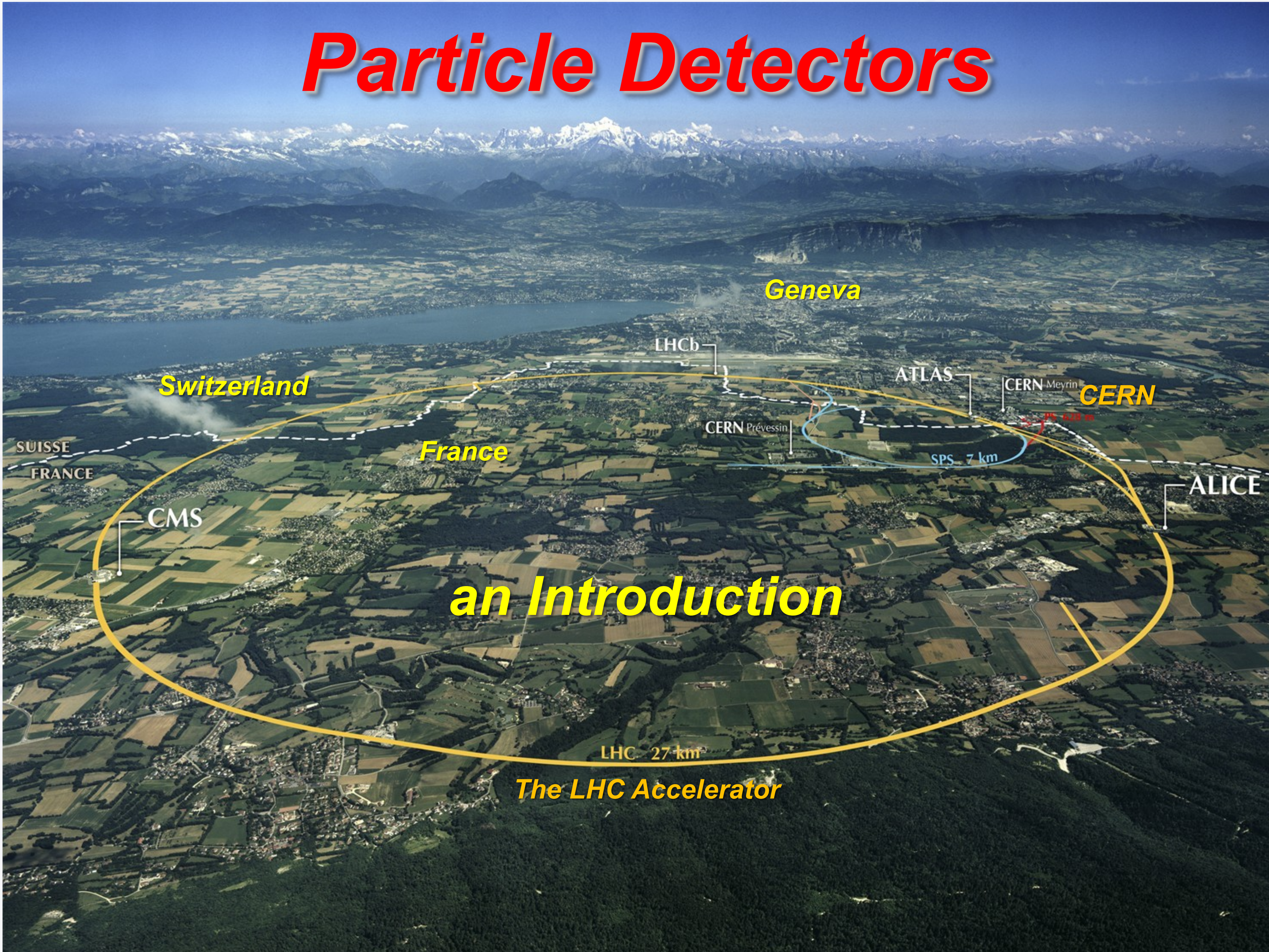
Particle Detectors

an Introduction

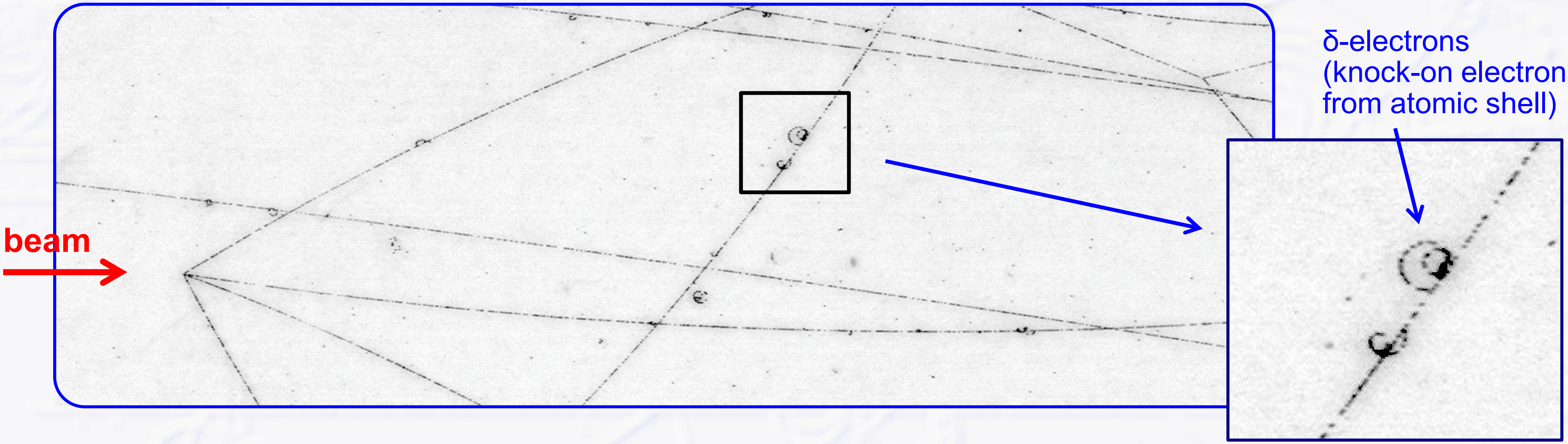


Historic Detector: Bubble Chamber

- **Invented 1952 by Donald Glaser (Noble Prize 1960)**
  - **chamber with liquid (e.g. H_2) at boiling point** ("superheated")
  - **charged particles leave trails of ions**
    - formation of small gas bubbles around ions
    - take photos of interactions and look for interesting events…
  - **nice pictures, but SLOW!!!**
    - only 1 photo/event every few seconds, need something faster → electronic detectors

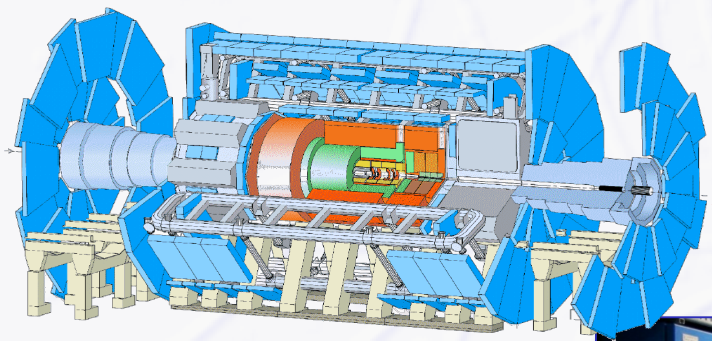
BEBC bubble chamber

tracks in CERN 2m bubble chamber



LHC Detectors

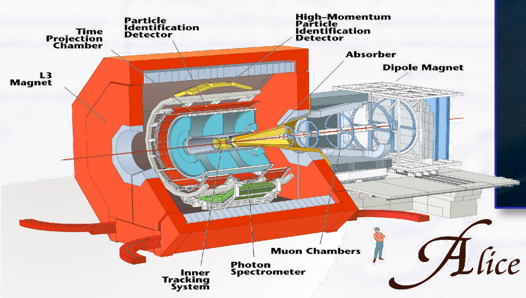
General purpose detectors (good for everything...)



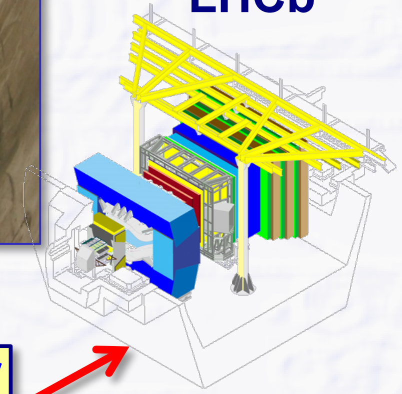
ATLAS

CMS

ALICE



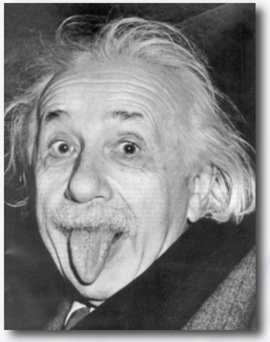
LHCb



dedicated for Heavy Ion collisions

dedicated for b-physics

Particle Physics Methods

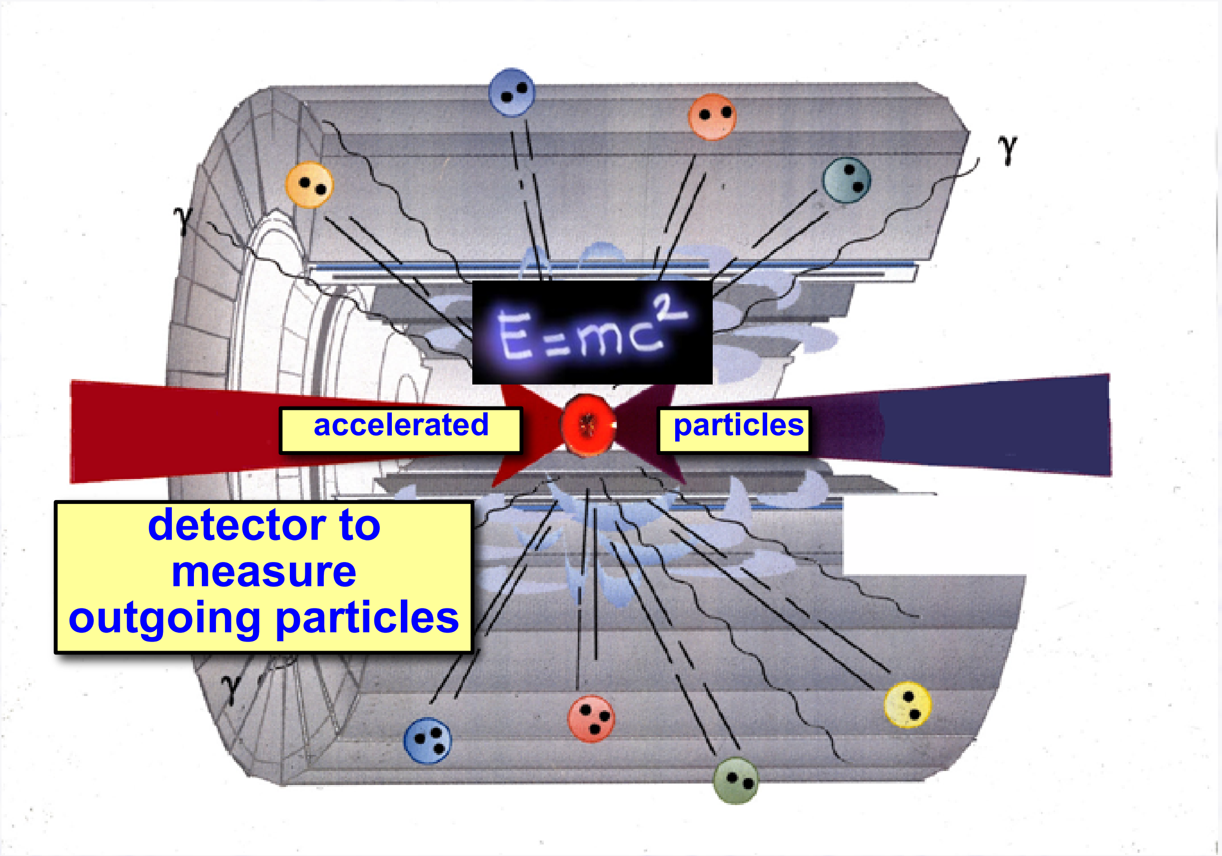


Einstein (1905):

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)**

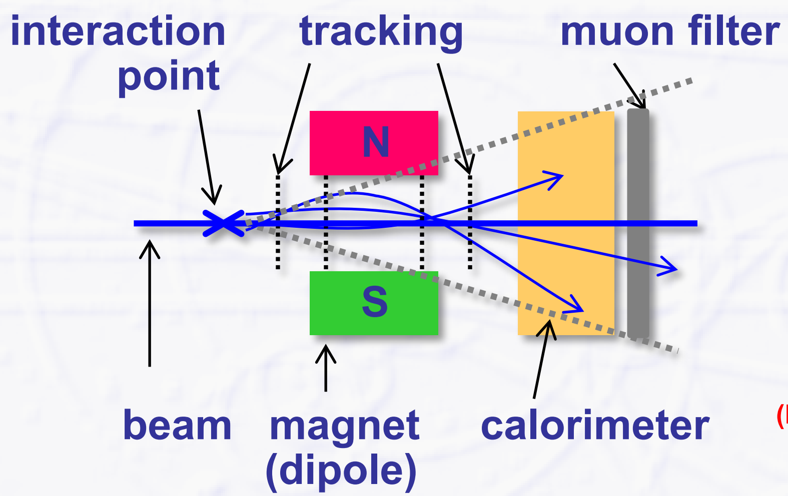
The Perfect Detector...

- ...should reconstruct any interaction of any type with 100% efficiency and unlimited resolution
  - get "4-momenta" of basic physics interaction
  - = energy / momentum / mass + charge of ALL involved particles
    - in practice: limitations by detector inefficiency (not all particles detected) + detector resolution (measurements have statistical + systematic uncertainties)

Fixed target geometry

"Magnetic spectrometer"

LHCb



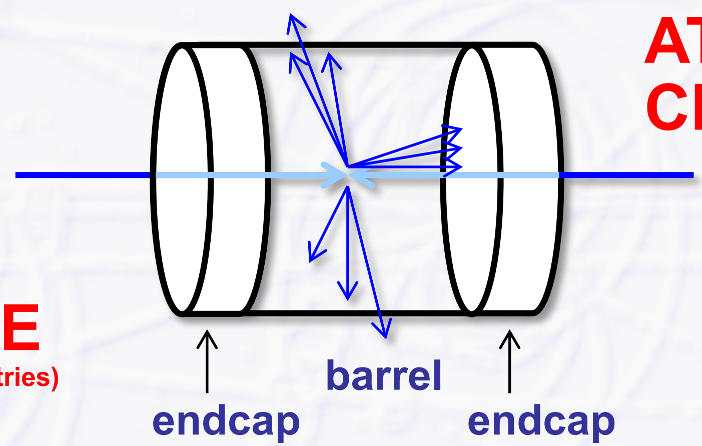
- Limited solid angle dΩ coverage
- rel. easy access (cables, maintenance)

ALICE (both geometries)

Collider geometry

"4π multi purpose detector"

