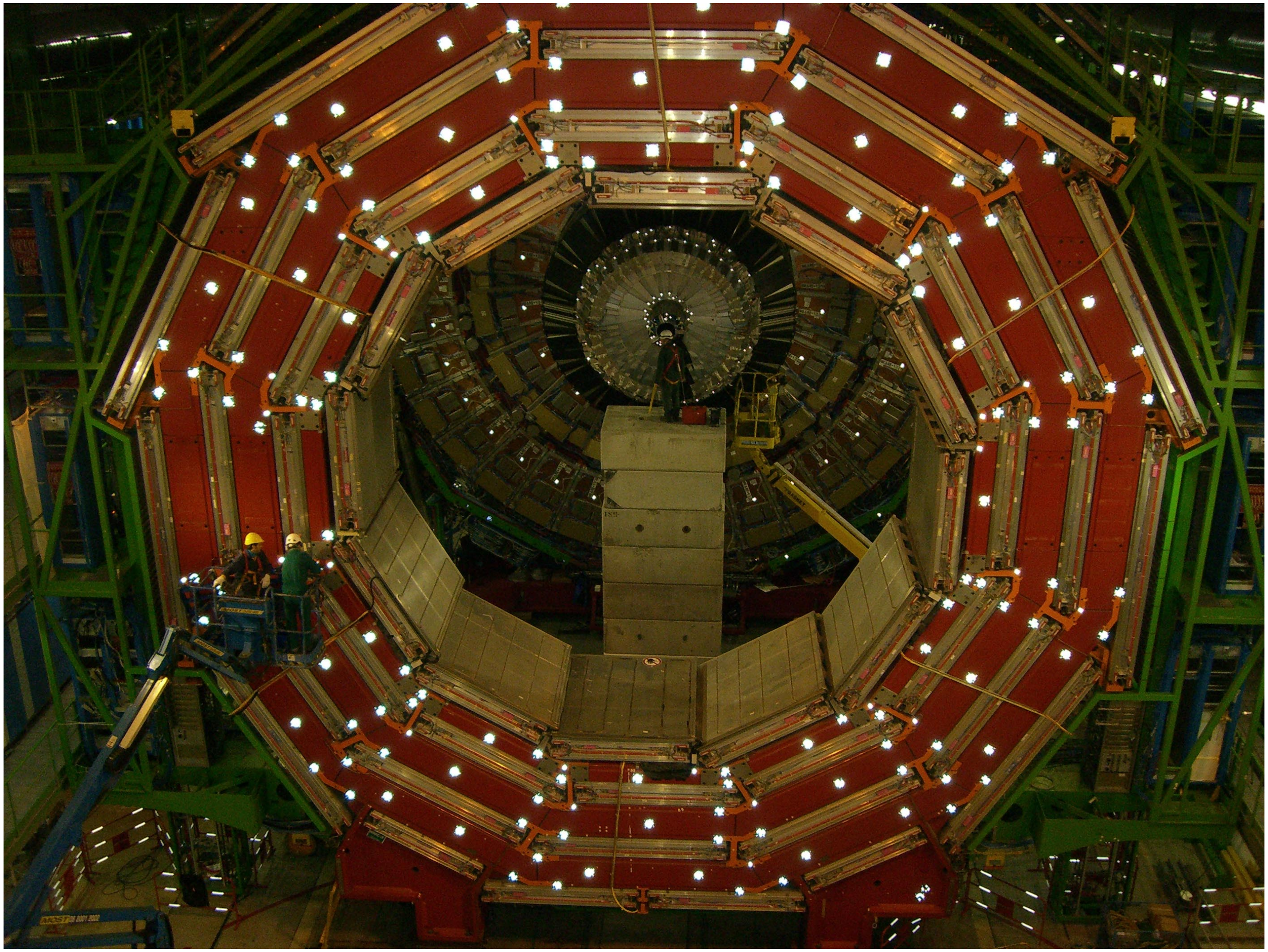
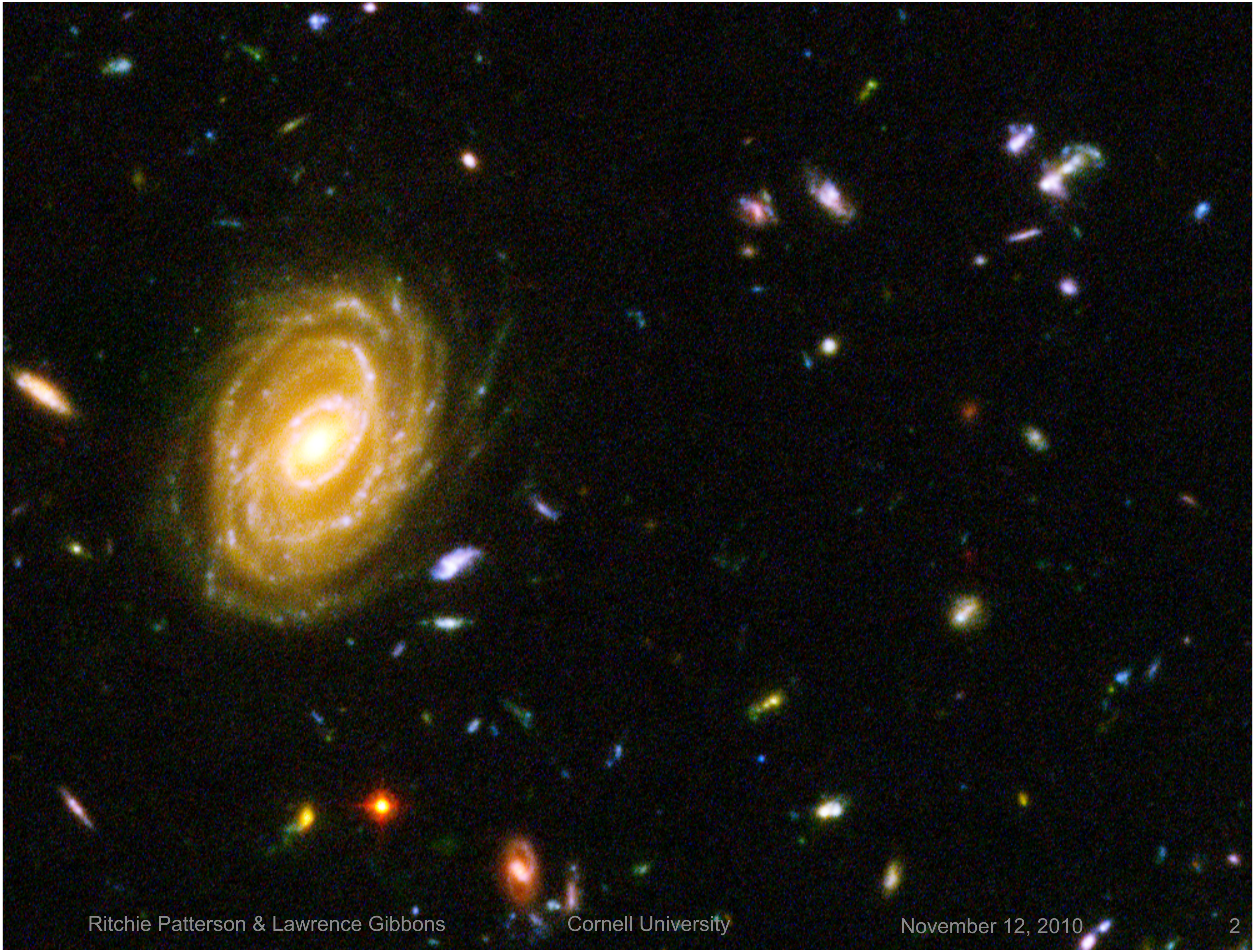


Collisions at the Large Hadron Collider

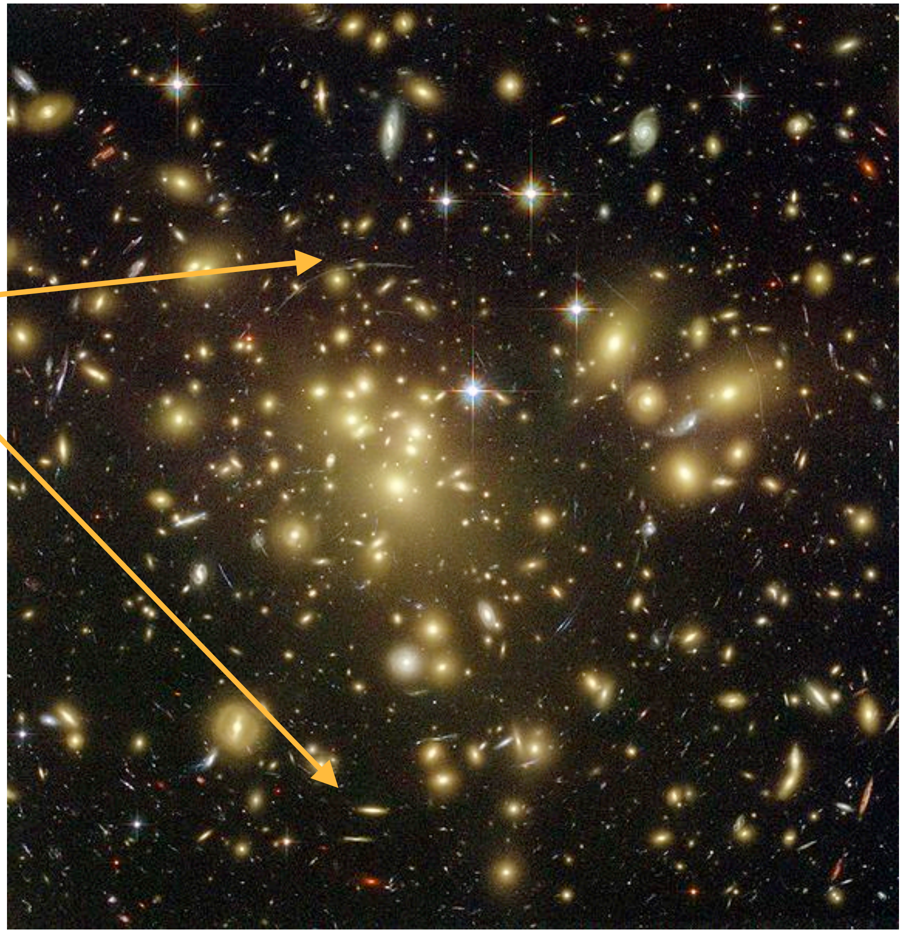
Ritchie Patterson
Lawrence Gibbons
Cornell University

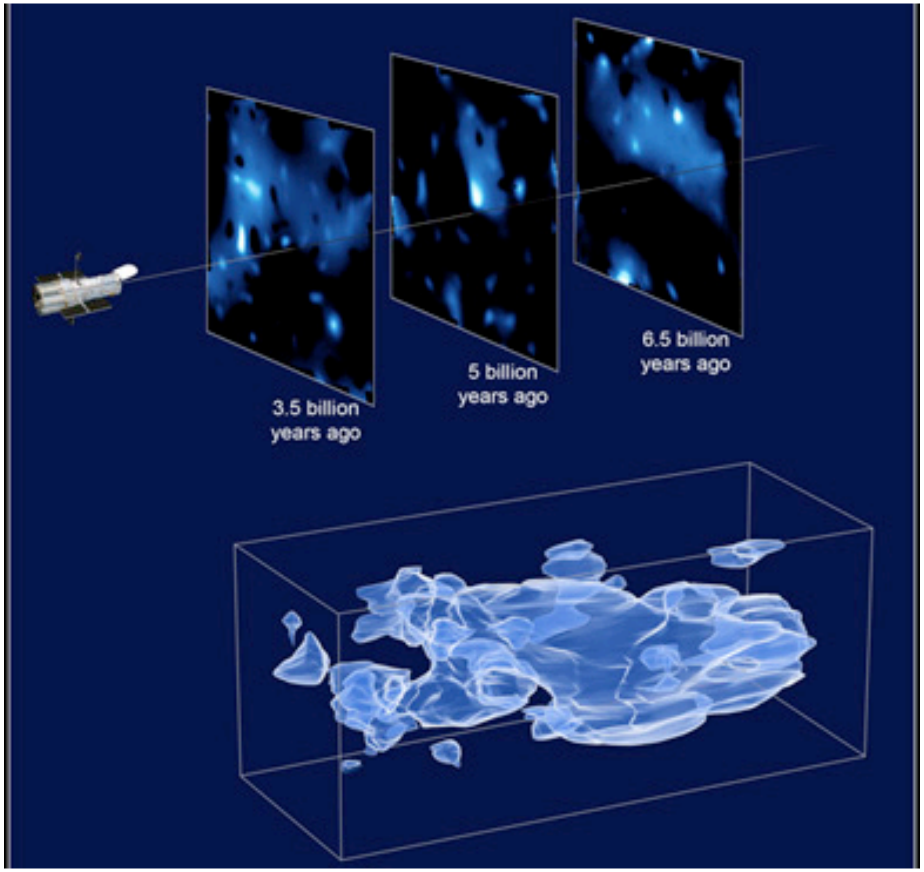
Lycée de l'Oiselet
Bourgoin-Jallieu
November 12, 2010



Dark Matter

Dark matter seems to cause the lensing arcs in this Hubble image





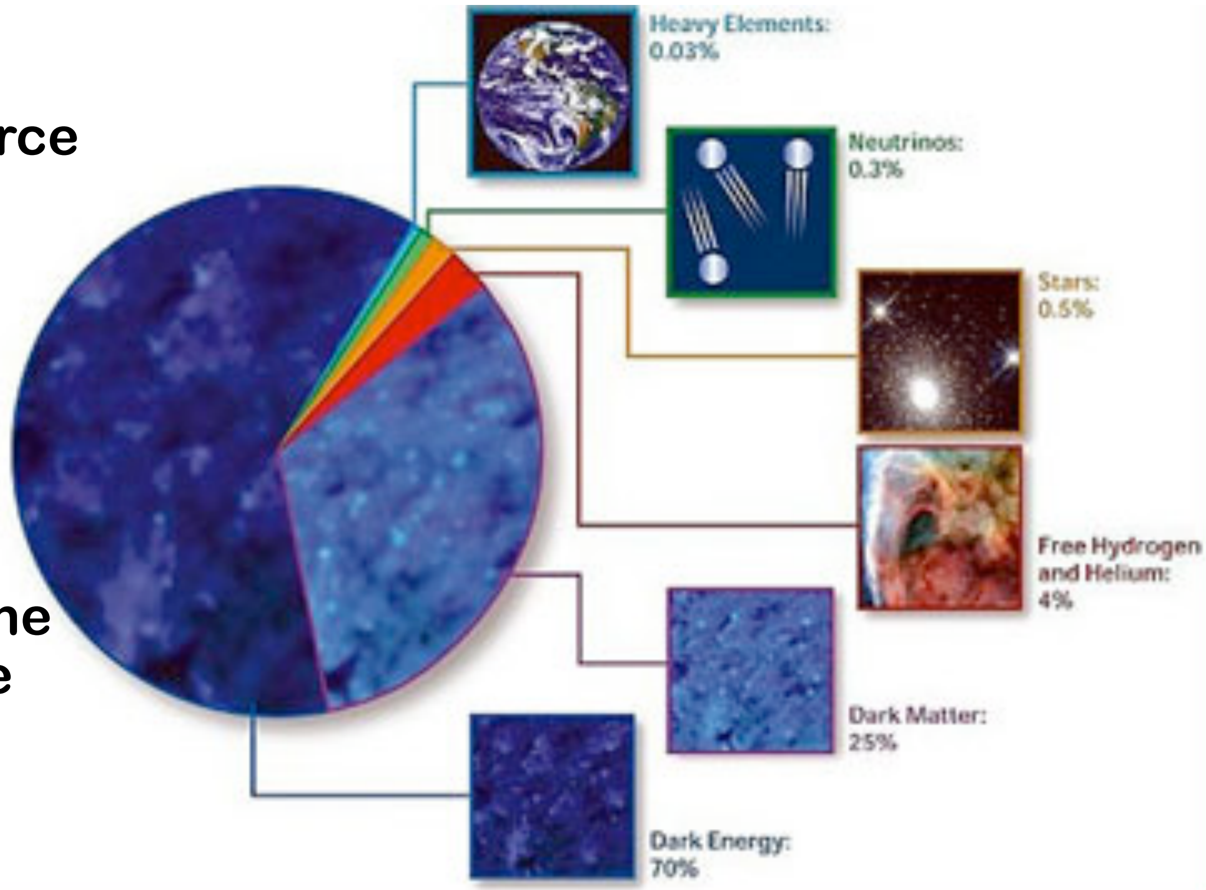
Massey et al (Caltech) used arcs like these to create a map of the dark matter in a section of the sky. (2007)

Dark Matter and the Universe

What do we know about it?

