2. The ATLAS and CMS detectors

2.1 LHC detector requirements

2.2 Detection principles

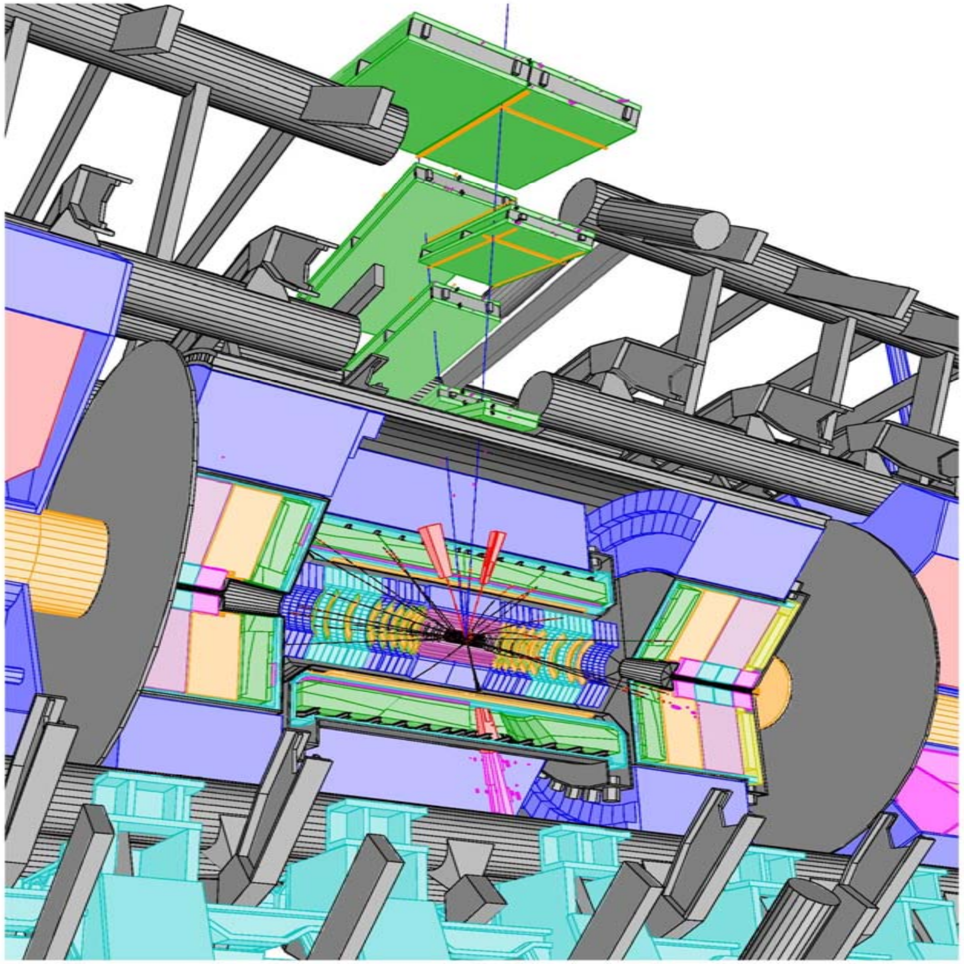
2.3 Introduction to detector physics

2.4 Tracking detectors, momentum measurement

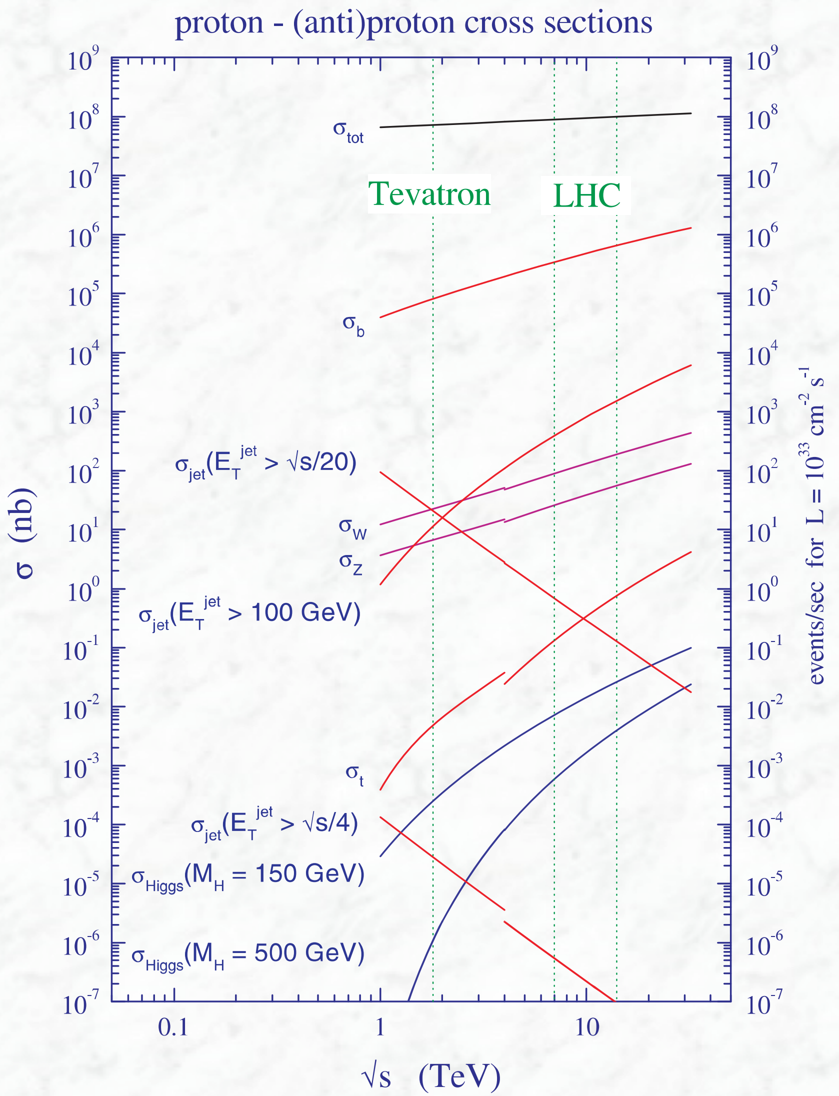
2.5 Energy measurements in calorimeters

2.6 Muon detectors

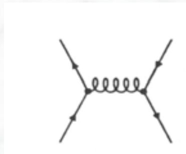
2.7 Important differences between ATLAS and CMS



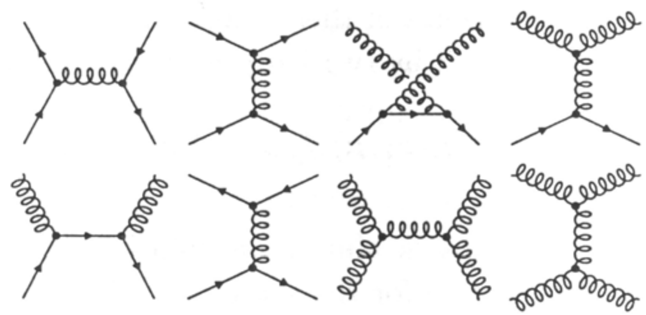
Production rates at the LHC



Rates for $\sqrt{s}$ = 7 TeV, L = 10^{34} cm^{-2} s^{-1}:

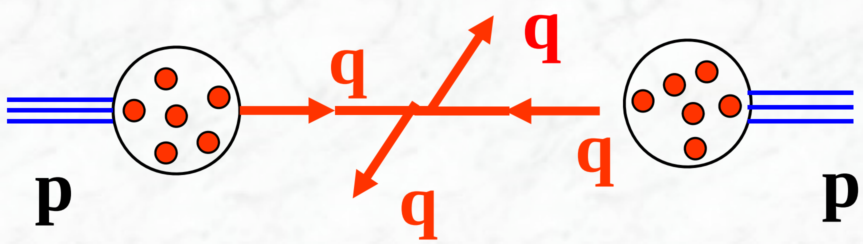
• Inelastic proton-proton reactions: • Quark –quark/gluon scattering with large transverse momentum	10^9 / sec ~ 5 10^7 / sec
• b-quark pairs • Top-quark pairs 	5 10^6 /sec 8 / sec
• W $\rightarrow$ e ν • Z $\rightarrow$ e e	150 / sec 15 / sec
• Higgs (150 GeV) • Gluino, squarks (1 TeV)	0.2 / sec 0.03 / sec

Dominant hard scattering processes: quark - quark
quark - gluon
gluon - gluon



What experimental signatures can be used ?

Quark-quark scattering:

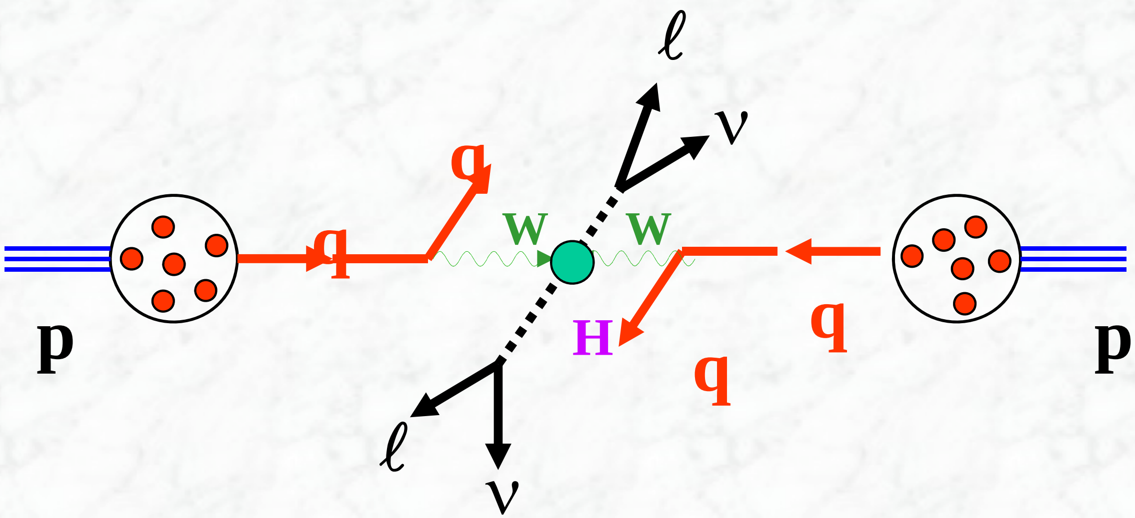


No leptons / photons in the initial and final state

If leptons with large transverse momentum are observed:

$\Rightarrow$ **interesting physics !**

Example: Higgs boson production and decay

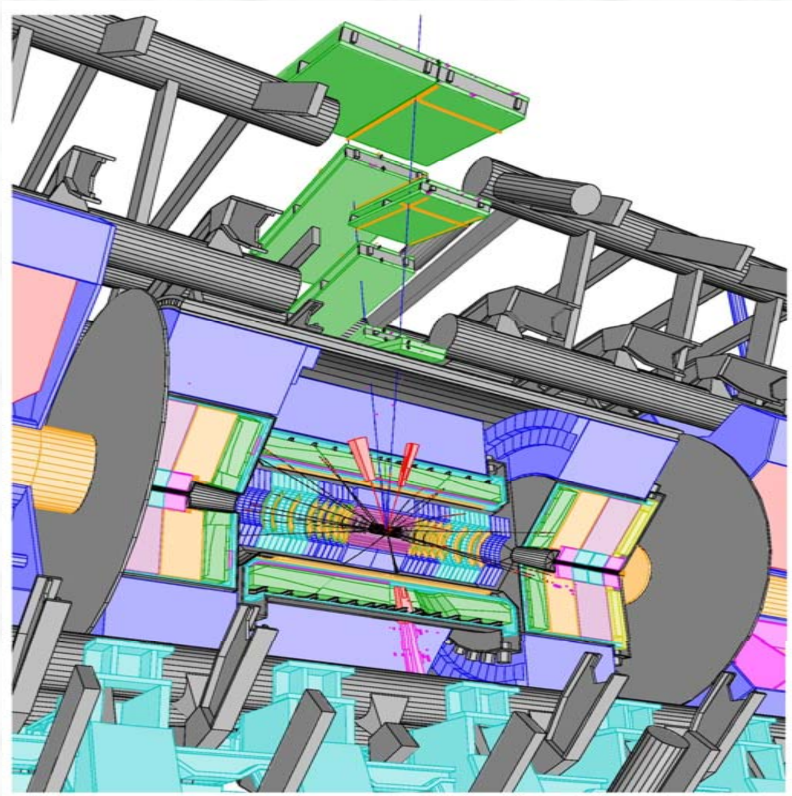


<u>Important signatures:</u>

- Leptons und photons
- Missing transverse energy

Detector requirements from physics

- Good measurement of leptons (e,μ) and photons with large transverse momentum p_T