ATLAS CMS



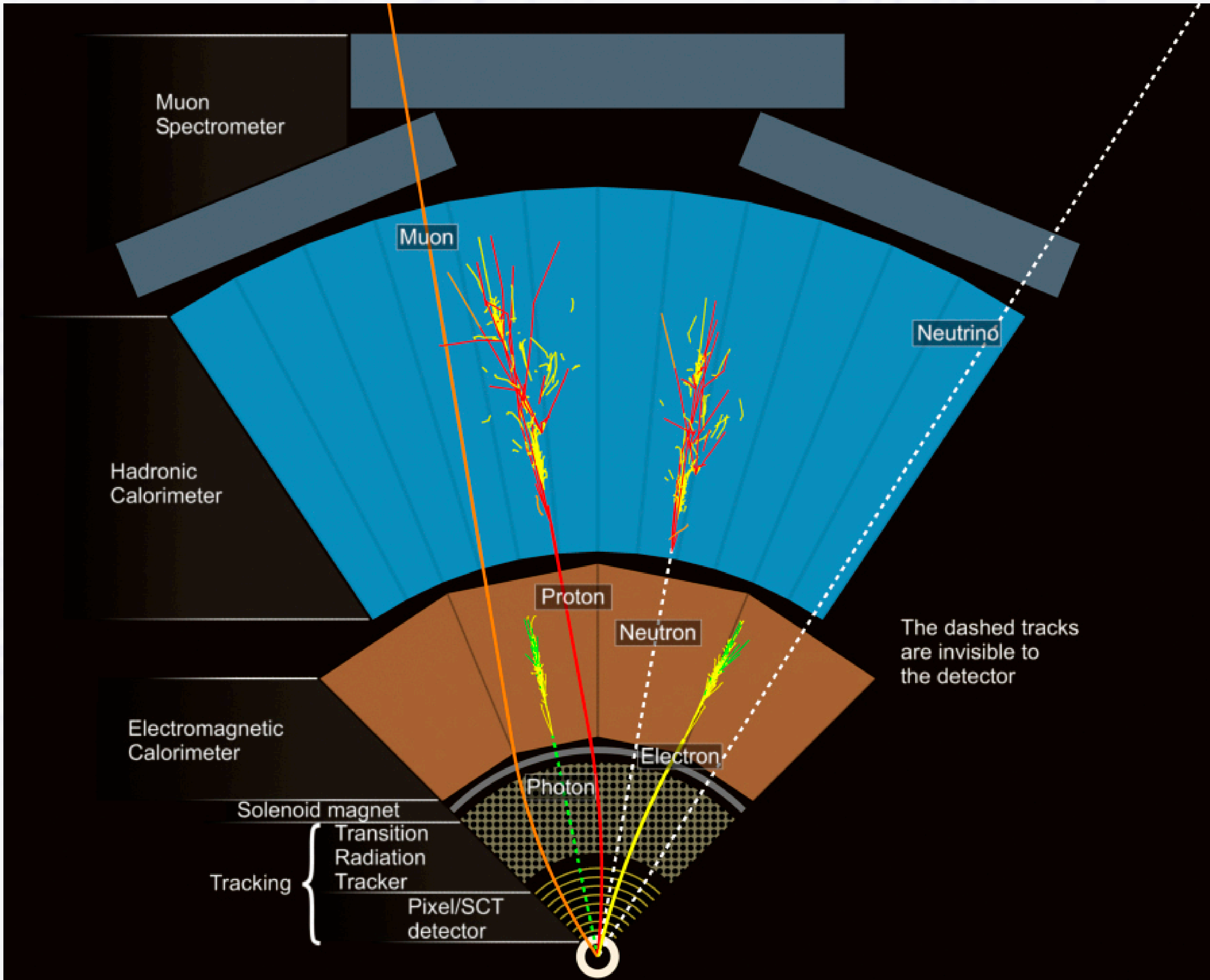
- "full" dΩ coverage
- very restricted access

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 + charge of particle**
- **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)**
  - **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**

A typical Particle Detector

- **Cut-away view of ATLAS: several layers of detectors**



Muon Detector
→ muon ident.
+ muon mom. p
+ charge

Calorimeter
→ energy E

Coil

Tracker
→ momentum p
+ charge

Detector Challenges at LHC

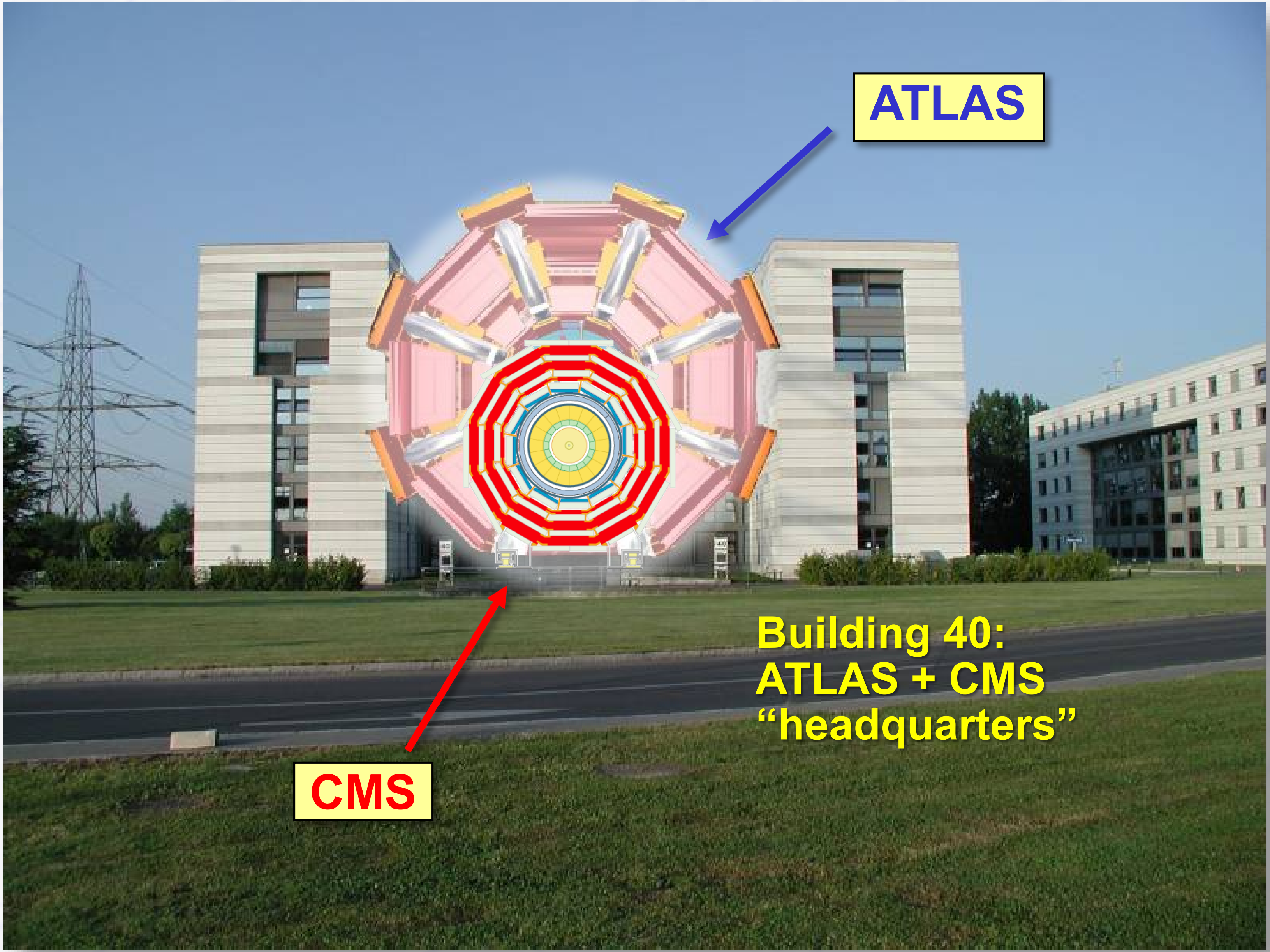
- **High energy collisions**
  - sufficiently **high momentum resolution** up to TeV scale
- **High luminosity (high interaction rate)**
  - **high rate** capabilities, **fast** detectors (25 ns bunch crossing rate)
- **High particle density**
  - **high granularity**, sufficiently **small detector elements** 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...

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

LARGE Detectors

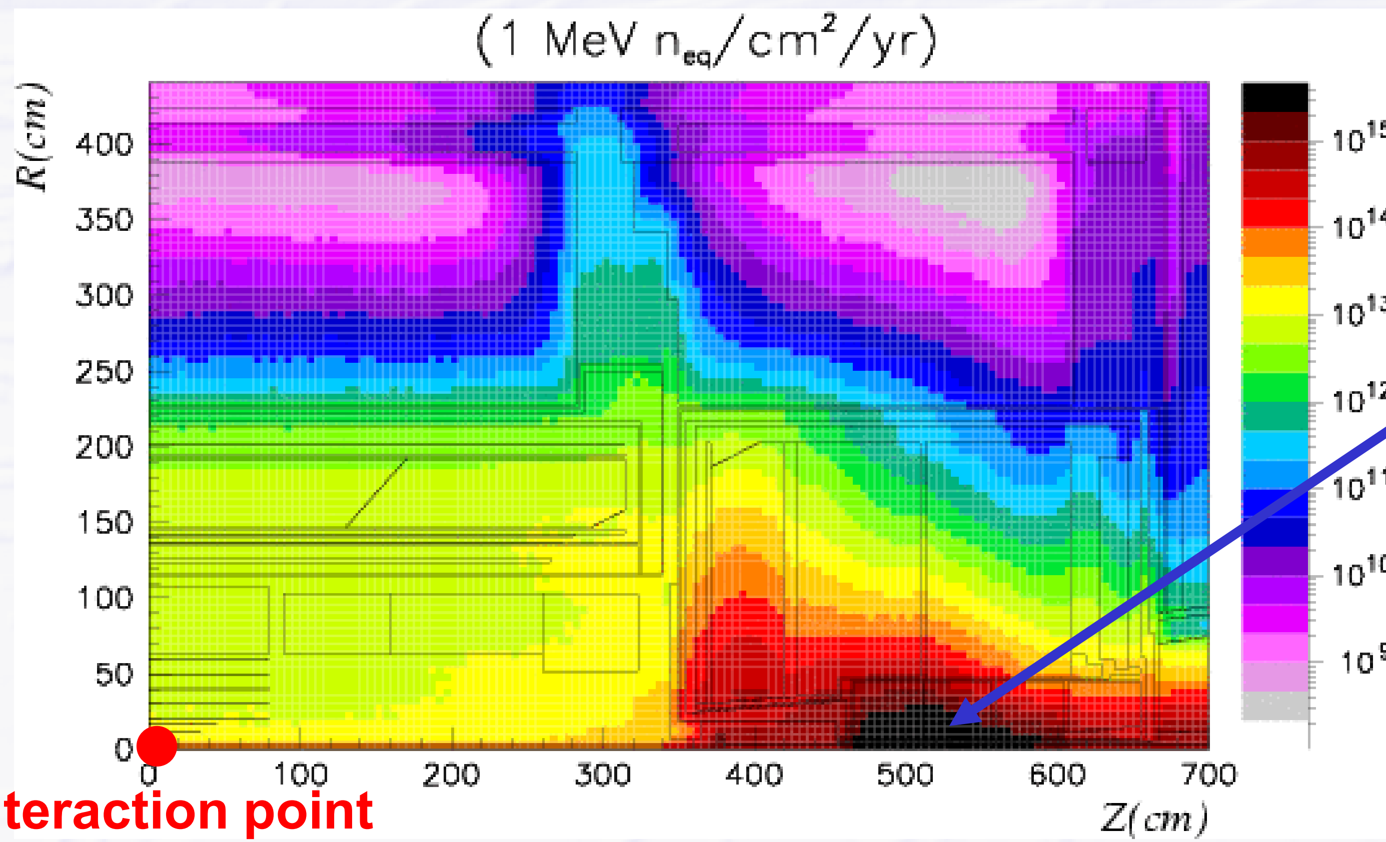
- **Everything is LARGE at the LHC…**



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

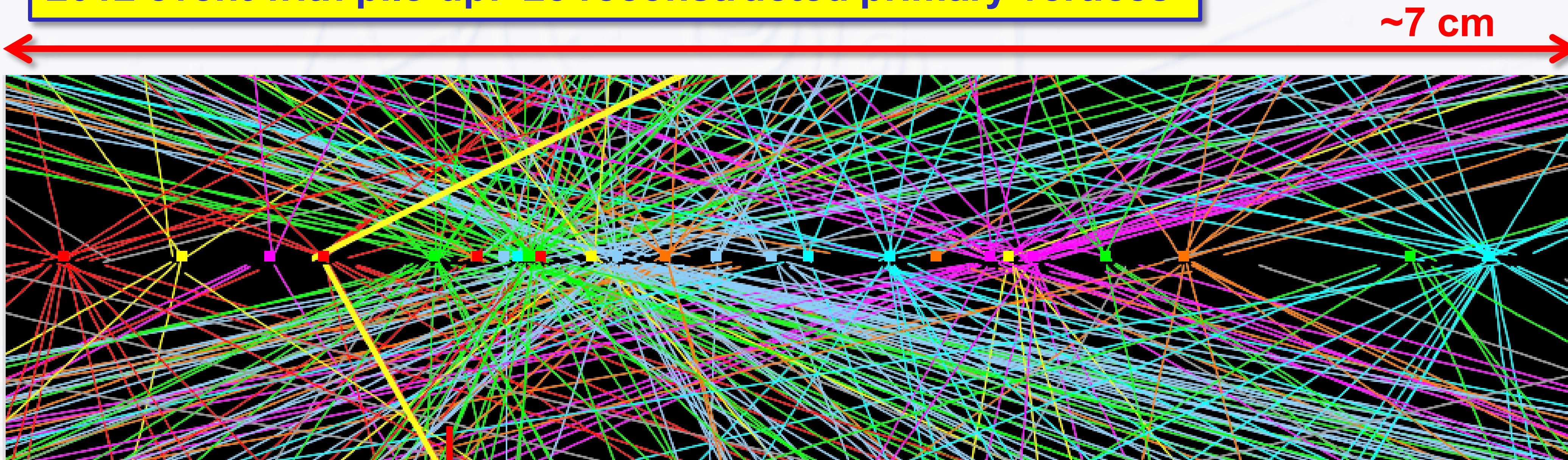


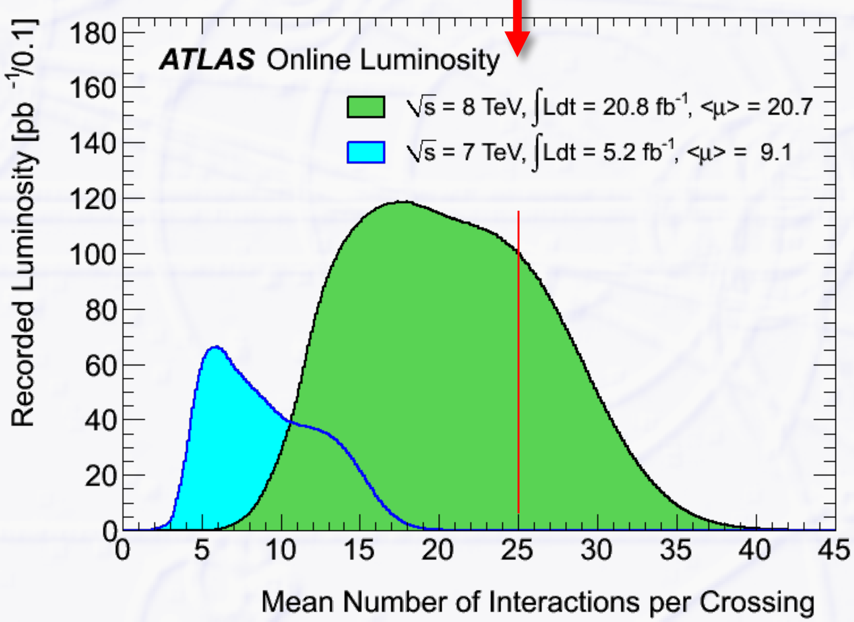
ATLAS neutron fluences:

