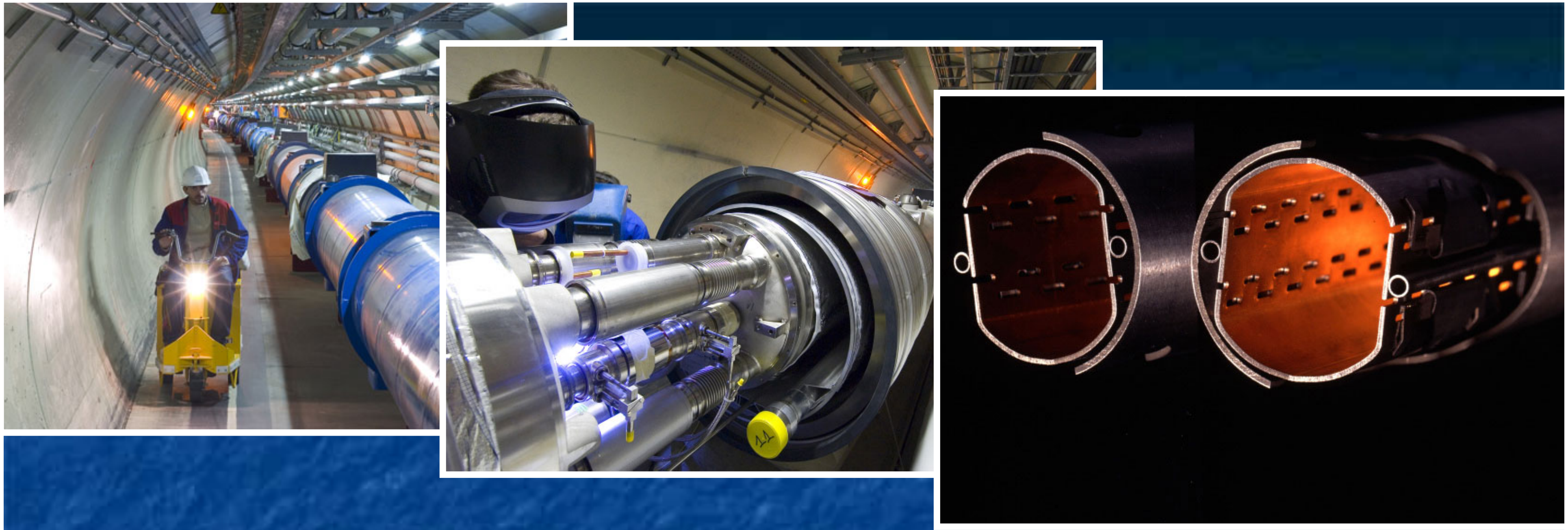
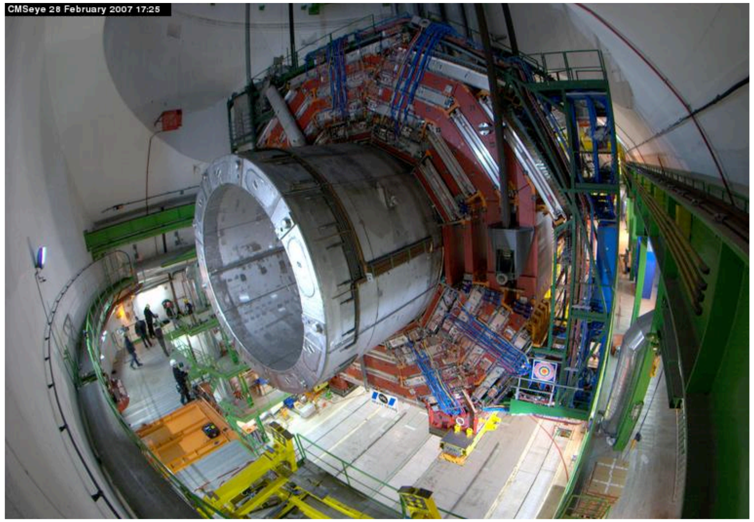
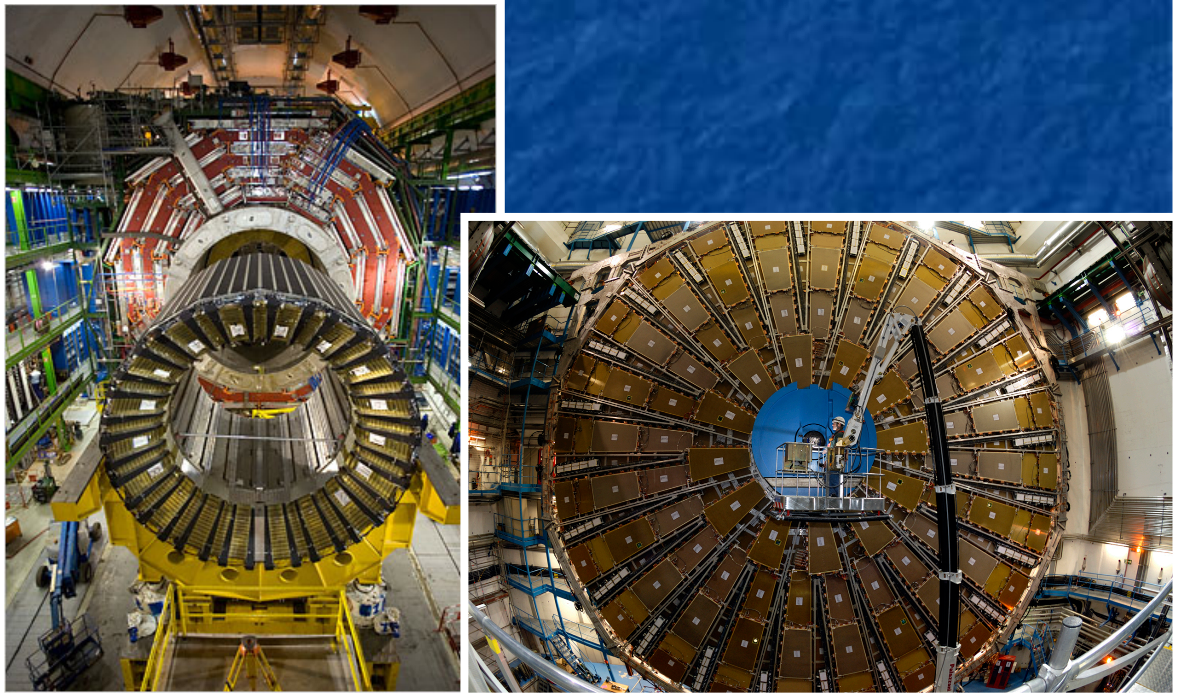


Particles detectors: some basic principles





Duccio Abbaneo
IPM School
October 8, 2013

Introduction

Five lectures on particle detectors

- Basic concepts of particle detection
    - Duccio Abbaneo
- Trigger and data processing
    - Andrea Bocci
- Silicon detectors
    - Thomas Bergauer
- Gas detectors
    - Archana Sharma
- Calorimetry
    - Riccardo Paramatti

Five presentations on CMS upgrades

- Tracker Upgrade
    - Duccio Abbaneo
- Trigger Upgrade
    - Andrea Bocci
- Silicon sensors R&D
    - Thomas Bergauer
- Upgrade of Forward Calorimetry
    - Riccardo Paramatti
- Muon Upgrade
    - Archana Sharma

Introductory lectures

- Meant for students
  - Certainly boring for senior particle physicists!
- Meant to be understandable
  - Do not hesitate to ask questions!
- Will not try to cover the topics in an exhaustive way…
  - Would require a 1-year long course!
- … but rather to explain some of the basic concepts that should help to understand the CMS detector and its upgrades

Outline of this lecture

- Very basic principles
- Implementation in CMS
  - Entertaining pictures from the CMS construction
- Some more about tracking

Particle detector for high-enery physics experiments

- High energy collisions (e^+e^-,ep,pp…)
  - production of a multitude of particles (charged, neutral, photons)
- The ‘ideal’ detector should provide....
  - coverage of full solid angle (no cracks, fine segmentation)
  - detect, track and identify all particles (mass, charge)
  - measurement of momentum and/or energy, fast response, no dead time
- Practical limitations (technology, space, budget)
- Particles are detected via their interaction with matter
  - Many different physical principles are involved (mainly of electromagnetic nature).
- Finally we will observe: ionization and excitation of matter

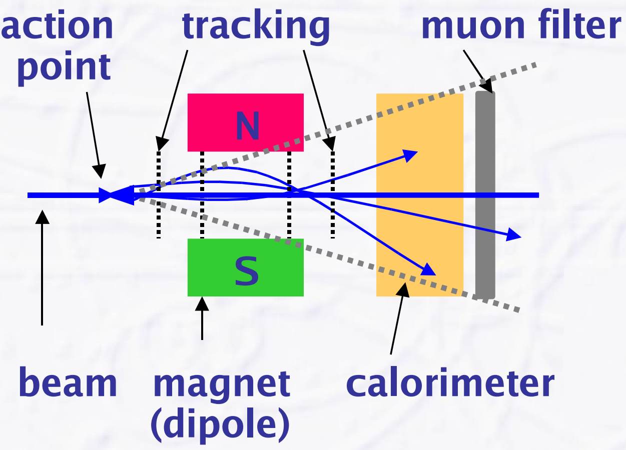
Detector Geometries

- Two main families:

Fixed target geometry

“Magnet spectrometer”

LHCb

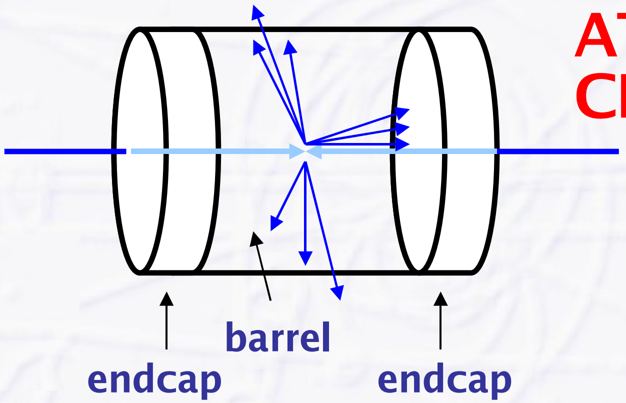


- Limited solid angle $d\Omega$ coverage
- rel. easy access (cables, maintenance)

Collider geometry

“4π multi purpose detector”

ATLAS
CMS

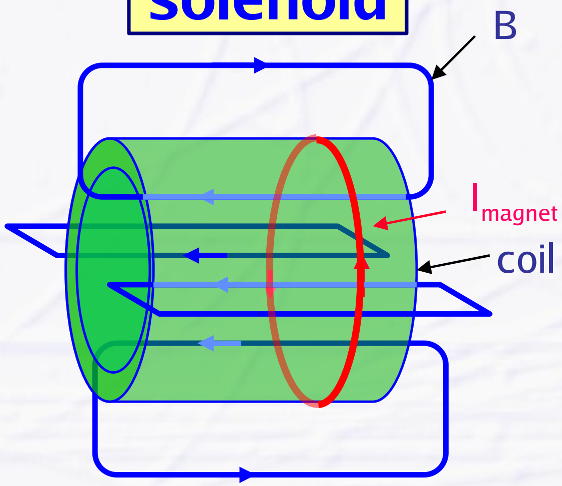


- “full” $d\Omega$ coverage
- very restricted access

- The collider geometry is typically much more difficult to design and engineer!
  - Hermeticity is normally a very strong requirement

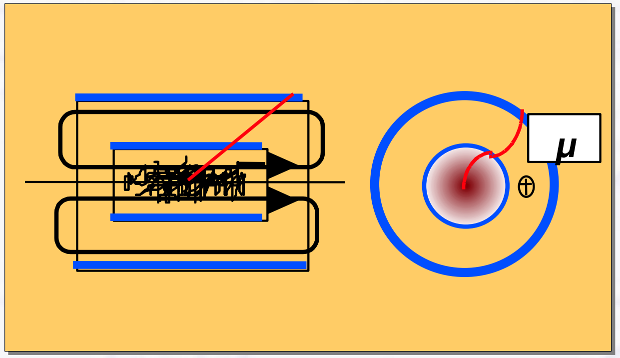
Magnet concepts

solenoid

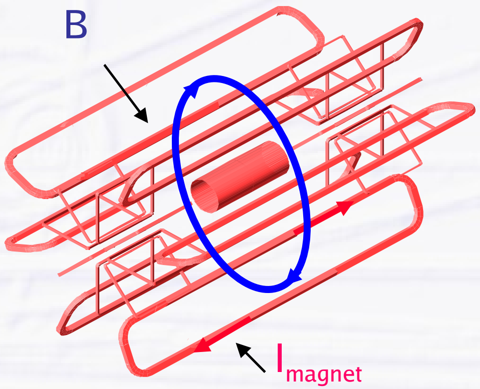


- \+ large homogenous field inside coil
- \- needs iron return yoke (magnetic shortcut)
- \- limited size (cost)
- \- coil thickness (radiation lengths)

CMS, ALICE, LEP detectors

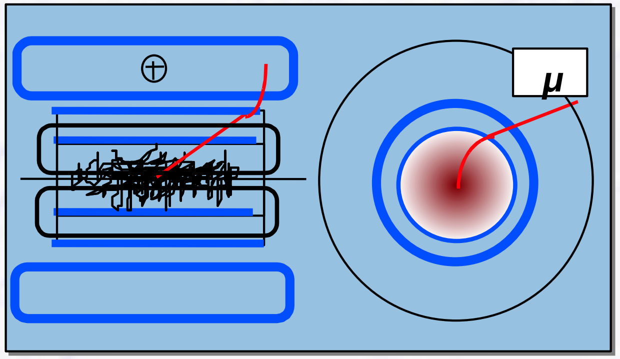


(air-core) toroid



- \+ can cover large volume
- \+ air core, no iron, less material
- \- needs extra small solenoid for general tracking
- \- non-uniform field
- \- complex structure

ATLAS



What do we really observe?

- We observe "stable" particles
  In practice: those that travel long enough inside the detector before disintegrating into lighter decay products

Charged particles
  leptons: electrons, muons
  hadrons: pions, K mesons, protons

Neutral hadrons: neutrons and some neutral K mesons

Photons

To be noted:
(1) Neutrinos do not interact in our detectors
  Signature: "missing energy"
  - requires a very hermetic and fully efficient detector
(1) For all other particles: we measure their decay products

Interactions exploited

At the high energies we are working with, the relevant interactions are:

Leptons:	***bremsstrahlung**, ionisation (or excitation)*
Charged hadrons:	***nuclear interactions**, ionisation (or excitation)*
Neutral hadrons:	***nuclear interactions***
Photons:	***conversion to electron-positron pairs***

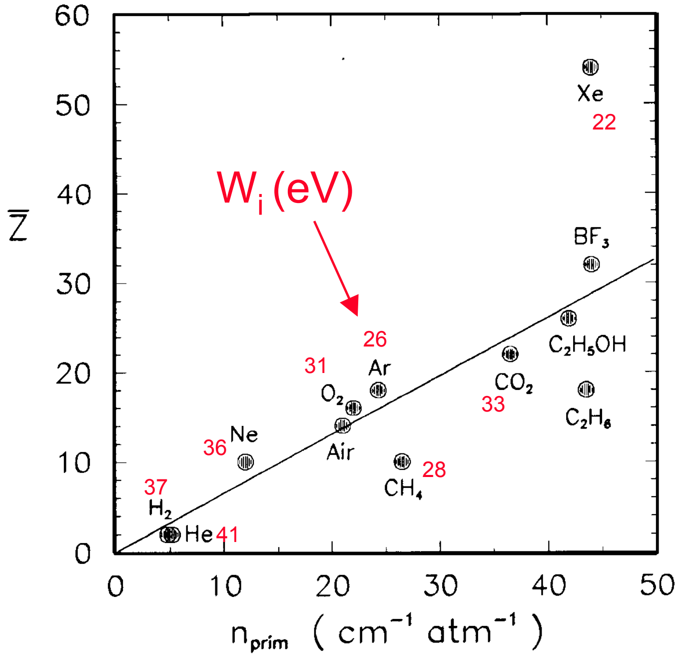
(Photo effect to detect e.g. the low-energy photons from excitation of matter)

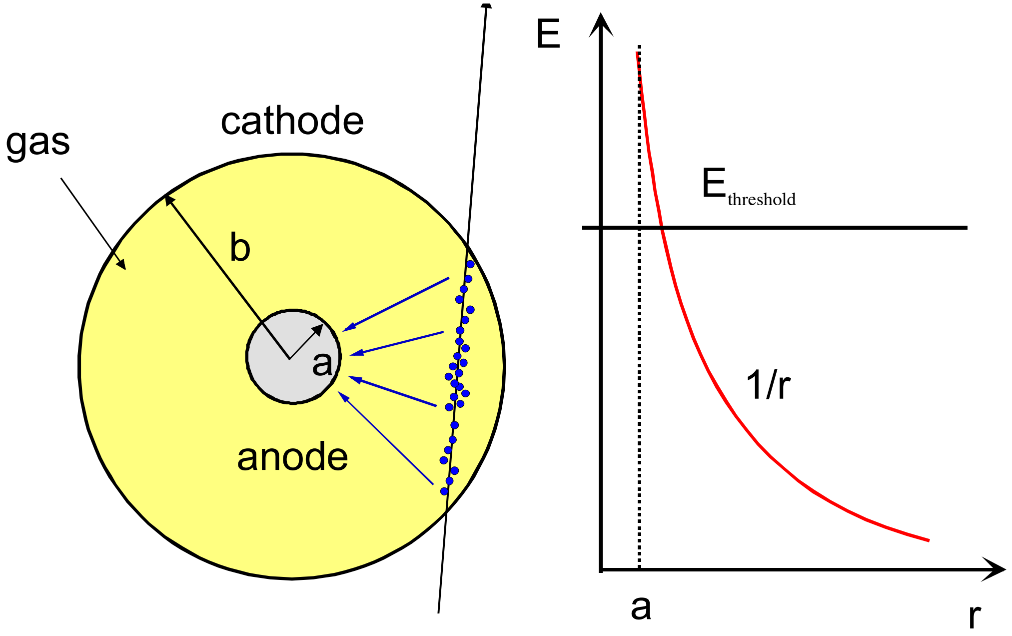
Interaction of particles with matter

Ionisation

Small and progressive energy loss
Observable signal with minimal perturbation for a multi-GeV particle

