CMS at LHC

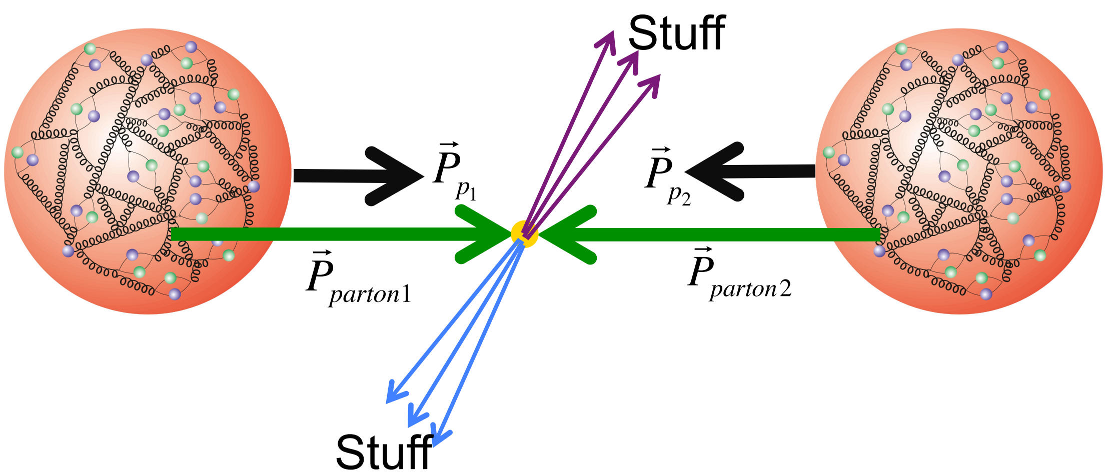
LHC

LHC

- 27 km in circumference, 100 m underground
- pp collisions
- 14 TeV center of mass energy (8 TeV in 2012)
- 10^{34} $cm^{-2}s^{-1}$ luminosity
  - proton bunches collide every 25 ns
  - 20 pp collisions per bunch crossing
- beam energy 0.4 GJ
- beam pipe vacuum—better than inter-planetary space
- 1,234 superconducting magnets (14 m, 8 T) at 2 K
- 90 tons of liquid He at 2 K
- energy stored in dipole magnets 10 GJ

LHC

- **pp collisions** == collisions of gluons and light quarks (aka partons)

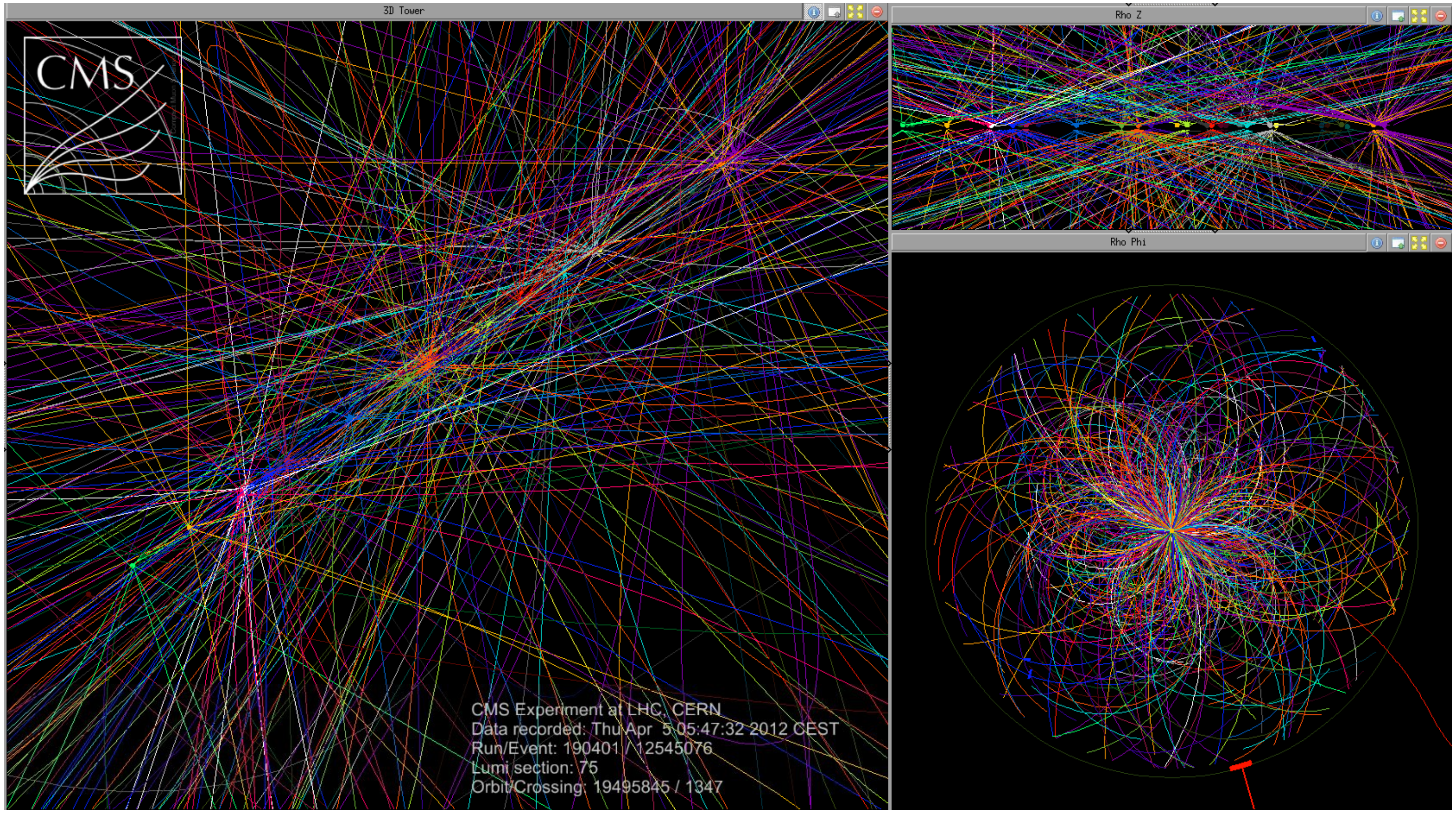


- **Outgoing stuff:** What kind of stuff is actually detectable?
  - electrons and muons (tau leptons decay too fast)
  - quarks/gluons: they combine to make hadrons of which only a few live long enough to interact with the detectors ($\pi^{\pm}$, $K^{\pm}$, K^0, p, n);

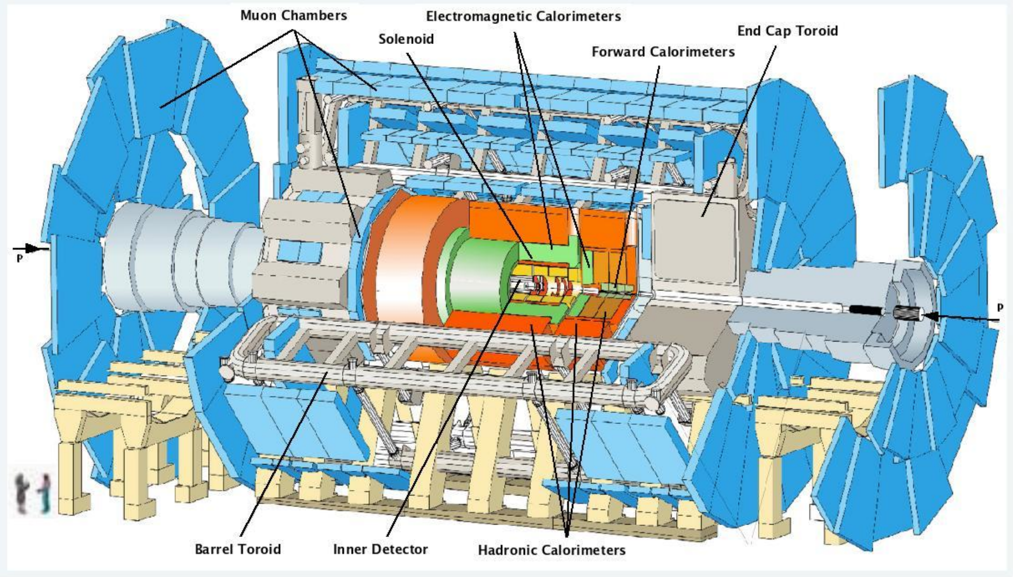
    note that high energy quarks/gluons actually produce jets of hadrons…
  - photons
  - neutrinos interact too weakly and escape undetected
  - dark matter particles, if they are ever produced, also interact too weakly

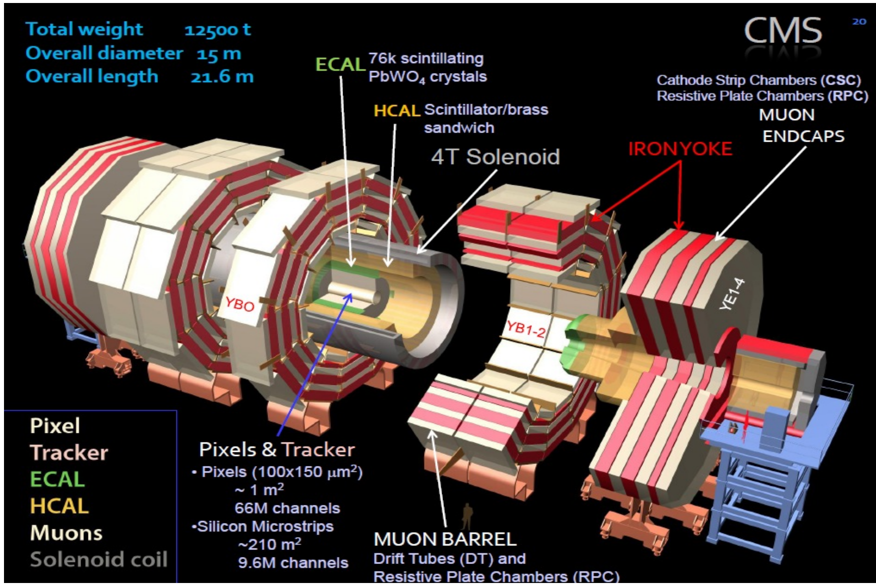
pp collisions at LHC

1 bunch of protons: 20 cm, 20 µm, 10^{11} protons
50 pp collisions per bunch crossing
bunch crossings every 50 ns
10^9 pp collisions per second



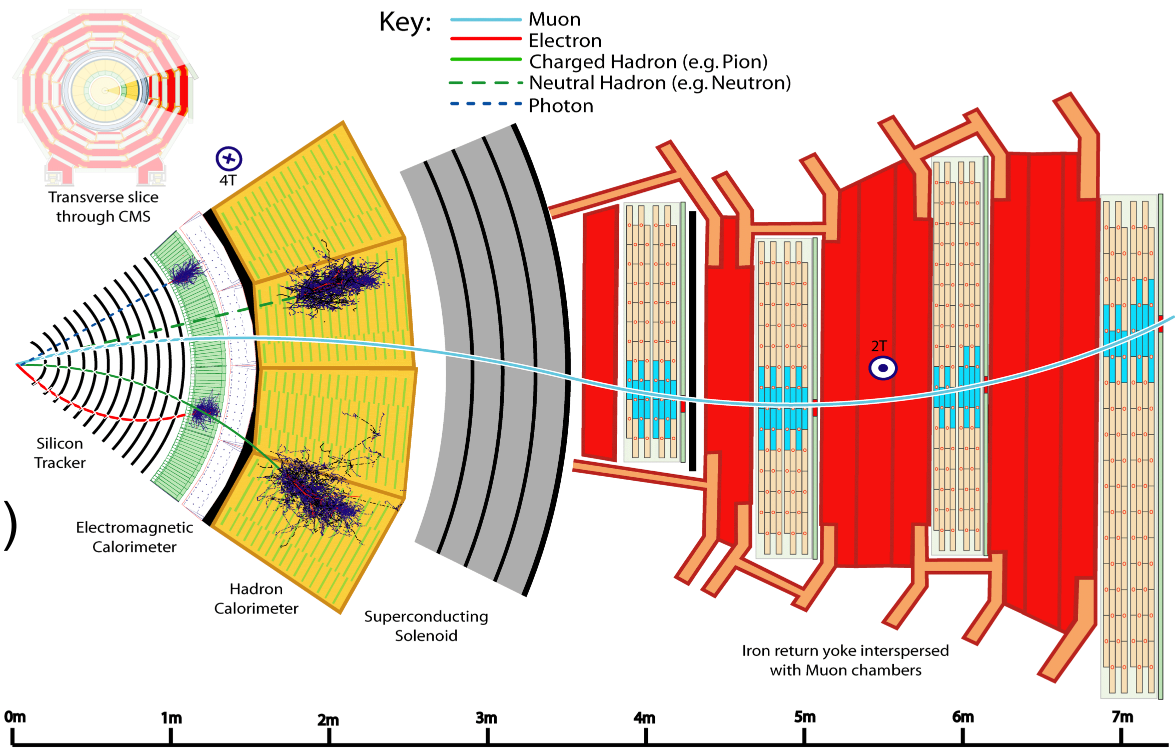
ATLAS and CMS





- Two general-purpose detectors
- Each costs about $1B
- Why bother to have two? To verify each others results:
  - independent hardware (and different technologies!)
  - independent software
  - independent analyses