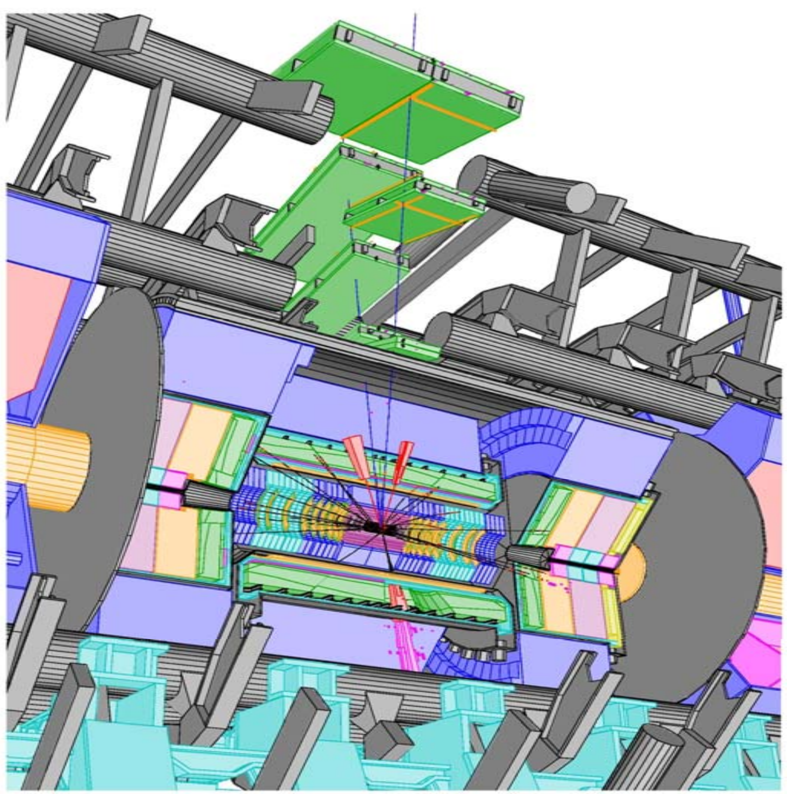
- Good measurement of missing transverse energy (E_T^{miss})

  and

  energy measurements in the forward regions
  $\Rightarrow$ calorimeter coverage down to about 1 deg. to the beam pipe

- Efficient b-tagging and τ identification (silicon strip and pixel detectors)

Detector requirements from the experimental environment (pile-up)

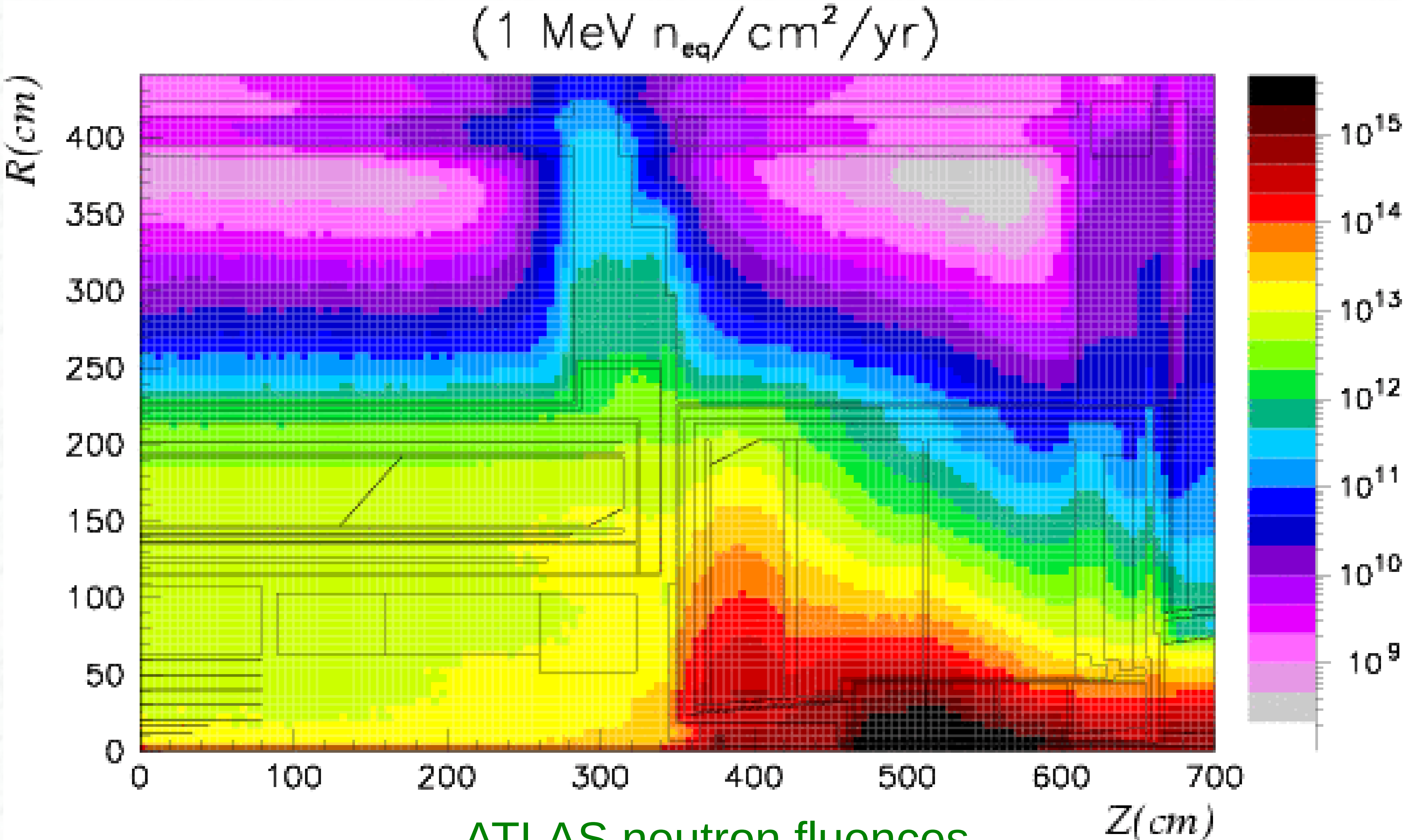


- LHC detectors must have **fast response**, otherwise integrate over many bunch crossings → too large pile-up

  Typical response time : 20-50 ns
  → integrate over 1-2 bunch crossings
  → pile-up of 25-50 minimum bias events
  ⇒ very challenging readout electronics

- **High granularity** to minimize probability that pile-up particles be in the same detector element as interesting object
  → large number of electronic channels, high cost

- LHC detectors must be **radiation resistant**: high flux of particles from pp collisions → high radiation environment
  e.g. in forward calorimeters: up to 10^{17} n / cm^2 in 10 years of LHC operation



ATLAS neutron fluences

What parameters should be measured?

- Identification of leptons (e,μ) and photons (γ)
- Precise measurement of the lepton / photon four-vector (momentum and energy)

  Momentum measurement in a magnetic field (works for e, μ)

  Energy measurement in so-called electromagnetic calorimeters (e, γ)

- Identification and energy measurement of jets (quarks and gluons) ($\rightarrow$ energy measurement of hadrons)

  Energy measurement in so-called hadron calorimeters (charged and neutral hadrons)

- Measurement of the vector sum of the transverse energy (ΣE_x, ΣE_y); modulus = total transverse energy

  electromagnetic and hadronic calorimeter
  (energy sum over all calorimeter units / cells, both electromagnetic and hadronic calorimeter)

- Missing transverse energy: = - (ΣE_x, ΣE_y)

- Identification of the third generation particles (b-quarks and τ–leptons)

3rd generation particles are very important in many physics scenarios

* they are heavy → strong coupling to the Higgs boson

* appear in top-quark decays: $t \rightarrow W\,b \rightarrow l\nu\,b$

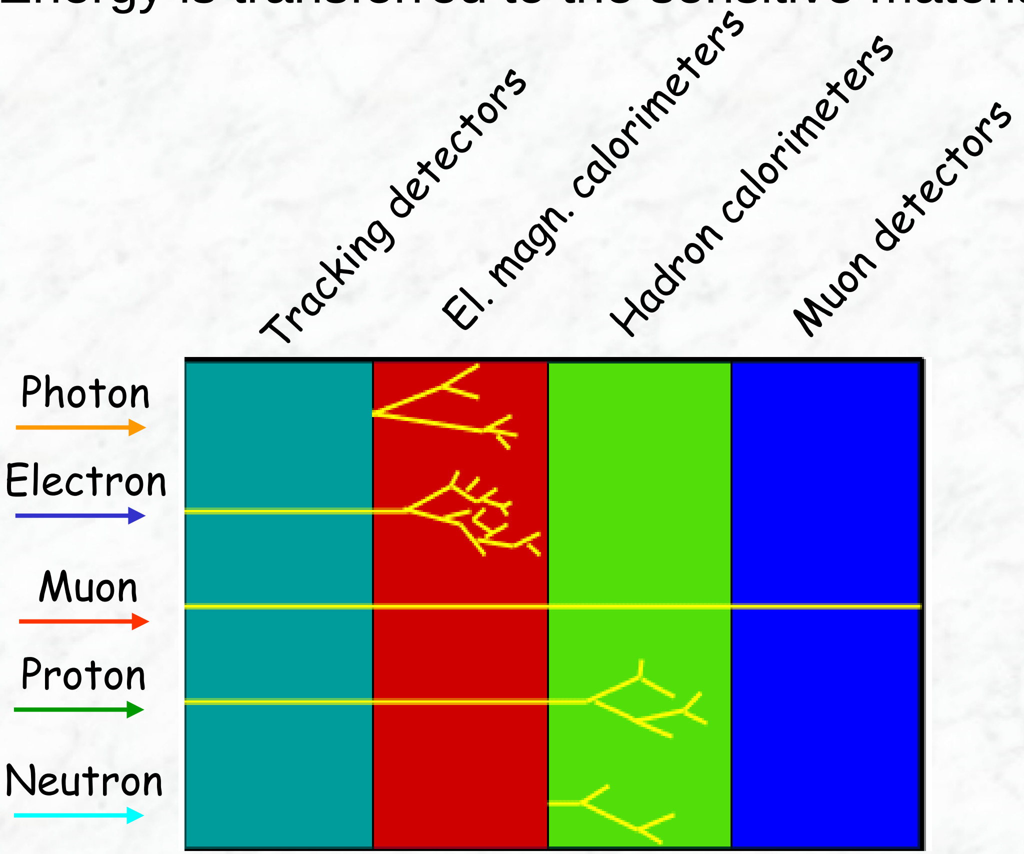
* appear in decays of SUSY particles
(the supersymmetric partners of the b- and t-quark might be the lightest squarks)

