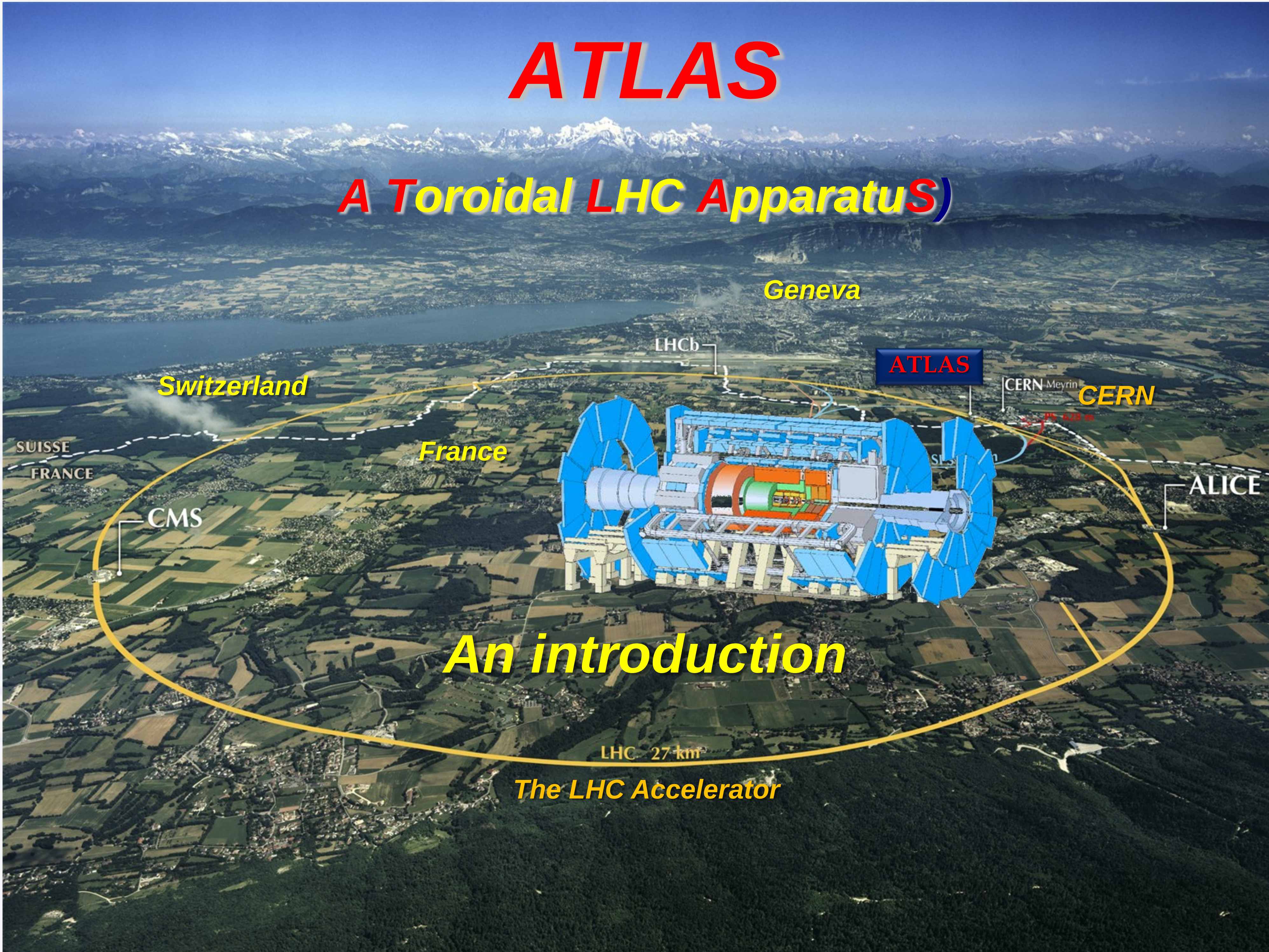
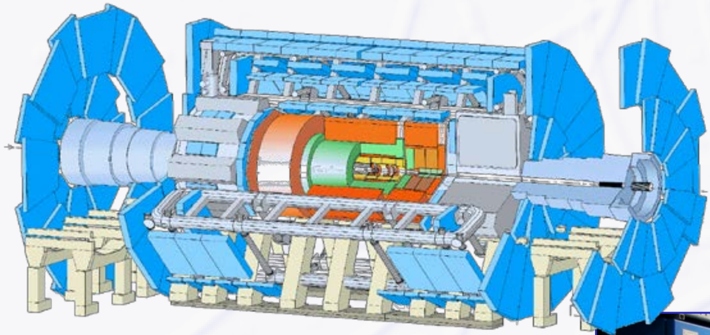

ATLAS
A Toroidal LHC ApparatuS)
Geneva
LHCb
ATLAS
CERN Meyrin
CERN
Switzerland
SUISSE
FRANCE
France
CMS
ALICE
An introduction
LHC 27 km
The LHC Accelerator

LHC Detectors

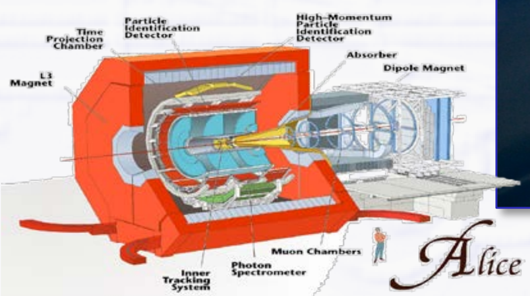
General purpose detectors (good for everything...)



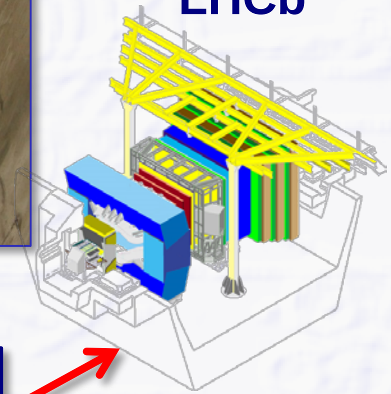
ATLAS

CMS

ALICE



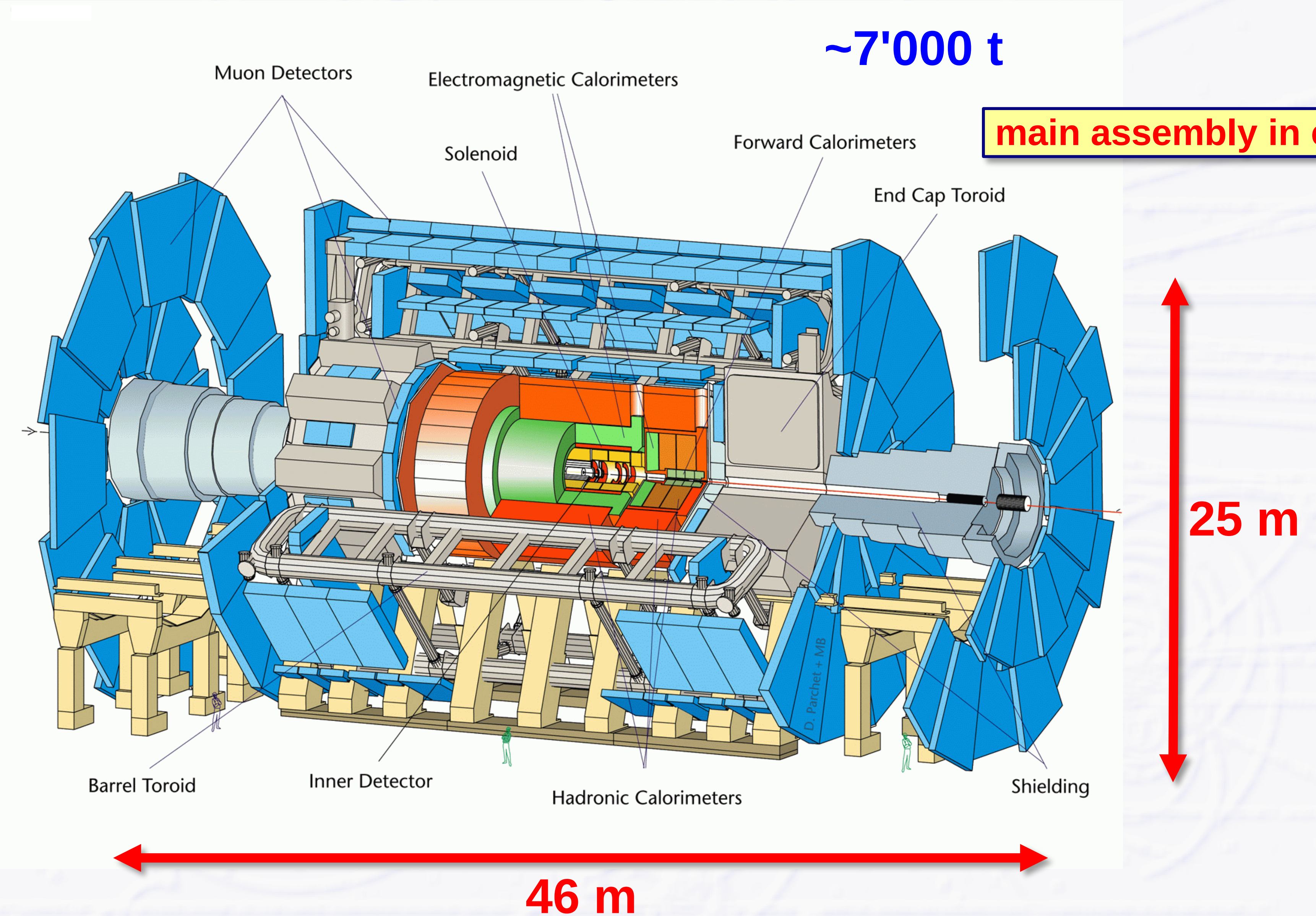
LHCb



dedicated for Heavy Ion collisions

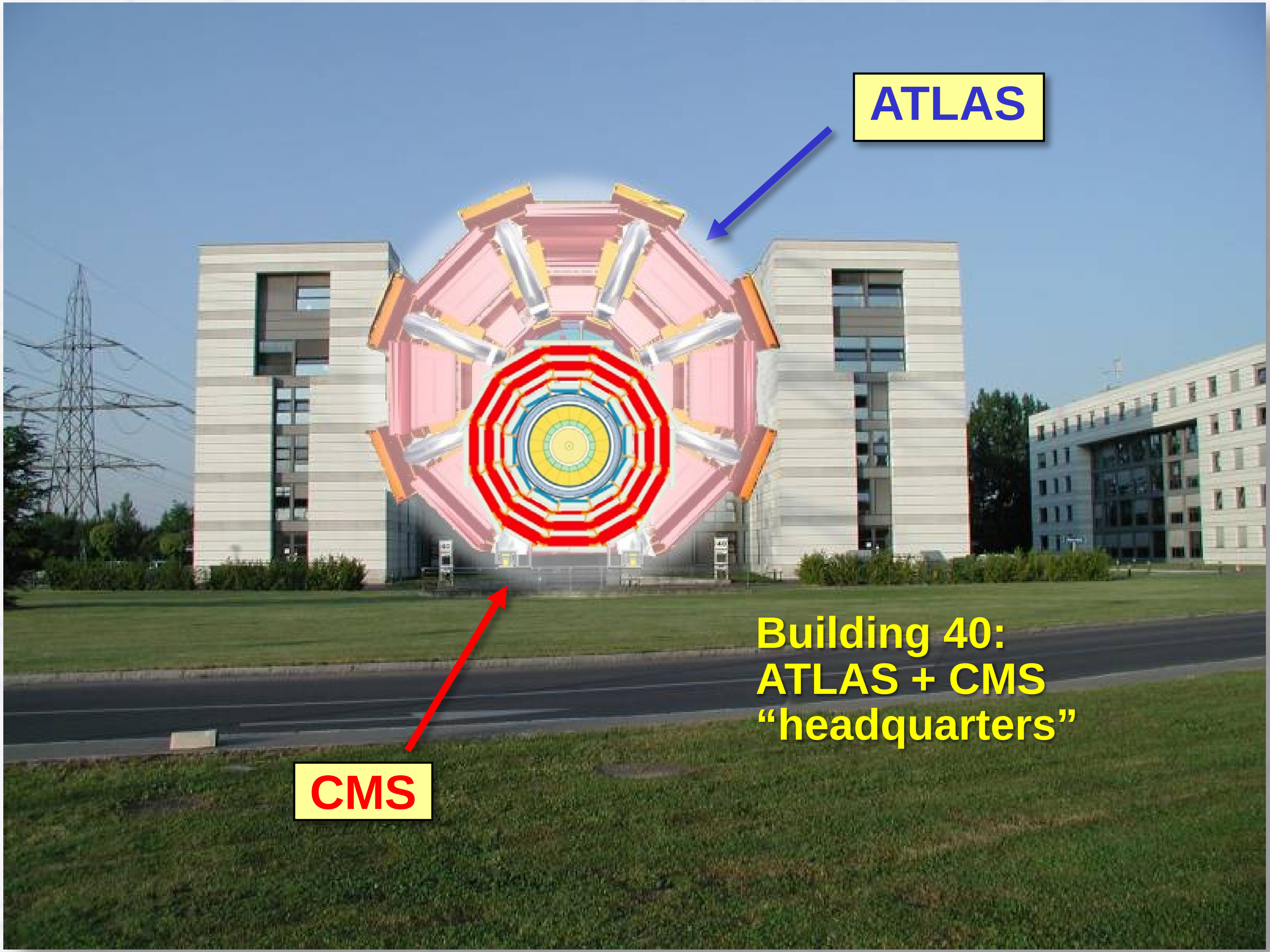
dedicated for b-physics

ATLAS (A Toroidal LHC ApparatuS)