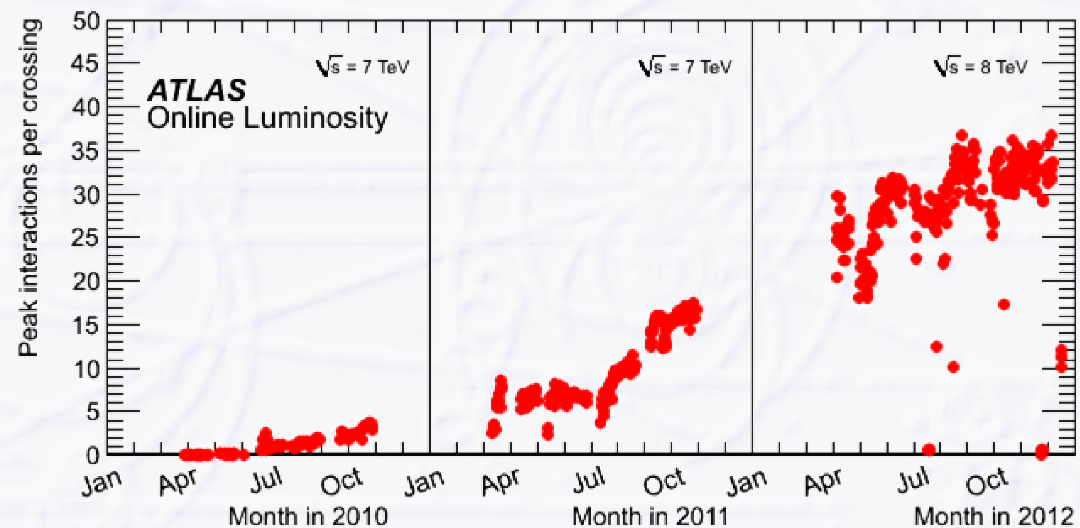
> 10^{15} n/cm²/yr close to beam line

Challenging Conditions: Pile-up

2012 event with pile-up: 25 reconstructed primary vertices







Tracking Detectors

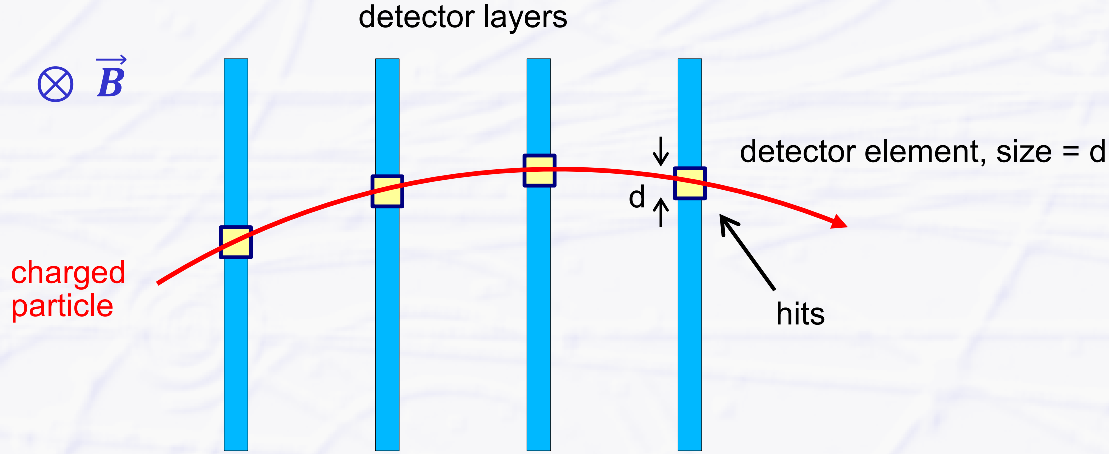
How to measure momentum and charge?

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)

Tracking Detector Principles

- **Typical: several layers of sensitive detector elements**
  - **each layer gives a 2D hit coordinate (+ detector position → 3D)**
- **Magnetic field bends (charged) particle trajectories**



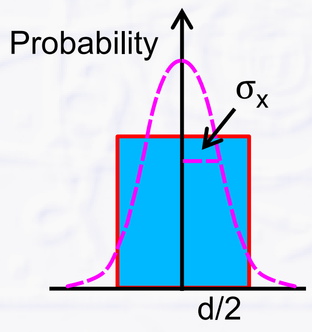
can reconstruct + fit track (radius) with at least 3 hits

- **resolution of each hit depends on size d of detector elements**

→ some uncertainly where the particle passed the detector element d
→ probability distribution is "flat"

→ take the width of an equivalent Gaussian distribution as resolution

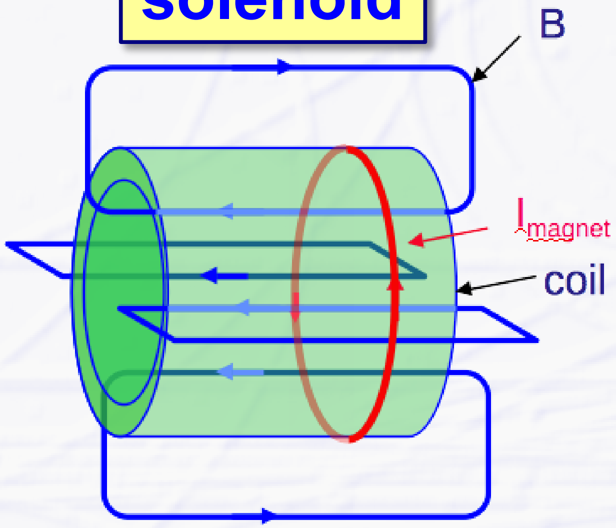
e.g. for d = 30 µm → ~10 µm resolution



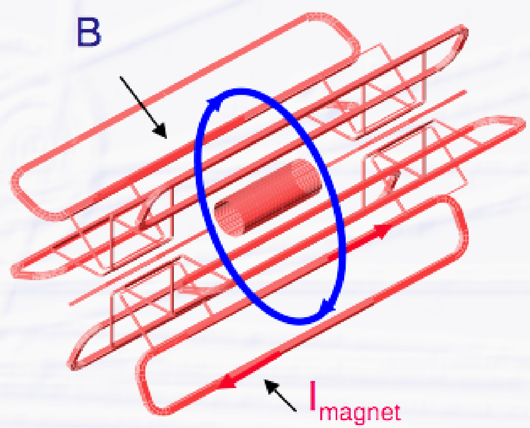
$$\sigma_x \approx \frac{d}{\sqrt{12}}$$

Magnet Concepts at LHC experiments

solenoid



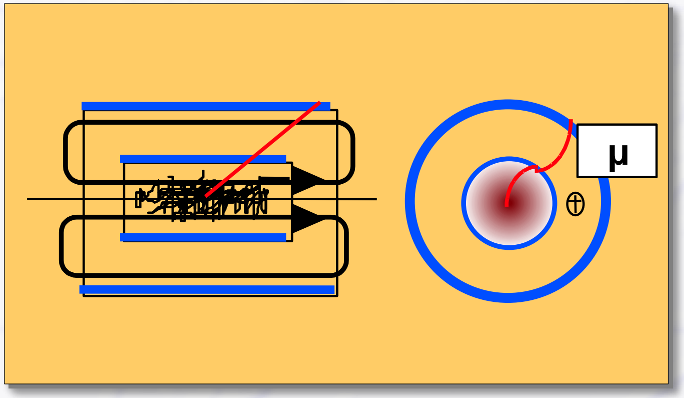
(air-core) toroid



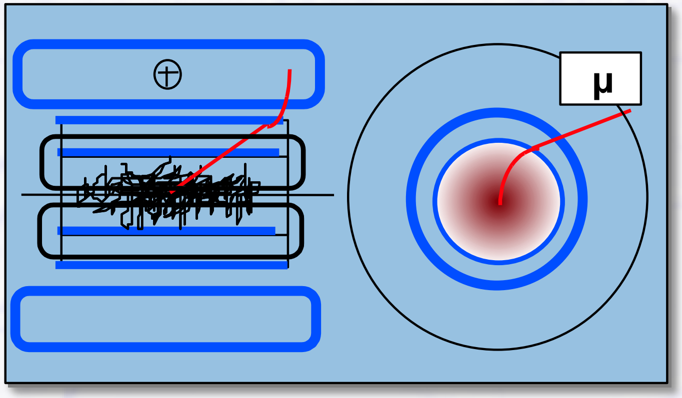
+ large homogenous field inside coil
- needs iron return yoke (magnetic shortcut)
- limited size (cost)
- coil thickness (radiation lengths)

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

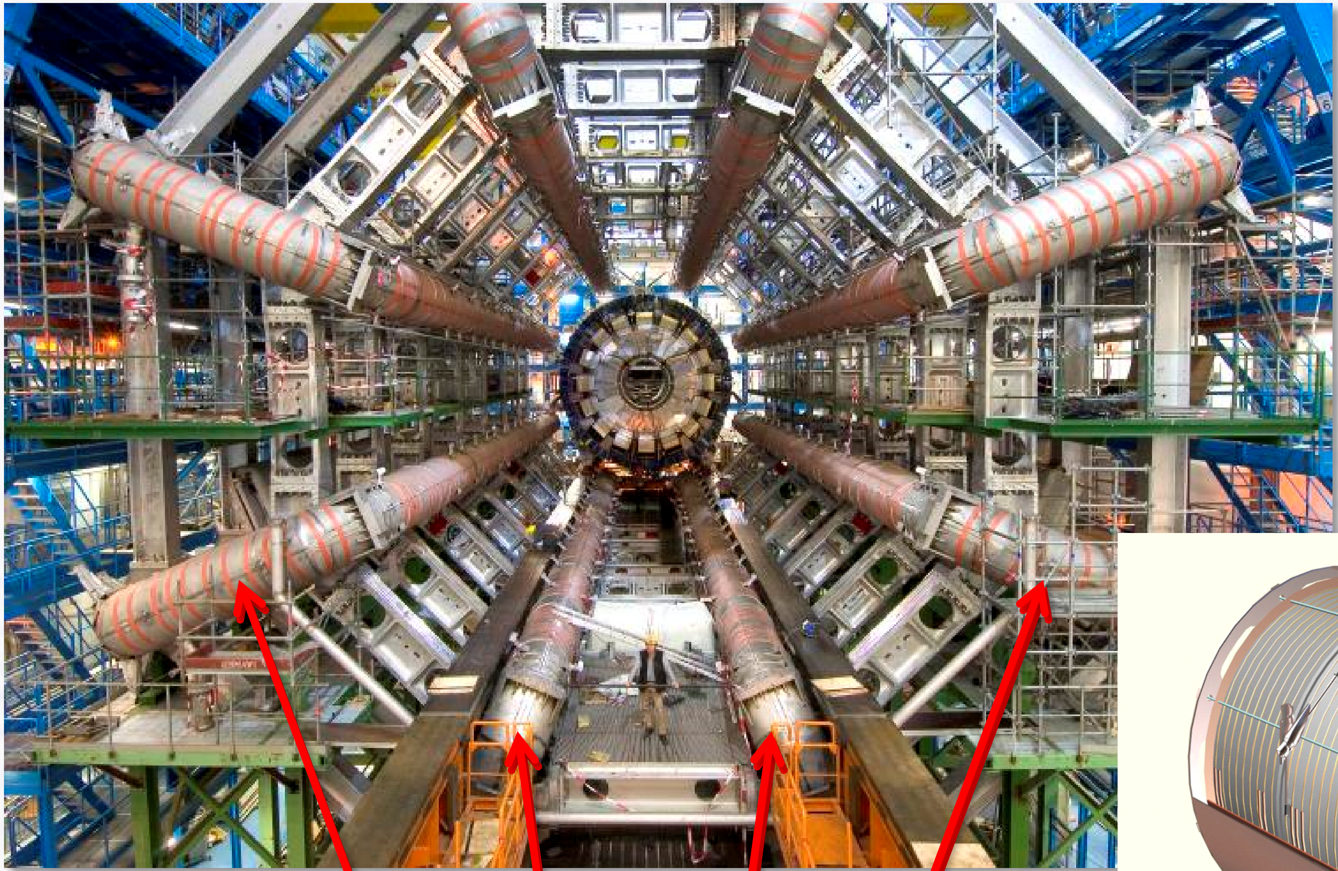
CMS, ALICE



ATLAS



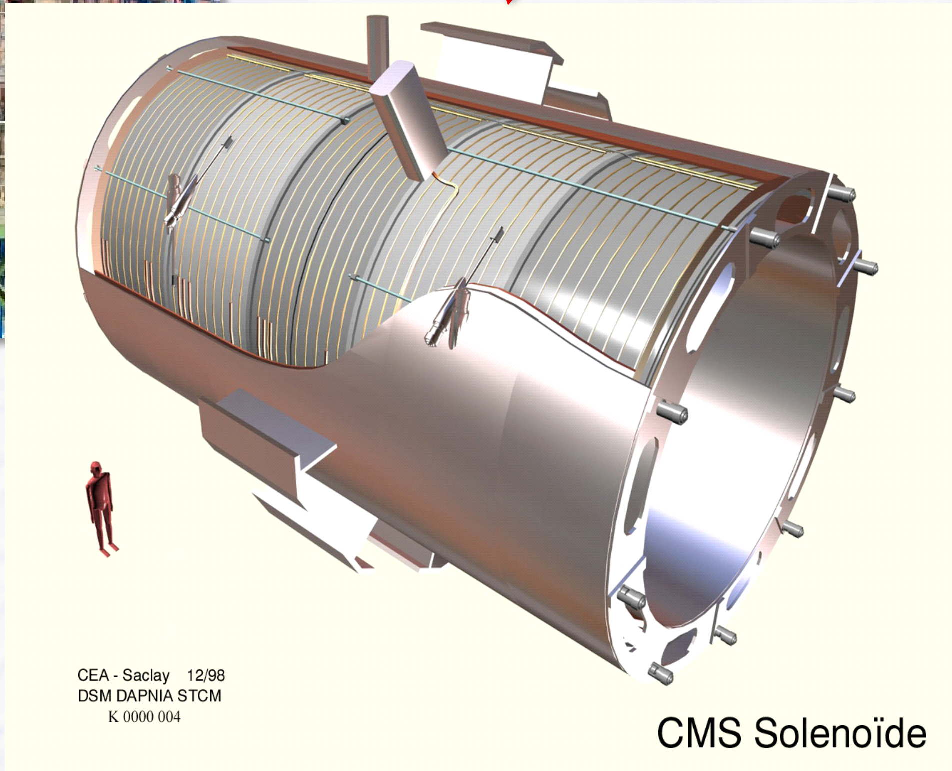
ATLAS and CMS Coils



CMS solenoid
(5 segments)

ATLAS barrel toroid coils

autumn 2005



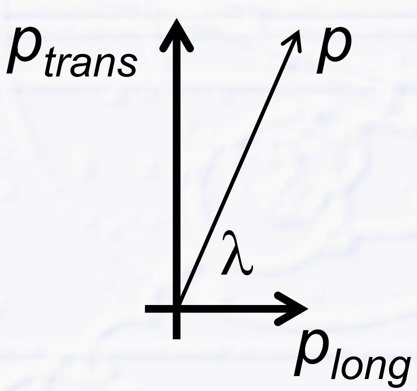
Momentum Measurement

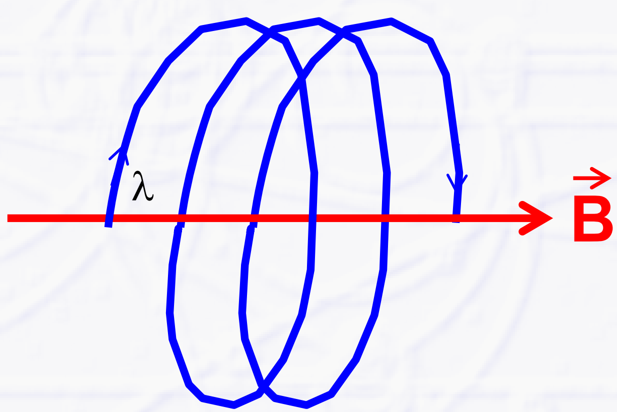
- (Only) charged particles are deflected by magnetic fields
  - homogeneous B-field → particle follows a circle with radius r

$$p_t[GeV/c] = 0.3 \cdot B[T] \cdot r[m]$$

measurement of p_t by measuring the radius

  - this is just the momentum component perpendicular to the B-field = **transverse momentum p_t**
  - no particle deflection parallel to magnetic field
  - if particle has **longitudinal momentum** component → particle follows a **helix**