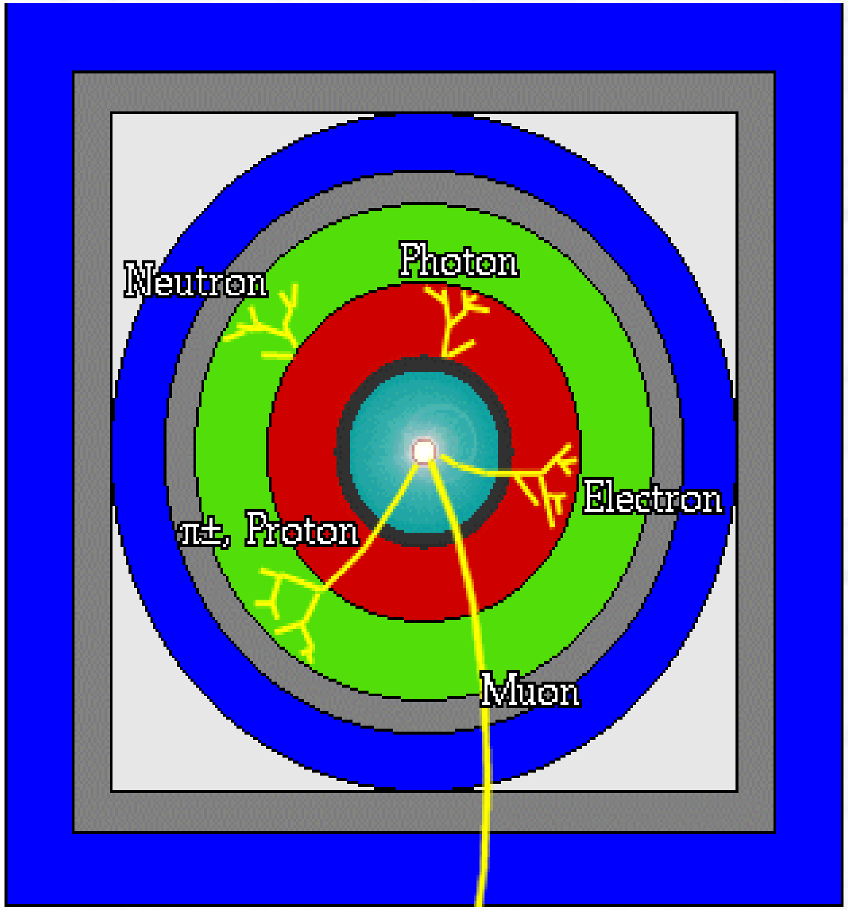
Characteristic signatures: lifetime in the order of picoseconds
τ (B-hadrons) ~1.5 ps $c\gamma\tau$ ~ 2-3 mm
τ (τ lepton) ~ 0.3 ps

Reconstruction of the decay vertices (secondary vertices) in the vicinity of the primary vertex (interaction point)

2.2 Detection principles

- Particles are detected via their interaction with matter, i.e. with the detector material; in general: full solid angle (4π) is covered; many particles → high segmentation of detectors
- Different particles interact differently with the detector media → possibility for their identification
- Energy is transferred to the sensitive material layers → electrical or light signal

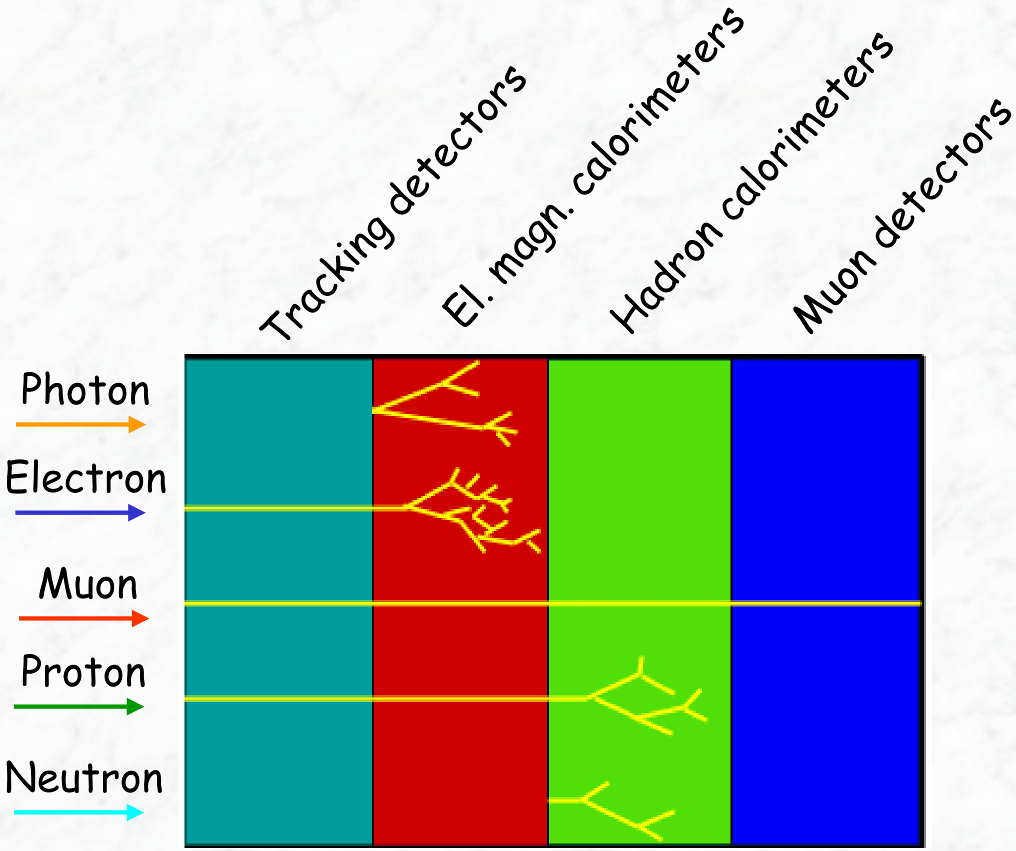


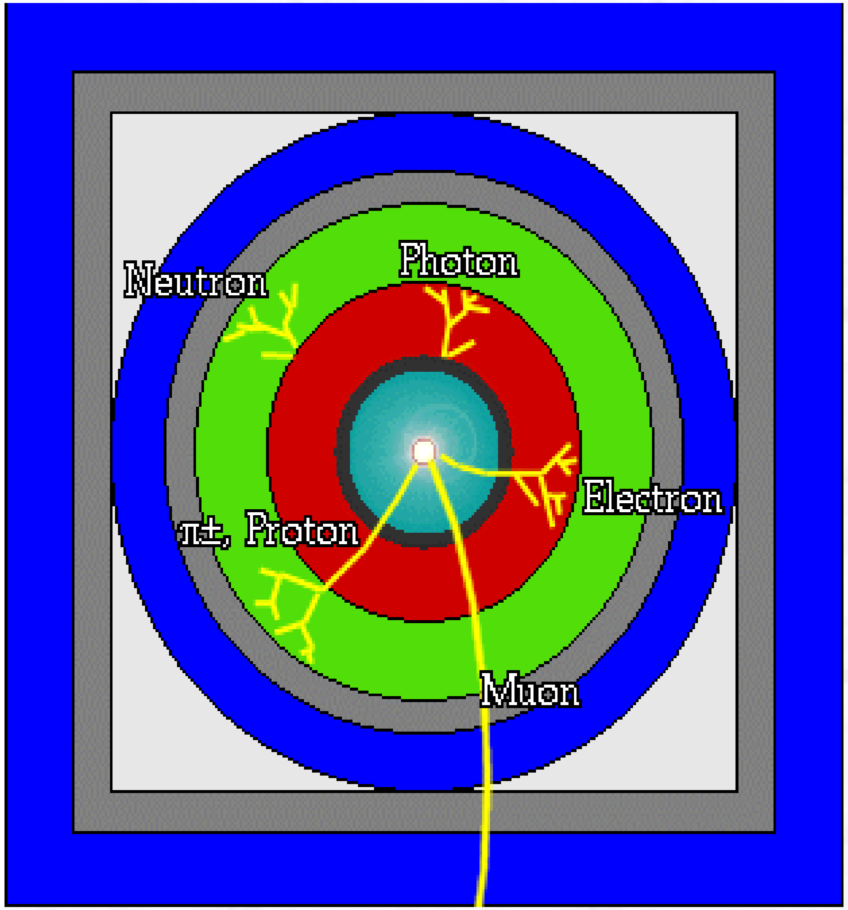


Detection principles (cont.)

(i) Tracking detectors:

- Measure the position (space information) of the particle several times; based on electromagnetic interaction, electric charge required
  → track of charged particles
- If a magnetic field in tracking volume → Lorentz force on charged particle
  → curvature of track
  → momentum p of charged particles



