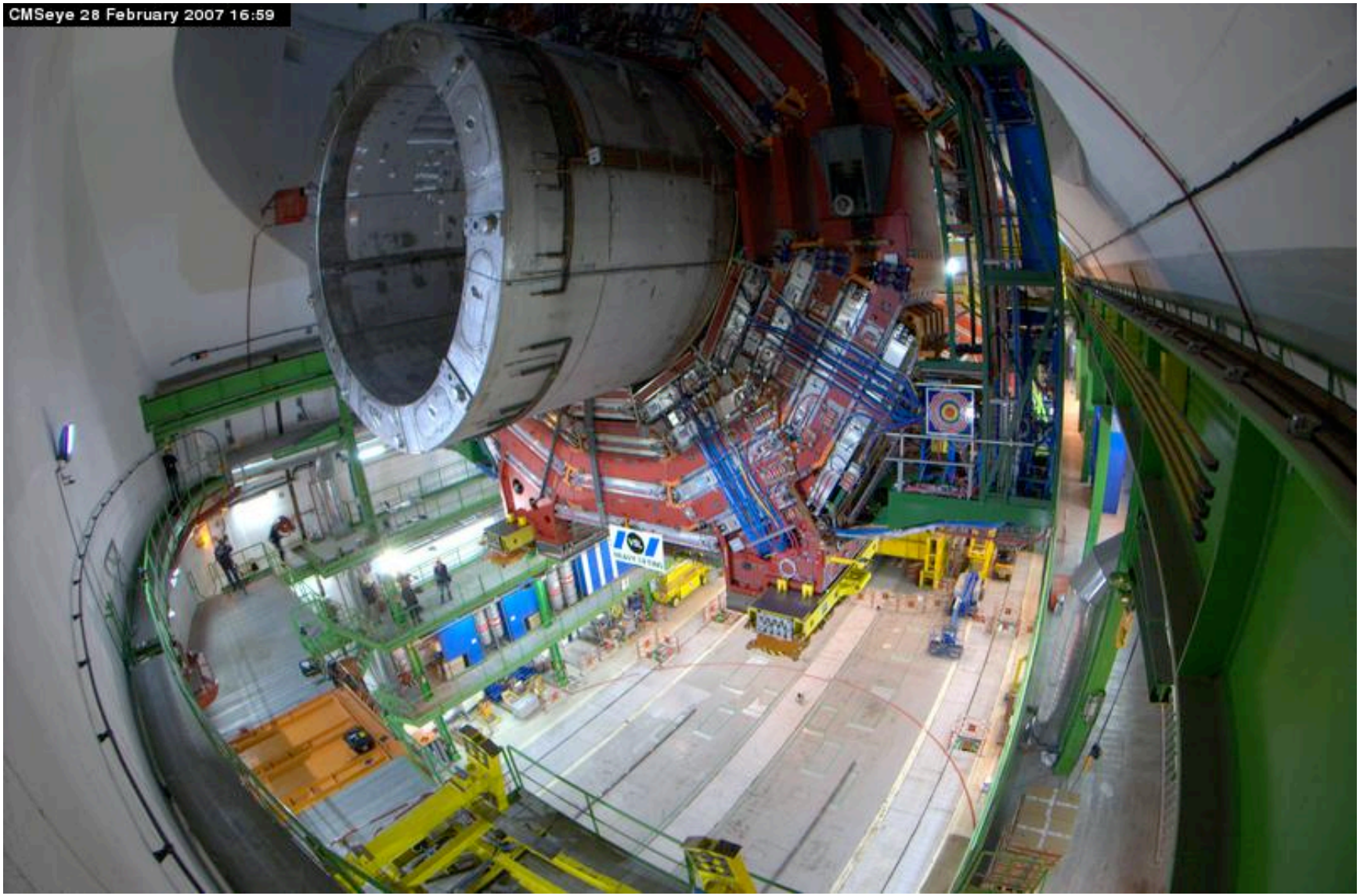
Lowering of part of CMS detector

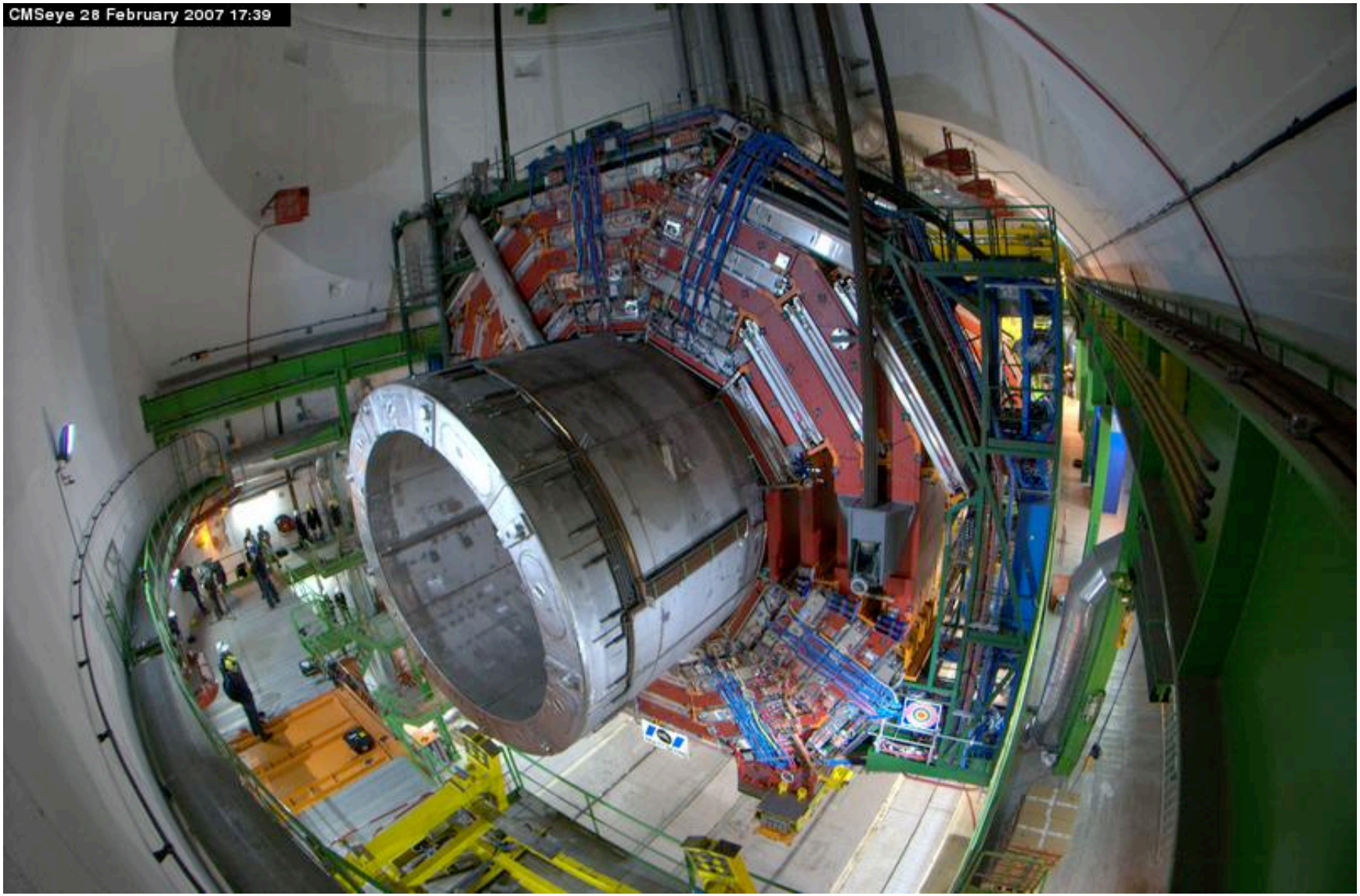
- The next slides show the lowering of the central part of the CMS detector February 2007
- Each picture represents a snapshot 40 min after the previous one.
- It's a very delicate process!