Gas: a few 10 eV x a few 10 e^- / cm
Amplification (avalanche) inside the detector (e.g. gain ~ 10000)





Interaction of particles with matter

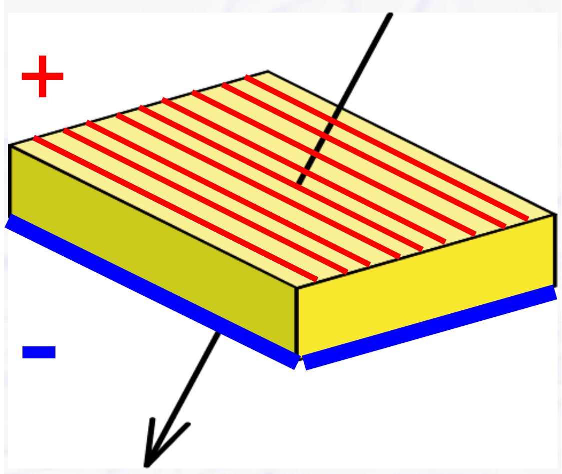
Ionisation

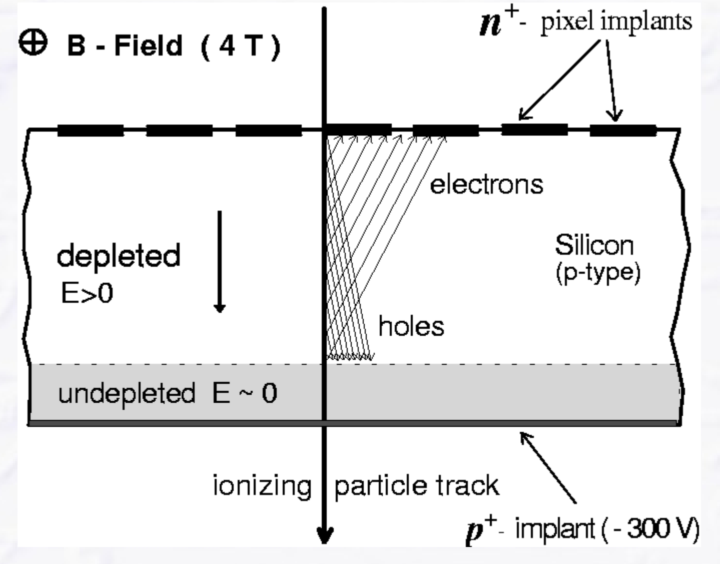
Small and progressive energy loss
Observable signal with minimal perturbation for a multi-GeV particle

Gas: a few 10 eV x a few 10 e^- / cm
Amplification (avalanche) inside the detector (e.g. gain ~ 10000)

Semiconductors (not *really* ionisation):
few eV x 100,000 e^- / mm
Signal directly collected by readout electronics

The readout electrode gives the coordinate of the track





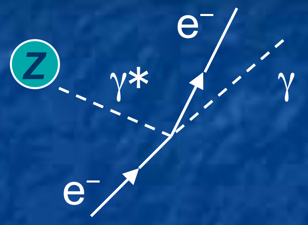
Interaction of particles with matter

Bremsstrahlung

Emission of photons in the electric field of a nucleus

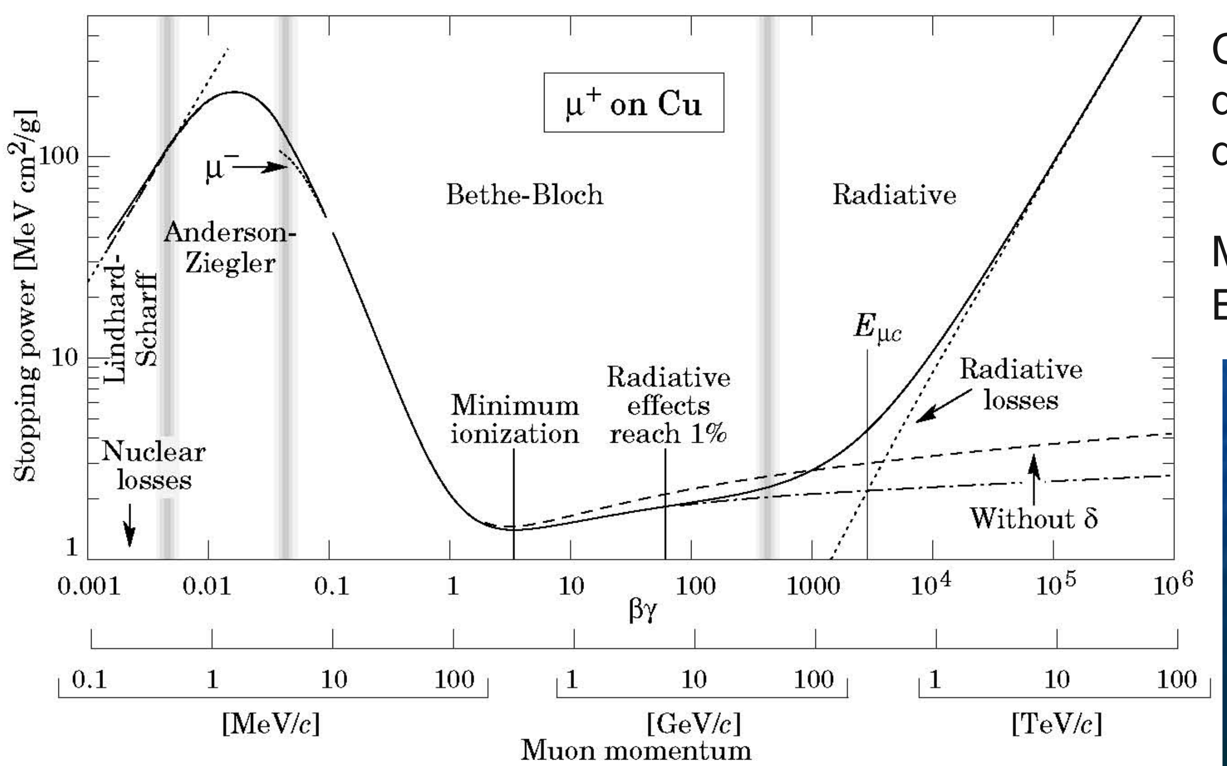
For electronics it is the dominant energy loss for E > 500 MeV / Z

→ Dominant for electrons, but (almost) negligible for all other particles



Radiation length X_0 (energy reduced to 1/e) $\propto 1/Z^2$ [cm]

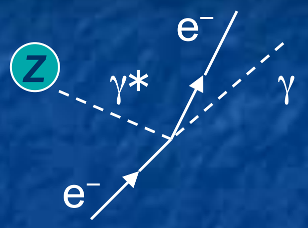
(air $X_0 \approx$ 300 m, carbon fiber ≈ 25 cm, Si ≈ 9.4 cm, Cu ≈ 1.4 cm, Pb ≈ 0.56 cm)



Critical Energy:
dE/dx (Ionization) =
dE/dx (Bremsstrahlung)

Muons in Copper: p ~ 400 GeV
Electrons in Copper: p ~ 20 MeV

Interaction of particles with matter



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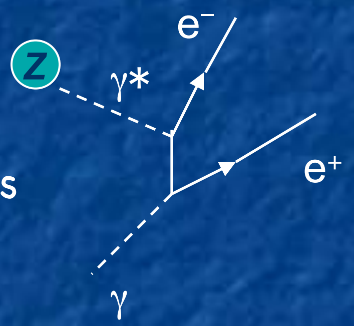


Photon conversions

Creation of e^+e^- pairs from energetic photons in the electric field of a nucleus

Process similar to bremsstrahlung. Mean free path $L = 9/7\ X_0$

Nuclear interactions

Mean free path for nuclear interactions λ_I is typically much larger than the radiation length: $\lambda_I \propto 1/A^{2/3}$ [cm] for solid materials ($X_0 \times 2$ in C, up to $X_0 \times 30$ in Pb)

Un rivelatore di particelle: sfruttare le interazioni in sequenza

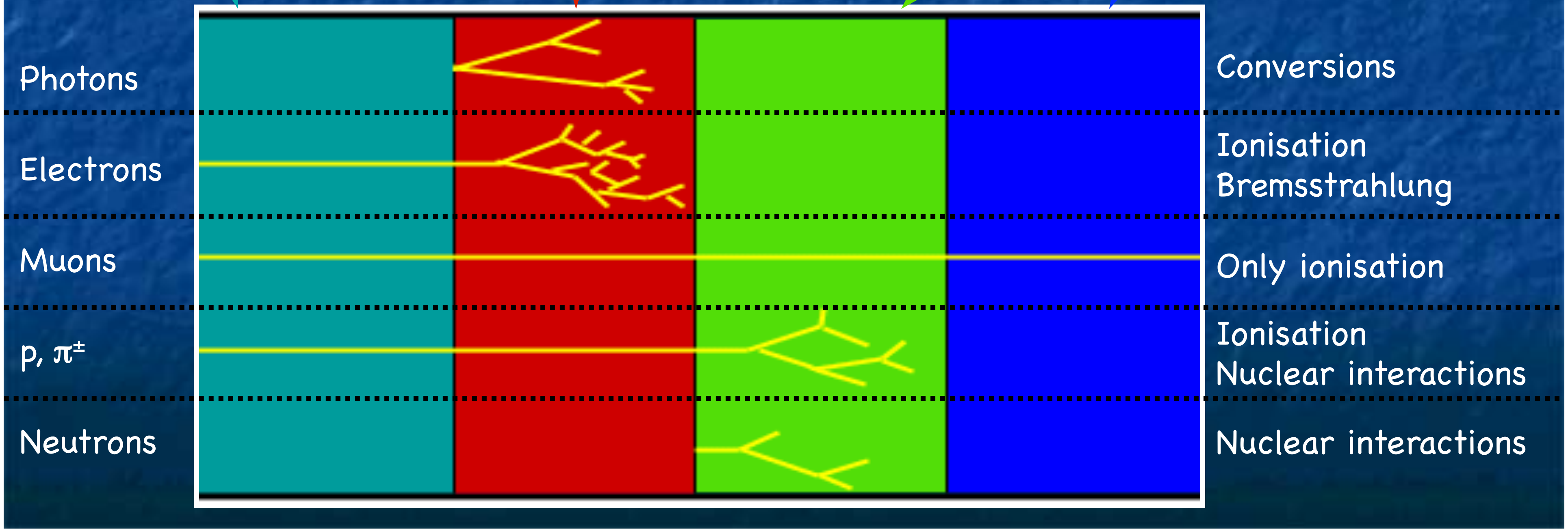
Ionisation in a high-granularity detector
Magnetic field to measure momentum
Minimize bremsstrahlung and photon conversions
Minimize nuclear interactions
Minimize amount of material

Reconstruct tracks of charged particles: TRACKER

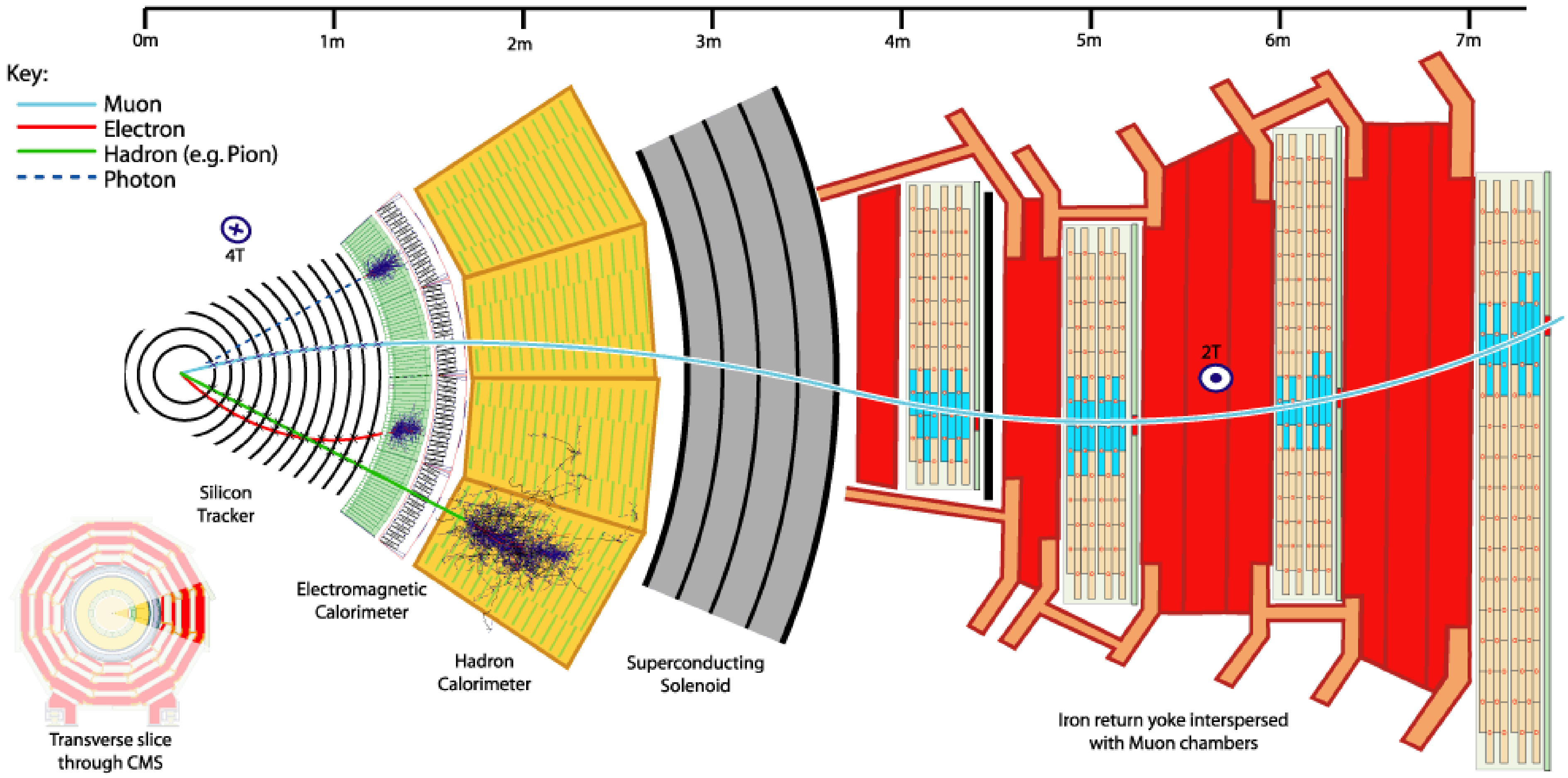
Stop (absorb) all hadrons and measure their energy
HADRON CALORIMETER
Large thickness (1-2 m) of heavy material
Often a sampling calorimeter

Bremsstrahlung and photon conversions
Absorb electroncs and photons, using high-Z material
Measure energy: ELECTROMAGNETIC CALORIMETER
Hadronic showers (can) start, but they are not contained ($\lambda_I >> X_0$)
Two families: sampling and homogeneous

External detectors measuring outgoing muons
MUON DETECTORS
Normally very big gas detectors (ionisation)
Can be interleaved with iron slabs for B-field return (for solenoid magnets)

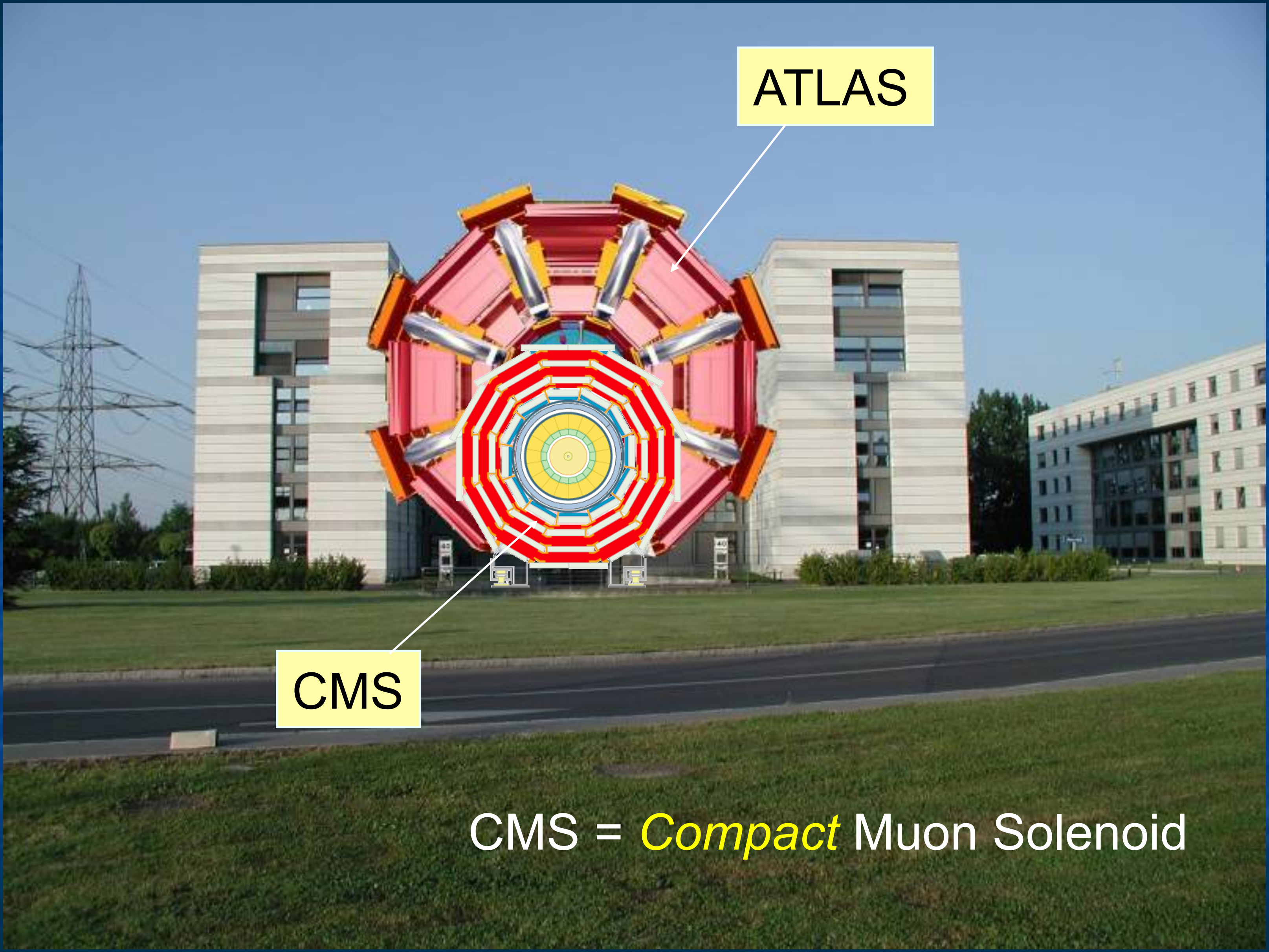


CMS: a direct application of the concept



Dimensions are dictated by the energy of the particles to be measured and by the precision required...