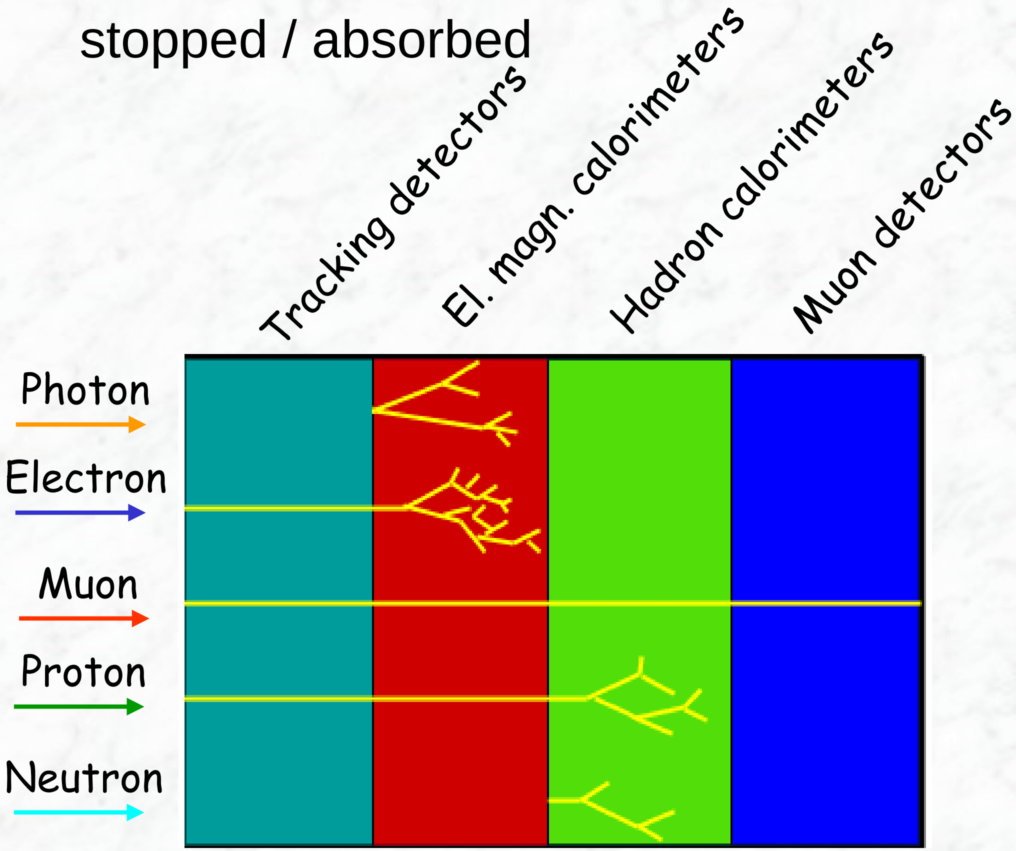


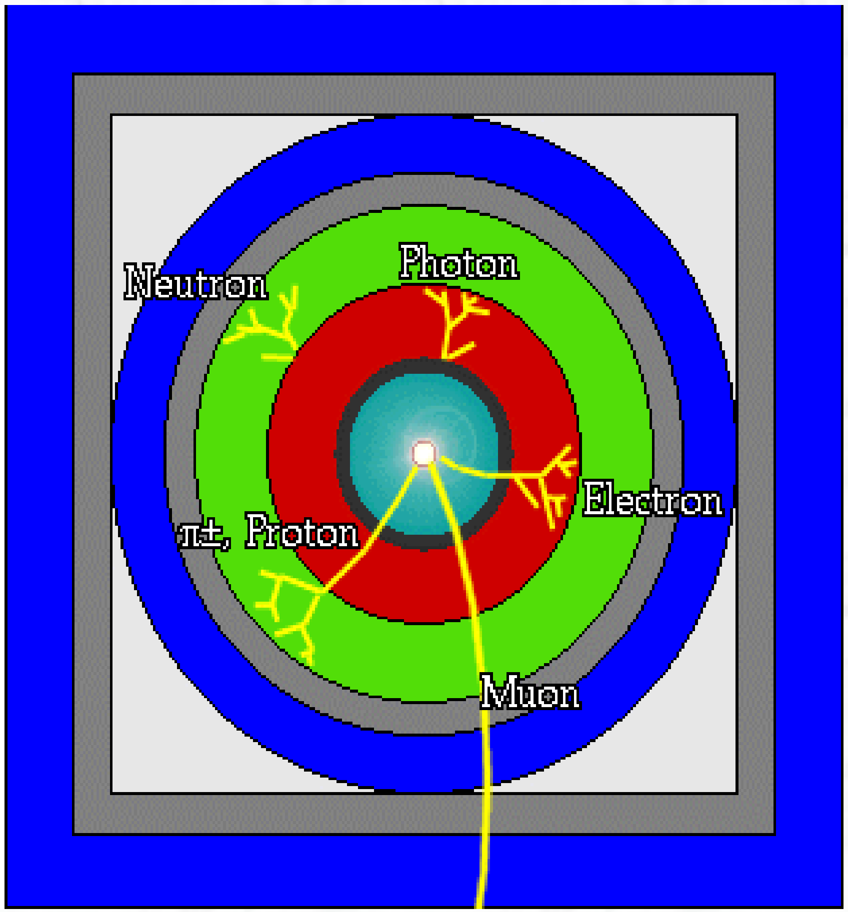
(ii) Calorimeters: measure the energy of the particles, particles are stopped, their full energy is deposited, part of it is transferred to a detector medium

Different particles (e, γ, π, K,…) differ in interactions and penetration length;

Usually two sections of the calorimeters:

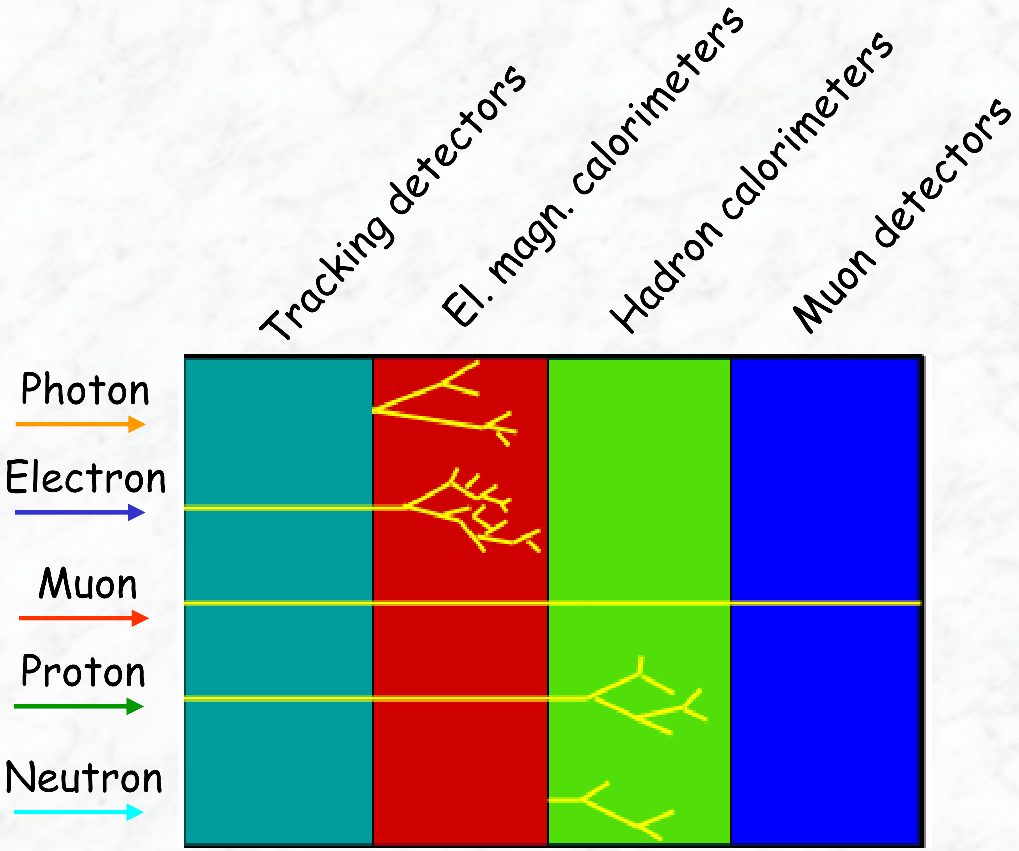
- Electromagnetic calorimeter: (e, γ) are stopped / absorbed;
- Hadronic calorimeter: hadrons are stopped (π, K, p, n, …..)
- note: muons and neutrinos are NOT stopped / absorbed

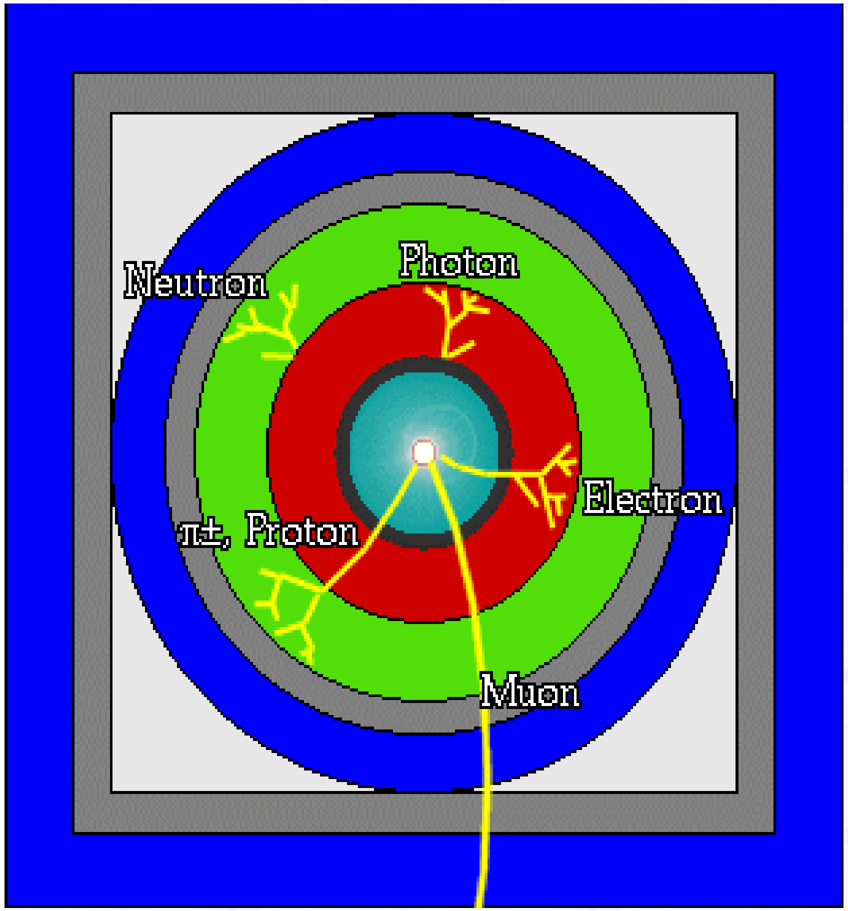




(iii) Muon detectors:

- Due to their relatively large mass and their lepton nature, muons have a "small" interaction with the detector material;
- They penetrate the calorimeters and give signals in "tracking detectors" behind the calorimeters; these are called muon detectors;
- Signature: track, small signals in calorimeters, track in muon detector





(iv) How to detect neutrinos?

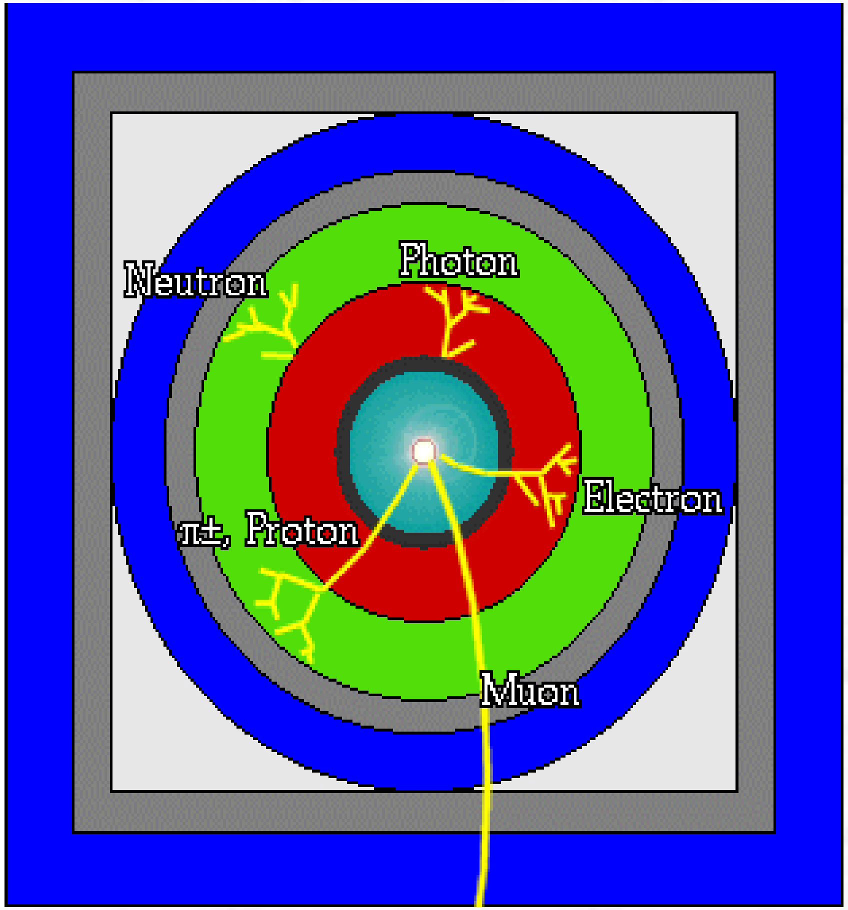
- Neutrinos interact only weakly, i.e. via the weak interaction, with the detector material