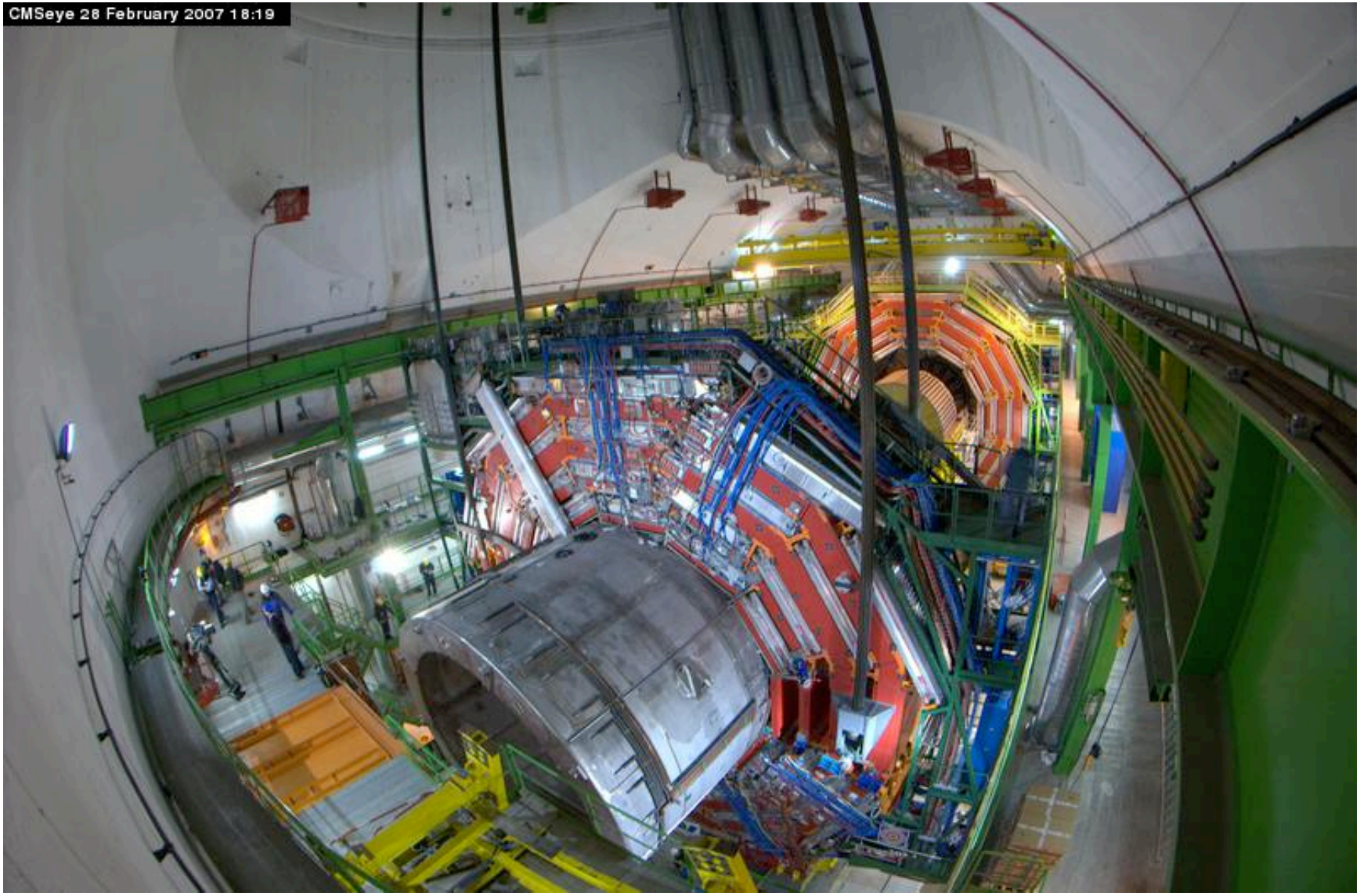

CMSeye 28 February 2007 15:01


CMSeye 28 February 2007 15:39

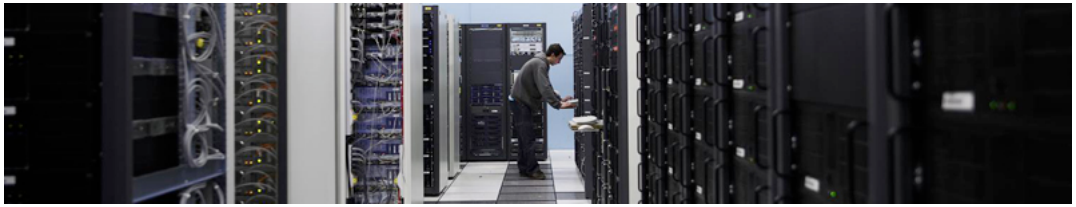

CMSeye 28 February 2007 16:19


CMSeye 28 February 2007 16:59


CMSeye 28 February 2007 17:39

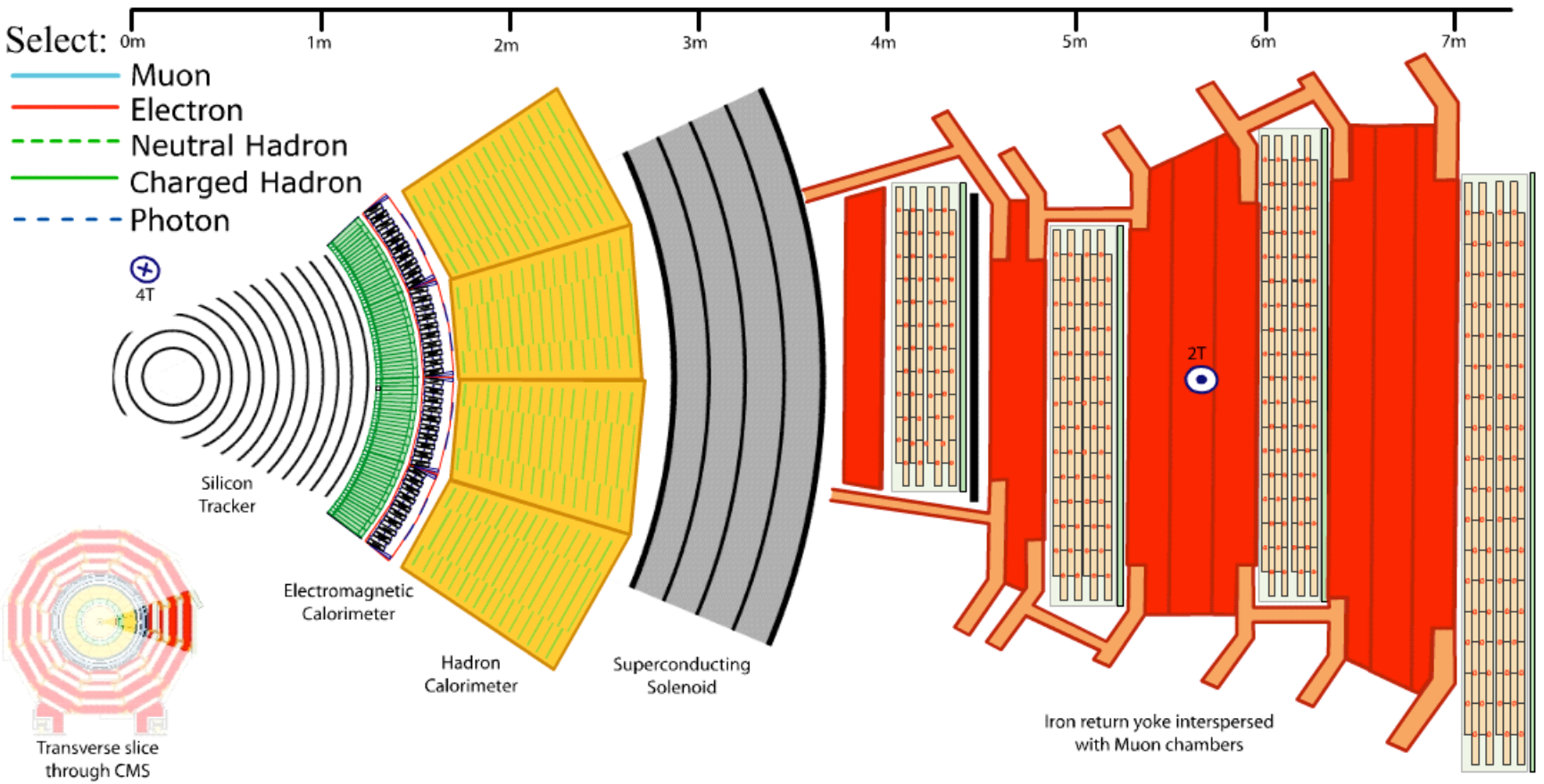

CMSeye 28 February 2007 18:19

The most powerful supercomputer system in the world