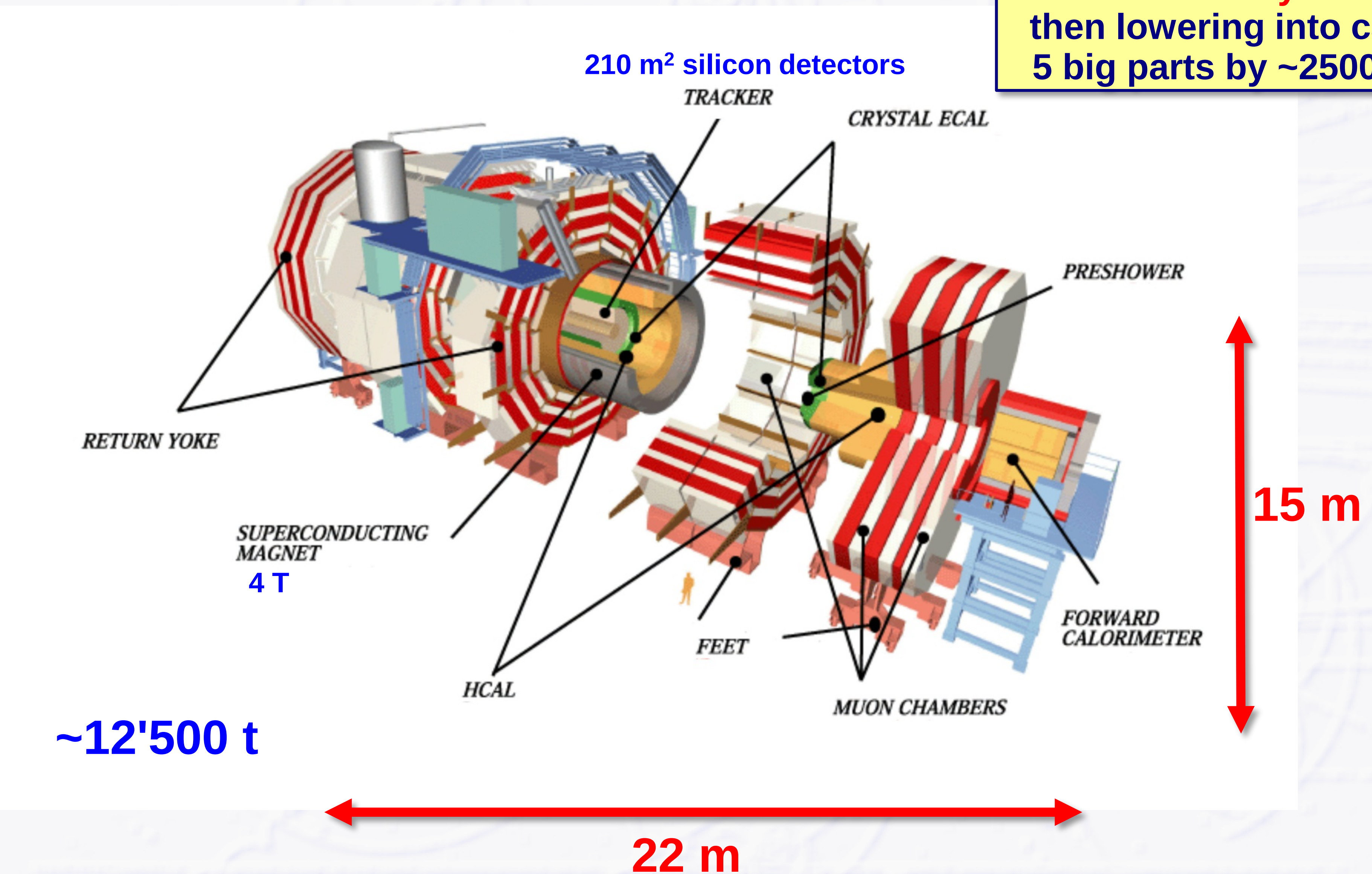
LARGE Detectors

- **Everything is LARGE at the LHC…**

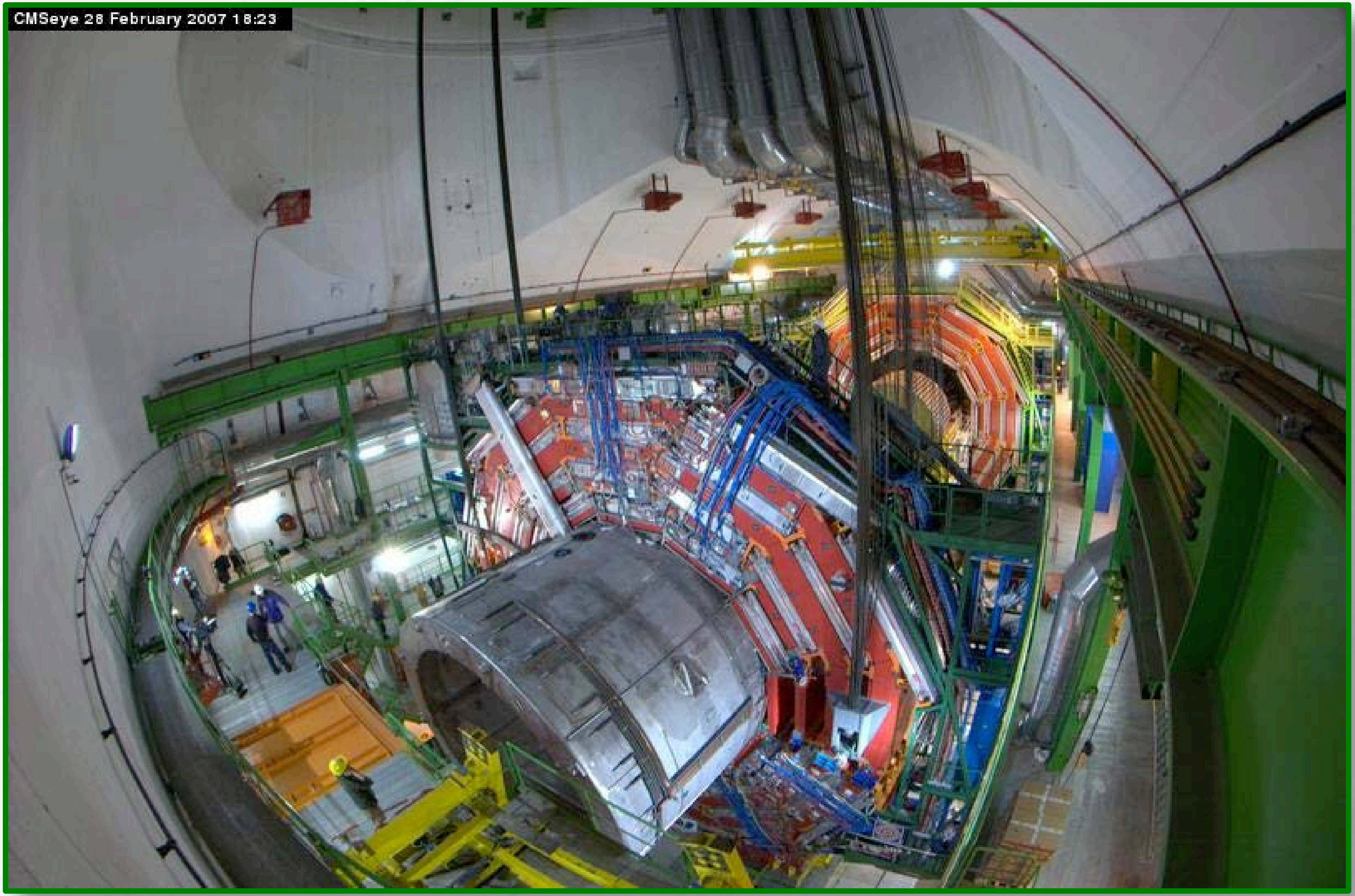


CMS (Compact Muon Spectrometer)

main assembly on surface, then lowering into cavern in 5 big parts by ~2500 t crane

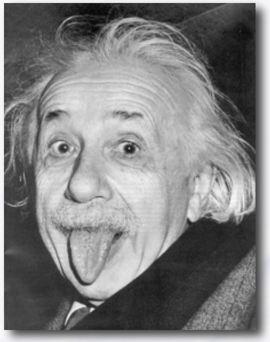


CMS Lowering of 2000 t Central Part



38 countries, 177 institutes,
3000 researchers (1000 PhD students)

Particle Physics Methods

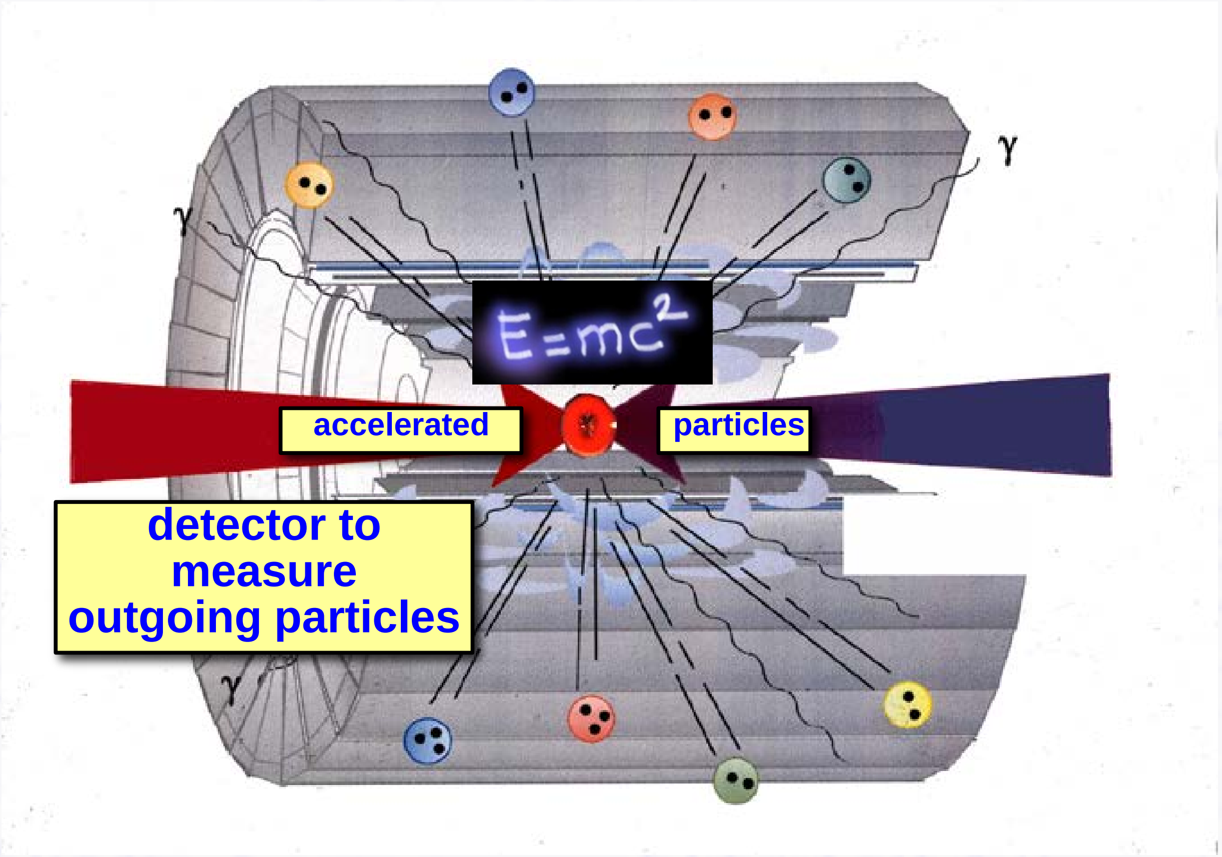


Einstein (1905):

Matter is concentrated energy!