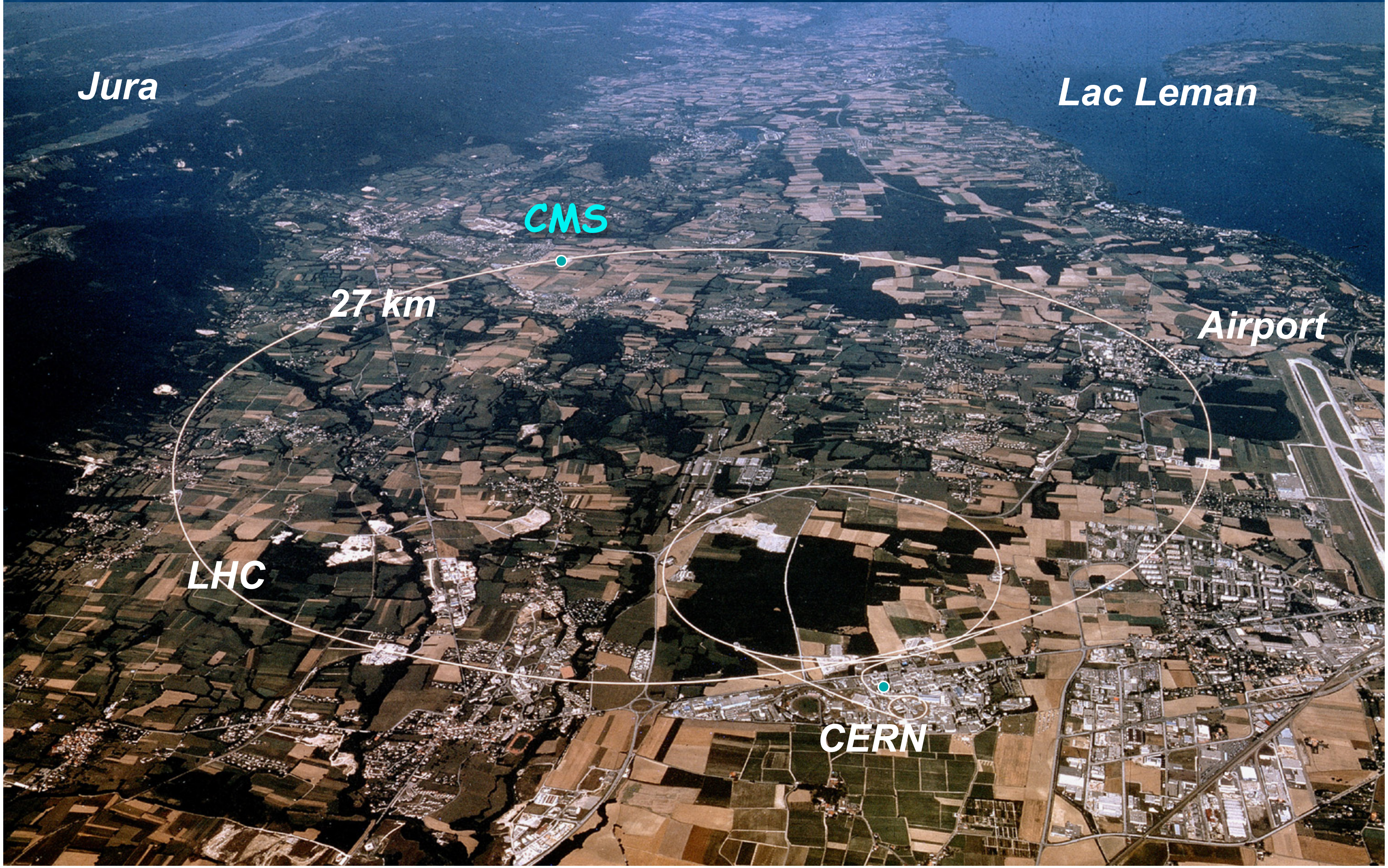
CMS and ATLAS



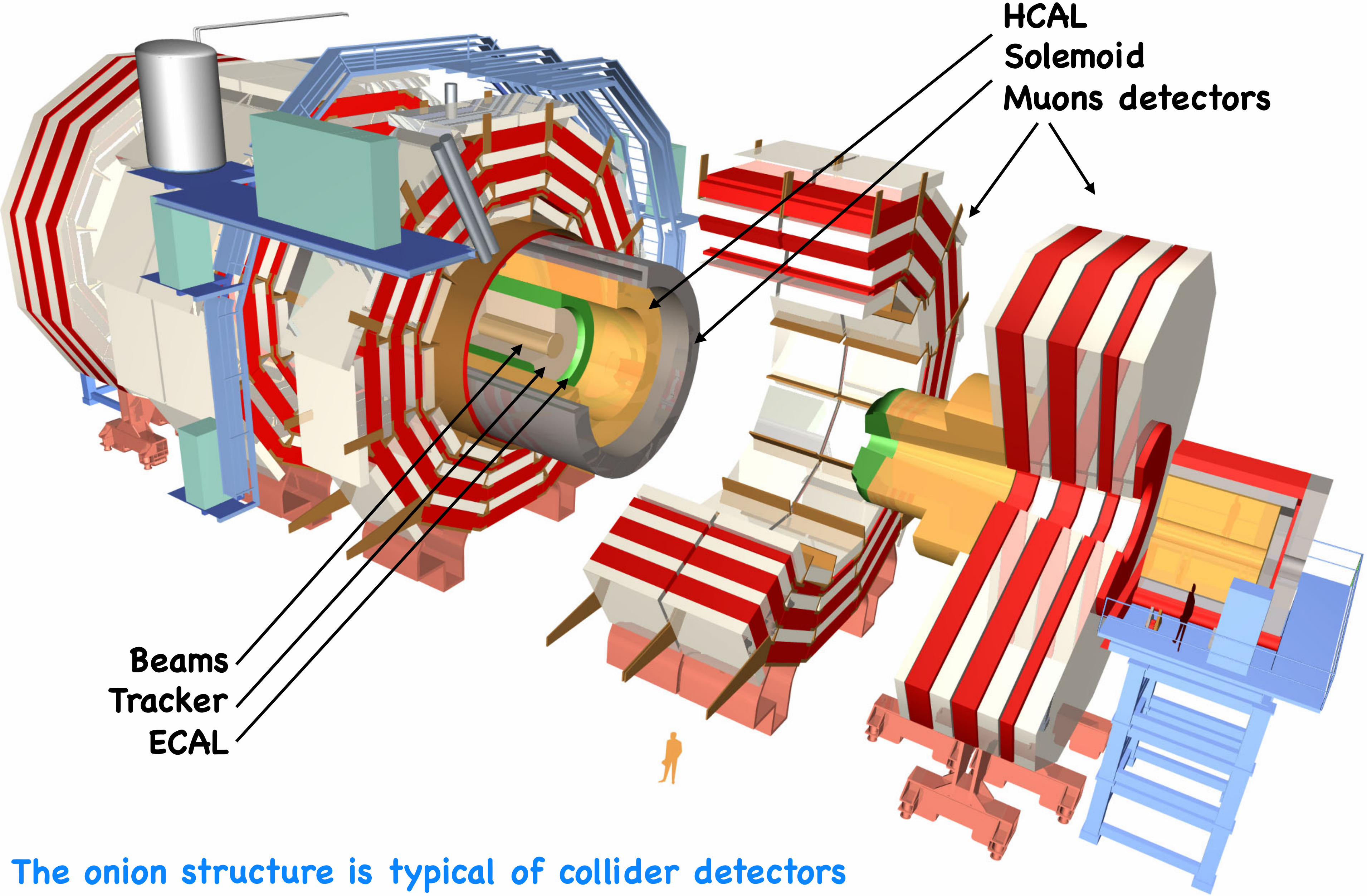
CMS = *Compact* Muon Solenoid

… and also by the options chosen!

LHC in the landscape

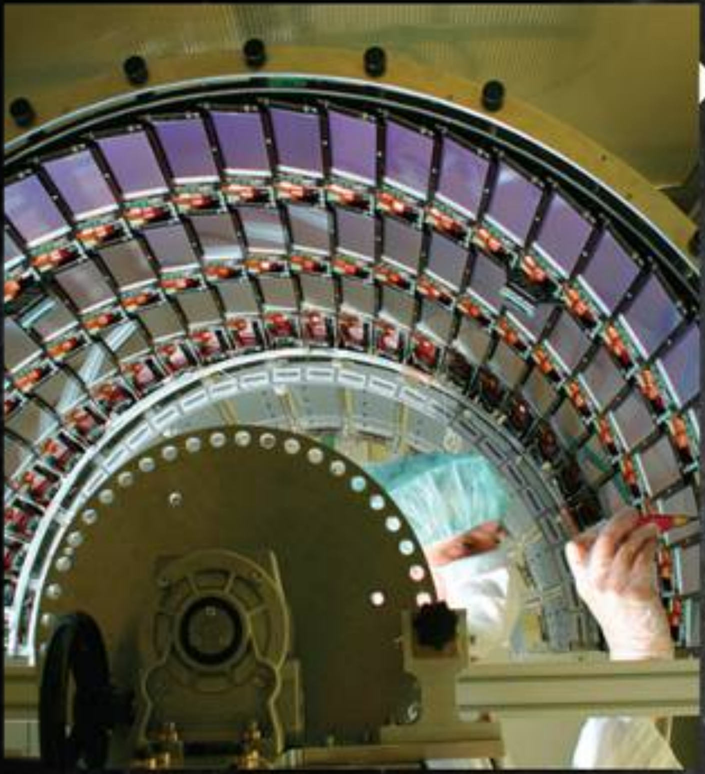


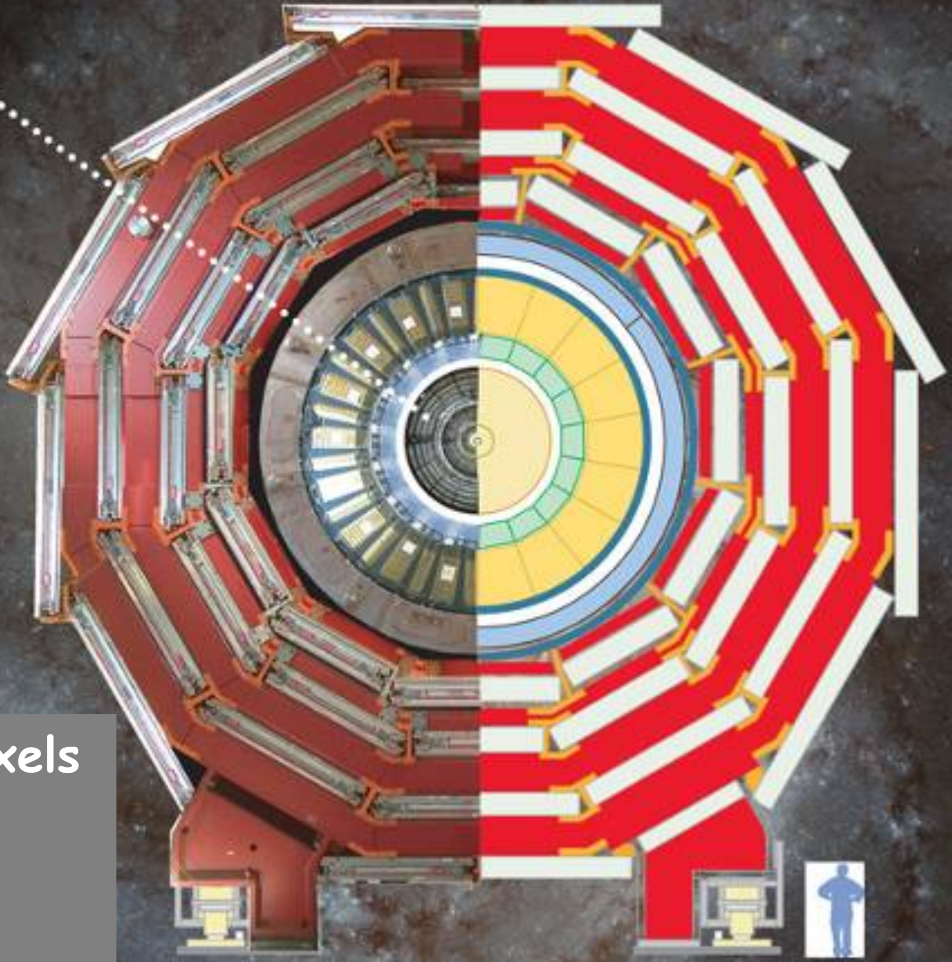
Scheme of CMS



The onion structure is typical of collider detectors

CMS subdetectors: the tracker



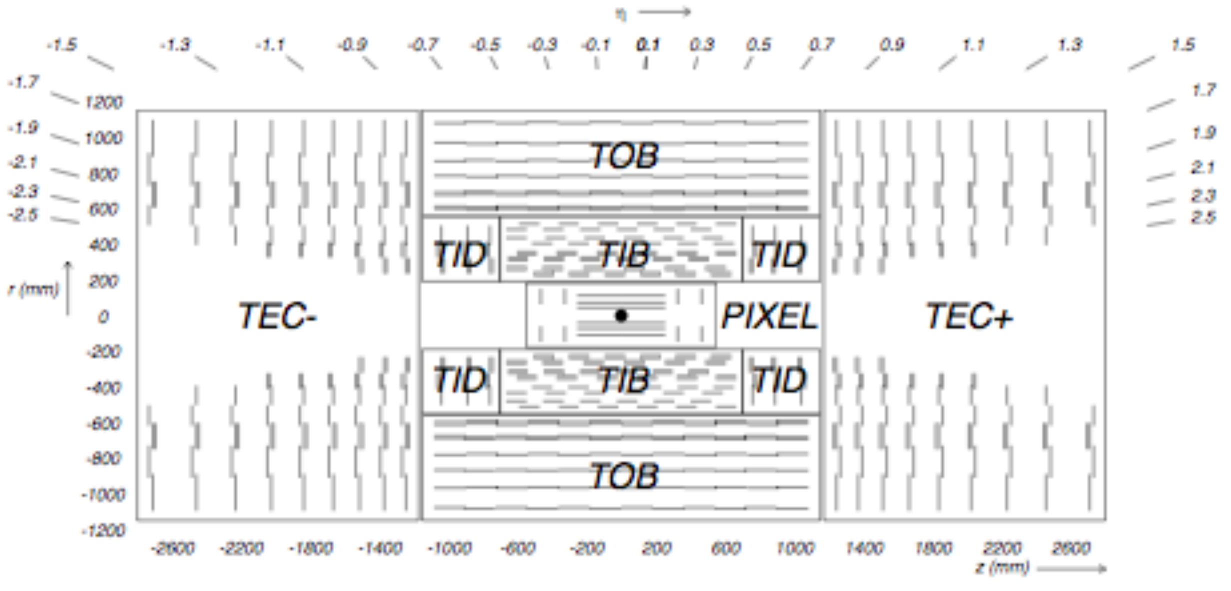


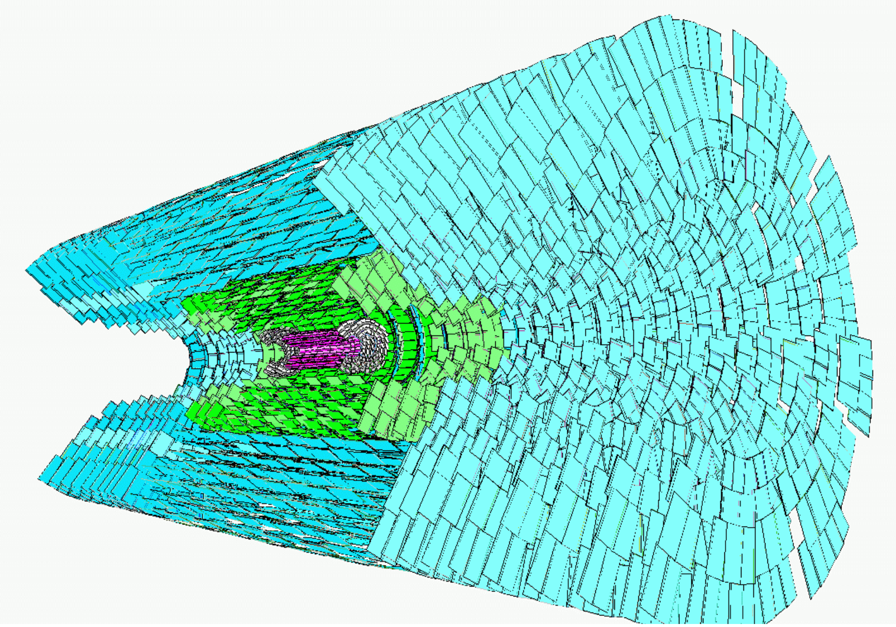
Finely segmented silicon sensors (pixels in the inner part, then strips).

Reconstruct the trajectories of charged particles and measure their momentum in the magnetic field

The largest silicon tracker ever built!