- The data recorded by each of the big experiments at the LHC will fill around 100 000 dual layer DVDs every year.
- This would create a stack 450 feet high every second, which would reach to the moon and back twice each year. The data rate is also equivalent to 50 billion telephone calls at the same time.
- To allow the thousands of scientists scattered around the globe to collaborate on the analysis over the next 15 years (the estimated lifetime of the LHC), tens of thousands of computers located around the world are being harnessed in a distributed computing network called the Grid.

Slice of CMS

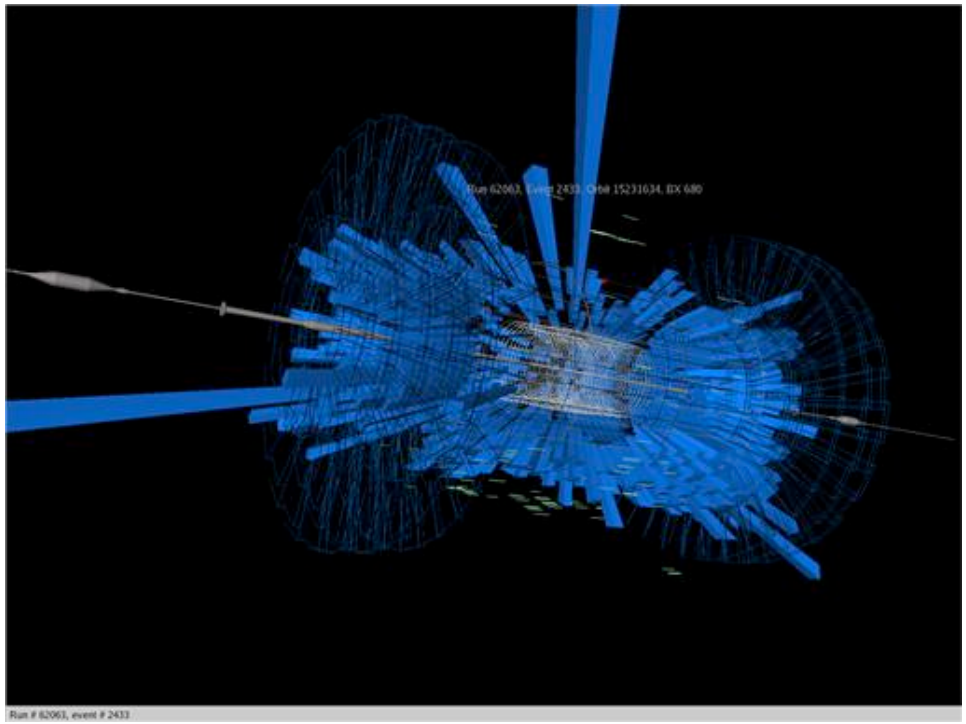

Select:
0m
1m
2m
3m
4m
5m
6m
7m
Muon
Electron
Neutral Hadron
Charged Hadron
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D. Barney, CERN, 2004