Matter can be transformed into energy and back!

$E = m c^2$



- We use this at a particle accelerator
  - protons are accelerated ⇒ energy
  - kinetic energy is transformed into matter at the collision
  - new particles are being produced (new matter)

Detector Challenges at LHC

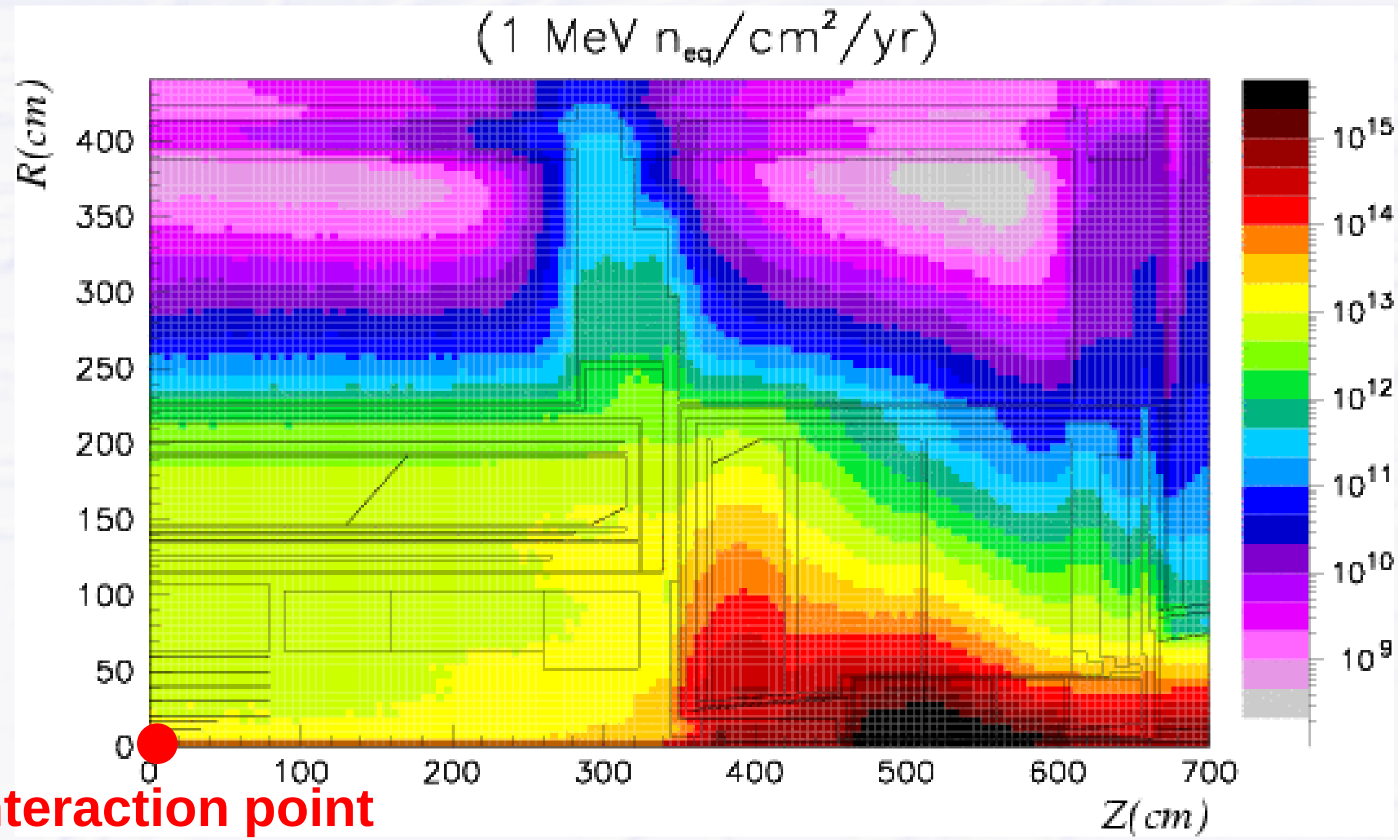
- **High energy collisions**
  - **sufficiently high momentum resolution up to TeV scale**
- **High luminosity (high interaction rate)**
  - **high rate capabilities, fast detectors (25 ns bunch crossing rate)**
- **High particle density**
  - **high granularity, sufficiently small detector cells to resolve particles**
- **High radiation (lots of strongly interacting particles)**
  - **radiation mainly due to particles emerging from collisions, not machine background**
  - **radiation-hard detectors and electronics (have to survive ~10 years)**

- **LARGE collaborations!!!**
  - **~O(3000) physicists for ATLAS and CMS each**
  - **communication, sociological aspects**
    - **exponential raise of meetings, phone + video conferences...**

200 MRad

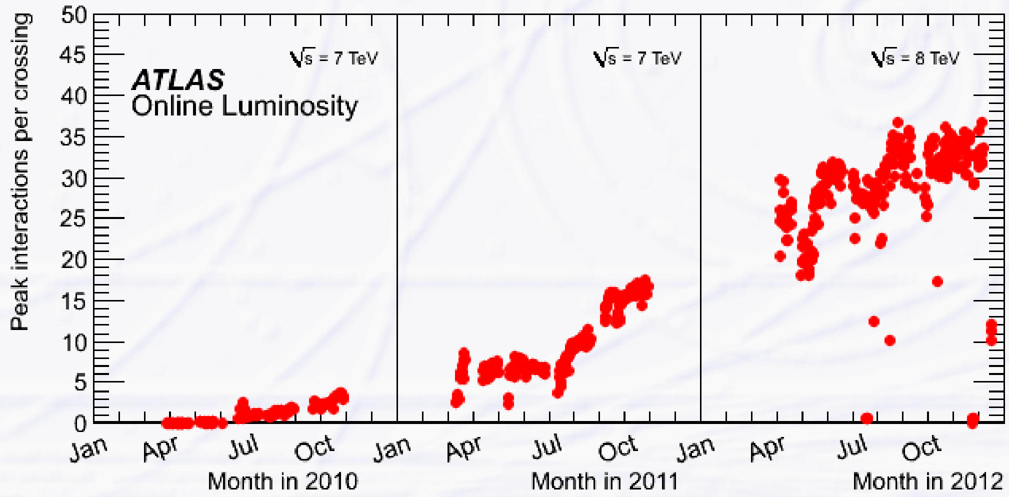
Radiation Doses at LHC

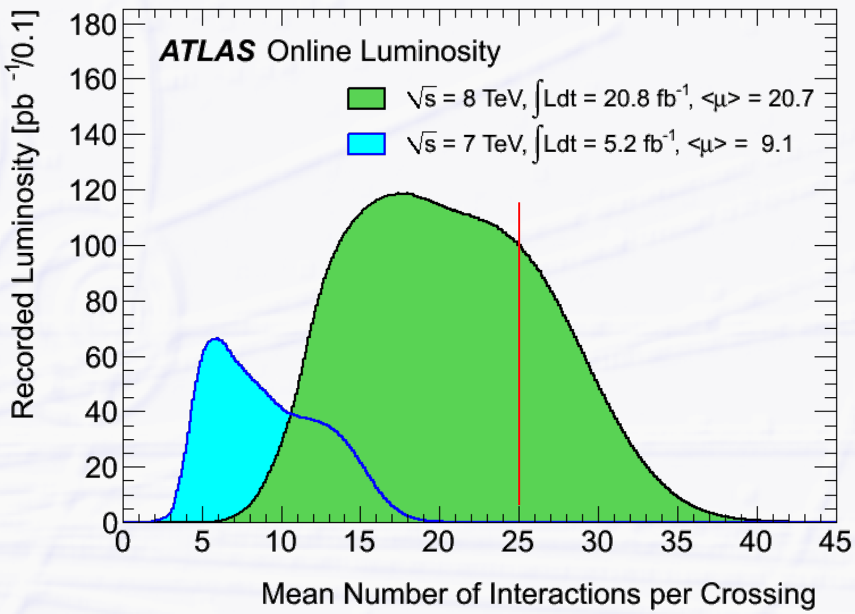
- ~ 2 x 10^6 Gray / r_T^2 / year at LHC design luminosity
  - where r_T [cm] = transverse distance to the beam
- Lots of R&D over >10 years to develop rad.-hard silicon detectors, gaseous detectors and electronics