Not much.

- **It exerts gravitational force – so it has mass**
- **It is widely distributed, but not uniformly (this rules out very light particles such as neutrinos).**
- **It rarely interacts with the particles we know -- the quarks, electrons, neutrinos, etc. (that's why we can't see it.)**



It's not any of the particles we know.

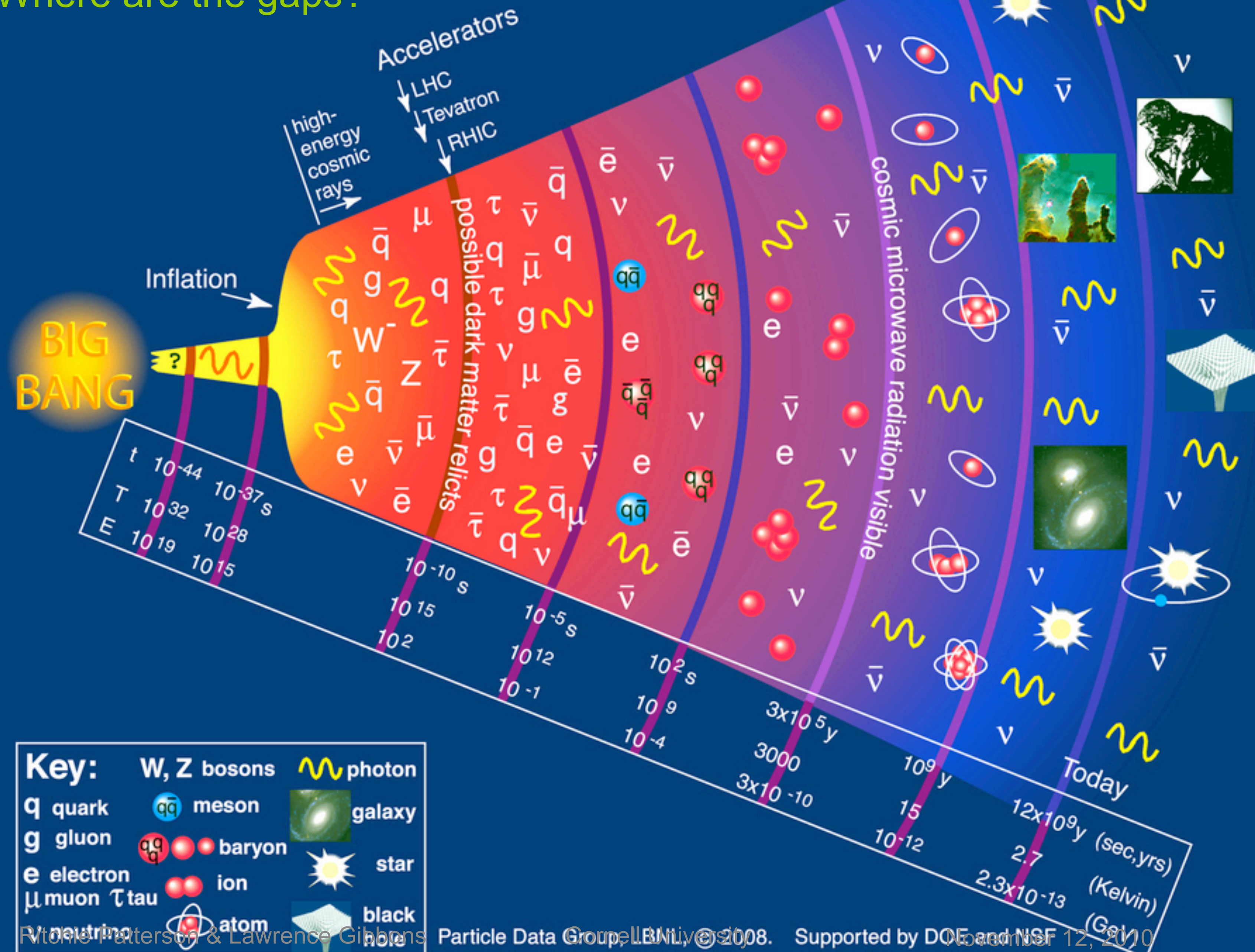
- 13.7 billion years ago there was a giant explosion
- 10^{-20} seconds later, the universe was a hot soup of particles and radiation
- No planets, no stars, not even atoms
- Instead, particles and radiation in *thermal equilibrium* ($E=mc^2$)

- Then the universe cooled
- Most heavy particles decayed away, and radiation had too little energy to produce more.
- Atomic nuclei formed
- Then stars and galaxies
- And planets
- And you and me

- Some types of heavy particles may have remained as dark matter
- These may be recreated only when enough energy is available
- In nature
- Or at the Large Hadron Collider

History of the Universe

Where are the gaps?

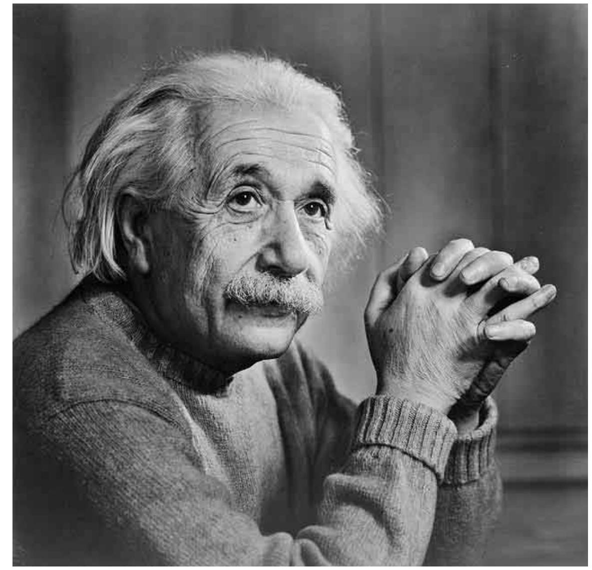


Some big gaps in understanding

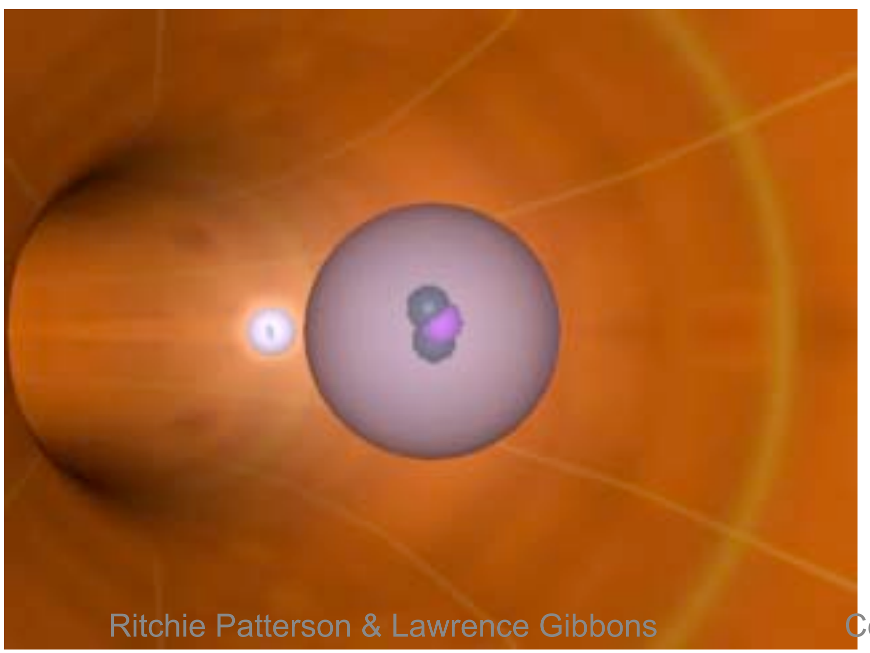
- **What is the dark matter?**
- **Where did the antimatter go?**
- **Why do particles have mass?**
    - **What is the Higgs particle and why is it so light?**
- **What is dark energy?**
- **What was the nature of gravity in the very early universe?**

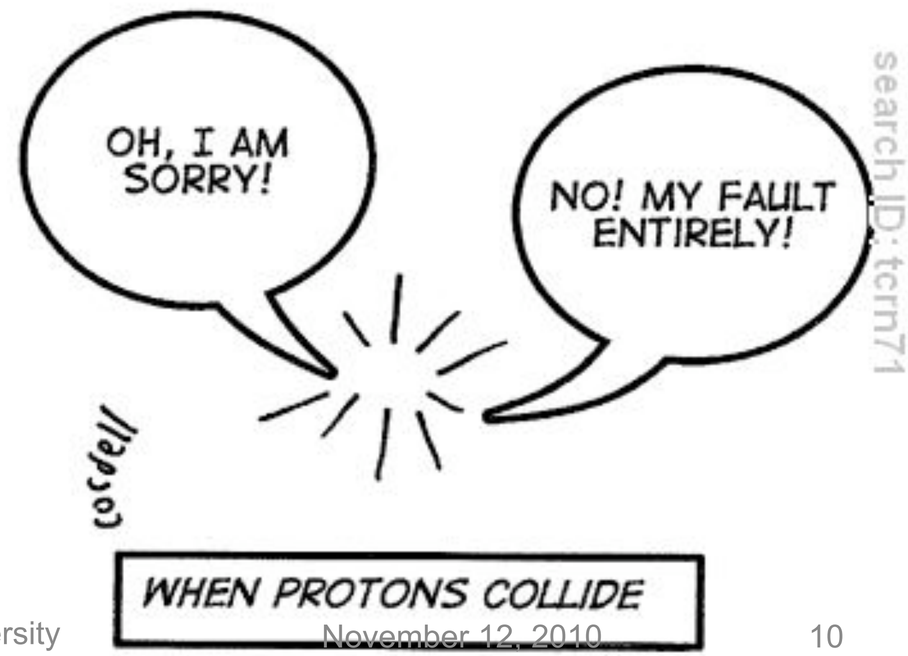
The LHC will push back to the energies of the early universe to address some of these questions

How do colliders work?



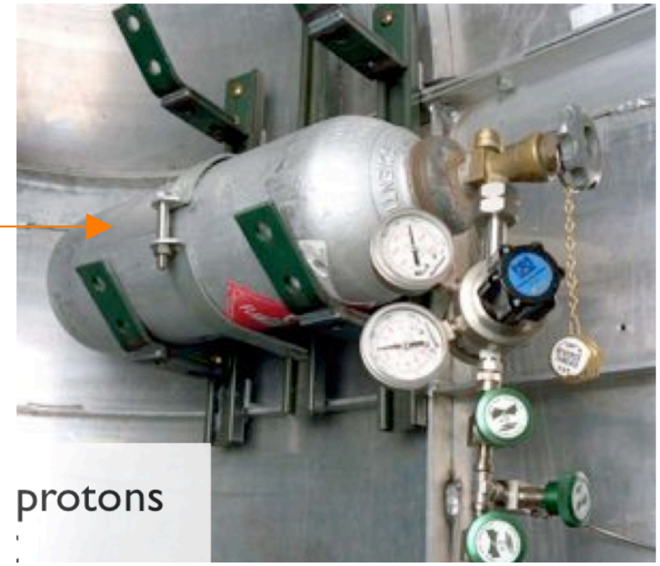
- They use $E = mc^2$
- Accelerate particles to near the speed of light and smash them together. Their kinetic energy and mass energy combine to create heavy particles.
- At the LHC, protons are accelerated and the quarks inside them collide. The total energy will be E = 14 TeV.





What do you need?

