CMS at the LHC: The TeV Frontier

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What is CMS?

Compact

- As small as possible to keep costs down

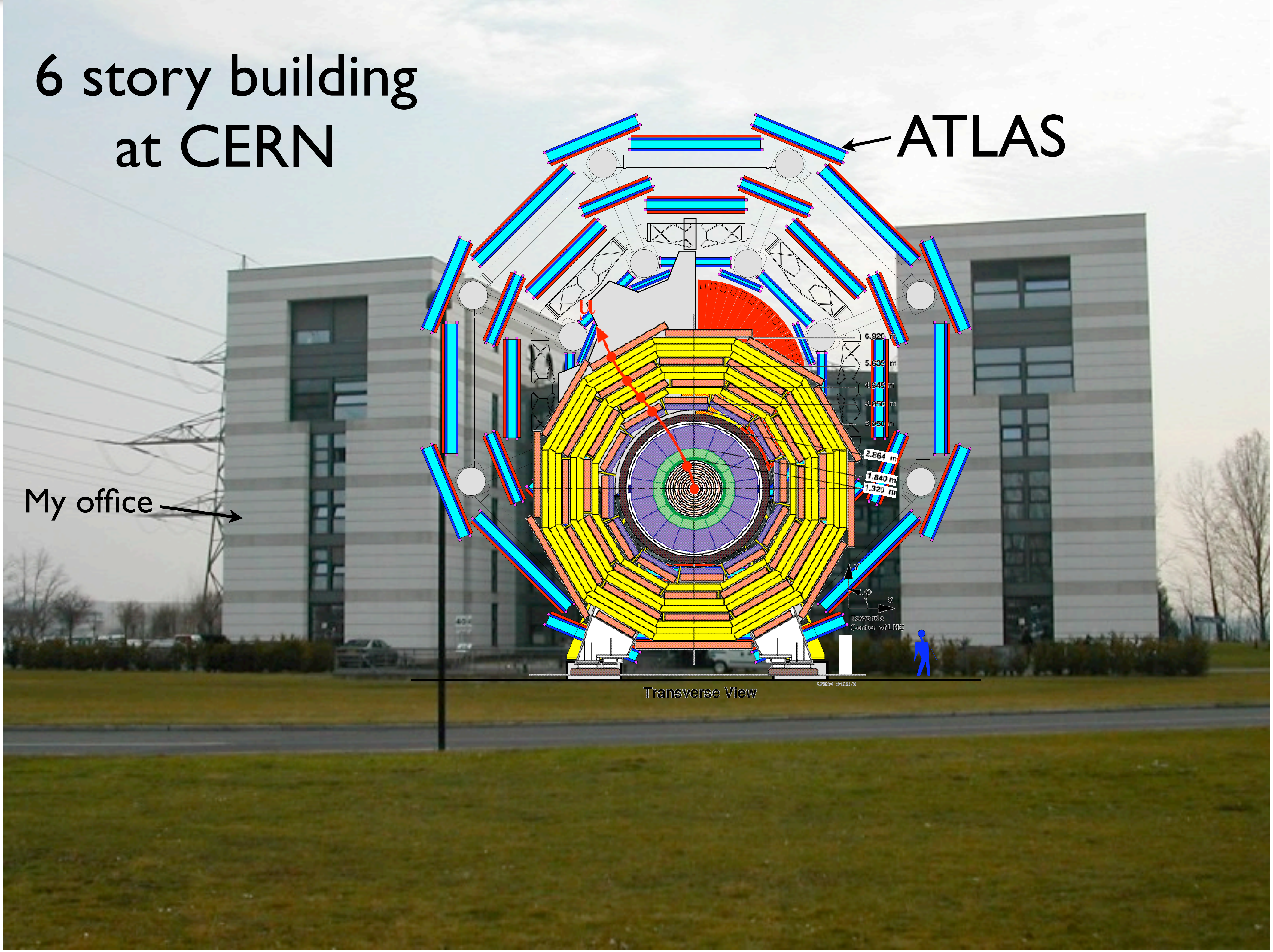
Muon

- Muons are an excellent probe for new physics
  - Used in the discovery of (among many others):
    - J/Ψ, ϒ, W, Z, top quark

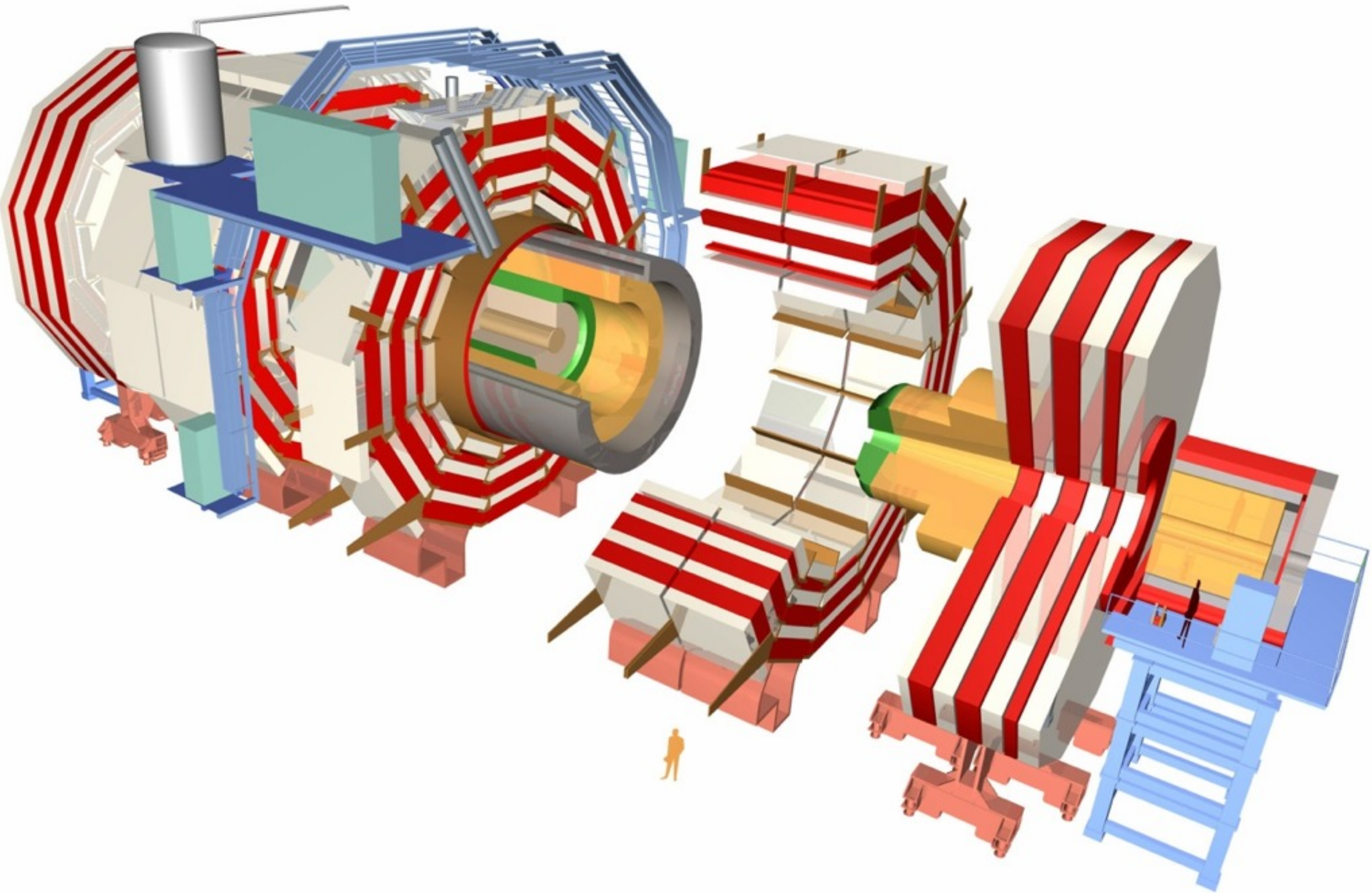
Solenoid

- Need a magnet to analyze the momentum of charged particles
- Most experiments have a central solenoid
- The CMS solenoid is one of the major elements of the overall detector design

Compact, but not small!



