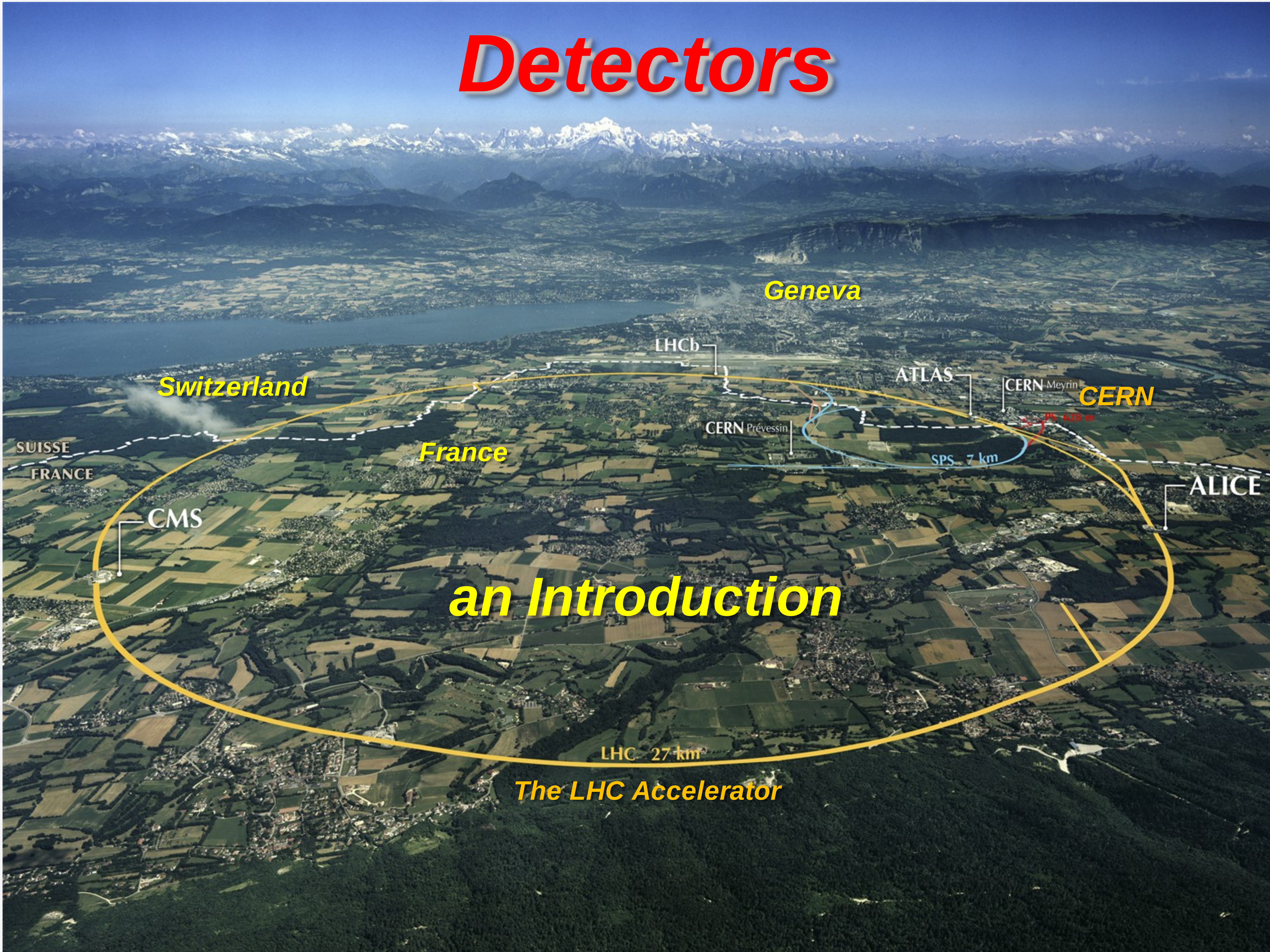
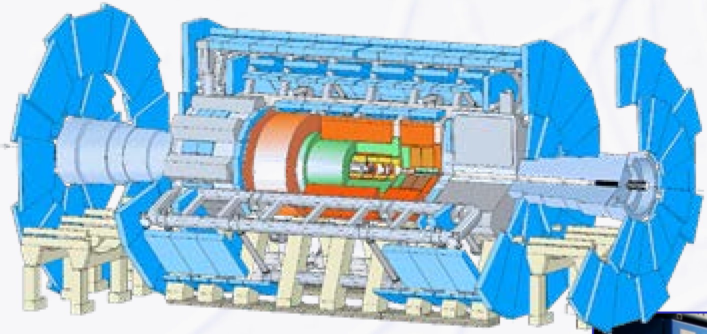
Detectors

an Introduction



LHC Detectors

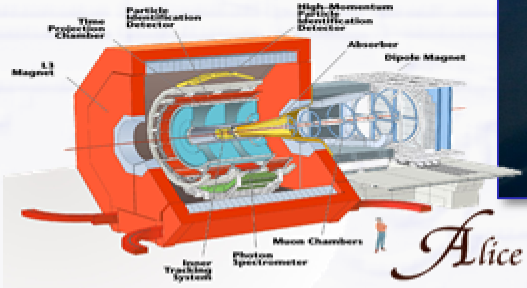
General purpose detectors (good for everything...)



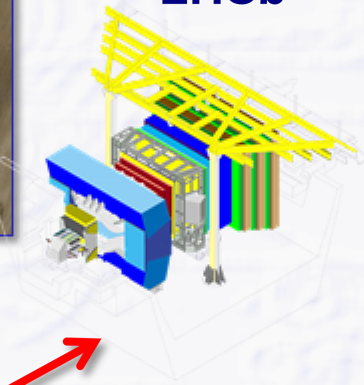
ATLAS

CMS

ALICE



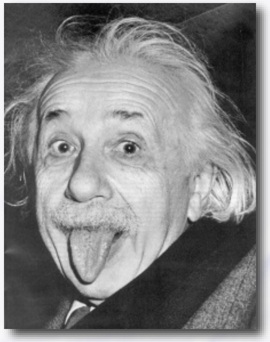
LHCb



dedicated for Heavy Ion collisions

dedicated for b-physics

Particle Physics Methods

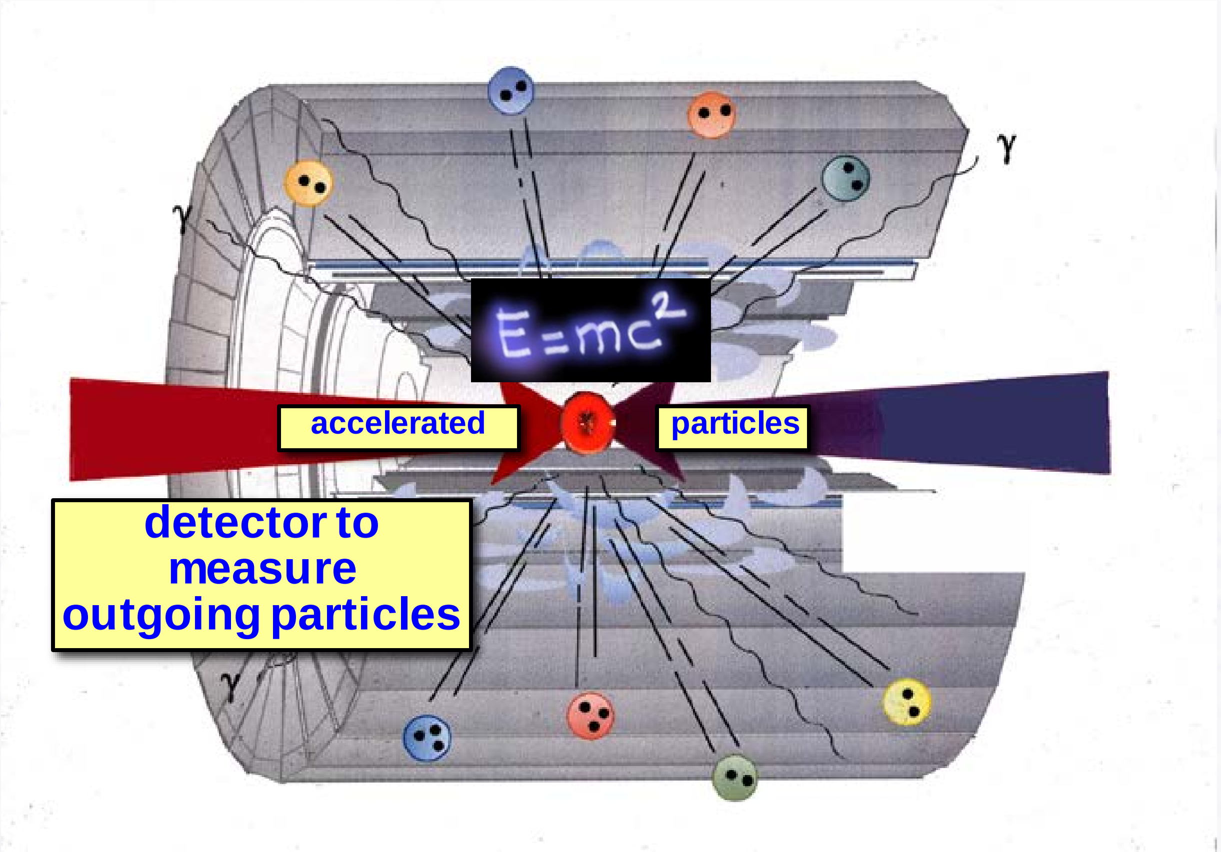


Einstein (1905):

Matter is concentrated energy!

Matter can be transformed into energy and back!

$E = m c^2$



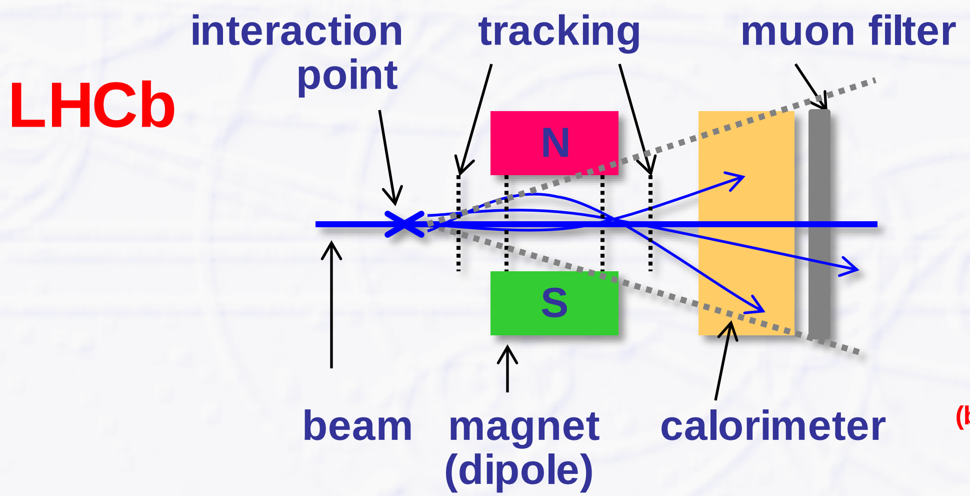
- We use this at a particle accelerator
  - protons are accelerated ⇒ energy
  - kinetic energy is transformed into matter at the collision
  - new particles are being produced (new matter)

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 + charge of ALL involved particles
  - limitations by efficiency (not all particles detected) + resolution (measurements have statistical + systematic uncertainties)

Fixed target geometry

"Magnetic spectrometer"

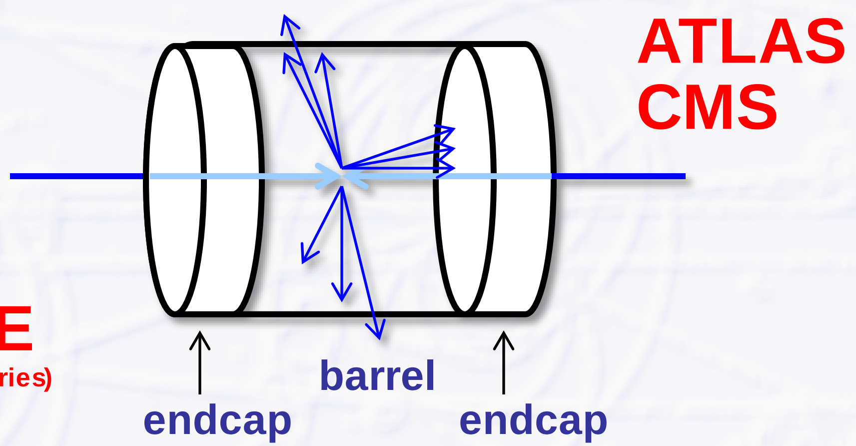


- Limited solid angle $d\Omega$ coverage
- rel. easy access (cables, maintenance)

ALICE (both geometries)

Collider geometry

"4π multi purpose detector"



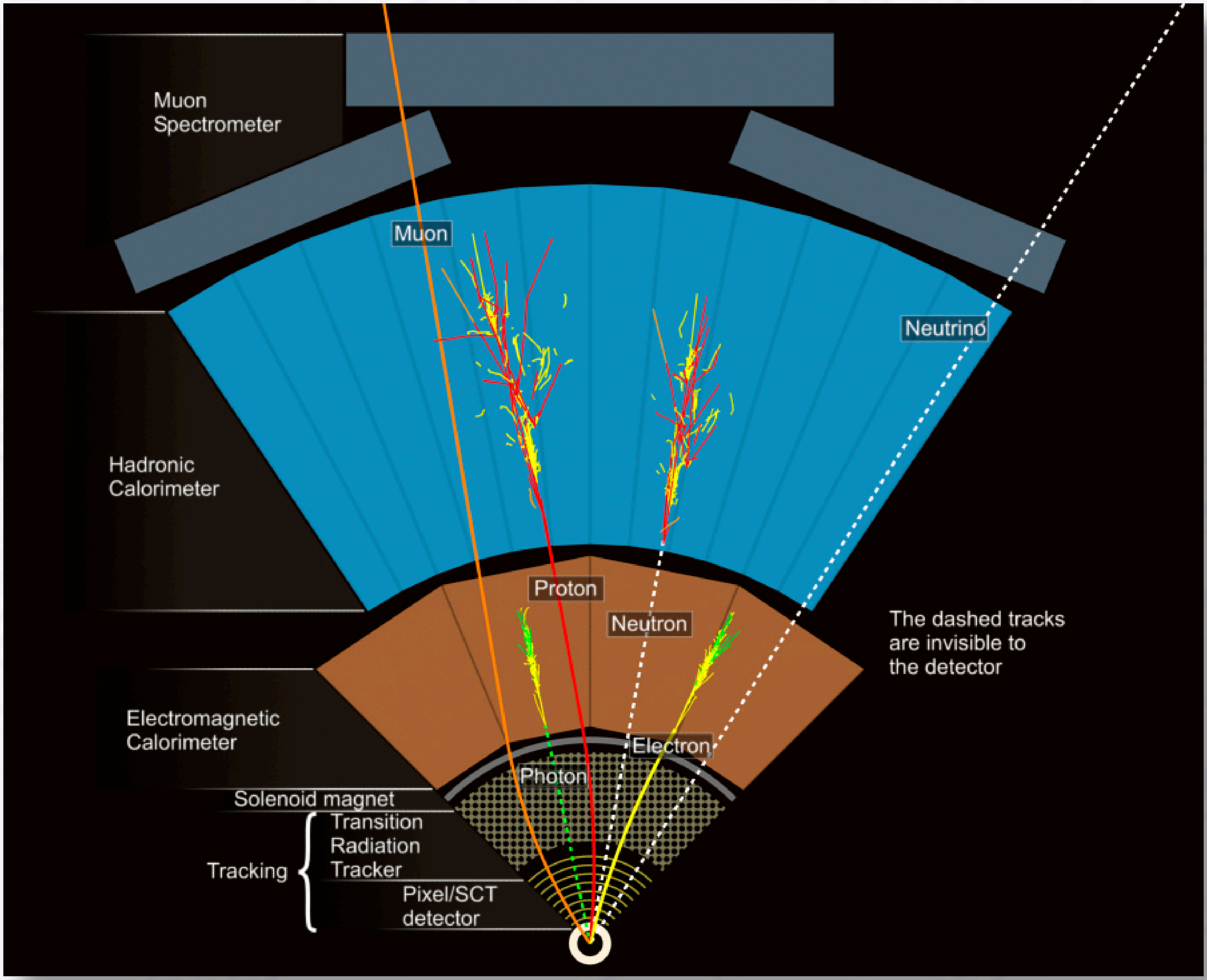
- "full" $d\Omega$ coverage
- very restricted access