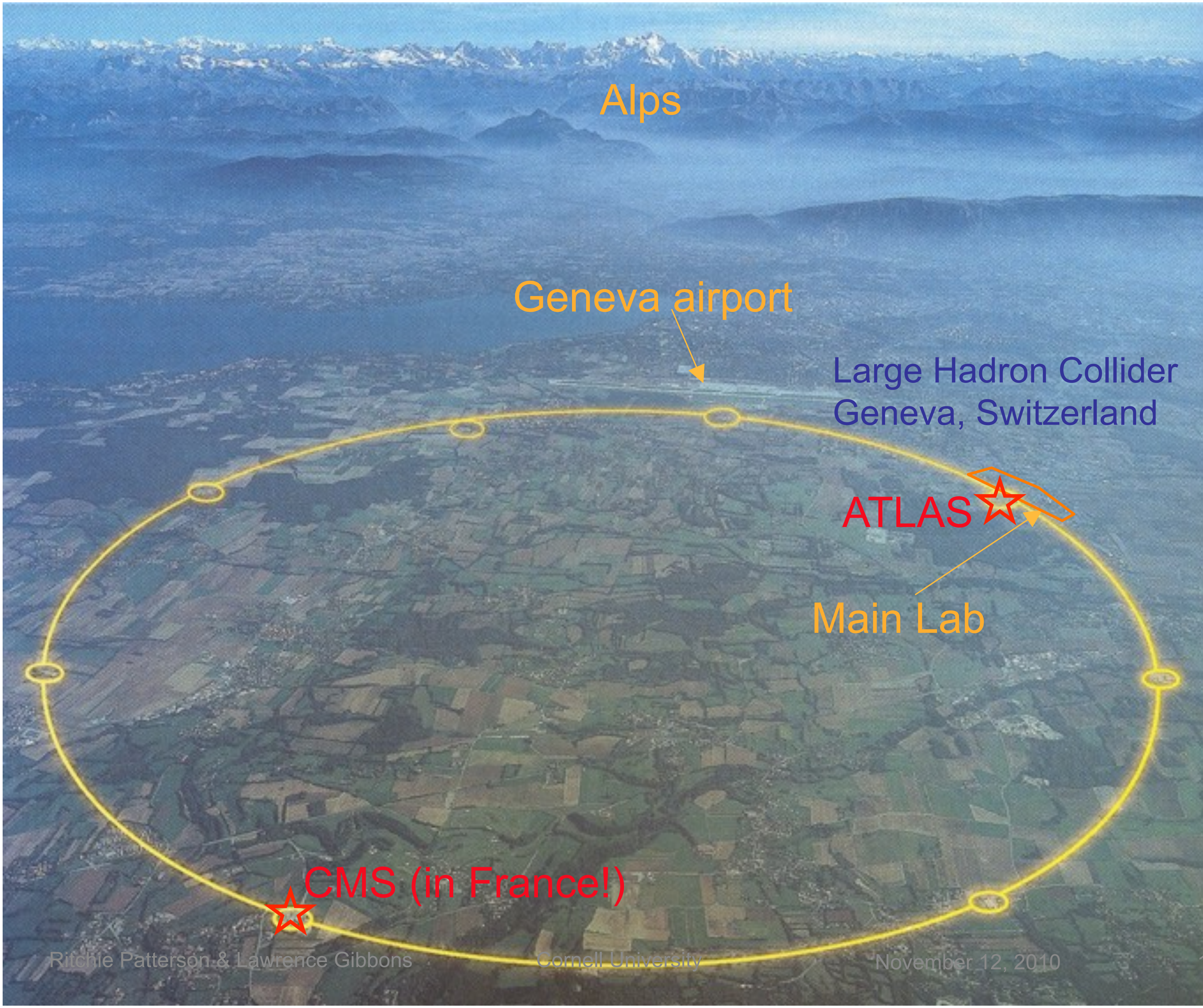
- Lots of protons to smash together
  - Proton source (hydrogen tank)

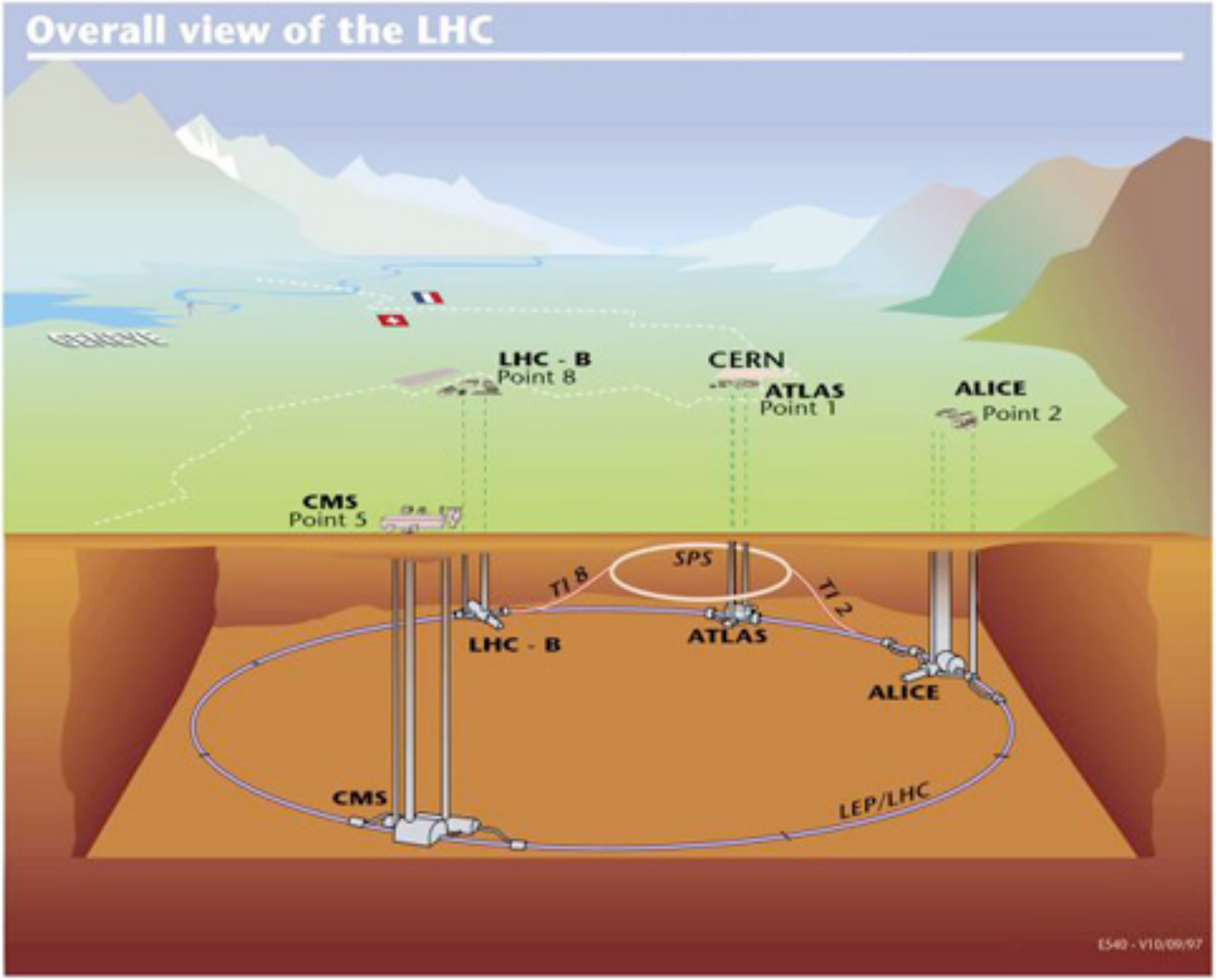


- Mechanism for accelerating them
  - Protons at the LHC travel at 99.99% of the speed of light

- Racetrack (ring) for storing and colliding beams of protons
  - Only a couple of protons interact each time the beams collide, so we collide them over and over again.

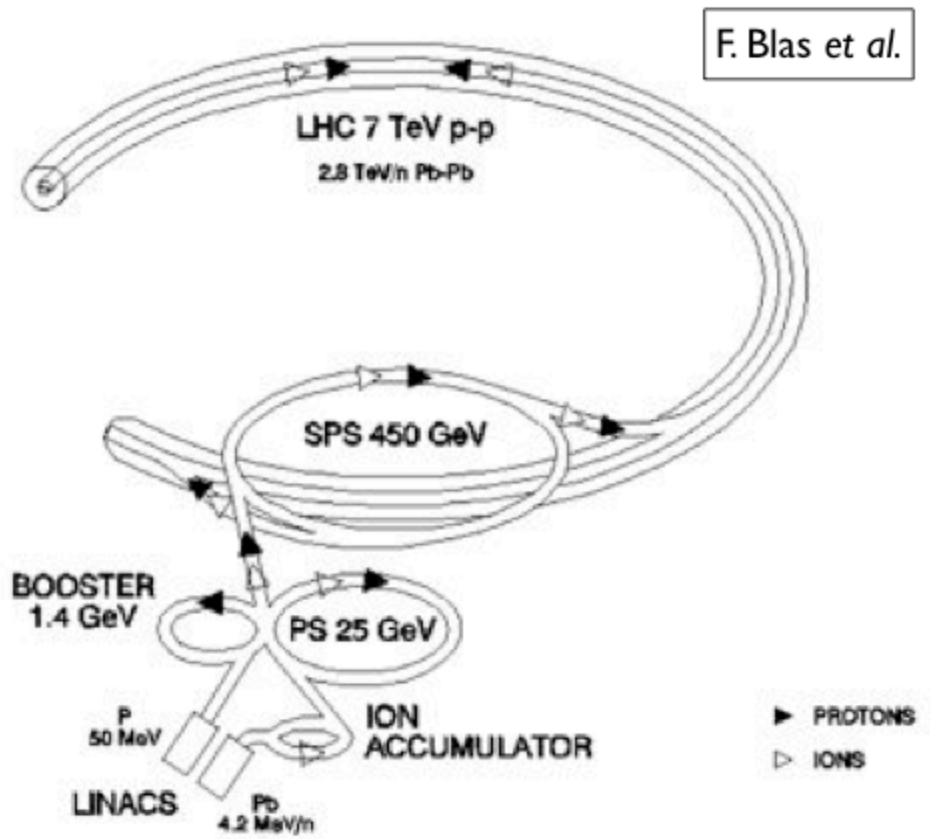
- Detector to observe, and disentangle the collision products

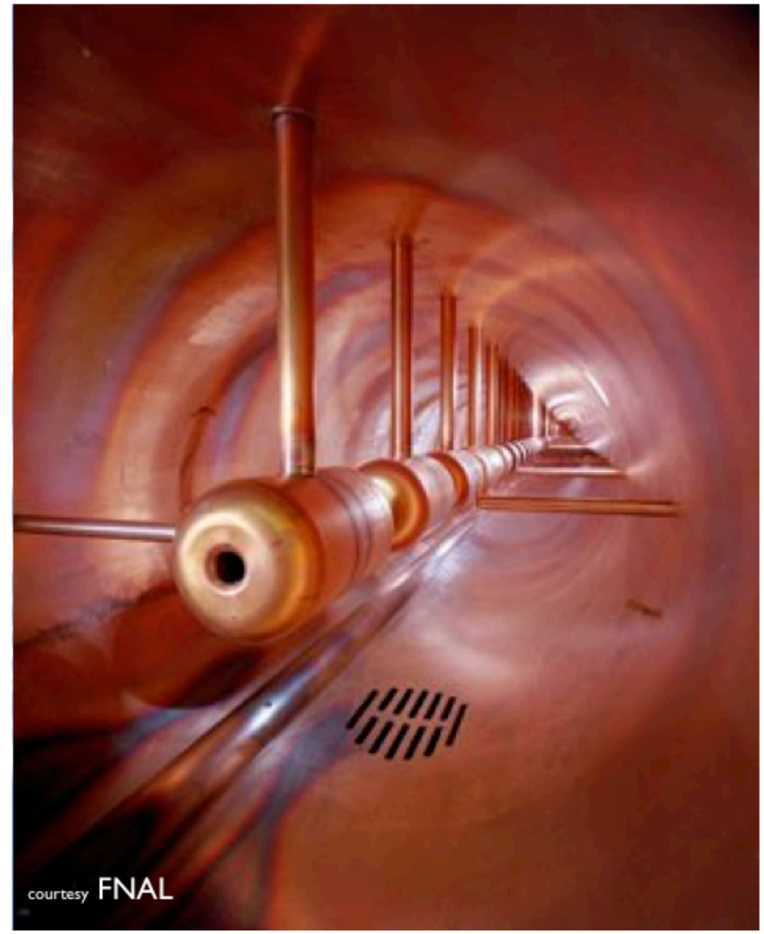

Alps
Geneva airport
Large Hadron Collider
Geneva, Switzerland
ATLAS
Main Lab
CMS (in France!)


Overall view of the LHC
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
E540 - V10/09/97

The ring

Electric and magnetic fields accelerate and steer the beams





- **Beams are in 2808 bunches, each with 1.15 x 10^{11} protons**
- **Total energy in each beam is 360 MJ (equivalent to 60 kg TNT)**

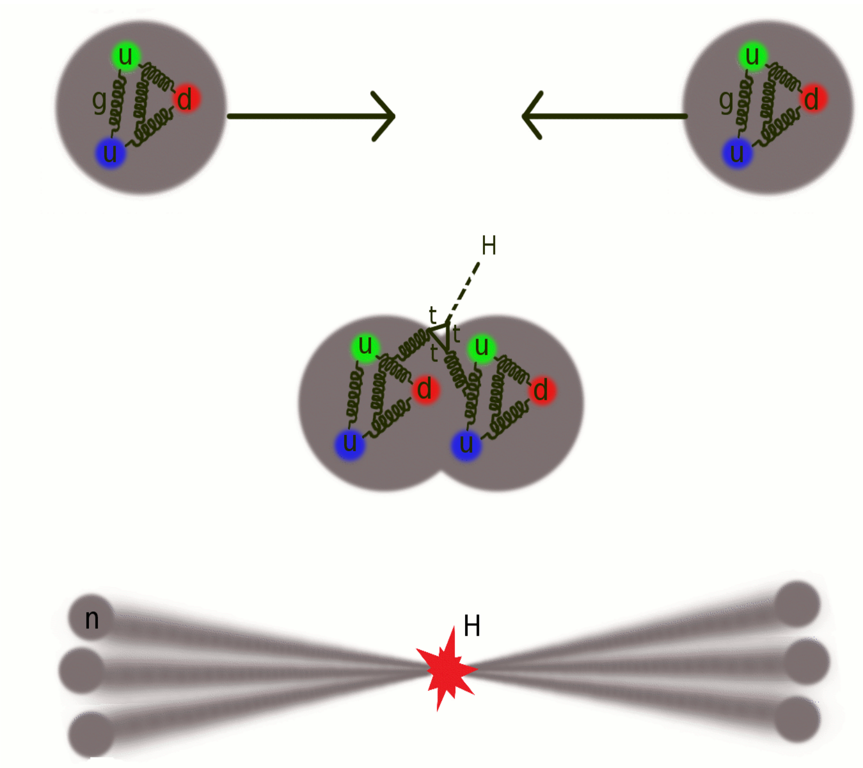
LHC Steering Magnet

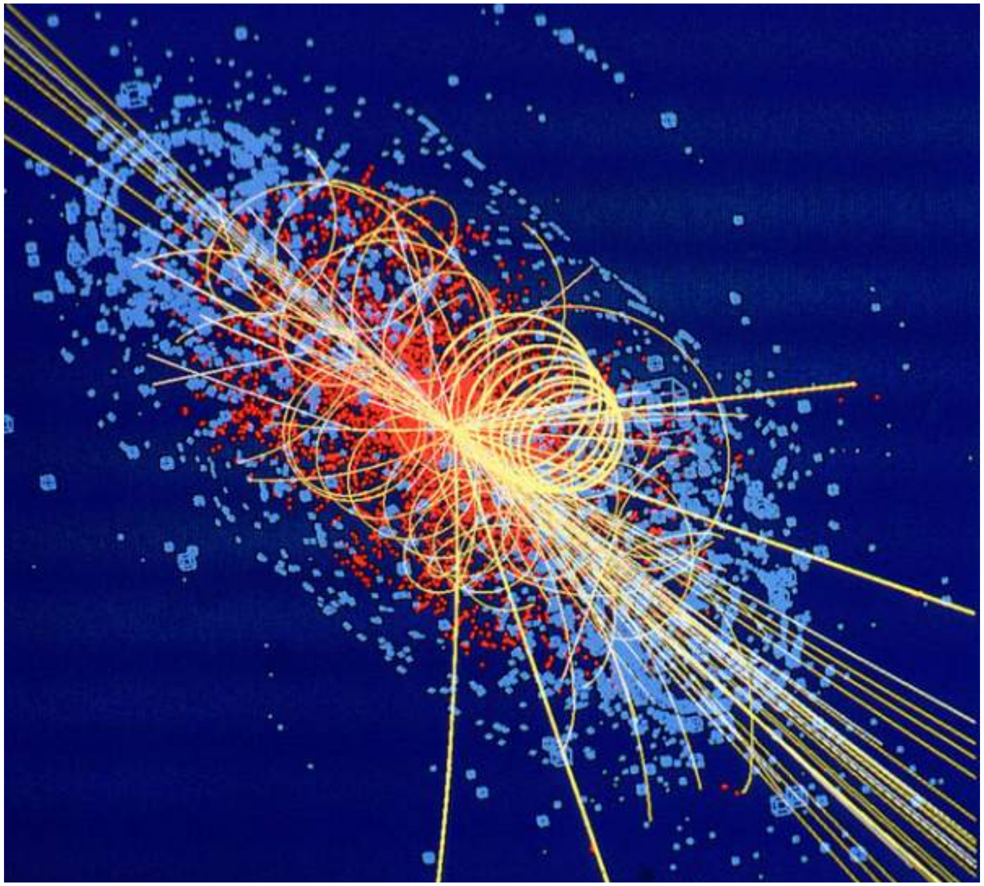
The last one being lowered into place

The magnets

- Steer the protons around the 17 mile circular track
- Are superconducting with a field of 8.3 Tesla
- Use 96 tons of superfluid helium