- Detector thickness is far too small to stop/absorb them

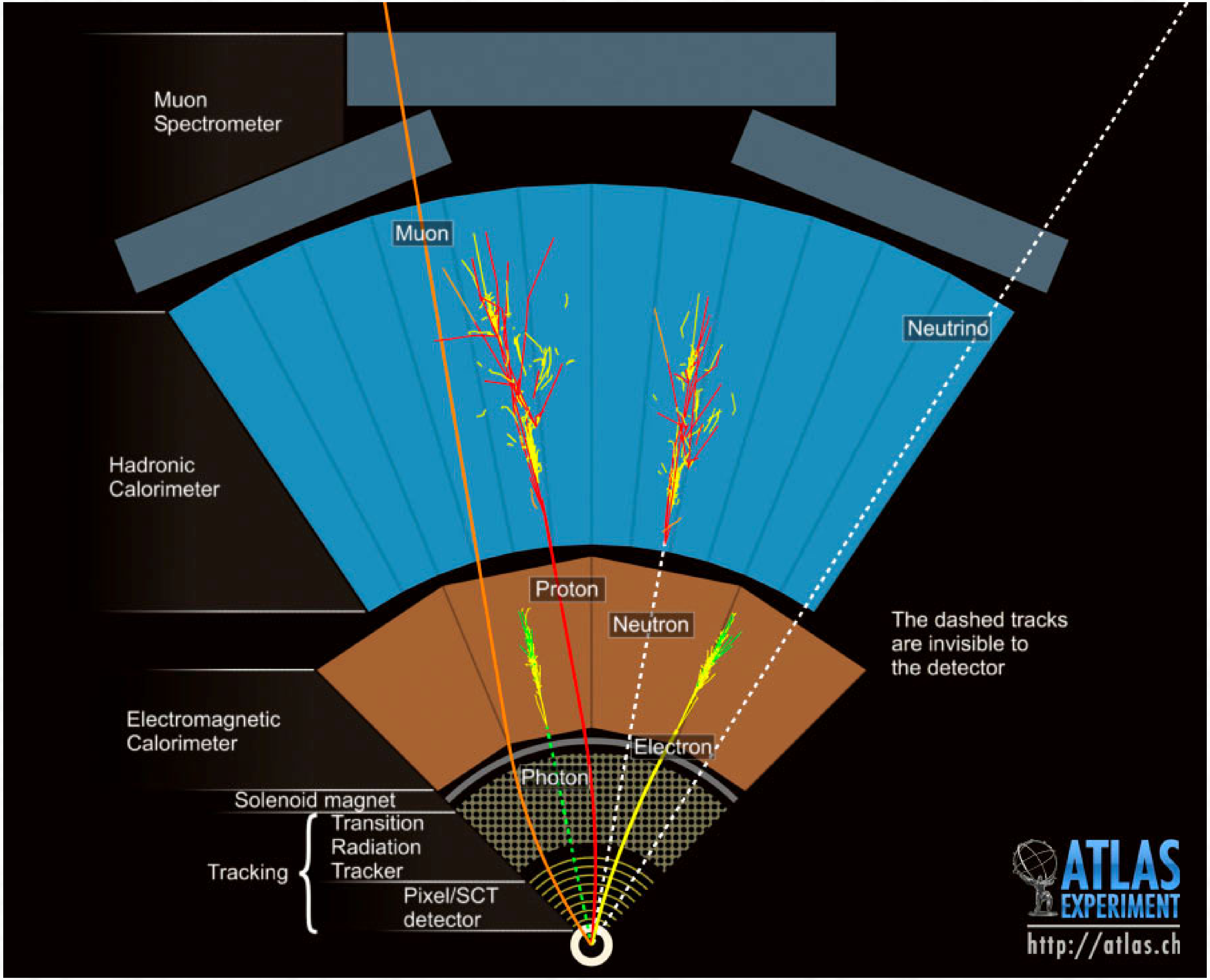
- They carry away energy and momentum

- Their presence can only be inferred via an apparent violation of energy and momentum conservation

  i.e. indirect detection of neutrinos
  (and other purely weakly interacting particles)



Layers of the ATLAS detector



2.3 Introduction to Detector Physics

- Detection through the interaction of particles with matter, e.g. via energy loss in a medium (ionization and excitation)

- Energy loss must be detected, made visible, mainly in form of electric signals or light signals

- Fundamental interaction for charged particles: electromagnetic interaction
  Energy is mainly lost due to interaction of the particles with the electrons of the atoms of the medium

  Cross sections are large: $\sigma \sim 10^{-17} - 10^{-16}$ cm^2 !!

  Small energy loss per collision, however, large number of them in dense materials

- Interaction processes (energy loss, scattering,..) are a nuisance for precise measurements and limit their accuracy

Overview on energy loss / detection processes

Charged particles	Photons, γ
Ionisation and excitation Bremsstrahlung	Photoelectric effect Compton scattering Pair creation
Cherenkov radiation Transition radiation	

2.3.1 Energy loss by ionisation and excitation

- A charged particle with mass m_0 interacts primarily with the electrons (mass m_e) of the atom;
  Inelastic collisions → energy loss

- Maximal transferable kinetic energy is given by: $$T^{max} = \frac{2 m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e / m_0 + (m_e / m_0)^2}$$

  max. values: Muon with E = 1.06 GeV (γ = 10): E_{kin}^{max} ~100 MeV

  Two types of collisions:
  Soft collision: only excitation of the atom
  Hard collision: ionisation of the atom
  In some of the hard collisions the atomic electron acquires such a large energy that it causes secondary ionisation (δ-electrons).

  → Ionisation of atoms along the track / path of the particle;
  In general, small energy loss per collision, but many collisions in dense materials → energy loss distribution
  one can work with average energy loss

- Elastic collisions from nuclei cause very little energy loss, they are the main cause for deflection / scattering under large angles

Bethe-Bloch Formula

Bethe-Bloch formula gives the mean energy loss (stopping power) for a heavy charged particle ($m_0 >> m_e$)*

$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

PDG 2008

A : atomic mass of absorber

$\frac{K}{A} = 4\pi N_A r_e^2 m_e c^2 / A = 0.307075$ MeV g^{-1}cm^2, for A = 1g mol^{-1}

z: atomic number of incident particle

Z: atomic number of absorber

I : energy needed for ionization

T^{max}: max. energy transfer (see previous slide)

$\delta\,(\beta\gamma)$: density effect correction to ionization energy loss

$x = \rho\, s$, surface density or mass thickness, with unit g/cm^2
(where ρ is the density and s is the path length)

dE/dx has the units MeV cm^2/g

---

* note: Bethe-Bloch formula is not valid for electrons (equal mass, identical particles)

History of Energy Loss Calculations: dE/dx

1915: Niels Bohr, classical formula, Nobel prize 1922.
1930: Non-relativistic formula found by Hans Bethe
1932: Relativistic formula by Hans Bethe

Bethe's calculation is leading order in pertubation theory, thus only z^2 terms are included.

Additional corrections:

- z^3 corrections calculated by Barkas-Andersen
- z^4 correction calculated by Felix Bloch
  (Nobel prize 1952, for nuclear magnetic resonance).
  Although the formula is called Bethe-Bloch formula the z^4 term is usually not included.
- Shell corrections: atomic electrons are not stationary
- Density corrections: by Enrico Fermi
  (Nobel prize 1938, for the discovery of nuclear reaction induced by slow neutrons).

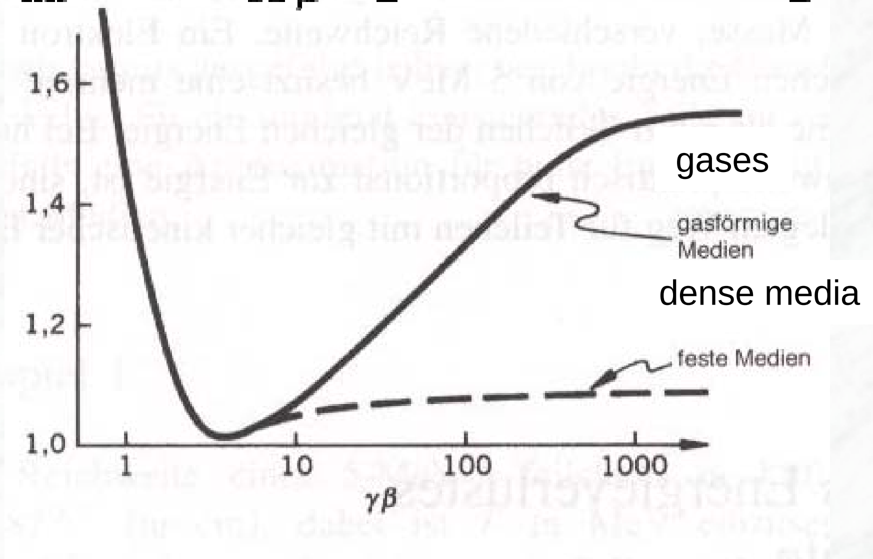
Hans Bethe (1906-2005)

Studied physics in Frankfurt and Munich, emigrated to US in 1933. Professor at Cornell U.,

Nobel prize 1967 for the theory of nuclear processes in stars.

$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln f(\beta) - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

Important features / dependencies:



- Energy loss is independent of the mass of the incoming particle → universal curve

- depends quadratically on the charge and velocity of the particle: ~ z^2/β^2

- dE/dx is relatively independent of the absorber (enters only via Z/A, which is constant over a large range of materials)

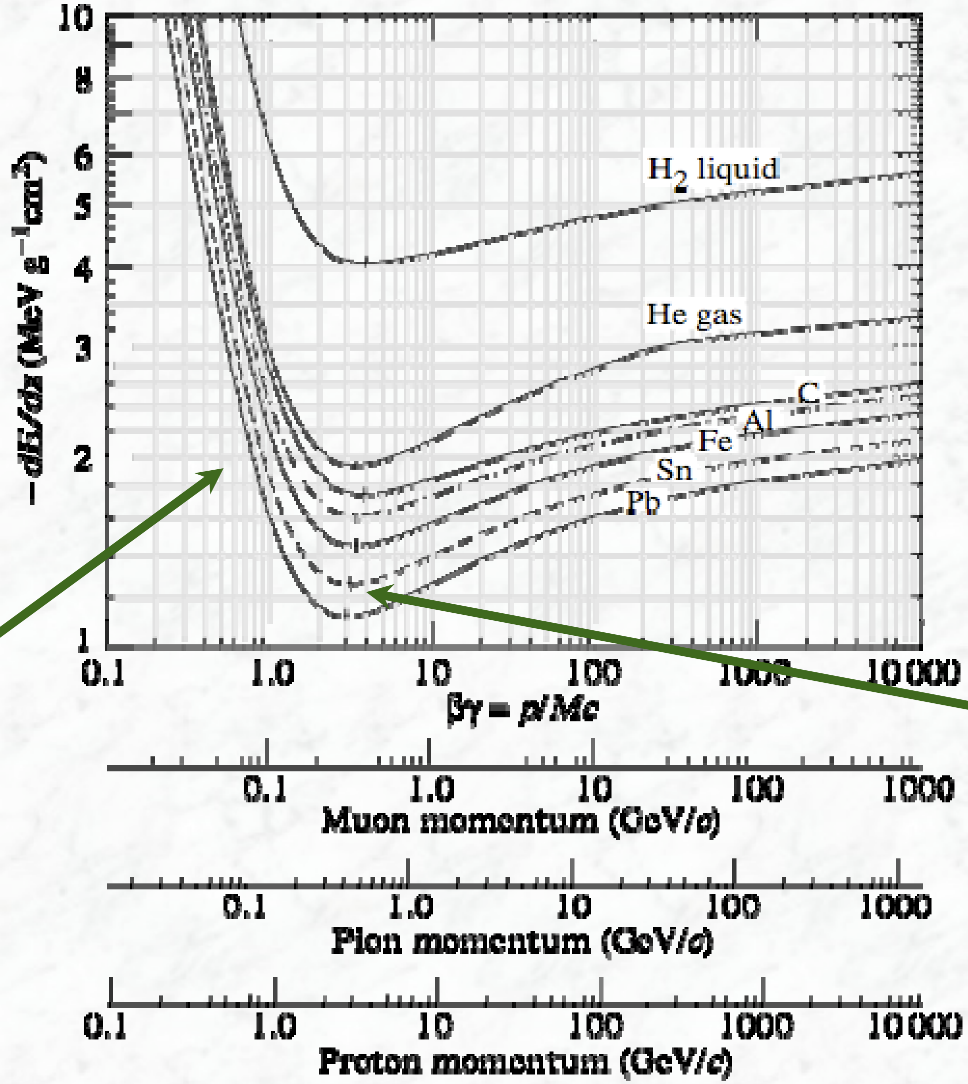
- Minimum for $\beta\gamma \approx 3.5$
  energy loss in the mimimum:

$$\boxed{\left.\frac{dE}{dx}\right|_{\min} \approx 1.5 \frac{MeV \cdot cm^2}{g}}$$

(particles that undergo minimal energy loss are called "mimimum ionizing particle" = mip)

- Logarithmic rise for large values of $\beta\gamma$ due to relativistic effects; This effect is damped in dense media $\delta(\beta\gamma)$

Examples of Mean Energy Loss



1/β^2

Figure 27.3: Mean energy loss rate in liquid (bubble chamber) hydrogen, gaseous helium, carbon, aluminum, iron, tin, and lead. Radiative effects, relevant for muons and pions, are not included. These become significant for muons in iron for $\beta\gamma \gtrsim 1000$, and at lower momenta for muons in higher-Z absorbers. See Fig. 27.21.