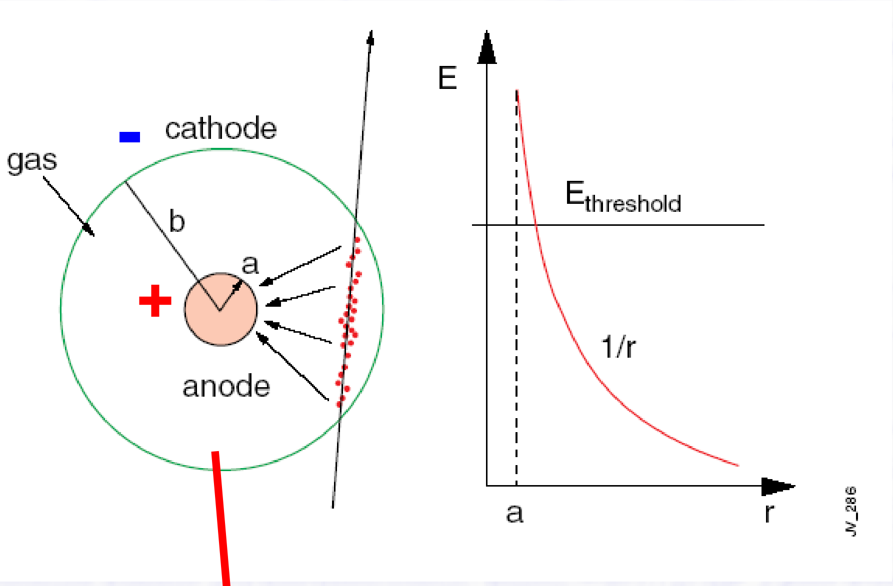


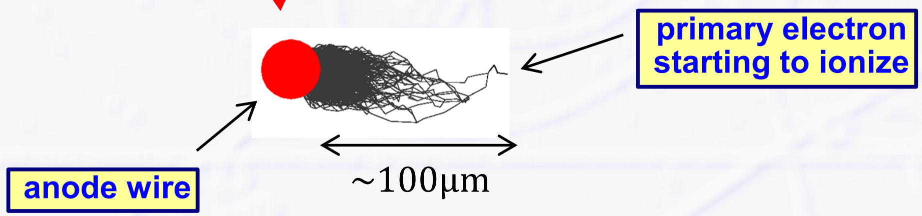
total momentum p to be measured by dip angle λ

$$p = \frac{p_t}{\sin \lambda}$$

Basic Gaseous Detector – Geiger-Müller Tube

- **Geiger-Müller tube by Hans Geiger and Walther Müller 1928**
  - tube filled with inert gas (He, Ne, Ar) + organic vapour (e.g. CH_4) or CO_2
  - central thin wire (20 – 50 μm ∅) , high voltage (several 100…1000 Volts) between wire and tube





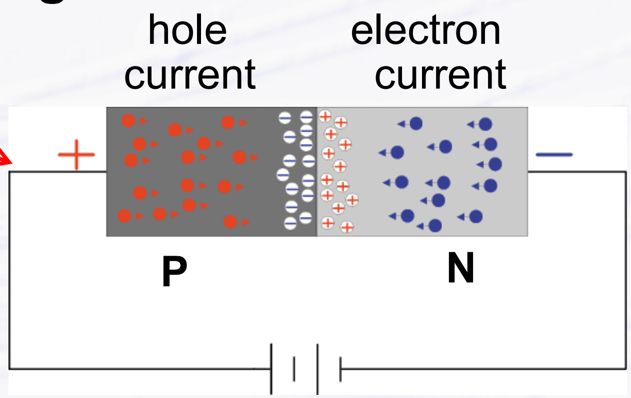
- strong increase of E-field close to the wire
  - electron gains more and more energy
- above some threshold (>10 kV/cm)
  - electron energy high enough to ionize other gas molecules
  - newly created electrons also start ionizing
- avalance effect: exponential increase of electrons (and ions)
  - measurable signal on wire
  - organic substances or CO_2 responsible for "quenching" (stopping) the discharge
    - absorption of UV photons

Solid State Detectors

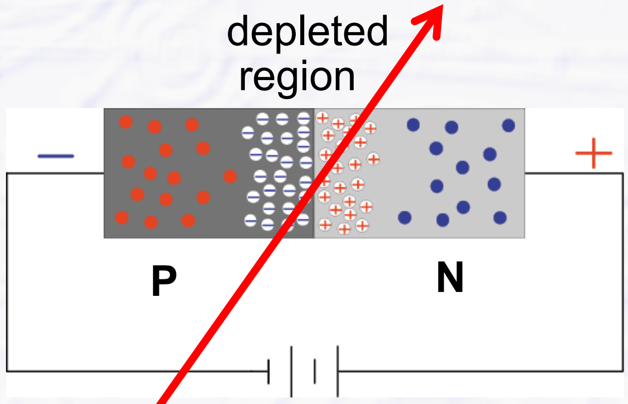
- **Basic element of a solid state (silicon) detector is... a diode**
  - **p-type and n-type doped silicon material is put together**

more holes **more electrons**

Current flow through diode if connected like this



  - **for use as particle detector diode needs to be connected in opposite way**



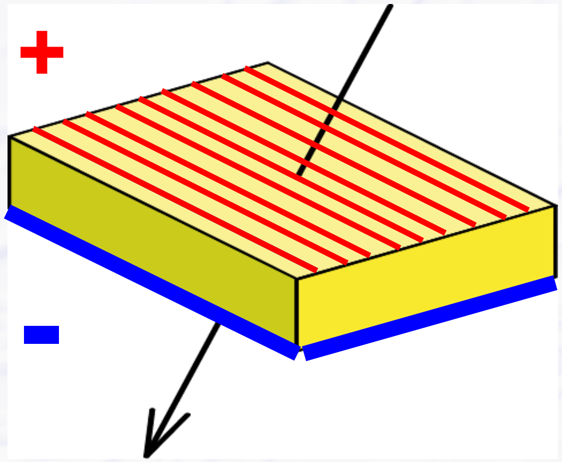
- **around junction of p- and n-type material depletion region is created**
  - **zone free of charge carriers**
    - **no holes, no electrons**
    - **thickness of depletion region depends on voltage, doping concentration**

charged particle can create new electron/hole pairs in depletion area sufficient to create a signal

typically 20'000 – 30'000 electron/hole pairs in 300 μm thick material

Silicon Strip Detectors

- Now take a large Si crystal, e.g. 10 x 10 cm^2, 300 µm thick

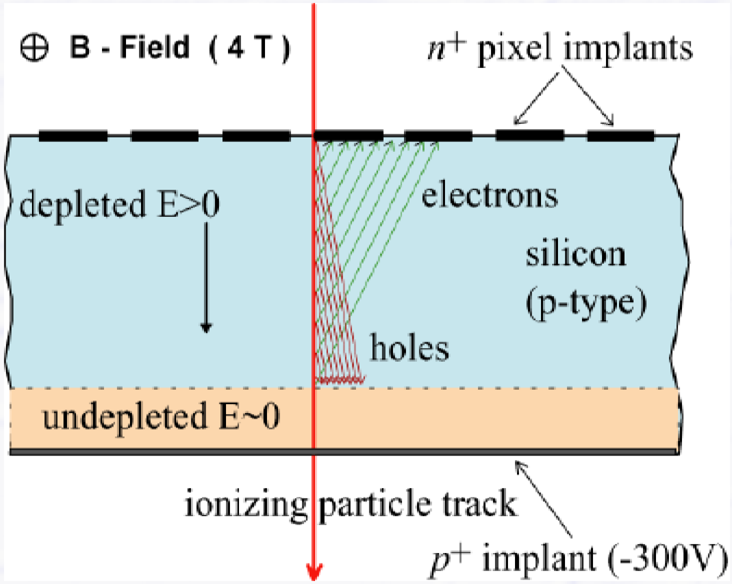


make bottom layer p-type

and subdivide the top n-type layer into **many strips with small spacing**

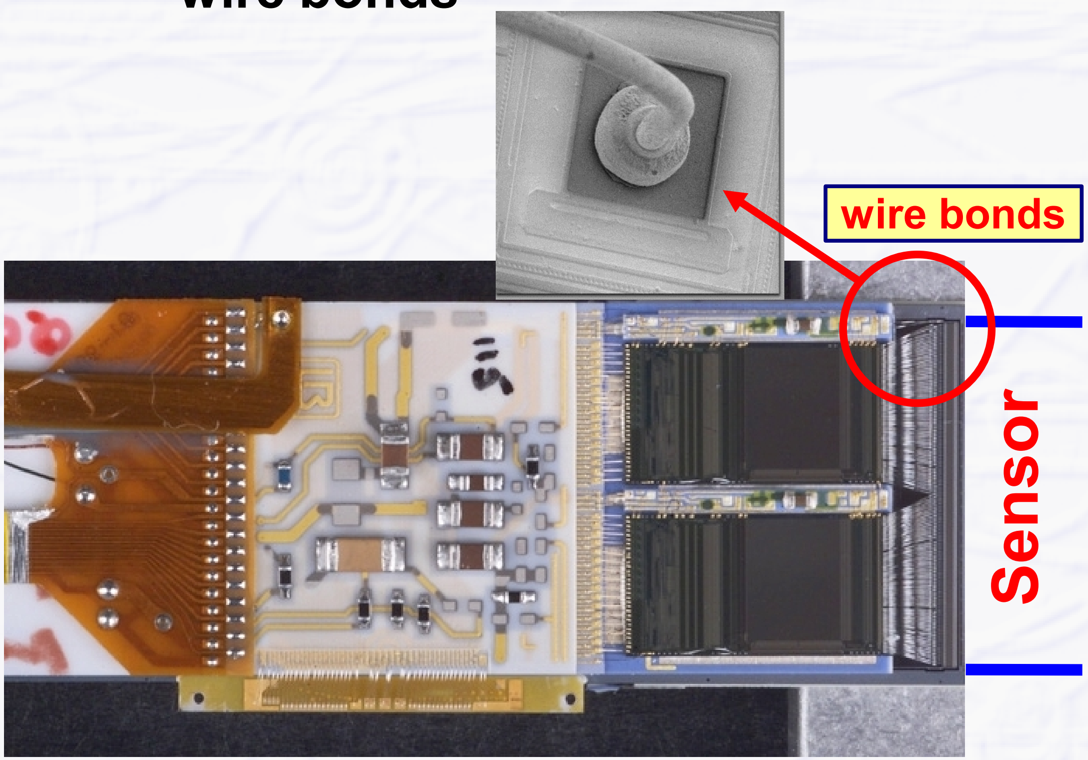
→ **many diodes next to each other with position information (strip number)**

- Advantage compared to wire/gas detectors
  - strip density (pitch) can be rather high (e.g. ~20 µm)
    - high single point accuracy: σ_x = 20 µm / √12 = 5.8 µm
    - but also many electronics channels

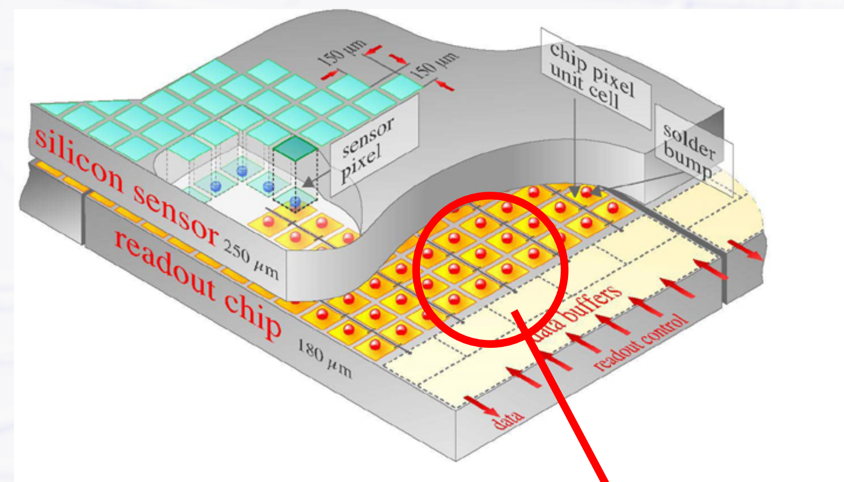


Si-Detector Electronics and Si-Pixels

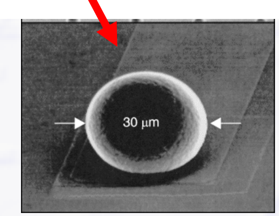
- **Silicon strip detectors have a laaaarge number of electronics channels, ~10^7 each for ATLAS and CMS Si trackers**
  - **requires highly integrated chips for amplification, shaping, zero suppression (only information of strips with signals is read-out) and multiplexing (put all strip signals on a few cables only)**
  - **→ electronics is directly connected to the sensor (the "multi-diode") via wire bonds**



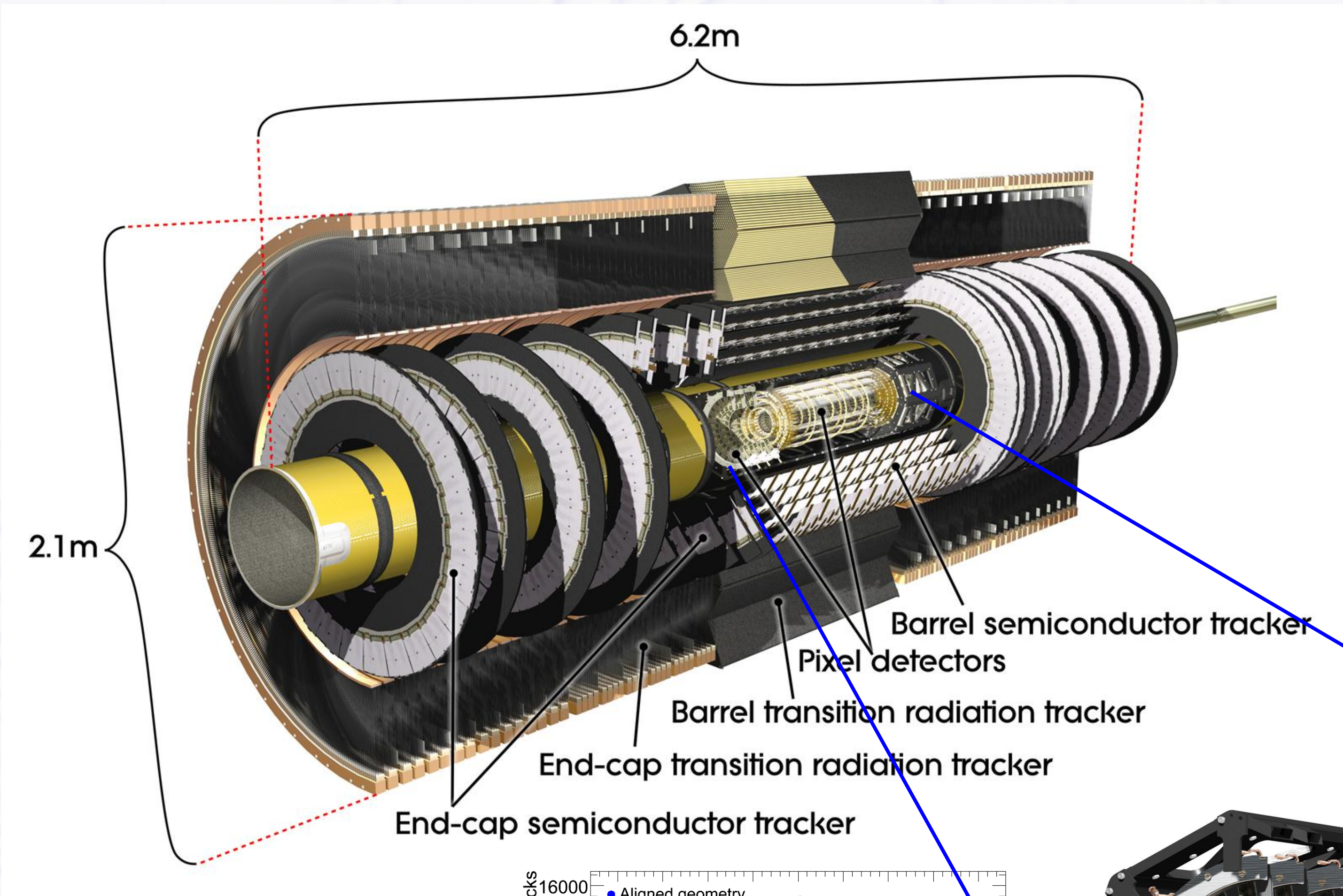
Si-strip detectors provide only 1 coordinate, Pixel detectors are 2D detectors