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**



Muon Detector
→ muon ID
+ p for muons

Calorimeter → E

Coil

Tracker → p

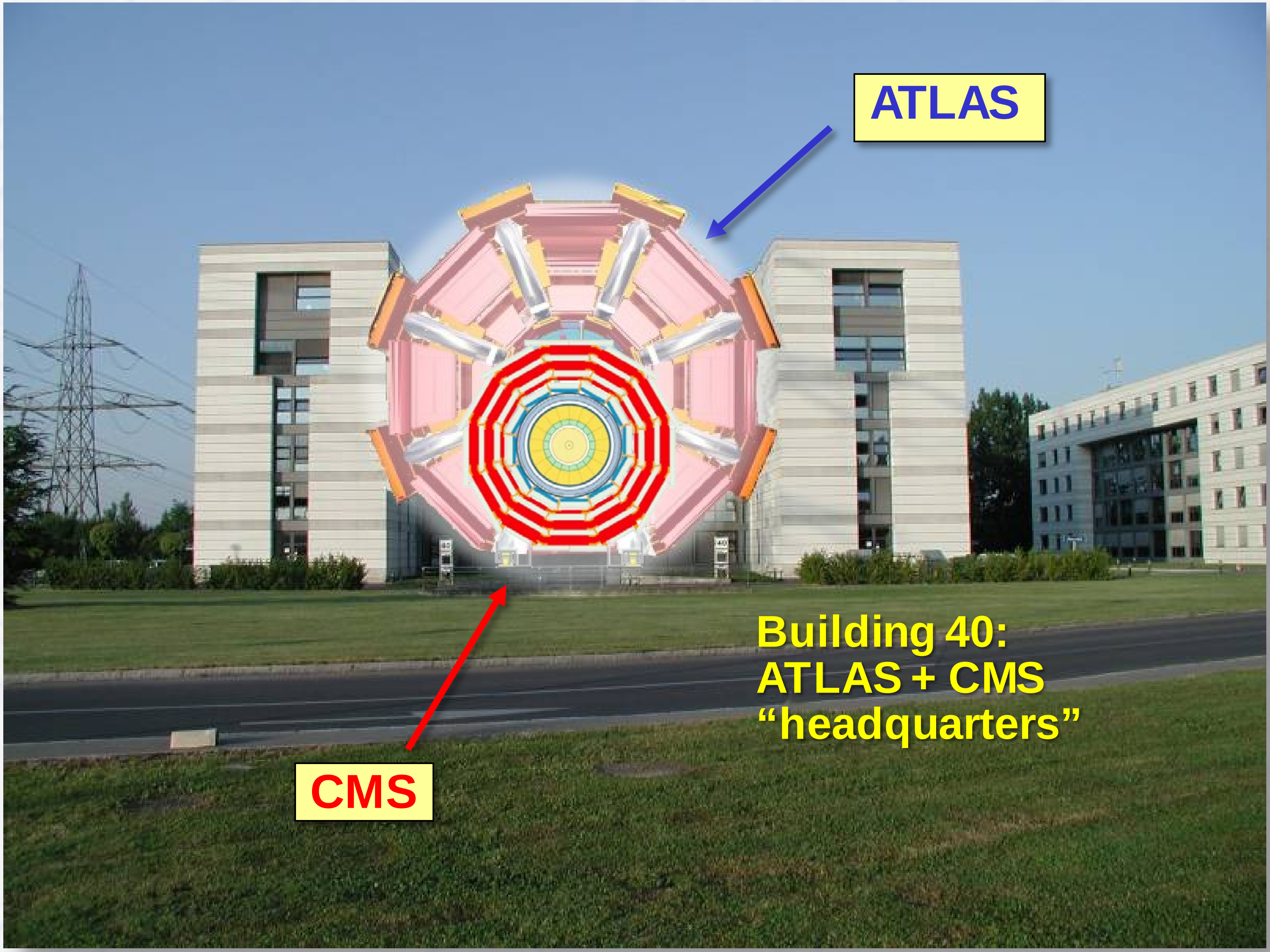
Detector Challenges at LHC

- **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...

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

LARGE Detectors

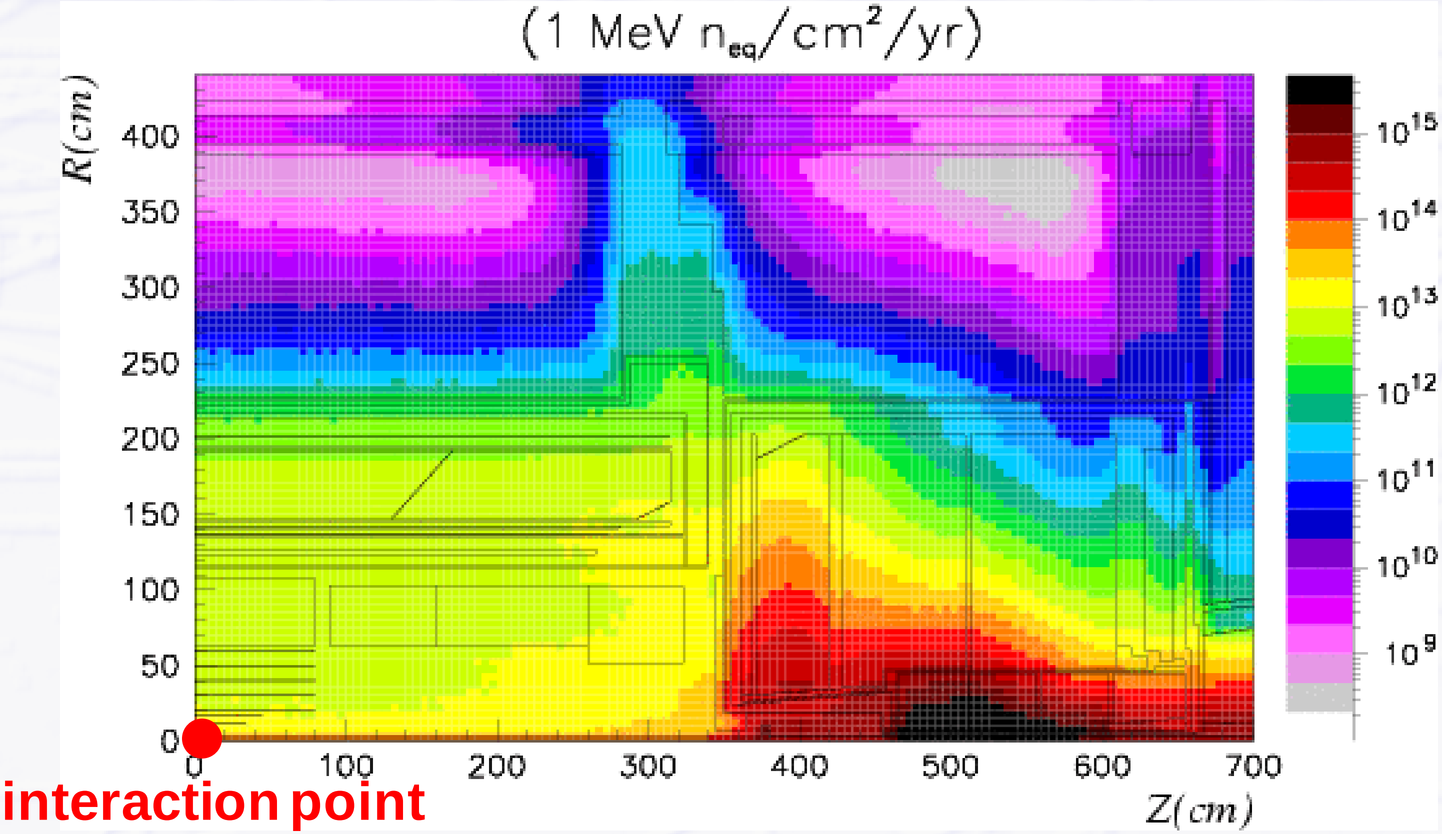
- **Everything is LARGE at the LHC…**



Radiation Doses at LHC

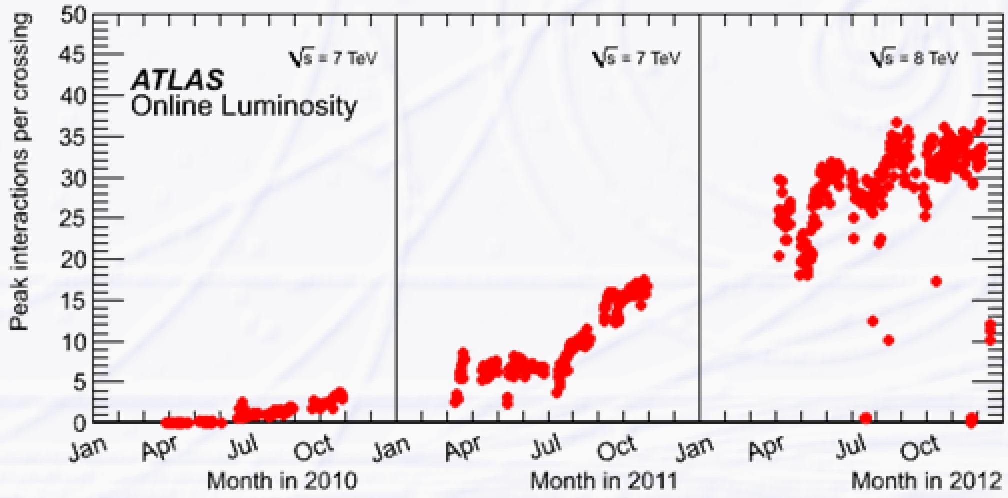
200 MRad

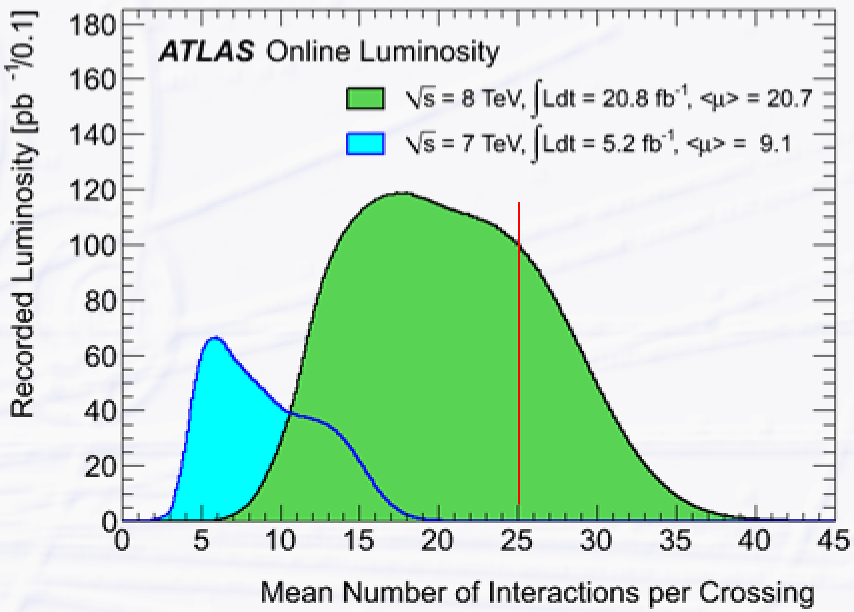
- ~ 2 x 10^6 Gray / r_T^2 / year at LHC design luminosity
  - where r_T [cm] = transverse distance to the beam
- Lots of R&D over >10 years to develop rad-hard silicon detectors, gaseous detectors and electronics



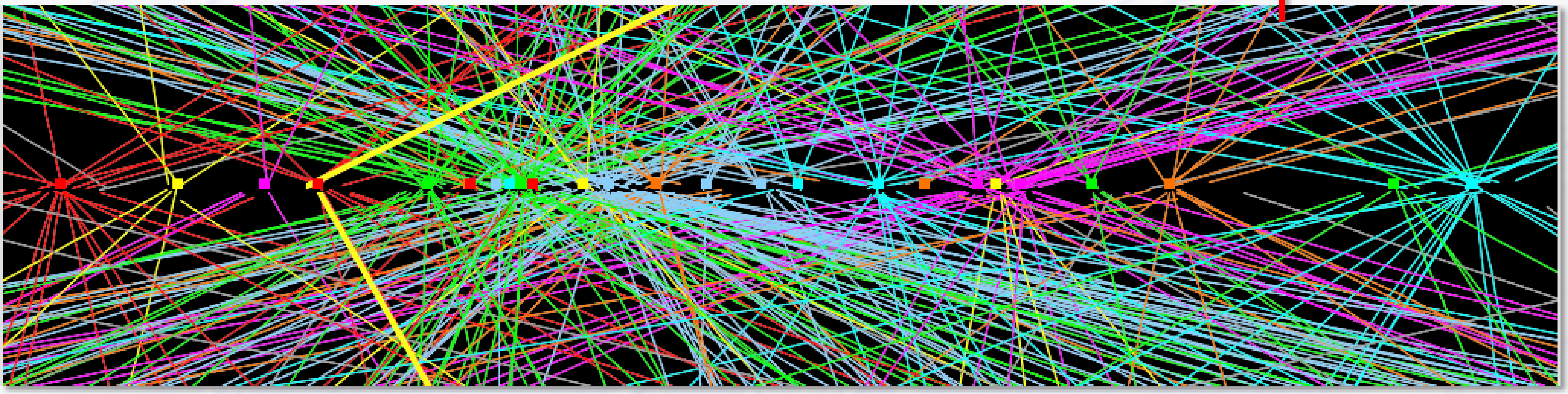
ATLAS neutron fluences

Challenging Conditions: Pile-up





2012 event with pile-up: 25 reconstructed primary vertices



~7 cm

Tracking Detectors

How to measure momentum, charge and vertices?