Proton-proton collision



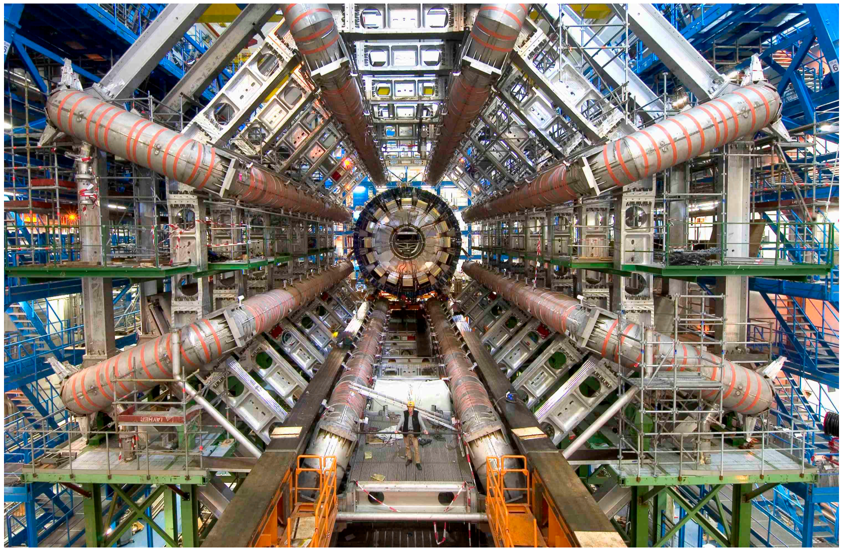


Particle detectors

CMS

- Heavy particles produced in the collisions typically decay within 10^{-24} seconds into particles we know and love: electrons, muons, pions, etc.
- The detector records traces of these well-known and well-understood particles.

ATLAS

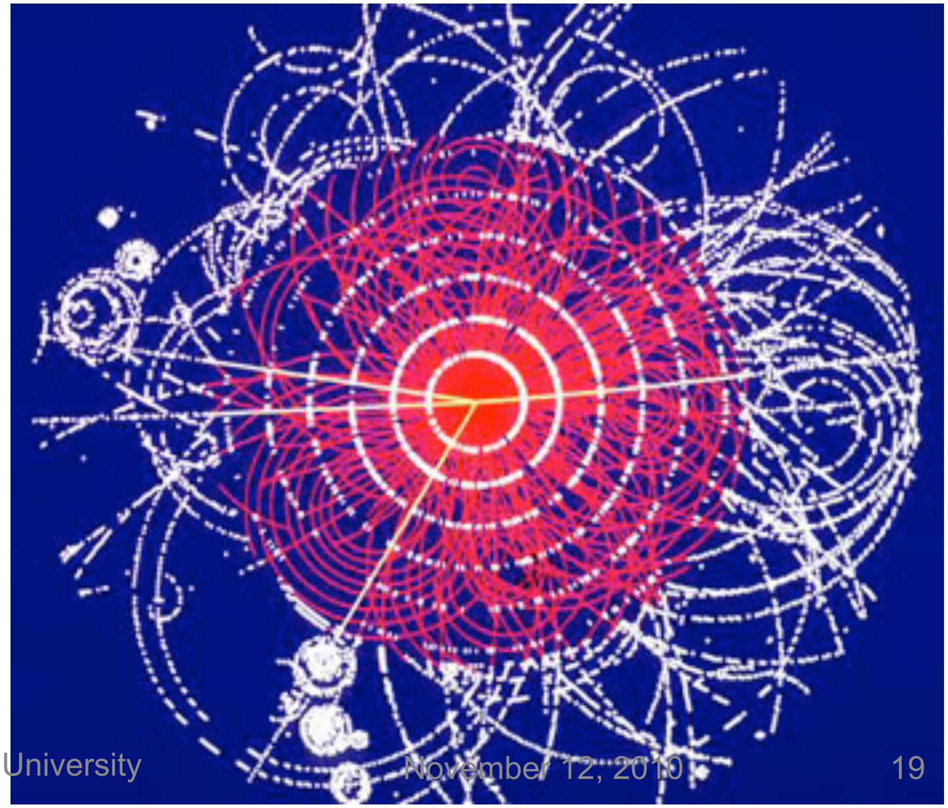


What do we want from our detector?

Imagine that a bomb explodes mid-air, and you want to study the fragments to find out everything you can about the bomb.

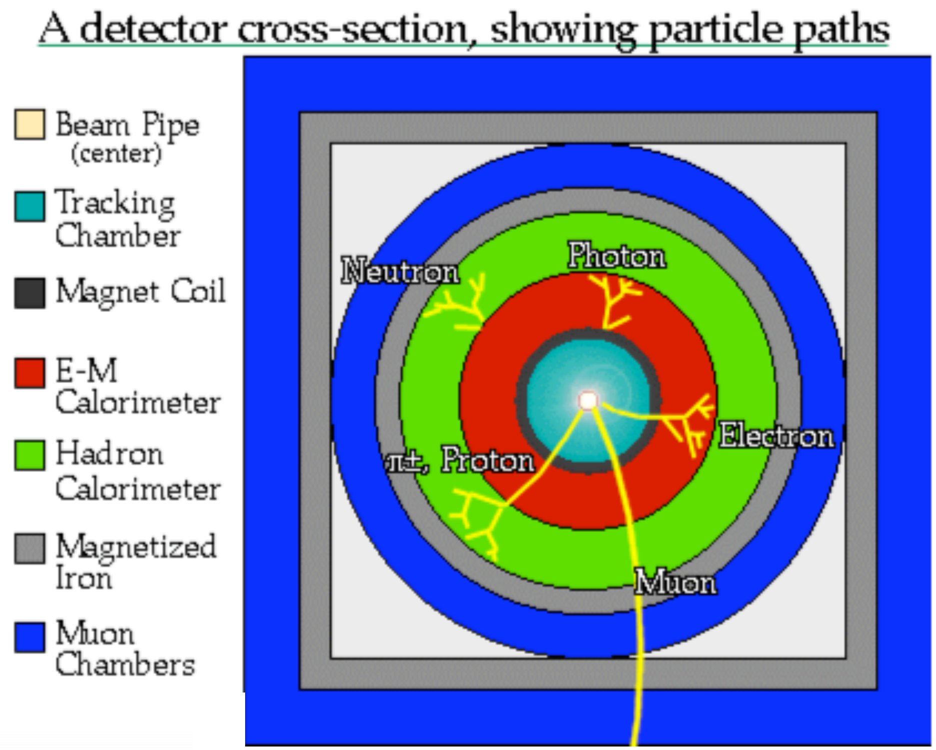
What properties of the fragments would you want to measure?

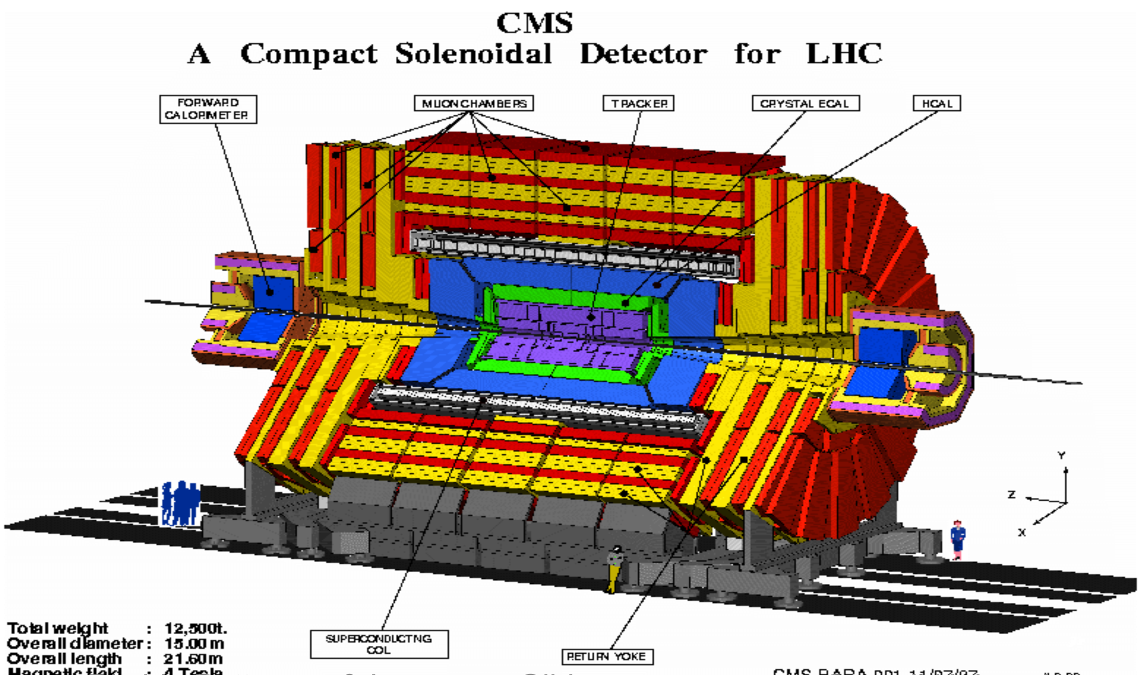
- **Direction of motion of each fragment just after explosion**
- **Speed (or momentum) of each fragment**
- **Mass of each fragment**



CMS Detector at the LHC

- CMS stands for “Compact Muon Solenoid”
- Weighs 12,500 tons
- Six stories tall

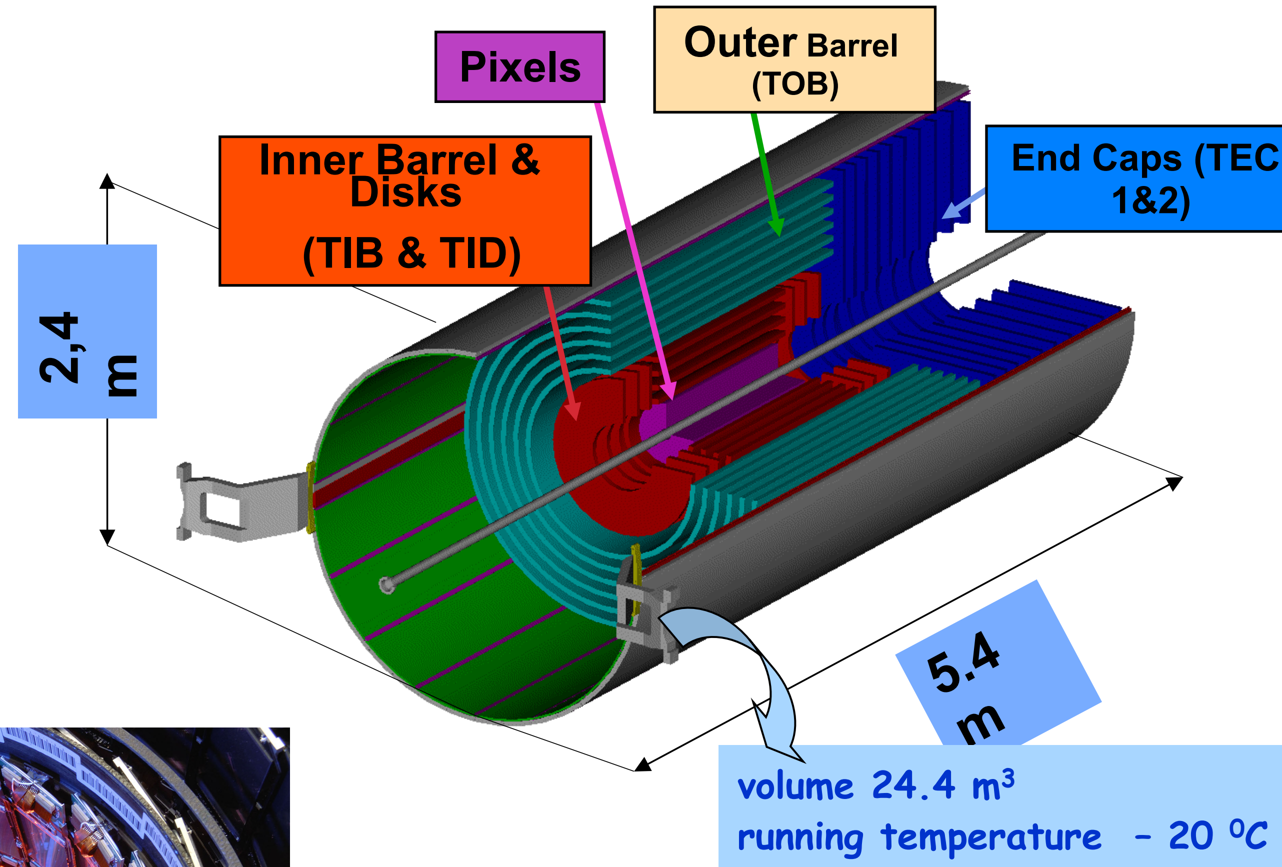


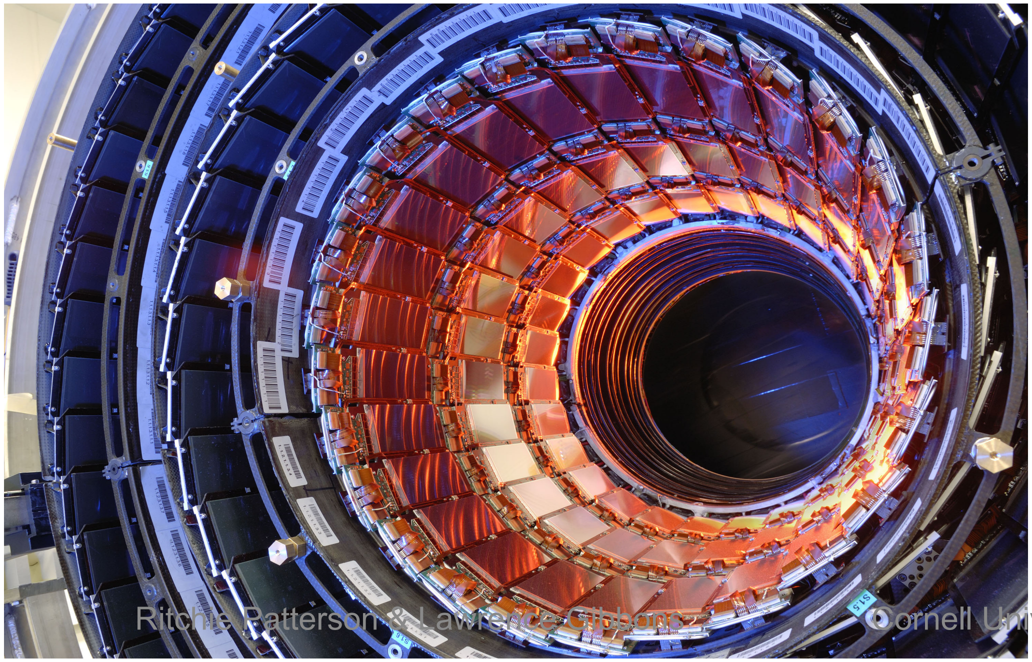


CMS is “compact” because its diameter is 60% that of ATLAS, the other big LHC detector. But CMS weighs 1.7 times more.