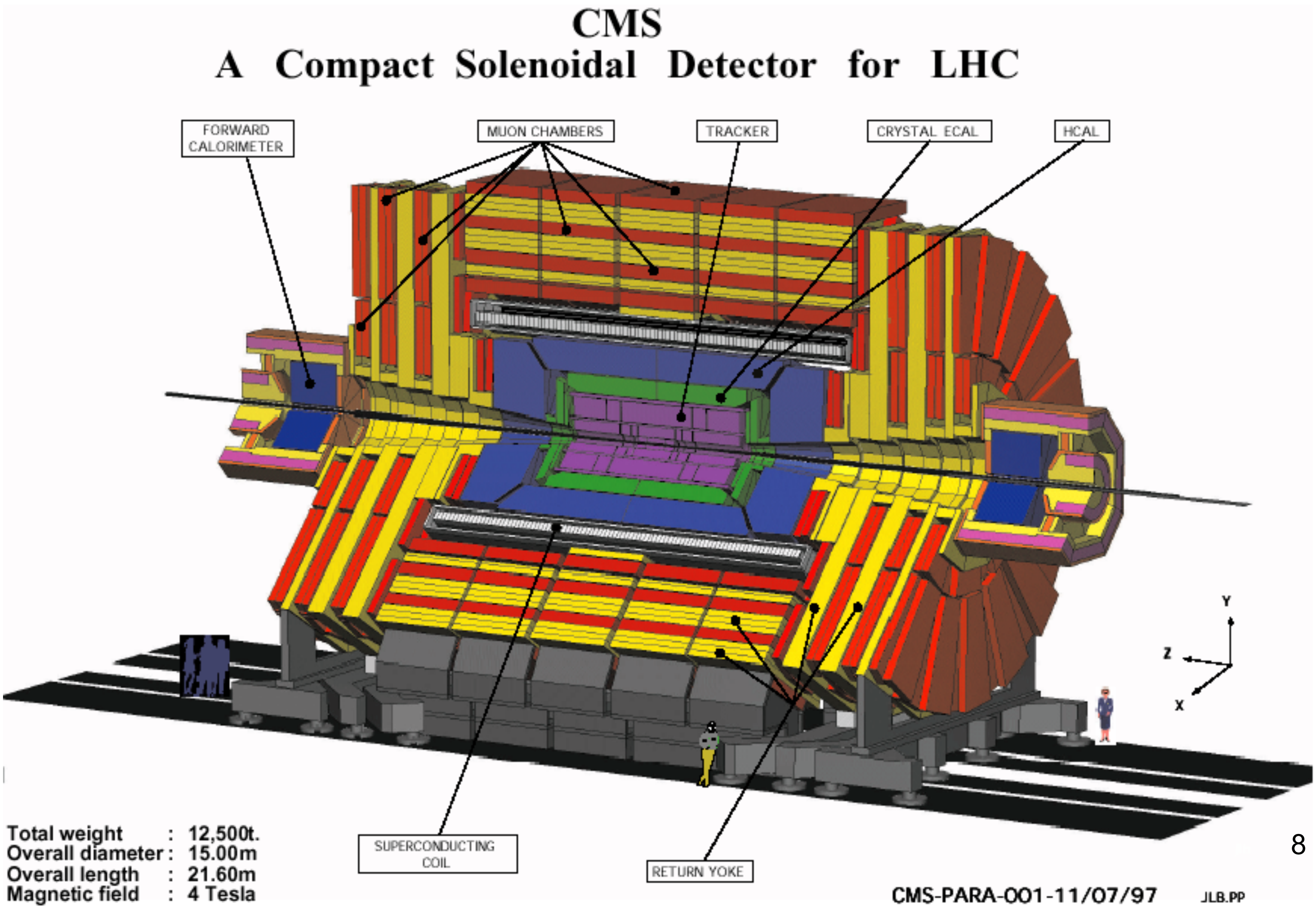
Conceptual design



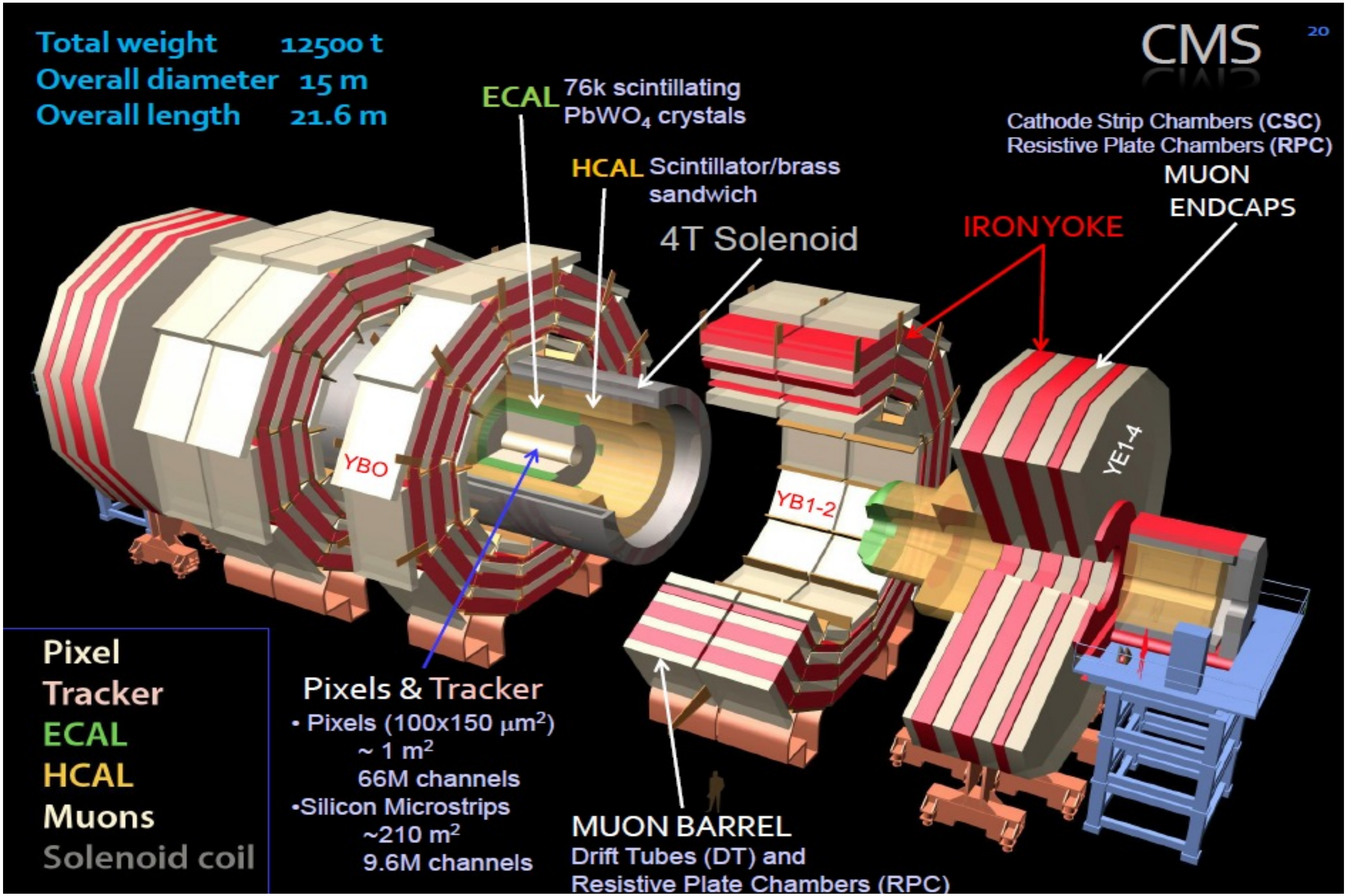
- What you can see
  - electrons
  - muons
  - hadrons ($\pi^{\pm}$, $K^{\pm}$, K^0, p, n)
  - photons

- What you can't see is assessed from
  - missing transverse momentum ("energy"), which may be due to:
    - neutrinos
    - dark matter particles (if produced)
    - (and cracks/mismeasurements in the detector, of course)

CMS Overview



CMS

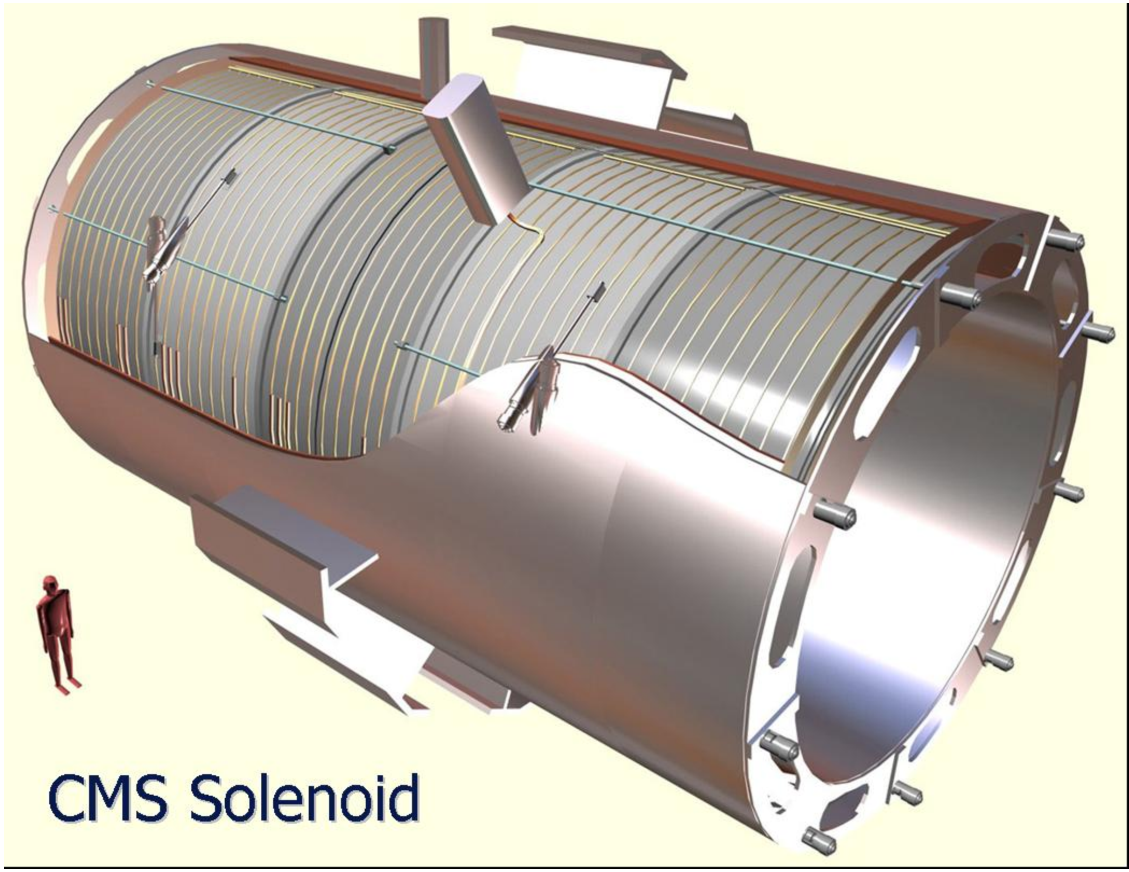


Total weight 12500 t
Overall diameter 15 m
Overall length 21.6 m
CMS
20
ECAL 76k scintillating $PbWO_4$ crystals
HCAL Scintillator/brass sandwich
4T Solenoid
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)
MUON ENDCAPS
IRONYOKE
YBO
YB1-2
YE1-4
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
Pixels & Tracker
• Pixels (100x150 μm^2)
~ 1 m^2
66M channels
•Silicon Microstrips
~210 m^2
9.6M channels
MUON BARREL
Drift Tubes (DT) and
Resistive Plate Chambers (RPC)

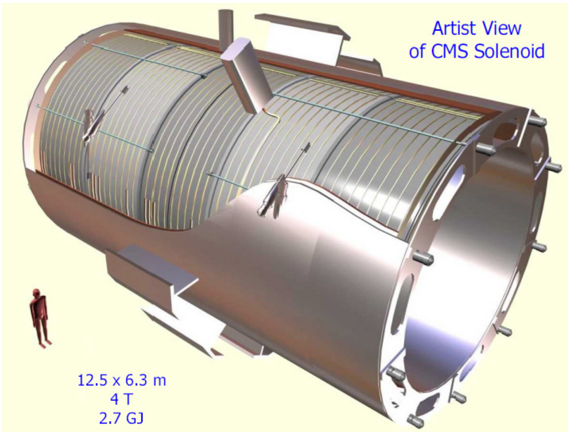
Solenoid

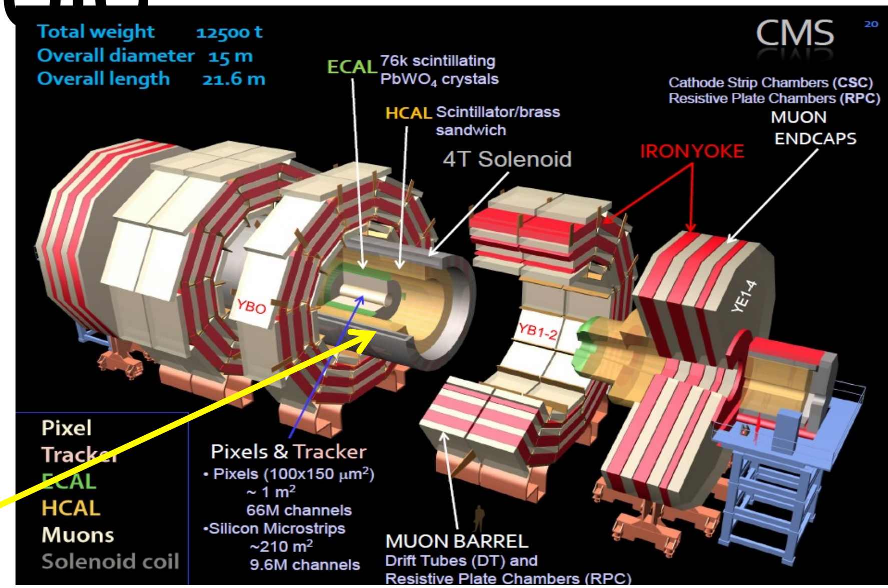
- 4 T field
- 8 m in diameter
- 12 m long
- 3 GJ stored energy

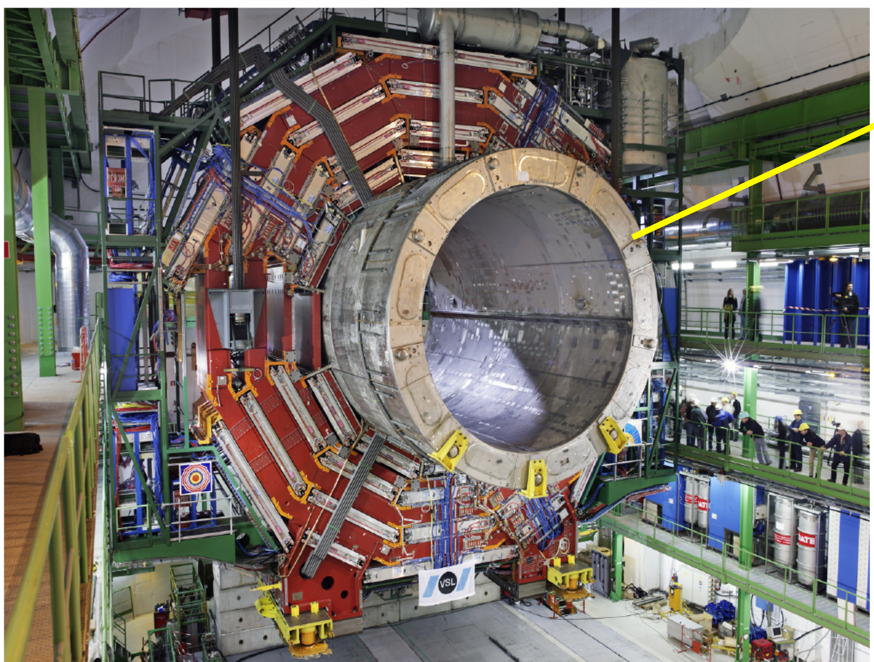
  (1500 cars on a highway)