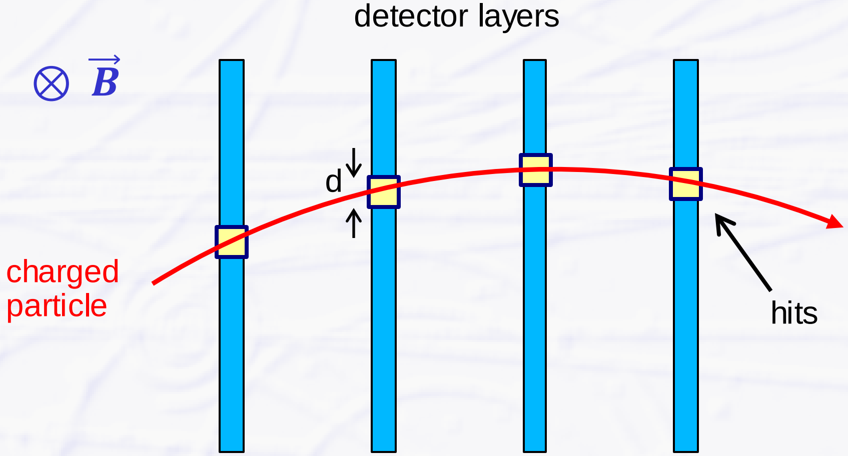
Tracker Technologies

- 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)
- **Silicondetectors (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 detectors**
  - **each layer gives a 2D hit coordinate (+ detector position → 3D)**
- **Magnetic field bends (charged) particle trajectories**



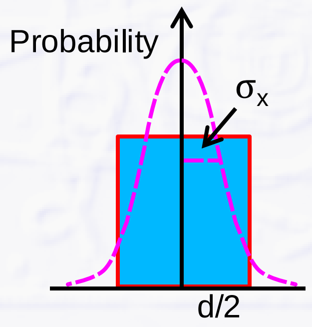
can reconstruct + fit track (radius) with at least 3 hits

- **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

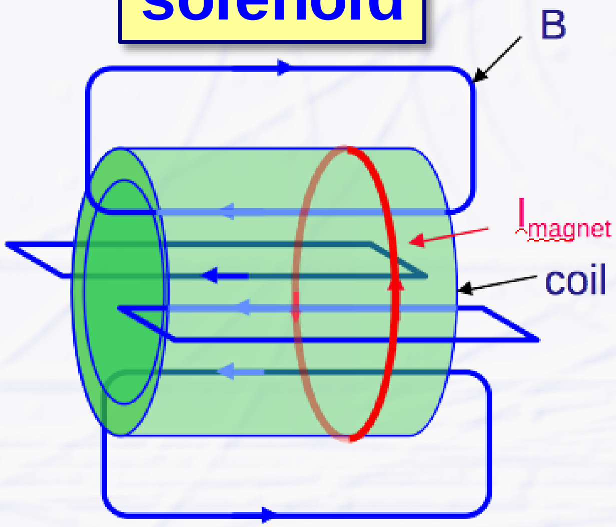
e.g. for d = 30 μm → ~10 μm resolution



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

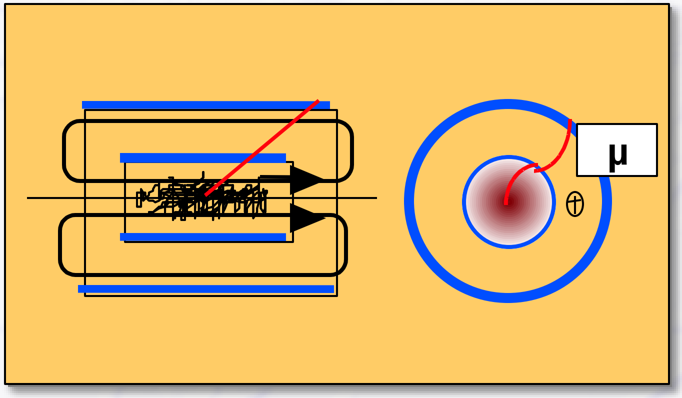
Magnet Concepts at LHC experiments

solenoid

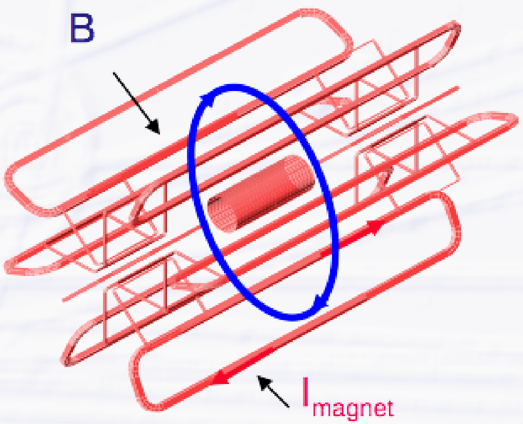


+ large homogenous field inside coil
- needs iron return yoke (magnetic shortcut)
- limited size (cost)
- coil thickness (radiation lengths)

CMS, ALICE, LEP detectors

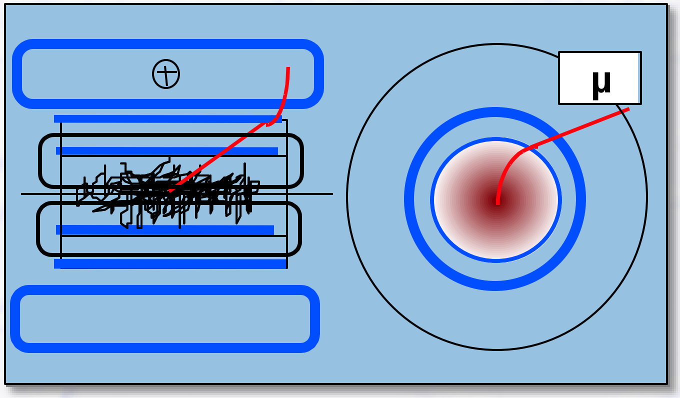


(air-core) toroid

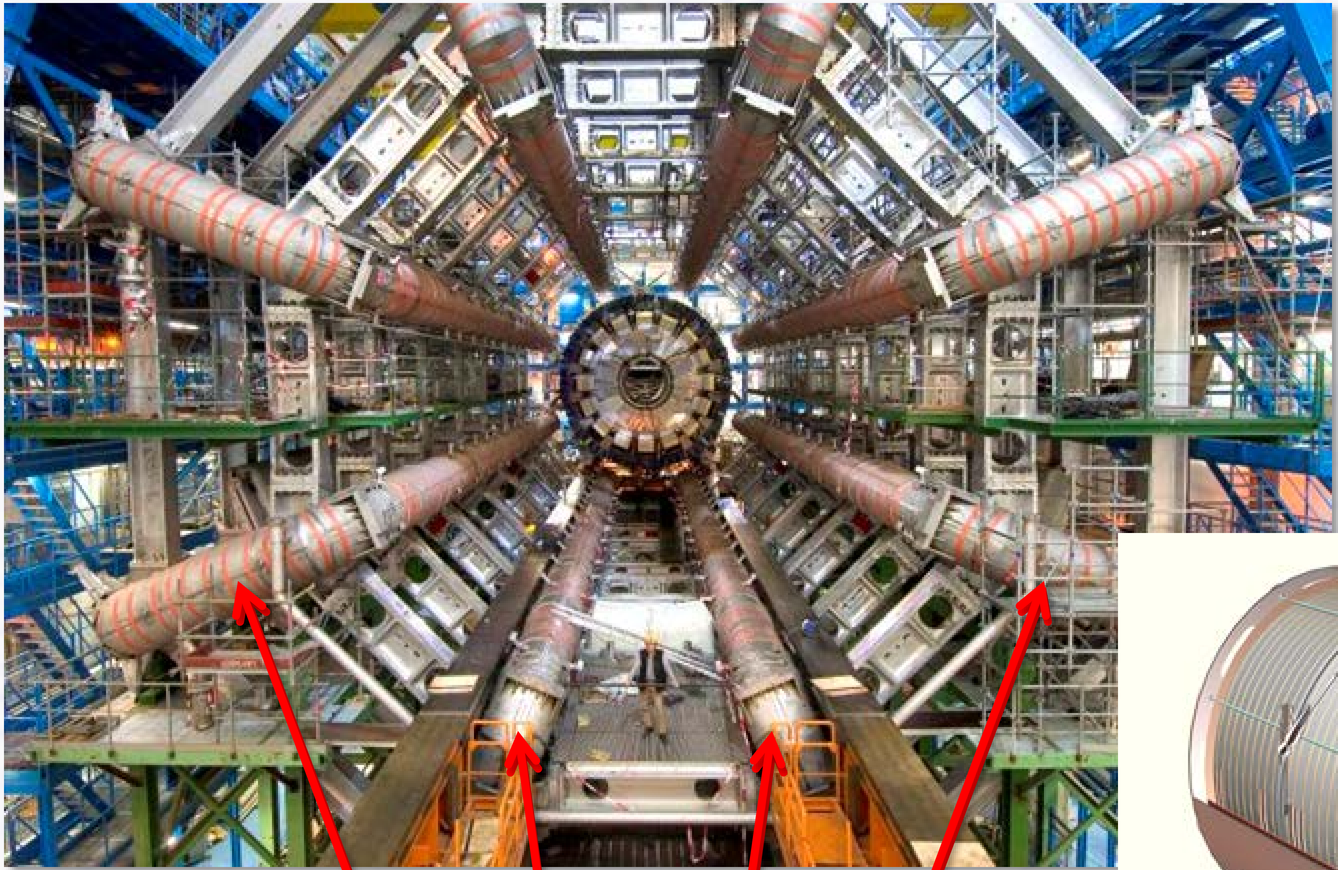


+ can cover large volume
+ air core, no iron, less material
- needs extra small solenoid for general tracking
- non-uniform field
- complex structure

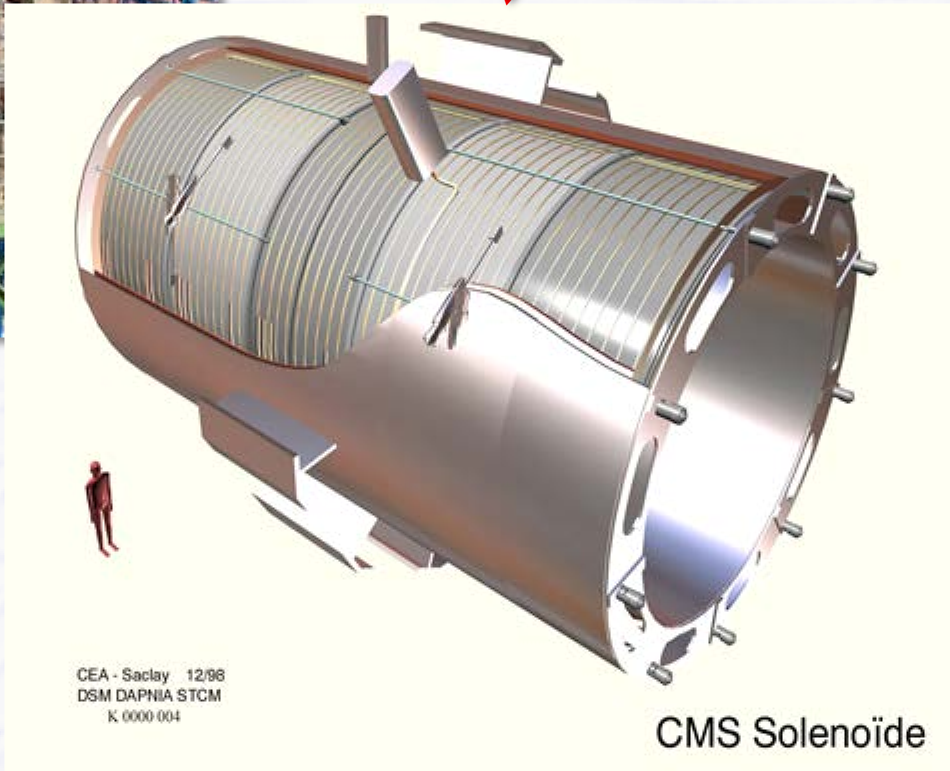
ATLAS



ATLAS and CMS Coils



autumn 2005



Momentum Measurement

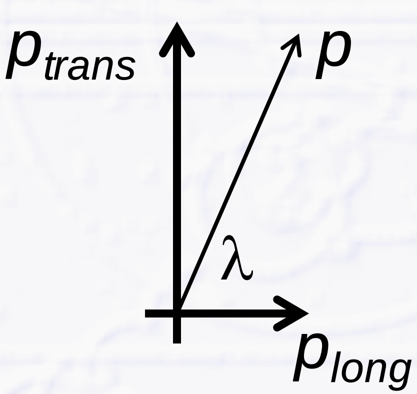
- (Only) charged particles are deflected by magnetic fields
  - homogeneous B-field → particle follows a circle with radius r

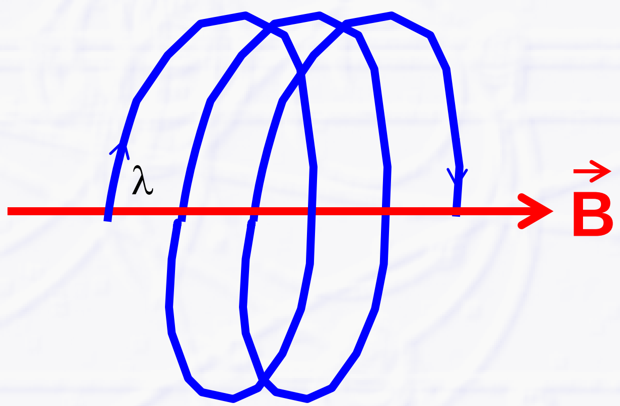
$$p_t\,[GeV/c] = 0.3 \cdot B\,[T] \cdot r\,[m]$$

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





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

Momentum Resolution

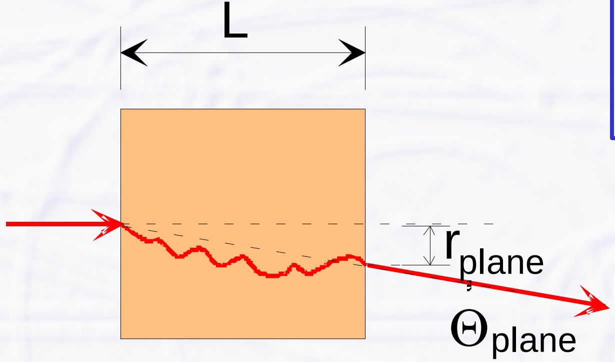
- The (transverse) momentum resolution is dominated by two components
  - contribution from single point **measurement error** σ_x:
  - contribution from **multiple scattering**

$$\frac{\sigma_{p_t}}{p_t} \propto \frac{8\, p_t}{0.3\, B\, L^2} \cdot \frac{\sigma_x}{\sqrt{N}}$$

- incoming particle is continuously scattering with atoms of the detector material and deviates from initial path

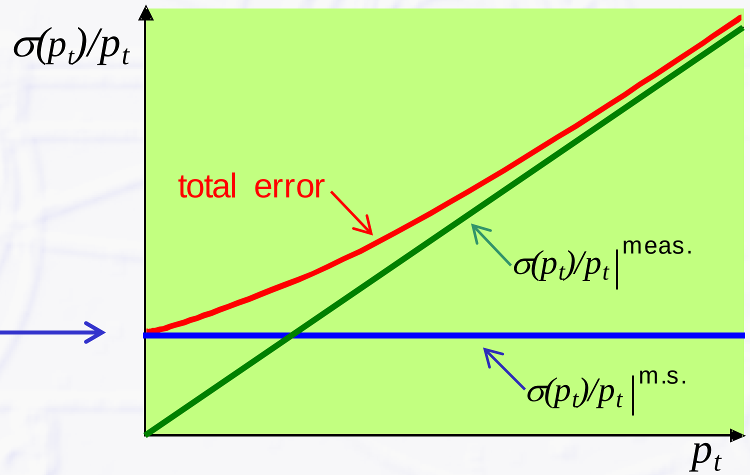
$$\frac{\sigma_{p_t}}{p_t} \propto \sqrt{\frac{L}{X_0}} = const\,(!)$$

Radiation Length (material constant)