CMS Tracker

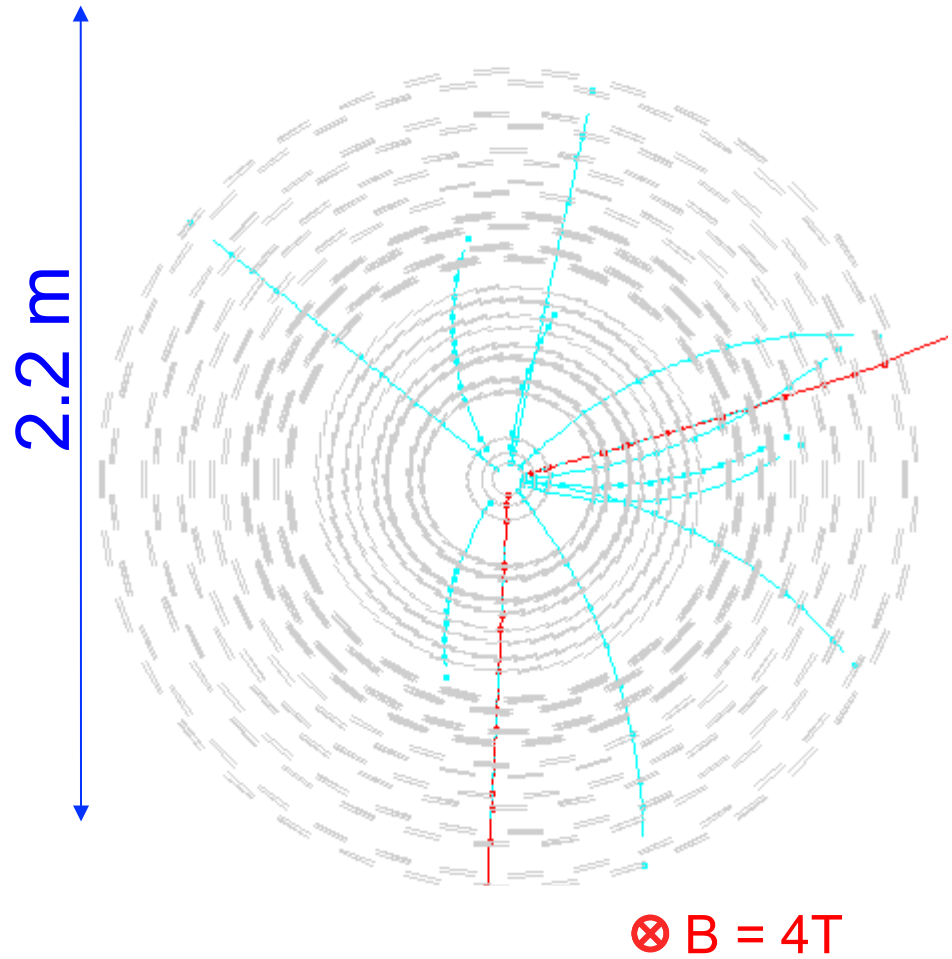
- Solid state detector
- Charged particles produce a signal (or "hit") on each layer
- Resolution is 10-60 microns per hit

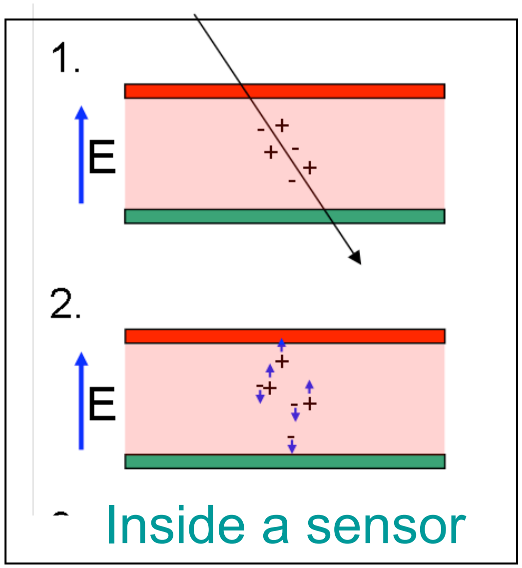




Immersed in 4 Tesla solenoidal magnetic field … Why?

Particles in the tracker



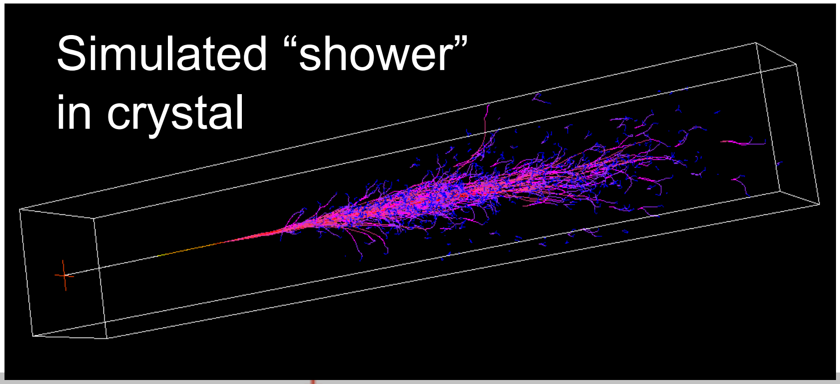


Which particle(s) have the greatest momentum?

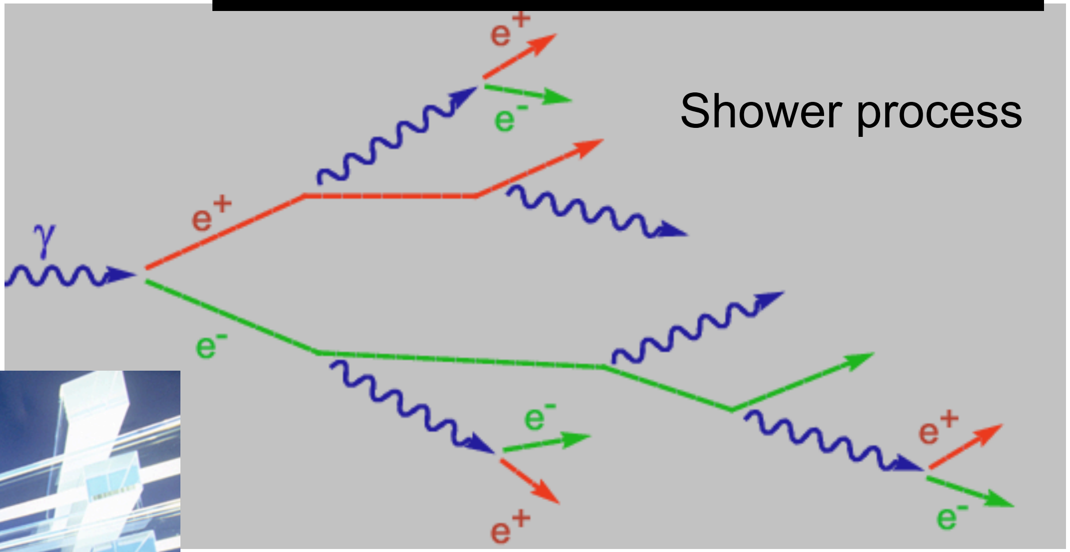
The smallest?

Which have positive electric charge?

Electromagnetic Calorimeter

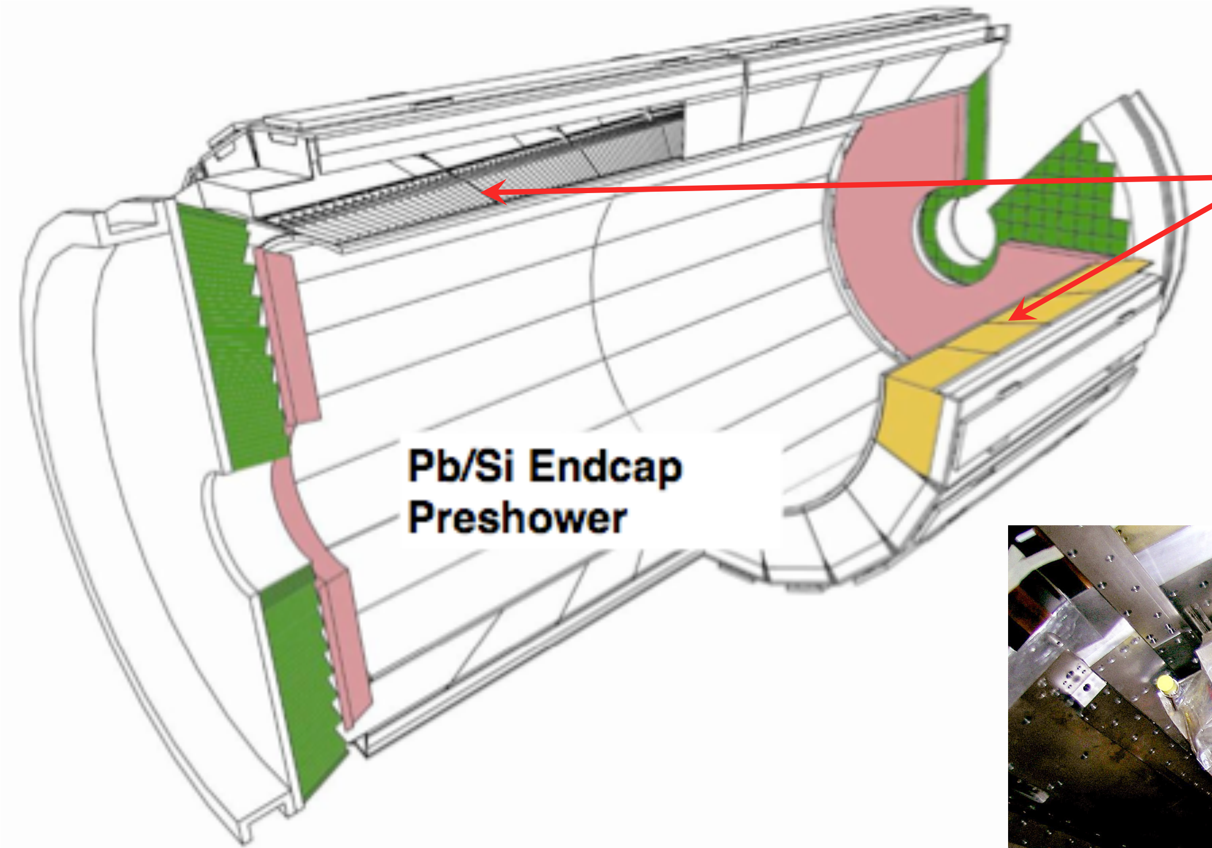


Absorbs electrons and photons to measure their energies



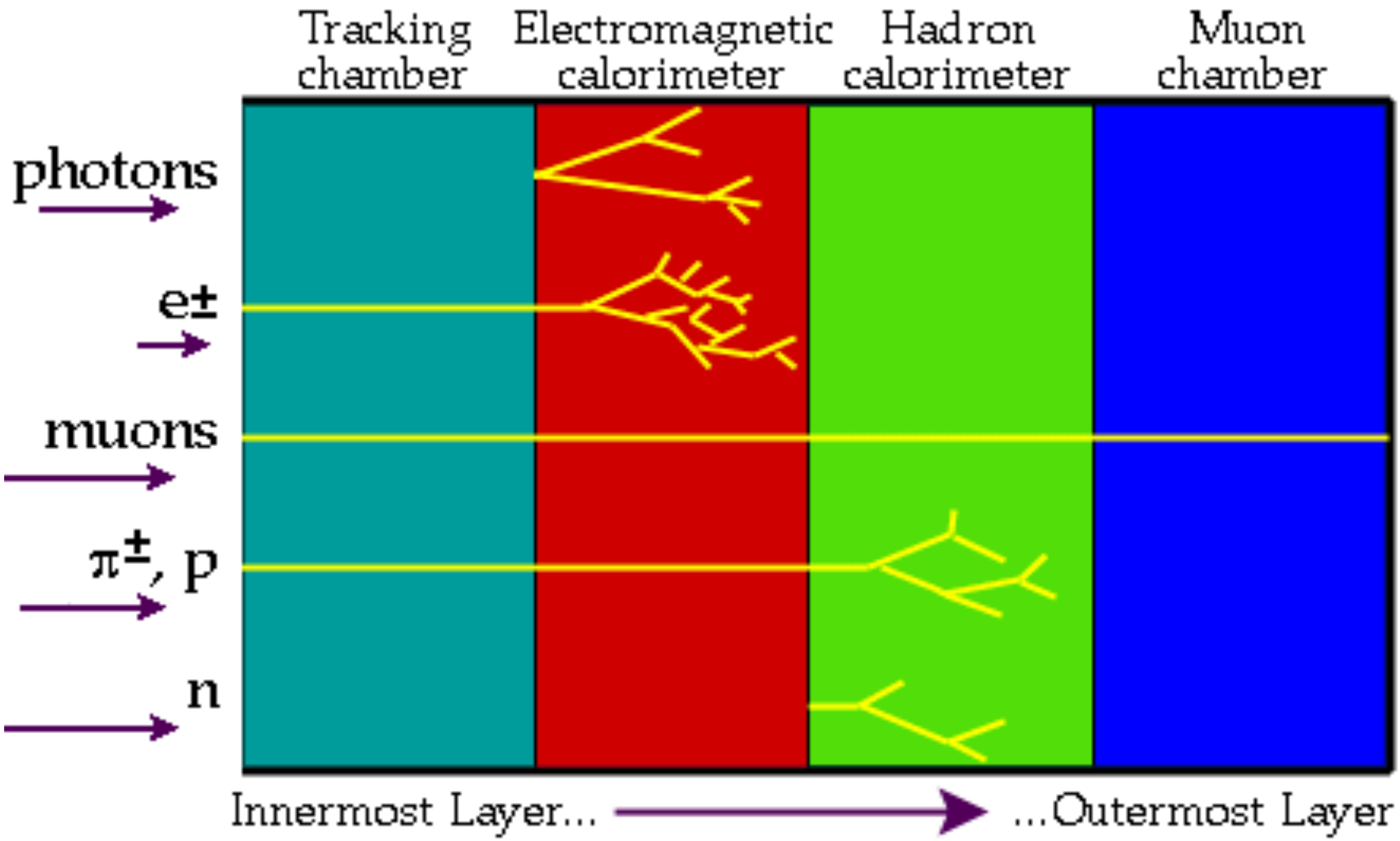
Shower particles produce scintillation light, detected at the back of the crystal