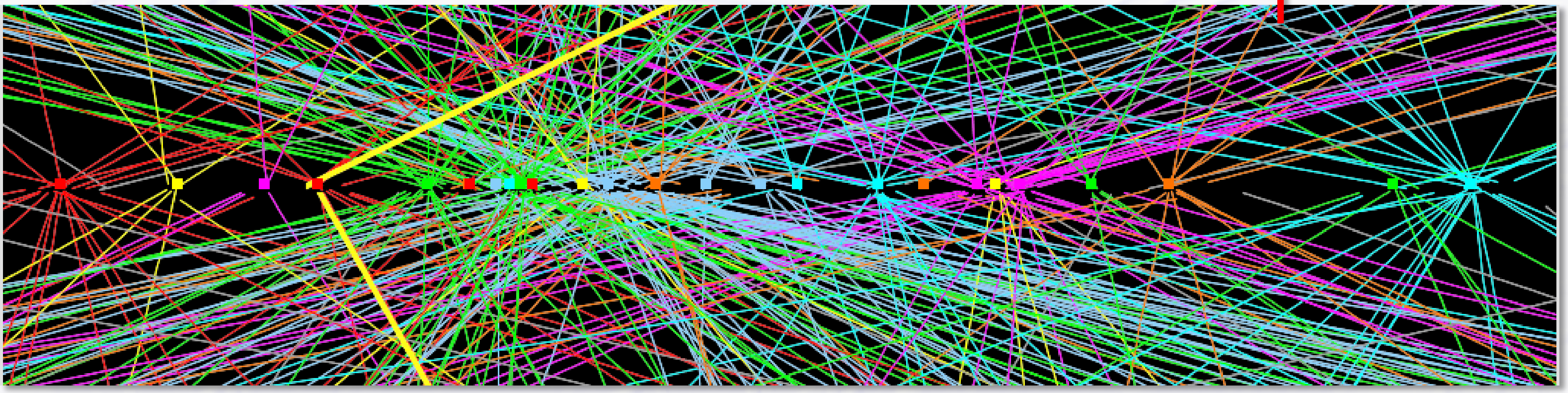
ATLAS neutron fluences

Challenging Conditions: Pile-up





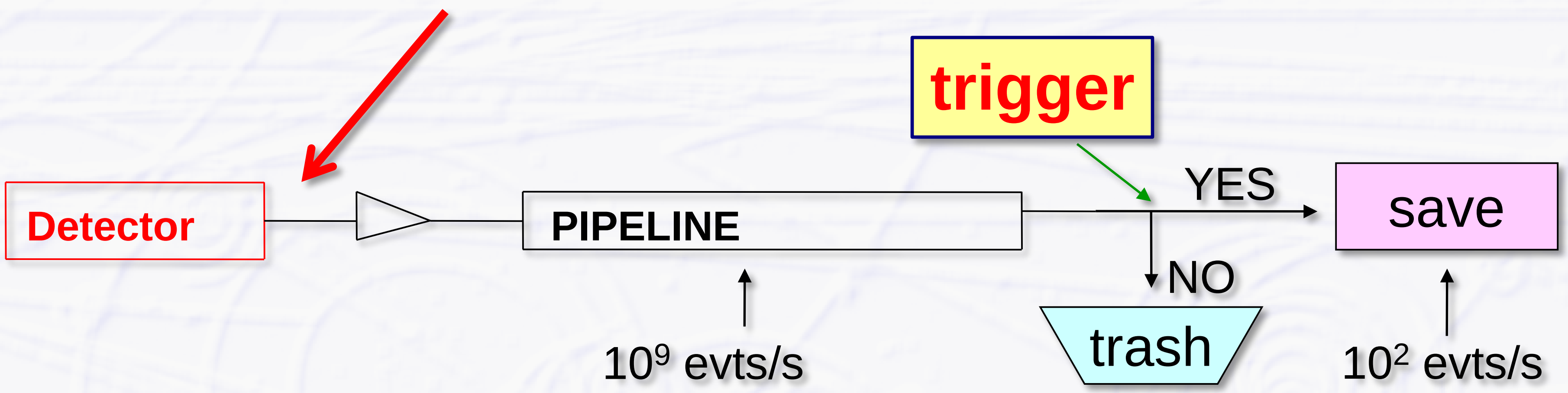
2012 event with pile-up: 25 reconstructed primary vertices



~7 cm

How to Select Interesting Events?

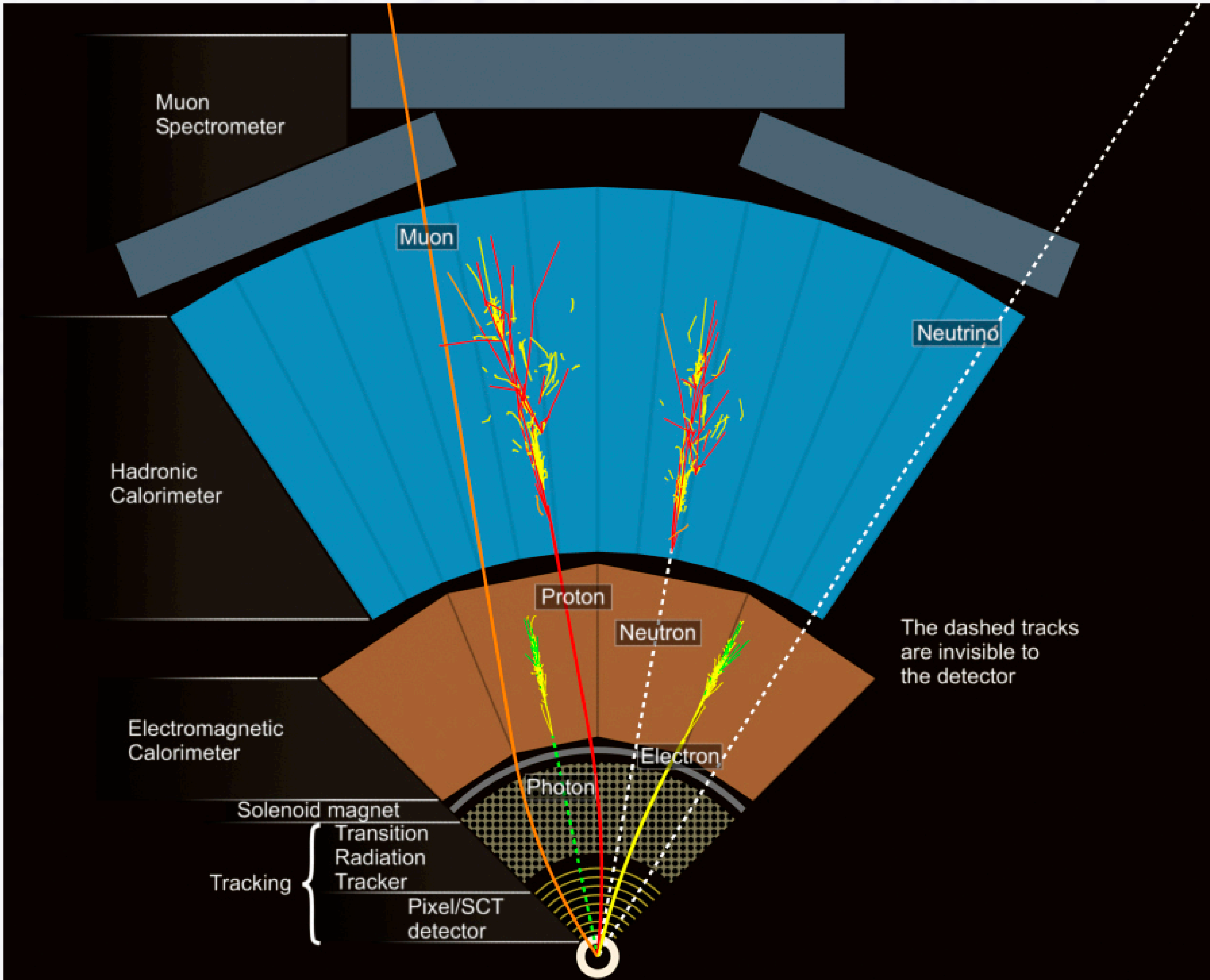
- **Bunch crossing rate: 40 MHz, ~20 interactions per BX** **(10^9 evts/s)**
  - **can only record ~300 event/s (1.5 MB each), still ~450 MB/s data rate**
- **Need highly efficient and highly selective TRIGGER**
  - **raw event data (1 PB/s) are stored in pipeline until trigger decision**



- **ATLAS trigger had 3 levels in Run-1 (CMS similar with 2 levels)**
  - **Level-1: hardware, ~3 μs decision time, 40 MHz → 75 kHz**
  - **Level-2: software, ~40 ms decision time, 75 kHz → 2 kHz**
  - **Level-3: software, ~4 s decision time, 2 kHz → 300 Hz**

A typical Particle Detector

- **Cut-away view of ATLAS**



Muon Detector
→ muon ID
+ p for muons

Calorimeter → E

Coil

Tracker → p

High Energy Collider Detectors

- **Tracking Detector (or Tracker) = momentum measurement**
  - **closest to interaction point: vertex detector (often silicon pixels)**
    - **measures primary interaction vertex and secondary vertices from decay particles**
  - **main or central tracking detector**
    - **measures momentum by curvature in magnetic field**
- **Calorimeters = energy measurement**
  - **electro-magnetic calorimeters (light particles: e^-, e^+, γ)**
    - **measures energy of light EM particles (electrons, positrons, photons) based on electro-magnetic showers by bremsstrahlung and pair production**
    - **two concepts: homogeneous (e.g. CMS) or sampling (e.g. ATLAS, ILD, SiD, CLIC)**
  - **hadron calorimeters (heavy hadronic particles: π, K, p, n)**
    - **measures energy of heavy (hadronic) particles (pions, kaons, protons, neutrons) based on nuclear showers created by nuclear interactions**
- **Muon Detectors = momentum measurement for muons (more precise)**
  - **outermost detector layer, basically a tracking detector**

Tracker Technologies

- 3 major technologies of tracking detectors

Gaseous detectors

- ionization in gas
  - typically ~100 e^-/cm → not sufficient to create significant signal height above noise for standard amplifiers
    - typical amplifier noise = some 100…1000 ENC (equivalent noise charge, in electrons)
- requires gas amplification ~10^4 to get enough signal over noise (S/N)

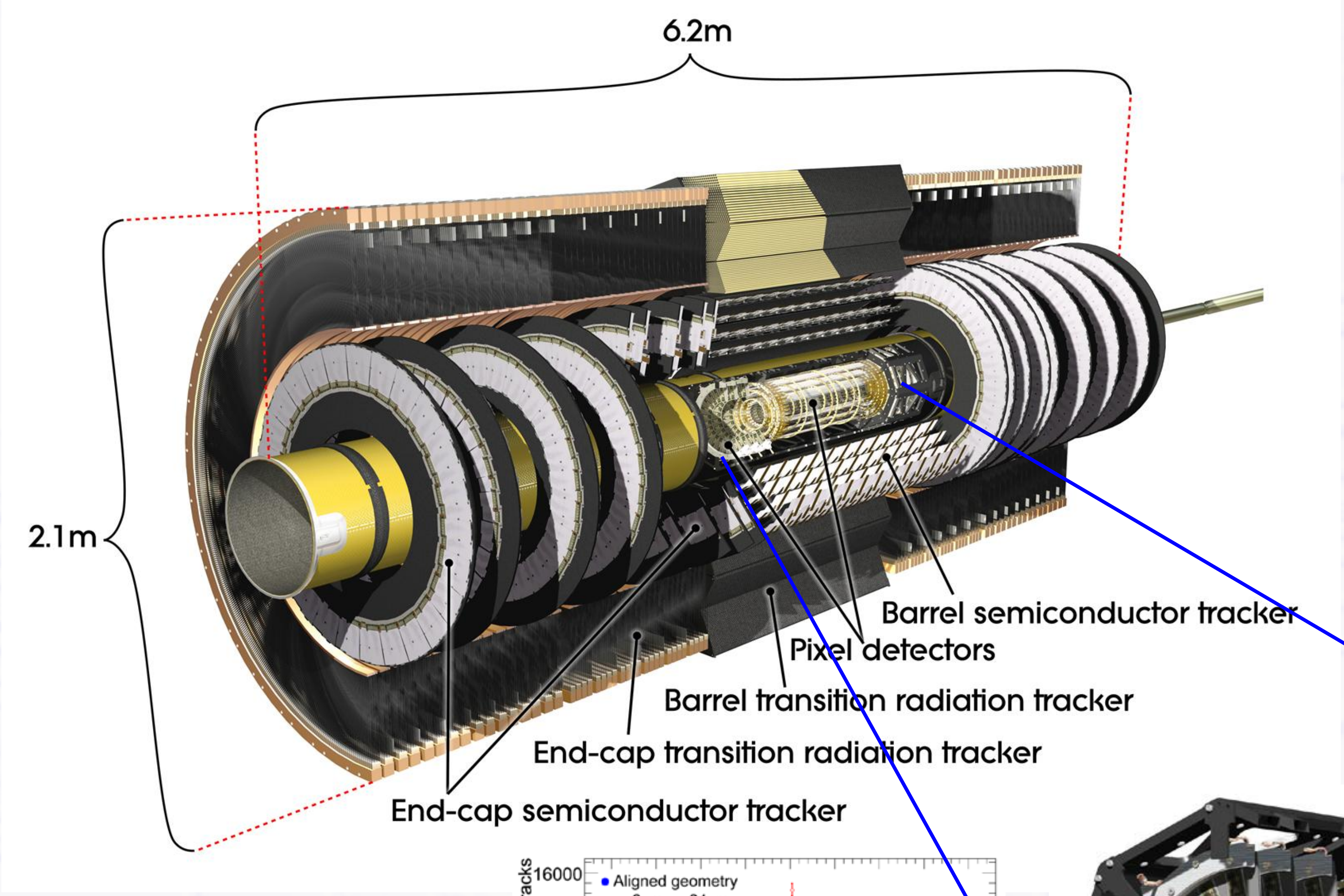
Silicon detectors (solid state detectors)

- creation of electron – hole pairs in solid state material
  - typically ~100 e^- - hole pairs/µm = 10^4 more than in gaseous detectors
- 300 µm thick detector creates high enough signal w/o gas amplification
  - ~30’000 charge carriers per detector layer, noise ~1000 ENC, S/N ~ 30:1