"Exploded" view of CMS



Physics Goals of CMS and the LHC

To look for:

- New particles, such as the Higgs (predicted by the Standard Model), Supersymmetric particles (a lot of theorists like them), gravitons (quantum gravity), mini black holes, completely unexpected ones

To understand:

- why the world is the way it is
- why some particles weigh more than others (top is 350,000 times more massive than an electron)
- what is dark matter (quarks & leptons are only 4% of the universe!)
- are there more dimensions of space (we know of 4: *x*, *y*, *z*, *t*)
- the properties of the hot, dense matter that existed in the early universe

Particle Detectors

Cannot directly "see" the collisions/decay

- Interaction rate is too high
- Lifetimes of particles of interest are too small
  - Even moving at the speed of light, some particles (e.g. Higgs) may only travel a few mm (or less)

Must infer what happened by observing long-lived particles

- Need to identify the visible long-lived particles
  - Measure their momenta
  - Energy
  - (speed)
- Infer the presence of neutrinos and other invisible particles
  - Conservation laws – measure missing energy

Particle Momentum Measurement

Charged particles moving in a magnetic field curve

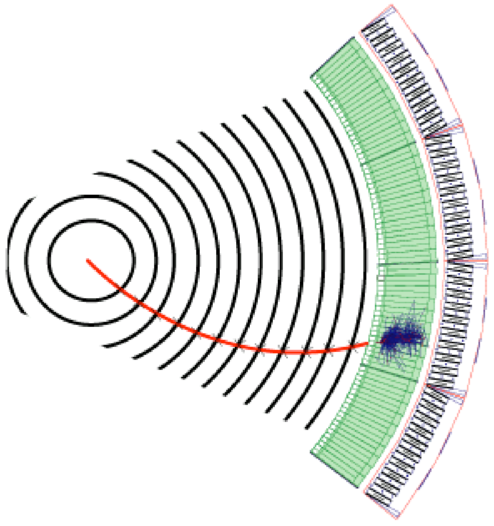
The radius of curvature is related to the momentum:

- $R = p/0.3B$
  - R in meters; p in GeV/c and B in Tesla.

The device measuring the curvature should disturb the particle as little as possible

- Need low mass detectors

Make many measurements and then join the dots!



Energy measurement: Calorimetry

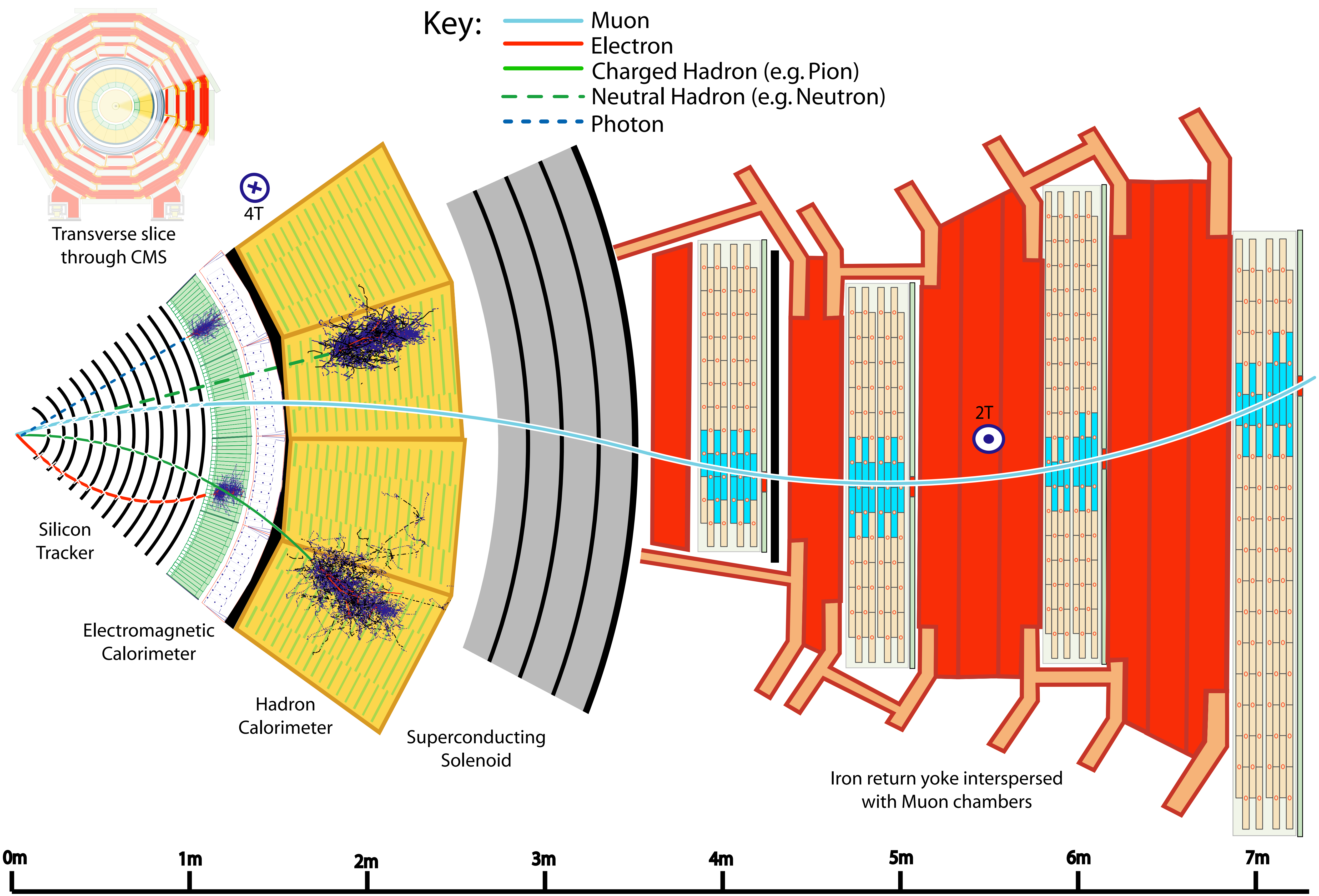
The idea is to 'stop' the particle and measure its energy.

Particles slow down via an energy loss mechanism that produces a 'shower' of other particles. The size of the shower is proportional to the energy of the original particle.

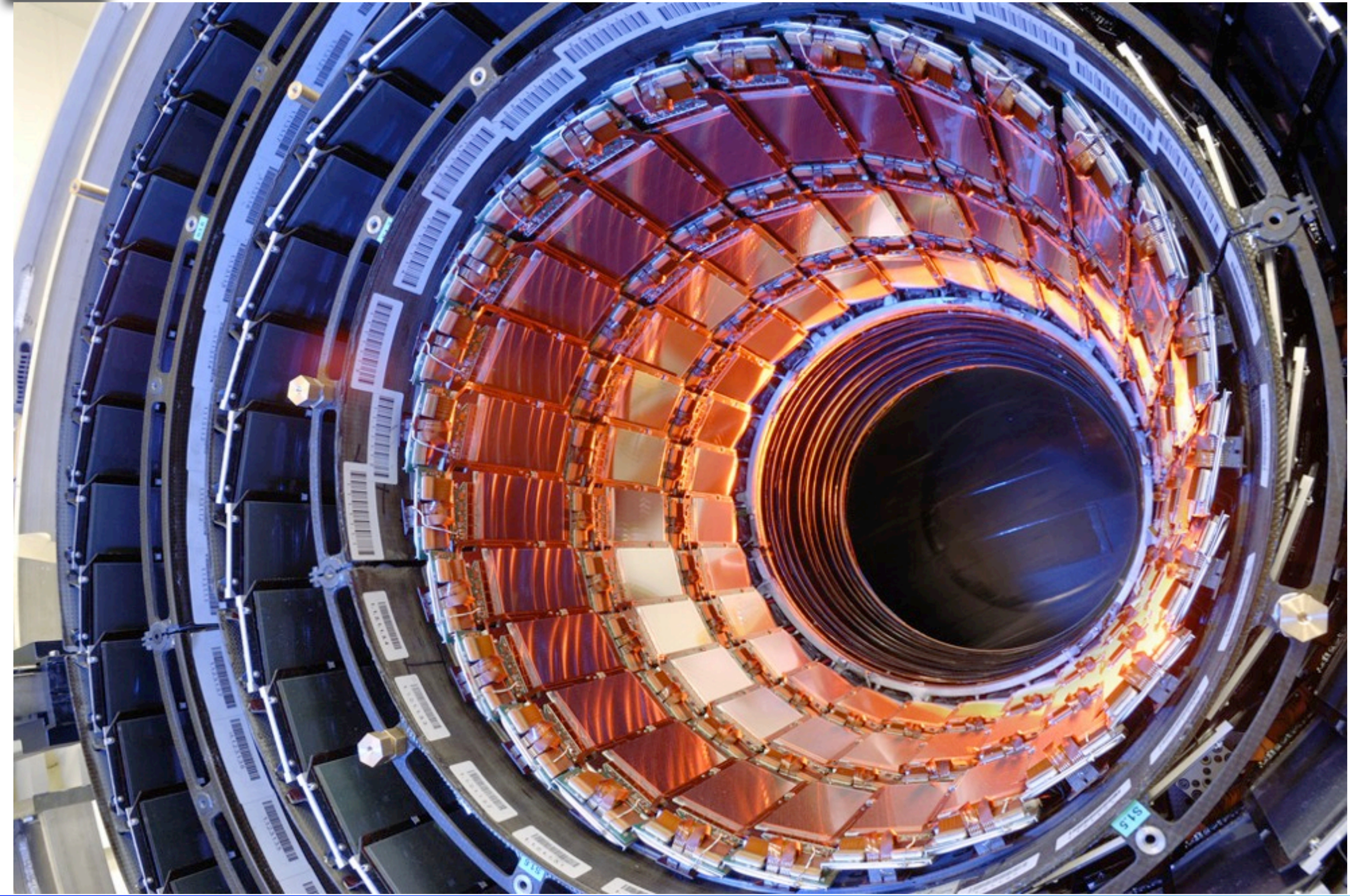
Two main methods to determine the size of the shower:

- Homogeneous detectors: the shower medium is also used to produce the signal that is measured. The CMS ECAL is an example.
- Sampling detectors: the shower develops in one material and the size is 'sampled' in another. The CMS HCAL is a such a detector.

Particle Identification in CMS



Silicon Tracker



Silicon Tracker

220 m^2 of silicon sensors - the largest silicon detector ever built

- Enough to 'parquet' a large (2400 ft^2) house!
- Over 77 million channels (66 million pixels, 11.5 million strips)
  - Compare to a 6 megapixel camera
    - This one takes 40 million 'pictures' per second!

5.4 m long; 2.4 m diameter

Operates at -15°C

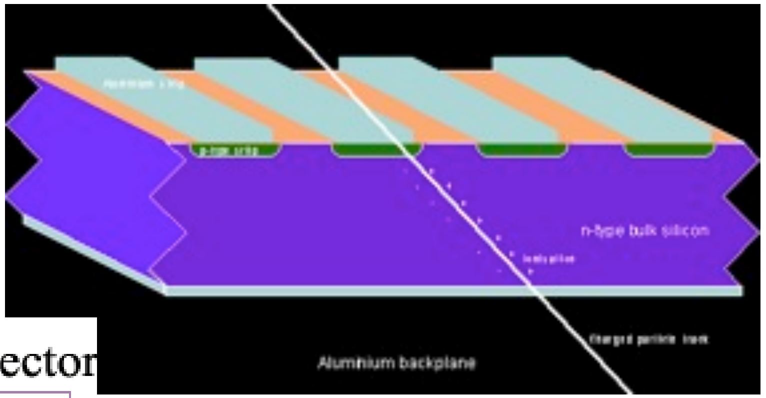
Contributions from UCR: testing/repairing silicon sensors

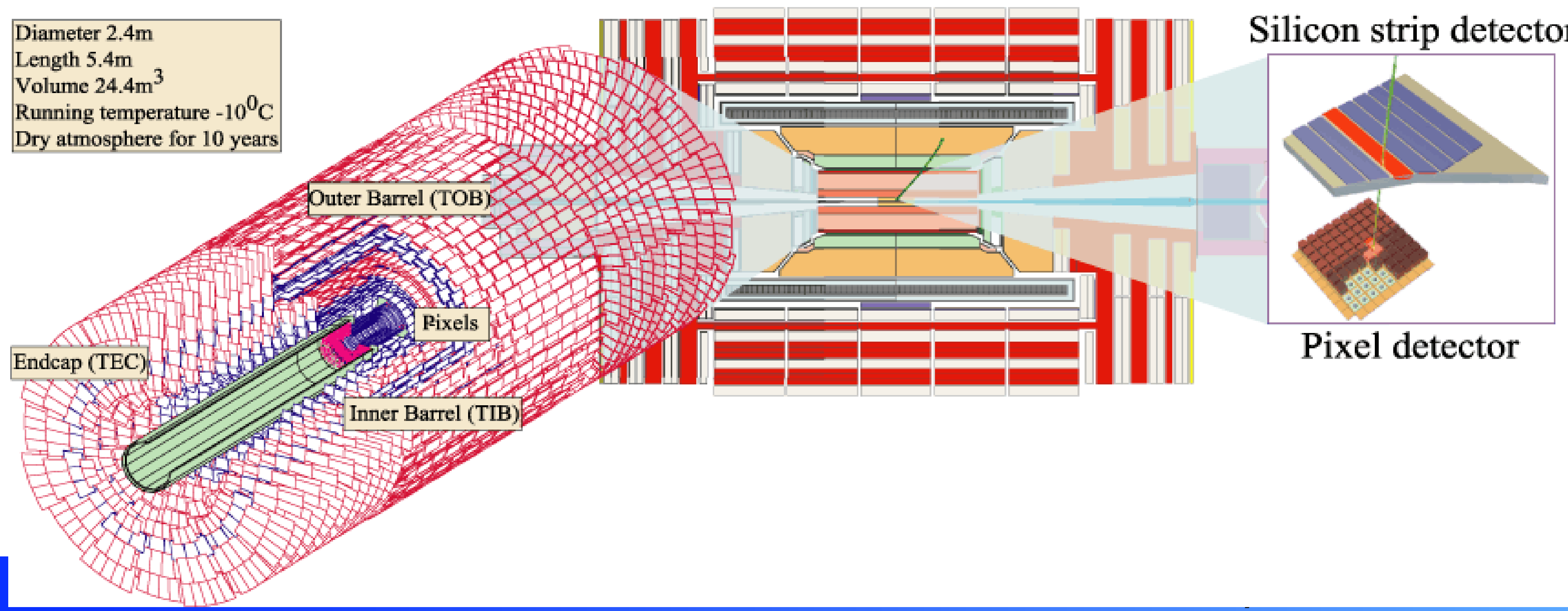
Silicon Tracker

Charged particles traveling through the silicon wafers will ionize the silicon, creating electron-hole pairs.

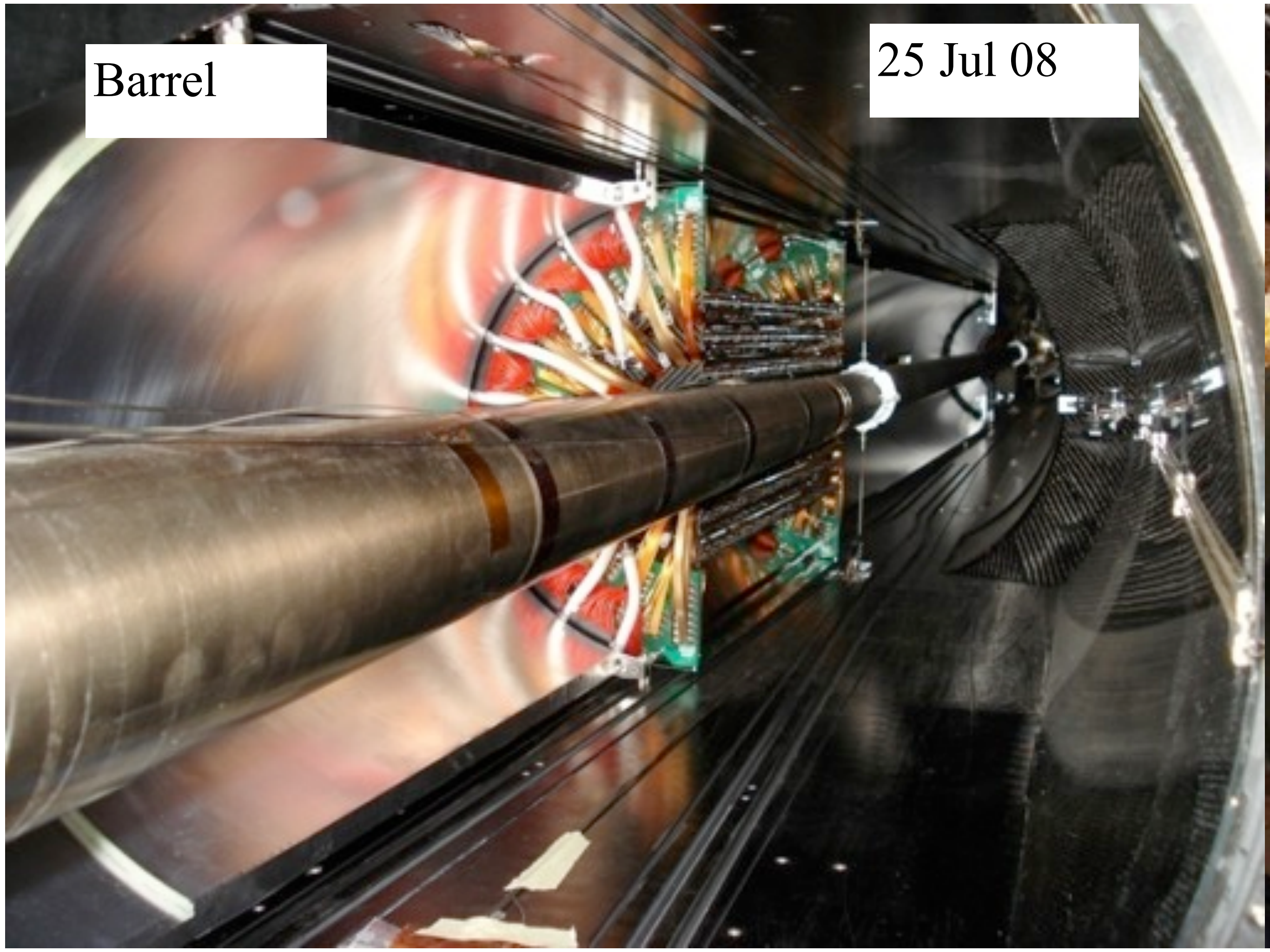
An electric field is applied across the silicon, causing the ‘holes’ to drift to the strips. (The electrons drift to the other side.)