LHC Startup

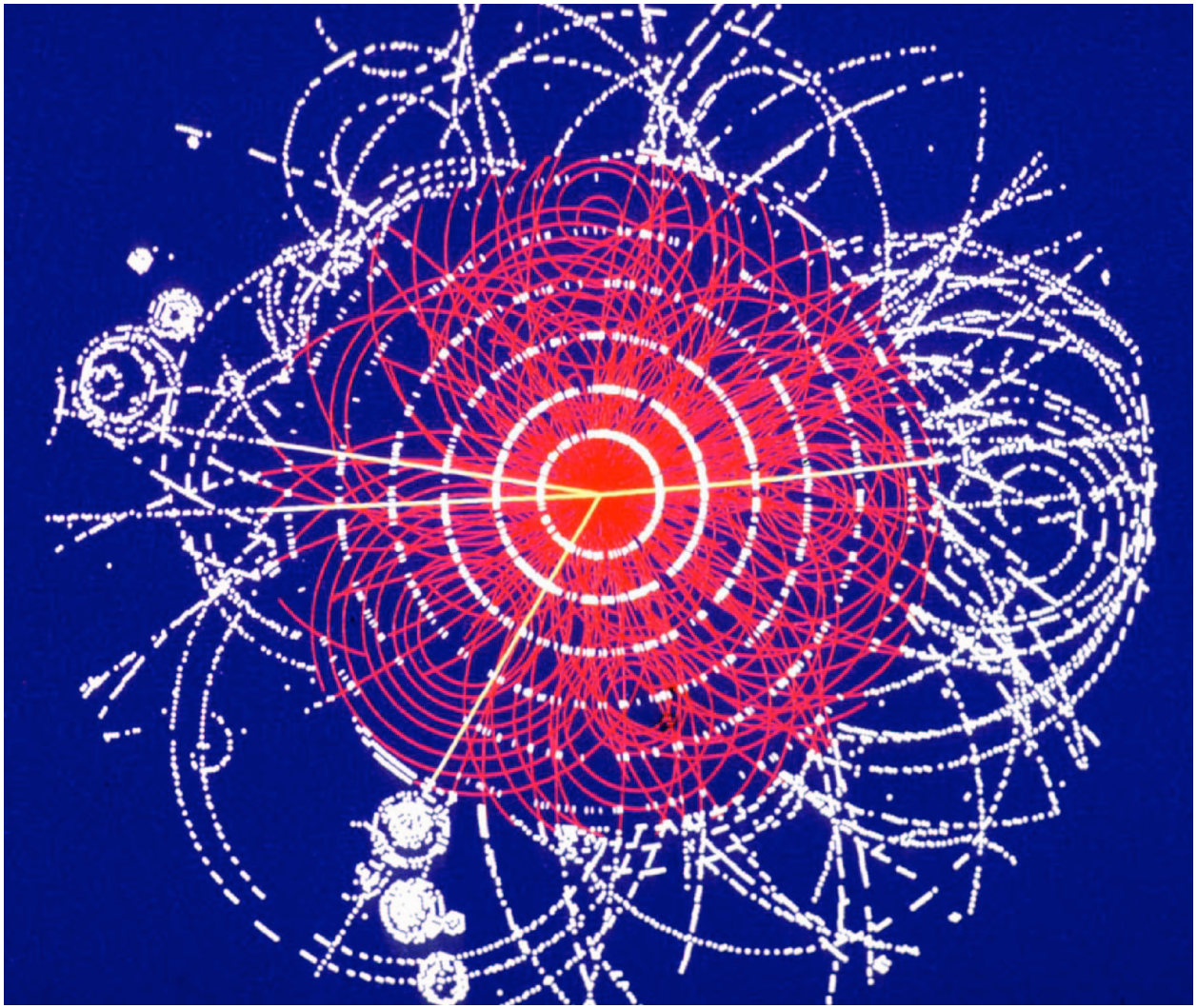
- The first beams were circulated successfully on 10th September 2008.
- Unfortunately on 19th September a fault developed on a small number of superconducting magnets.
- The repair will required a long technical intervention which overlaps with the planned winter shutdown.
- The LHC beam will, therefore, not see beam again before spring 2009.