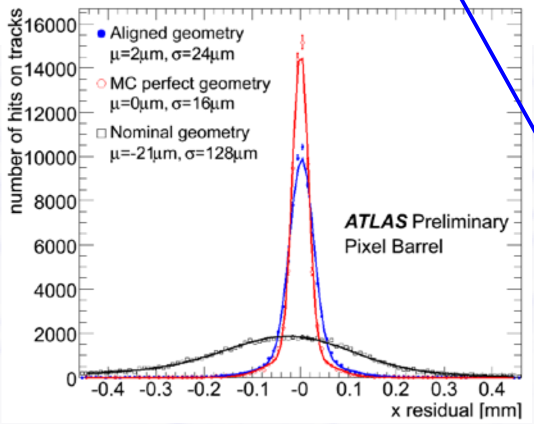
rarely used: fiber trackers

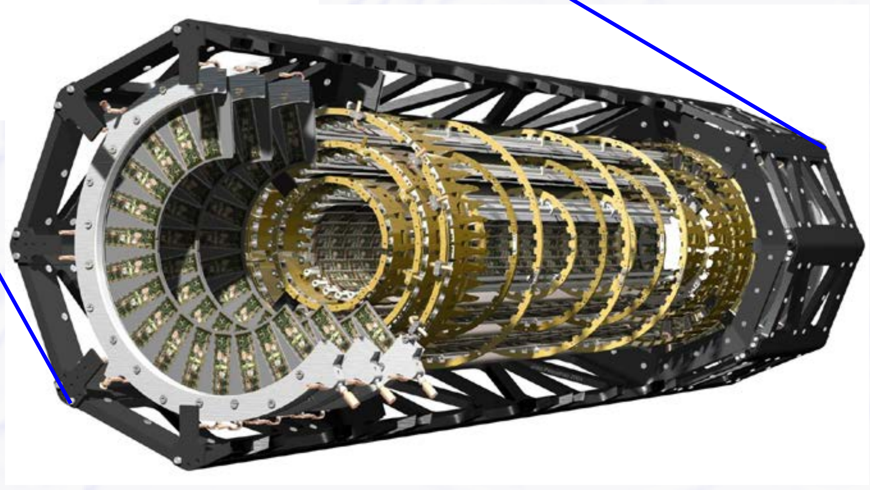
- scintillating fibers
  - scintillation light detected with photon detectors (sensitive to single electrons)

ATLAS Inner Tracker



- **3-layer Si Pixel**
- **4-layer Silicon Strips**
- **Transition Radiation Tracker (gaseous)**

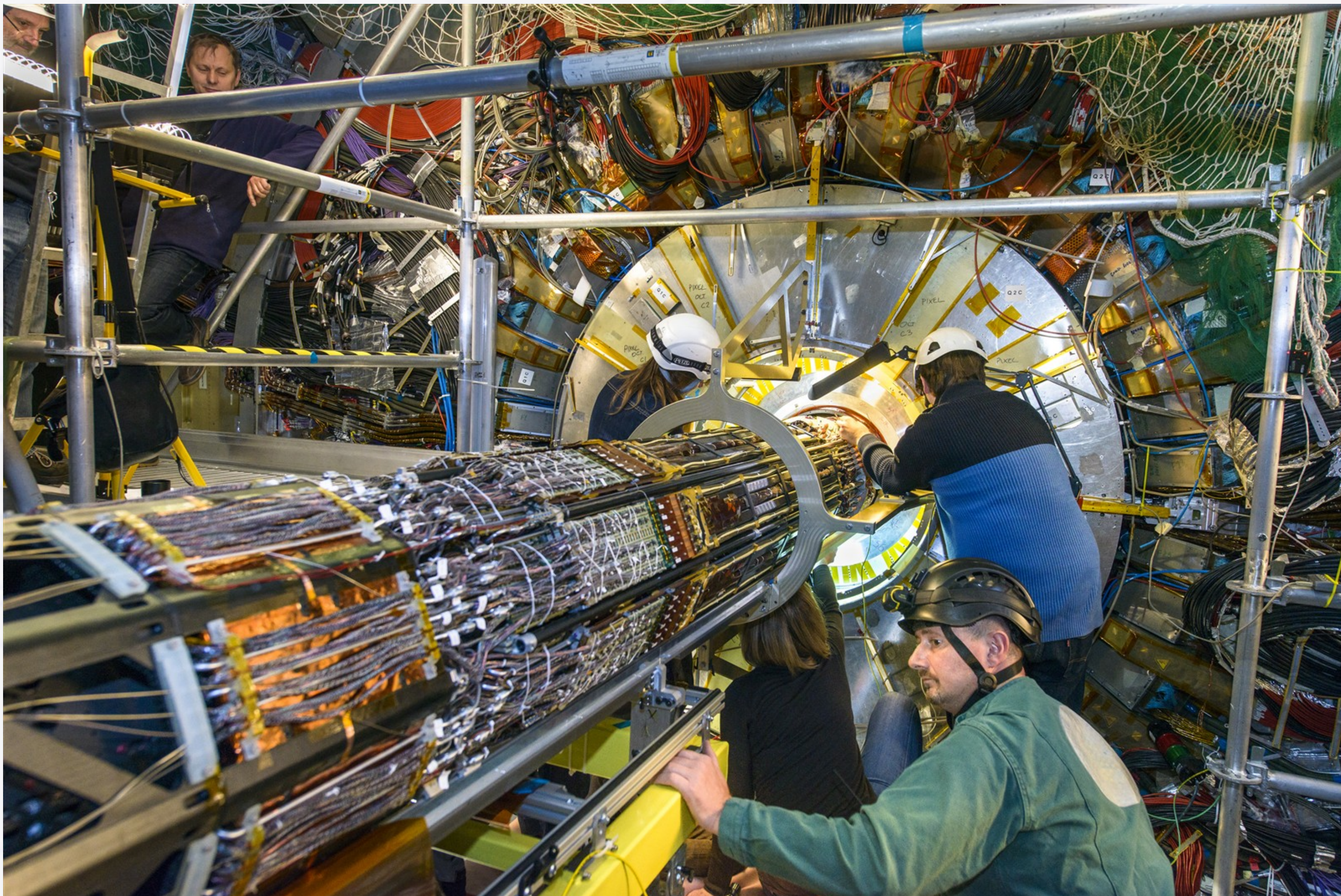




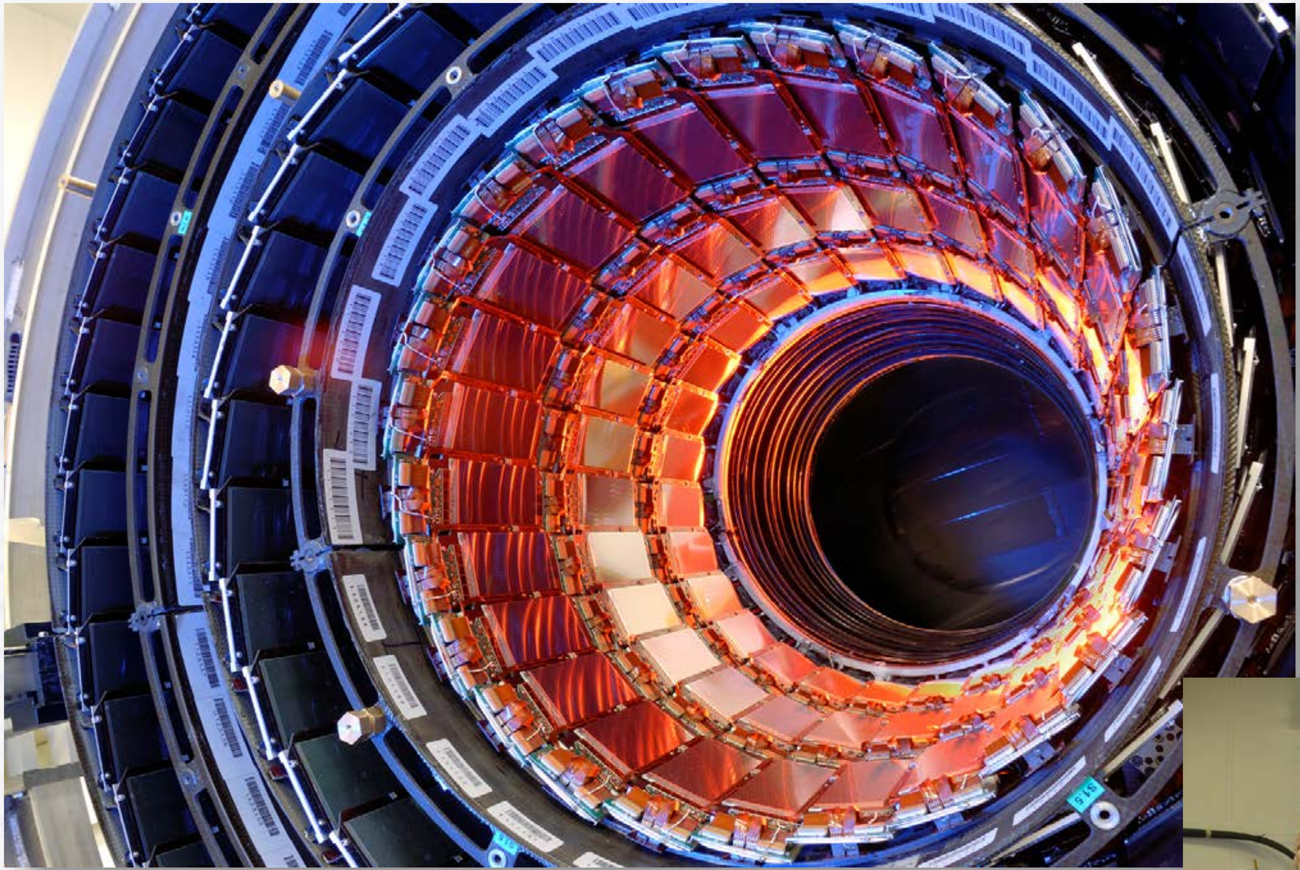
Pixel alignment with cosmic rays 2008

The ATLAS Pixel Detector

- **Re-insertion in December 2013 during Long Shutdown 1**

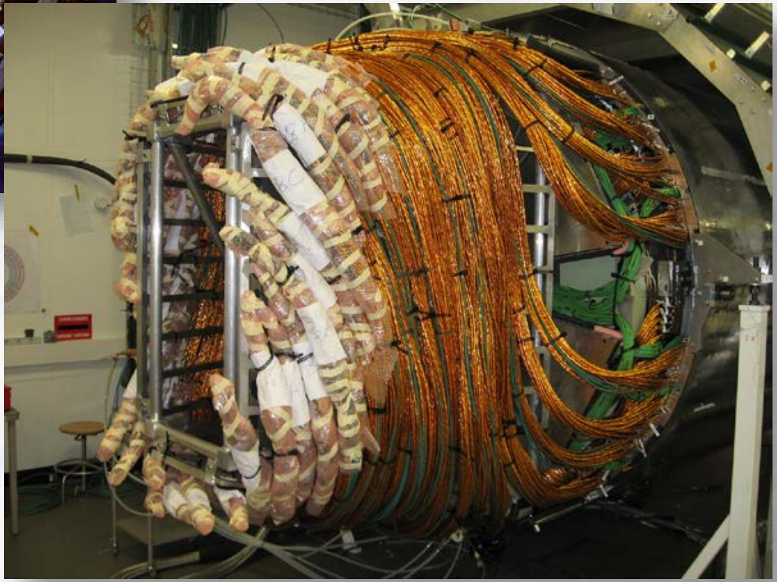


CMS Full Silicon Tracker



Tracker Inner Barrel TIB

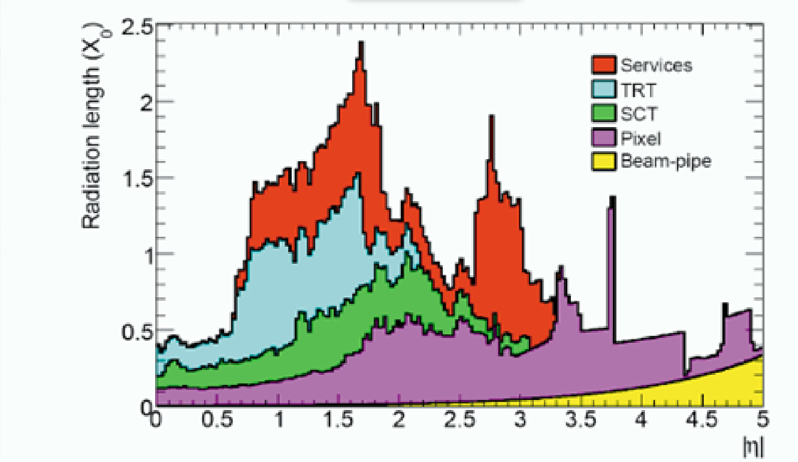
- 3-layers Si Pixel
- 10-layers Silicon Strips
  - 210 m², largest silicon detector ever built