PDG 2008

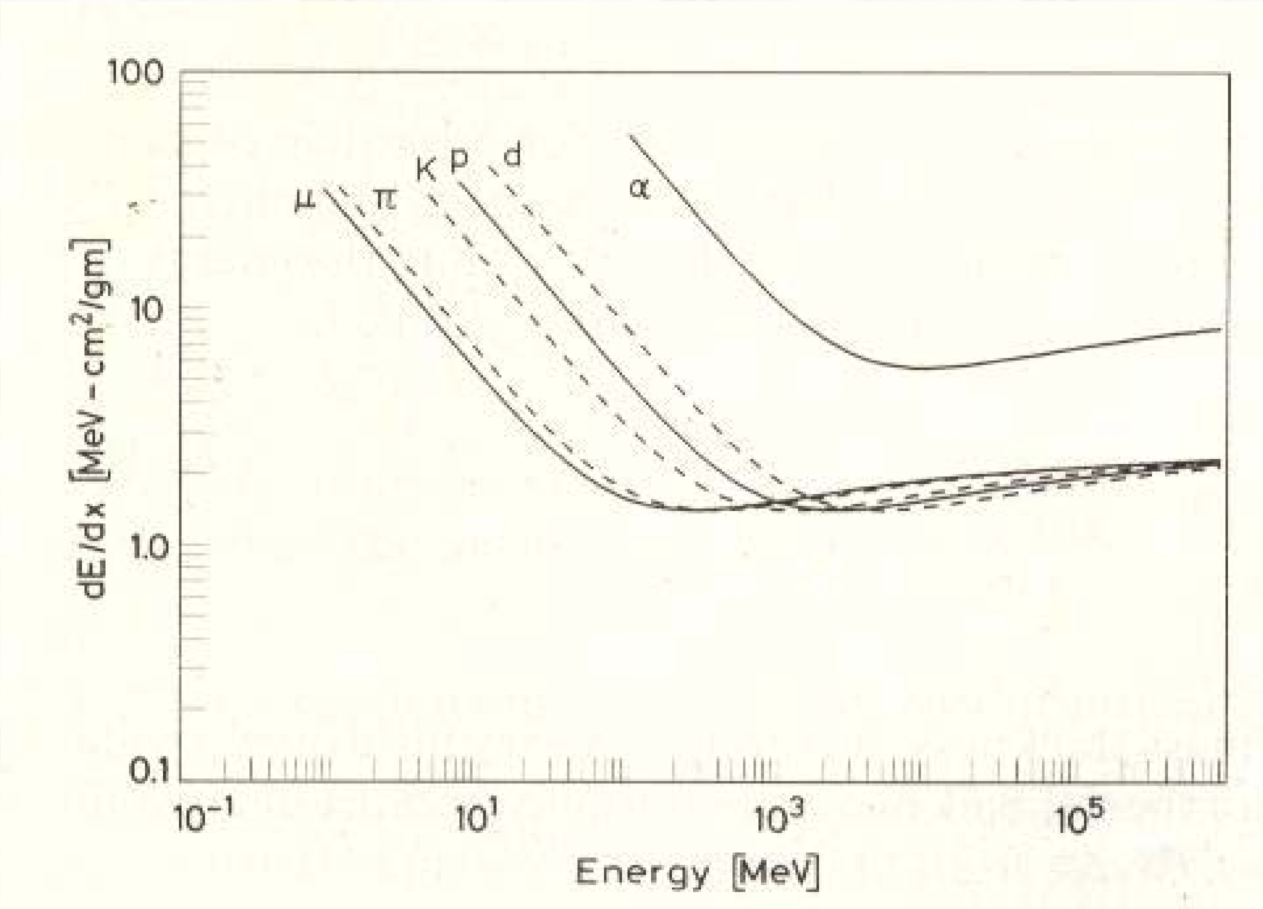
Bethe-Bloch formula:

$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln f(\beta) - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

Except in hydrogen, particles of the same velocity have similar energy loss in different materials.

The minimum in ionisation occurs at βγ = 3.5 to 3.0, as Z goes from 7 to 100

Consequence: dE/dx measurements can be used to identify particles

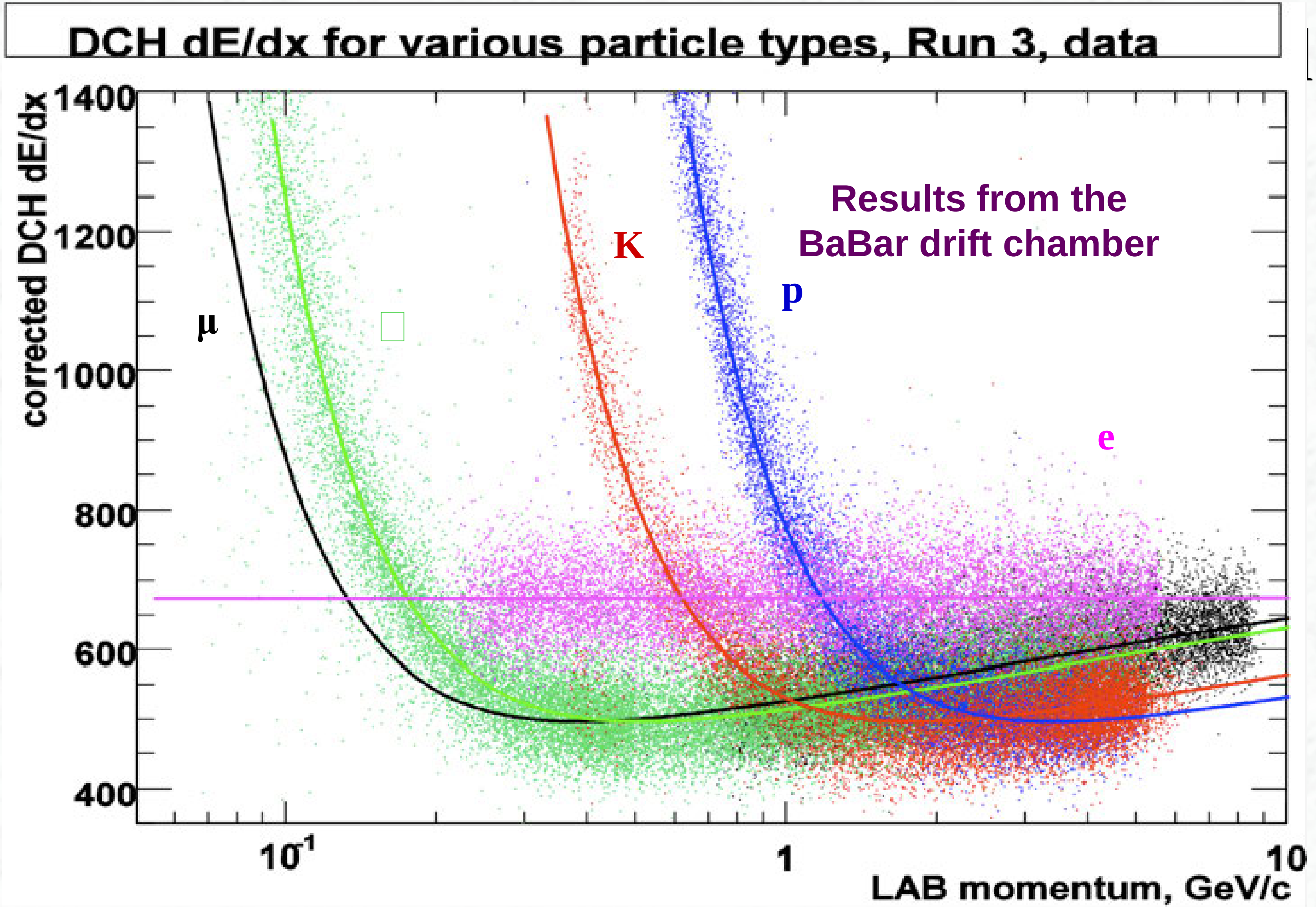


$$\beta\gamma = \frac{p}{E}\frac{E}{m} = \frac{p}{m}$$

- Universal curve as function of $\beta\gamma$ splits up for different particle masses, if taken as function of energy or momentum

→ a simultaneous measurement of dE/dx and p (or E) → particle identification

Example: BaBar experiment at SLAC



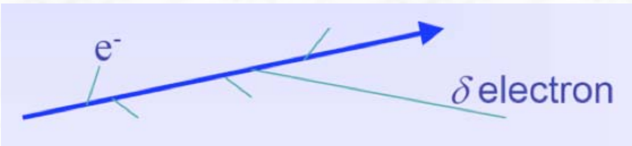
A simultaneous measurement of dE/dx and momentum p can provide particle identification. Works well in the low momentum range (< ~1 GeV)

Fluctuations in Energy Loss

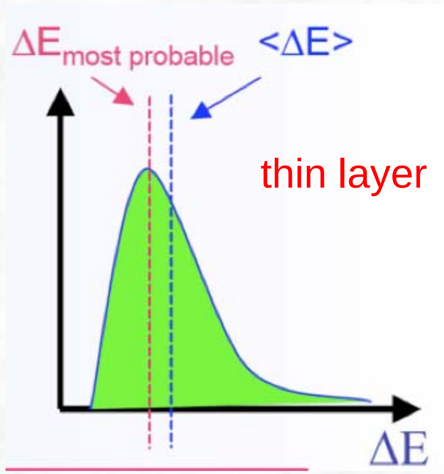
- A real detector (limited granularity) measures the energy ΔE deposited in layers of finite thickness Δx;

- Repeated measurements → sampling from an energy loss distribution

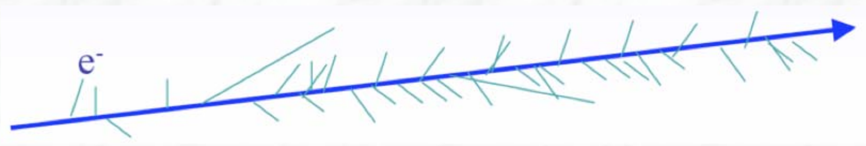
- For thin layers or low density materials, the energy loss distribution shows large fluctuations towards high losses, so called Landau tails.