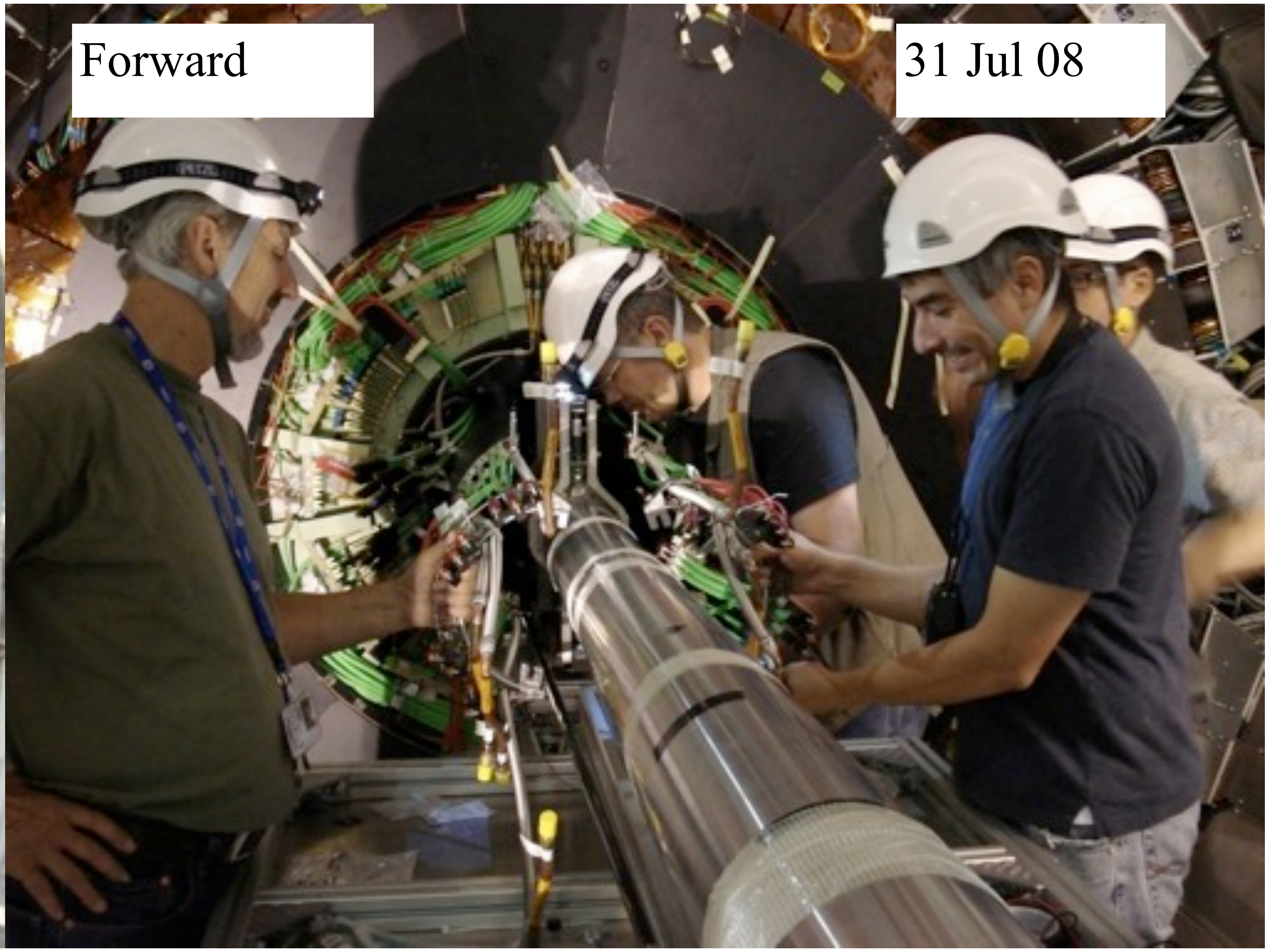
The position of the particle can be determined to about 10 microns





Pixel Installation





ECAL

The Electromagnetic Calorimeter consists of almost 80000 $PbWO_4$ crystals

- Used because the crystals are dense but very clear.
  - Dense so that electromagnetically interacting particles (electrons, photons) produce showers of particles
  - The particle showers excite the molecules in the crystals which then scintillate
  - The scintillation light travels through the clear crystal and is registered in photodiodes attached to the end of the crystal
  - The size of the shower, and thus the amount of light is proportional to the energy of the original particle

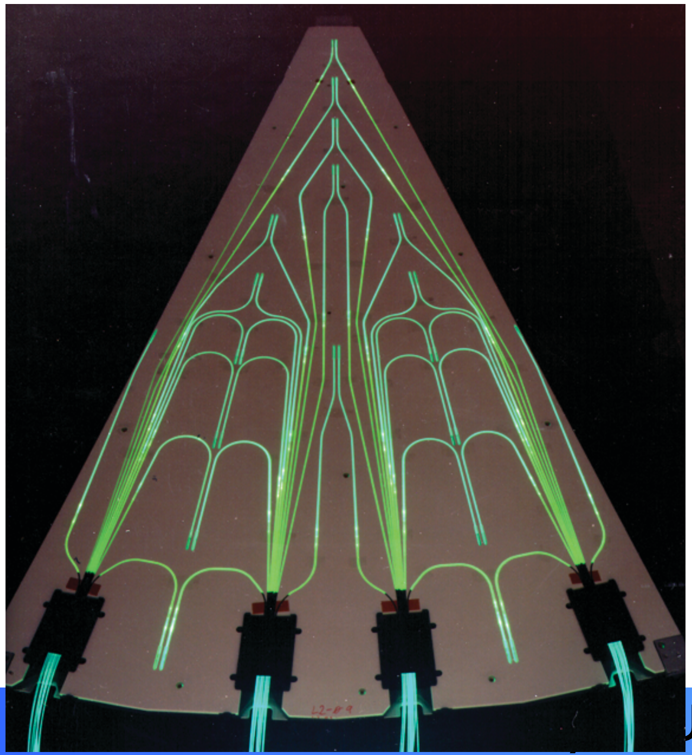
HCAL

The Hadron Calorimeter consists of layers of dense material (brass or steel) interleaved with plastic scintillator or quartz fibers.

It measures the energy of hadronically interacting particles, such as pions, kaons, neutrons and protons

Barrel HCAL consists of 36 brass/scintillator wedges, each weighing 35 tons.

Endcap HCAL brass was recuperated from Russian military shells.