Cylinder of 2.2 m diameter and nearly 6 m length





Pixel detector

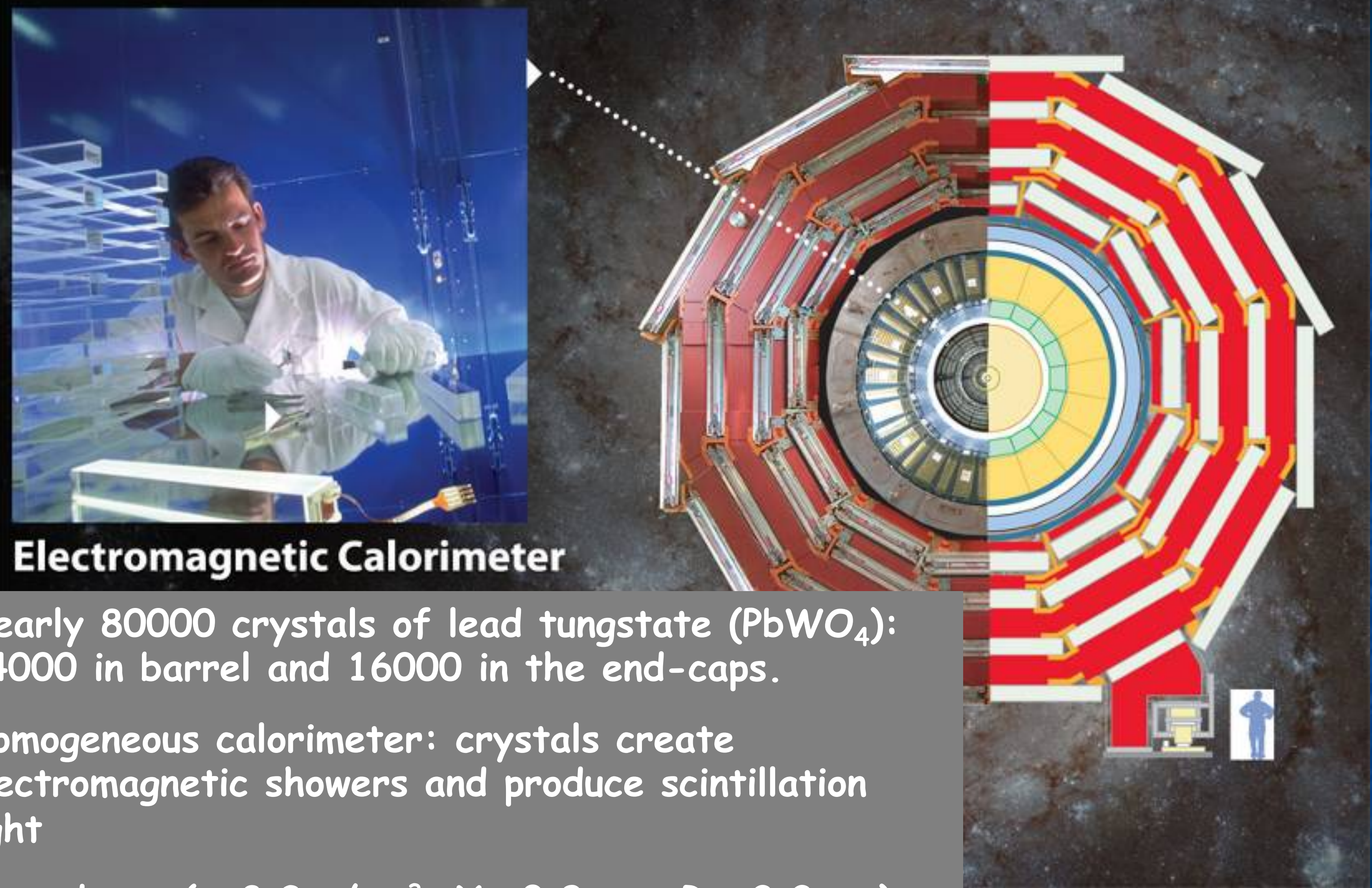
800 modules, 66 million channels

Strips detector:

15000 modules, 10 milion strips,
220 m^2 active surface.

Tracker parts during construction

Electromagnetic calorimeter

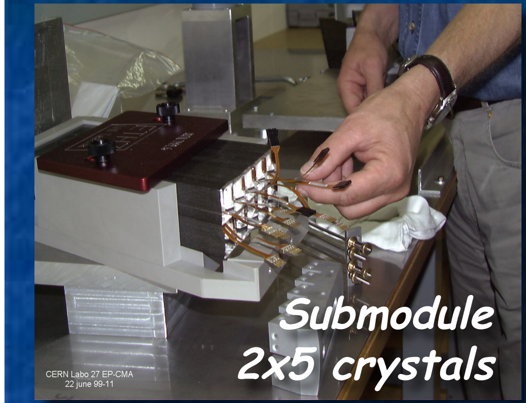


Nearly 80000 crystals of lead tungstate ($PbWO_4$): 64000 in barrel and 16000 in the end-caps.

Homogeneous calorimeter: crystals create electromagnetic showers and produce scintillation light

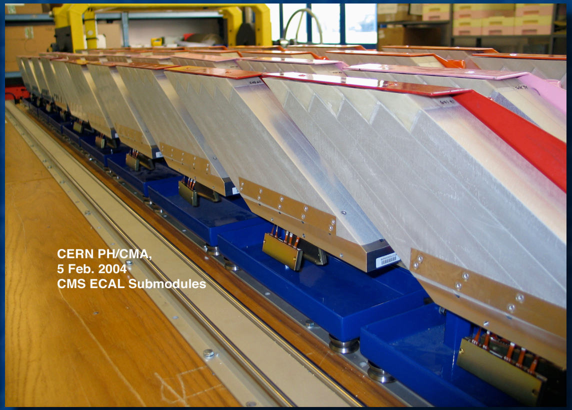
Very dense ($\rho=8.3\ g/cm^3$, $X_0=0.9$ cm, $R_M=2.2$ cm) but transparent to the light that they produce.

ECAL assembly

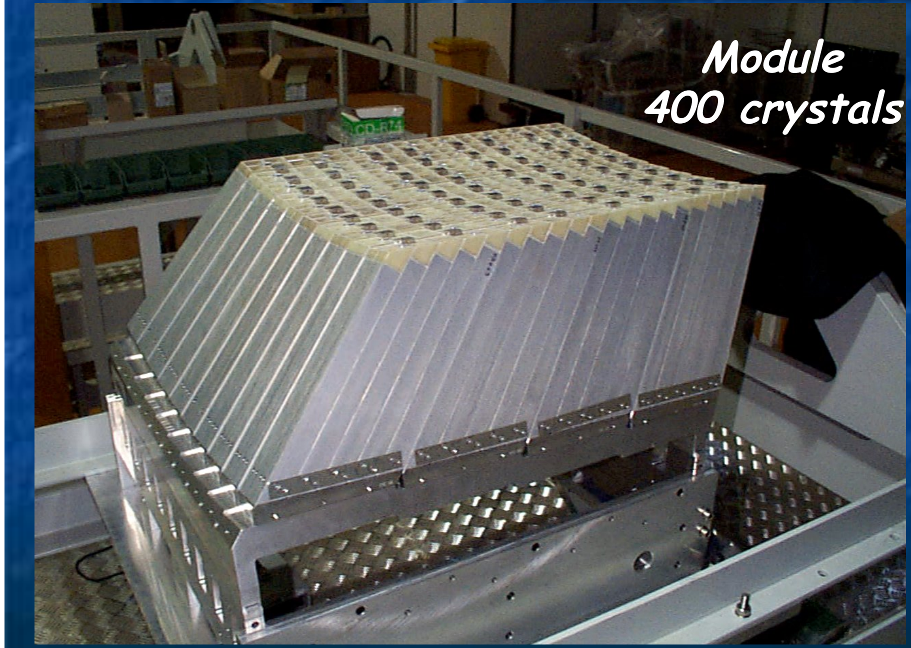


Submodule
2x5 crystals

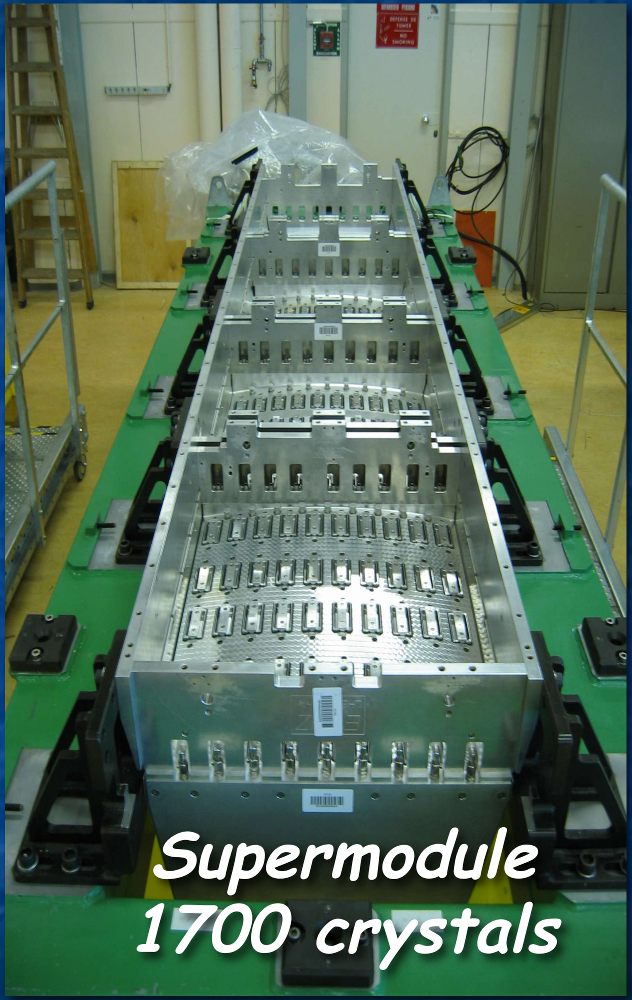
CERN Labo 27 EP-CMA
22 june 99-11



CERN PH/CMA,
5 Feb. 2004
CMS ECAL Submodules



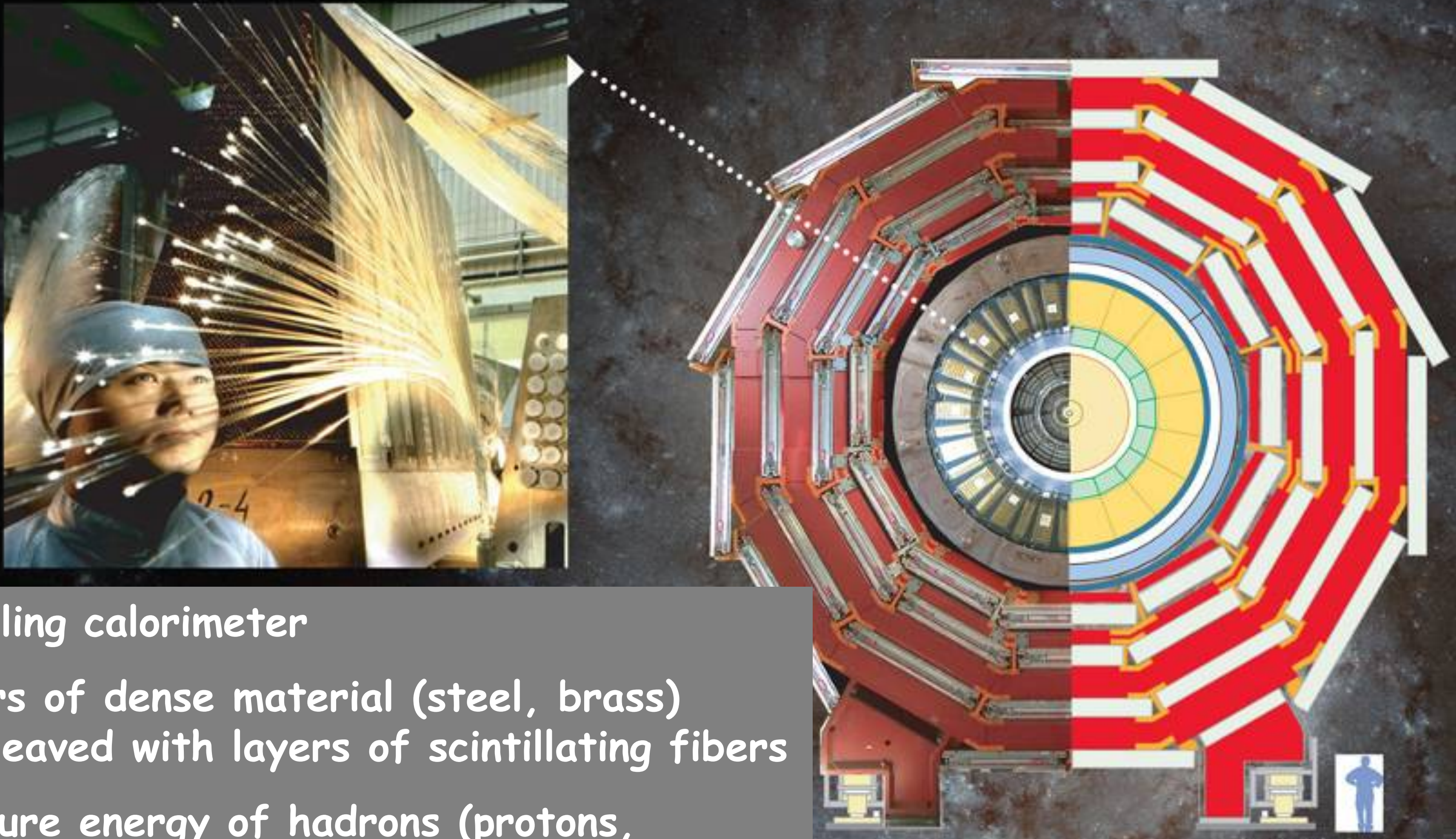
Module
400 crystals



Supermodule
1700 crystals

In total 36 supermodules

Hadron calorimeter

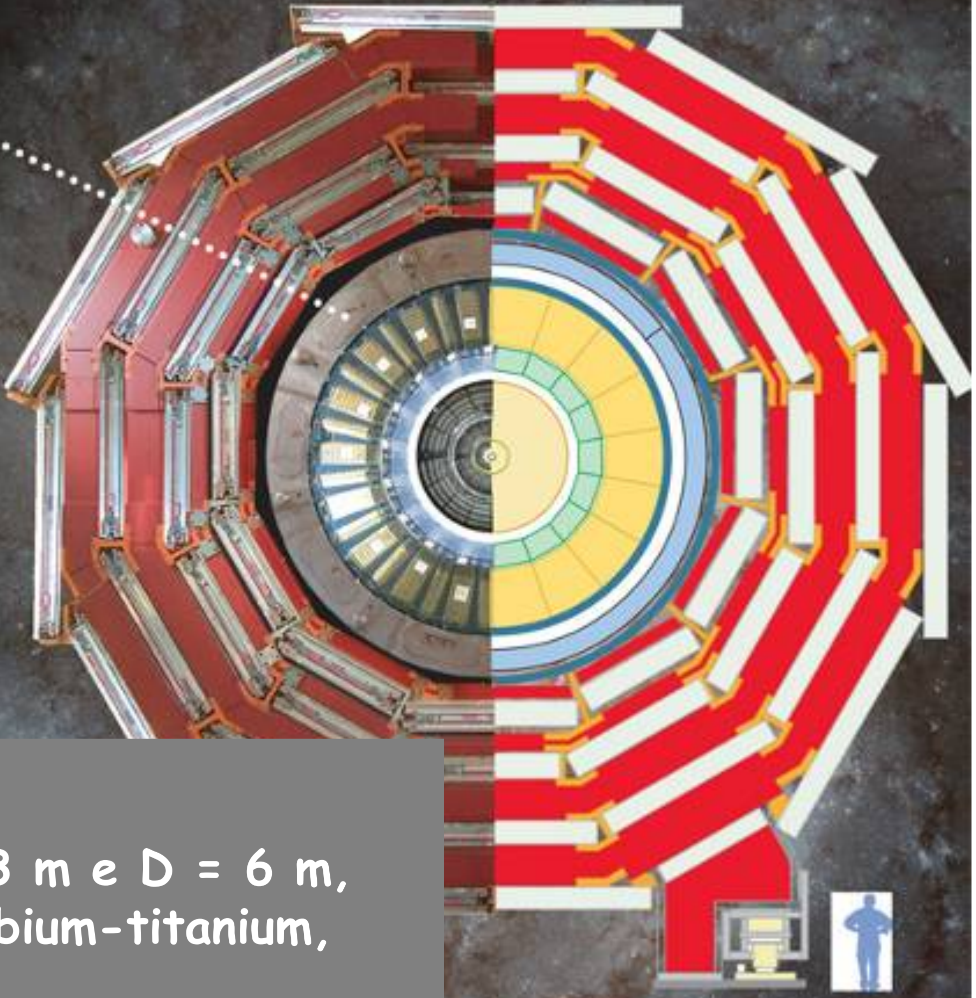


Sampling calorimeter

Layers of dense material (steel, brass) interleaved with layers of scintillating fibers

Measure energy of hadrons (protons, neutrons, pions…), not absorbed by the electromagnetic calorimeter

The solenoid



Superconducting magnet

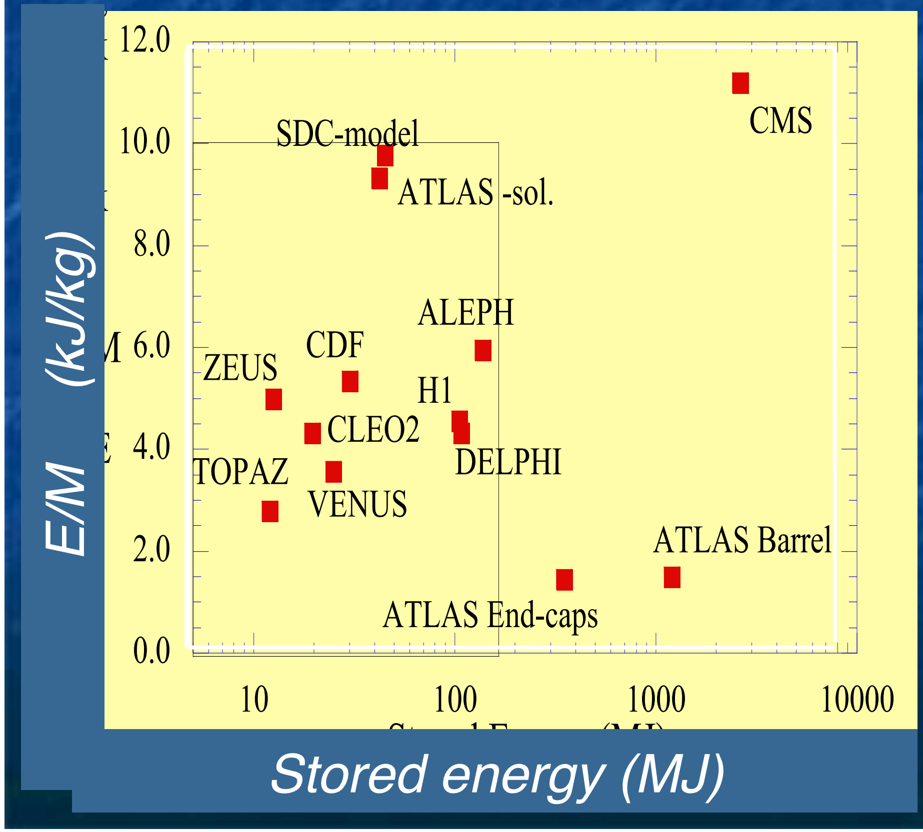
20.000 Amperes in a solenoid of L = 13 m e D = 6 m, made of a duperconducting cable of niobium-titanium, working at -270°C.