CMS: Superconducting Solenoid





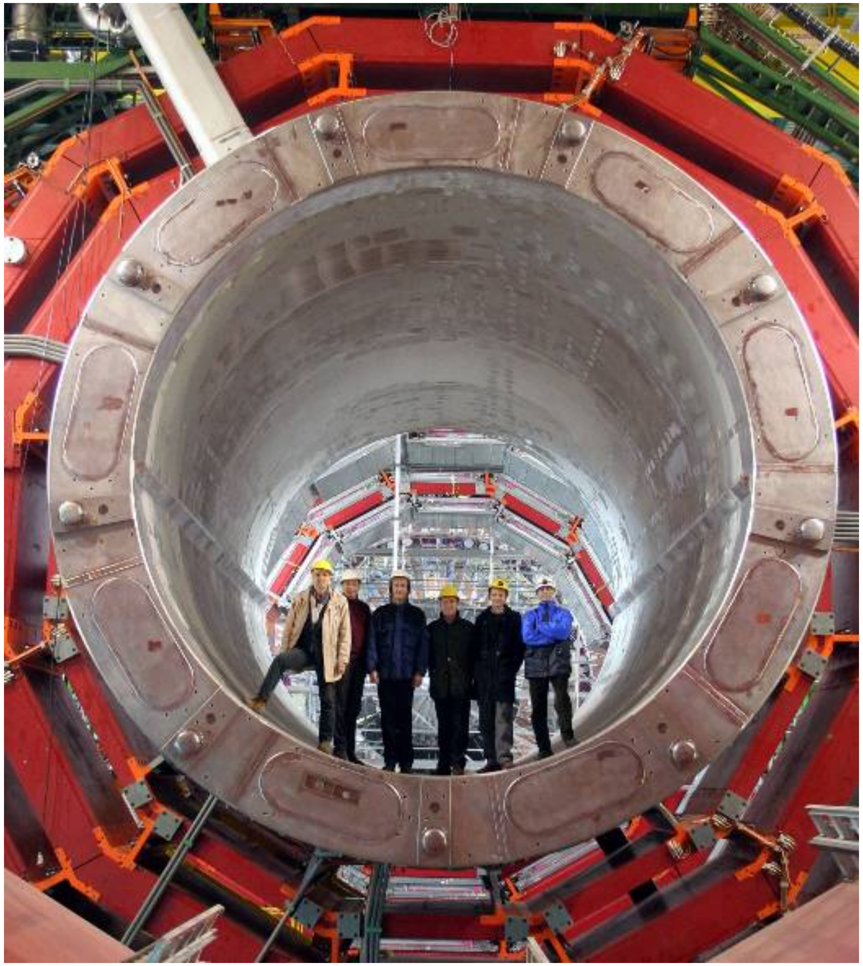


YB0 landing in the CMS experiment hall

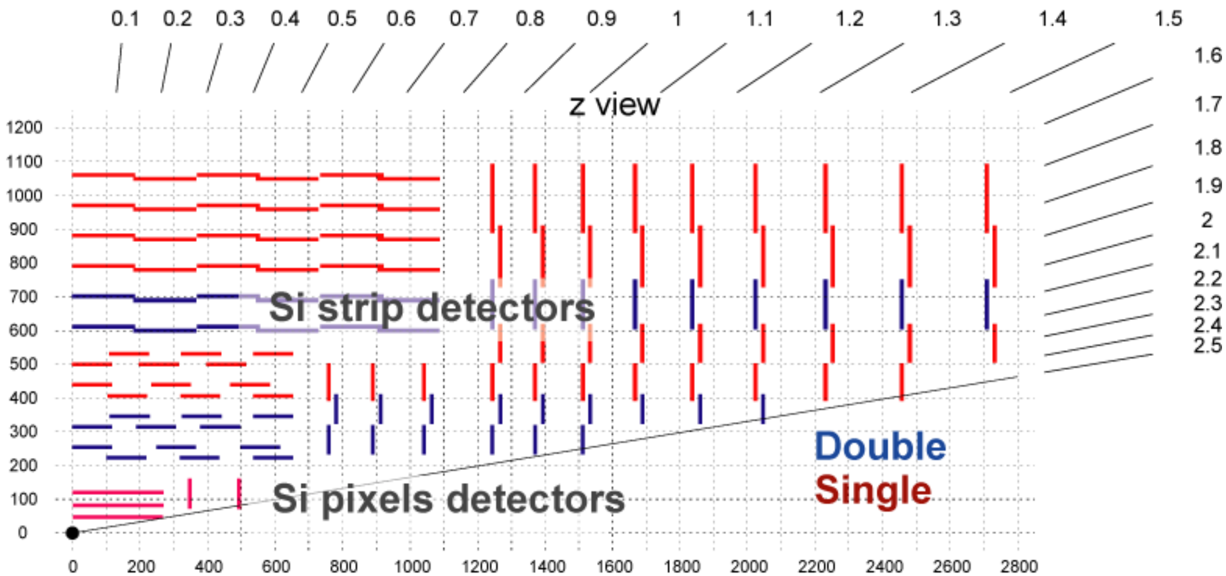
6 m inner diameter
12 m length
4 T field

3 GJ of stored energy
(1000 car on highway)

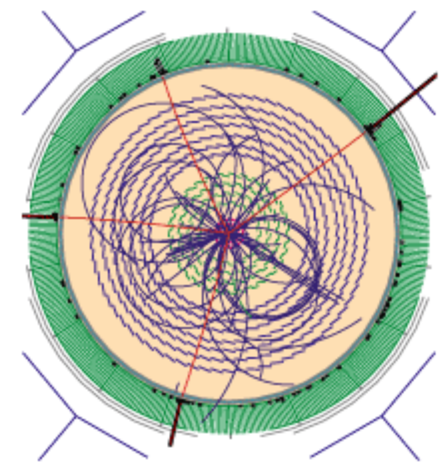
Solenoid



Si Tracker

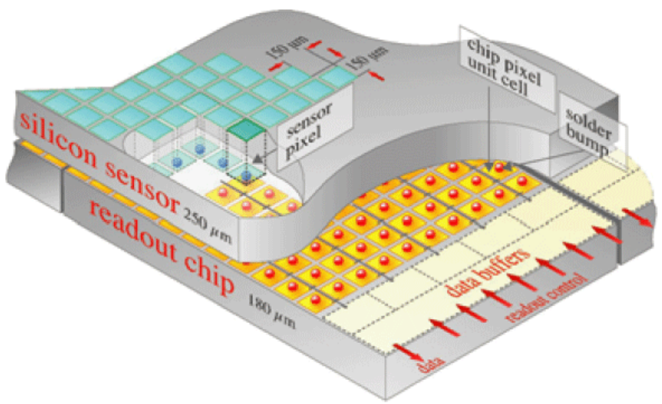


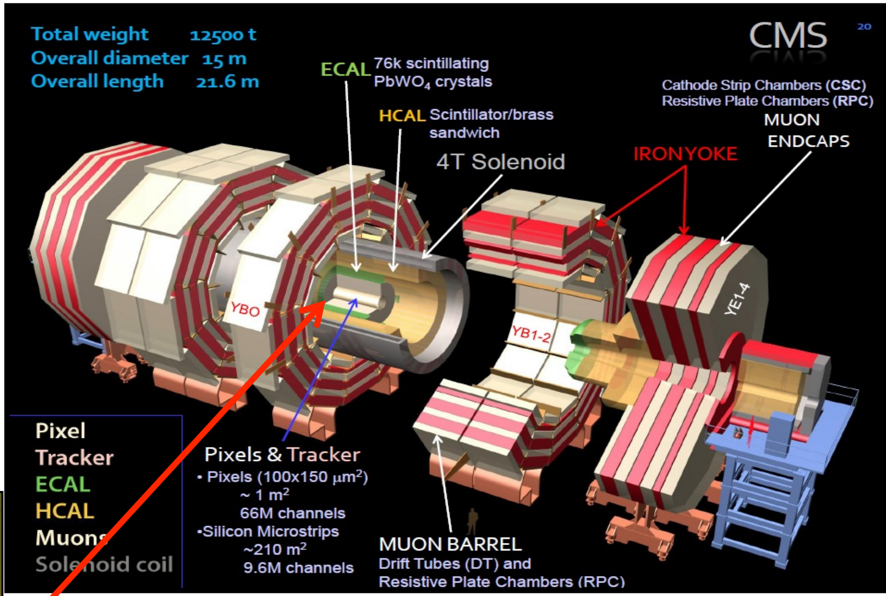
The layout of the CMS inner tracker



- Largest silicon-sensor system ever made
- 2.2 m diameter, 6 m long, operates at -15^{o} C
- more than 220 m^2 of sensors
- more than 60 million electronics channels (pixels and microstrips)

CMS: Si pixel inner tracker





1 m^2 of sensitive area

100x150 μm^2 pixels

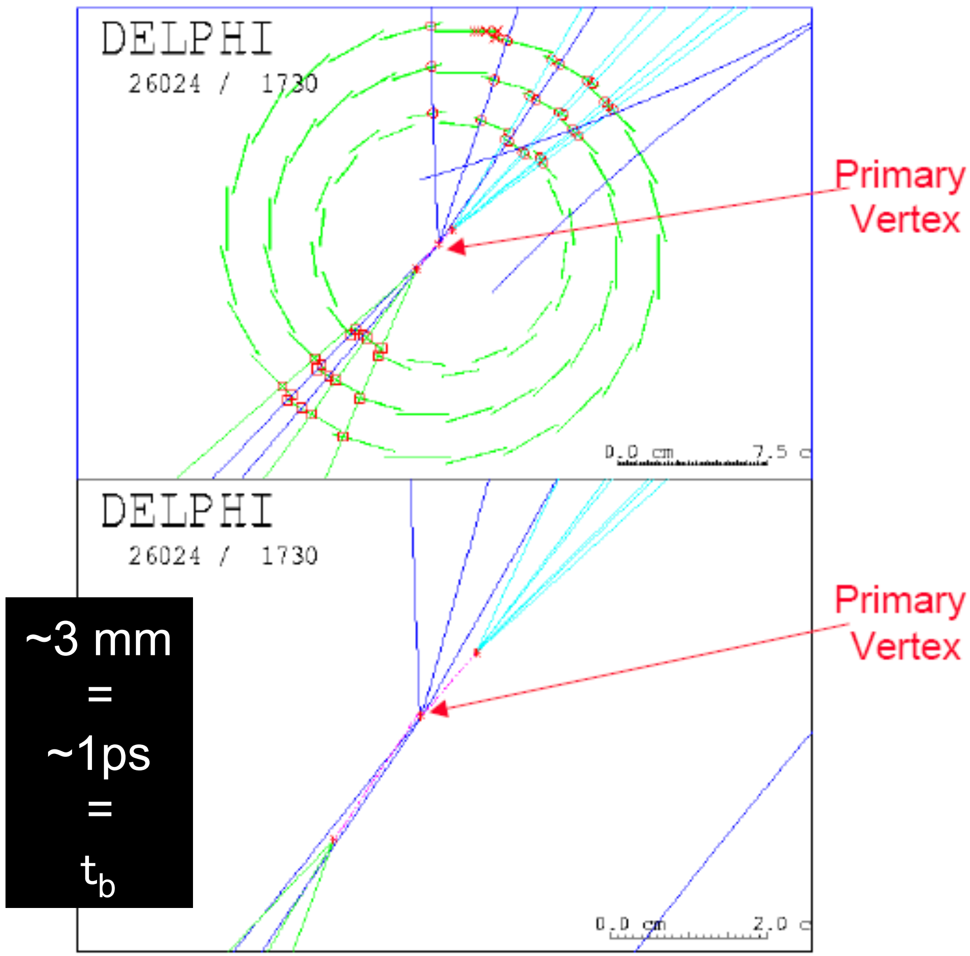
Spatial resolution: **13 μm**

66 M channels

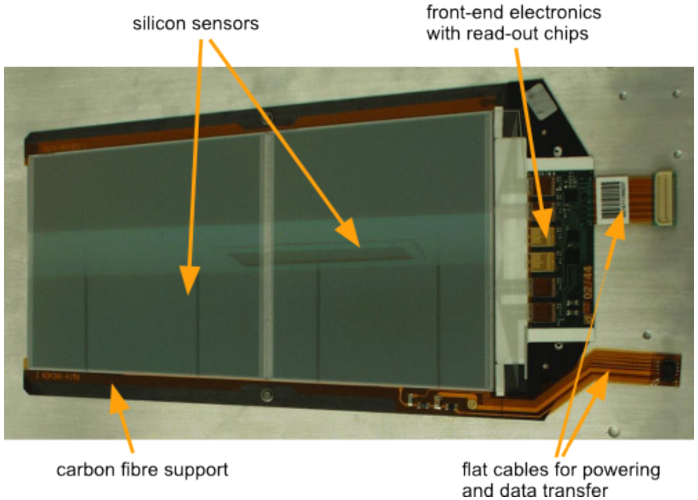
Why do we need so high spatial resolution?

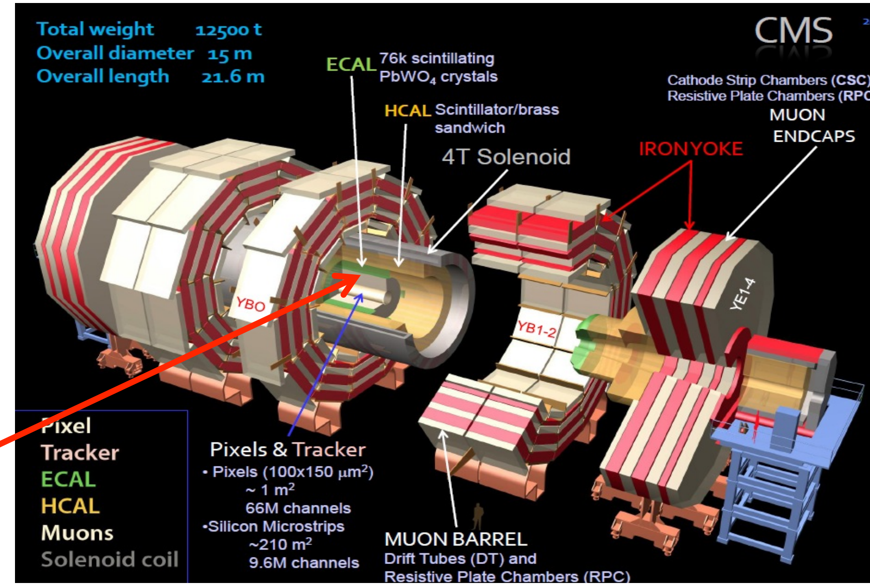
Reconstructed B-mesons in the DELPHI micro vertex detector

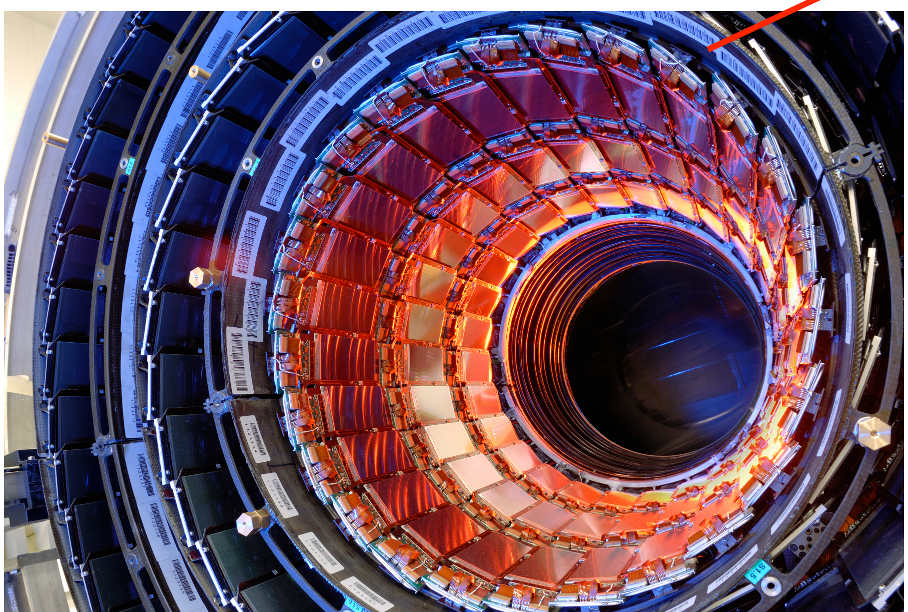
$\tau_B \approx 1.6\ \text{ps} \quad l = c\tau\gamma \approx 500\ \mu\text{m}\cdot\gamma$