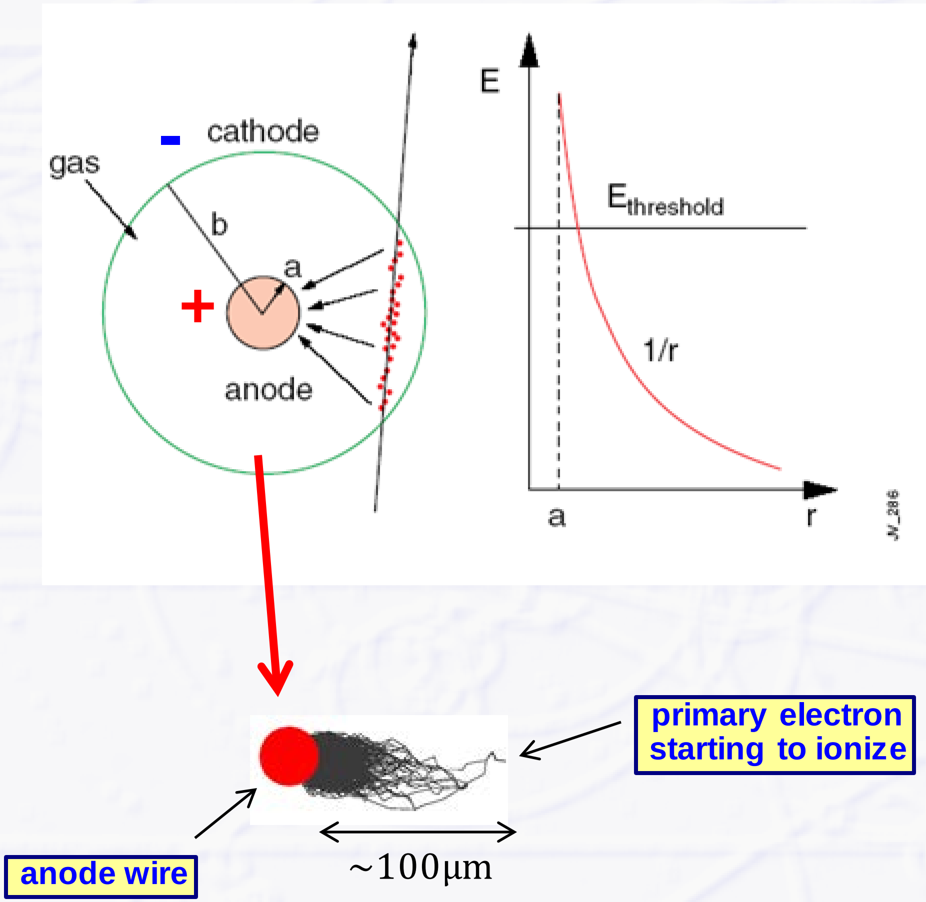
typical size of multiple scattering contribution ~0.5%

tracking detector filled with 1 bar Argon, 1 m track length



Basic Gaseous Detector –
Geiger-Müller Tube

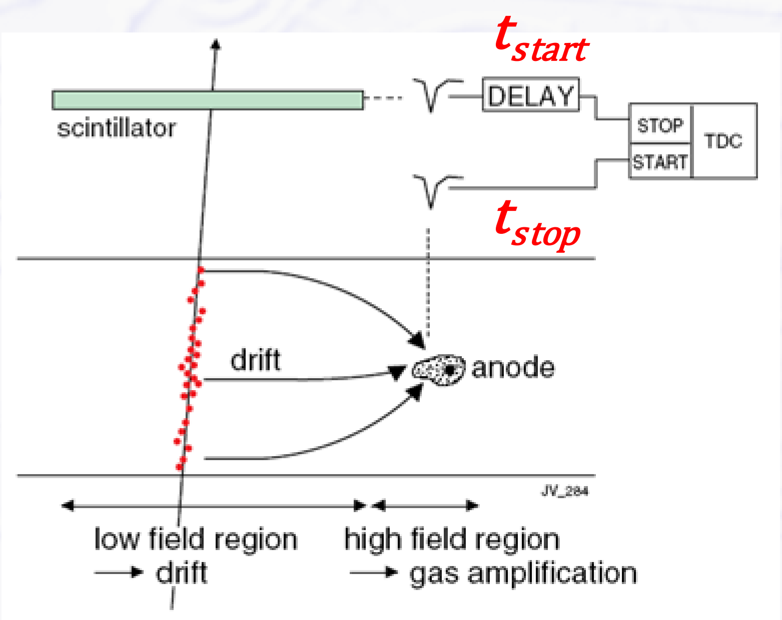
- **Geiger-Müller tube by Hans Geiger and Walther Müller 1928**
  - tube filled with inert gas (He, Ne, Ar) + organic vapour (e.g. CH_4) or CO_2
  - central thin wire (20 – 50 μm ∅), high voltage (several 100…1000 Volts) between wire and tube



- 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

Drift Chamber

- **Resolution of tubes limited to size of tube**
  - **better resolution → need smaller tubes (and more material)**
  - **can replace massive tubes by "cage" of wires, e.g. hexagonal structure**
    - **but larger wire forces (heavy mechanical structures needed) + (too) strong electrostatic forces when wires too close to each other**
- **Solution (A. H. Walenta, J. Heintze, B. Schürlein 1971)**
  - **obtain position information from drift time of electrons**
    - **drift time = time between primary ionization and arrival on wire (signal formation)**



start signal (track is passing drift volume) has to come from external source: scintillator or beam crossing signal (at collider)

- **Need to know drift velocity v_D to calculate distance s to wire**
  (= track position within the detector)

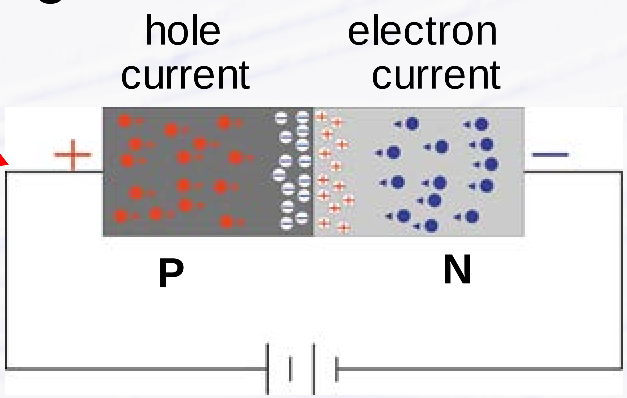
$$s = \int_{t_{start}}^{t_{stop}} v_D \, dt$$

Solid State Detectors

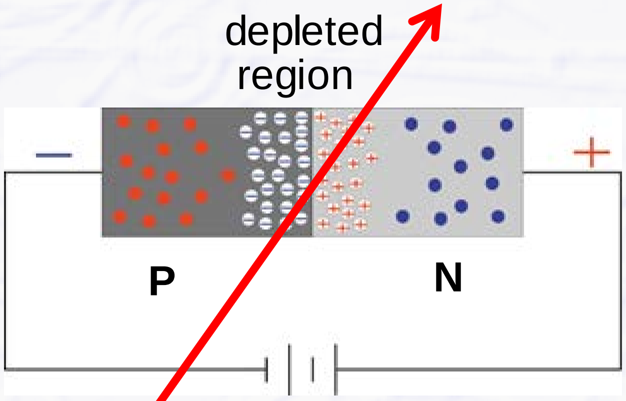
- **Basic element of a solid state (silicon) detector is... a diode**
  - **p-type and n-type doped silicon material is put together**

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**



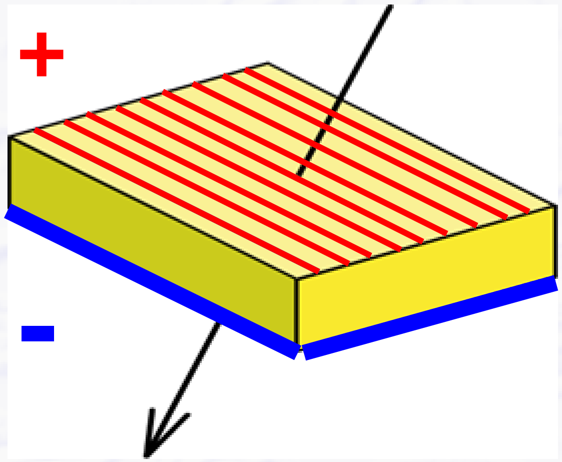
- **around junction of p - and n-type material depletion region is created**
  - **zone free of charge carriers**
    - **no holes, no electrons**
    - **thickness of depletion region depends on voltage, doping concentration**

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 cm², 300 µm thick

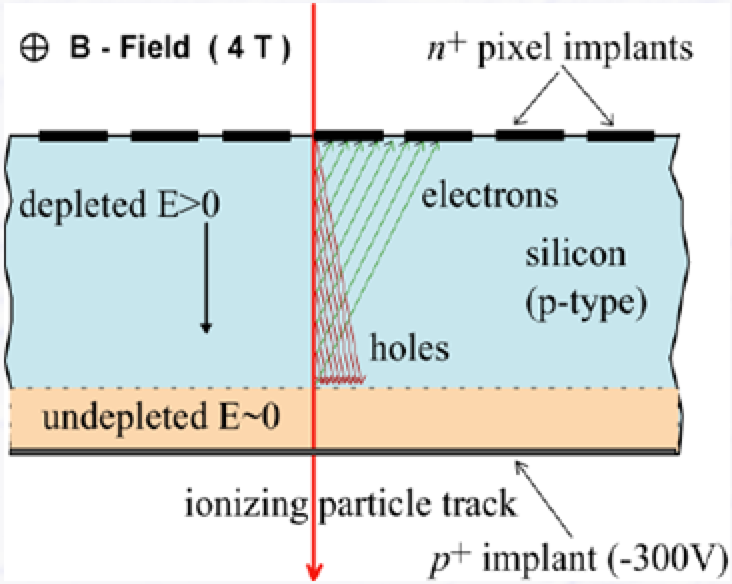


make bottom layer p-type

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

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

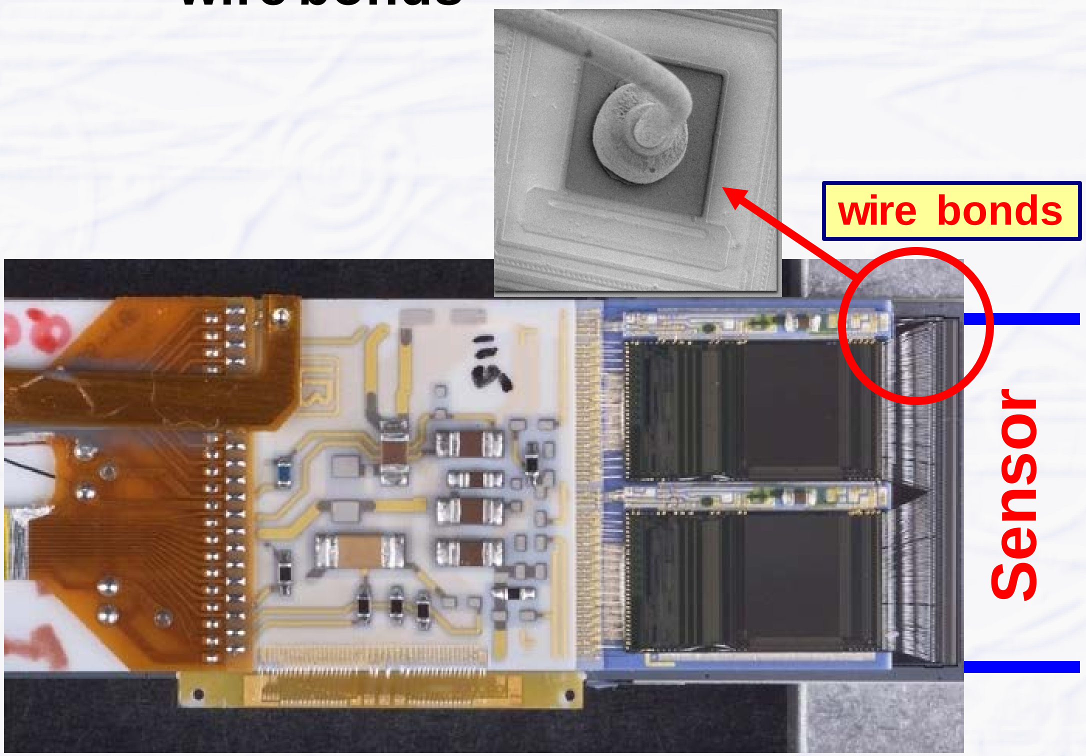
- Advantage compared to wire/gas detectors
  - strip density (pitch) can be rather high (e.g. ~20 µm)
    - high single point accuracy: σ_x = 20 µm / √12 = 5.8 µm
    - but also many electronics channels



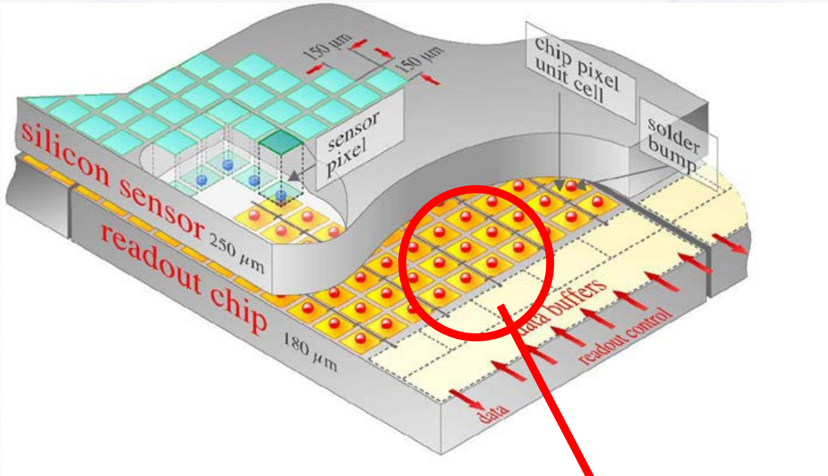
Si-Detector Electronics and Si-Pixels

- **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)

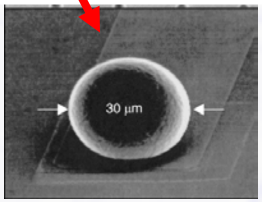
→ **electronics is directly connected to the sensor (the "multi -diode") via wire bonds**



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



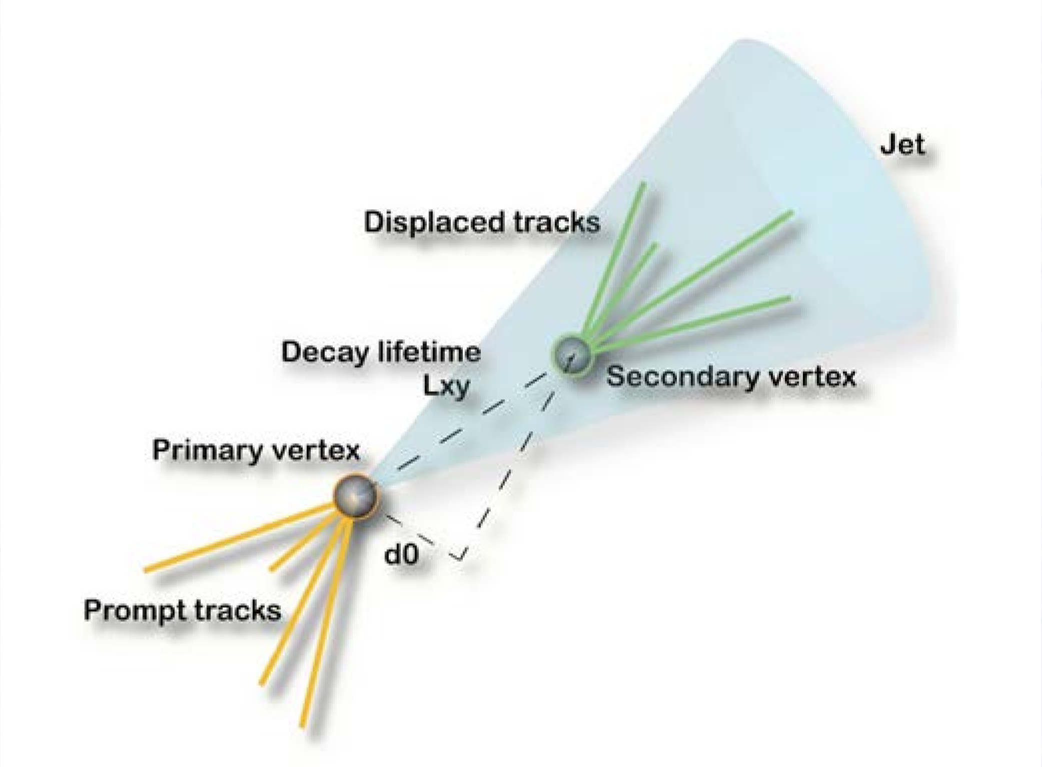
Vertex Detectors

- Beside momentum measurement tracking detectors have to measure

- **Primary and secondary decay vertices**
- **Figure of merrit for vertex detectors: impact parameter d_0**
  - impact parameter resolution