Field of ~ 4 Tesla, i.e. 100.000 times the earth field

The curvature of the charged particle trajectories in the B field yields the measurement of the momentm (and the electric charge)

The solenoid

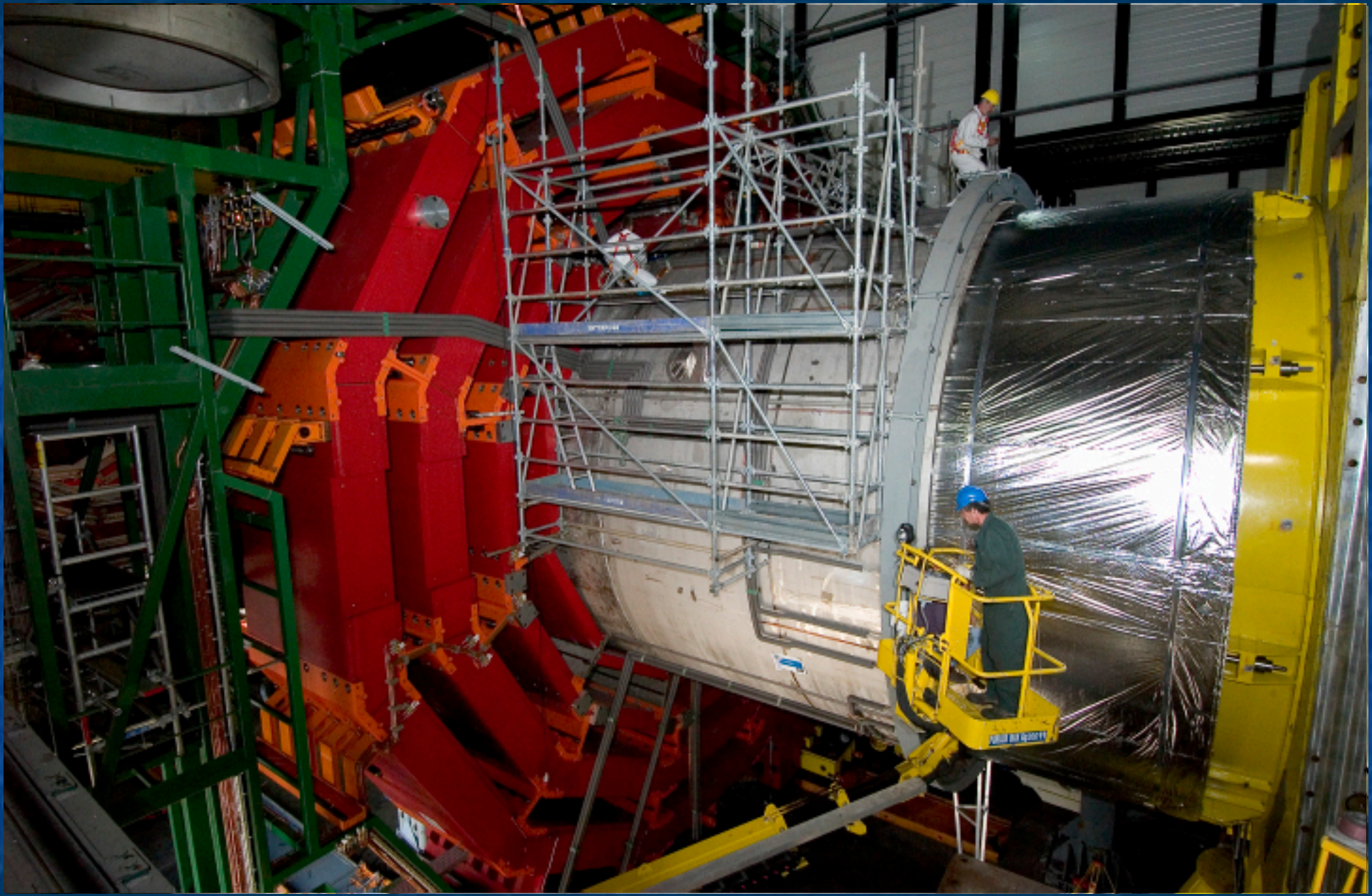
Most powerful magnet ever built, at the frontier of technology



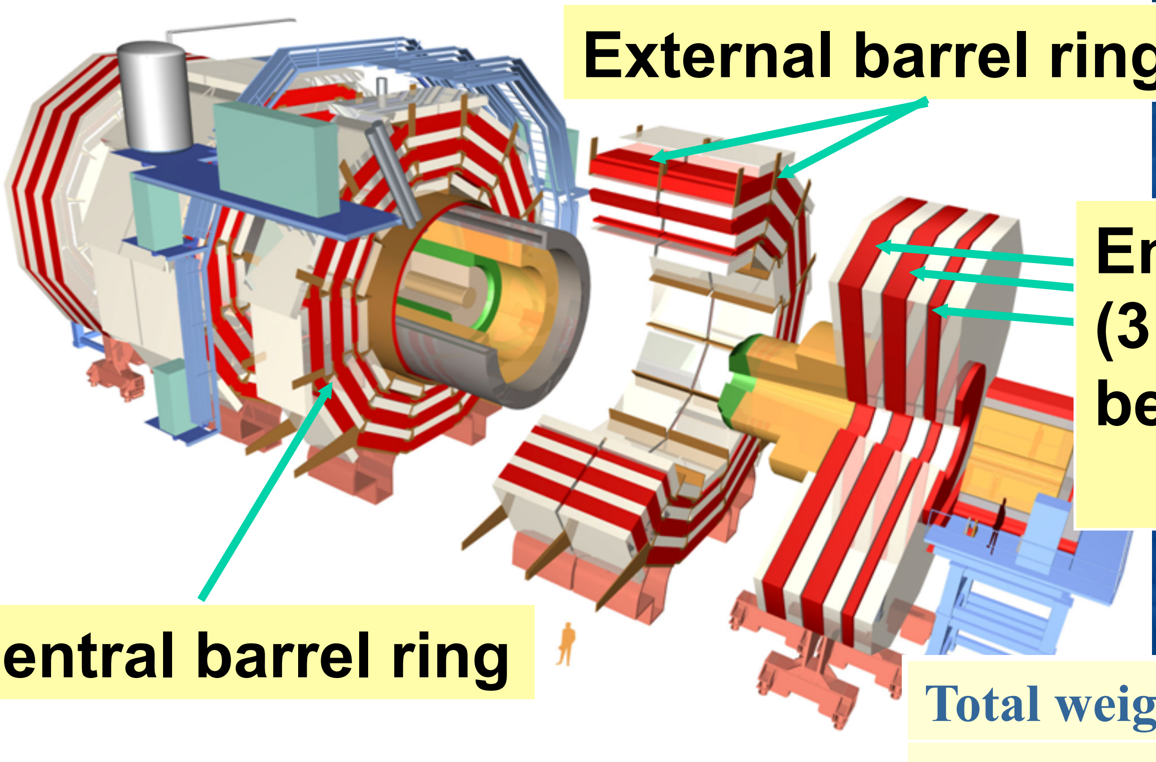
- External vacuum tank
  - Made of three parts, assembled at CERN
- Internal vacuum tank
  - Single piece, brought to CERN with a very special transport (~120 km)
- Solenoid : 5 coils joined together
- Return yoke: ~10500 tons of iron, also main support structure of CMS and house for the muon detectors

Transport and construction

Insertion in the vacuum tank



The iron yoke



External barrel rings x 4 – 2 per side

Endcap disks x 6 (3 per endcap – 4th being built now!)

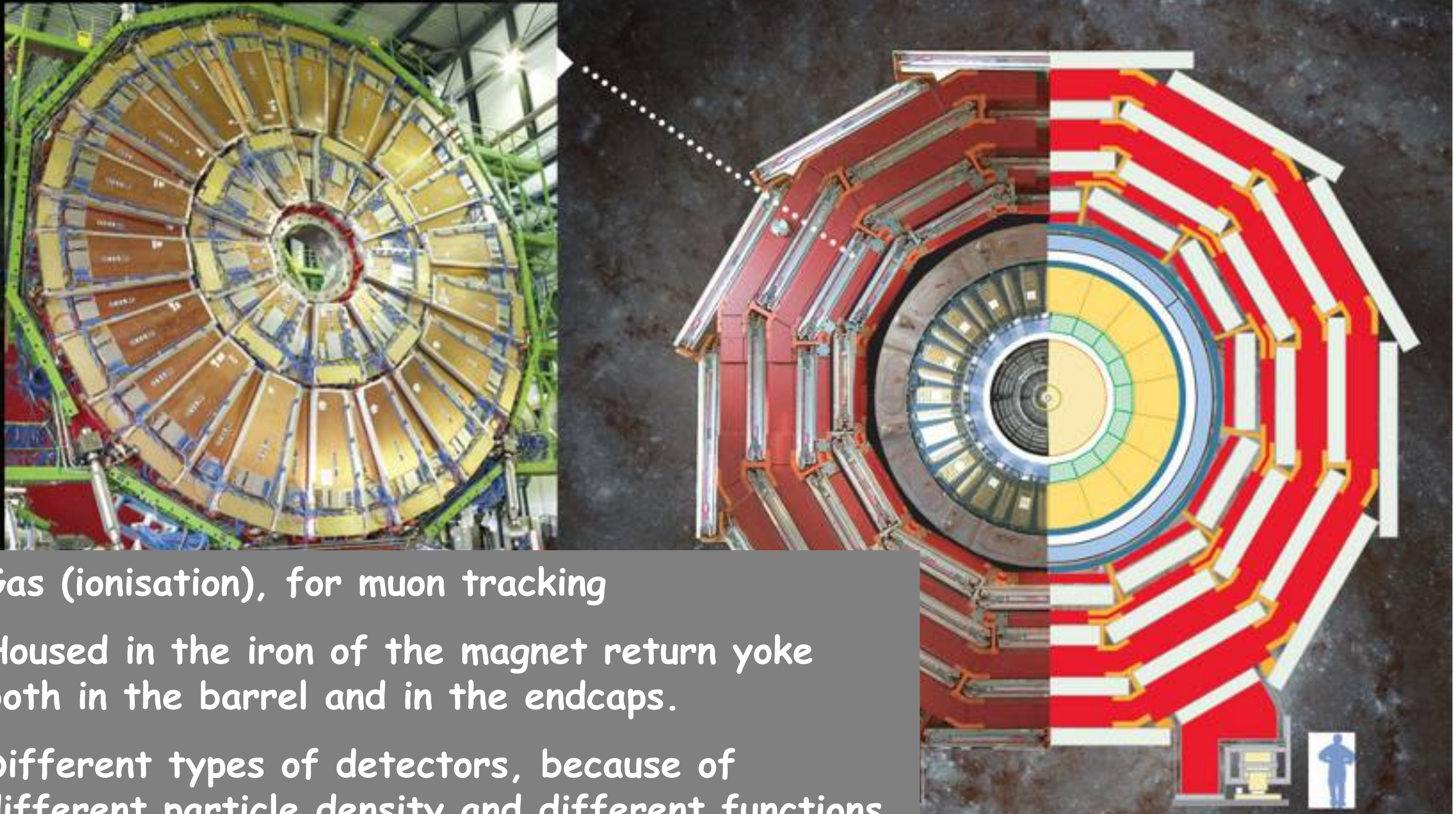
Central barrel ring

Total weight	14000 ton
Diameter	15m
Length	21.6m
Magnetic field	4 Tesla

	Central Ring	*Outer Rings*
Barrel ring	1250 tonnes	1174 tonnes
Vacuum vessel	264 tonnes	-
Superconducting coil	234 tonnes	-
Support feet	72 tonnes	66 tonnes
Cabling on vacuum vessel	150 tonnes	-
Support for racks and cables	10 tonnes	10 tonnes
Total	**1980 tonnes**	**1250 tonnes**

Endcap disk 1 (YE1)	~730 (disk) + 90 (cart) tonnes
Endcap disk 2 (YE2)	~730 (disk) + 90 (cart) tonnes
Endcap disk 3 (YE3)	~300 (disk) + 90 (cart) tonnes

Muon detectors



Gas (ionisation), for muon tracking

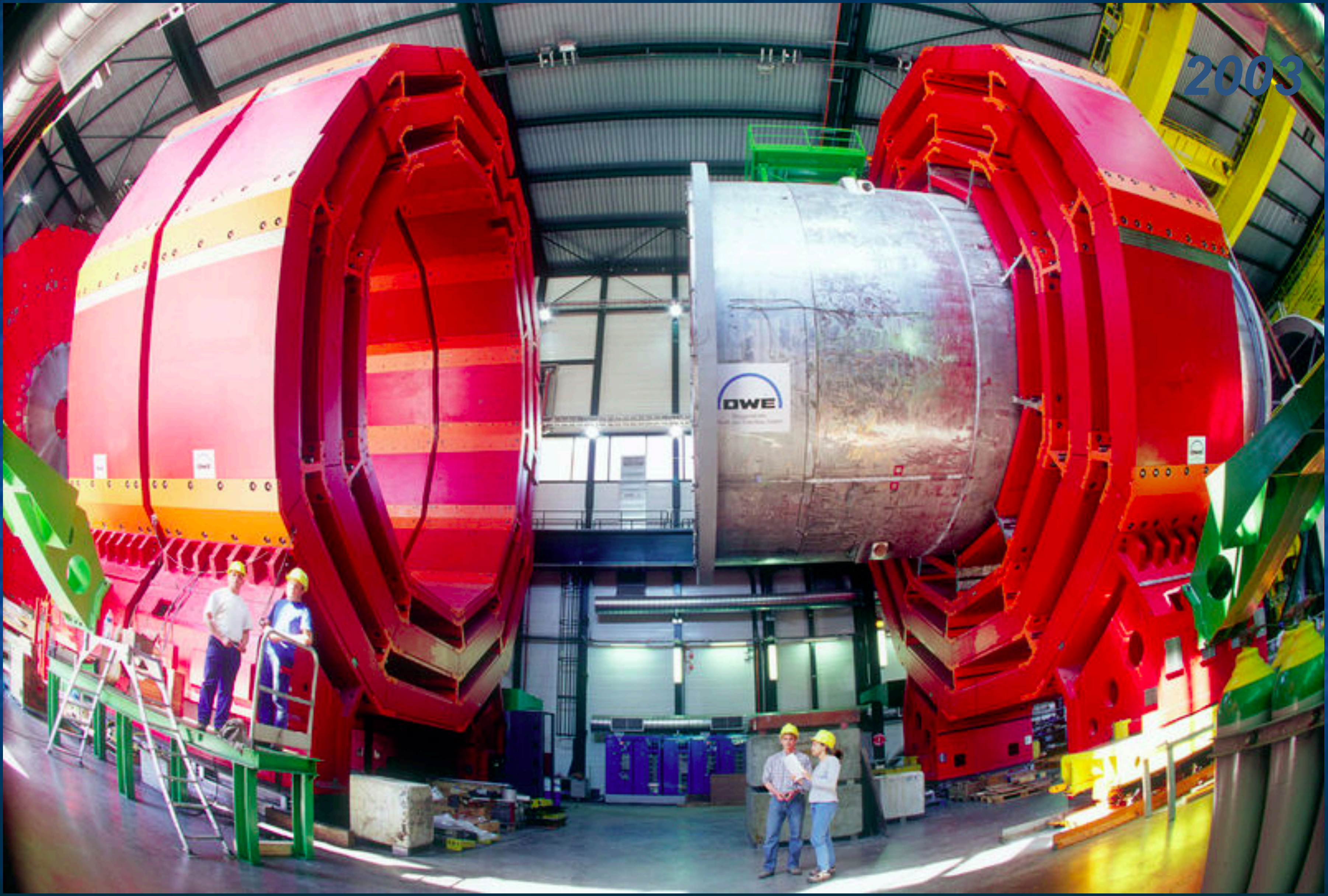
Housed in the iron of the magnet return yoke both in the barrel and in the endcaps.