Pixel detector need "bump" bonding and have even more channels, ~10^8 - 10^9

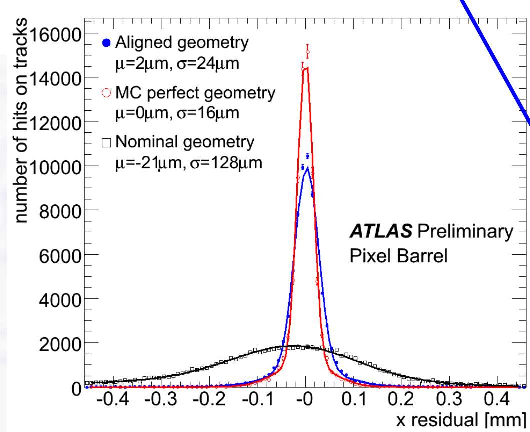


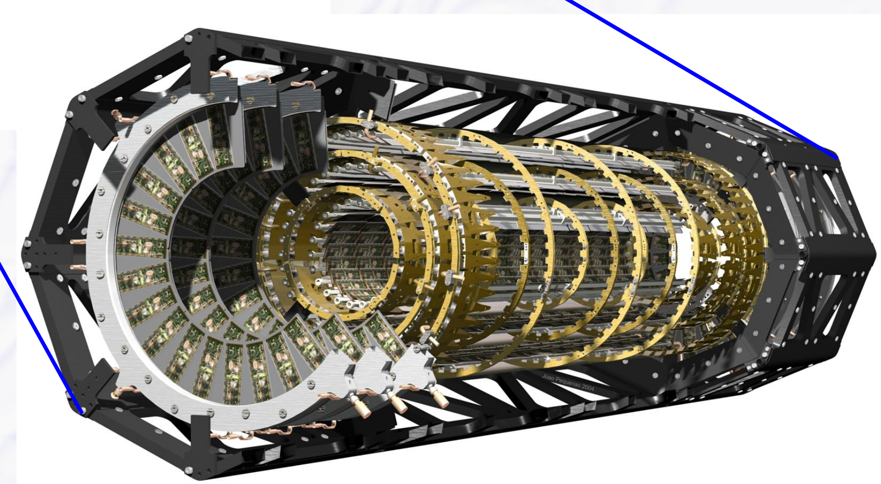
ATLAS Inner Tracker



- **4-layer Si Pixel**
  - **3 → 4 layers in 2014**
- **4-layer Silicon Strips**
- **Transition Radiation Tracker (gaseous)**

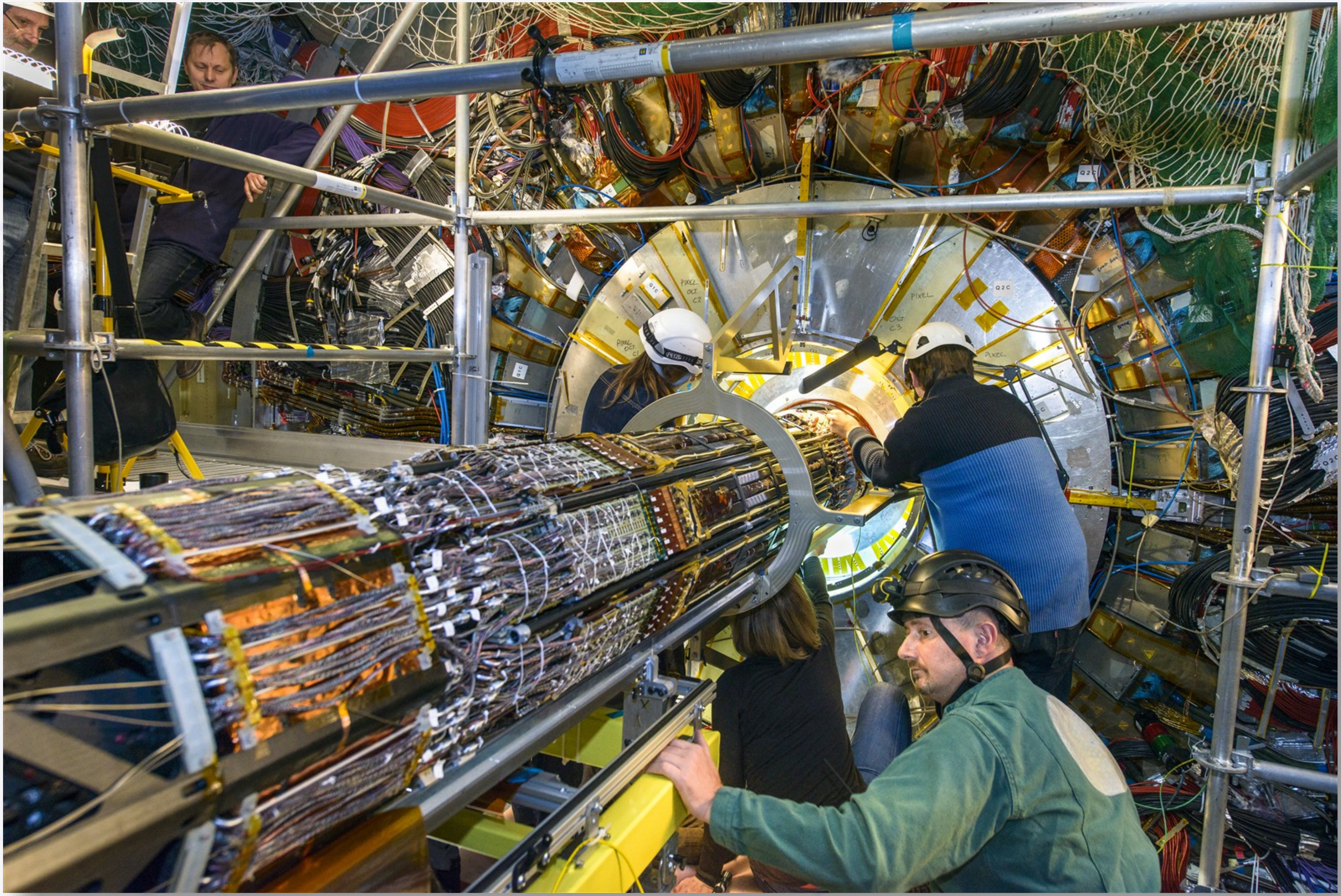
Pixel alignment with cosmic rays 2008



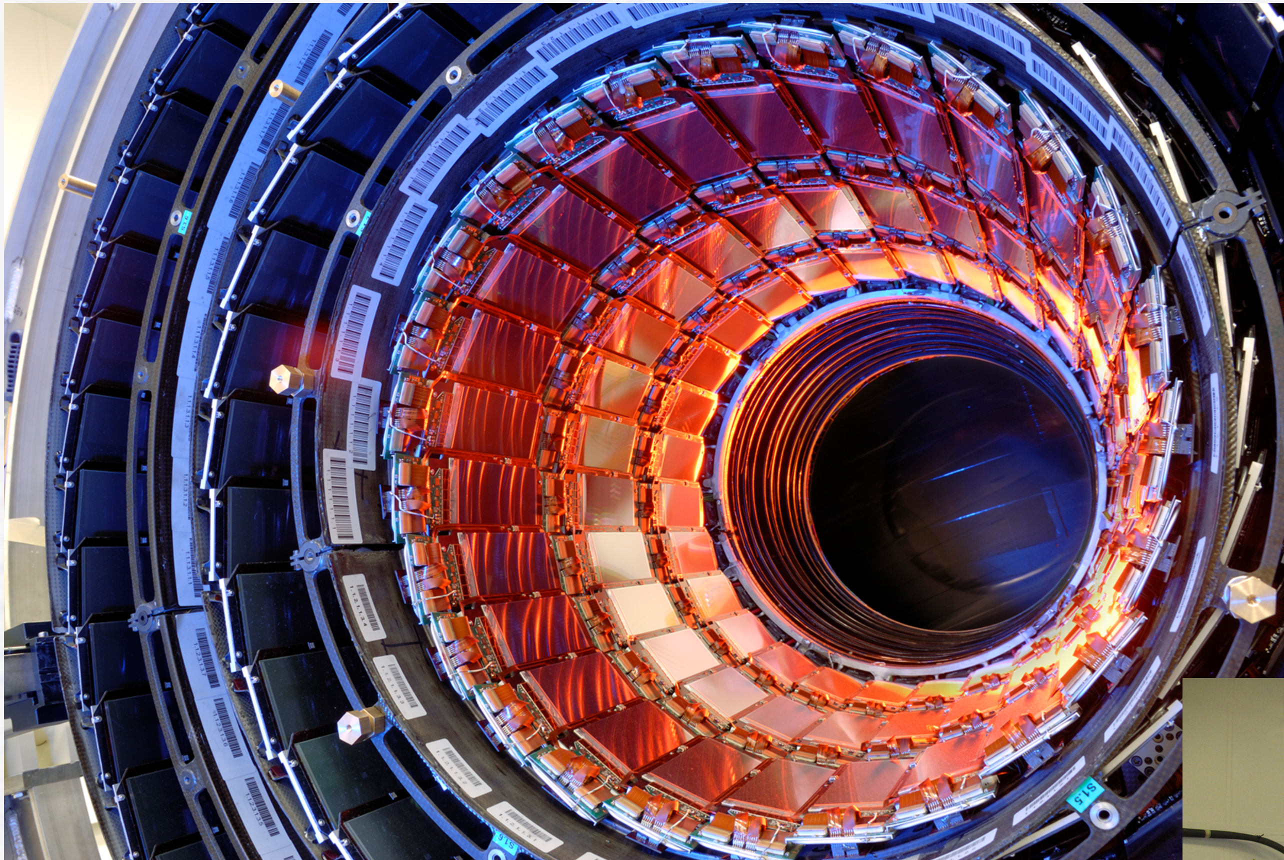


The ATLAS Pixel Detector

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

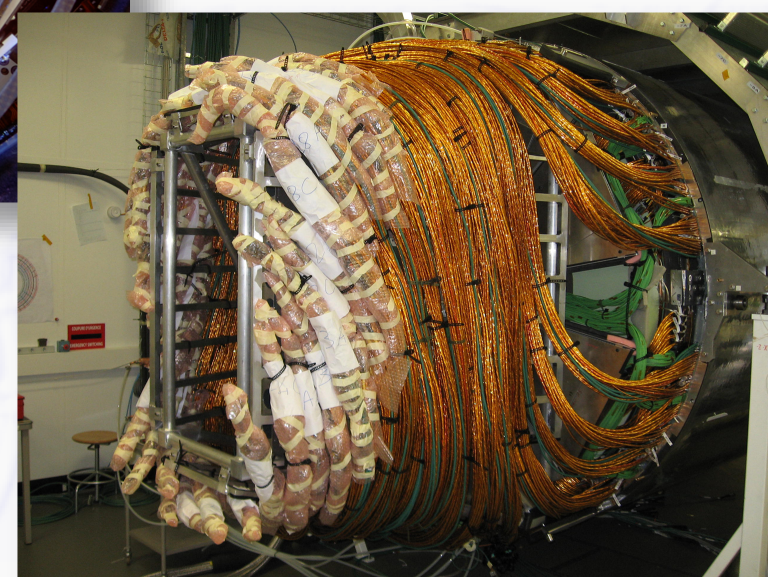


CMS Full Silicon Tracker



Tracker Inner Barrel TIB

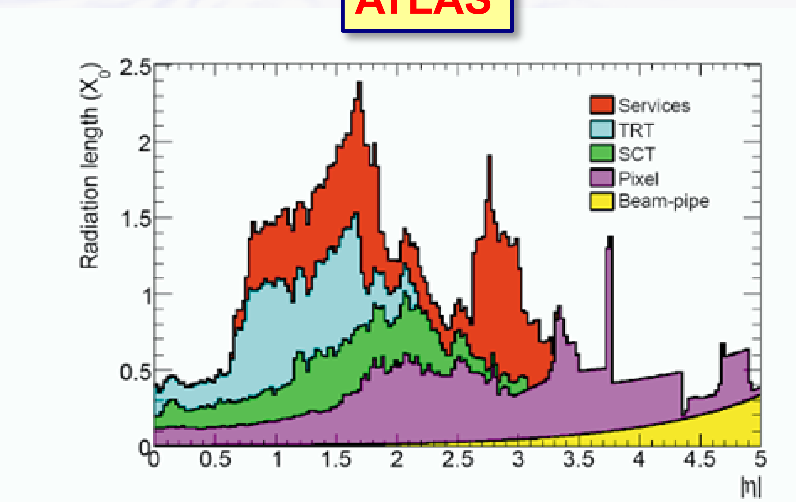
- 4-layers Si Pixel
  - 3 → 4 layers in 2017
- 10-layers Silicon Strips
  - 210 m^2, largest silicon detector ever built



Material Budget

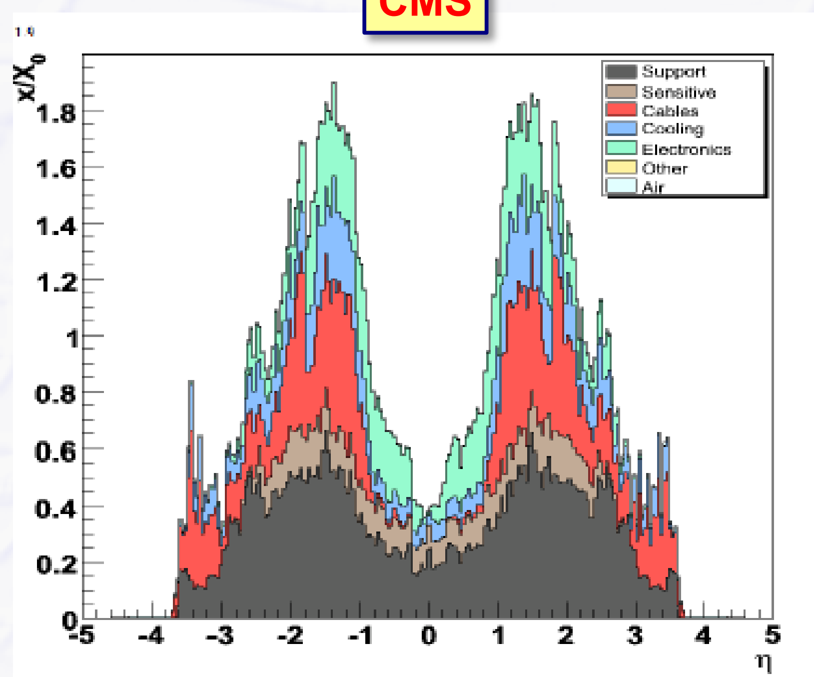
- **Tracking Detectors should be light-weighted and thin**
  - multiple scattering by material degrades resolution at low momenta
  - unwanted photon conversions in front of calorimeters
  - material often very inhomogeneous (in particular Si detectors)
- **Power & cooling adds most of the material**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

ATLAS



$\lvert\eta\rvert$	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

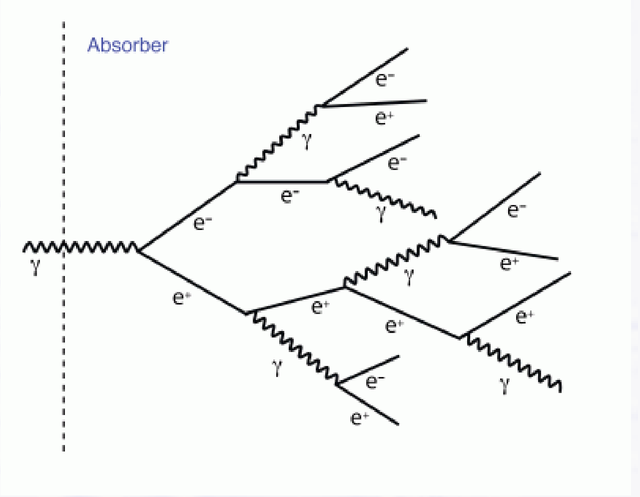


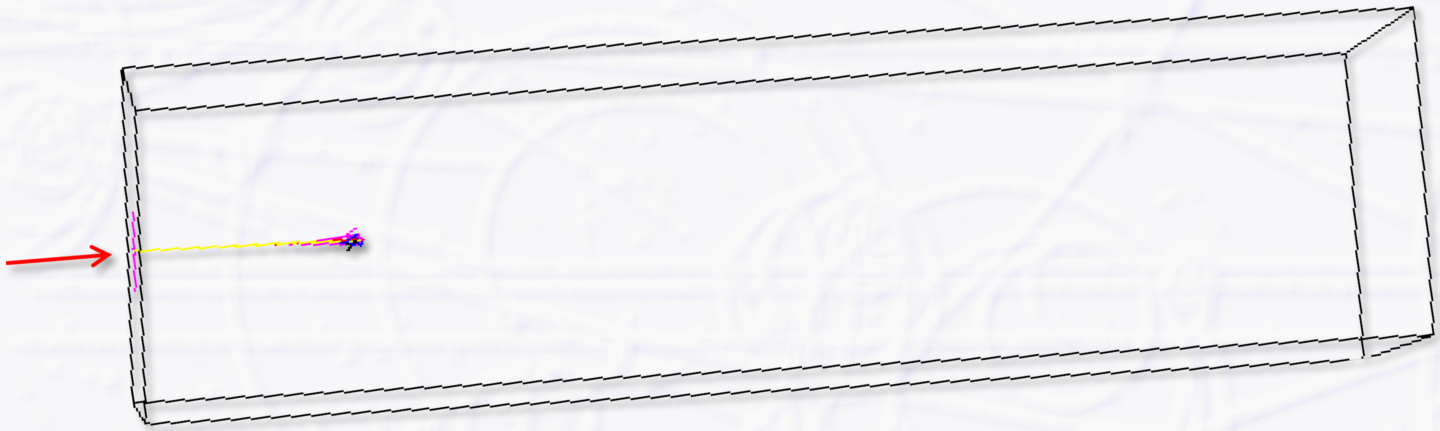
Calorimeters

How to measure energy?