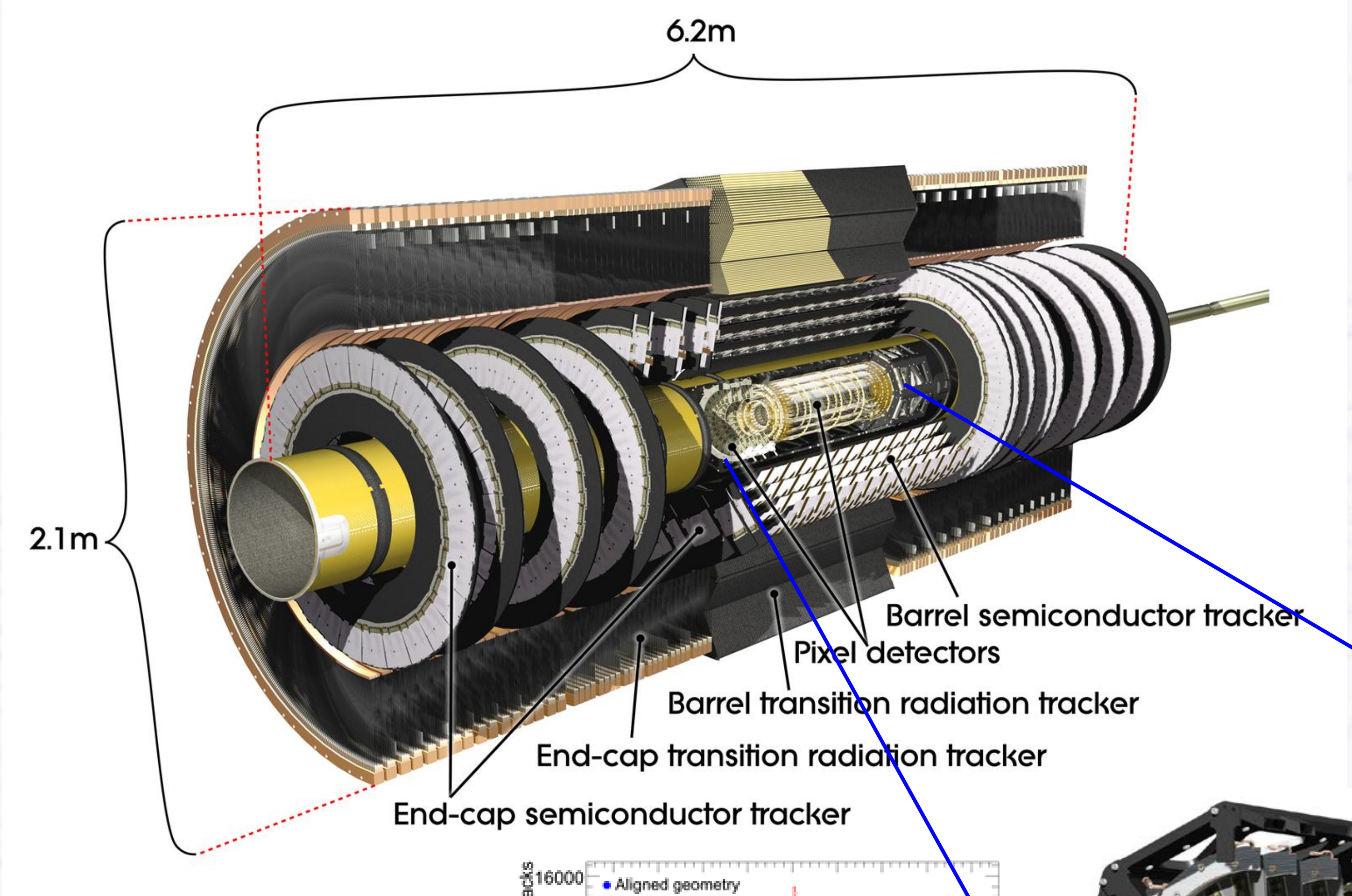
$$\sigma(d_0) \approx a \oplus \frac{b}{p_t[GeV]}$$

Accelerator	a (μm)	b (μm)
LEP	25	70
SLD	8	33
LHC	12	70
RHIC-II	13	19
ILC	**<5**	**<10**



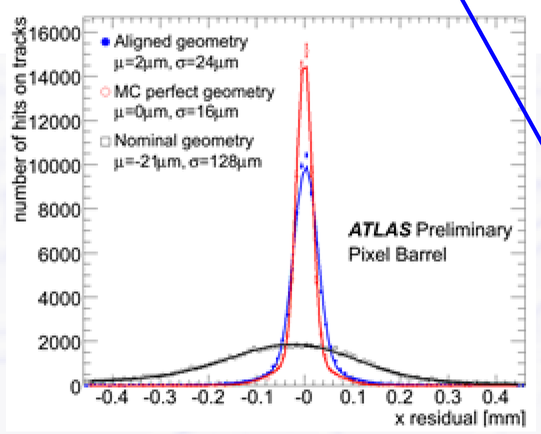
- best resolution if vertex detector is very close to interaction point
  - small beampipe radius helps (was strength of SLD)

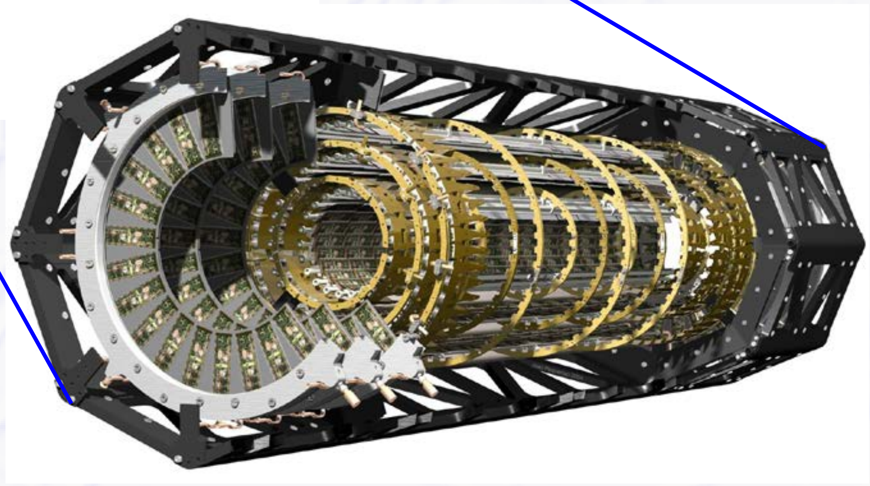
ATLAS Inner Tracker



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

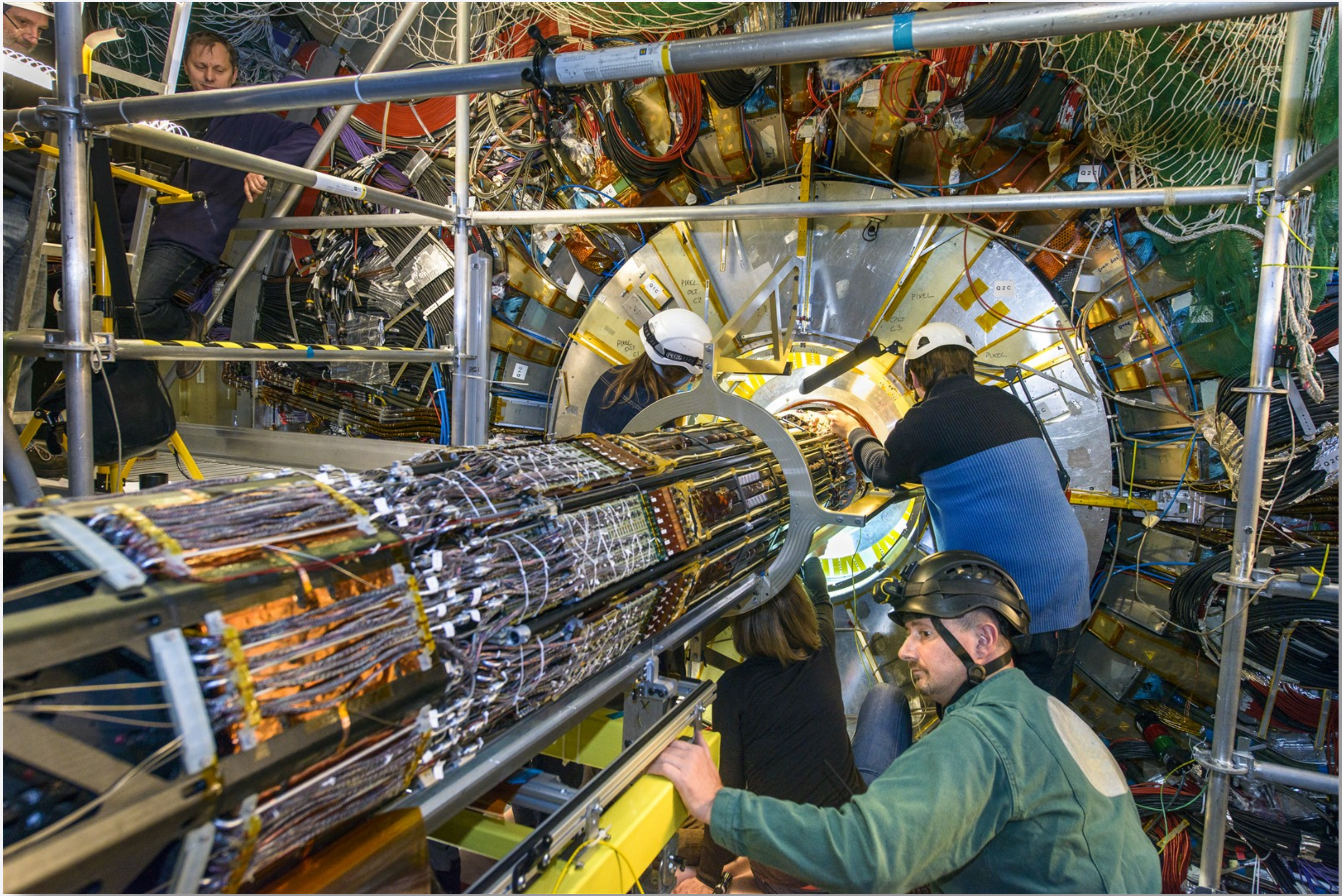
Pixel alignment with cosmic rays 2008



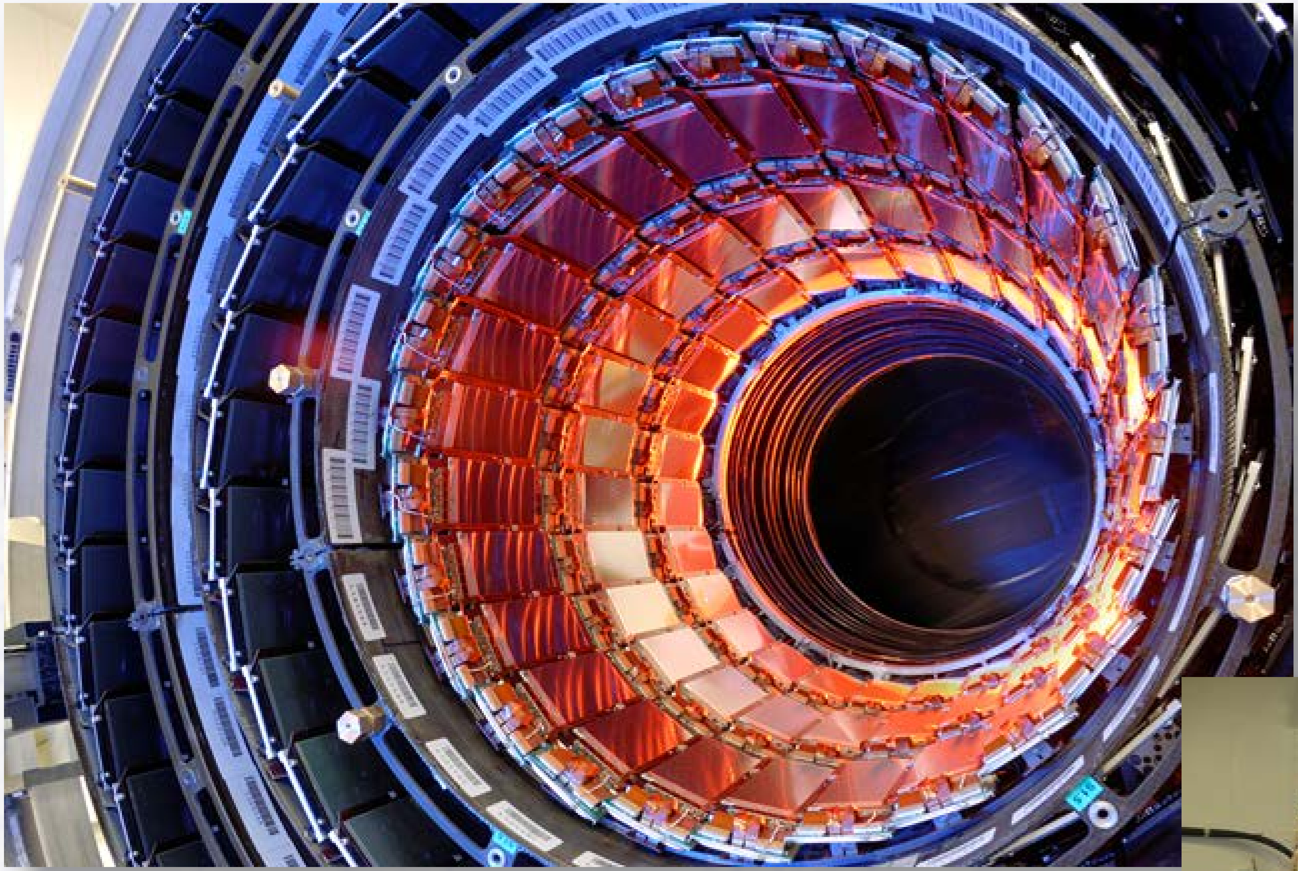


The ATLAS Pixel Detector

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

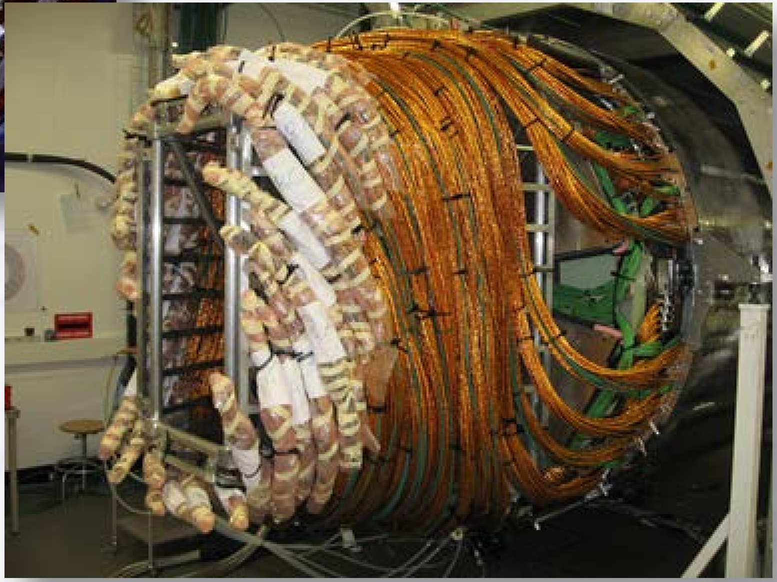


CMS Full Silicon Tracker



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

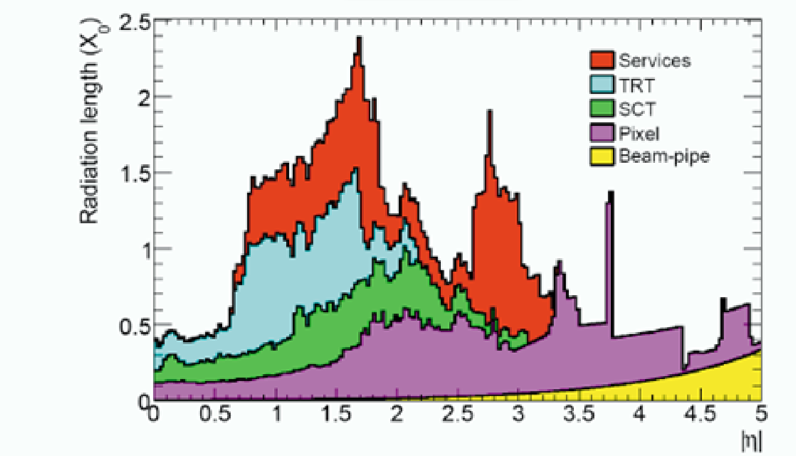
Tracker Inner Barrel TIB



Material Budget

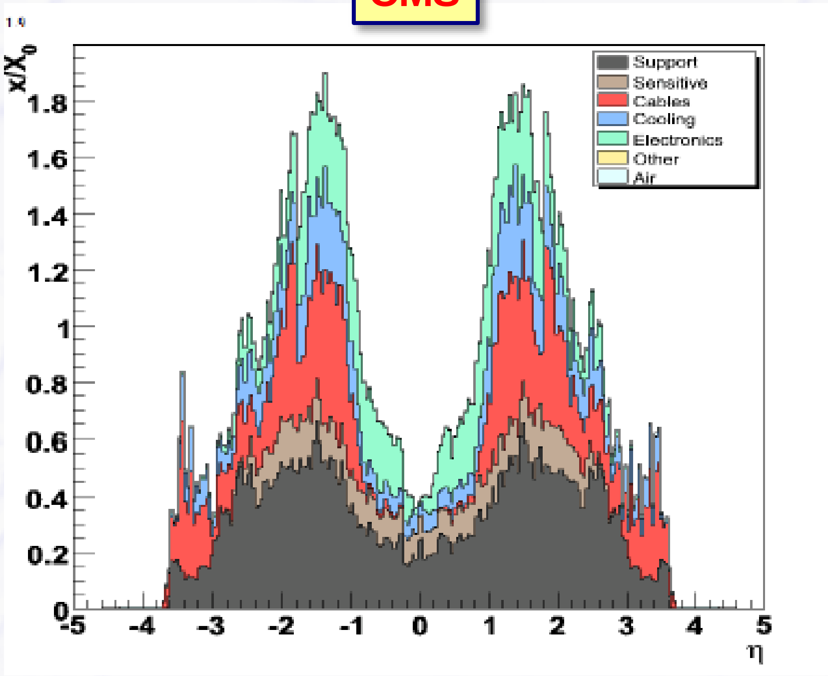
- **Tracking Detectors should be light -weighted and thin**
  - multiple scattering by material degrades resolution at low momenta
  - unwanted photon conversions in front of calorimeters
  - material often very inhomogeneous (in particular Si detectors)
- **Power & cooling adds most of the material**
  - 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