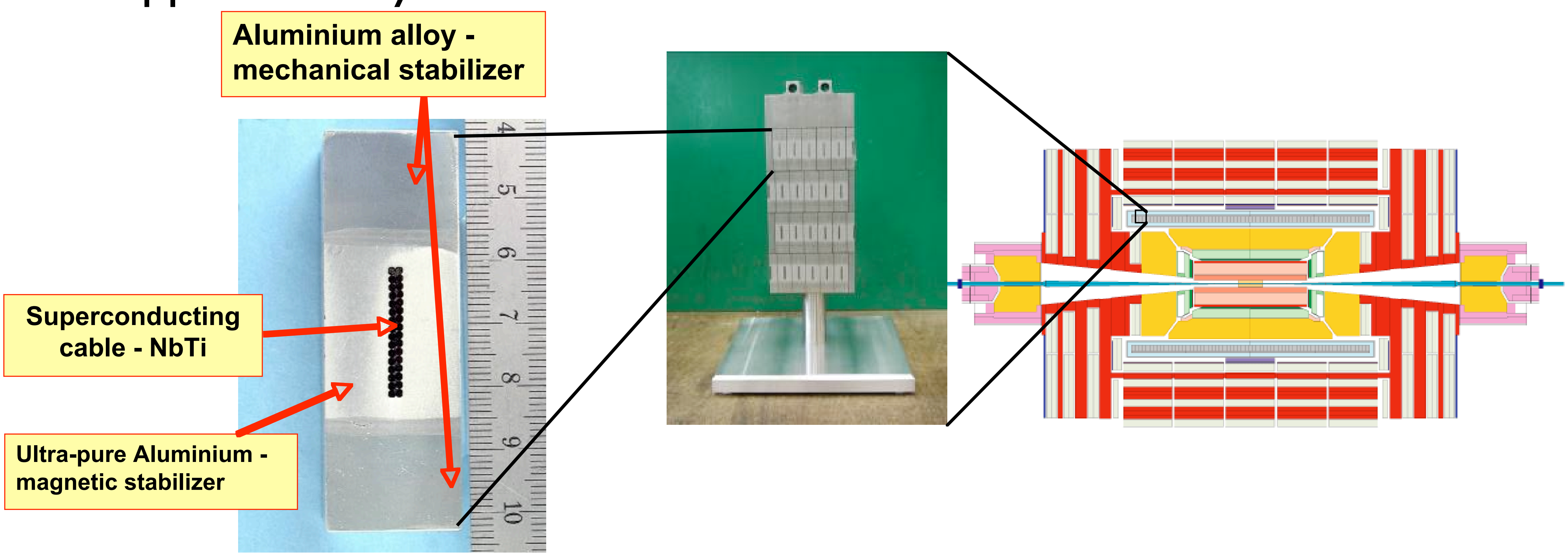


HCAL being inserted into CMS

The Solenoid

Need a high field to adequately bend charged particles

- The CMS solenoid provides a 4 Tesla field (100,000 times the Earth's magnetic field!)
- 20,000 amperes through the 13m long, 6 m diameter coil
  - Must be superconducting!
  - Approximately 1 million km of NbTi filaments!



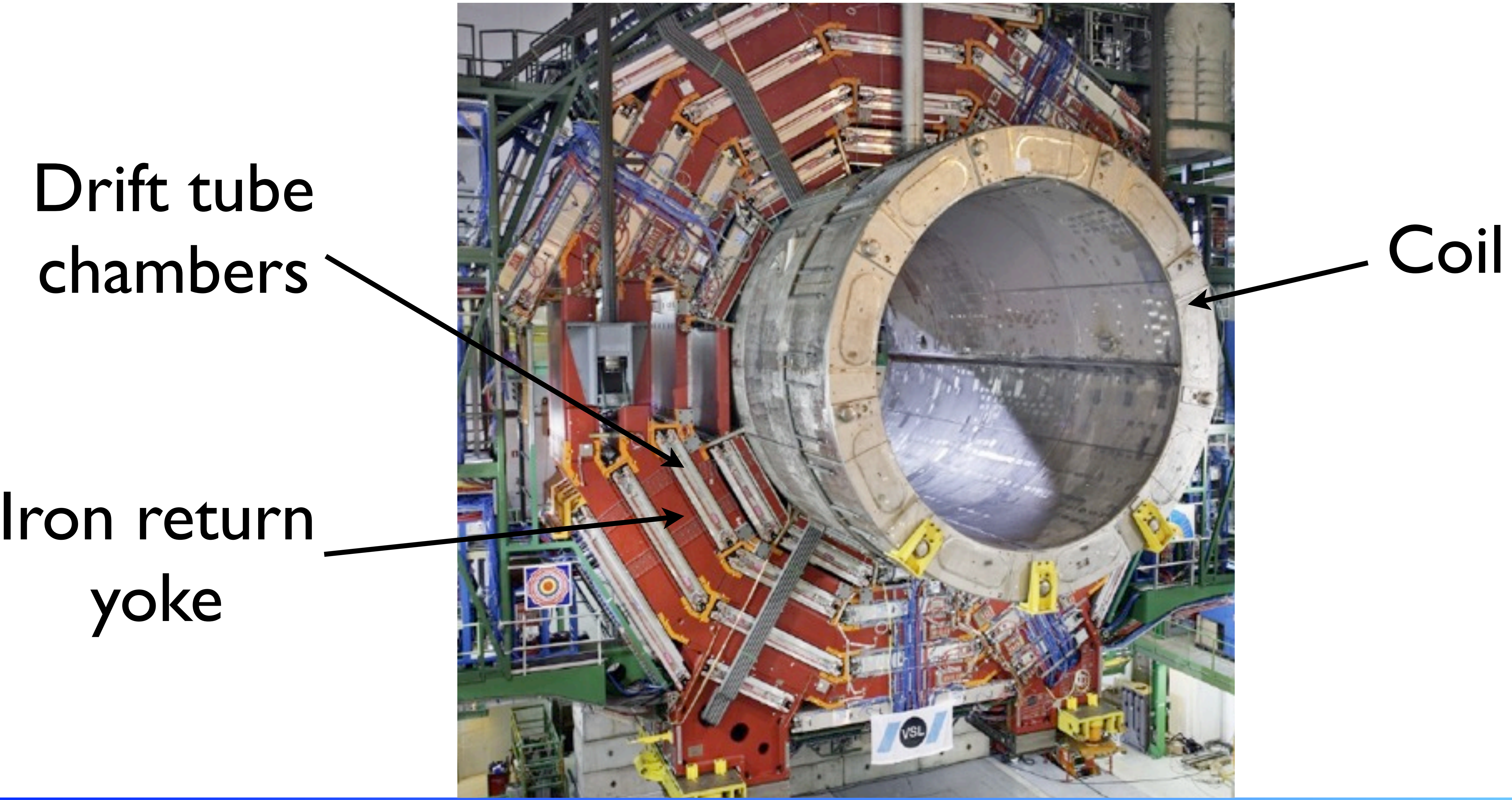
The Solenoid

Actually 5 coils put together, since it was impossible to ship the whole thing in one piece.

The Muon System

Large drift tube chambers in the barrel

Interleaved with thick iron plates, which serve both as a 'flux return' to control the magnet, as well as the 'skeleton' of CMS