Different types of detectors, because of different particle density and different functions (tracking and "trigger")

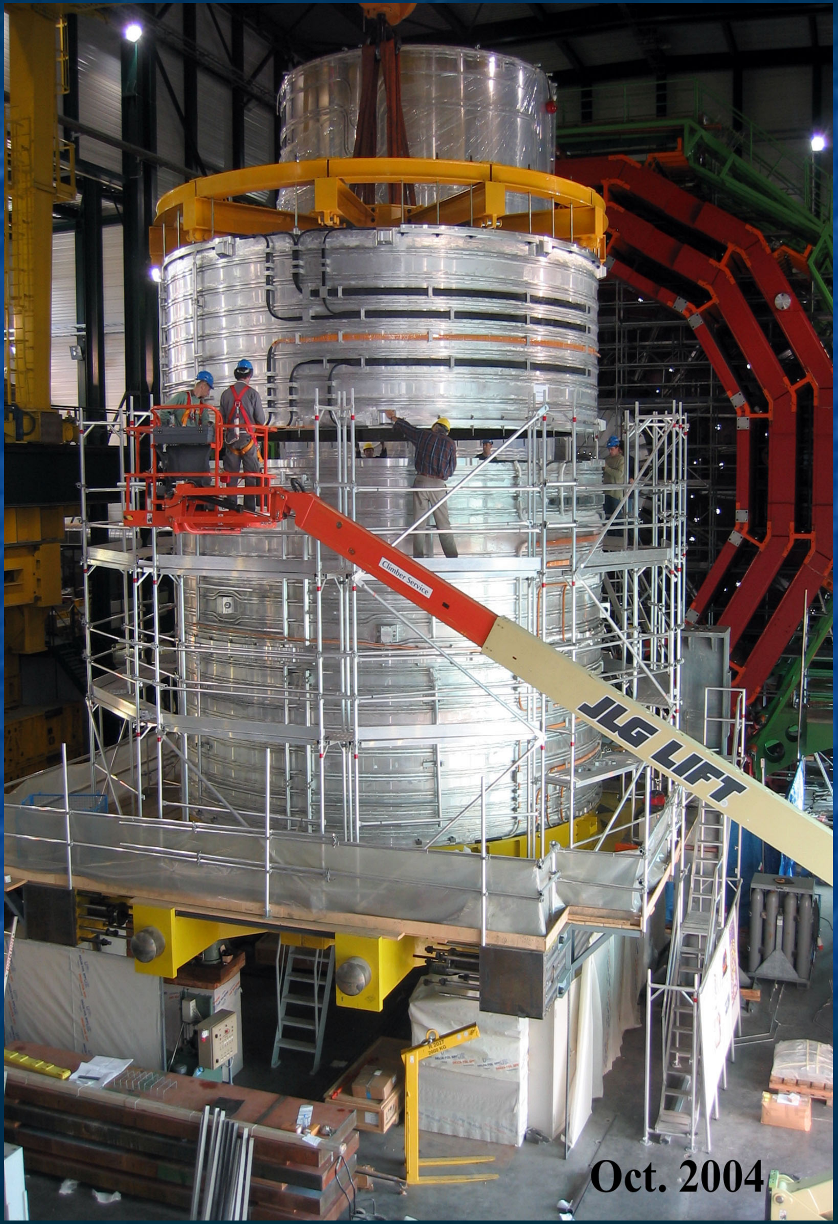
In total ~ 6000 m^2 of active surface

The CMS site in 2000

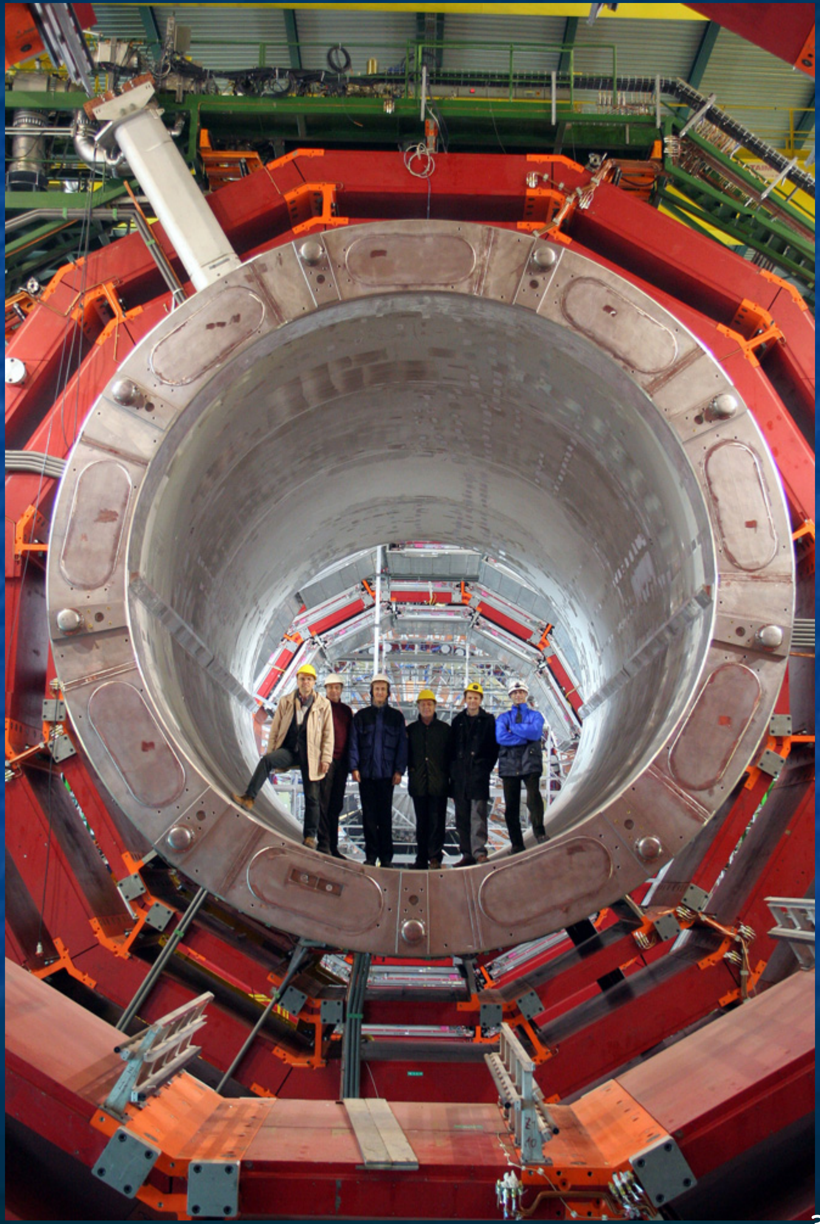
Assembly of the yoke (surface)