Particle Showers in Calorimeters

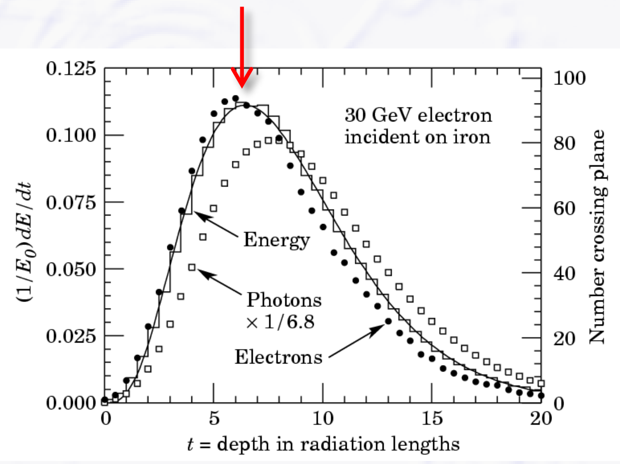
- Initial particle creates electro-magnetic shower of secondary particles (electrons, positrons, photons) in dense material
  - by bremsstrahlung and pair production
  - shower depth depends on radiation length X_0 (characteristic material constant)
    - for $e^{\pm}$ = length after all but 1/e of energy lost by Bremsstrahlung
    - for γ = 7/9 of mean free path length for pair production





80 GeV electron in lead glass block

shower maximum



energy profile

Energy Resolution of Calorimeters

- **Number of particles in shower is proportional to energy of initial particle** $N_{shower} \propto \frac{E}{E_c}$ ← Critical Energy (typically ~10 MeV)
  - **error of energy measurement determined by (statistical) fluctuations in the number of shower particles** $\sigma_{N_{Shower}} \propto \sqrt{N_{Shower}}$
  - **resulting relative energy measurement error is** $\frac{\sigma_E}{E} \propto \frac{1}{\sqrt{E}}$
- **More contributions from detector inhomogeneities and electronic noise**

$$\frac{\sigma_E}{E} \propto \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

convolution ($\oplus$)

stochastic (statistic) term (a): number of shower particles

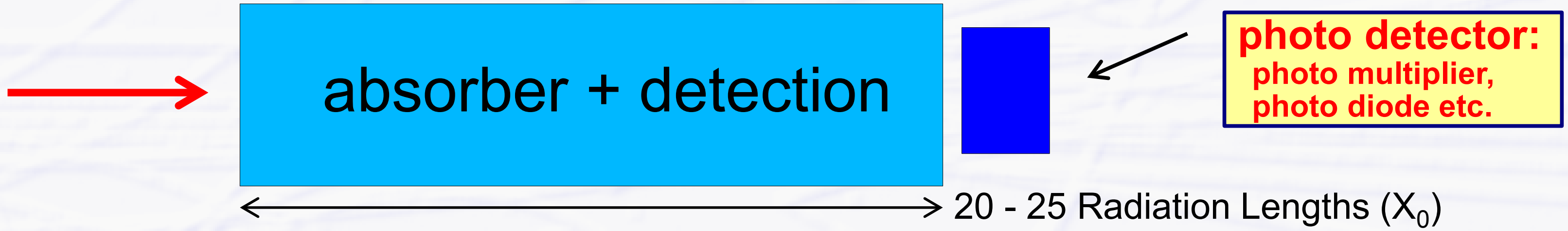
constant term (b): inhomogenities, non-linearities

noise term (c): electronics noise

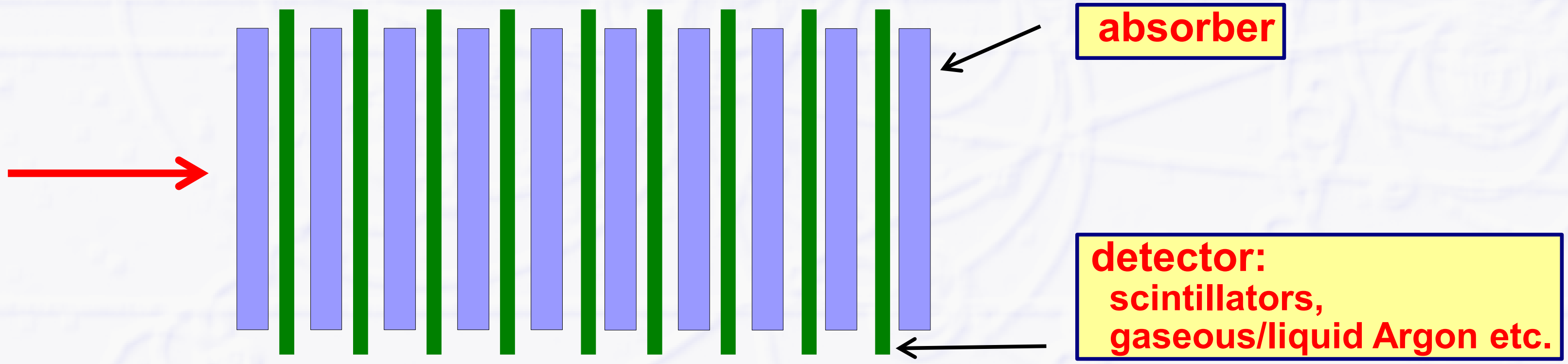
relationship valid for all types of calorimeters (homogeneous + sampling, electromagnetic and hadronic)

Calorimeter Concepts

- **Homogeneous calorimeters (e.g. CMS)**
  - **absorber material (generation of the shower) = detector material**
    - **typically an electromagnetic shower is created in an optical transparent absorber, photons created in the shower are collected and detected with some photo detector**

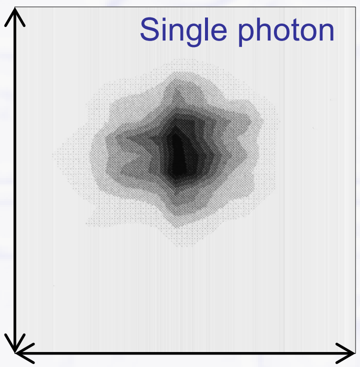


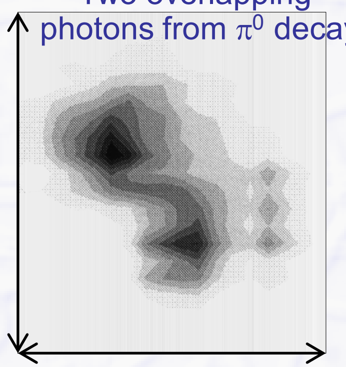
- **Sampling calorimeters (e.g. ATLAS)**
  - **passive (heavy) absorber material (iron, copper, lead, tungsten, uranium) interleaved with active detector material**



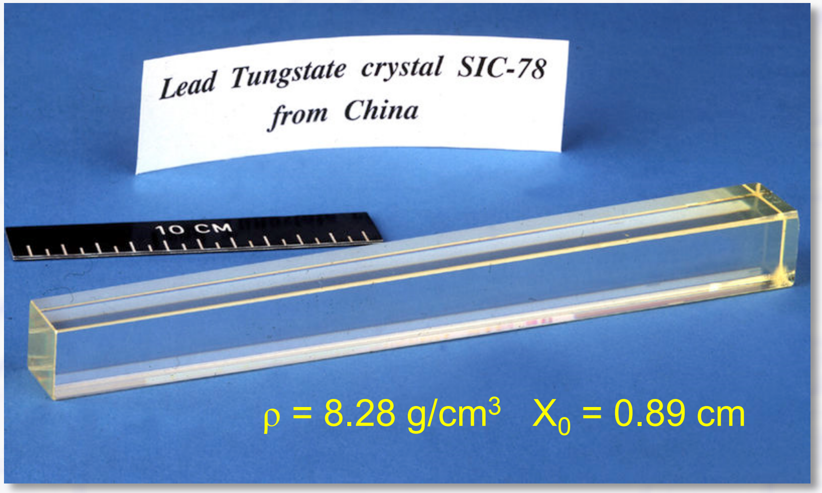
CMS: Homogeneous EM Calorimeter

- **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**





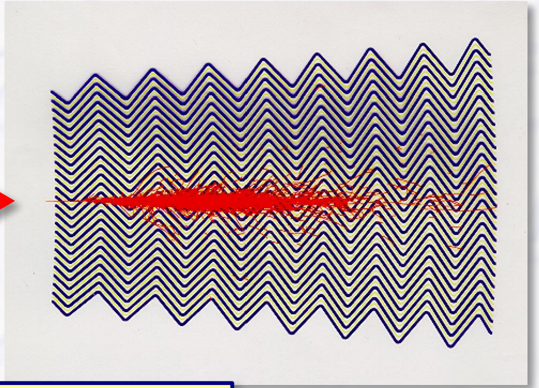
CMS $PbWO_4$ crystal



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

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

- **Measure energy of heavy hadronic particles: π, K, p, n, …**
- **Energy resolution much worse than for el.-magn. calorimeters**
  - shower created by nuclear interactions (hadronic shower, fewer particles in shower)
  - usually only a few nuclear interaction lengths 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

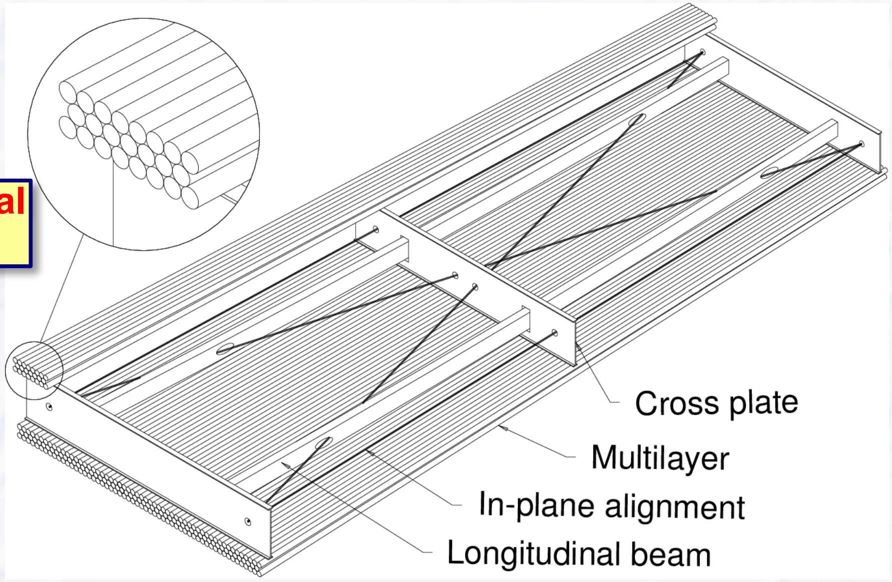
CMS

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

ATLAS Muon Detector Elements

Aluminum tubes with central wire filled with 3 bar gas



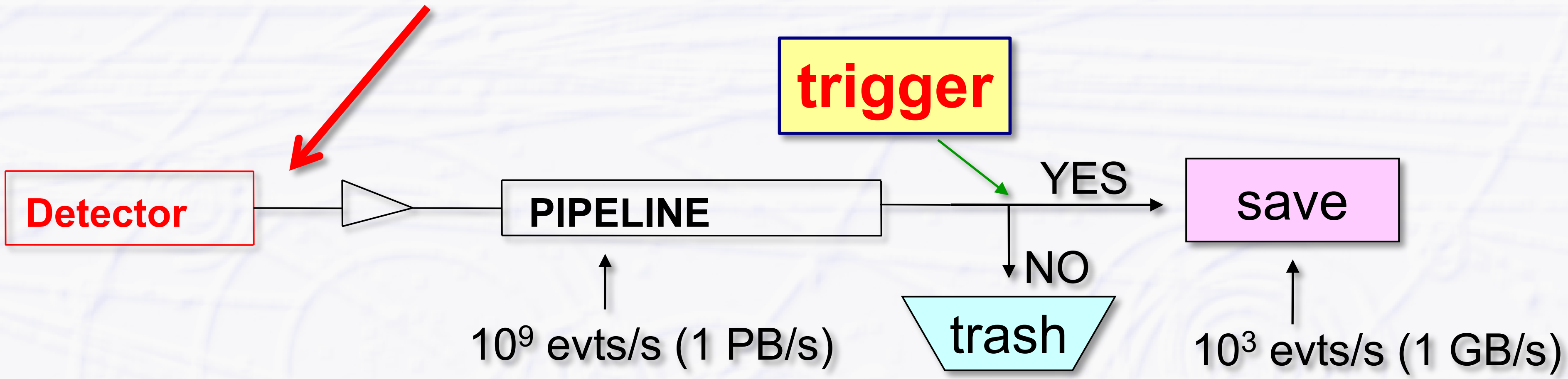
ATLAS Detector Status

(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%

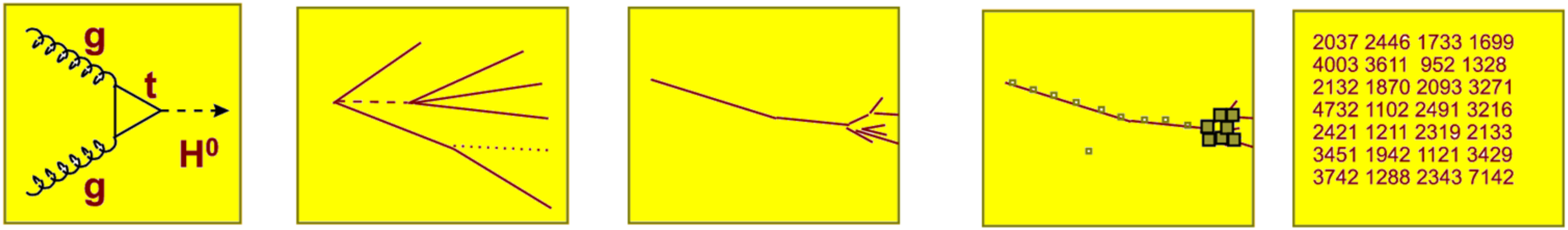
How to Select Interesting Events?