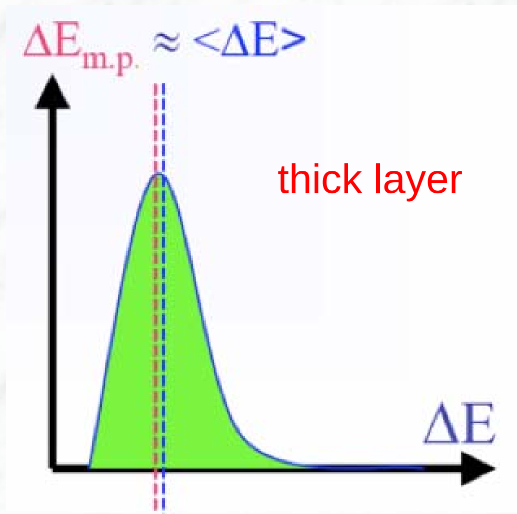


Example: Silicon sensor, 300 μm thick,
ΔE_{mip} ~82 keV, <ΔE> ~115 keV



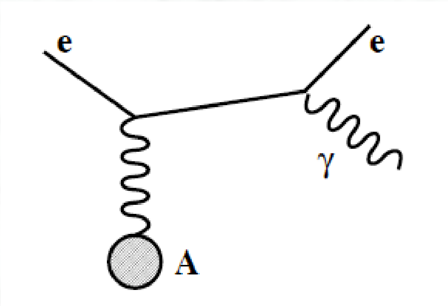
- For thick layers and high density materials, the energy loss distribution shows a more Gaussian-like distribution (many collisions, Central Limit Theorem)





2.3.2 Energy loss due to bremsstrahlung

- High energy charged particles undergo an additional energy loss (in addition to ionization energy loss) due to bremsstrahlung, i.e. radiation of photons, in the Coulomb field of the atomic nuclei



$$\boxed{-\frac{dE}{dx}\bigg|_{Brems} = 4\alpha N_A \left(\frac{e^2}{mc^2}\right)^2 \ln\frac{183}{Z^{1/3}}\frac{Z(Z+1)}{A} Q^2 E}$$

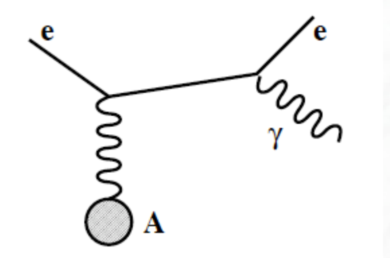
where: Q, m = electric charge and mass of the particle,
α = fine structure constant
A,Z = atomic number, number of protons of the material
N_A= Avogardo's number

- One can introduce the so-called radiation length X_0 defined via:

$$\boxed{\frac{1}{X_0} = 4\alpha N_A \left(\frac{e^2}{m_e c^2}\right)^2 \ln\frac{183}{Z^{1/3}}\frac{Z(Z+1)}{A}} \xrightarrow{\text{for electrons}} \boxed{-\frac{dE}{dx}\bigg|_{Brems} := \frac{1}{X_0}E}$$

It should be noted that in the definition of X_0 the electron mass is used (electron as incoming particle). It only depends on electron and material constants and chacterises the radiation of electrons in matter

$$\boxed{\beta\gamma = \frac{p}{E}\frac{E}{m} = \frac{p}{m}}$$



Most important dependencies:

- material dependence $$\frac{dE}{dx} \sim \frac{Z(Z+1)}{A}$$

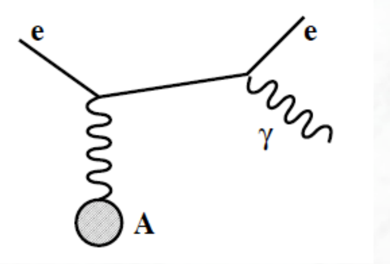
- depends on the mass of the incoming particle: $$\frac{dE}{dx} \sim \frac{1}{m^2}$$
  (light particles radiate more)
  This is the reason for the strong difference in bremsstrahlung energy loss between electrons and muons

$$\boxed{\left(\frac{dE}{dx}\right)_\mu / \left(\frac{dE}{dx}\right)_e \sim \frac{1}{40.000}}$$

- proportional to the energy of the incoming particle $$\frac{dE}{dx} \sim E$$

  This implies that this energy loss contribution will become significant for high energy muons as well

For electrons the energy loss equation reduces to



$$-\left.\frac{dE}{dx}\right|_{Brems} := \frac{1}{X_0} E \quad \Rightarrow \quad E(x) = E_0 e^{-x/X_0}$$

- The energy of an electron decreases exponentially as a function of the thickness x of the traversed material, due to bremsstrahlung;

After $x=X_0$: $\quad E(X_0) = \frac{E_0}{e} = 0.37 E_0$

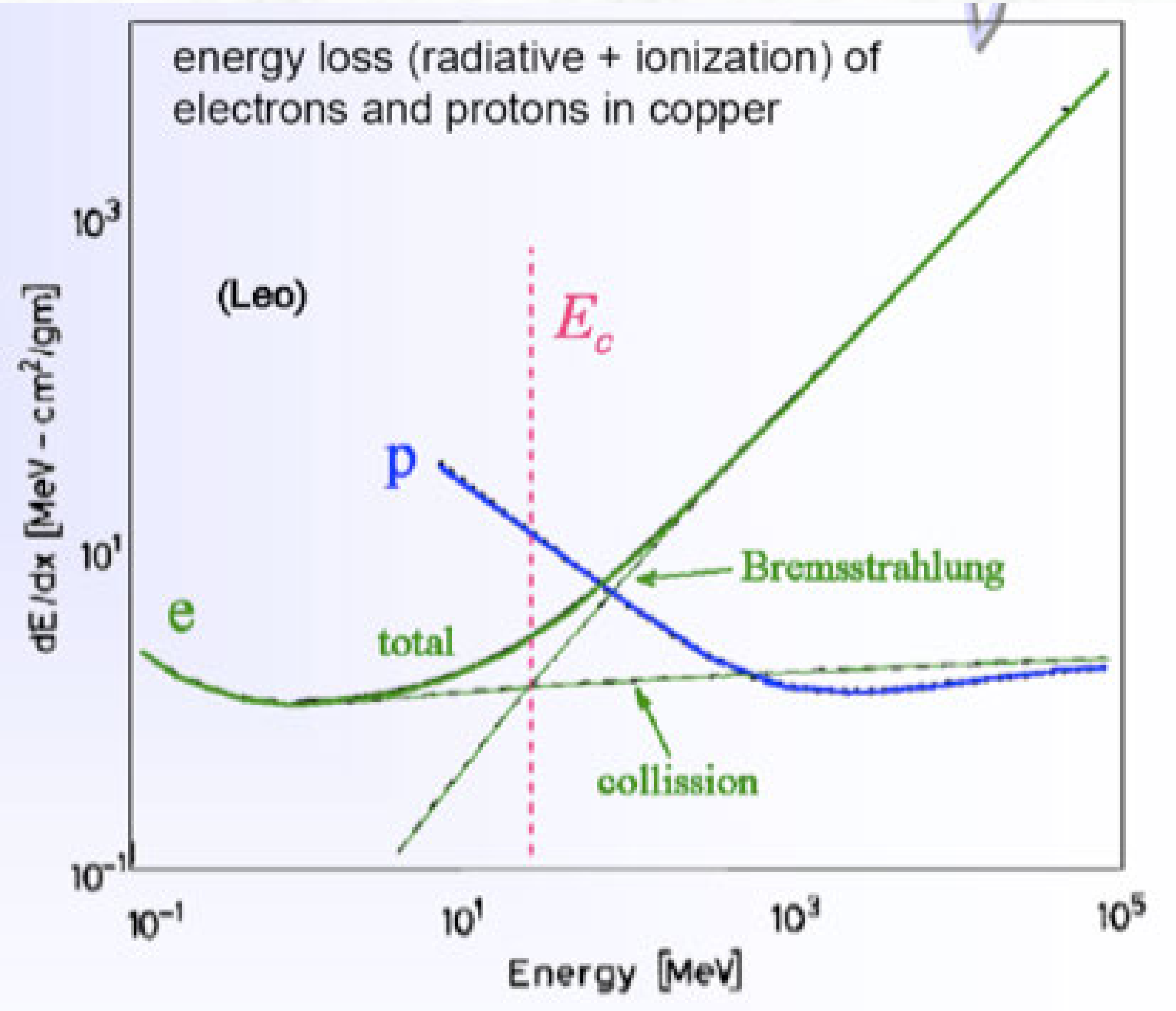
- Continuous 1/E energy loss spectrum, mainly soft radiation, with hard tail
- One defines the critical energy, as the energy where the energy loss due to ionization and bremsstrahlung are equal

$$\frac{dE}{dx} \sim \frac{Z(Z+1)}{A}$$

useful approximations for electrons:
(heavy elements)

$$E_c = \frac{550\,\mathrm{MeV}}{Z}$$

$$X_0 = 180 \frac{A}{Z^2} \left(\frac{\mathrm{g}}{\mathrm{cm}^2} \right)$$

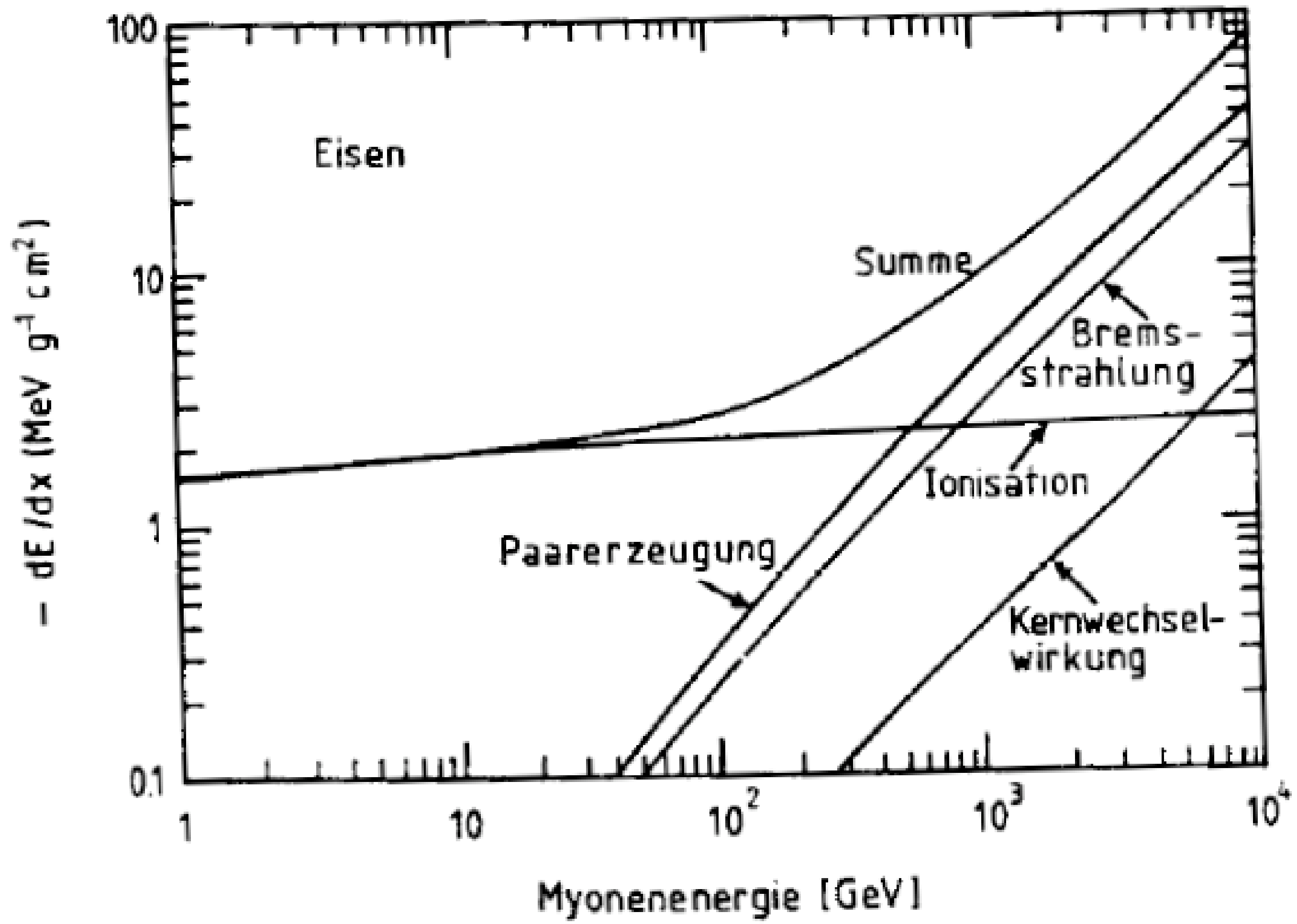


Critical energies in copper (Z = 29):