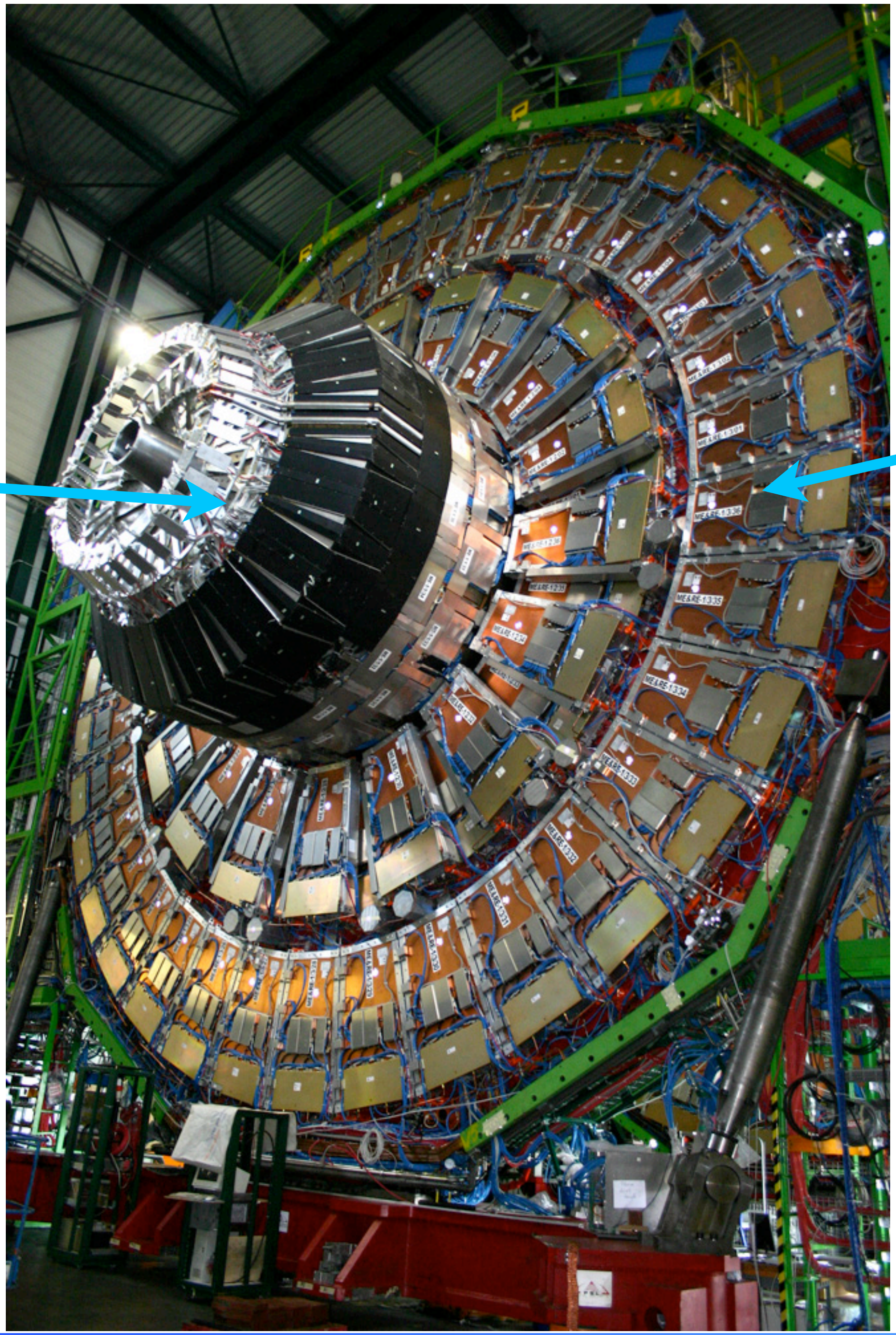


The Muon System

Cathode strip chambers in the endcaps

UCR helped design and build the chambers

ECAL/HCAL endcap



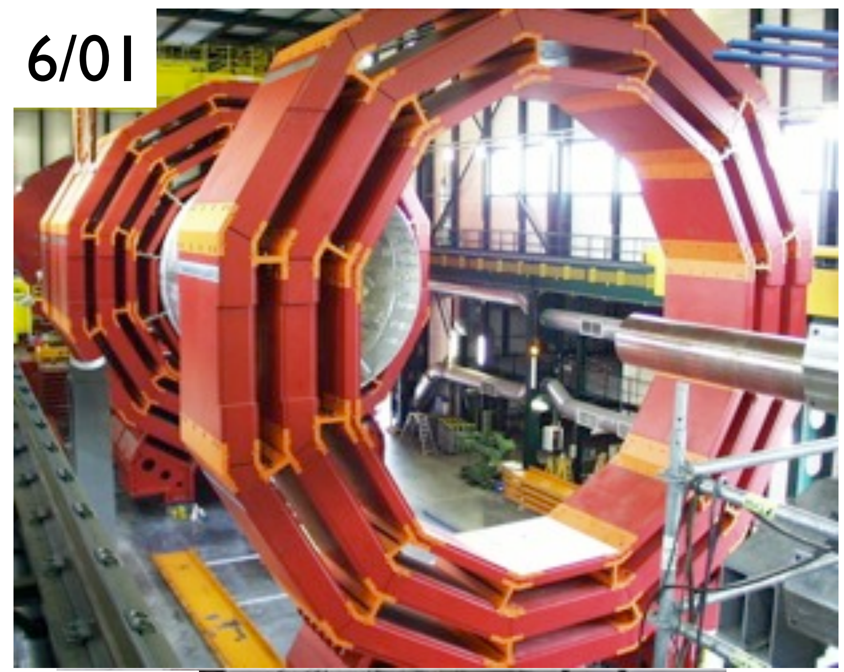
Cathode strip chambers

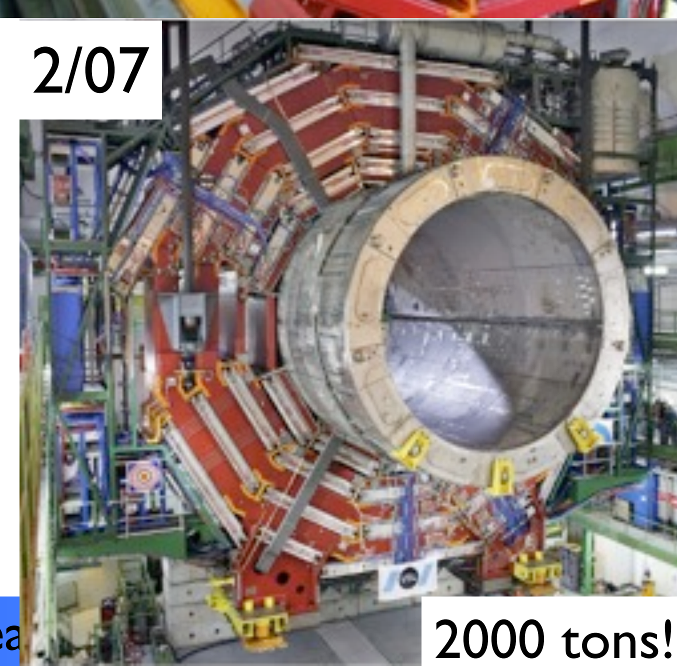
Overview

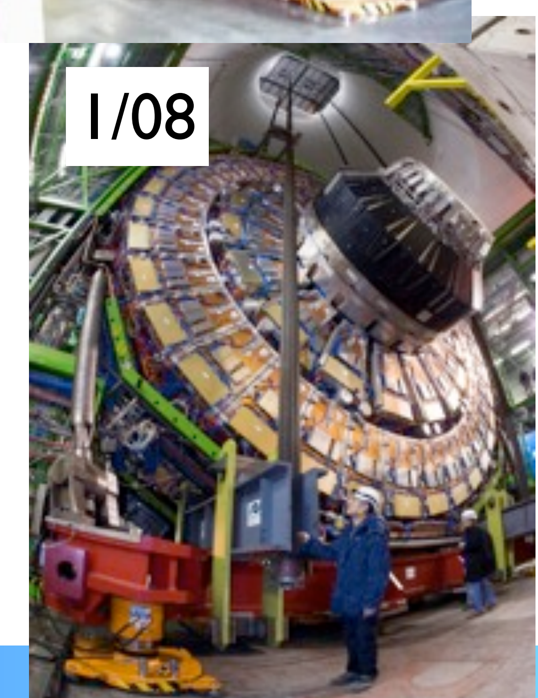
The design of CMS started about 19 years ago.

Major construction and assembly started about 9 years ago.

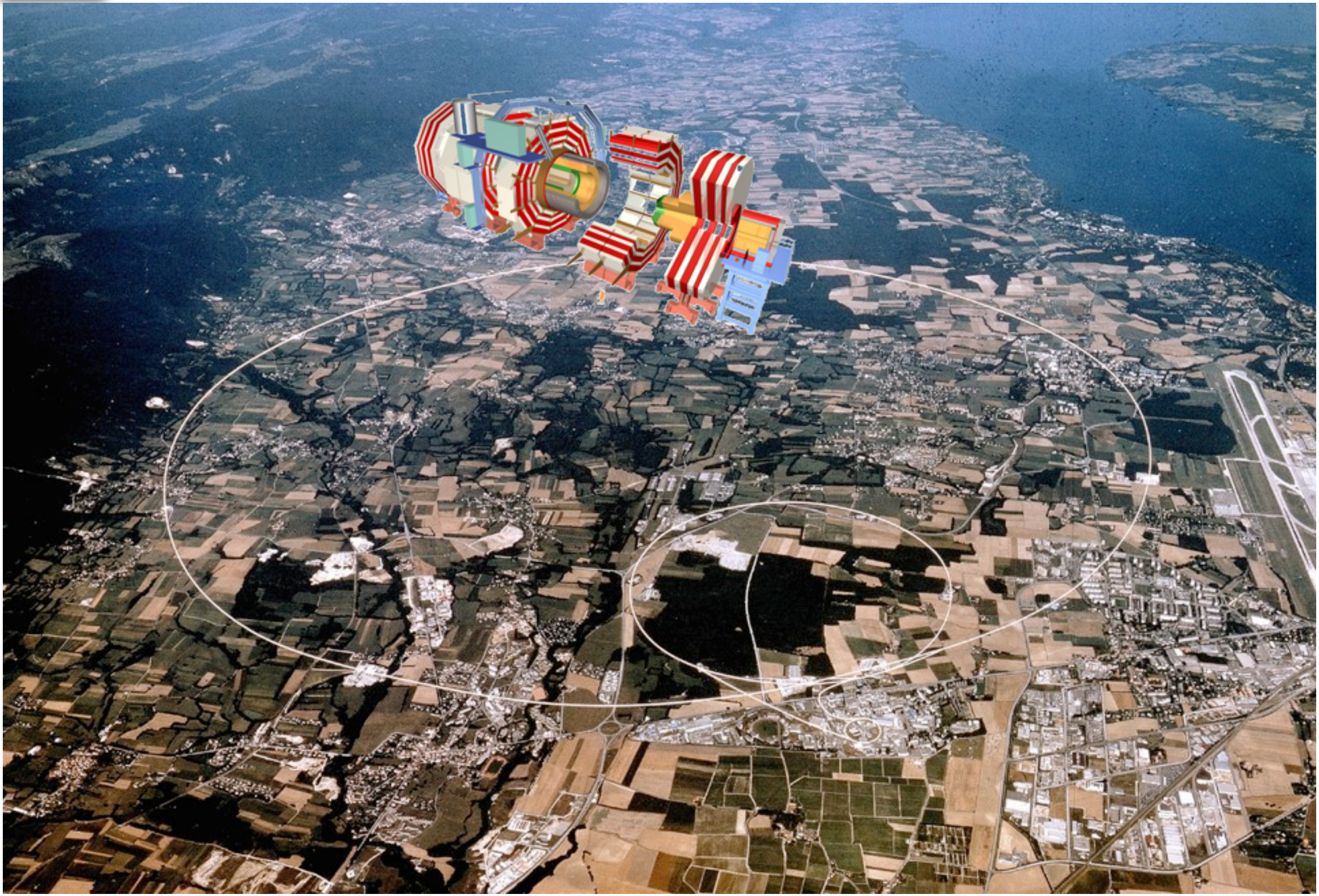
Lowering into the cavern started about 3 years ago, and only finished a about a year ago!