- **Bunch crossing rate: 40 MHz, ~20 interactions per BX** (**10^9 evts/s**)
  - **can only record ~1000 event/s (1 MB each), still ~1 GB/s data rate**
- **Need highly efficient and highly selective TRIGGER**
  - **raw event data (1 PB/s) are stored in pipeline until trigger decision**



- **ATLAS + CMS triggers have 2 levels**
  - **Level-1: hardware (FPGAs), ~3 μs decision time, 40 MHz → 100 kHz**
  - **Level-2: software (computer farm), ~4 s decision time, 100 kHz → 1 kHz**

From Physics to Raw Data



Basic physics

Collision Point

Fragmentation, Decay

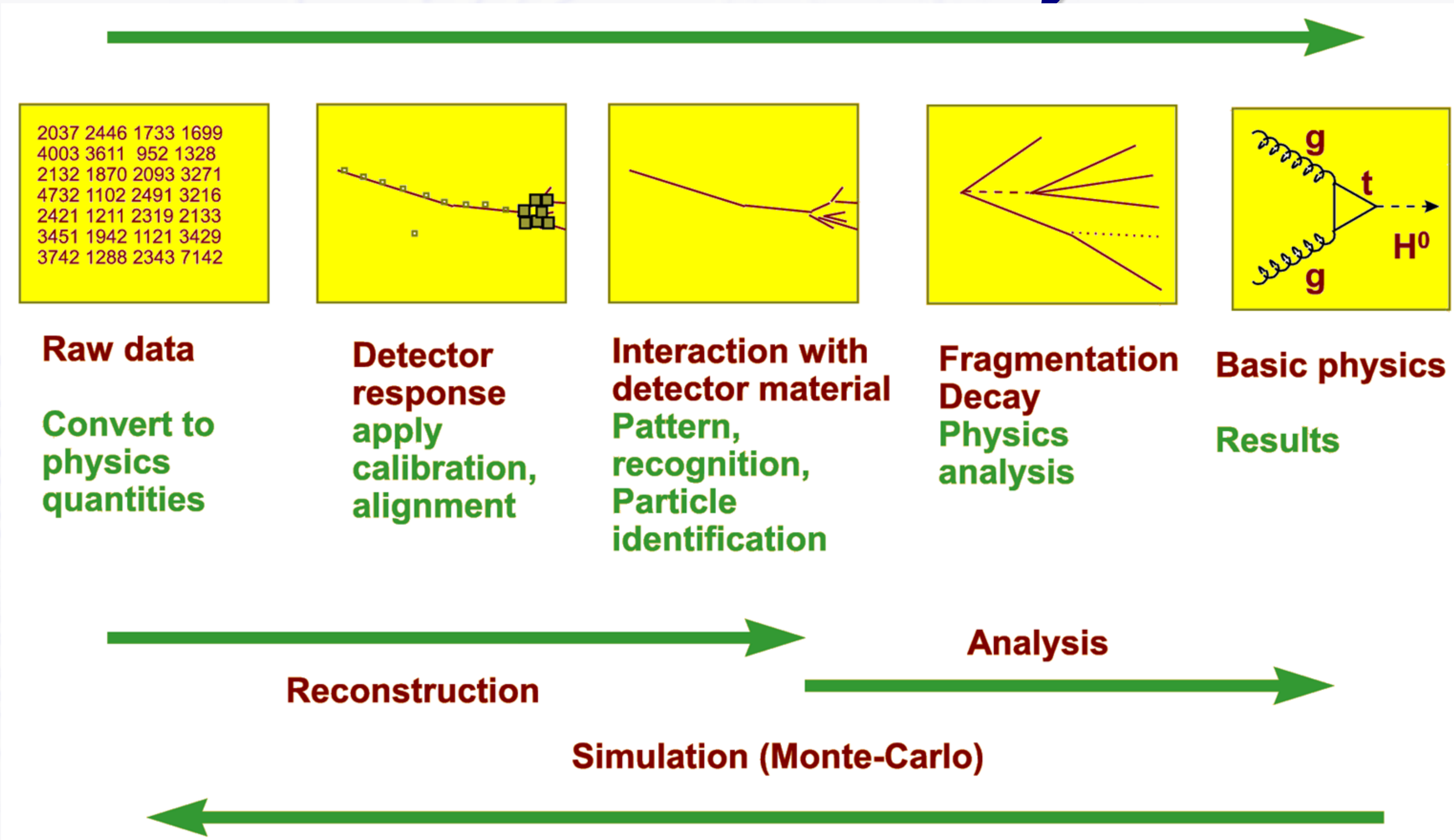
Interaction with detector material
Multiple scattering, interactions

Detector response
Noise, pile-up, cross-talk, inefficiency, ambiguity, resolution, response function, alignment

Raw data
Read-out addresses, ADC, TDC values, Bit patterns

- **Actually recorded are raw data with ~1 GB/s for ATLAS/CMS**
  - **mainly electronics numbers**
    - **e.g. number of a detector element where the ADC (Analog-to-Digital converter) saw a signal with x counts...**

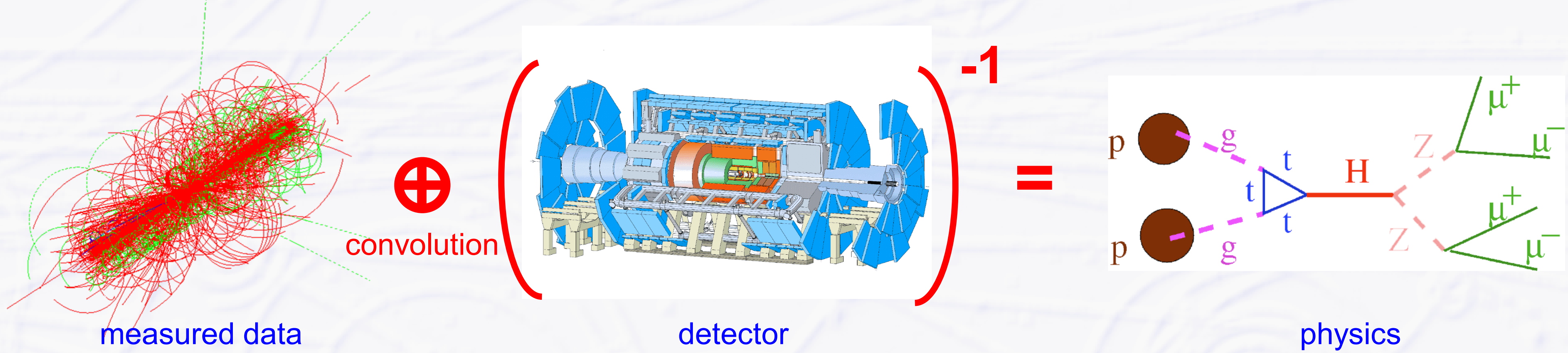
From Raw Data To Physics



- **We need to go from raw data back to physics**
  - **reconstruction + analysis of the event(s)**

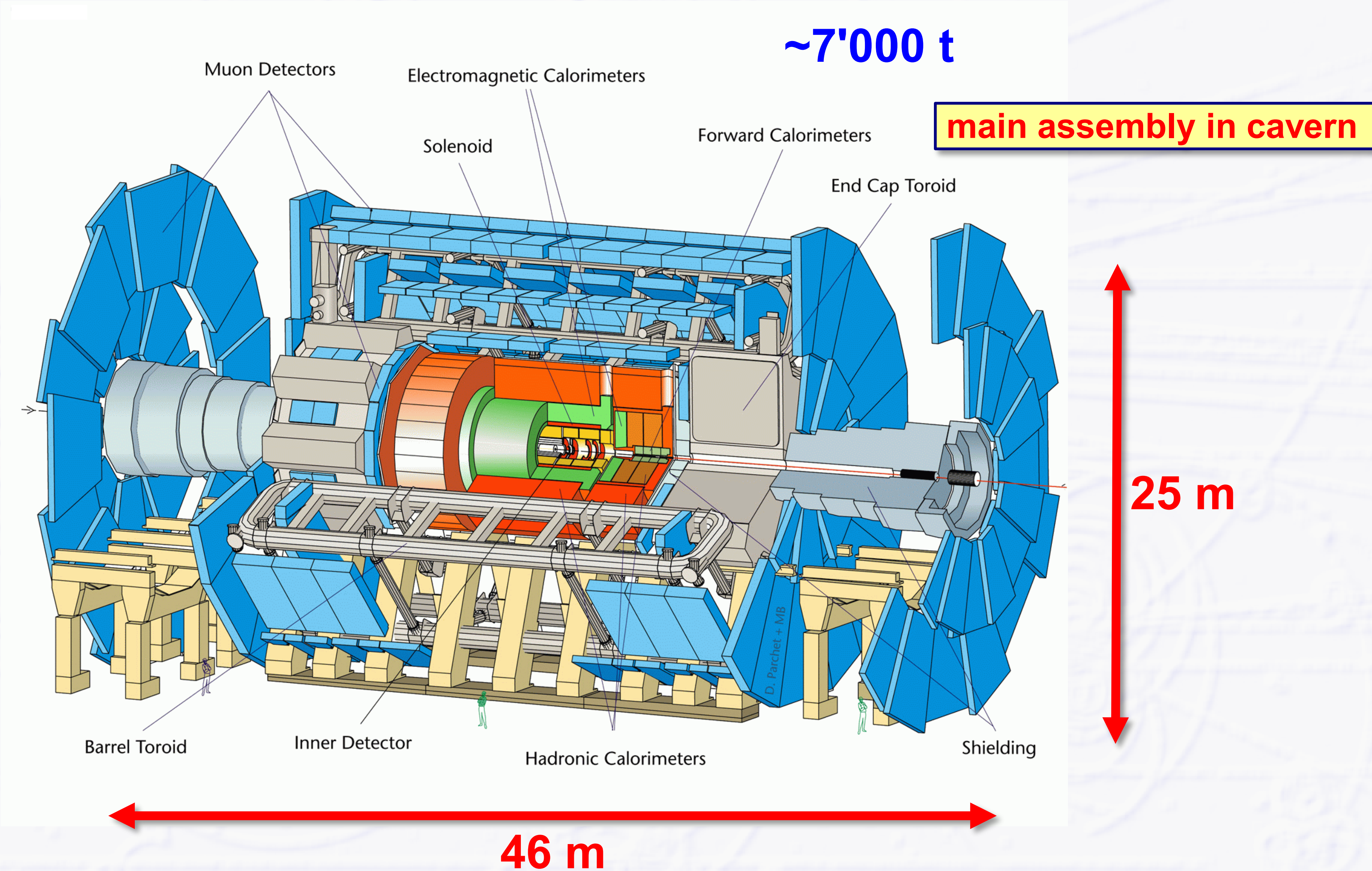
Simulation (Monte Carlo)

- **Even with best calibration + alignment**
  - **some detector influence, e.g. efficiency for track reconstruction etc. will not be known well enough from data**
  - **Use detector simulation (Monte Carlo) to “unfold” detector influence**



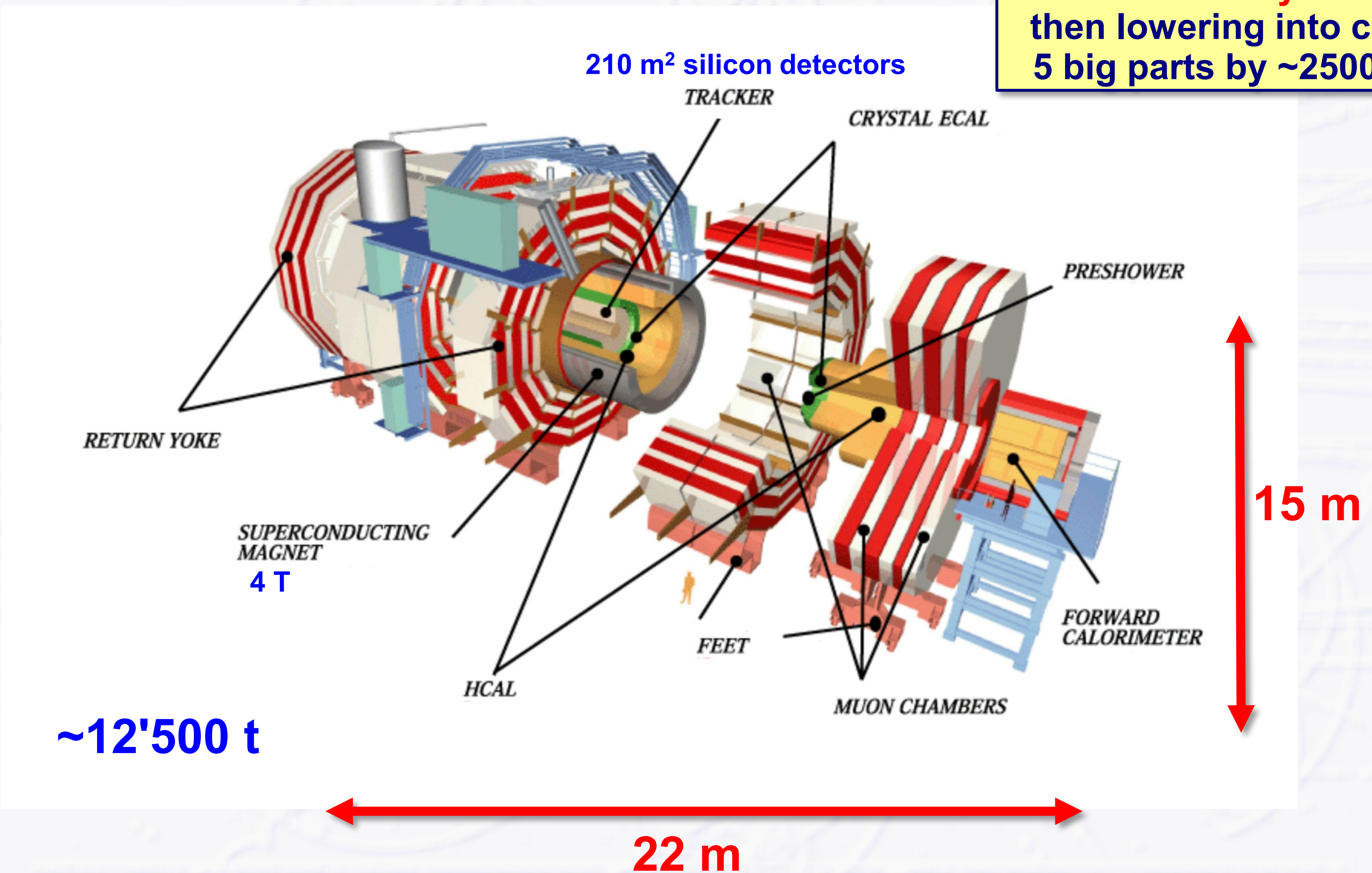
- **Event “generator” simulates physics processes**
- **Full detector description**
  - **geometry, detector volumes, detector response (noise etc.)**
  - **physics interactions with matter and tracking particles through detector volumes**
  - **also needed for detector design studies before detector actually built**

ATLAS (A Toroidal LHC ApparatuS)



CMS (Compact Muon Spectrometer)

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



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

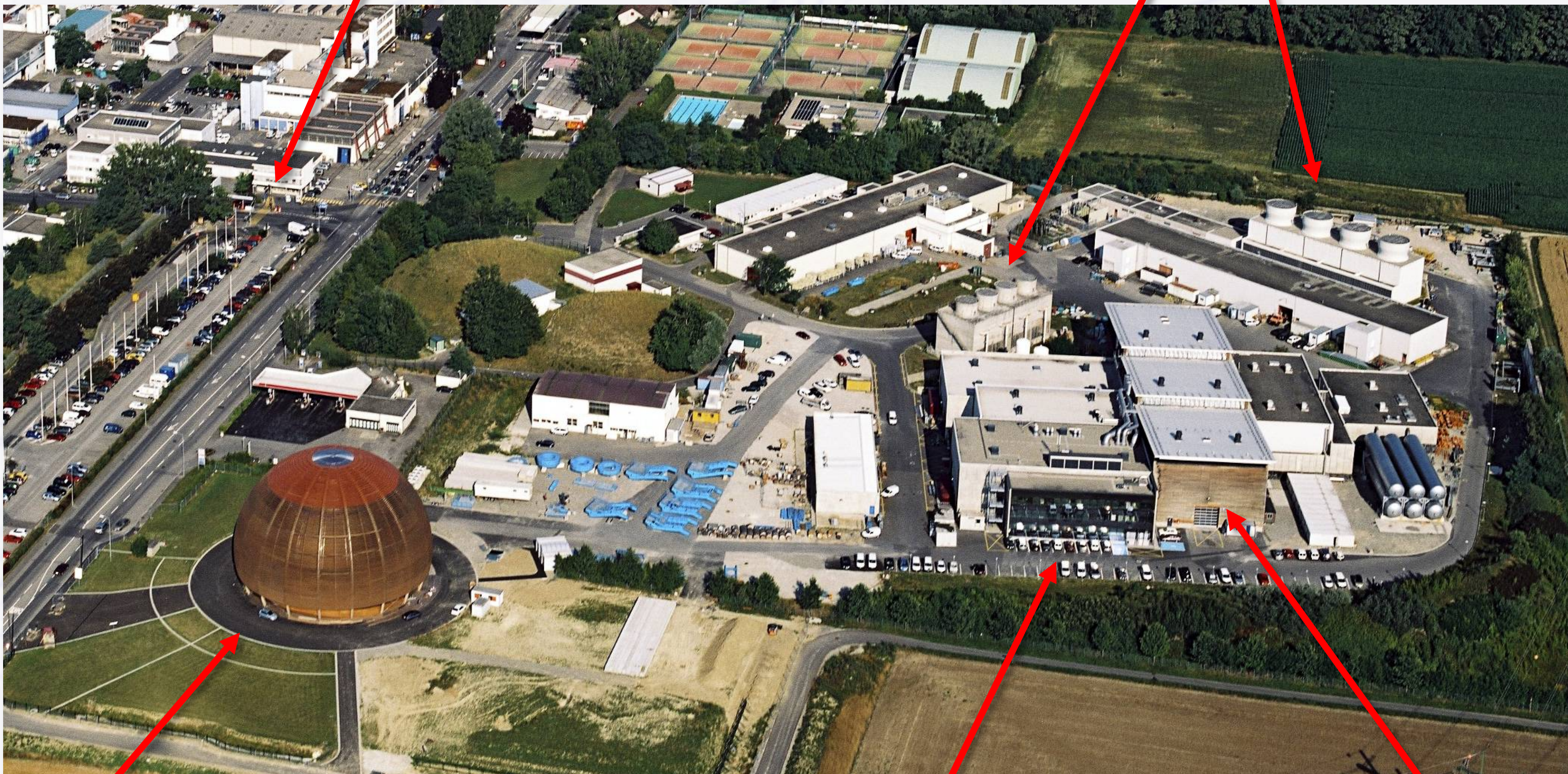
- However, both detector concepts have very similar performance for Higgs physics (efficiency, mass resolution…)