CMS: Si Strip Detector



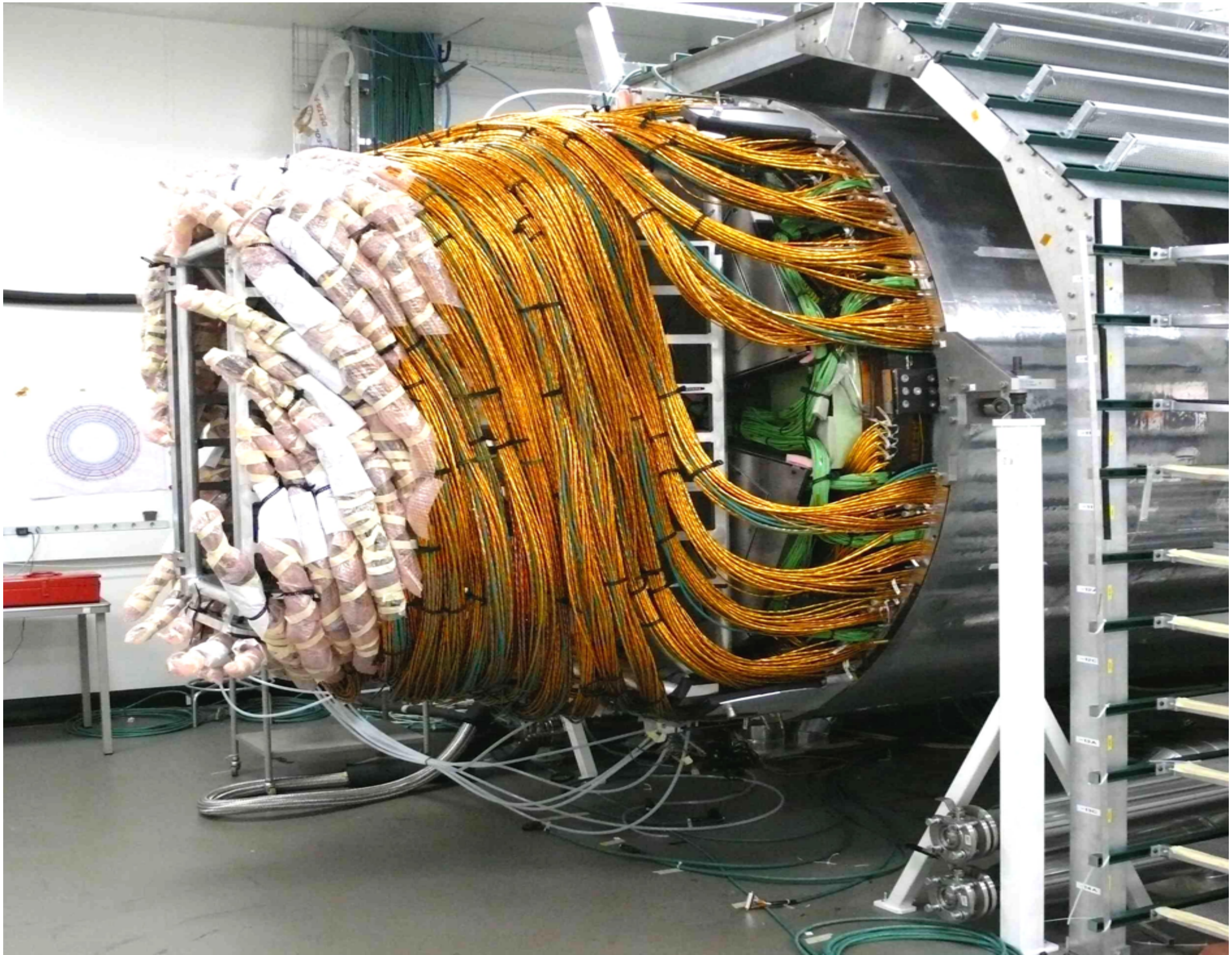




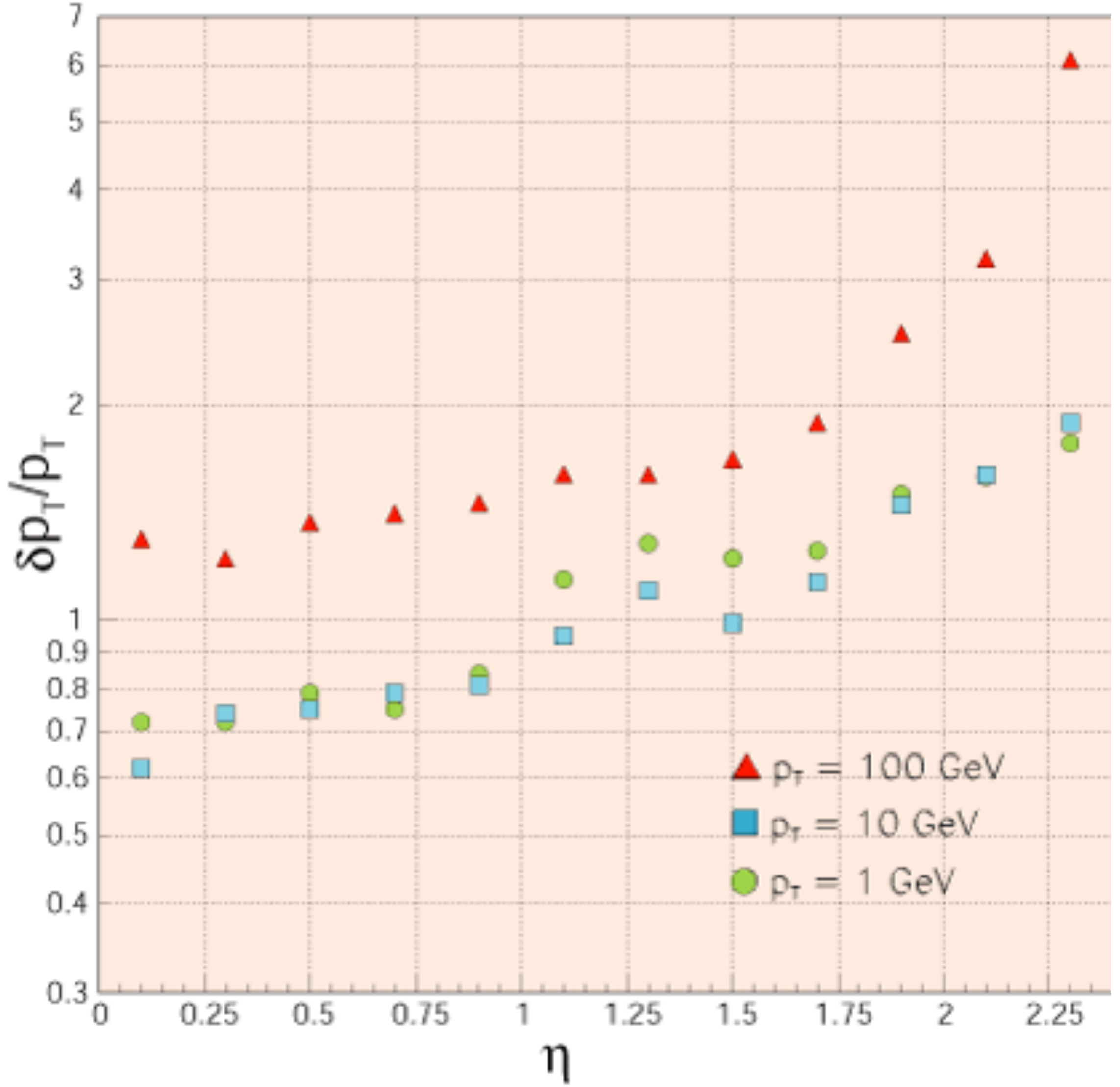
80 – 200 μm strips
Spatial resolution: **15-40 μm**

200 m^2 of sensitive area
(half of basketball court)
10 M channels

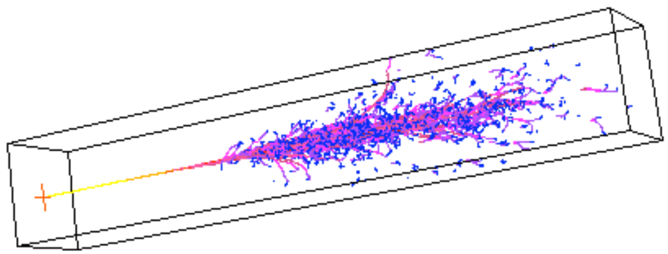
Si Tracker

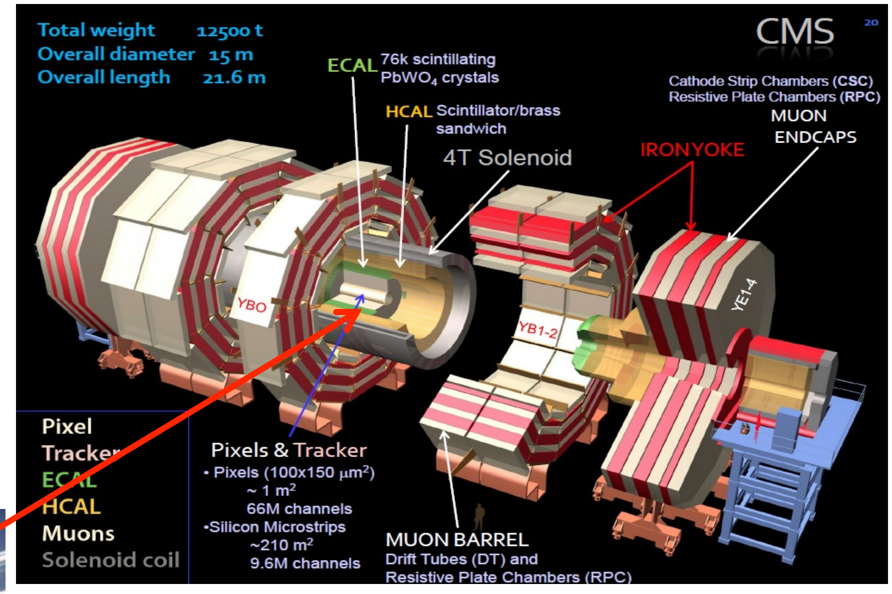


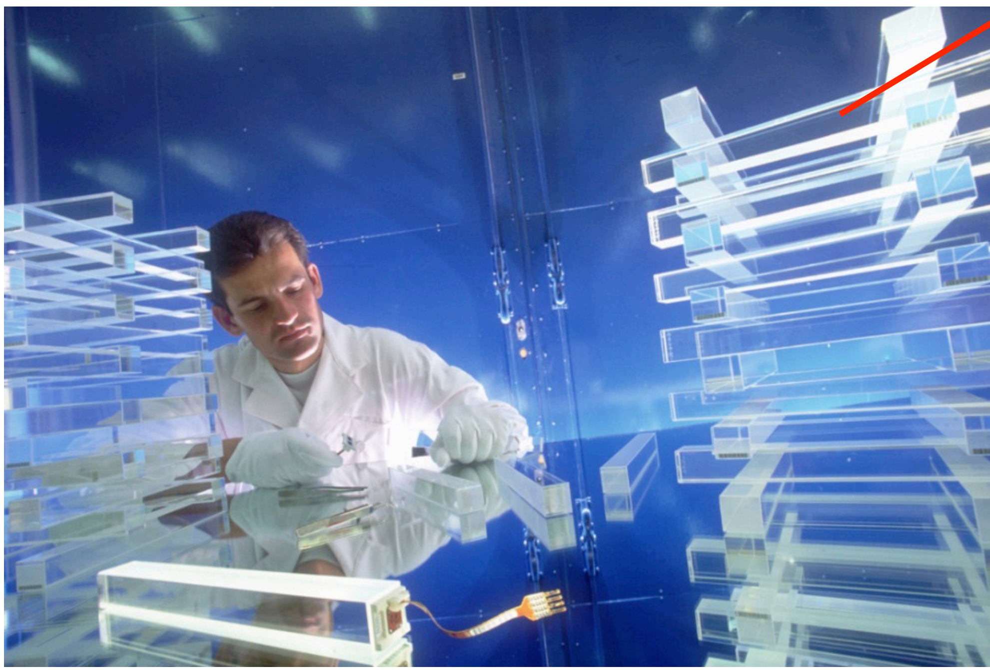
Tracker Performance



CMS: Electromagnetic Calorimeter







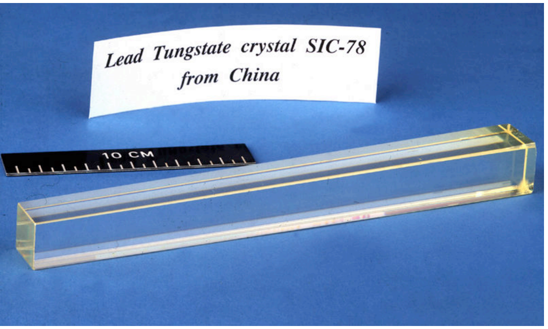
$PbWO_4$

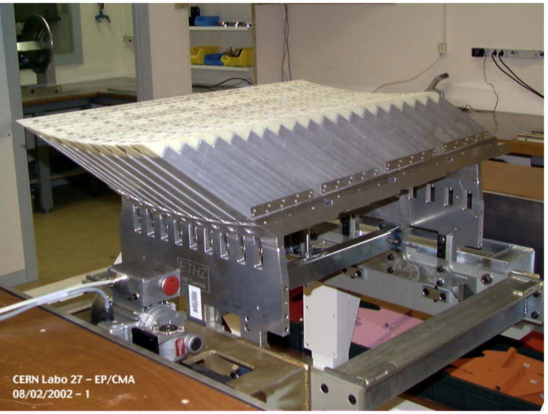
(heavy glass: SiO_2 → $PbWO_4$)