Data in the detectors

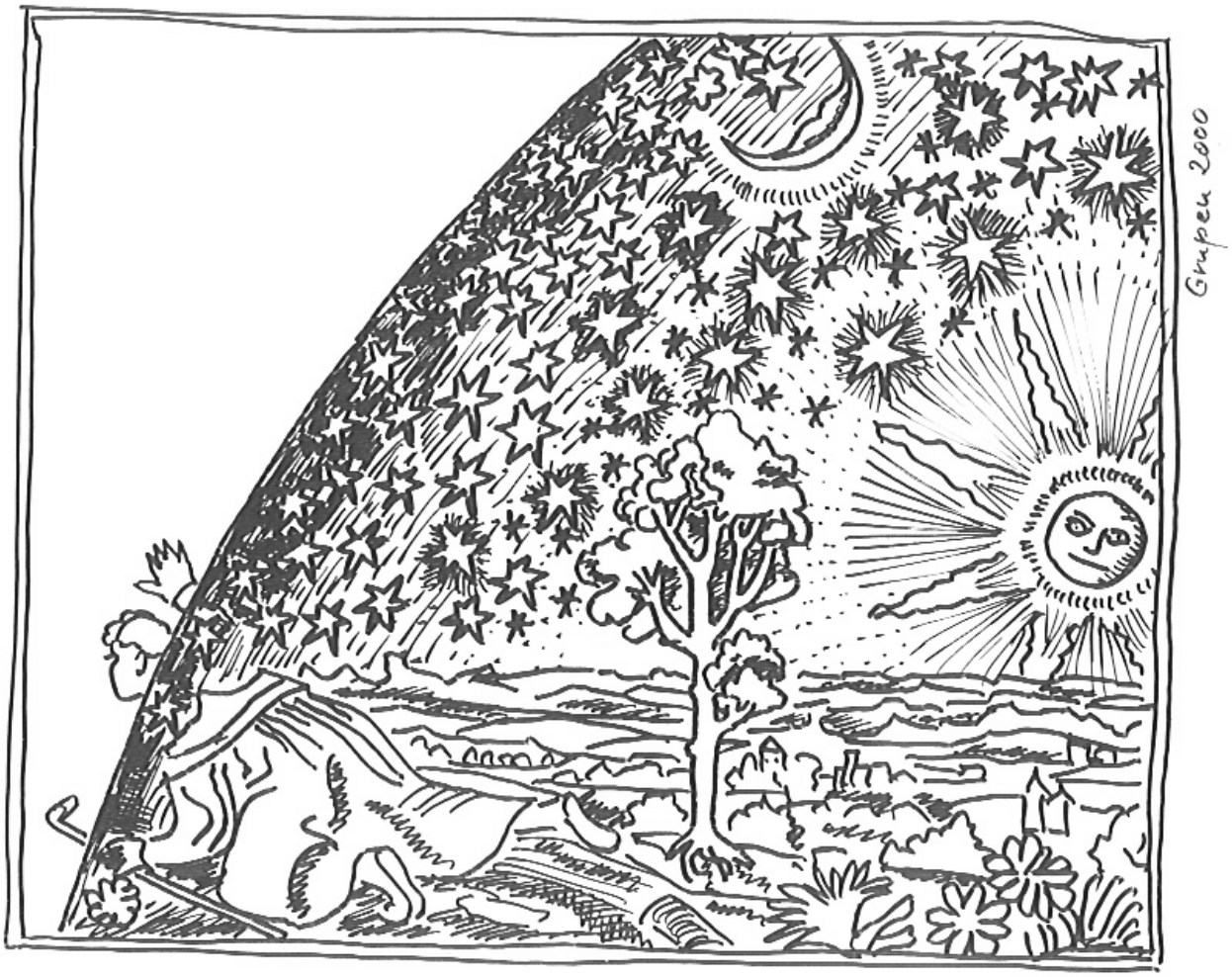
- One of the first images from CMS, showing the debris of particles picked up in the detectors



Typical Collisions Look Like This:



Can YOU find the Higgs or New Physics?



Is there anything beyond the Standard Model?

After all these years, we are still asking the same types of questions ….