Electromagnetic calorimeter

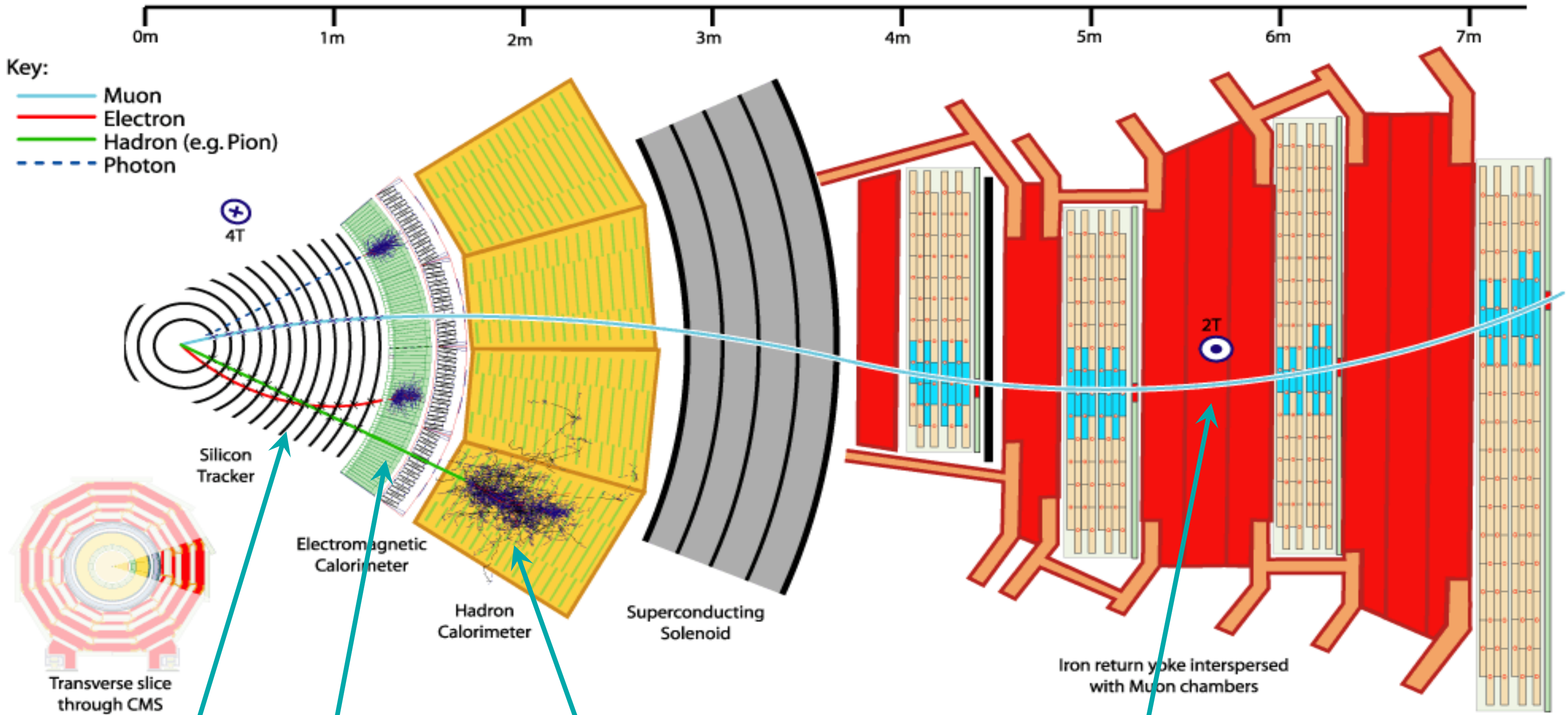


76,000 Lead-tungstate crystals

Each particle species leaves a distinct trail



Slice of CMS



Charged particles

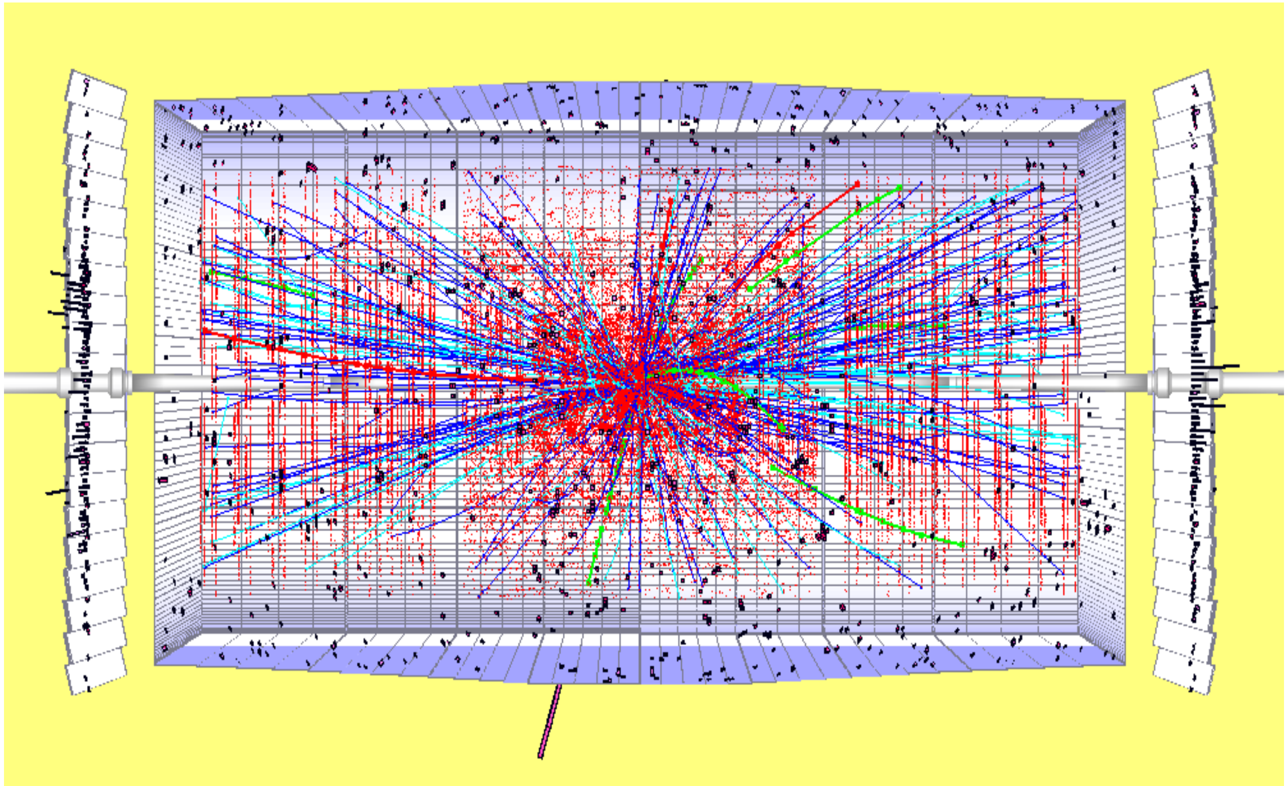
Electrons Photons

Particles made of quarks

Muons

Computing

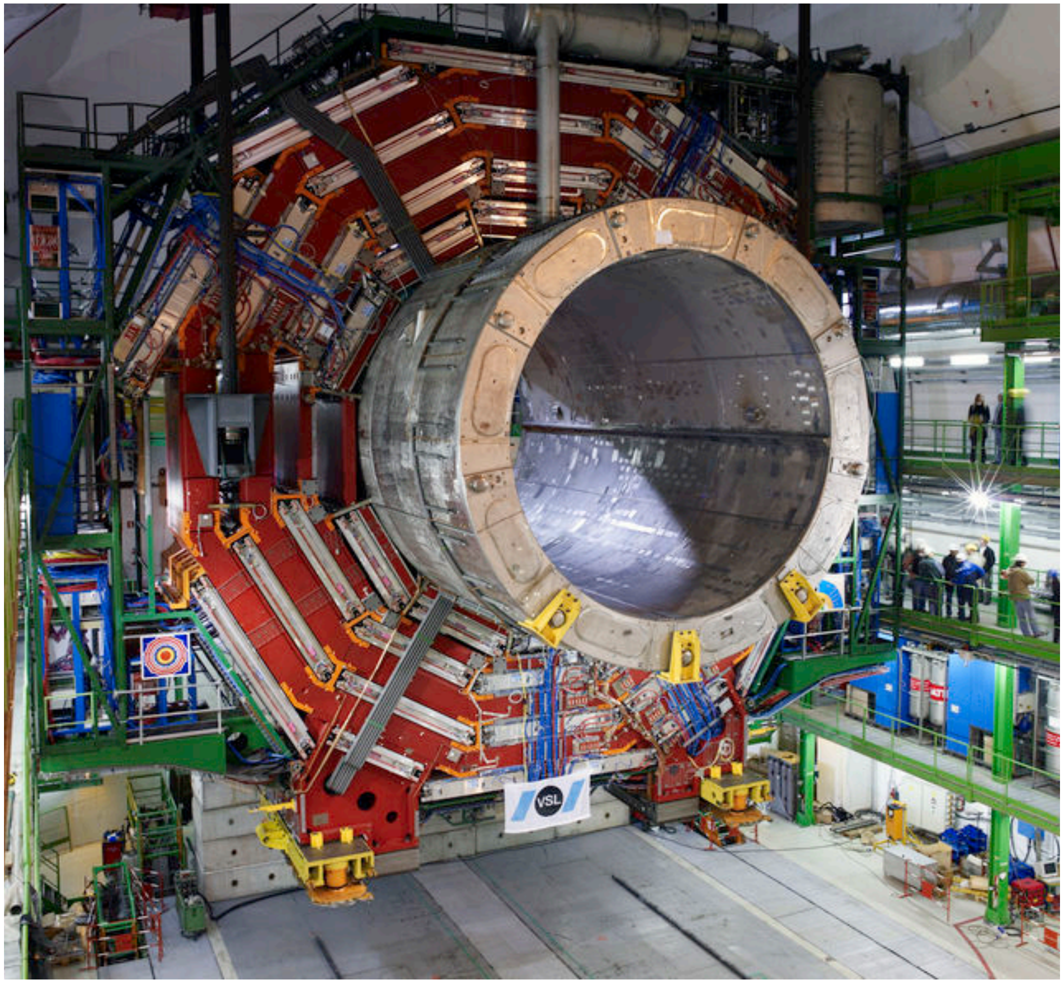
- 15 Petabytes of data per year
- Tiered computing structure
- Achieved data transfer rates of 110 Gbps
  - the world record



CMS Cavern

92 meters underground

Installing CMS



- Components were built on the surface and then lowered via crane.
- This is the largest one, weighing more than 2000 tons.
- After lowering, they move on air pads.

LHC timeline

Sept 10, 2008 First beam circulates

Sept 19 Technical failure

Electrical short between super-conducting magnets heats liquid helium causing overpressure and catastrophic vacuum failure. 53 magnets damaged.

Magnet repair
Quench protection upgrade

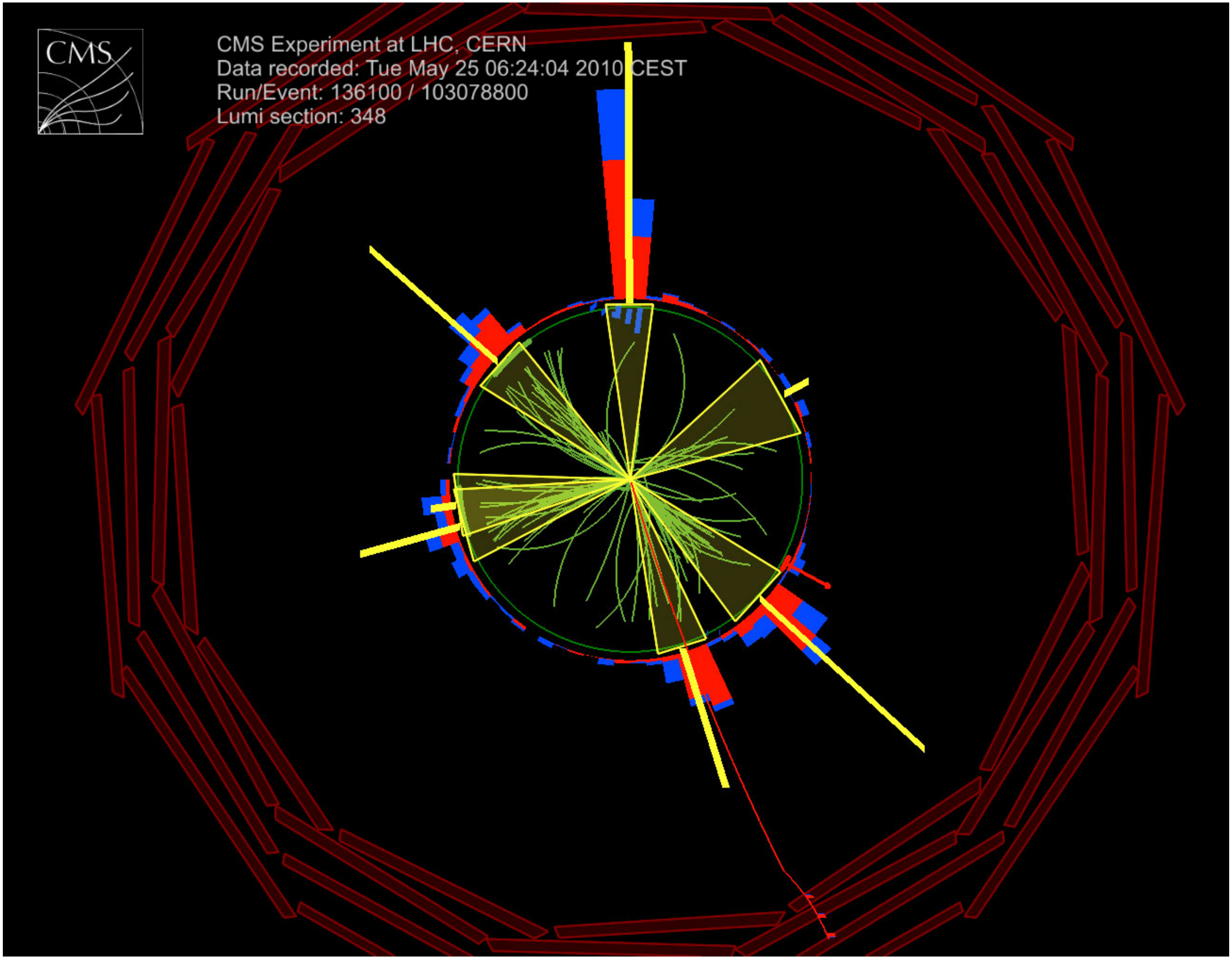
Nov 20, 2009 Beam circulates again!
Nov 23 First collisions 0.9 TeV
Dec 14 Collisions 2.36 TeV