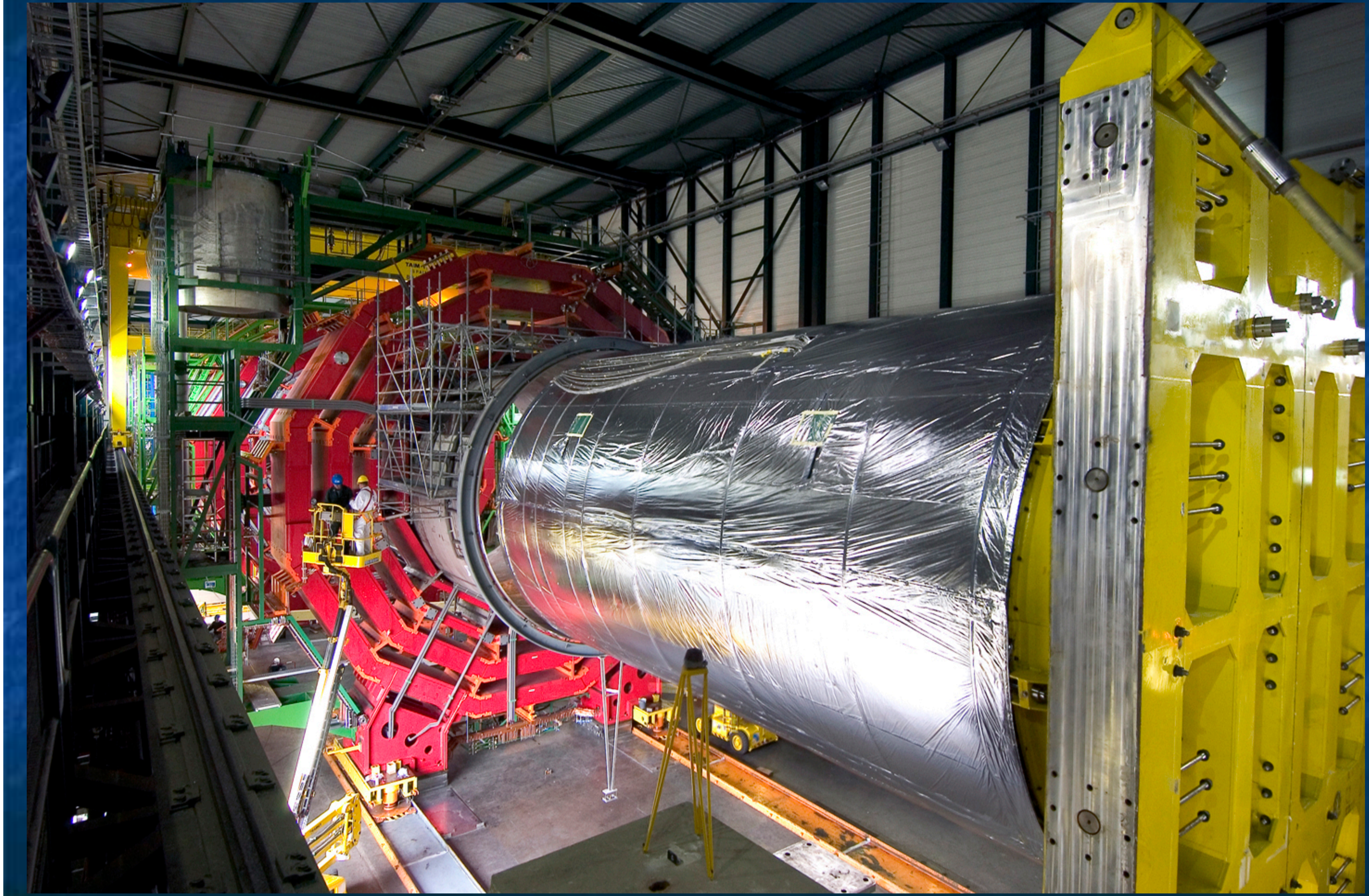
Assembly of the coil



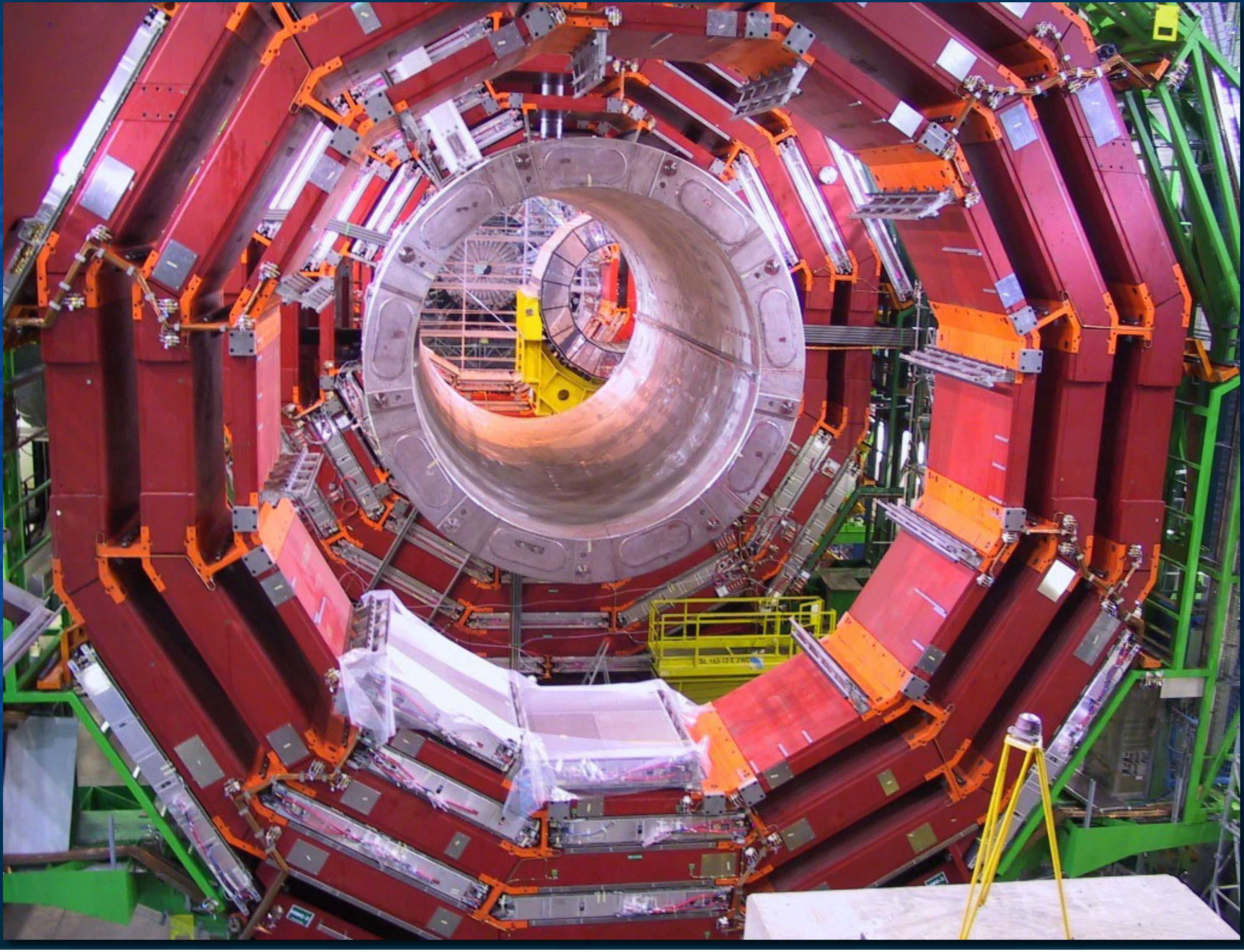
Oct. 2004



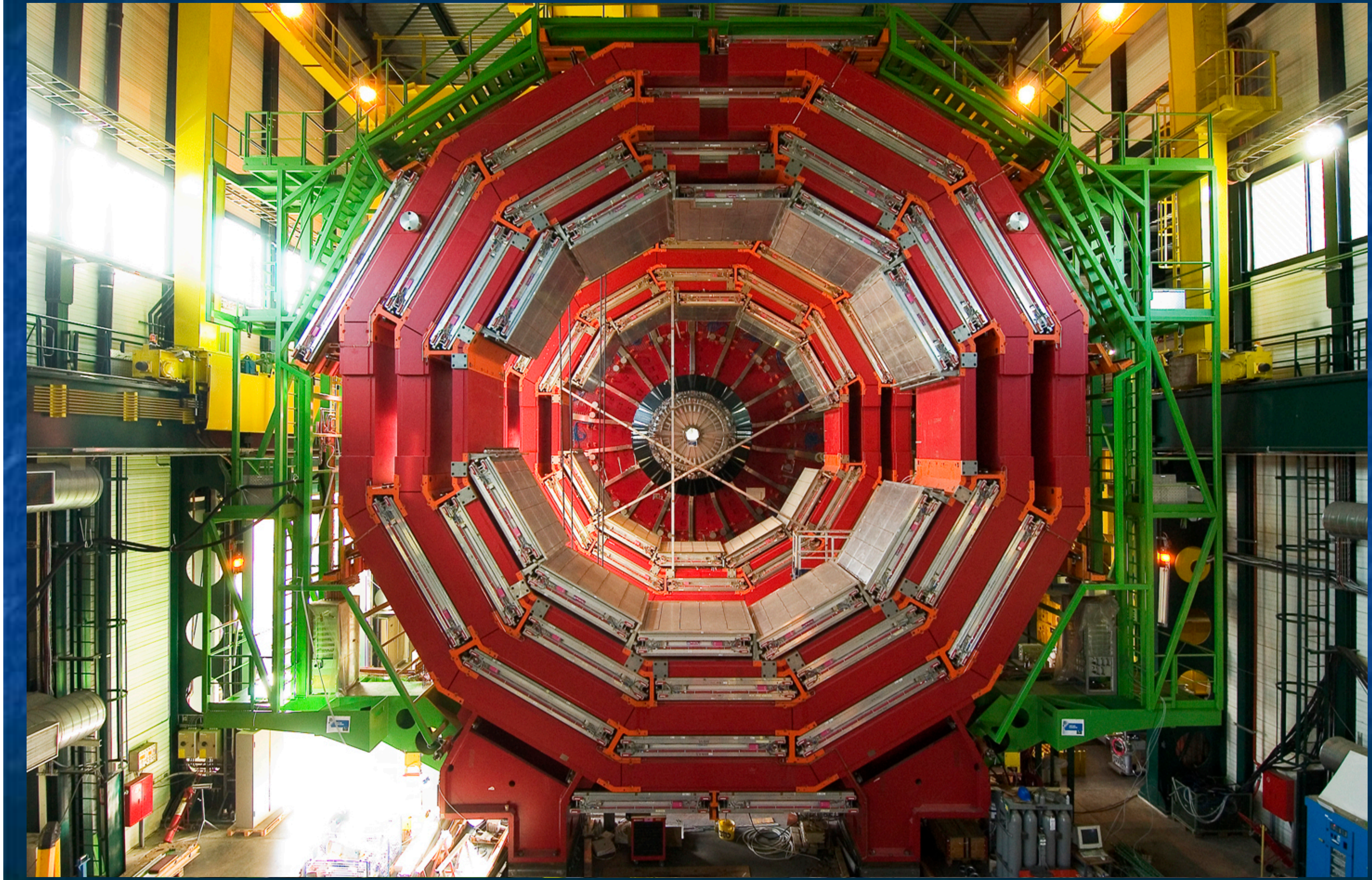
The insertion of the coil



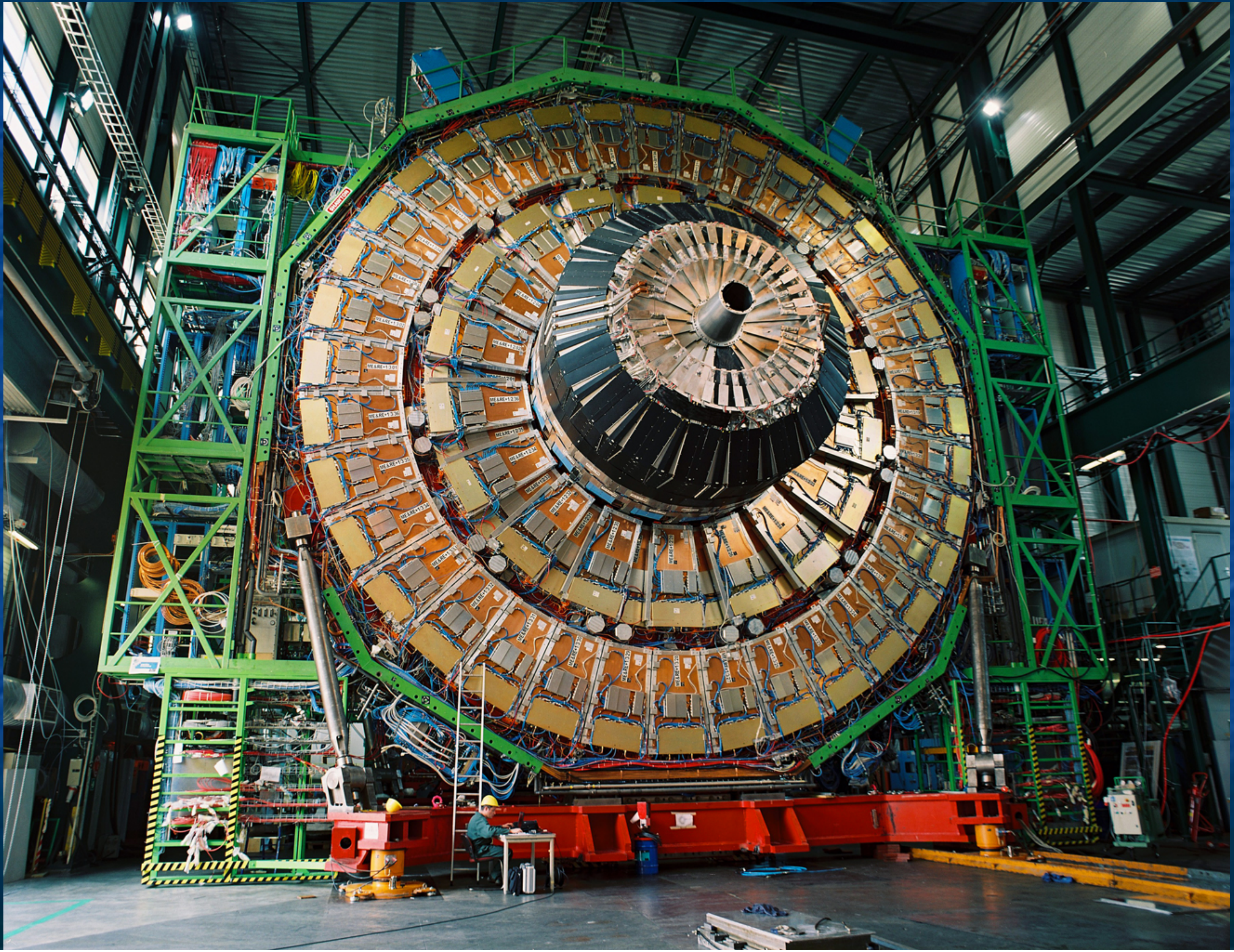
February 2006: muon assembly ongoing

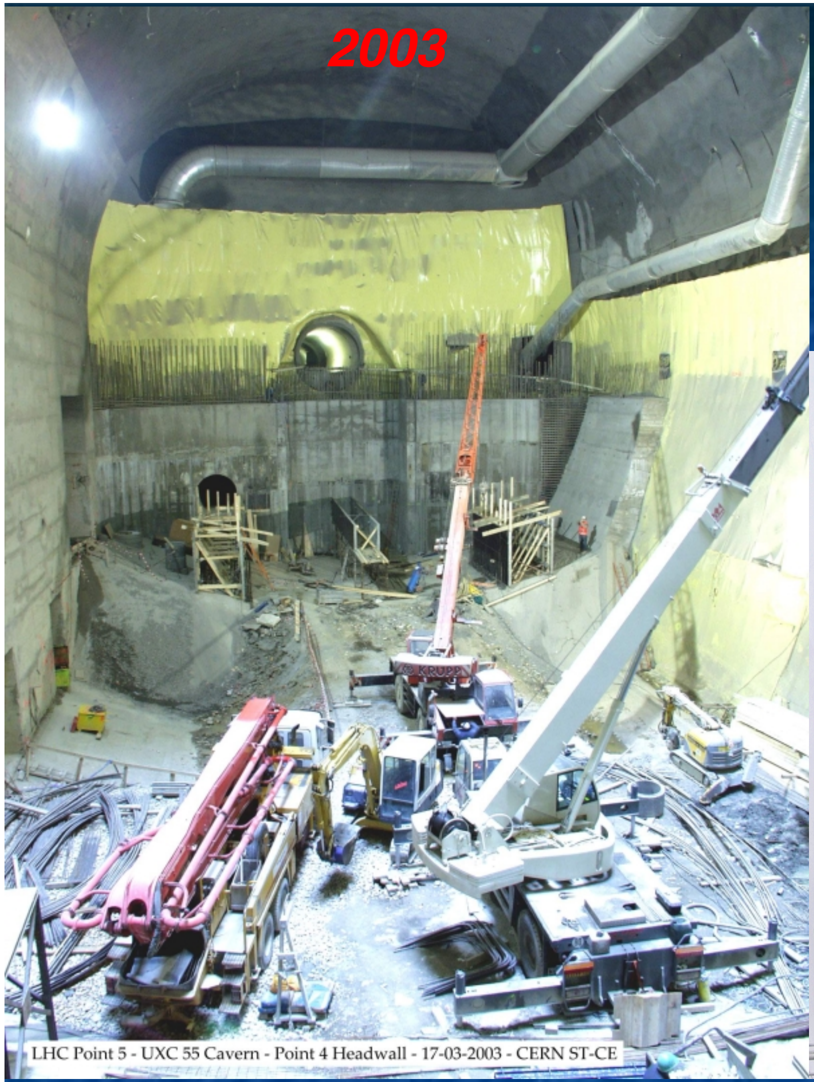


Muon barrel



Muon endcap





2003

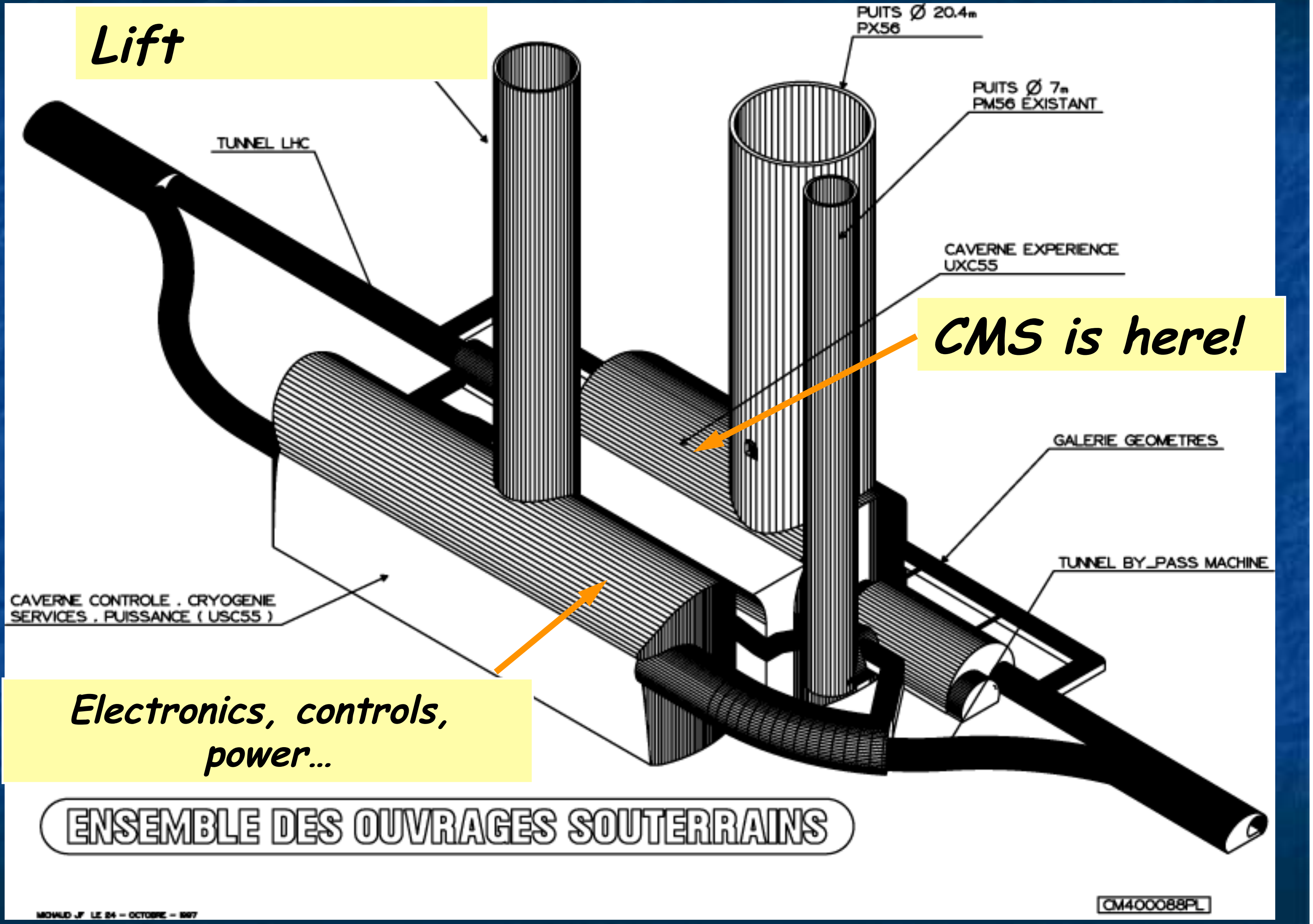
LHC Point 5 - UXC 55 Cavern - Point 4 Headwall - 17-03-2003 - CERN ST-CE

The cavern

2004

Prepared while CMS was assembled on the surface
(and several parts in many other different labs)

Underground caverns

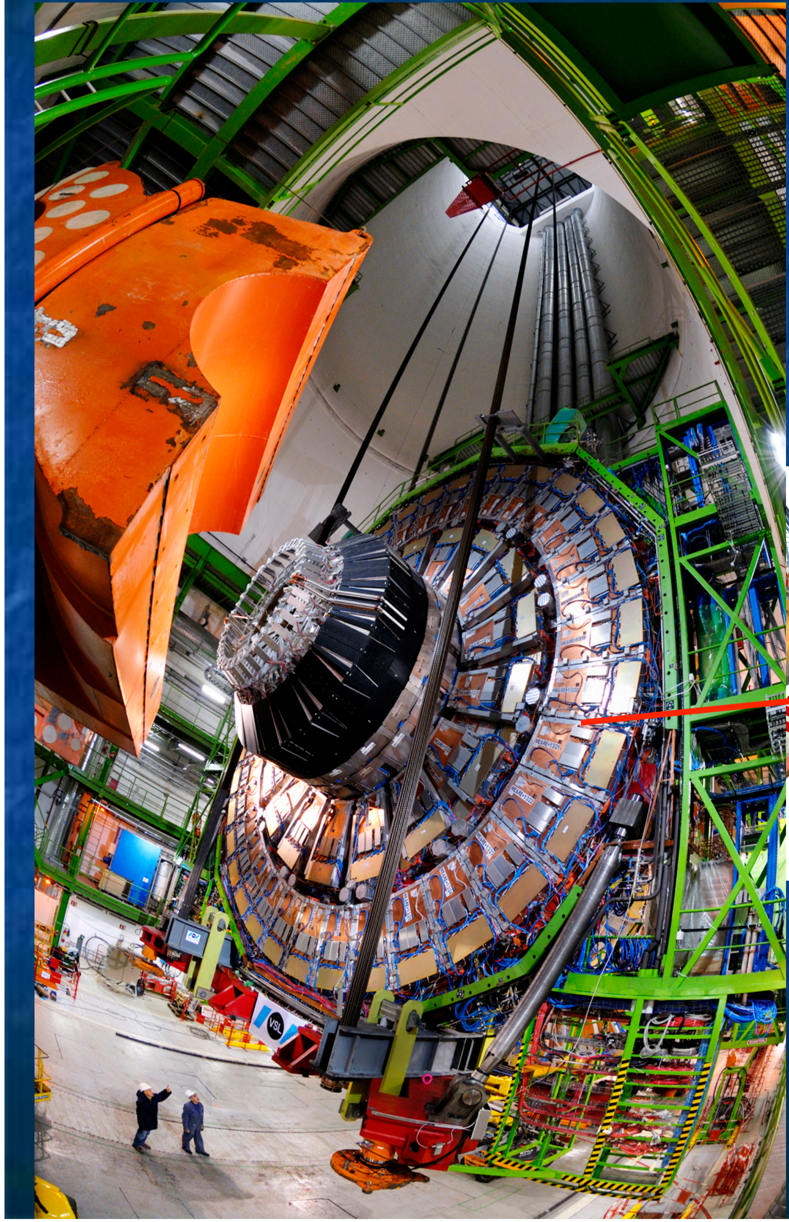


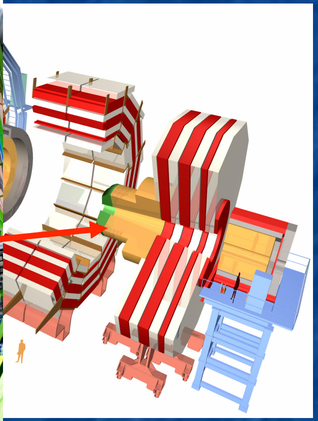
Lift

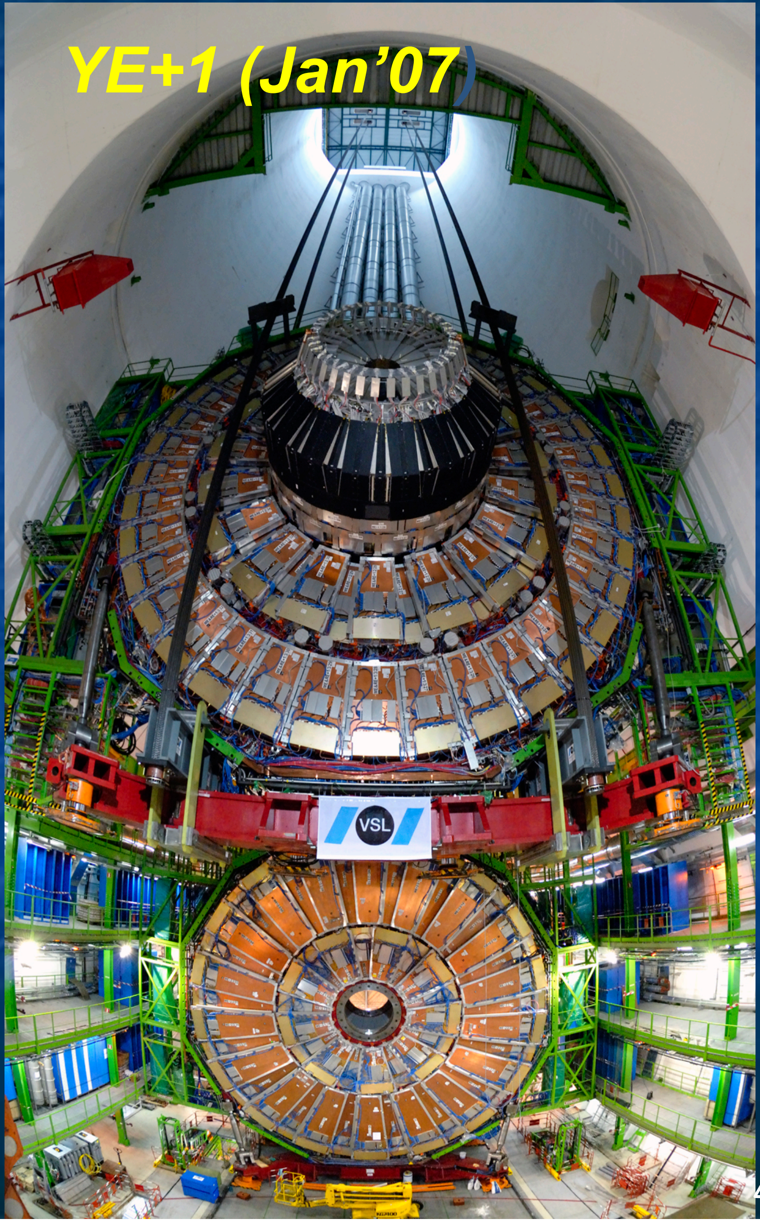
CMS is here!