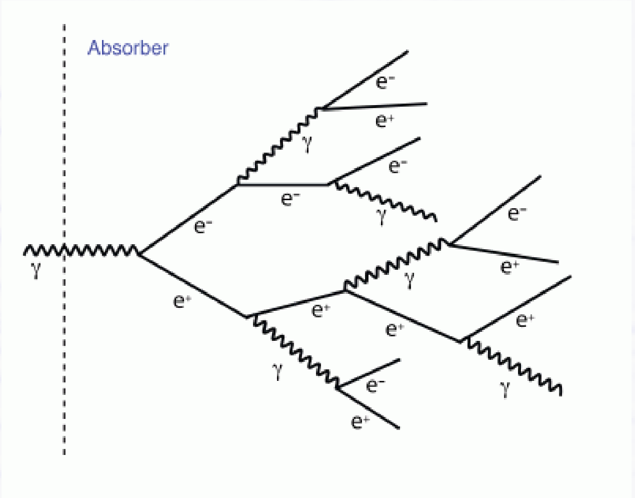


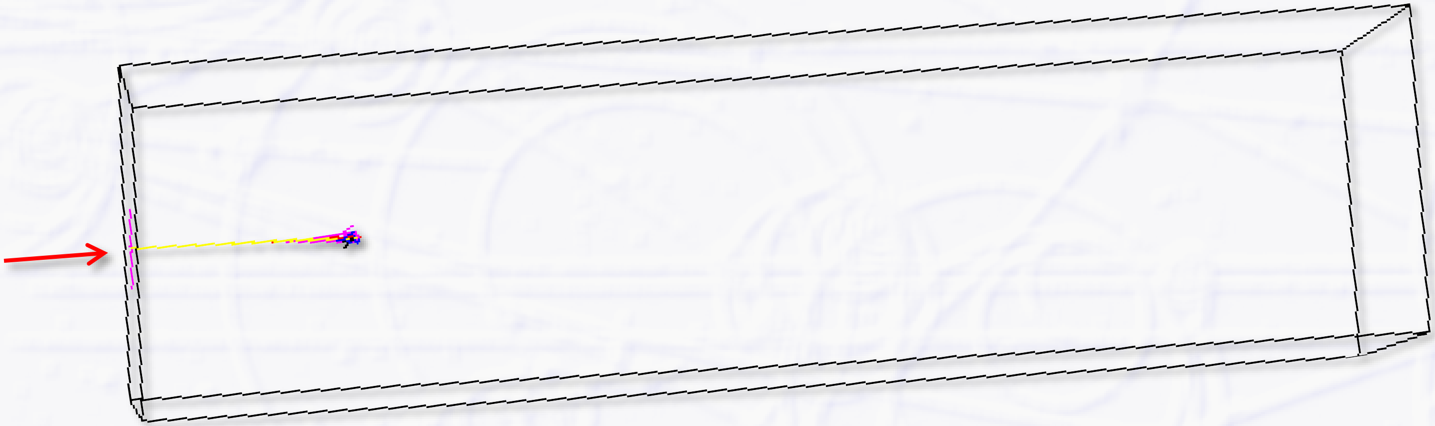
Calorimeters

How to measure energy?

Particle Showers in Calorimeters

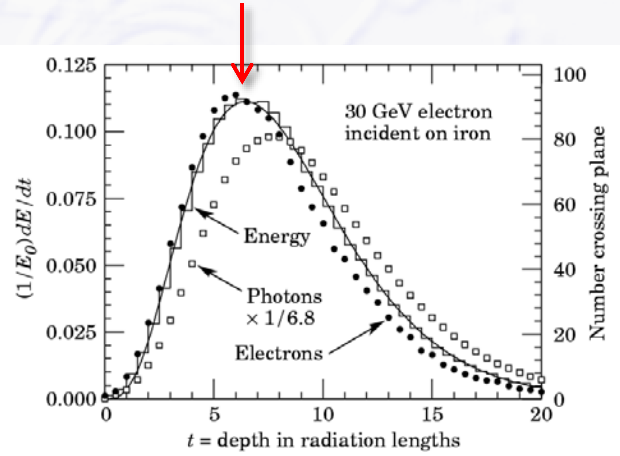
- **Initial particle creates electro-magnetic shower of secondary particles (electrons, positrons, photons) in dense material**
  - by bremsstrahlung and pair production
  - shower depth depends on radiation length X_0 (characteristic material constant)
    - for $e^{\pm}$ = length after all but 1/e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





80 GeV electron in lead glass block

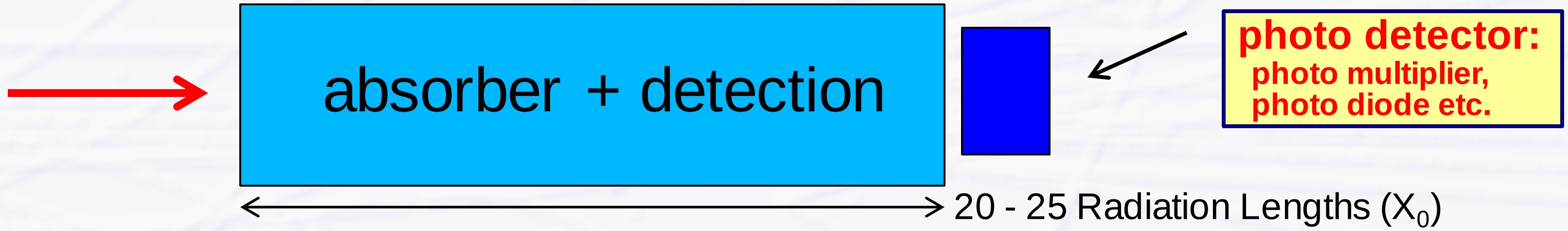
shower maximum



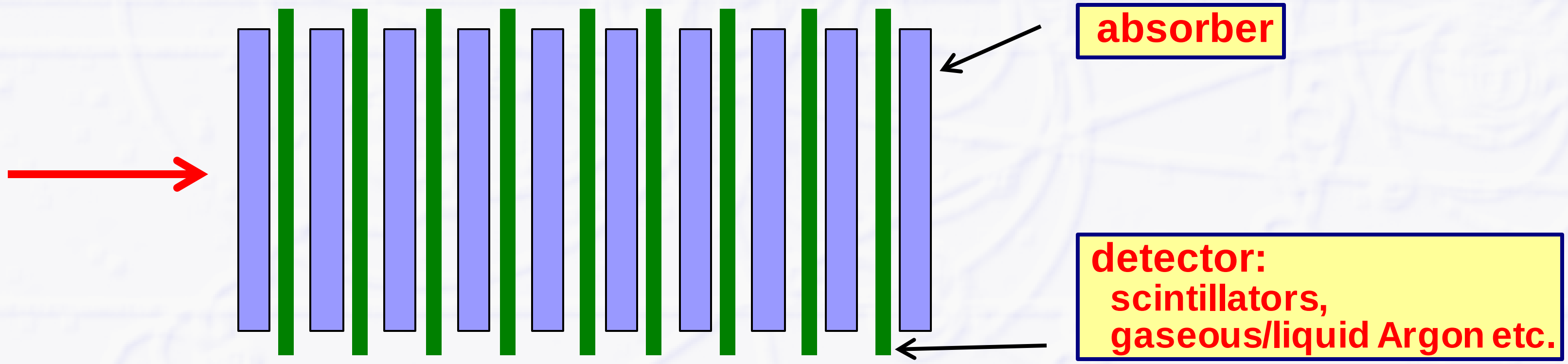
energy profile

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**

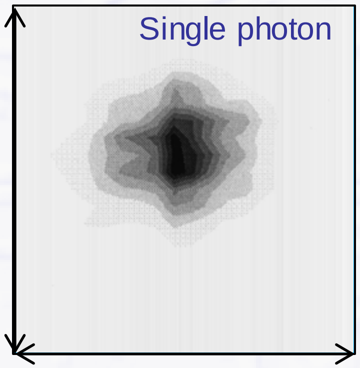


- **Sampling calorimeters (e.g. ATLAS)**
  - **passive (heavy) absorber material (iron, copper, lead, tungsten, uranium) interleaved with active detector material**



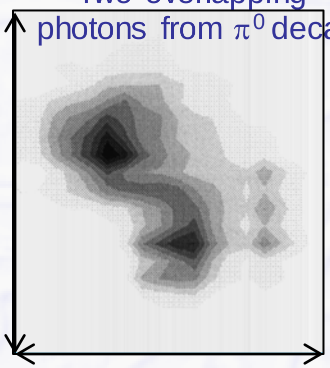
CMS: Homogeneous EM Calorimeter

- **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**



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

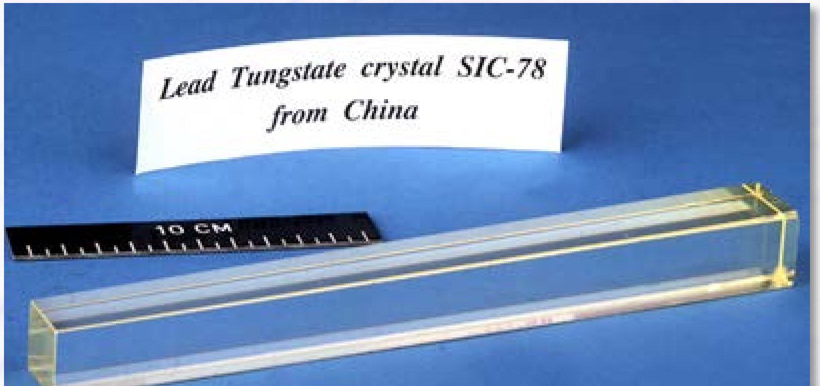
Two overlapping photons from π^0 decay



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

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

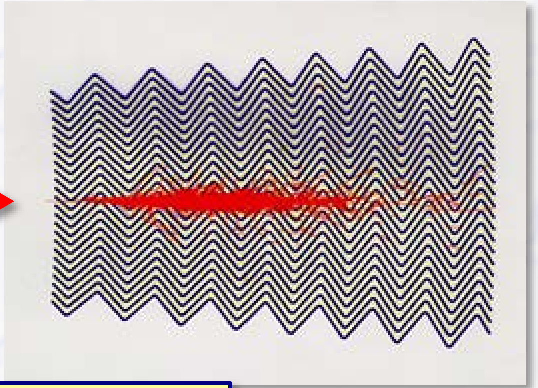
CMS $PbWO_4$ crystal



$\rho = 8.28\ g/cm^3 \quad X_0 = 0.89\ cm$

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**
  - **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

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 (⊕)

stochastic (statistic) term ($a/\sqrt{E}$): number of shower particles

constant term (b): inhomogenities, non-linearities

noise term (c/E): electronics noise

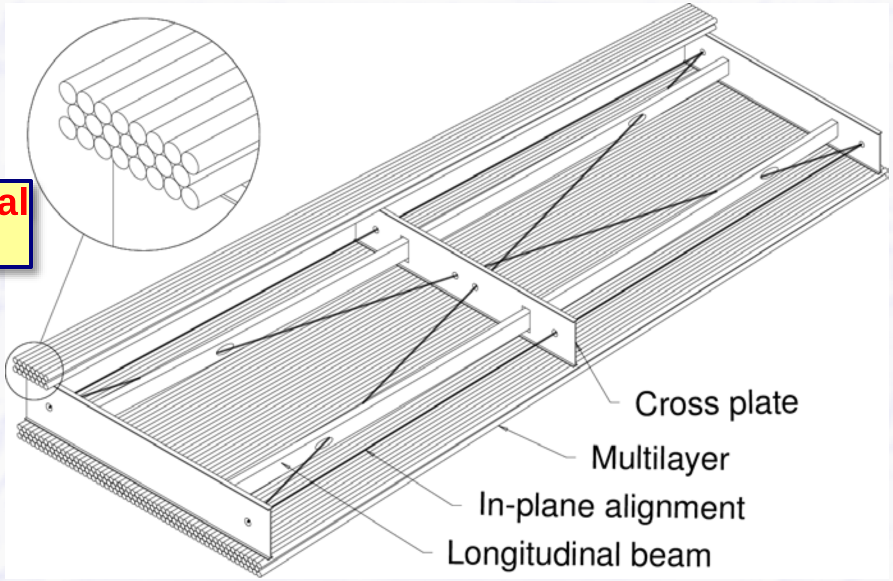
relationship valid for all types of calorimeters (homogeneous + sampling, electromagnetic and hadronic)

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



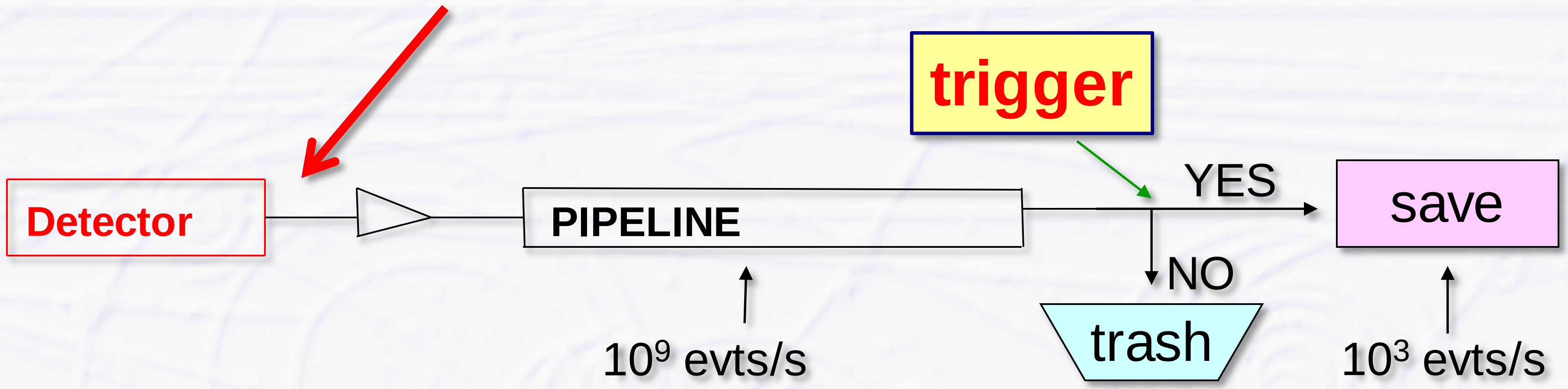
ATLAS Detector Status

(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%

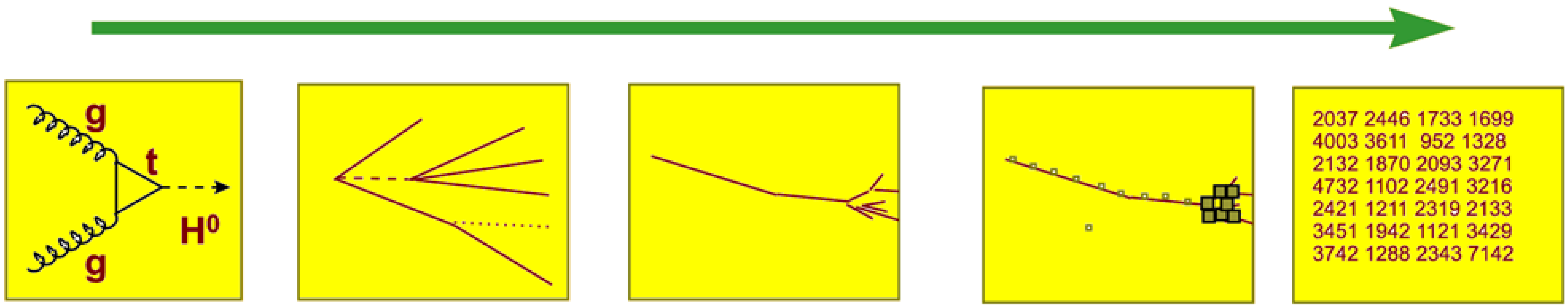
How to Select Interesting Events?