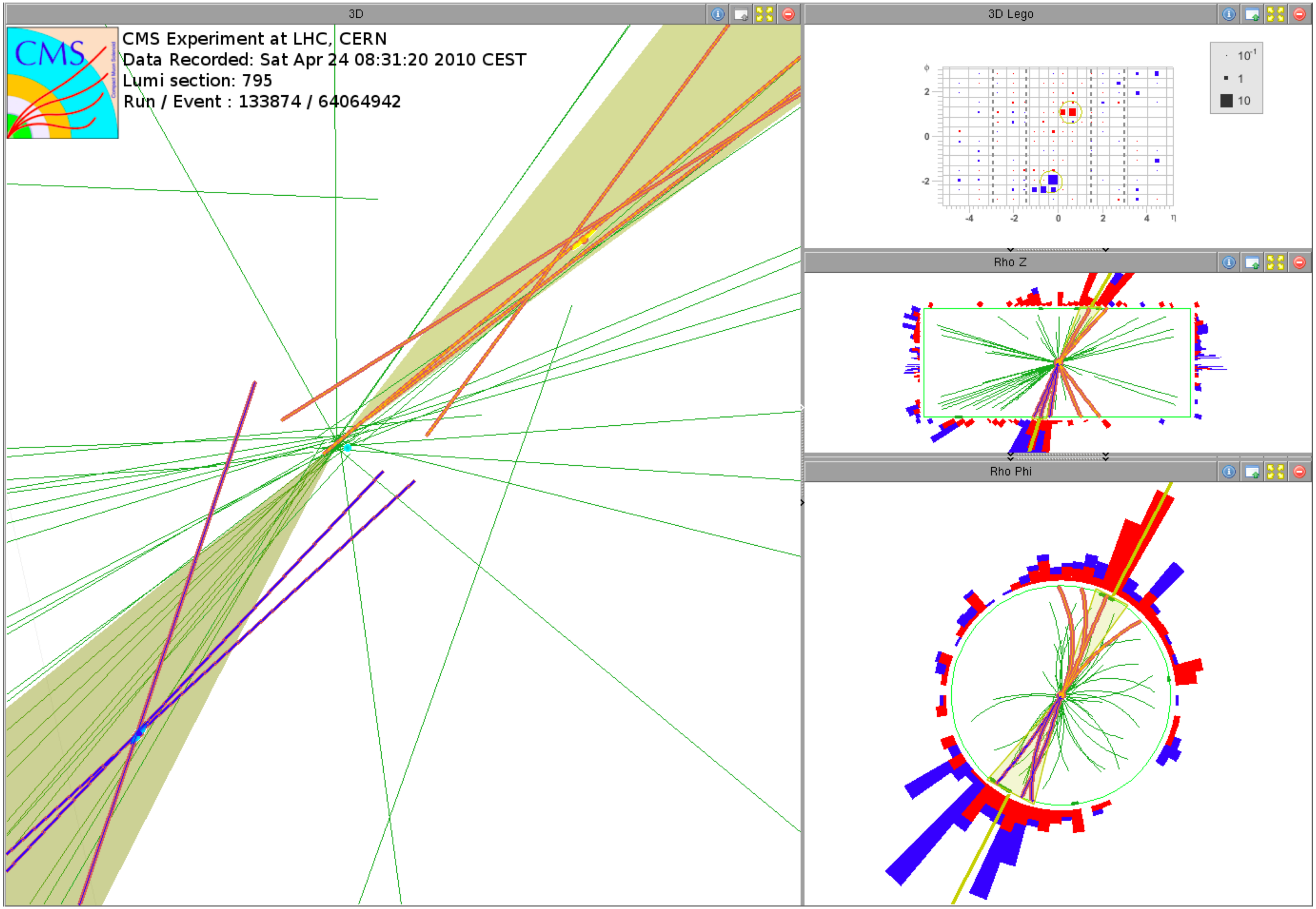
Mar 30, 2010 Collisions 7 TeV

Now

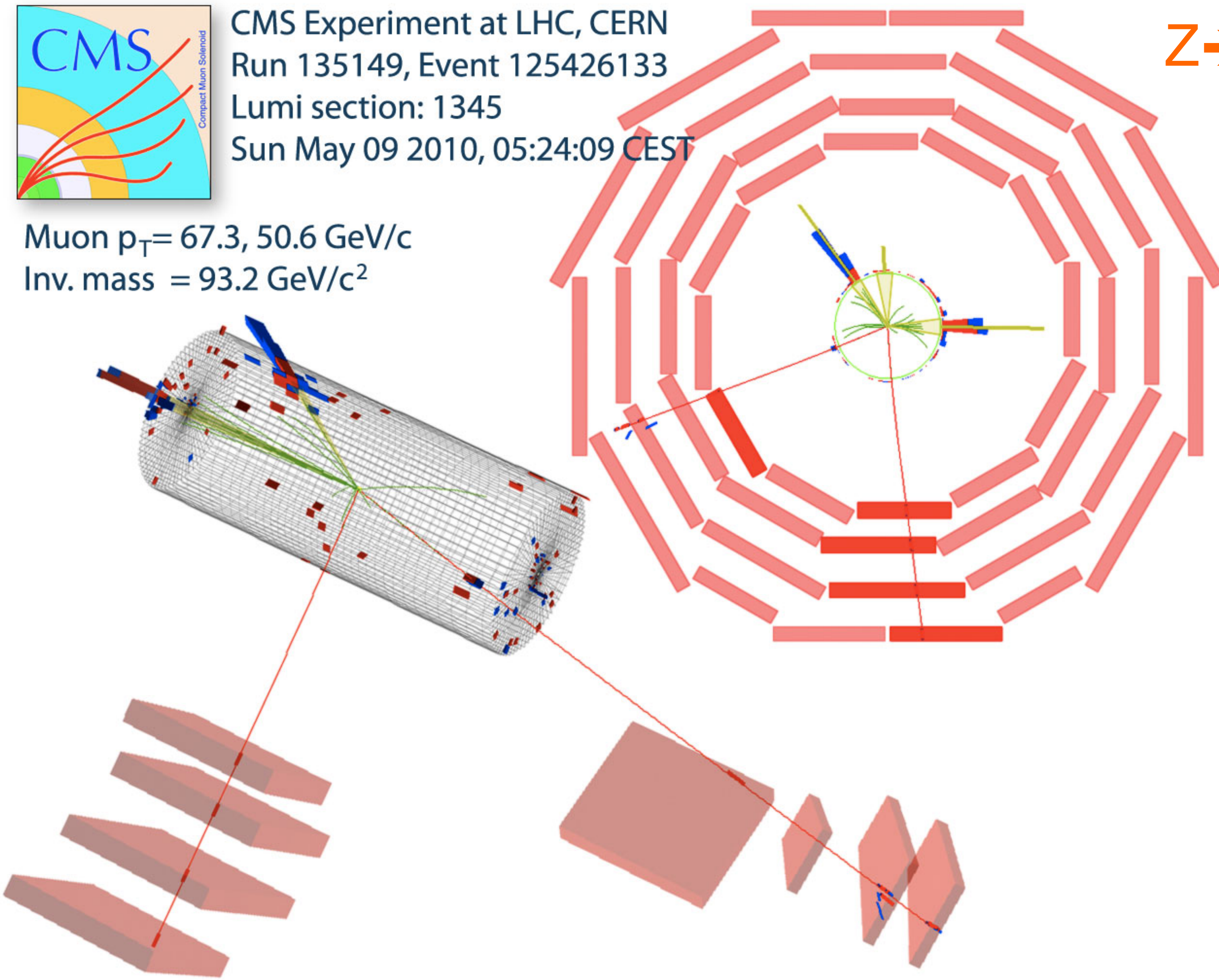
Plan: steady running

~Dec 2011 Shutdown for improvements toward 14 TeV (design)


CMS
CMS Experiment at LHC, CERN
Data recorded: Tue May 25 06:24:04 2010 CEST
Run/Event: 136100 / 103078800
Lumi section: 348


3D
CMS Experiment at LHC, CERN
Data Recorded: Sat Apr 24 08:31:20 2010 CEST
Lumi section: 795
Run / Event : 133874 / 64064942
3D Lego
Rho Z
Rho Phi

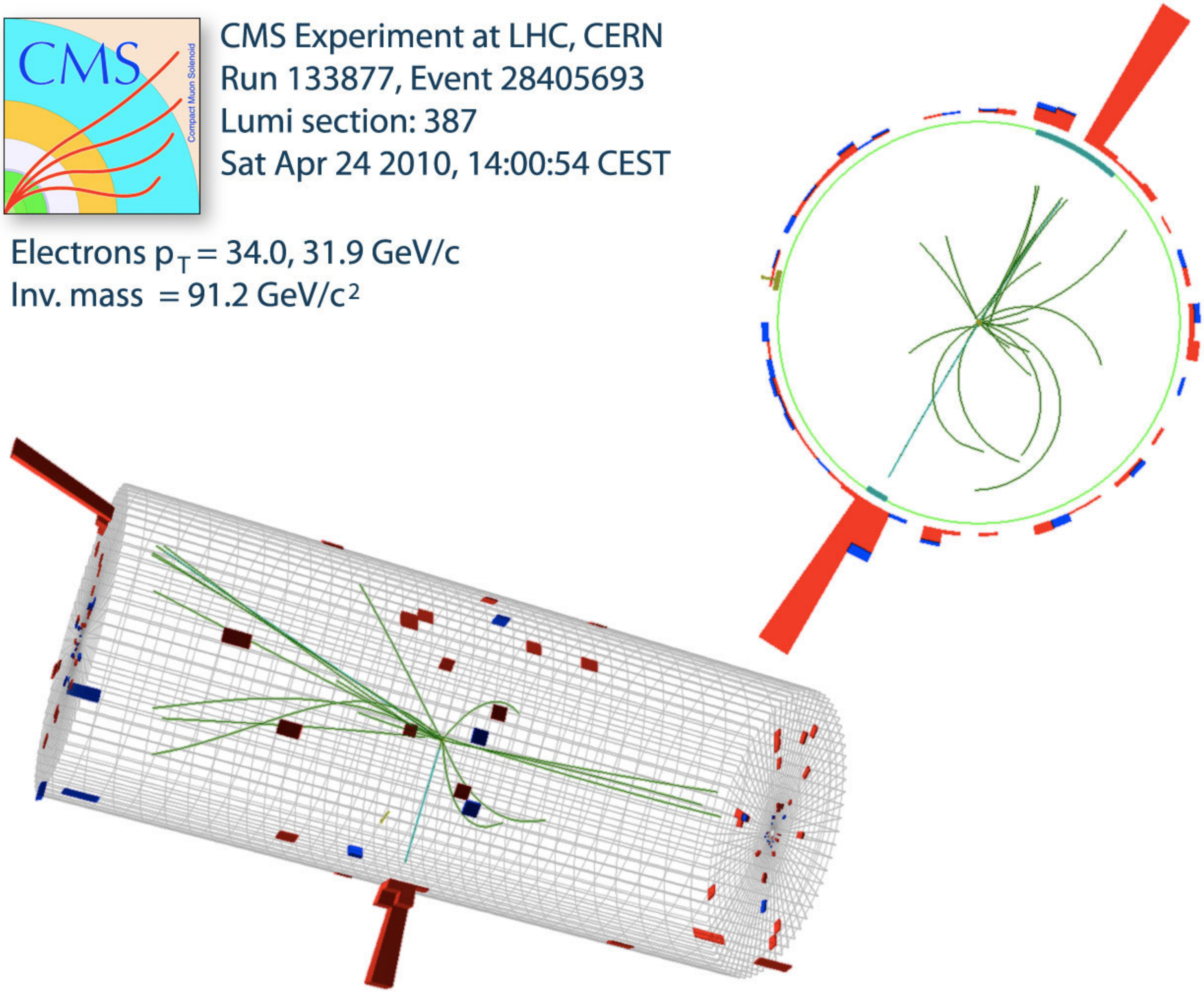
$Z \rightarrow \mu\mu$



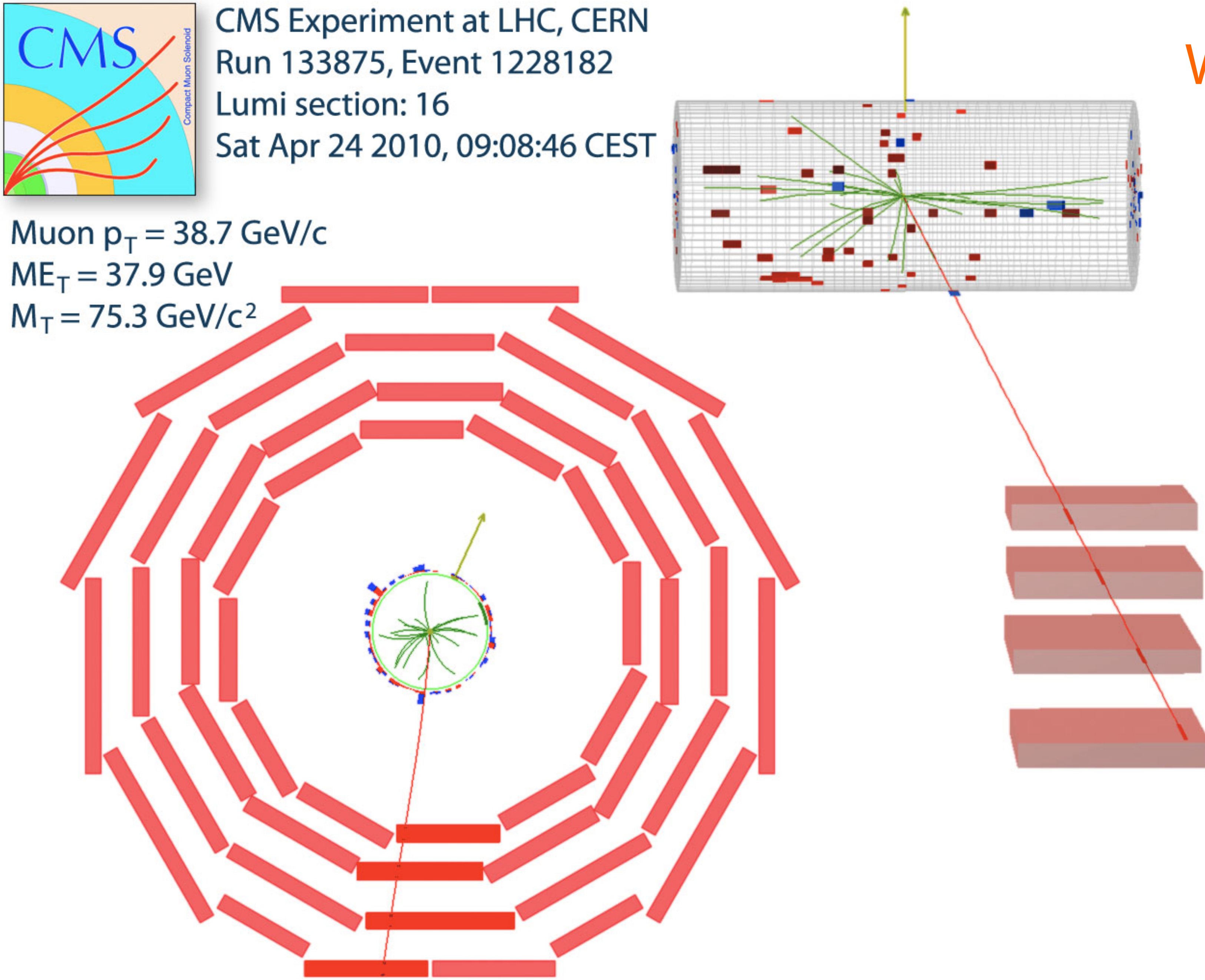
Z→ee

CMS Experiment at LHC, CERN
Run 133877, Event 28405693
Lumi section: 387
Sat Apr 24 2010, 14:00:54 CEST