Material Budget

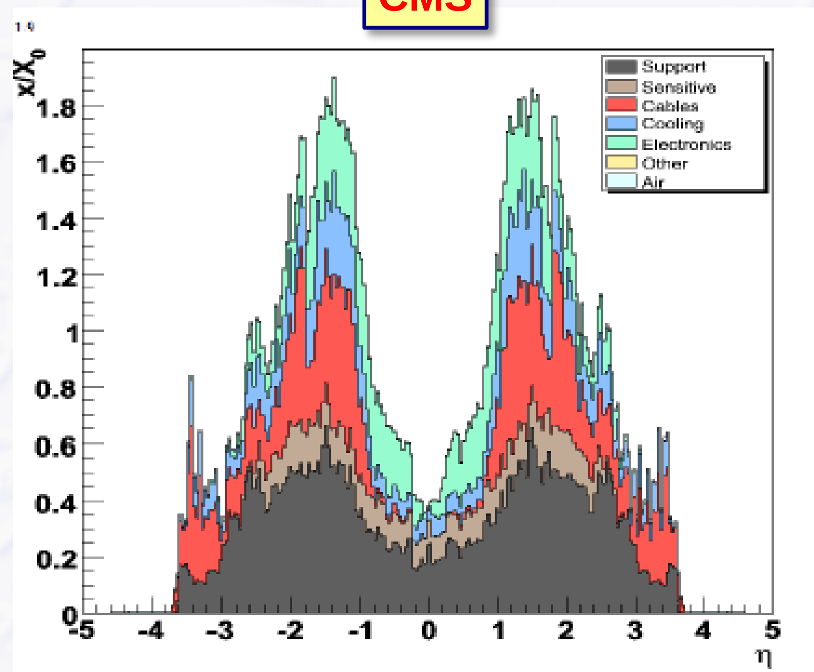
- **Tracking Detectors should be light-weighted and thin**
  - **multiple scattering by material degrades resolution at low momenta**
  - **unwanted photon conversions in front of calorimeters**
  - **material often very inhomogeneous (in particular Si detectors)**
- **Power & cooling adds most of the material**
  - **not the Si sensor material**

ATLAS



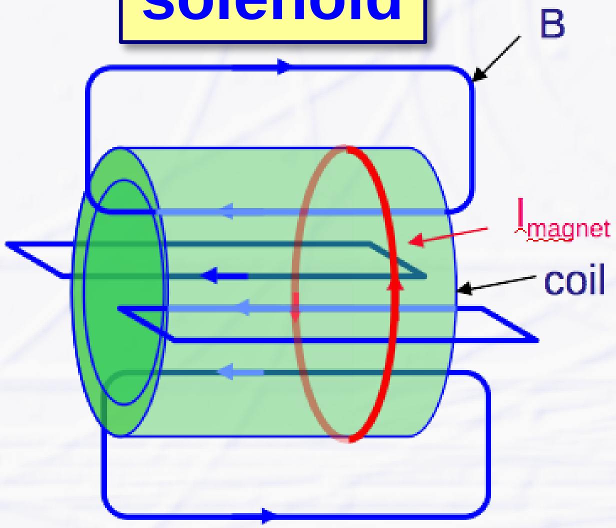
$\vert\eta\vert$	radiation length	interaction length
< 1	$\sim 0.2\,X_0$	$\sim 0.05\,\lambda$
< 3.3	$\lesssim 0.5\,X_0$	$\lesssim 0.2\,\lambda$

CMS

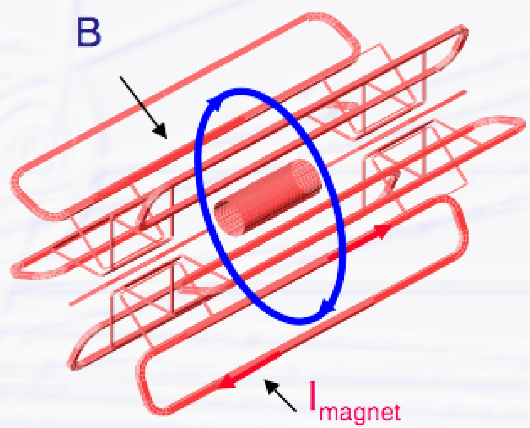


Magnet Concepts at LHC experiments

solenoid



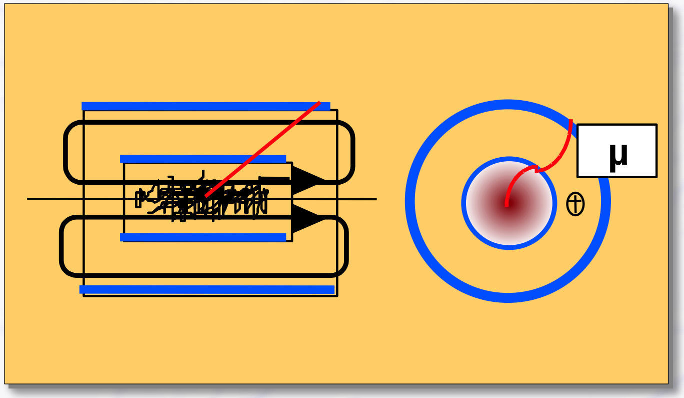
(air-core) toroid



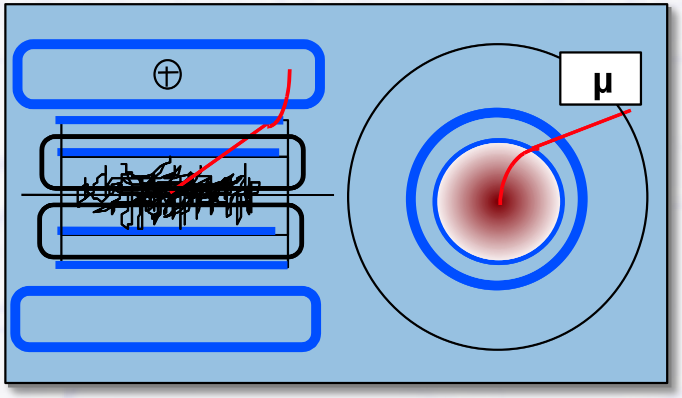
- \+ large homogenous field inside coil
- \- needs iron return yoke (magnetic shortcut)
- \- limited size (cost)
- \- coil thickness (radiation lengths)

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

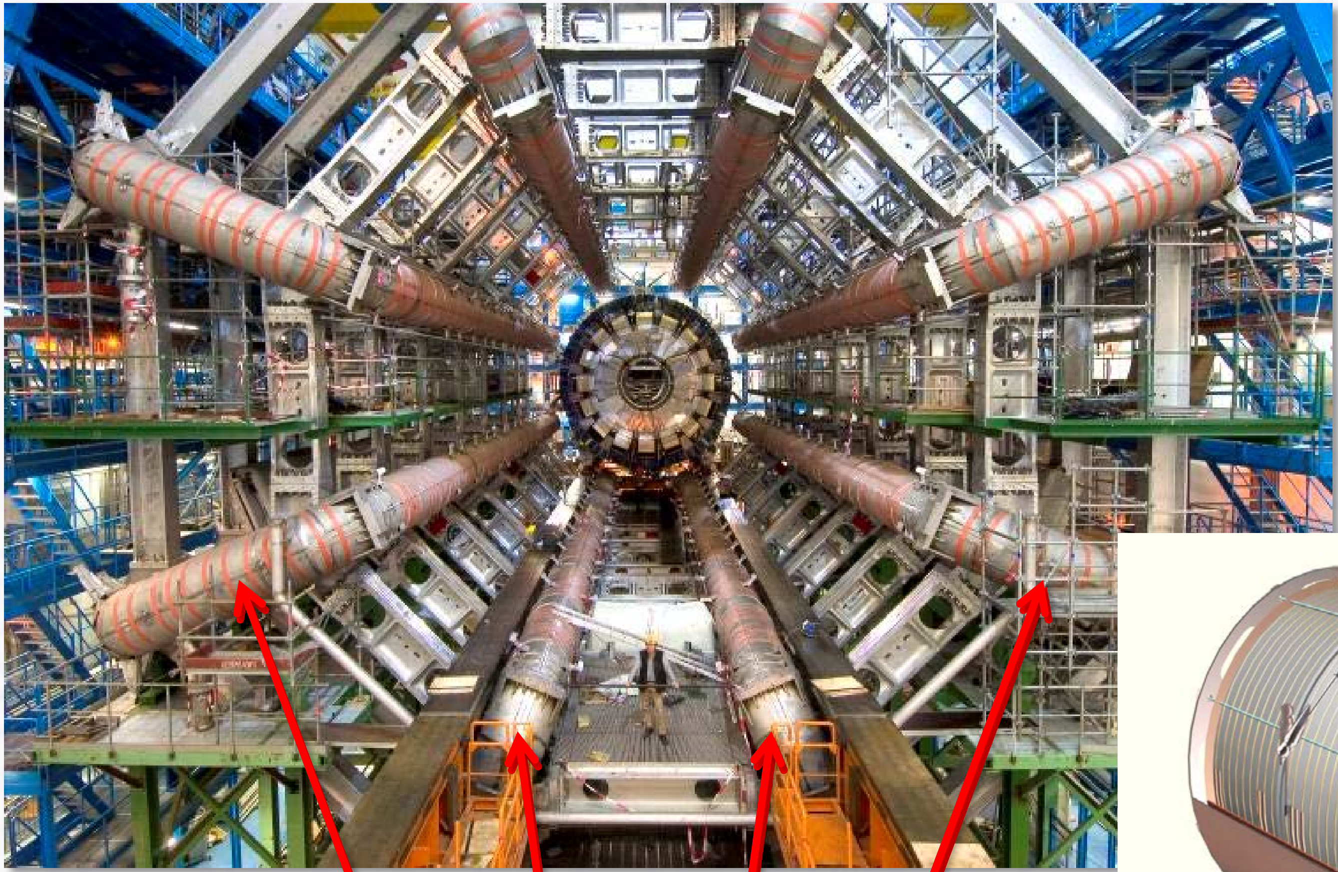
CMS, ALICE, LEP detectors



ATLAS



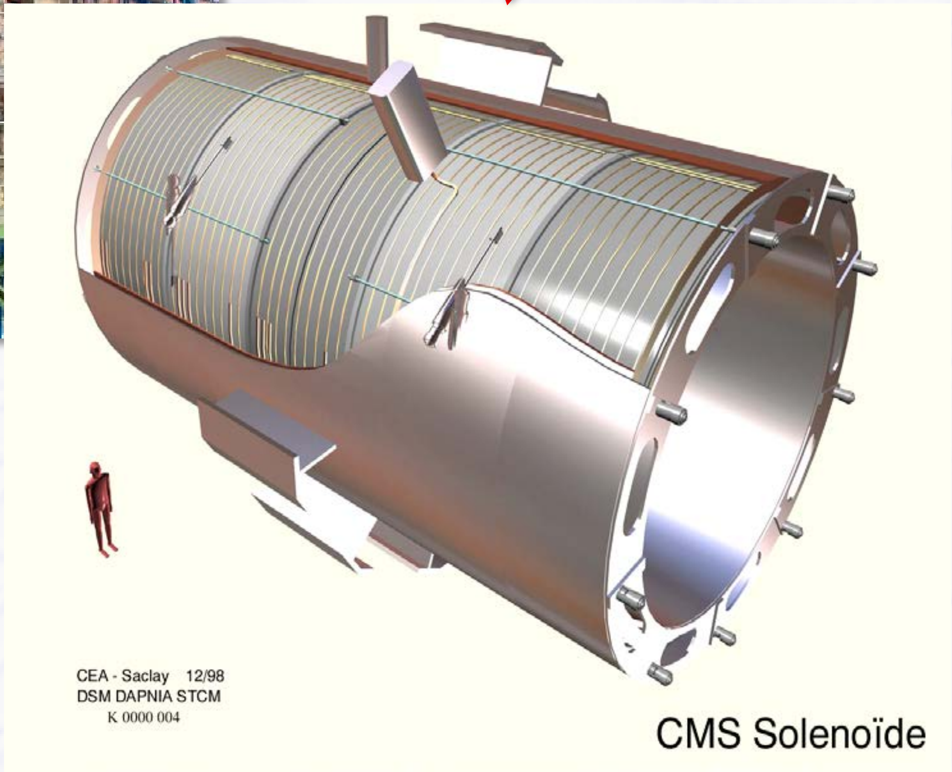
ATLAS and CMS Coils



CMS solenoid (5 segments)