The LHC

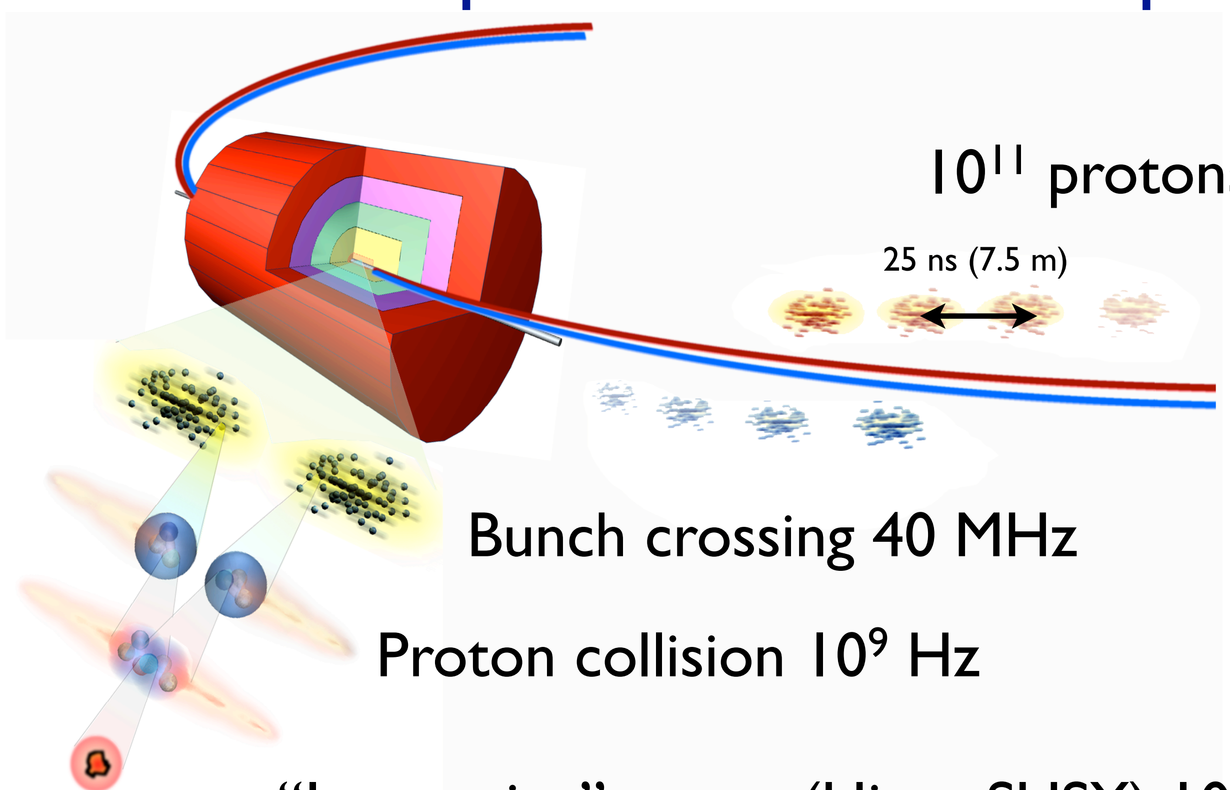


The LHC

Will accelerate protons eventually to 7 TeV. This will be 7 times the energy of the current highest energy accelerator on Earth (the Tevatron at FNAL).

- However, even a measly fly in flight has a kinetic energy of roughly 100 TeV!
- But a proton is much smaller than a fly. It is the energy density that is critical here.

We ***will*** collide a lot of protons on a lot of protons, and do it often!



10^{11} protons/bunch; 2800 bunches per beam

Bunch crossing 40 MHz

Proton collision 10^9 Hz

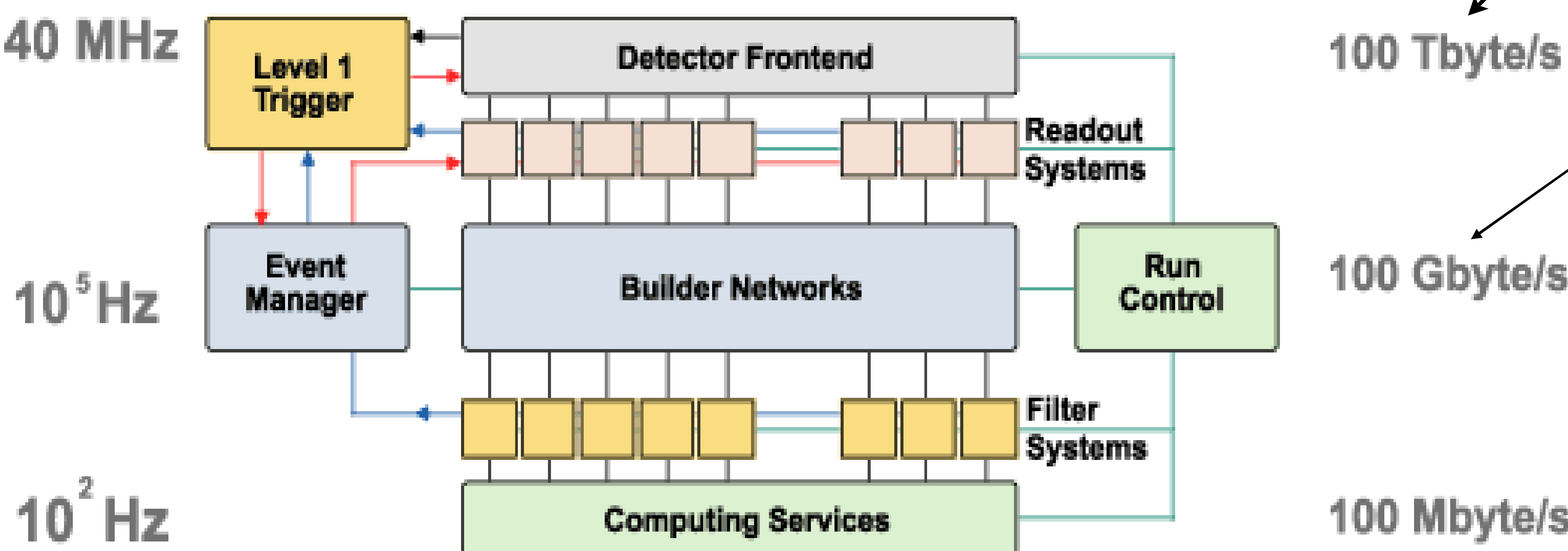
"Interesting" event (Higgs, SUSY) 10^{-4} Hz

Need a reduction of 1out of 10,000,000,000,000 !

A needle in a haystack is child's play!

How to reduce the rate?