Electrons p_T = 34.0, 31.9 GeV/c
Inv. mass = 91.2 GeV/c^2



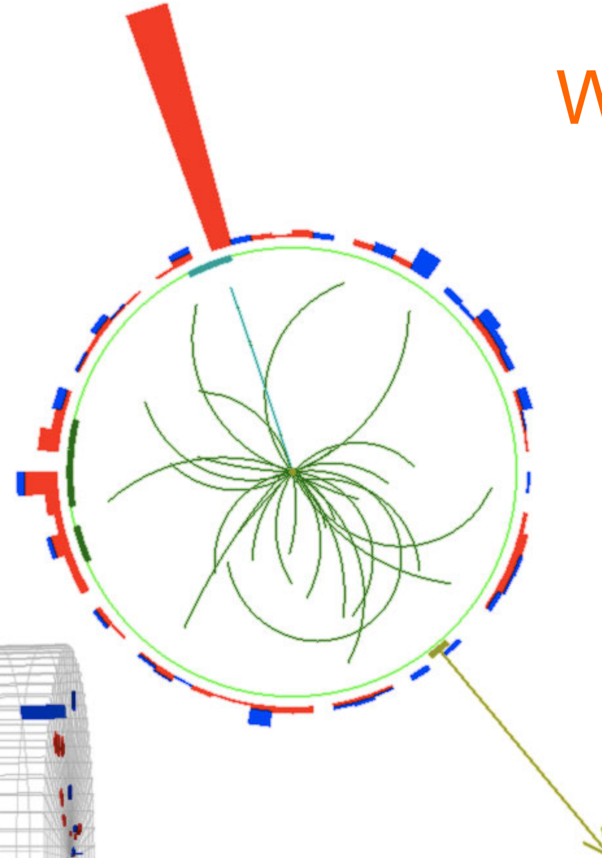
$W \rightarrow \mu\nu$

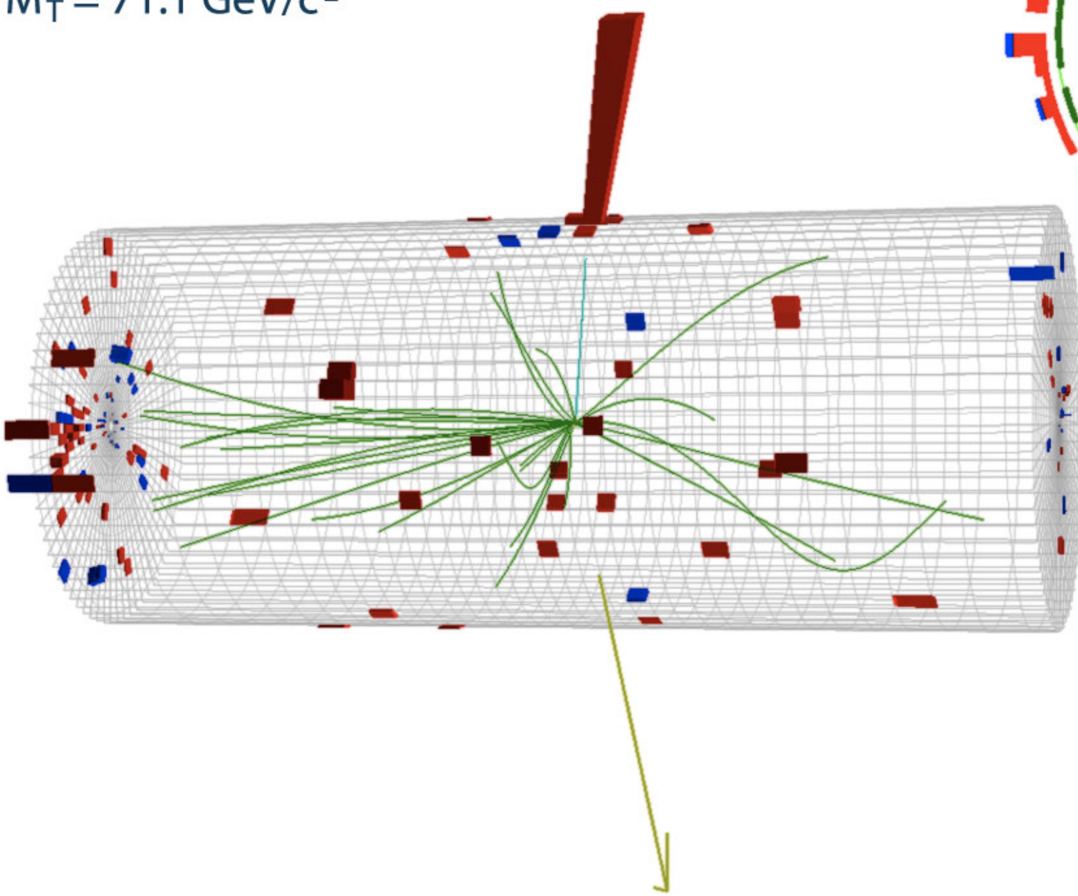


CMS Experiment at LHC, CERN
Run 133874, Event 21466935
Lumi section: 301
Sat Apr 24 2010, 05:19:21 CEST

$W \rightarrow e\nu$

Electron $p_T = 35.6$ GeV/c
$ME_T = 36.9$ GeV
$M_T = 71.1$ GeV/c^2





Results so far

- Momentum and angular distributions of particles produced in proton collisions

- Identification of familiar particles

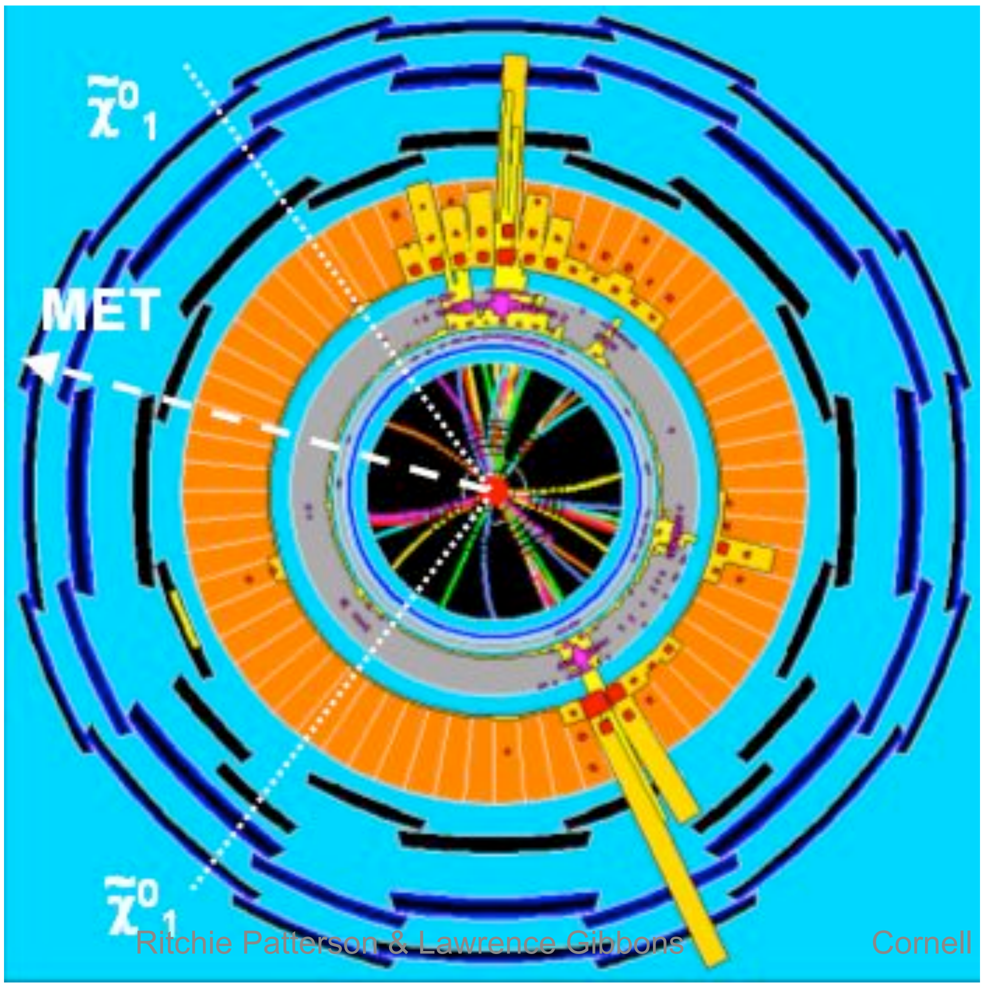
- Results will probe deeper in the future:

  - With more collisions, you can see rarer, heavier particles. (Important for detecting higgs)

  - Better calibration of the detector allows more nuanced analysis. (Important for seeing dark matter).

Finding Dark Matter

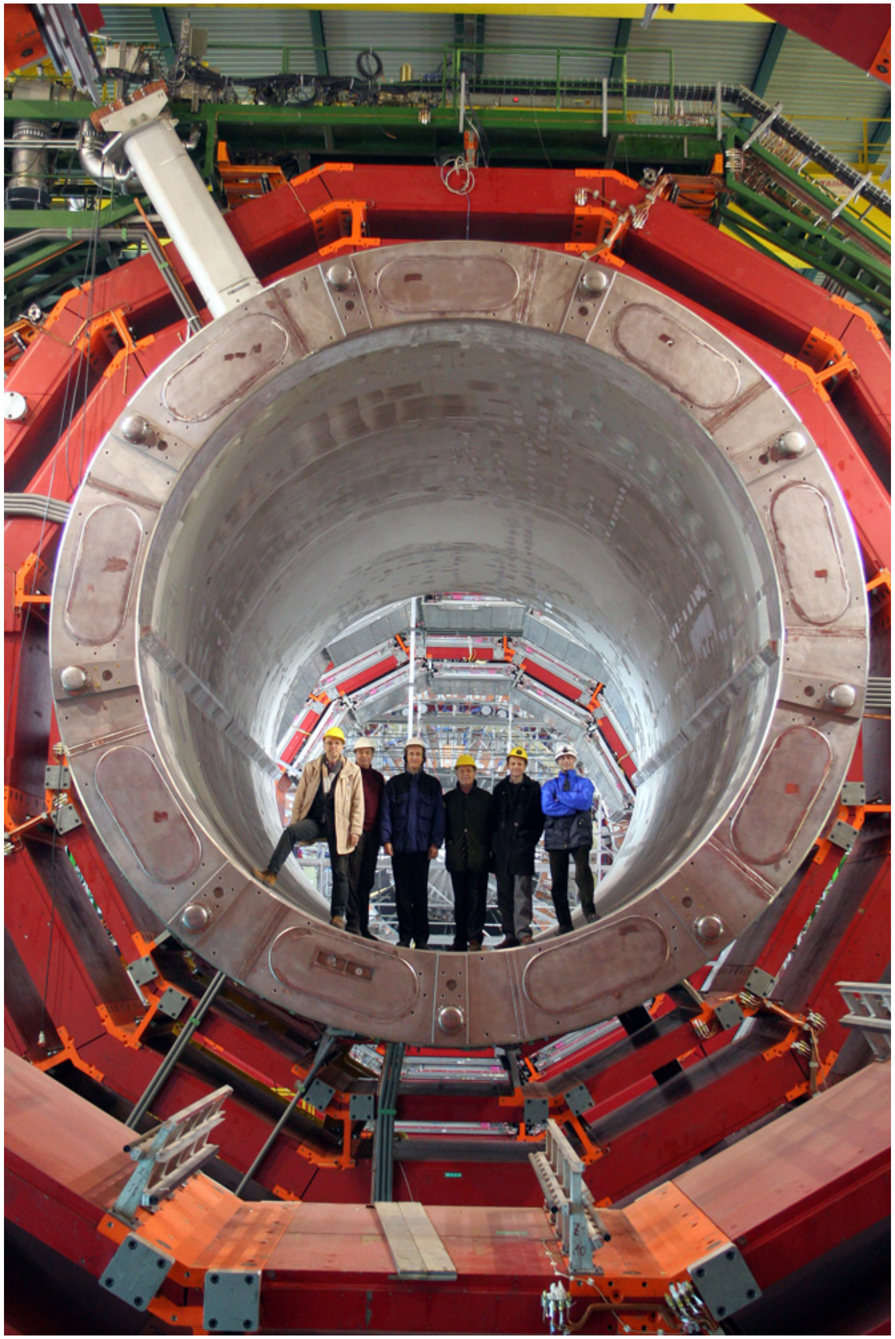
- **Leaves no trace in detector**
- **Find via momentum imbalance of detected particles: $\sum p \neq 0$**



This is a simulation of dark matter in ATLAS

This event is modeled based on a candidate theory called supersymmetry.

Other theories give similar momentum imbalance.



Conclusions

The LHC is now operating and CMS and ATLAS are working well.

First results have been published (more soon). More collisions and results will come over the next few years.

They will explore energies not seen since moments after the big bang.