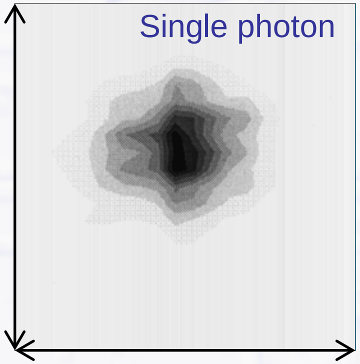
ATLAS barrel toroid coils

autumn 2005

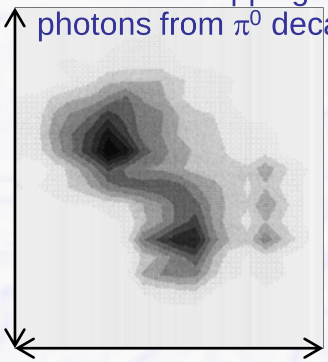


CMS: Homogeneous EM Calorimeter

- **Clear advantage: good energy resolution**
  - **the entire shower is kept in active detector material**
    - **no shower particle is lost in passive absorber**
- **Disadvantages**
  - **limited granularity, no information on shower shape in longitudinal direction (along particle flight direction)**
    - **position information is useful to resolve near-by energy clusters, e.g. single photons versus two photons from π^0 decay**



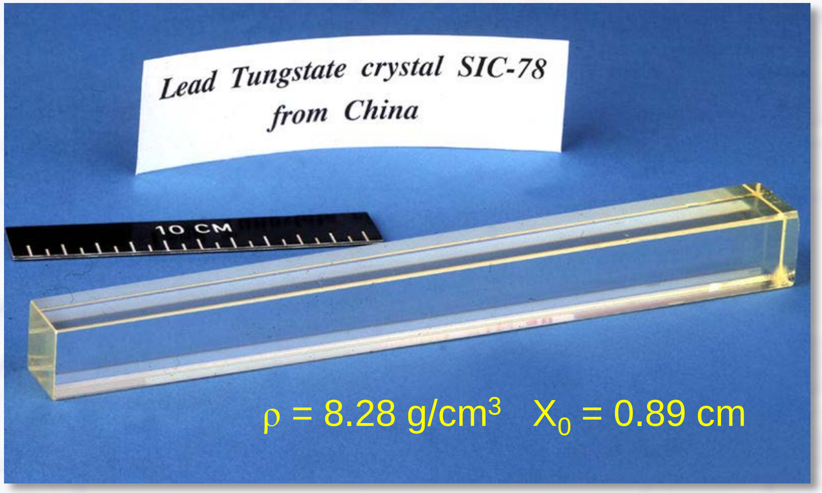
$\Delta\varphi \times \Delta\theta = 1^o \times 1^o$



$\Delta\varphi \times \Delta\theta = 1^o \times 1^o$

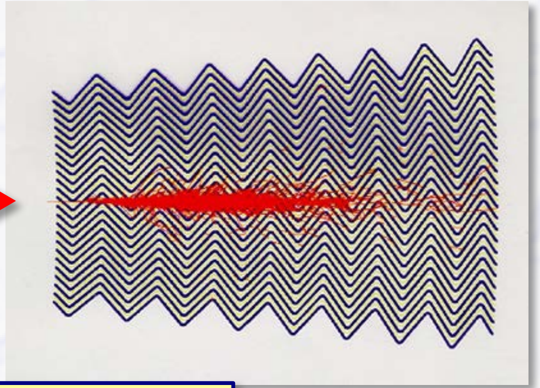
dense, transparent materials needed with short radiation length and high light yield

CMS $PbWO_4$ crystal



ATLAS: Sampling EM Calorimeter

- **Typical sampling calorimeters use iron or lead absorber material, variety of detectors in between possible**
  - **gas detectors (MWPCs), plastic scintillators, liquid noble gases (LAr, LKr)**
- **LAr with "acordeon" shaped Fe-Pb-Fe absorbers at ATLAS**
  - **LAr is ionized by charged shower particles**
  - **Charge collected on pads**
    - **ionization chamber, no "gas" amplification**
    - **pads can be formed as needed → high granularity**
  - **acordeon structure helps to avoid dead zones (cables etc.)**



simulated shower

ATLAS LAr calorimeter

ATLAS/CMS Hadron Calorimeters

- **Energy resolution much worse than for electromagnetic calorimeters**
  - **larger fluctuations in hadronic shower**
  - **usually only a few nuclear interactions length deep (5 – 6 λ_I)**
- **Both ATLAS and CMS use scintillators as detector material**

➔ **need many optical fibers to transport light from scintillators to photo detectors**

ATLAS

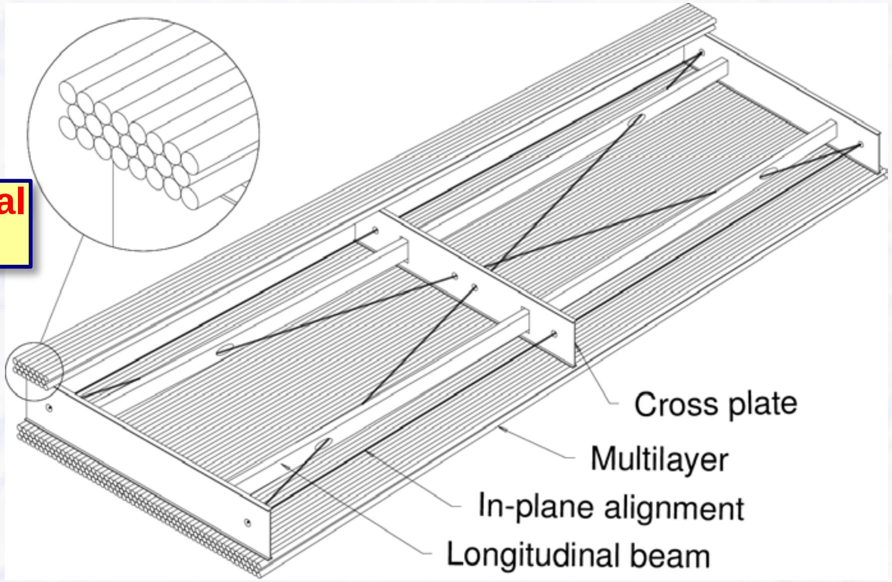
CMS

ATLAS Muon Detector

- **Muon detectors are tracking detectors (e.g. wire chambers)**
  - they form the outer shell of the (LHC) detectors
  - they are not only sensitive to muons (but to all charged particles)!
  - just by "definition": if a particle has reached the muon detector
    → it's considered to be a muon
  - all other particles should have been absorbed in the calorimeters
- **Challenge for muon detectors**
  - large surface to cover (outer shell)
  - keep mechanical positioning stable over time

ATLAS Muon Detector Elements

Aluminum tubes with central wire filled with 3 bar gas



- **ATLAS Muon System**
  - 1200 chambers with 5500 m^2
  - needs also good knowledge of (inhomogeneous) magnetic field

ATLAS Detector Status

(a 100 megapixel camera with 40 MHz framerate = 1 PB/second)

Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	92 M	98.2%
SCT Silicon Strips	6.3 M	98.6%
TRT Transition Radiation Tracker	350 k	97.3%
LAr EM Calorimeter	170 k	100%
Tile calorimeter	4900	99.2%
Hadronic endcap LAr calorimeter	5600	99.6%
Forward LAr calorimeter	3500	99.8%
LVL1 Calo trigger	7160	100%
LVL1 Muon RPC trigger	370 k	99.75%
LVL1 Muon TGC trigger	320 k	100%
MDT Muon Drift Tubes	357 k	99.7%
CSC Cathode Strip Chambers	31 k	98.4%
RPC Barrel Muon Chambers	370 k	96.6%
TGC Endcap Muon Chambers	320 k	99.6%

ATLAS/CMS Concept Overview

- The two large LHC detectors have somewhat different concepts
  - ATLAS
    - small inner tracker with moderate field (small 2 T solenoid)
    - electron identification by transition radiation tracker
    - sampling calorimeter with high granularity outside solenoid
    - air-core toroid system for good muon momentum measurement

    emphasis on granular calorimeter and good muon measurement

  - CMS
    - large inner tracker with high B-field (large 4 T solenoid)
    - no dedicated particle identification detector
    - homogeneous crystal calorimeter with good energy resolution inside solenoid

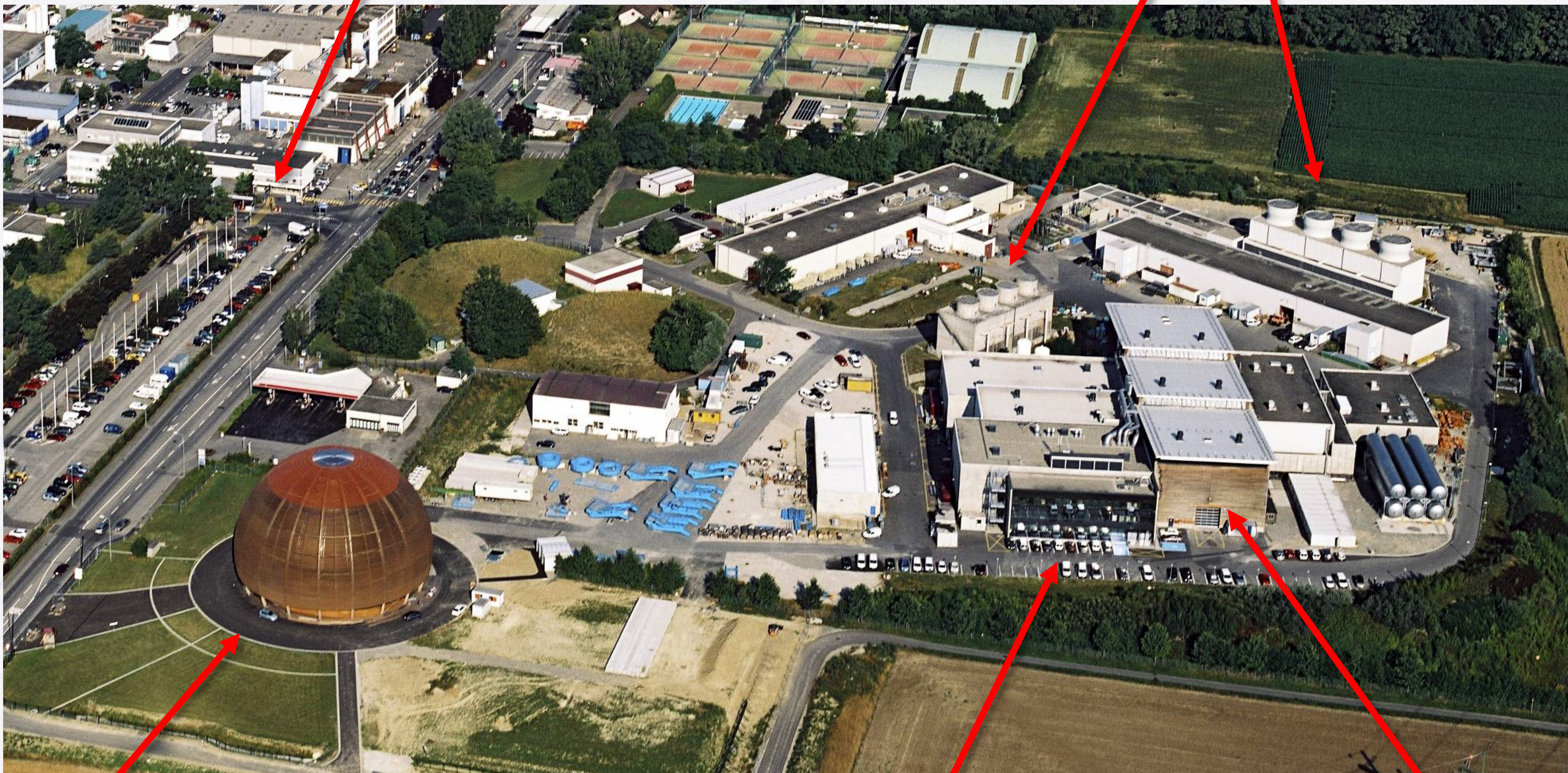
    emphasis on good general tracking and good energy resolution