Energy resolution: <0.5%

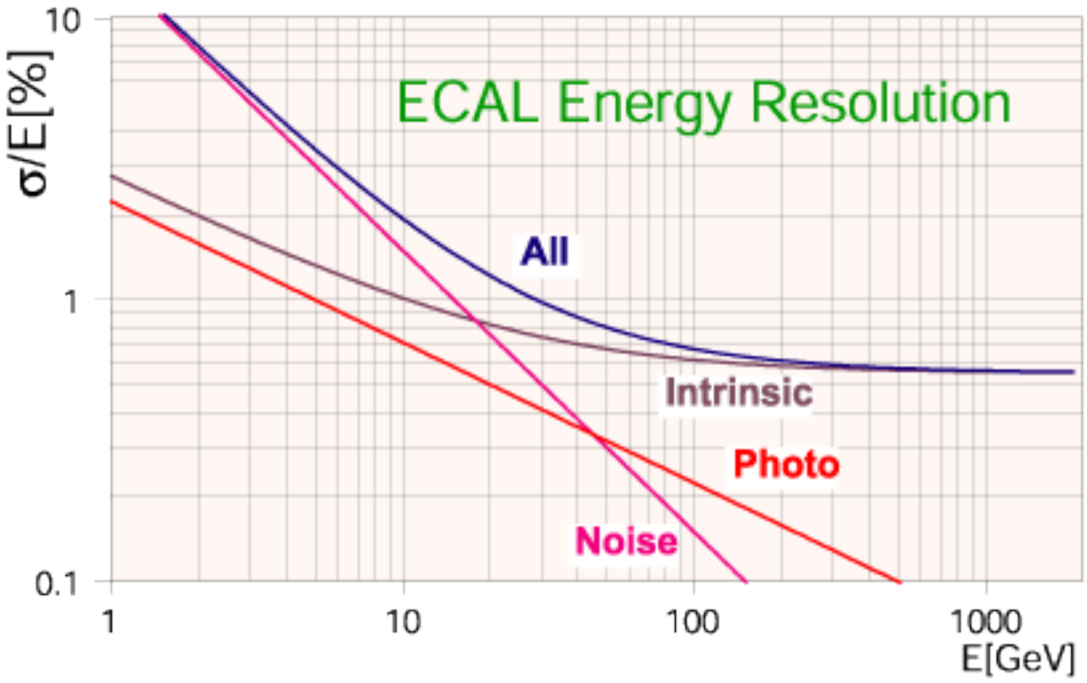
80 K crystals

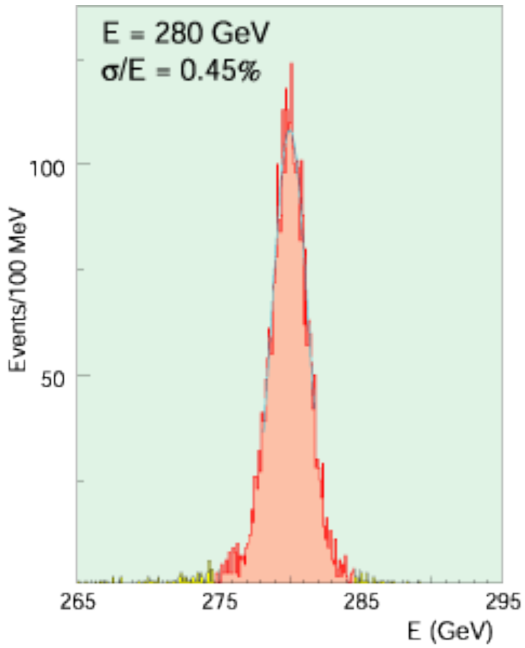
EM Calorimeter





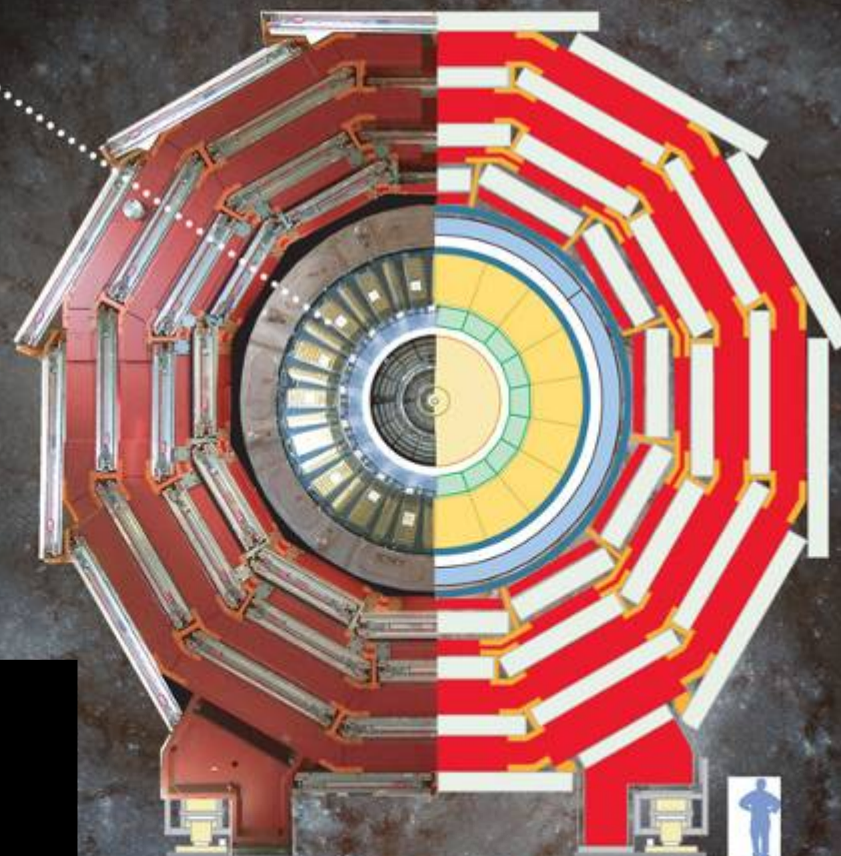
EM Calorimeter Performance





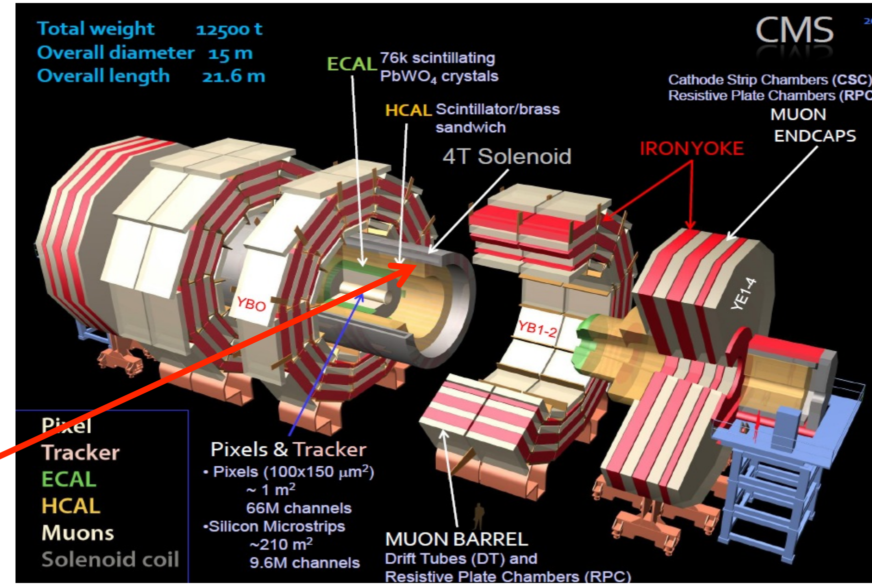
Hadronic Calorimeter

Hadron Calorimeter



- **Barrel Hadron Calorimeter:**
  brass interleaved with scintillating plates
- **Endcap Hadron Calorimeter:**
  steel threaded with quarts fibers

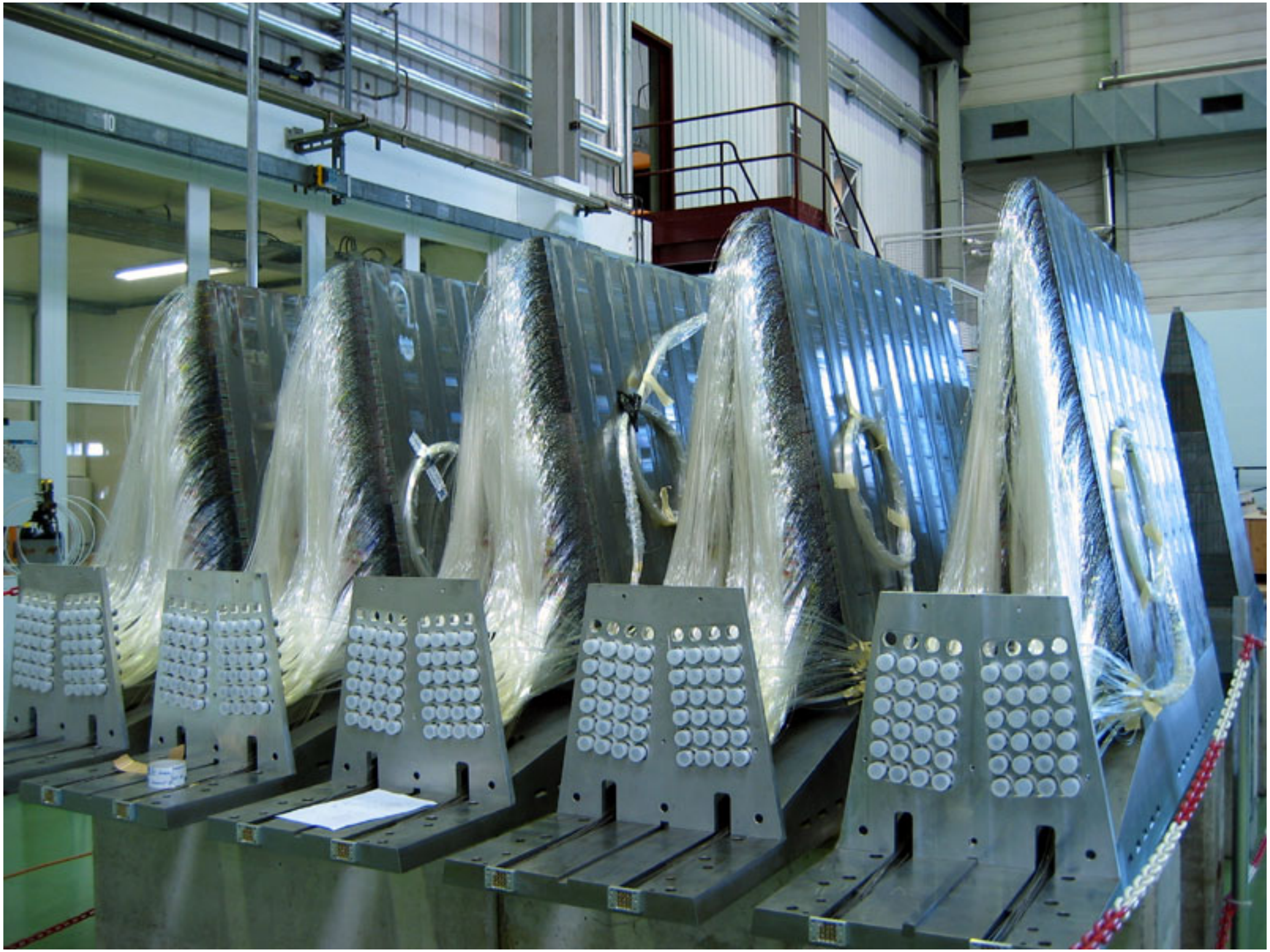
Barrel Hadron Calorimeter



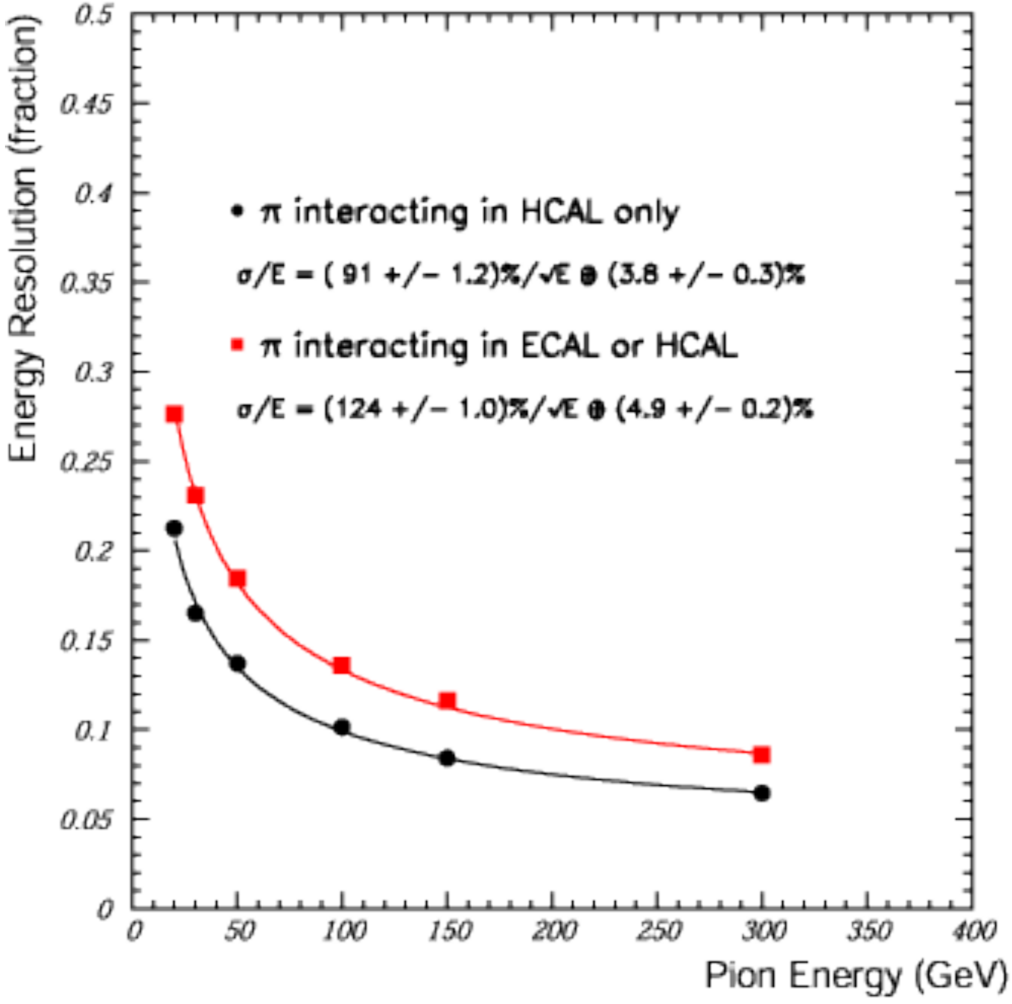
Brass-Scintillator sandwich

36 wedges, each weighs as much as 6 African elephants

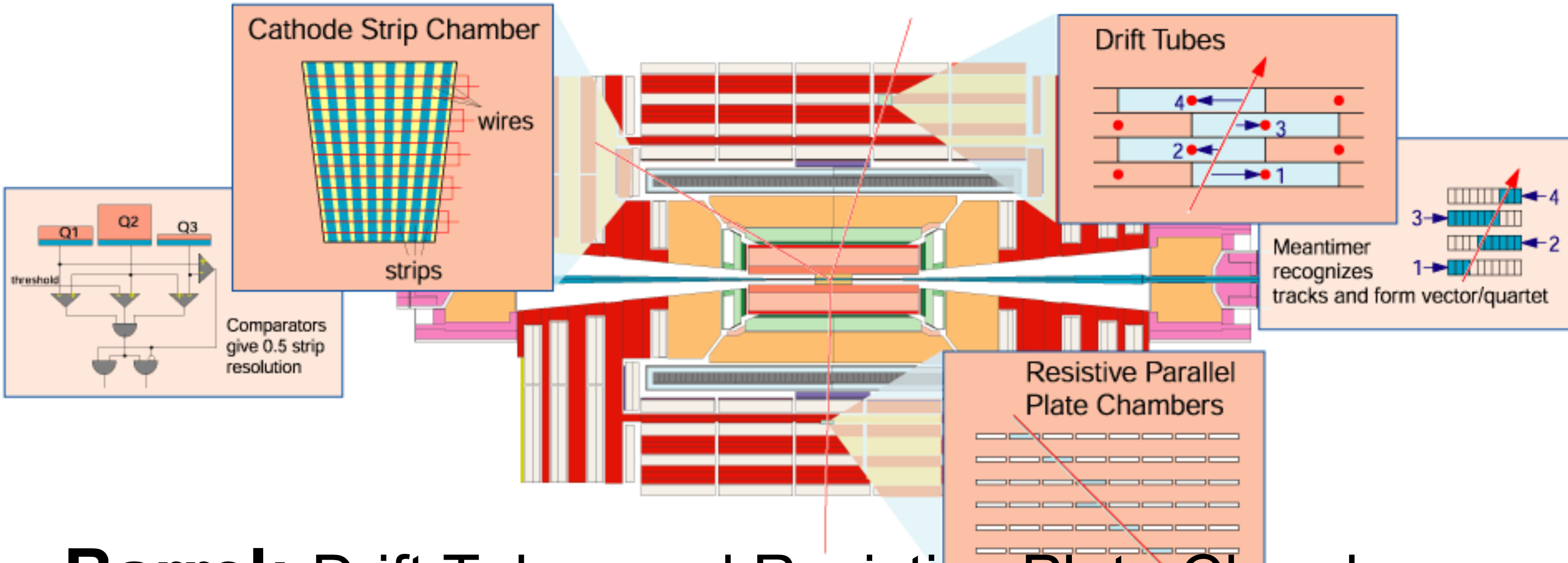
Endcap Hadron Calorimeter



Hadron Calorimeter Performance



Muon System

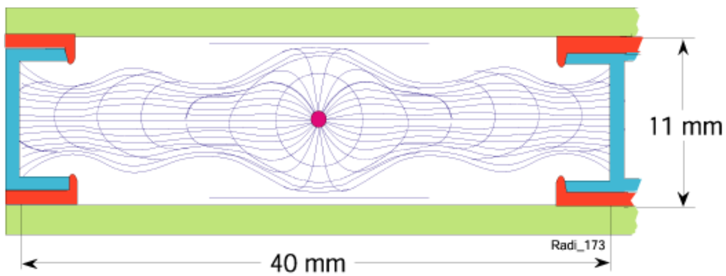


Barrel: Drift Tubes and Resistive Plate Chambers

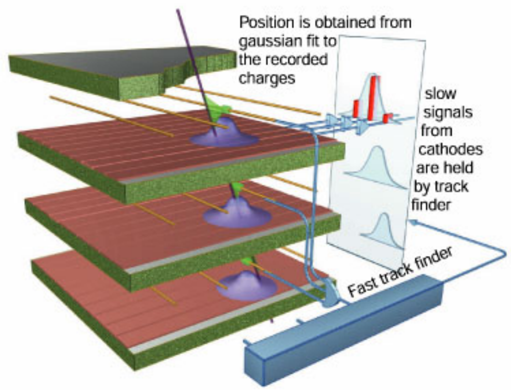
Endcaps:

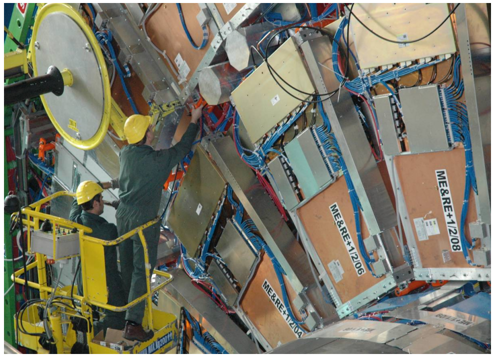
Cathode Strip Chambers and Resistive Plate Chambers

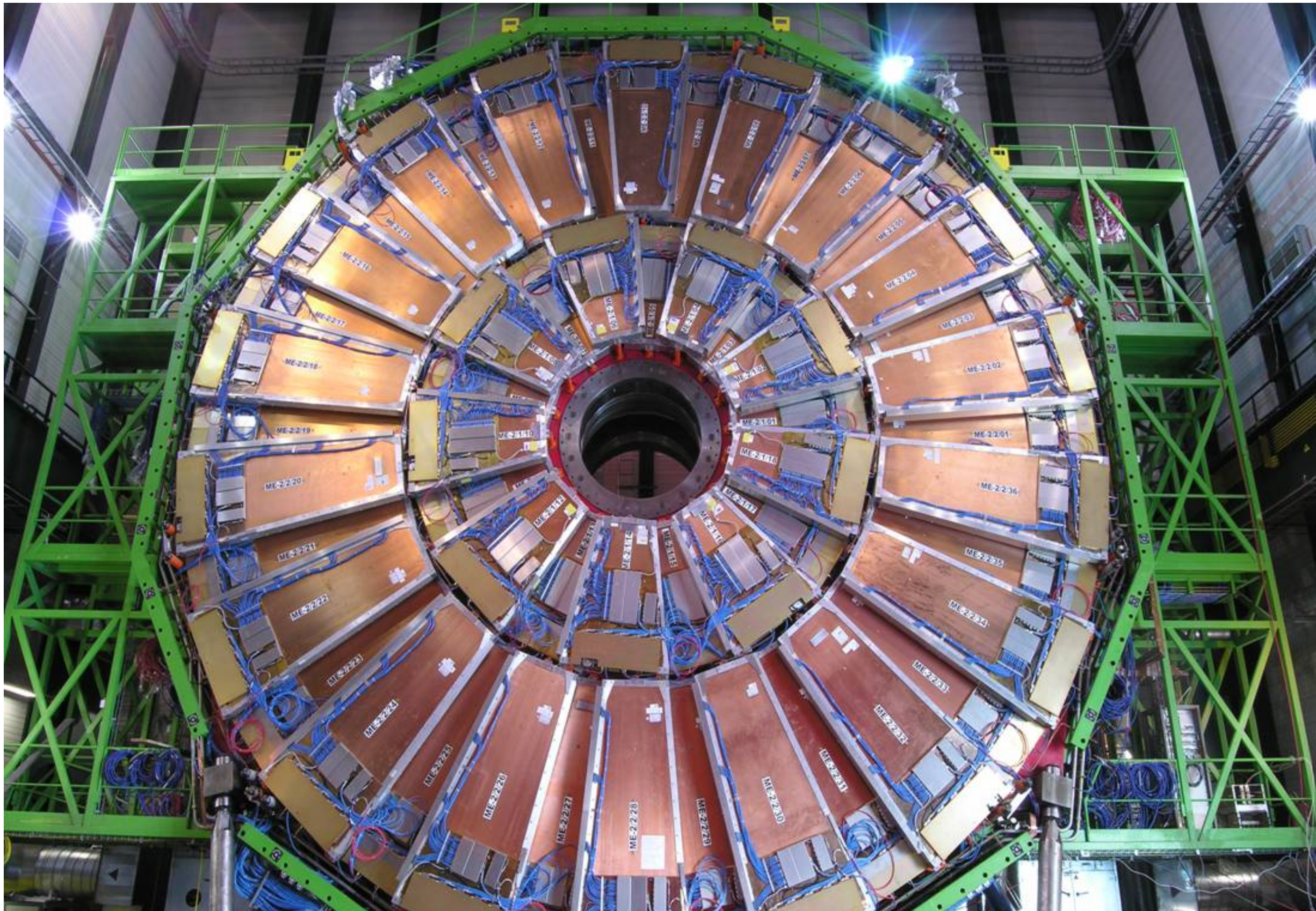
Barrel Muon System DTs



Endcap Muon System CSCs

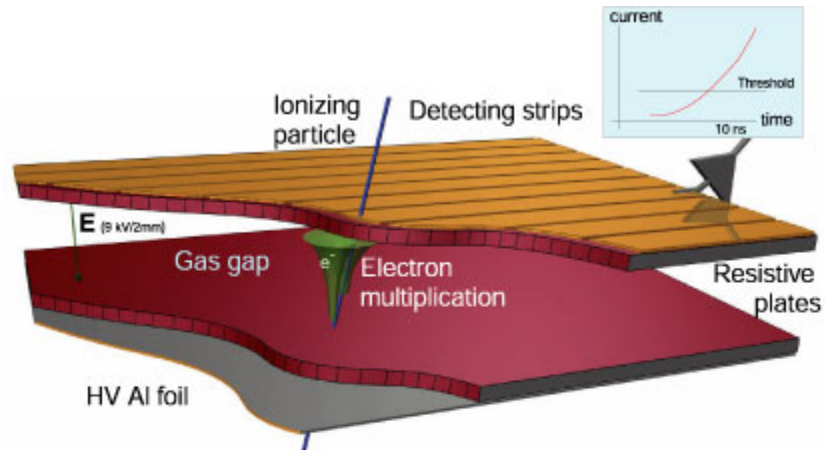




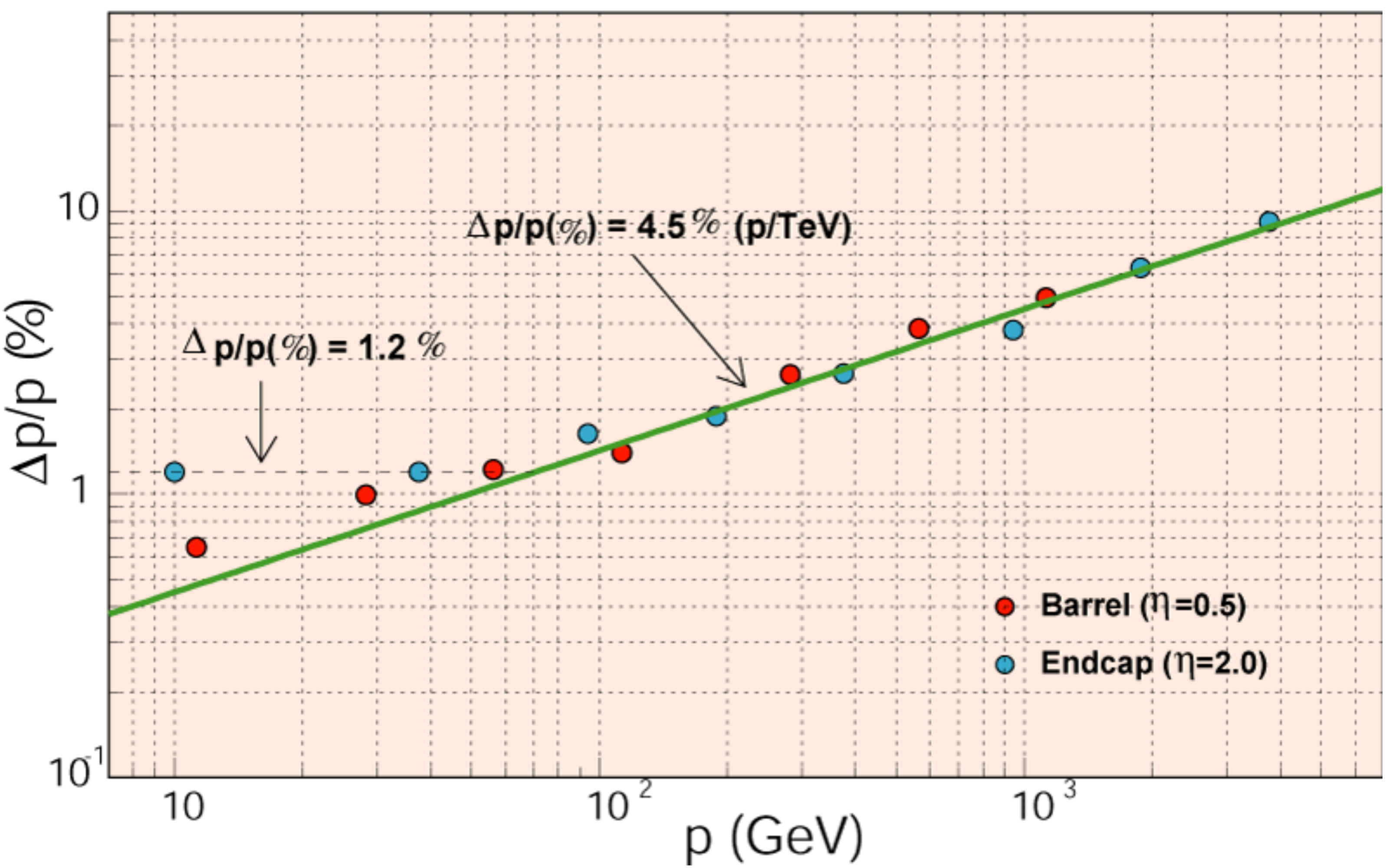


8 disks like that, 6 sensitive layers per chamber
6,000 m^2 of sensitive area (football filed)
100 µm spatial resolution

Muon System RPCs



Muon System Performance



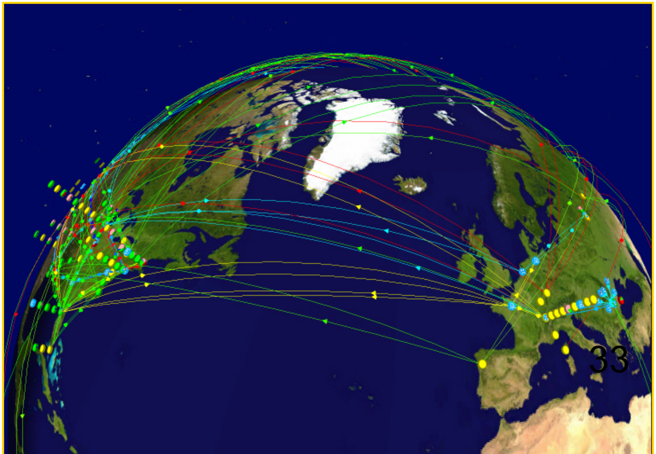
CMS on surface

CMS is ready to be closed

Enormous challenge of data flow

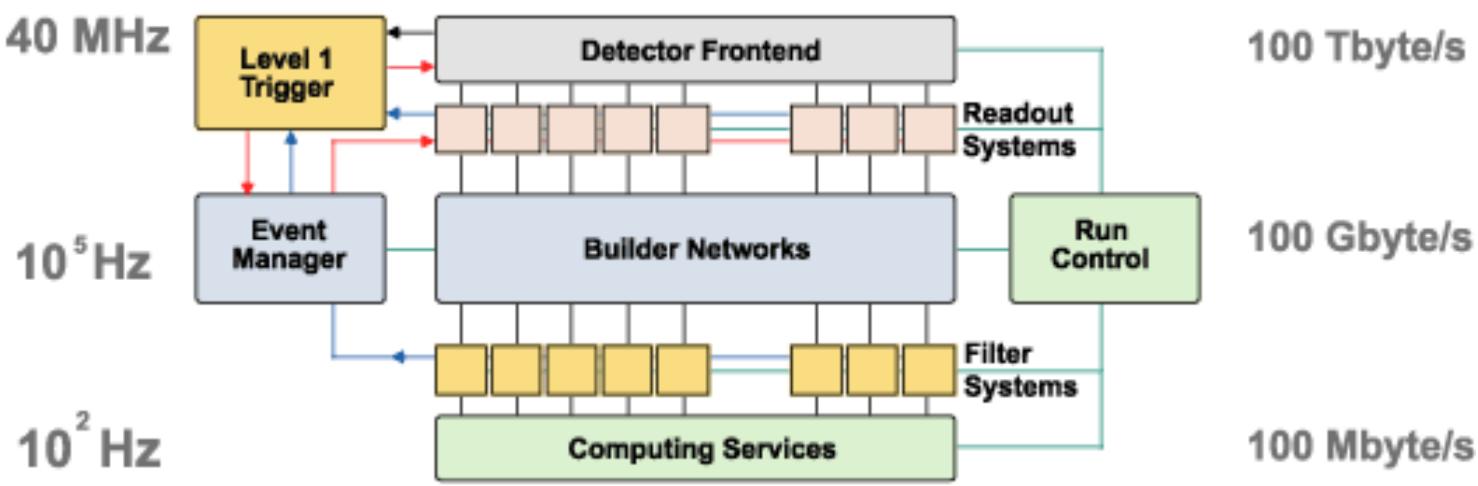
- **Detector:**
  - 80 Megapixel camera (3D pictures in a 15x15x20 m^3 volume)
  - Rapid snapshot mode: **40 M pictures/sec**
- **First-level selection:** 1:400
  - **100 K pictures/sec**
  - time allowed for a decision: 1 μs
  - specialized custom "computers"