- 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 → 75 kHz
  - Level-2: software (computer farm), ~4 s decision time, 75 kHz → 1 kHz

From Physics to Raw Data



Basic physics

Collision Point

Fragmentation, Decay

Interaction with detector material
Multiple scattering, interactions

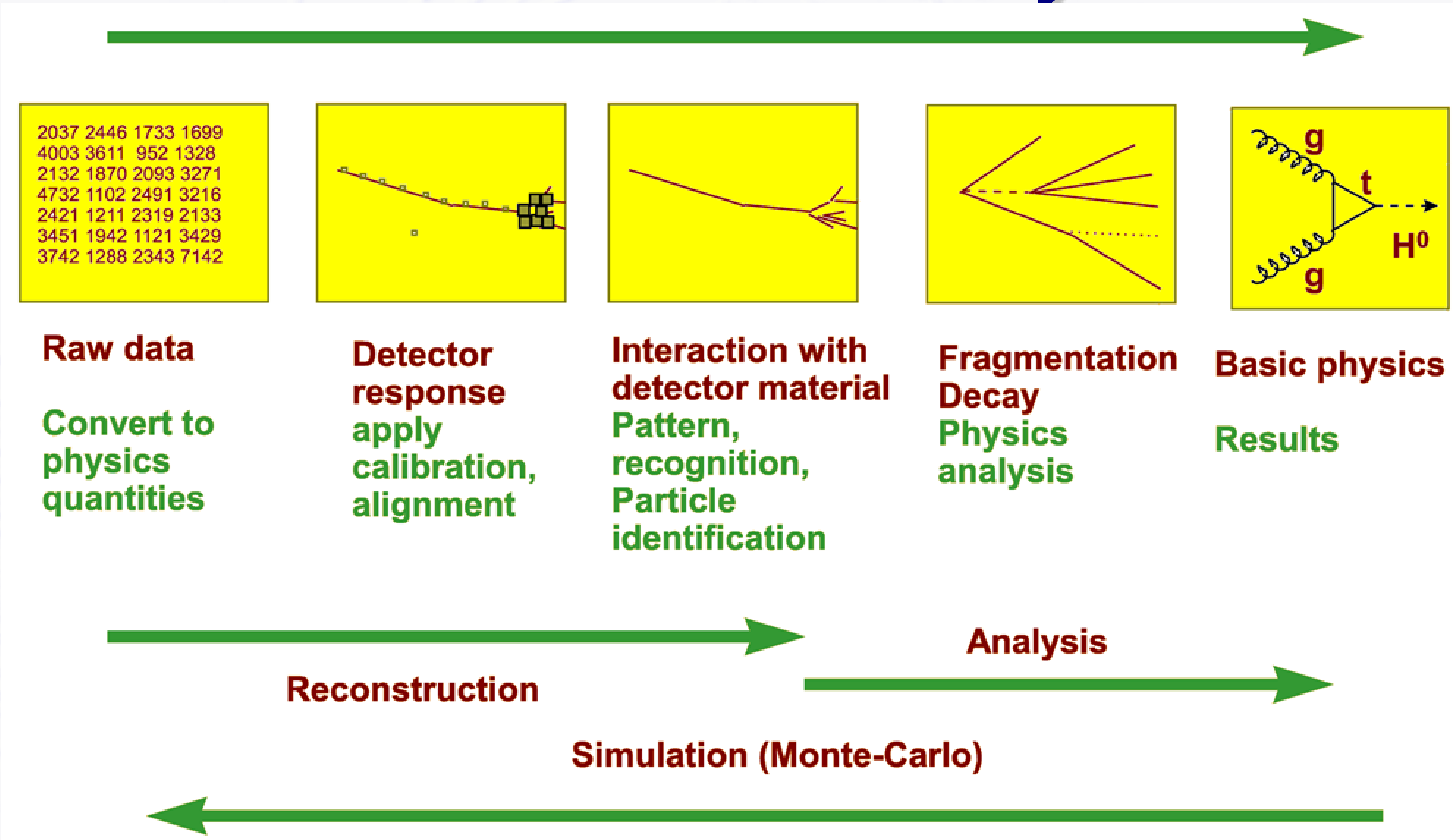
Detector response
Noise, pile-up, cross-talk, inefficiency, ambiguity, resolution, response function, alignment

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...**

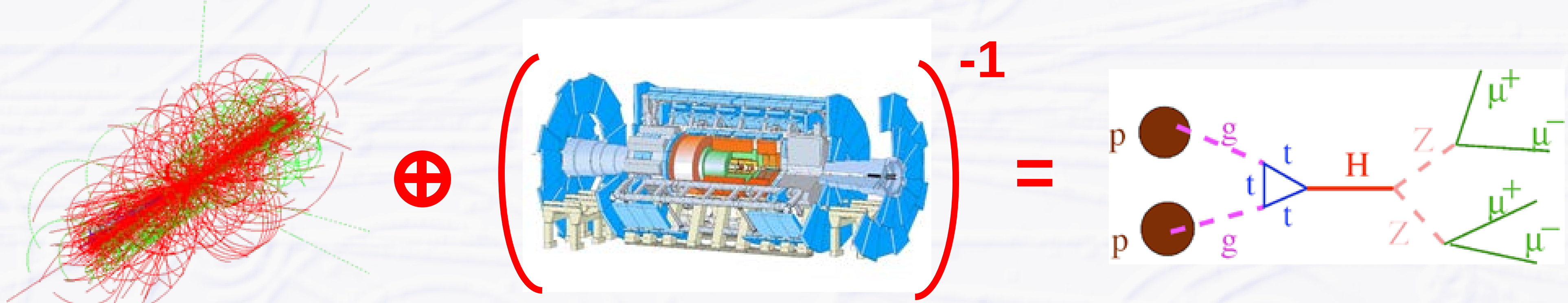
From Raw Data To Physics



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

Simulation (Monte Carlo)

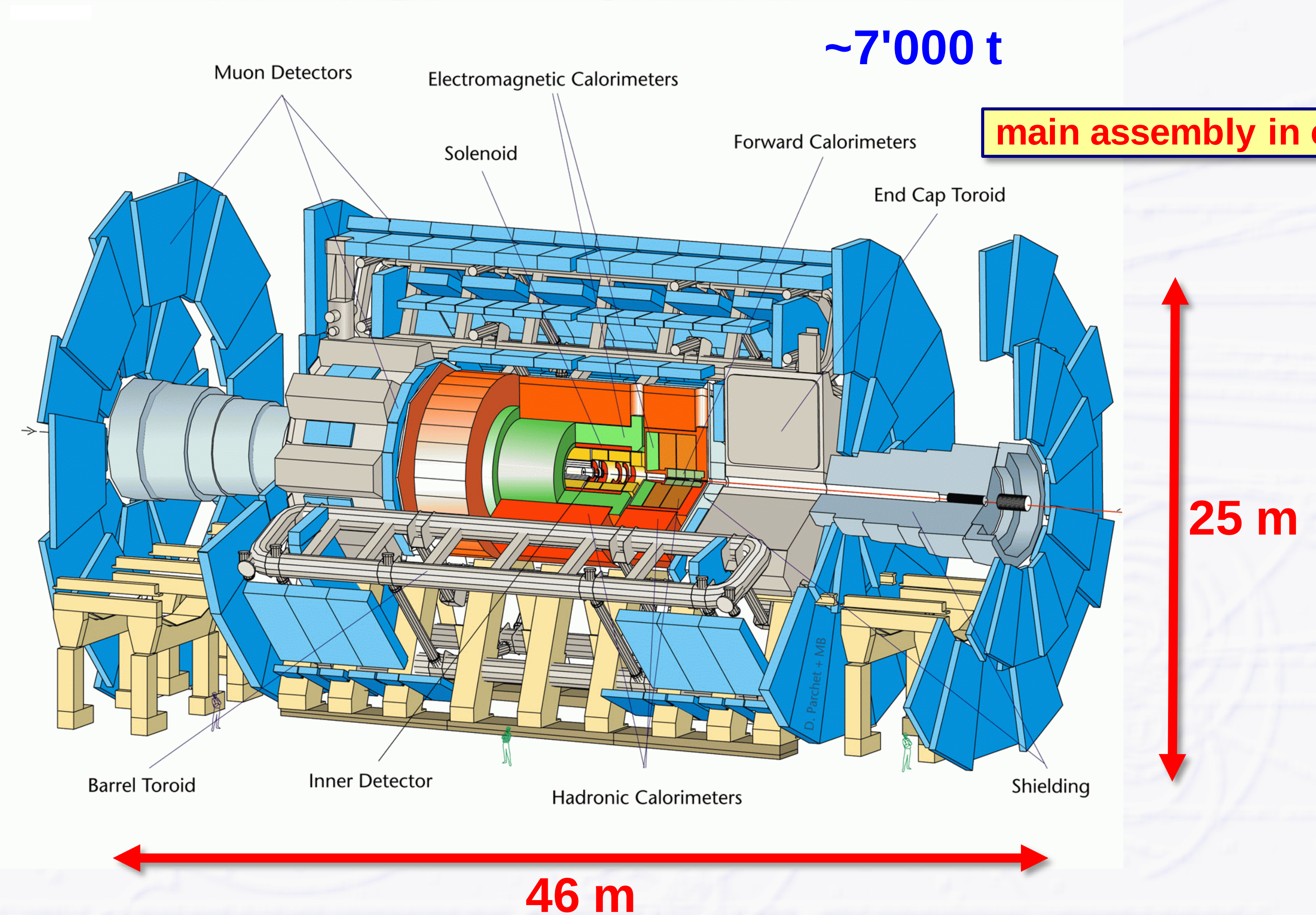
- **Even with best calibration + alignment**
  - **some detector influence, e.g. efficiency for track reconstruction etc. will not be known well enough from data**
  - **Use detector simulation (Monte Carlo) to "unfold" detector influence**



measured data | detector | physics

- **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**

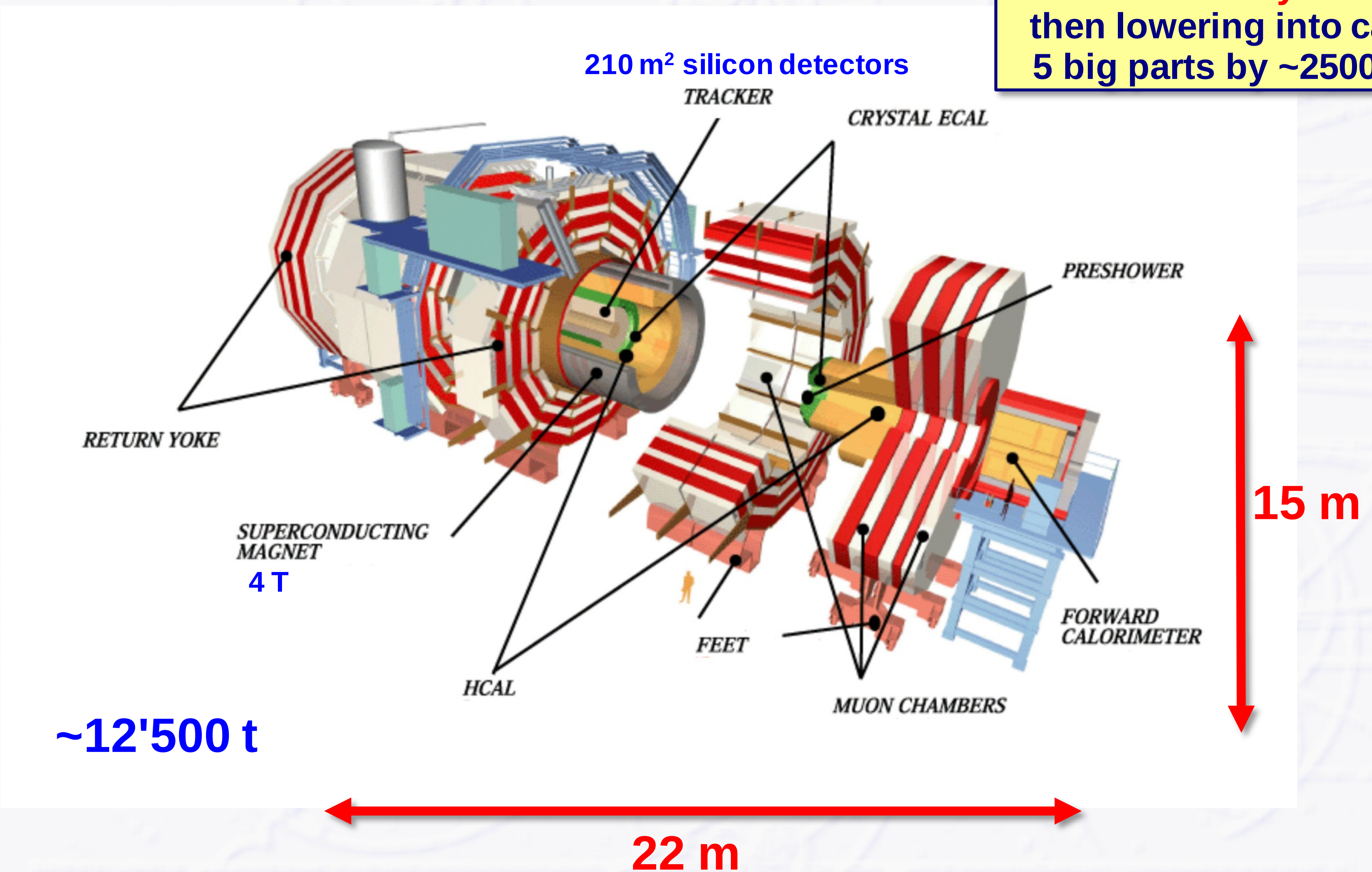
ATLAS (A Toroidal LHC ApparatuS)