- However, both detector concepts have very similar performance for Higgs physics (efficiency, mass resolution…)

The ATLAS Site 2005

CERN Main Entrance B

LHC Cooling Towers

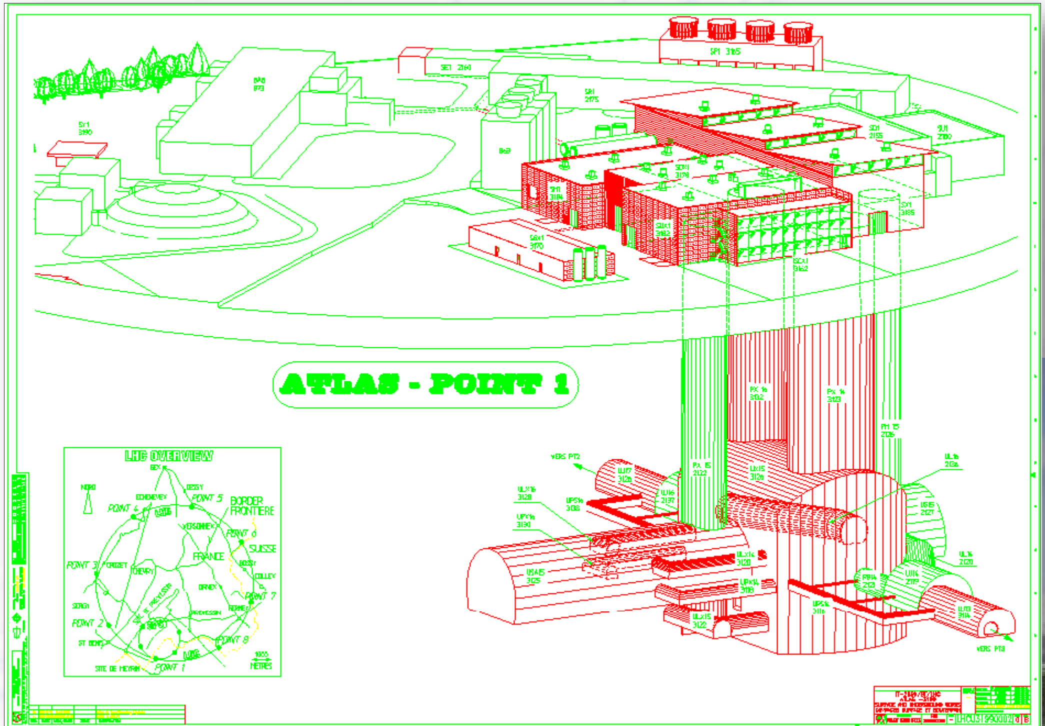


Globe of Innovation & Science

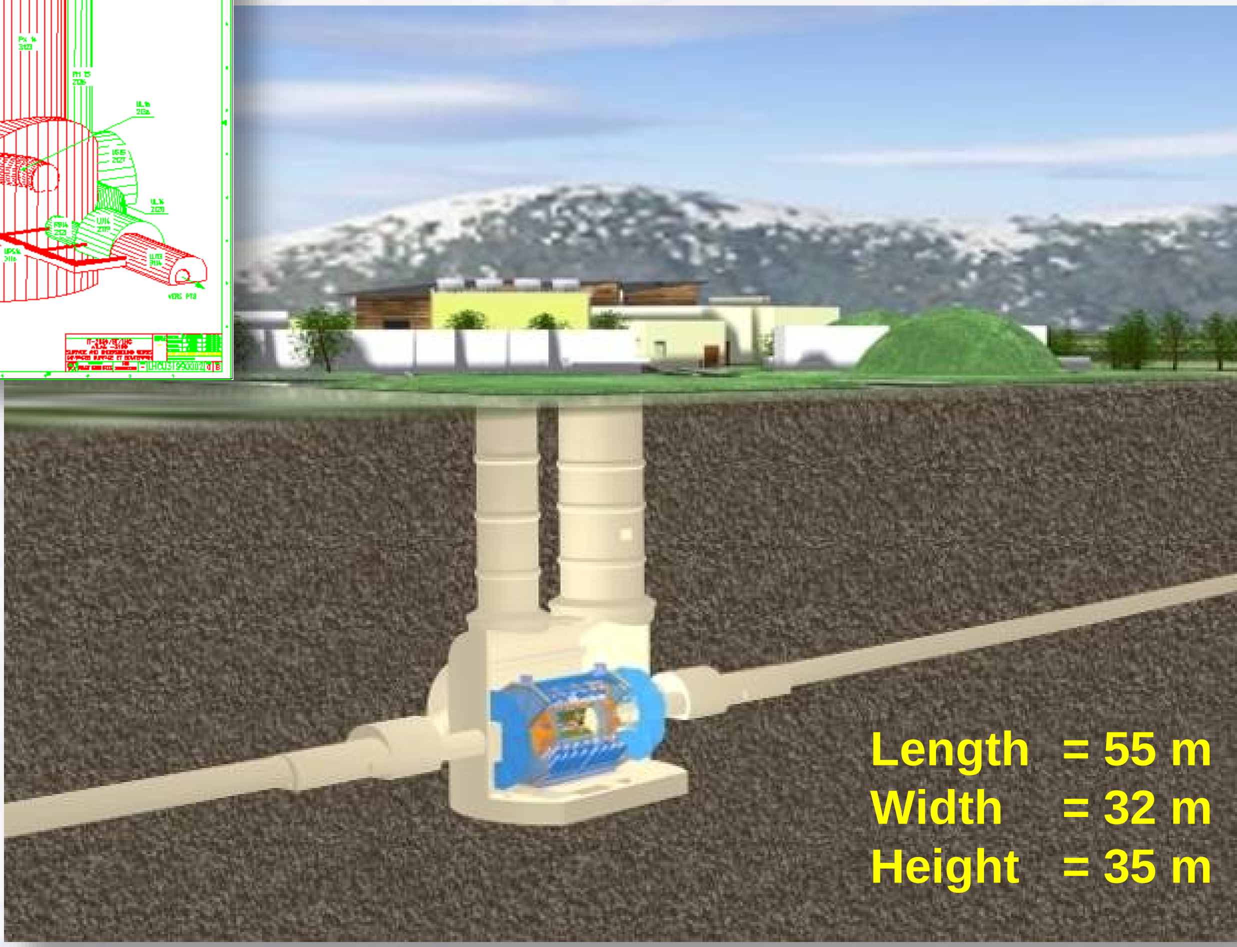
ATLAS Control Room
and Visitor Centre

ATLAS Main Hall

ATLAS Underground Cavern



huge cavern + surface buildings,
2 access shafts 18m + 12m Ø,
2 small shafts for elevators + stairs



First Digging started in 1998

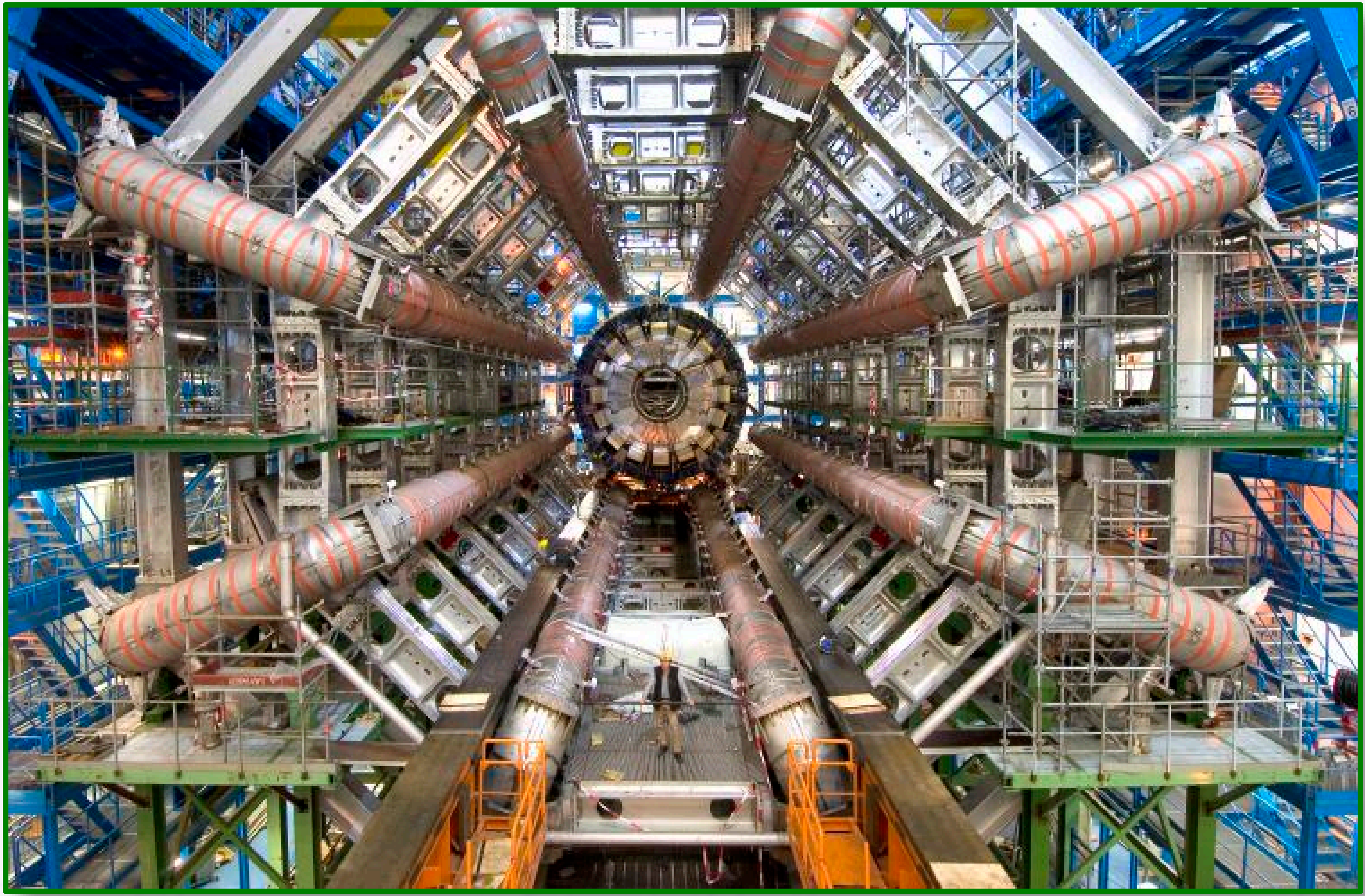
Gallo-roman remains
on future CMS site

ATLAS cavern
September 2000

Start of ATLAS Detector Construction

Transport and lowering of first superconducting Barrel Toroid coil

ATLAS Barrel Toroid Complete *(Nov 2005)*



Detector Technology and Arts

The first Higgs at LHC (4 April 2008)