Data Acquisition Main Parameters	
Collision rate	40 MHz
Level-1 Maximum trigger rate	100 kHz
Average event size	1 Mbyte
No. of electronics boards	10000
No. of readout crates	250
No. of In-Out units (200-5000 byte/event)	1000
Event builder (1000 port switch) bandwidth	1 Terabit/s
Event filter computing power	5 10^6 MIPS
Data production	Tbyte/day



Trigger and Data Acquisition baseline structure

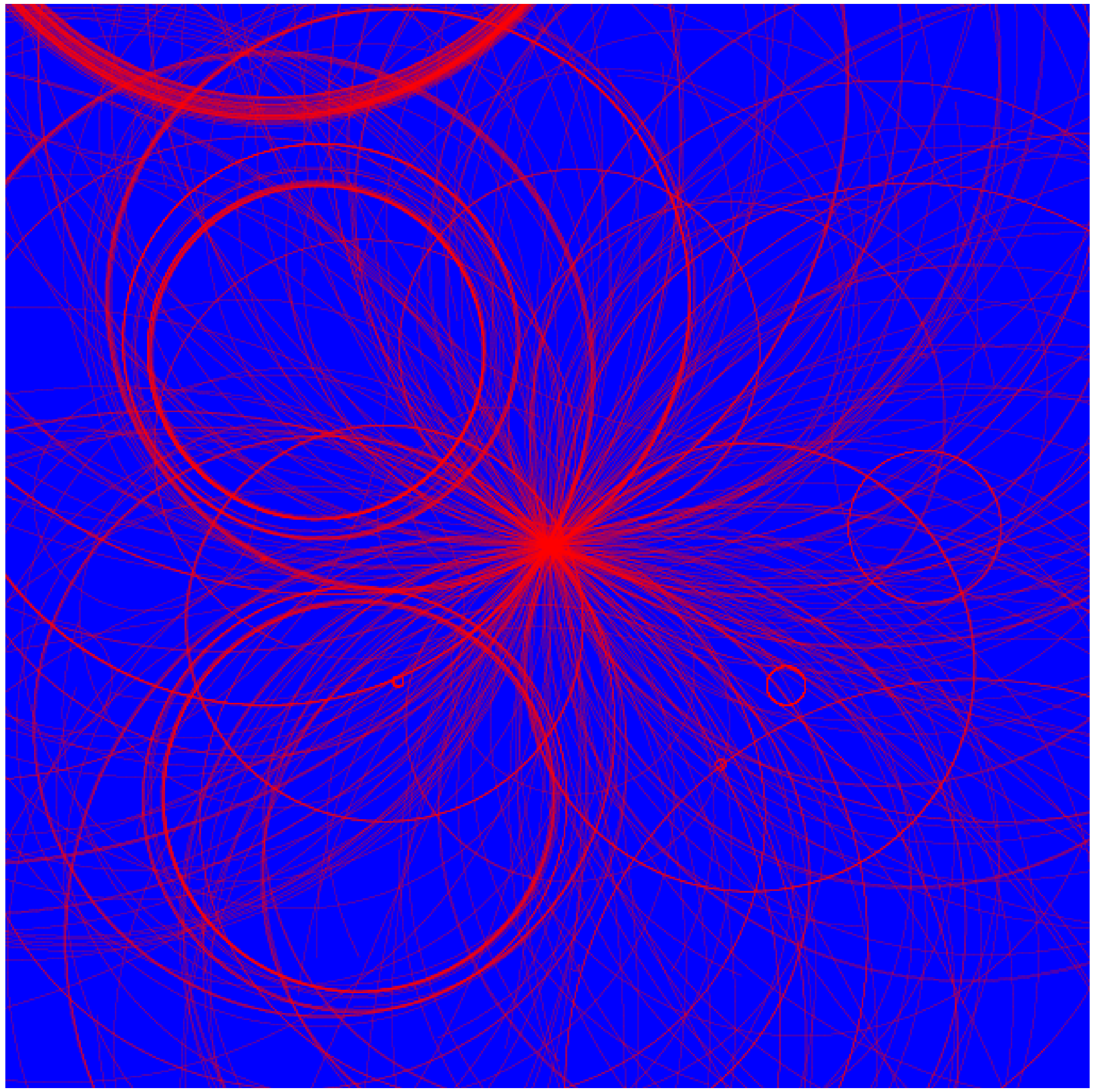
Can't handle that!

~same as whole world's telecom network!

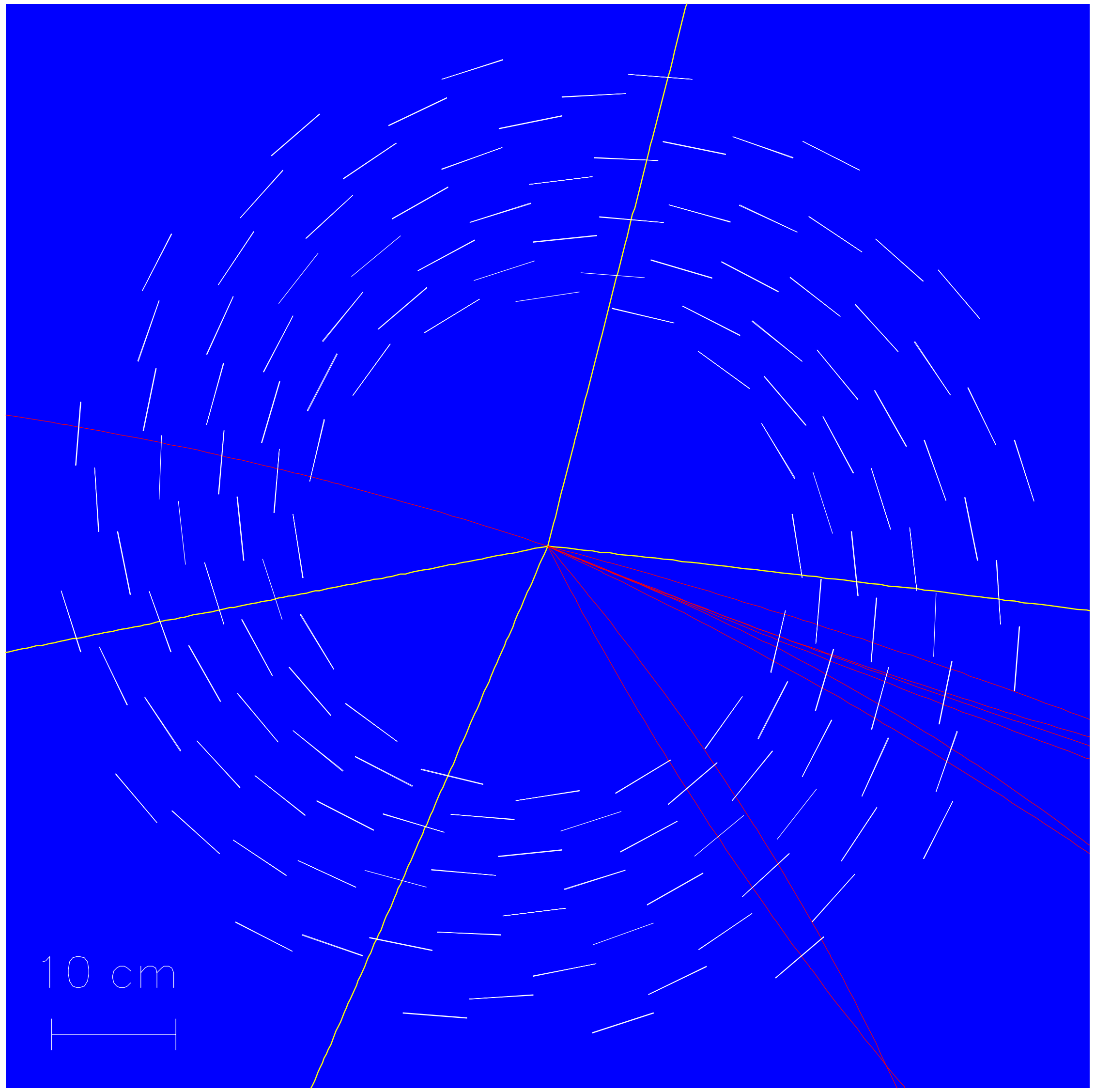
Can handle that;
still adds up to 1 PB/year

More Challenges

An event with Higgs decaying to 4 muons. There are 4 very high momentum tracks in the event, the 4 muons. Try to find them!



Trick: cut away the low momentum tracks. But this requires excellent pattern recognition!



If all goes well...

In a few years we might be able to show this plot, showing a mass peak for the Higgs...

Signal of the Higgs!