First Digging started in 1998

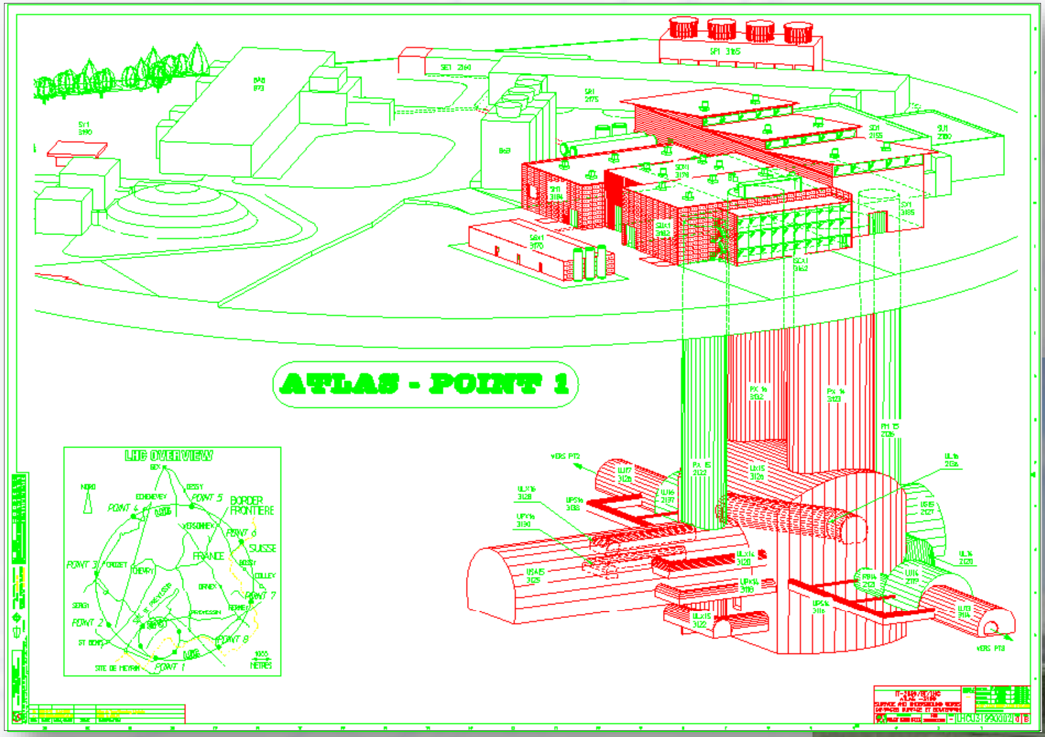
Gallo-roman remains on future CMS site

ATLAS cavern
September 2000

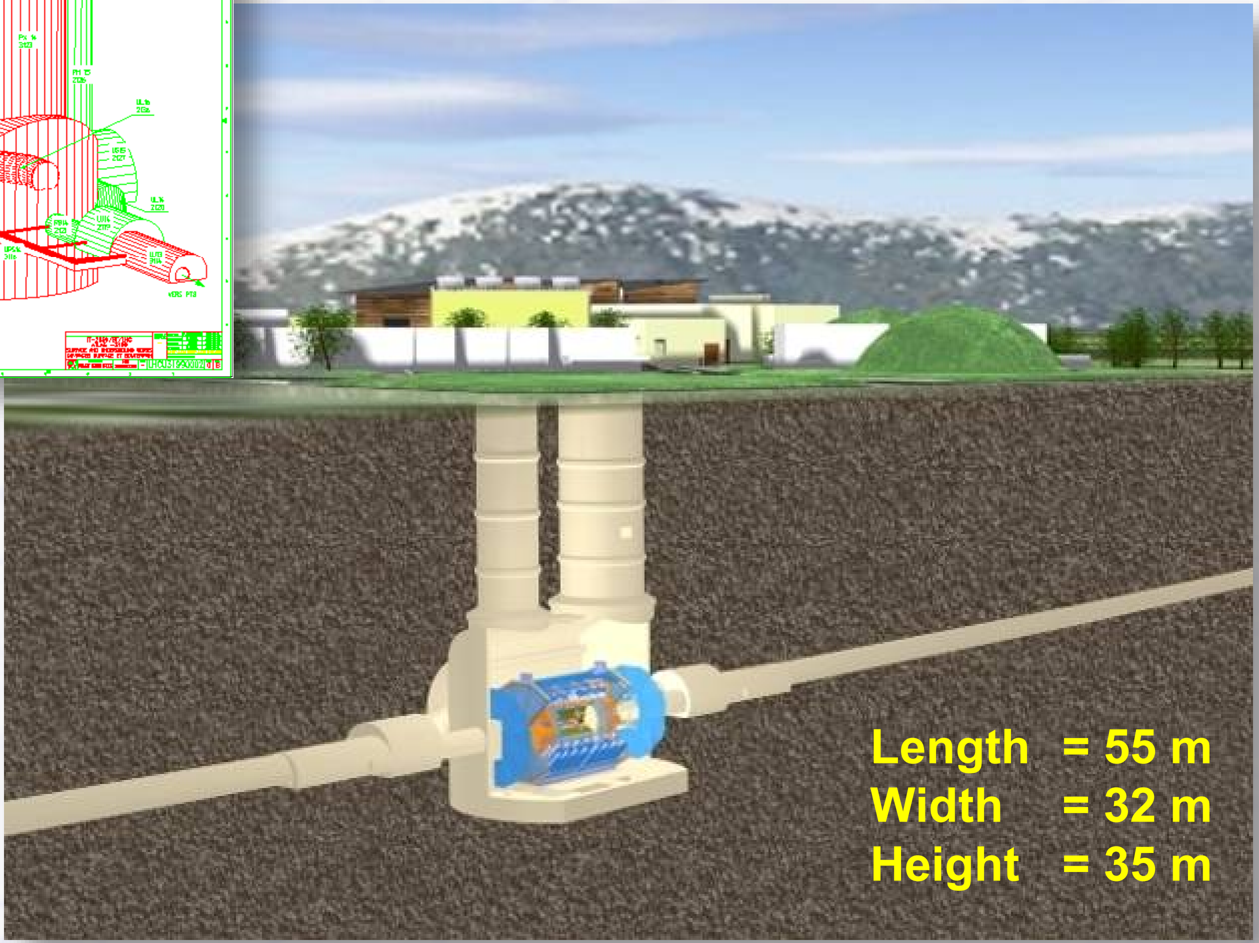
The ATLAS Site 2005



ATLAS Underground Cavern



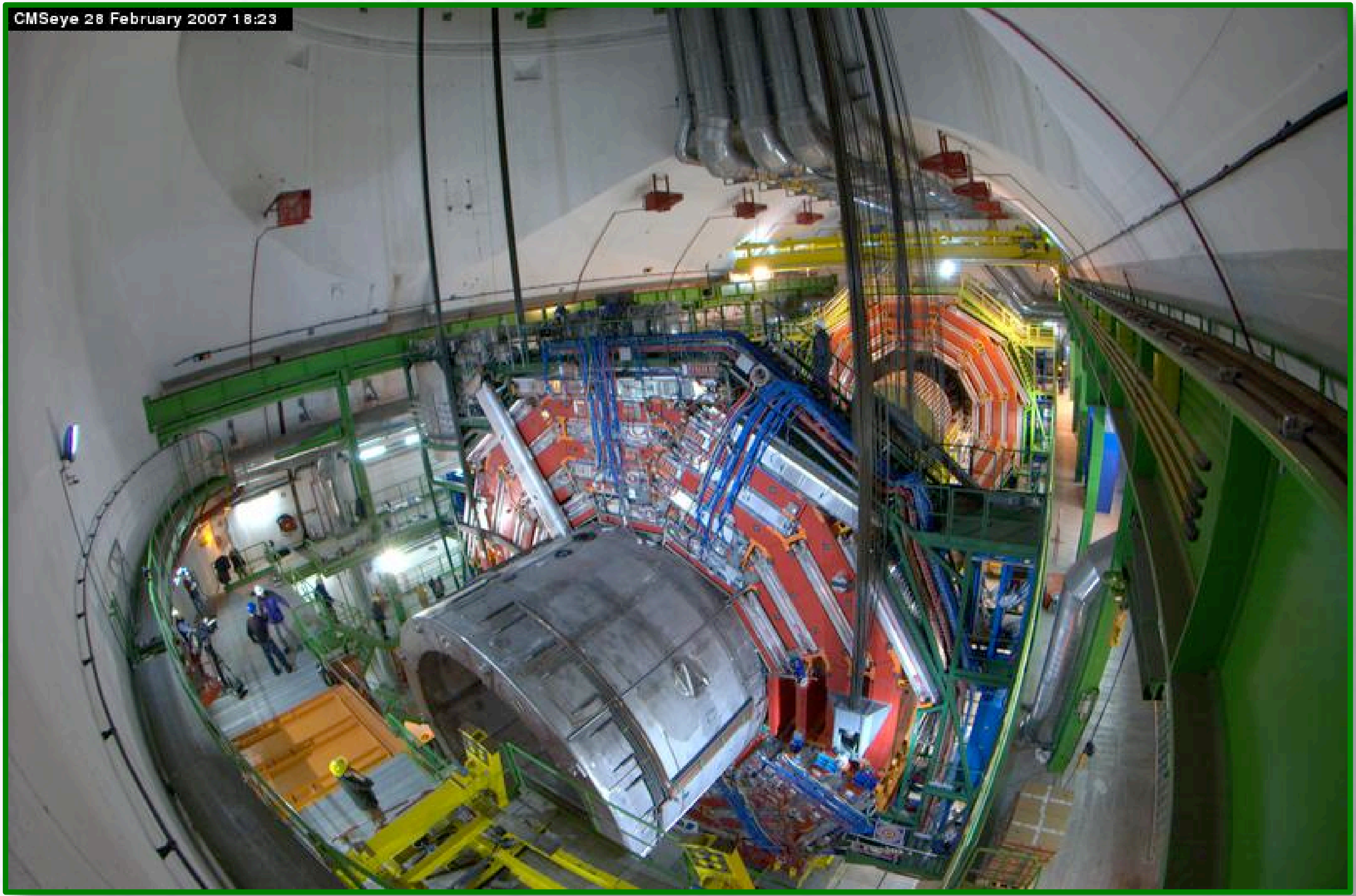
huge cavern + surface buildings,
2 access shafts 18m + 12m Ø,
2 small shafts for elevators + stairs



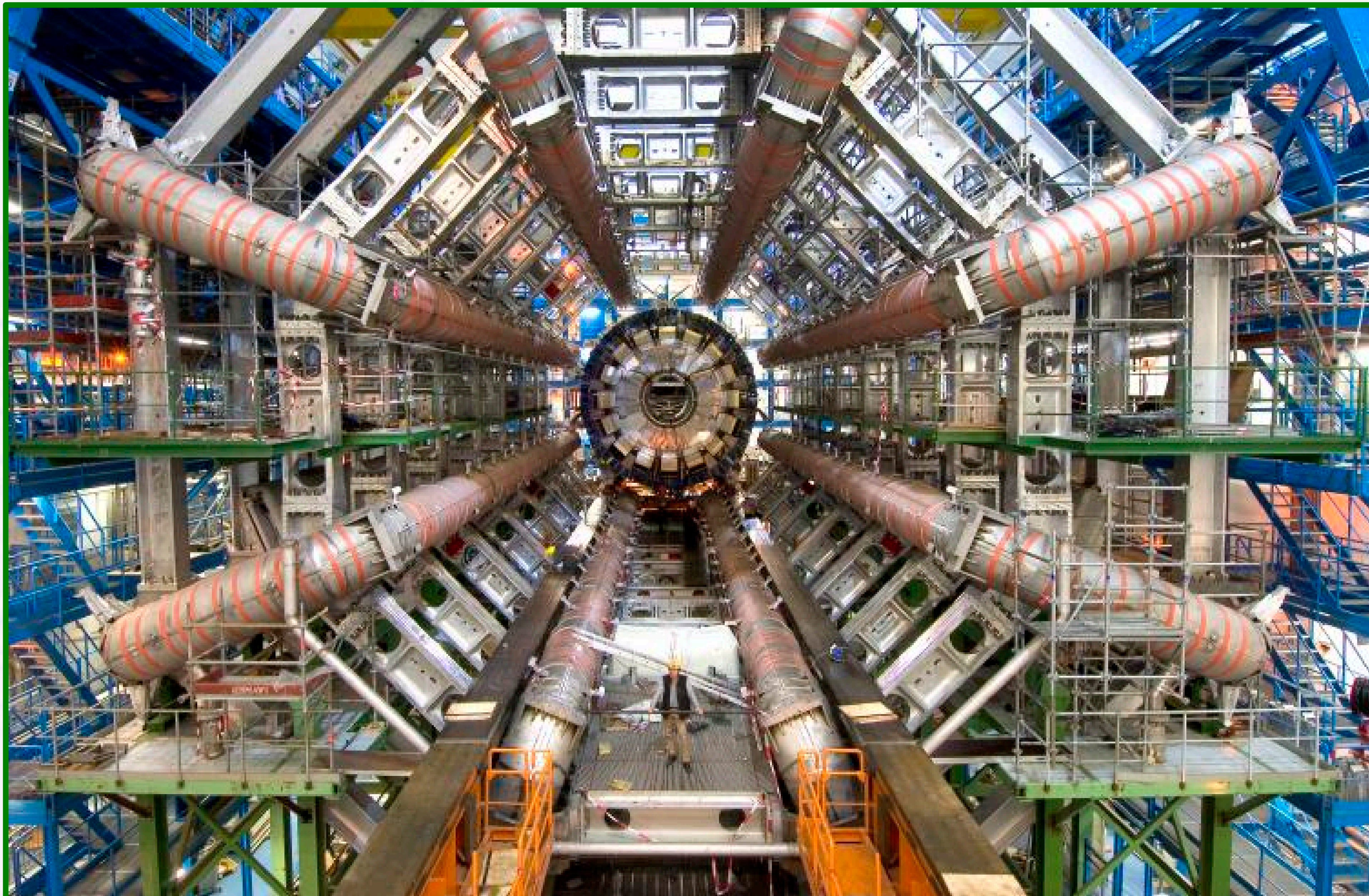
Start of ATLAS Detector Construction

Transport and lowering of first superconducting Barrel Toroid coil

CMS Lowering of 2000 t Central Part



ATLAS Barrel Toroid Complete *(Nov 2005)*



Detector Technology and Arts

The first Higgs at LHC (4 April 2008)

First LHC Collisions at High Energy