- **Second-level selection:** 1:300
  - **300 pictures/sec**
  - computer farm with 5,000 CPU cores
- **Storage and Data Analyses**
  - **10,000 TB/year** (3 million DVDs/year)
  - Distributed/accessible for analysis all over the globe: **GRID of 100K CPUs in 34 countries**



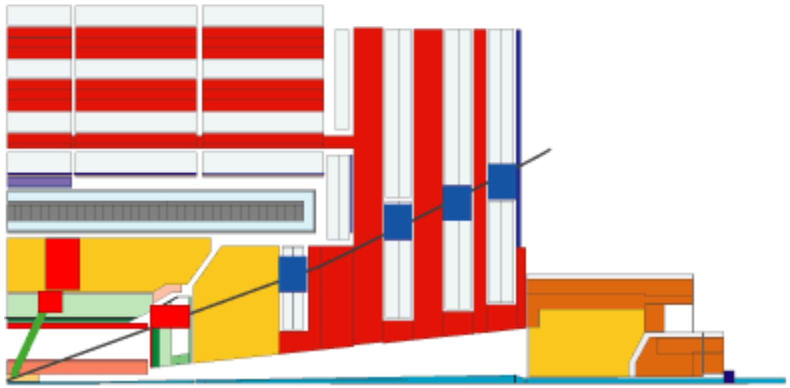
Trigger and Data Acquisition

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



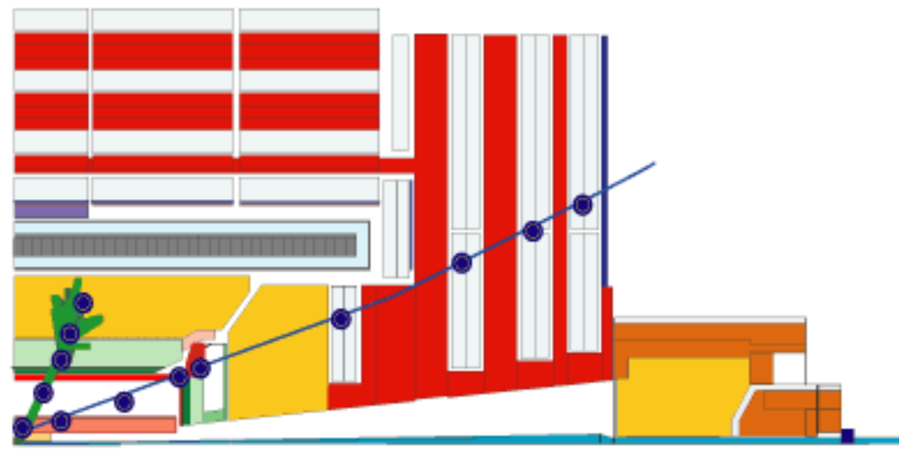
Trigger and Data Acquisition baseline structure

What is in Trigger?



Level-1 trigger. 40 MHz input :

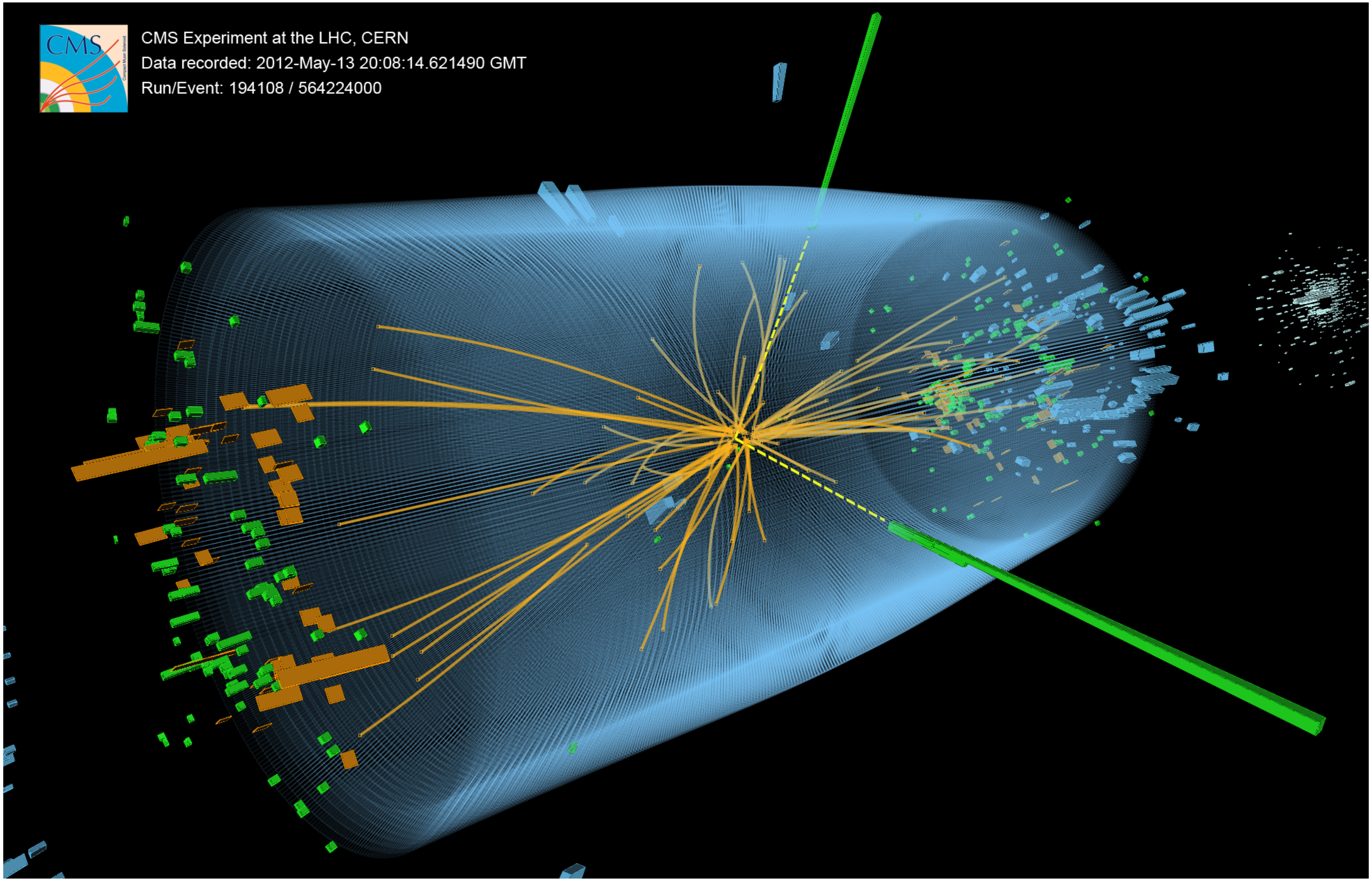
- Specialized processors (25 ns pipelined, latency < 1 s
- Local pattern recognition and energy evaluation on prompt macro-granular information from calorimeter and muon detectors
- Particle identification: high p_t electron, photon, muon, jets, missing E_T



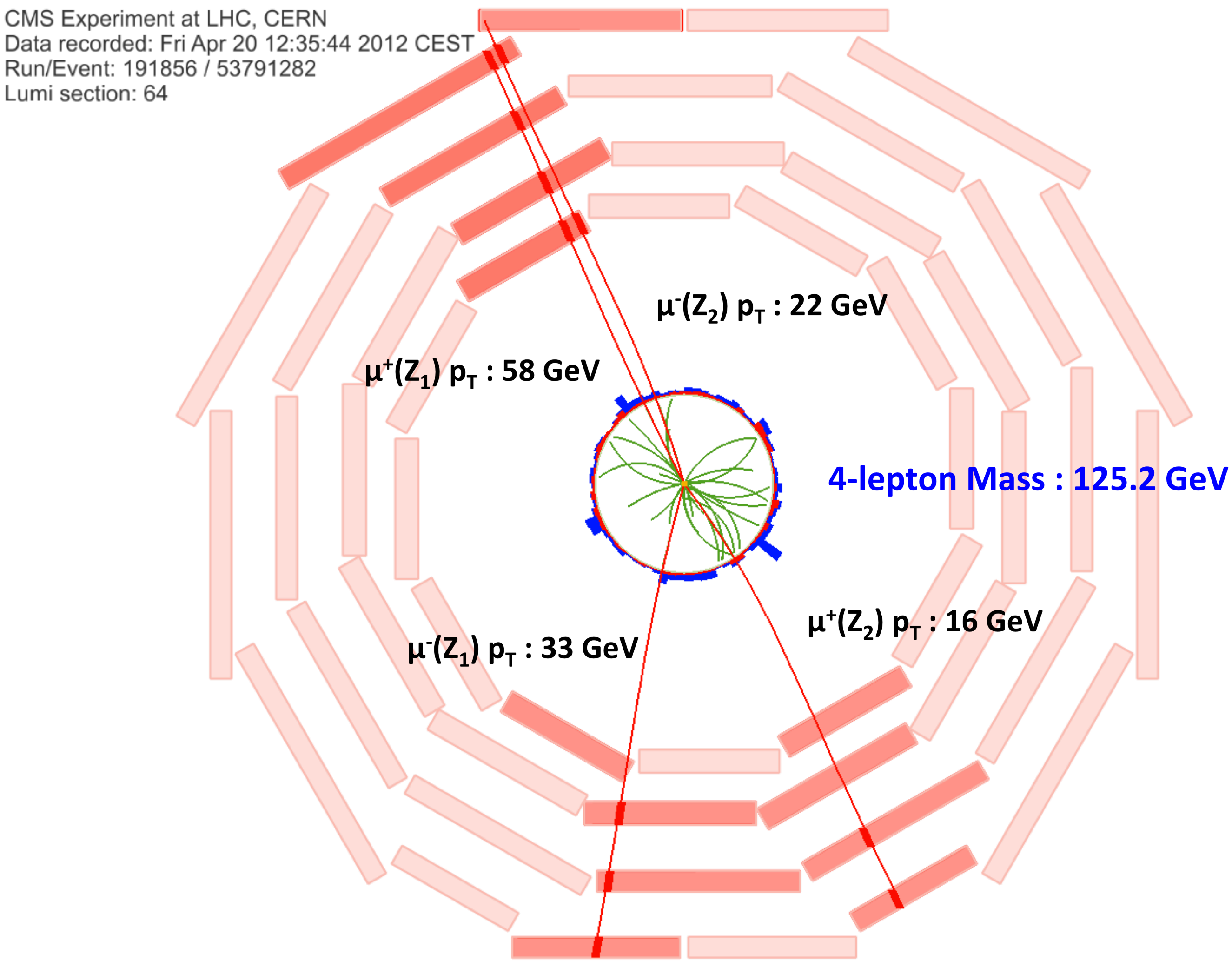
High trigger levels (>1). 100 kHz input :

- Large network of processor farms
- Clean particle signature. All detector data
- Finer granularity precise measurement
- Effective mass cuts and event topology
- Track reconstruction and detector matching
- Event reconstruction and analysis