main assembly in cavern

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

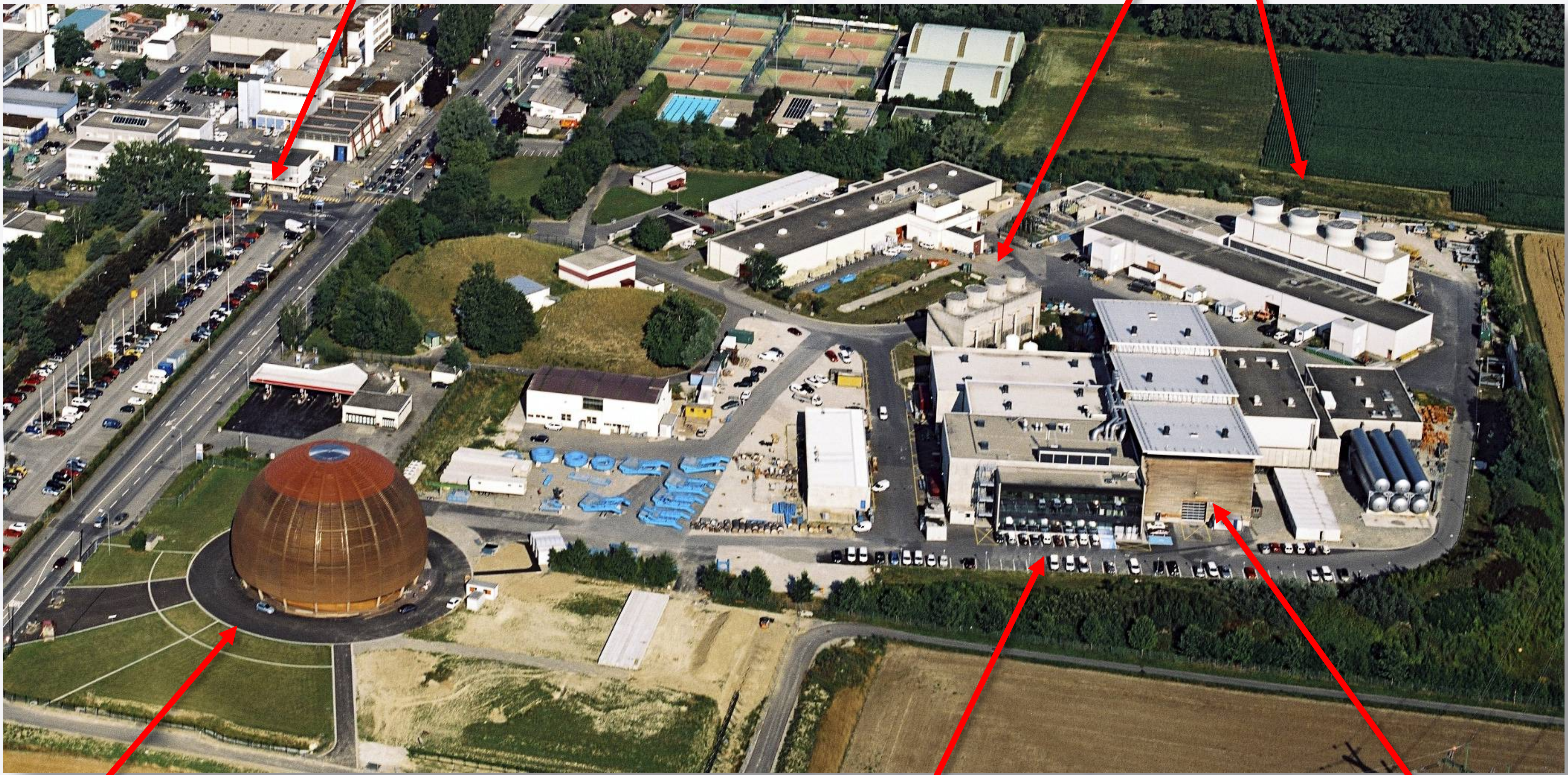
Gallo-roman remains
on future CMS site

ATLAS cavern
September 2000

The ATLAS Site 2005

CERN Main Entrance B

LHC Cooling Towers

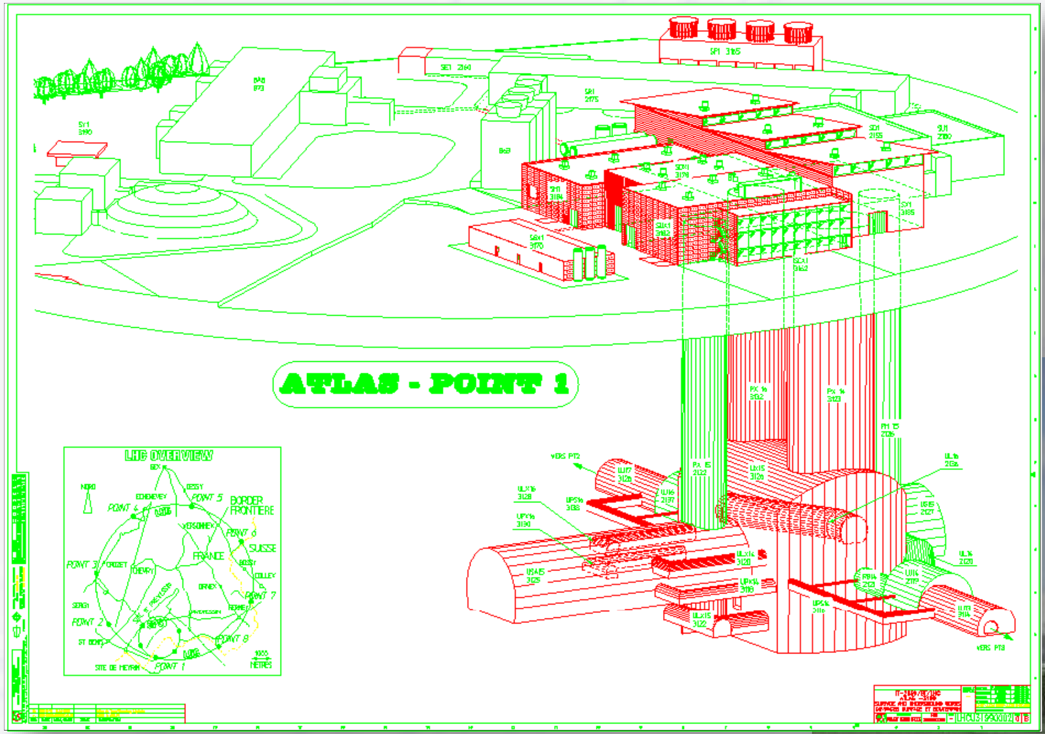


Globe of Innovation & Science

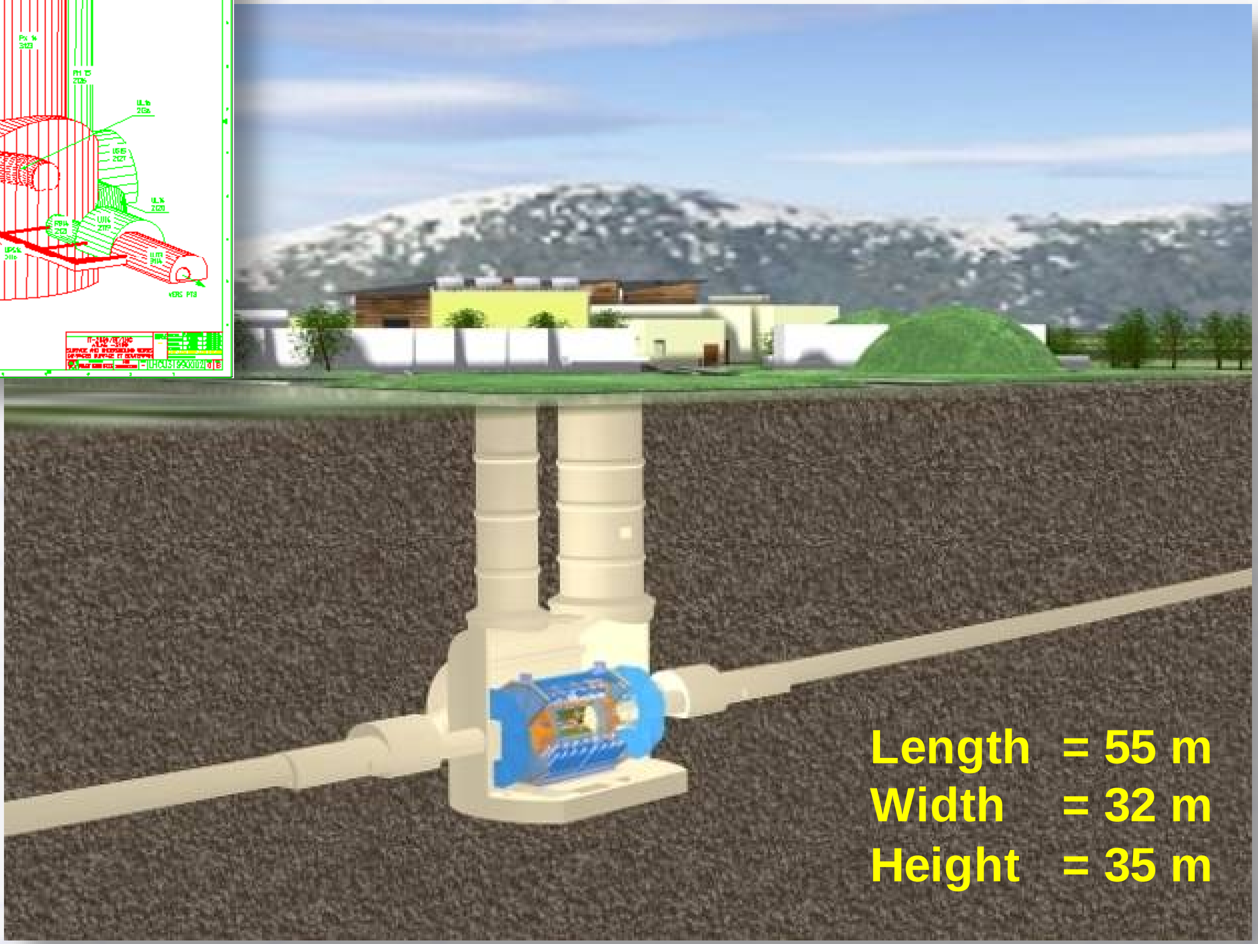
ATLAS Control Room and Visitor Centre

ATLAS Main Hall

ATLAS Underground Cavern



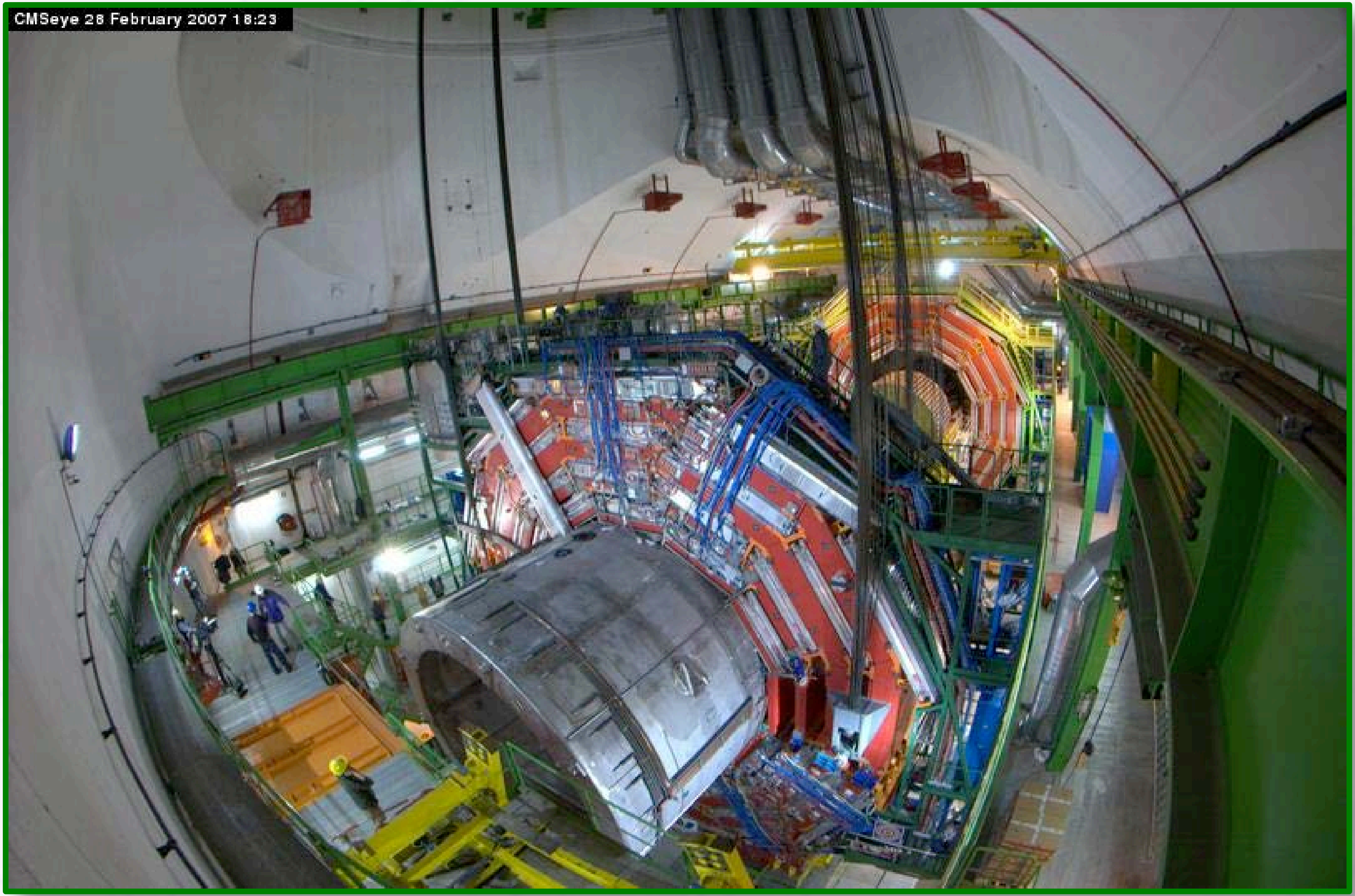
huge cavern + surface buildings,
2 access shafts 18m + 12m Ø,
2 small shafts for elevators + stairs



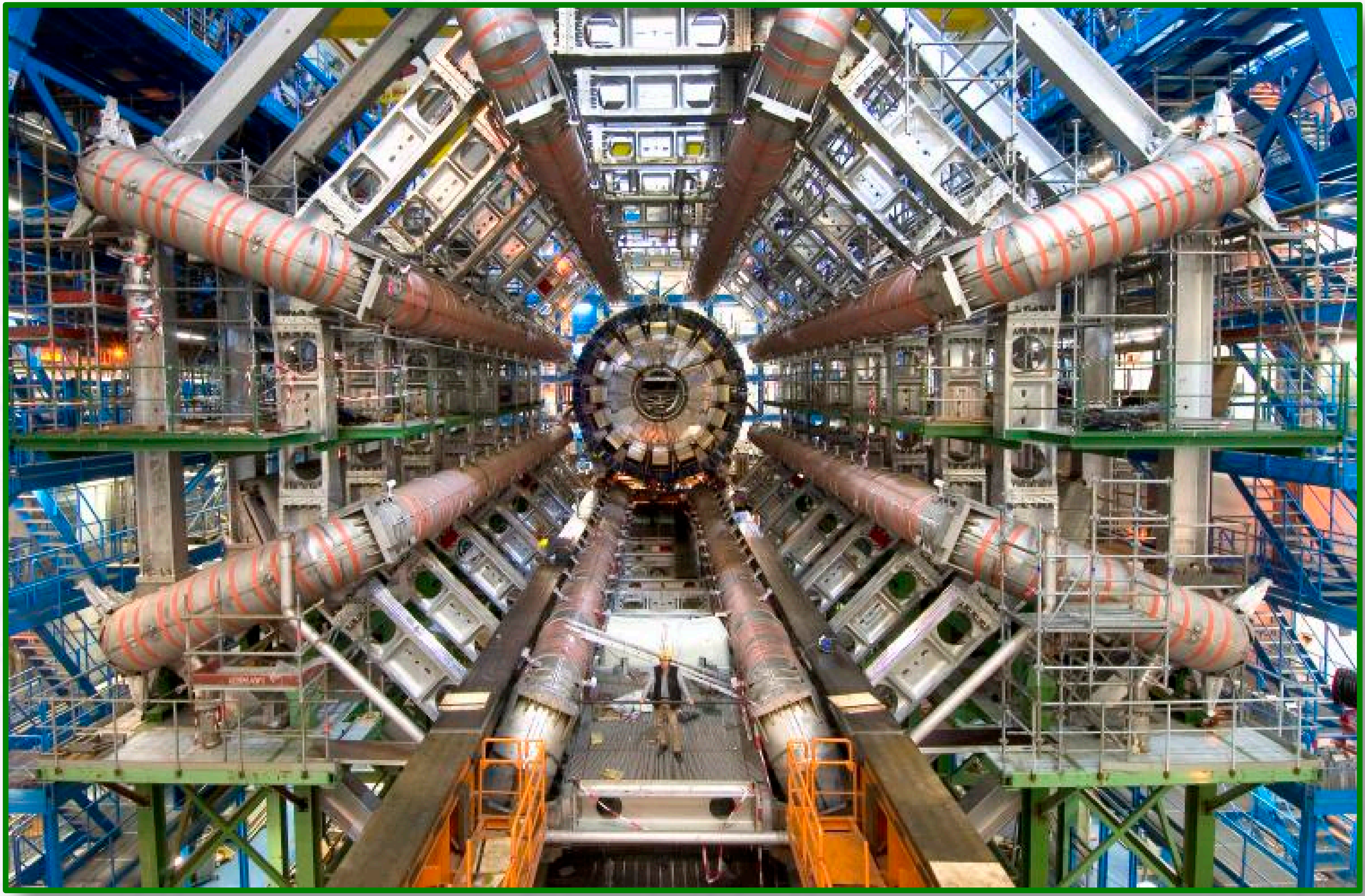
Start of ATLAS Detector Construction

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