Electronics, controls, power…

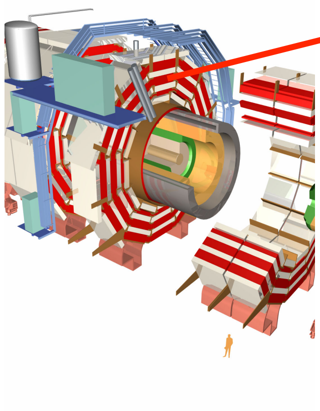
Lowering of CMS parts

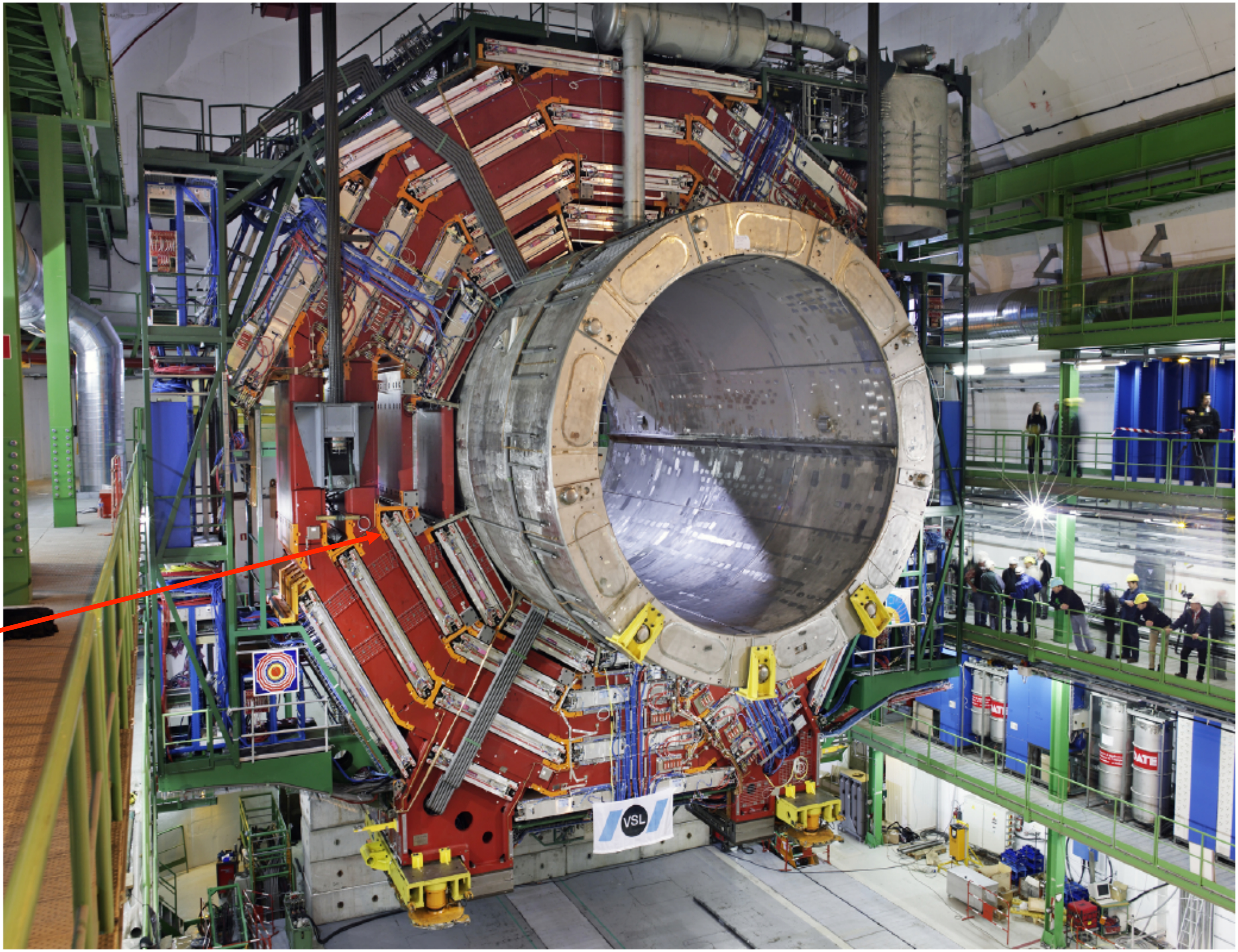




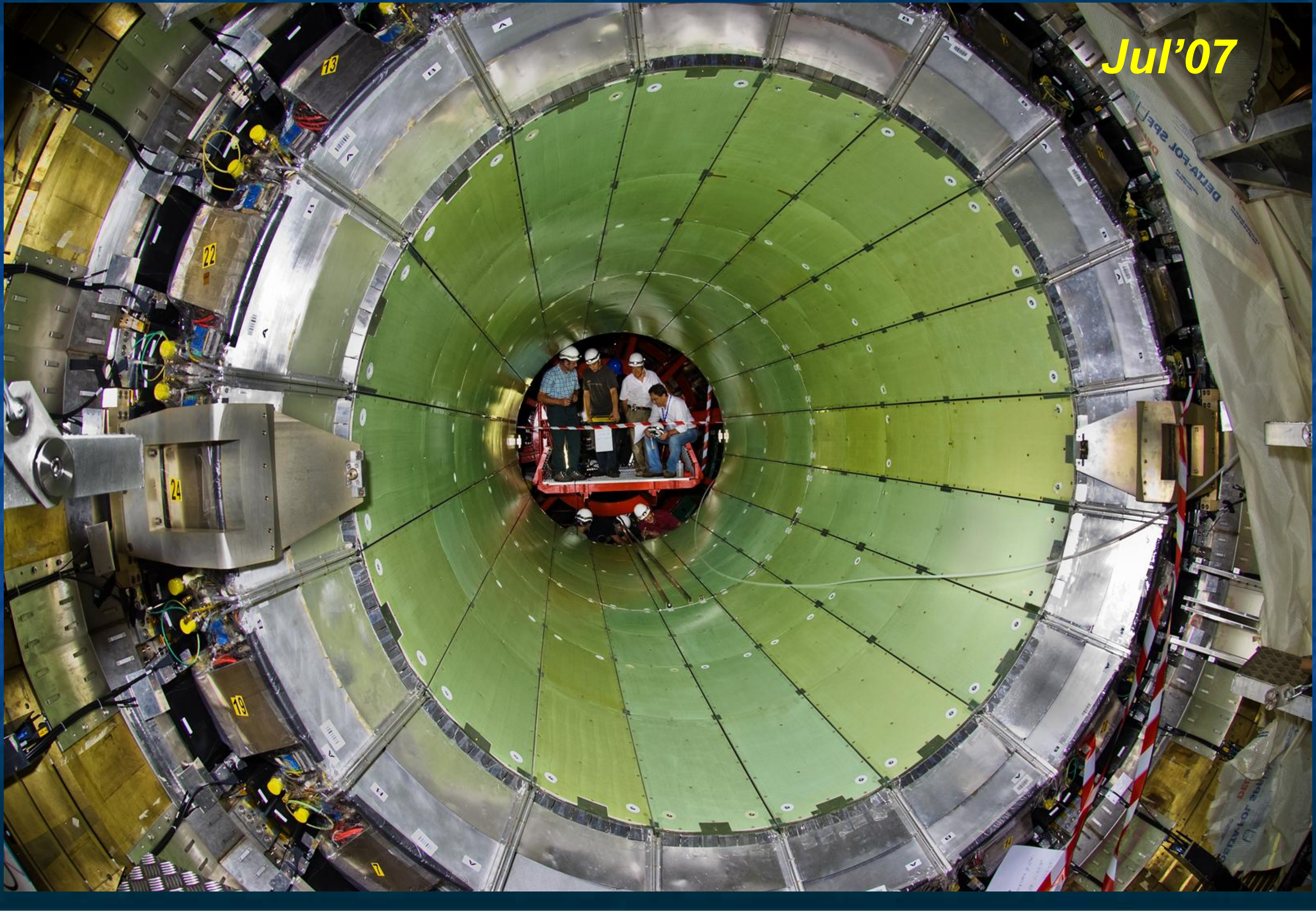


“YB0” – the heaviest piece



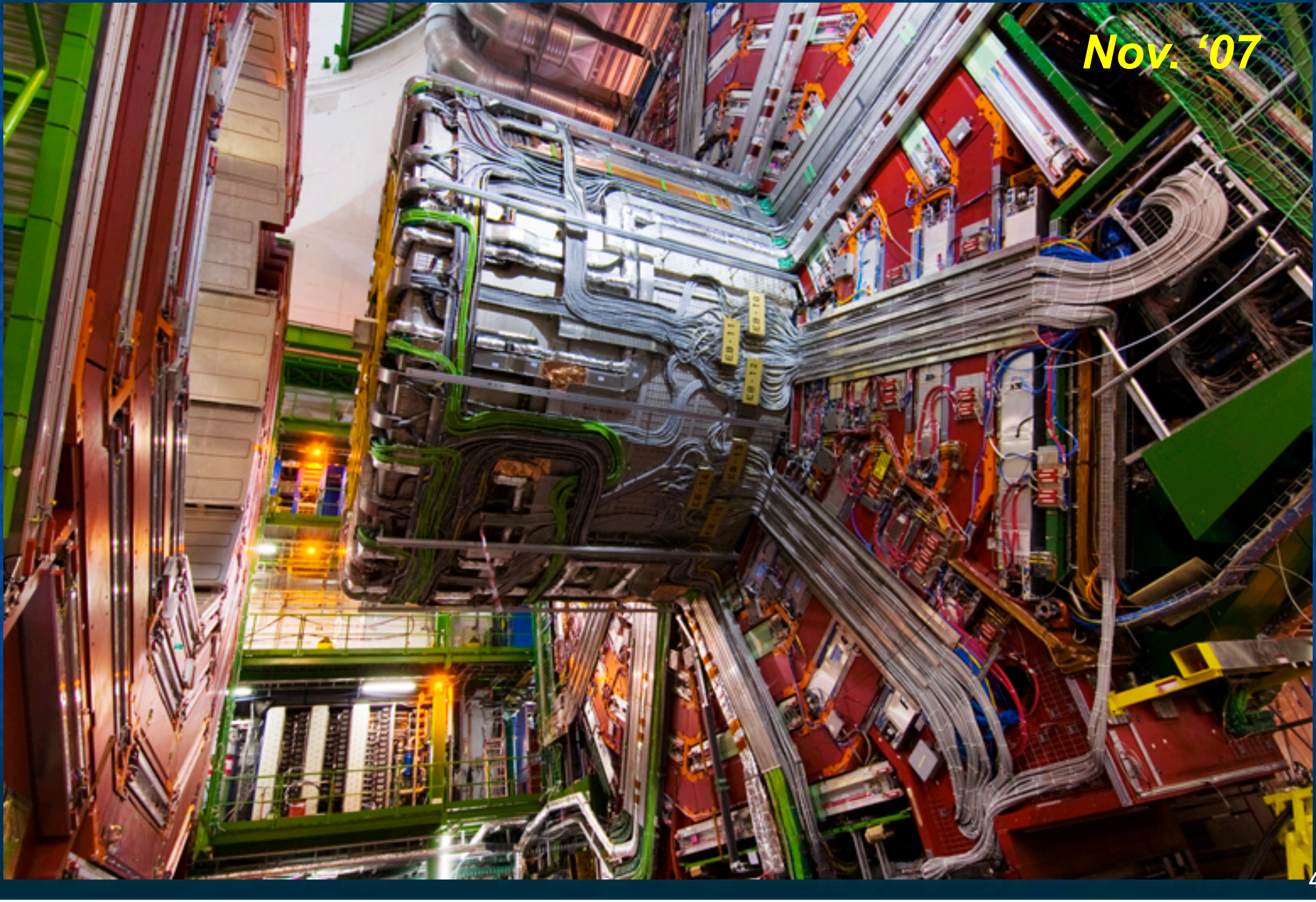


The insertion of the ECAL barrel



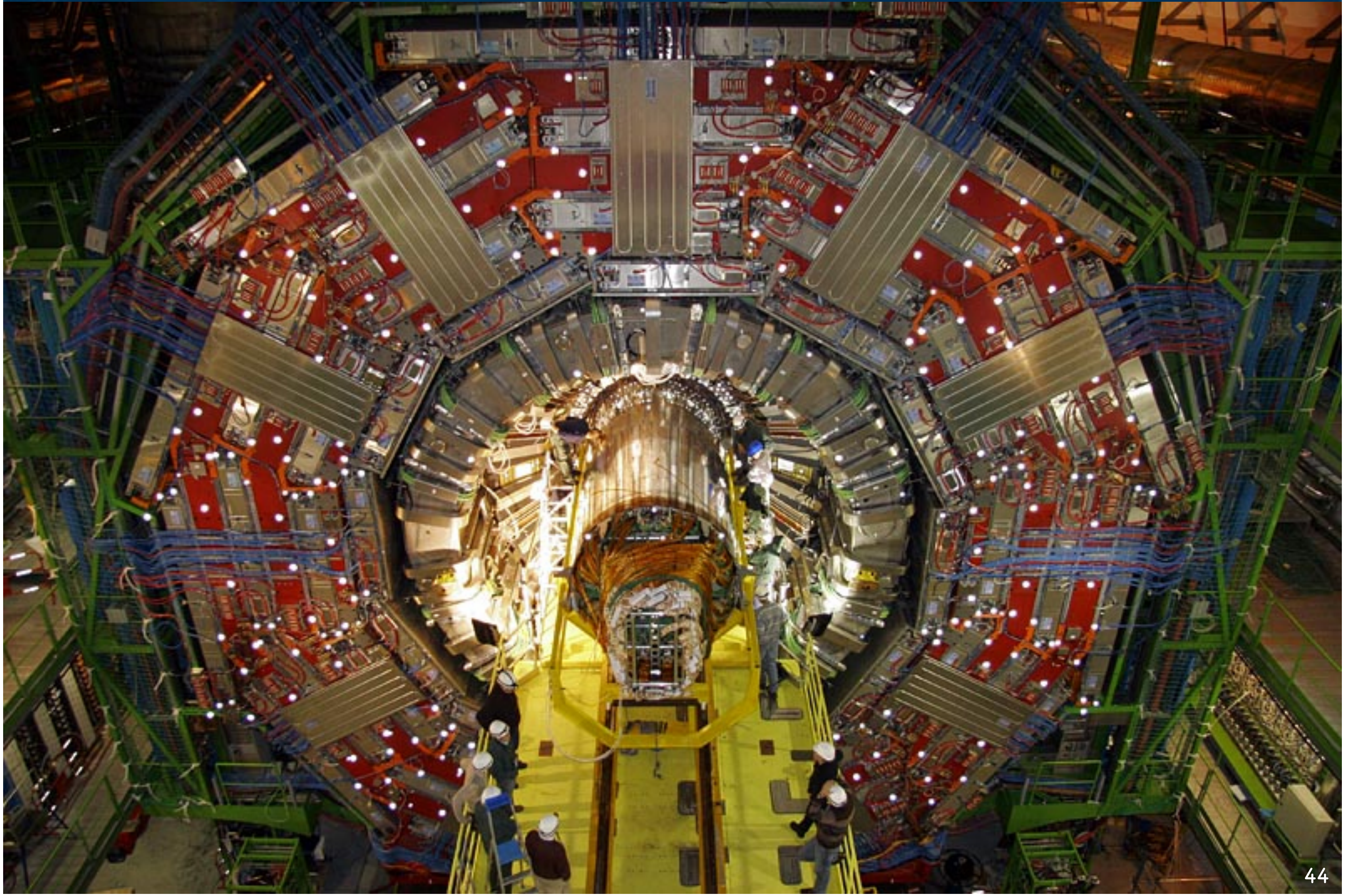
Jul'07

Cables, optical fibers, cooling pipes…



Nov. '07

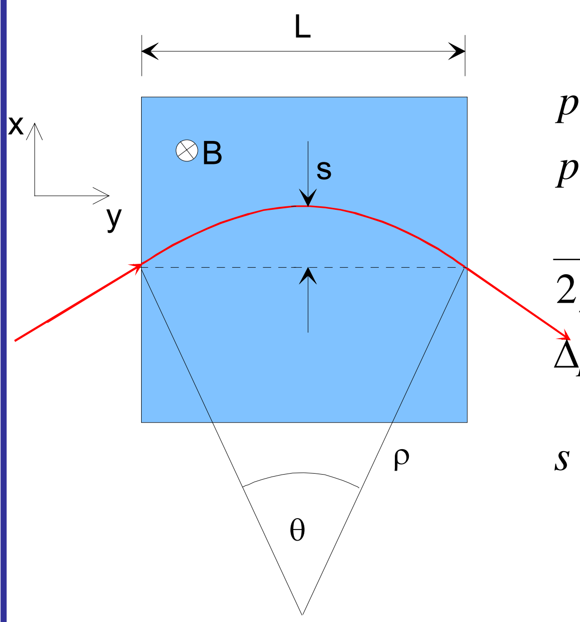
Insertion of the Tracker



Cabling the tracker (three months of intense team work)

Tracking precision

- Some basic maths:



$$p_T = qB\rho$$

$$p_T\ (\mathrm{GeV/c}) = 0.3B\rho \quad (\mathrm{T\cdot m})$$

$$\frac{L}{2\rho} = \sin\theta/2 \approx \theta/2 \quad \rightarrow \quad \theta \approx \frac{0.3L\cdot B}{p_T}$$

$$\Delta p_T = p_T \sin\theta \approx 0.3L\cdot B$$

$$s = \rho\left(1-\cos\theta/2\right) \approx \rho\frac{\theta^2}{8} \approx \frac{0.3}{8}\frac{L^2 B}{p_T}$$

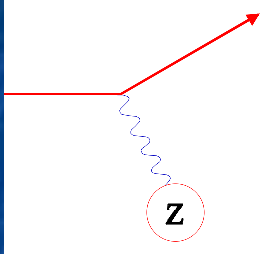
- σ(s) is purely geometrical: scales (roughly) as $\sigma_x N^{-1/2}$
- For N equidistant measurements:

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma(x)\cdot p_T}{0.3\cdot BL^2}\sqrt{720/(N+4)}$$

- Gives all the fundamental scaling laws for tracking precision…. in air!

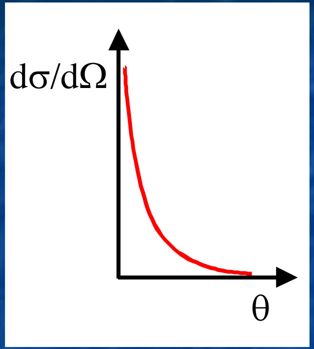
Multiple scattering

- Particles scatter off nuclei

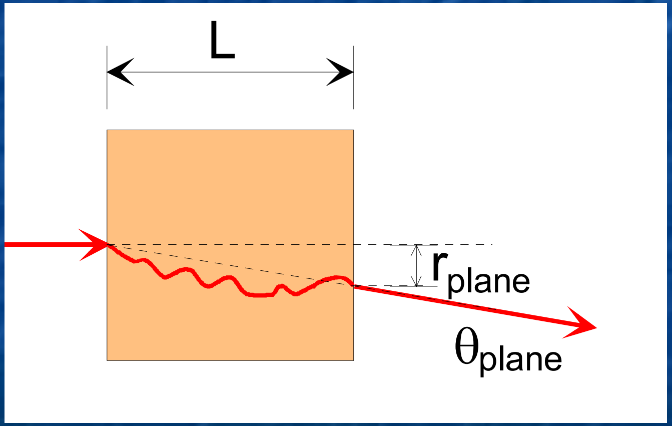


$$\frac{d\sigma}{d\Omega} = 4zZr_e^2\left(\frac{m_e c}{\beta p}\right)^2 \frac{1}{\sin^4\theta/2}$$

Rutherford formula



- Multiple scattering inside the tracking volume limits the tracking precision



$$\theta_0 = \theta^{RMS}_{plane} = \sqrt{\left\langle \theta_{plane}{}^2 \right\rangle} = \frac{1}{\sqrt{2}}\theta^{RMS}_{space}$$

$$\left.\frac{\sigma(p)}{p_T}\right|^{MS} = 0.045\,\frac{1}{BL}\sqrt{\frac{L}{X_0}}$$

- Contribution from MS independent of p_T ! For our heavy tracker becomes relevant already at p_T ~10 GeV/c

Readout electronics and trigger

(introducing the next presentation [...postponed to tomorrow])

The front-end electronics samples the detectors at 40 MHz.

The timing is tuned for each detector part to be in phase with the arrival of the particles (accounting also for the time of flight from the interaction point).

At least for the most congested parts, the shaping time of the readout electronics must be shorter than 25 ns, to avoid additional pileup from earlier bunch crossing.

The readout electronics contains <u>buffers</u> that store the information of the detectors at each bunch crossing.

The length of these buffers determines the max time during which these data remain available, before being overwritten by new events: <u>maximum latency available for the Level-1 trigger</u>

Thanks for your attention!

Questions?