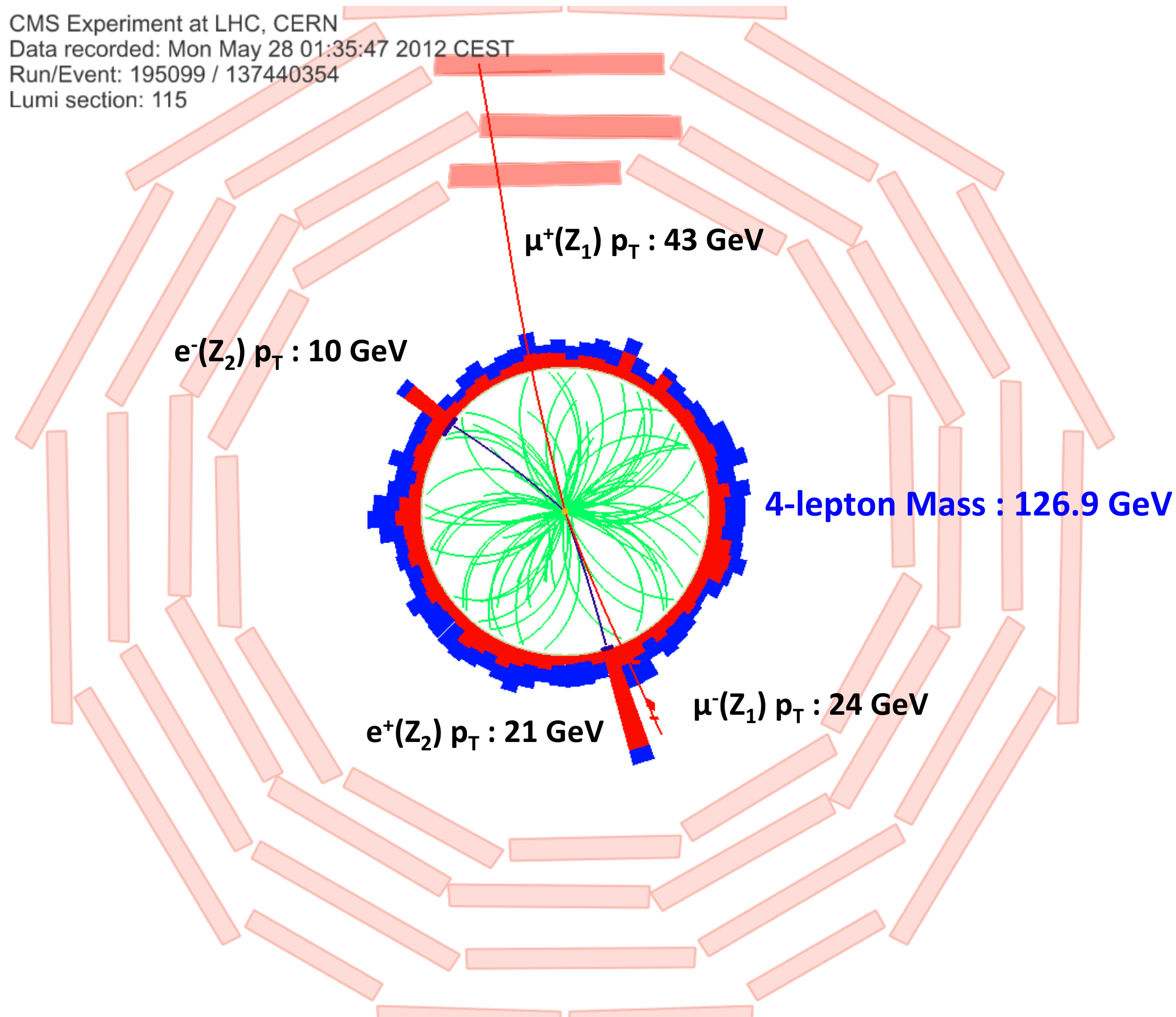
An example of an event: H→γγ candidate



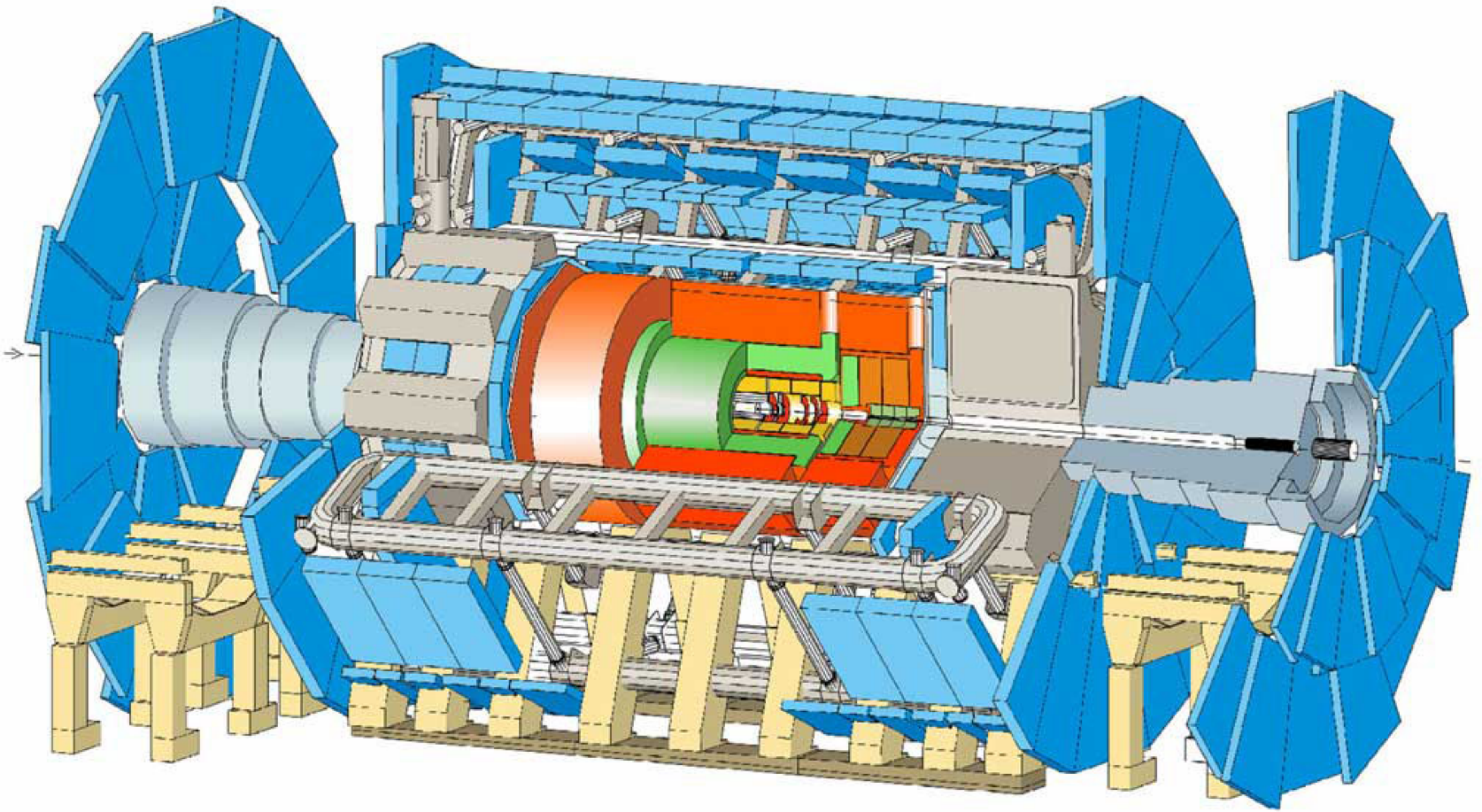
An example of an event: H→ZZ→4μ candidate



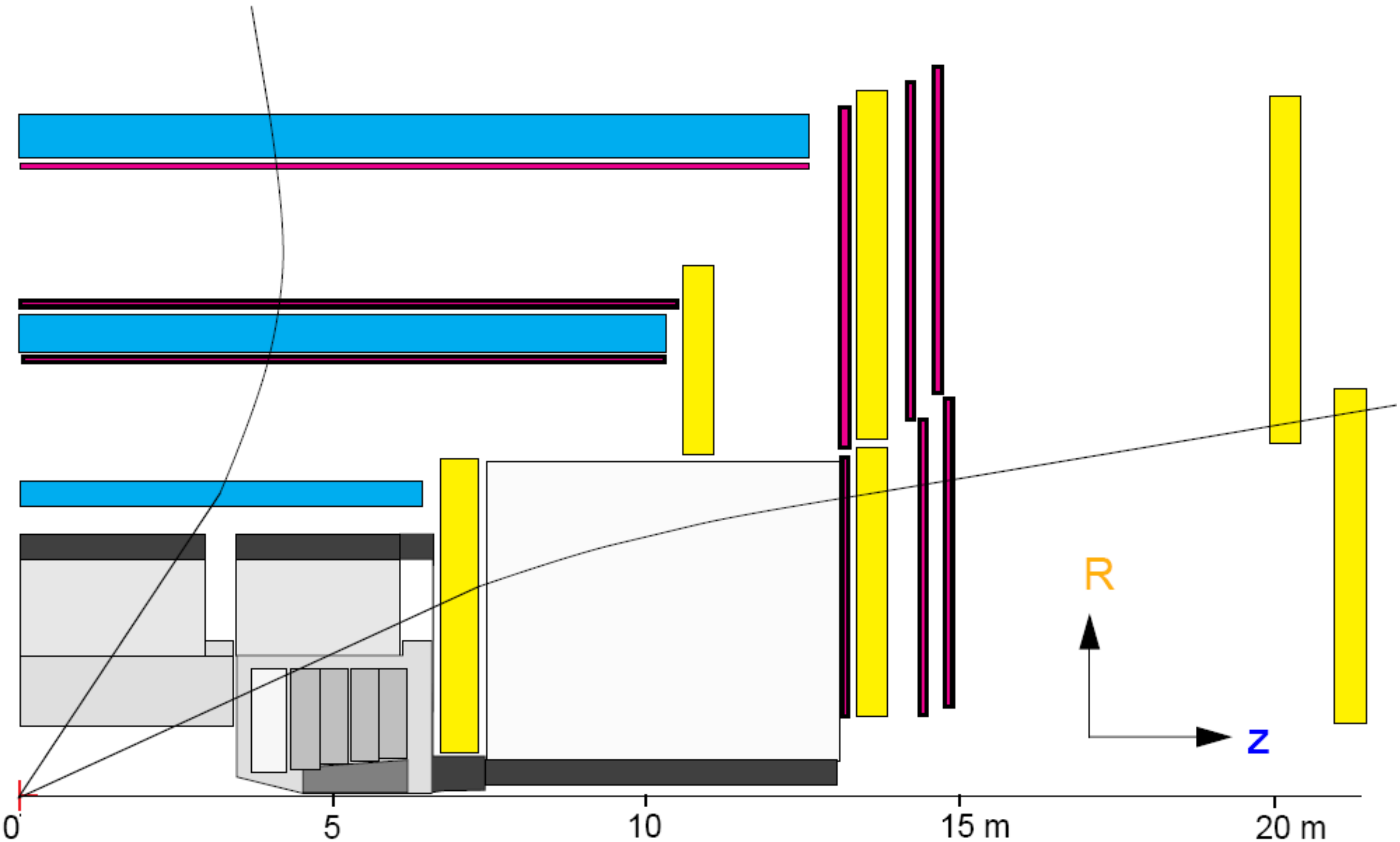
An example of an event: H→ZZ→2e2μ candidate



ATLAS (for comparison)

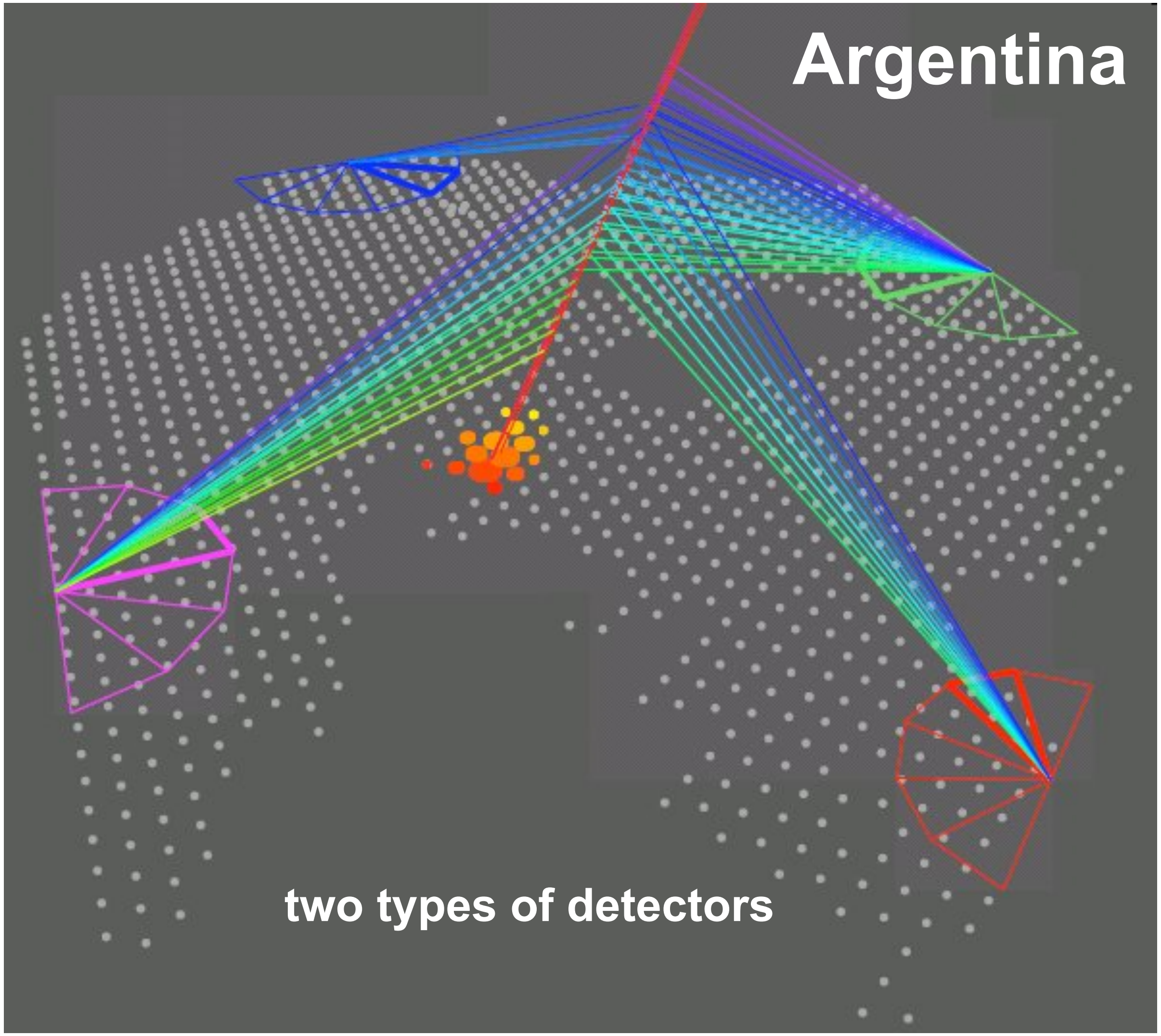


ATLAS concept (cf CMS)

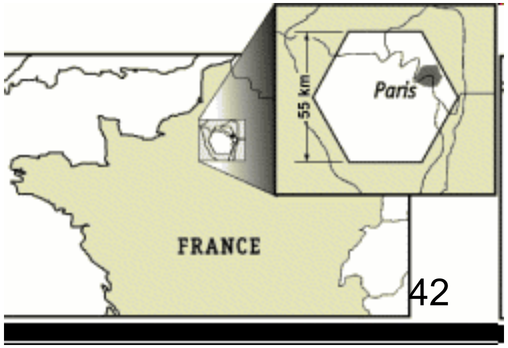


Pierre Auger Observatory
(largest cosmic ray shower detector)

Pierre Auger Observatory



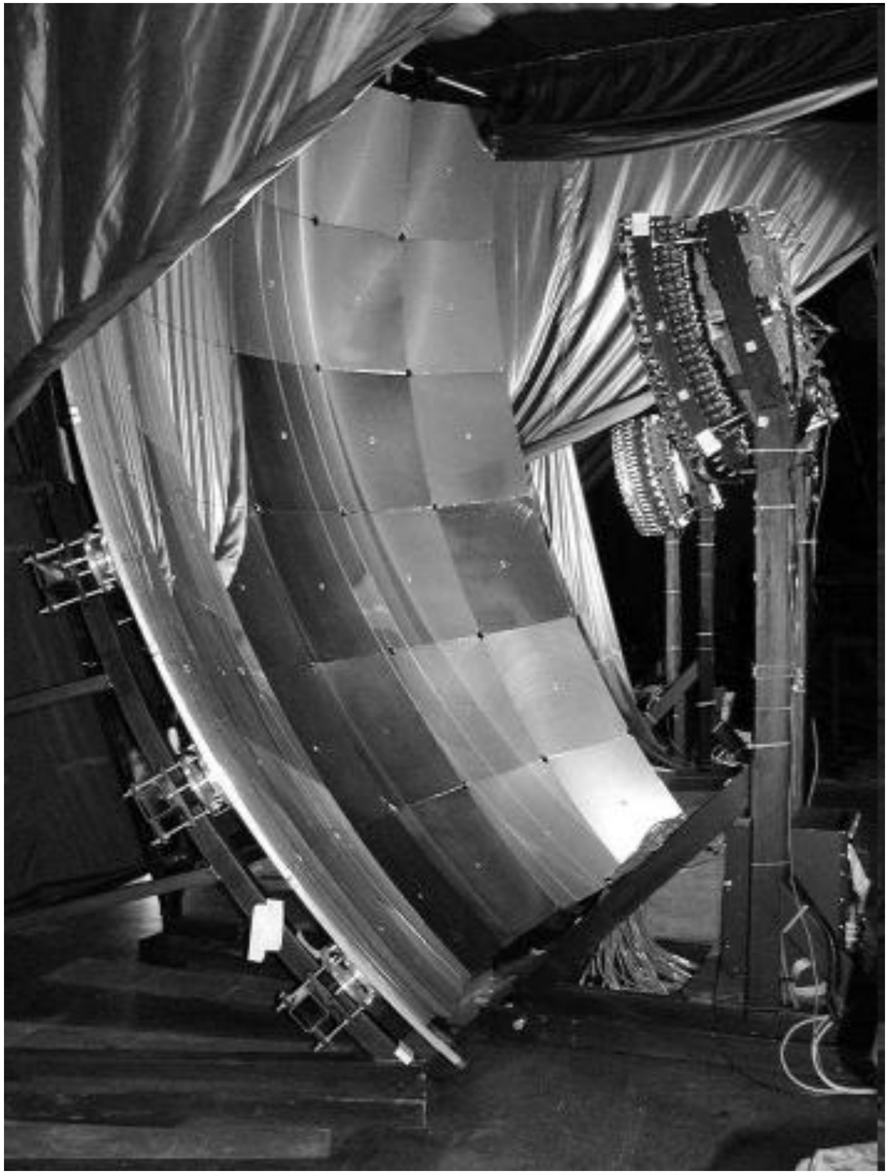
size of the detector site compared to Paris



Water Tanks

Cherenkov light from muons reaching the earth surface

Fluorescence Light Detector



Telescopes recording the development of cosmic ray showers (em and hadronic) in the upper layers of atmosphere via fluorescence light detection