$E_c(e) \approx 20$ MeV

$E_c(\mu) \approx 1$ TeV

- Muons with energies > ~10 GeV are able to penetrate thick layers of matter, e.g. calorimeters;
- This is the key signature for muon identification



Energy loss dE/dx for muons in iron;

- critical energy ≈ 870 GeV;

- At high energies also the pair creation $\mu\,(A) \rightarrow \mu\, e^+e^-\,(A)$ becomes important

Material	Z	X_0 (cm)	E_c (MeV)
H_2 Gas He	1 2	70000 53000	350 250
Li C	3 6	156 18.8	180 90
Fe Cu W Pb	26 29 74 82	1.76 1.43 0.35 0.56	20.7 18.8 8.0 7.4
Air SiO_2 Water	7.3 11.2 7.5	30000 12 36	84 57 83

Radiations lengths and critical energies for various materials (from Ref. [Grupen])

2.3.3 Strong interaction of hadrons

- Charged and neutral hadrons can interact with the detector material, in particular in the dense calorimeter material, via the strong interaction

- The relevant interaction processes are inelastic hadron-hadron collisions, e.g. inelastic πp, Kp, pp and np scattering;
  In such interactions, usually new hadrons (mesons) are created, energy is distributed to higher multiplicities

  Hadronic interactions are characterized by the hadronic interaction length λ_{had}

- A beam of hadrons is attenuated in matter due to hadronic interactions as

$$I(x) = I_0 e^{-x/\lambda_{had}}$$

where x = depth in material

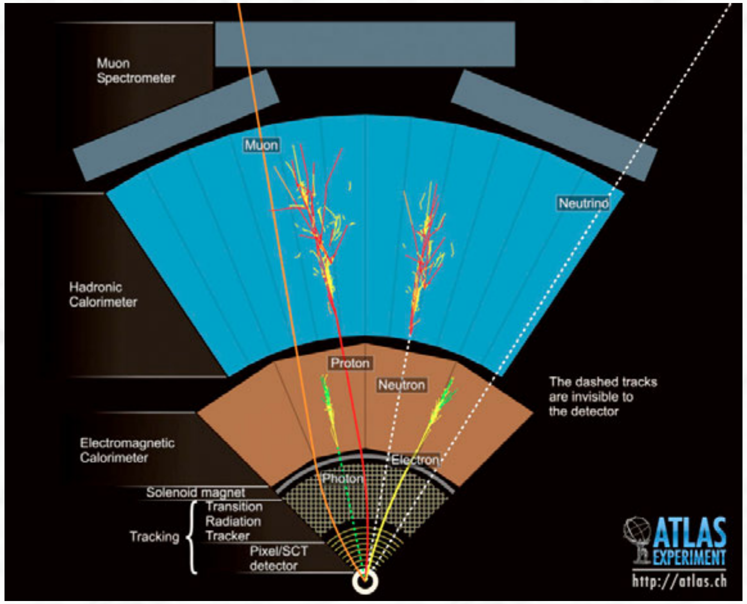
- The hadronic interaction length is a material constant and is linked to the inelastic interaction cross section σ_{inel}

$$\frac{1}{\lambda_{had}} = \sigma_{inel} \cdot \frac{N_A \cdot \rho}{A}$$

Approximation: $\lambda_{had} \approx 35\, A^{1/3}$ (cm)
note: in contrast to the radiation length X_0,
the hadronic interaction length are large (range of meters)

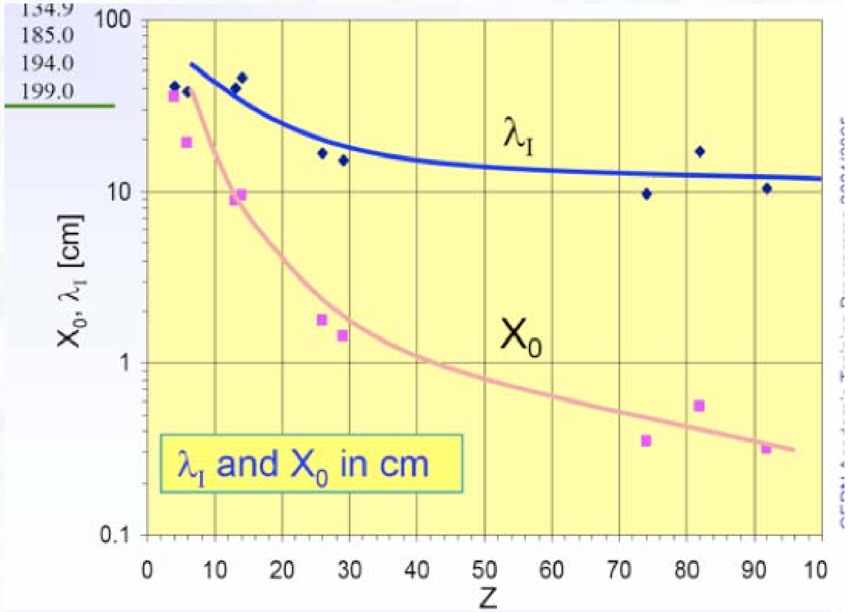
Some values for radiation and hadronic absorption lengths:

Material	X_0 (cm)	λ_{had} (cm)
H_2 Gas He	70000 53000	71800 52000
Be C	35.3 18.8	40.7 38.1
Fe Cu W Pb	1.76 1.43 0.35 0.56	16.76 15.06 9.59 17.09



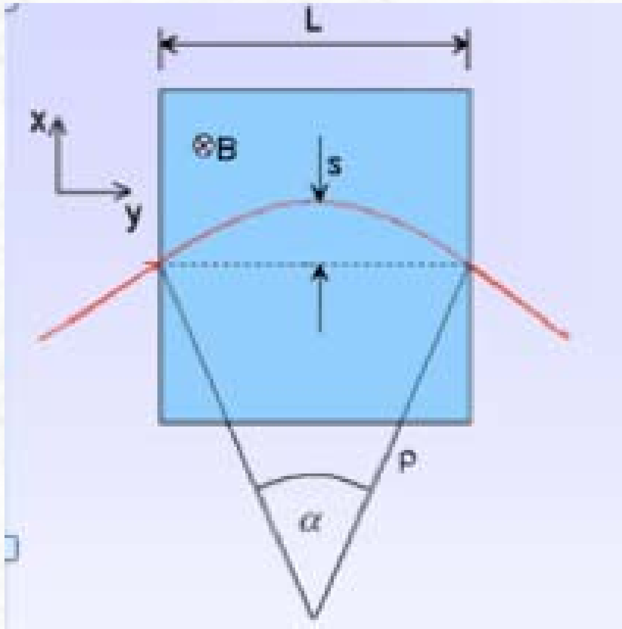
note: for high Z materials, the hadronic interaction lengths are about a factor 10-30 larger than the radiation lengths

→ much more material is needed to stop hadrons compared to electrons;
this explains the large extension of hadronic calorimeters



2.4 Basics on Momentum measurement, Tracking Detectors

- In general the track of a charged particle is measured using several (N) position-sensitive detectors in a magnetic field volume
- Assume that each detector measures the coordinates of the track with a precision of $\sigma(x)$
- The obtainable momentum resolution depends on:
  L (length of the measurement volume)
  B (magnetic field strength)
  σ (position resolution)



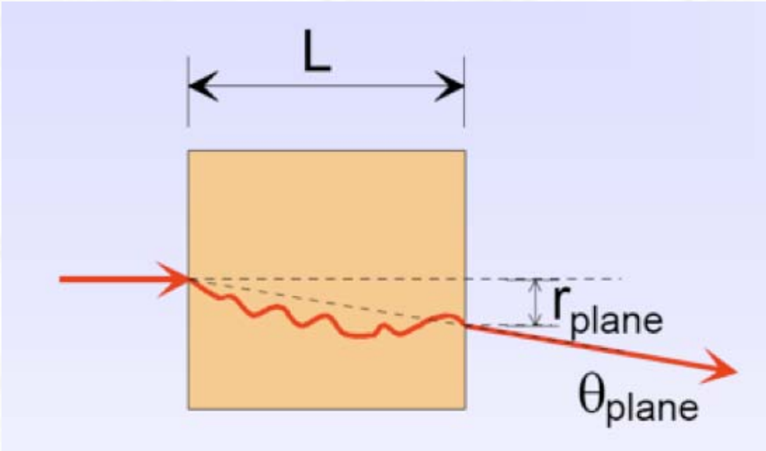
For N equidistant measurements, the momentum resolution is described by the Gluckstern formula (1963):

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma(x)\cdot p_T}{0.3\cdot BL^2}\sqrt{720/(N+4)} \qquad \text{(for } N \geq \sim 10\text{)}$$

note: $\Delta(p_T) / p_T \sim p_T$ (relative resolution degrades with higher transverse momentum)

Momentum measurement (cont.)

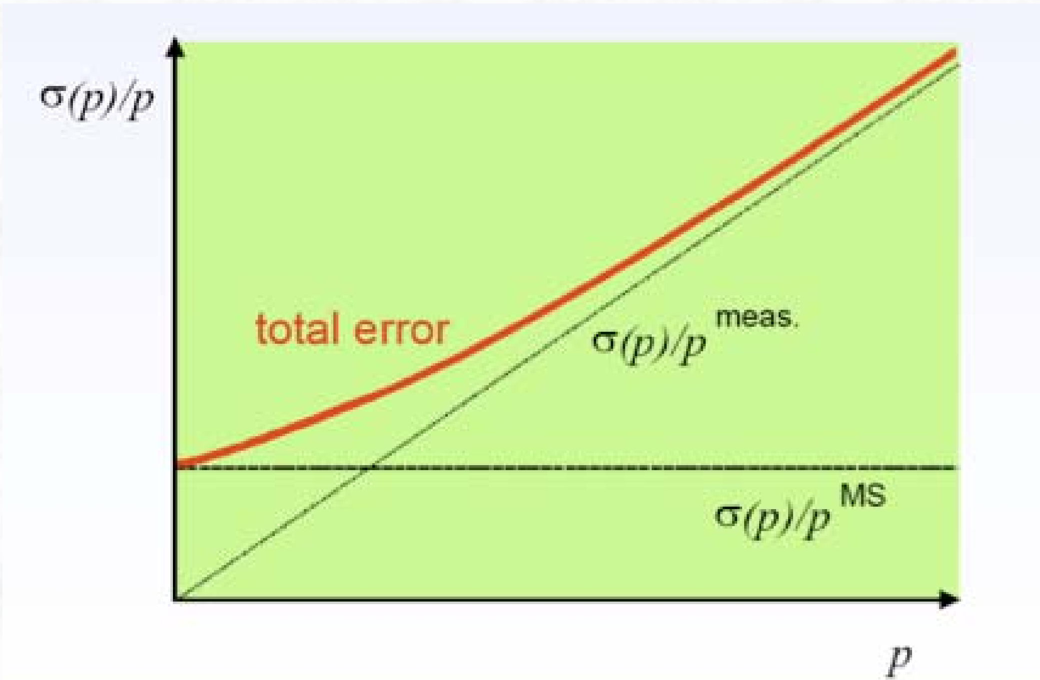
- Degradation of the resolution due to Coulomb multiple scattering (no ionization, elastic scattering on nuclei, change of direction)



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

$$\theta_0 \propto \frac{1}{p}\sqrt{\frac{L}{X_0}}$$

where X_0 = radiation length of the material



$$\left.\frac{\sigma(p)}{p_T}\right|^{MS} = 0.045 \frac{1}{B\sqrt{LX_0}}$$

Semiconductor detectors (silicon)

- In all modern particle physics experiments semiconductor detectors are used as tracking devices with a high spatial resolution (15-20 μm)

- Nearly an order of magnitude more precise than detectors based on ionisation in gas (which was standard up to LEP experiments)

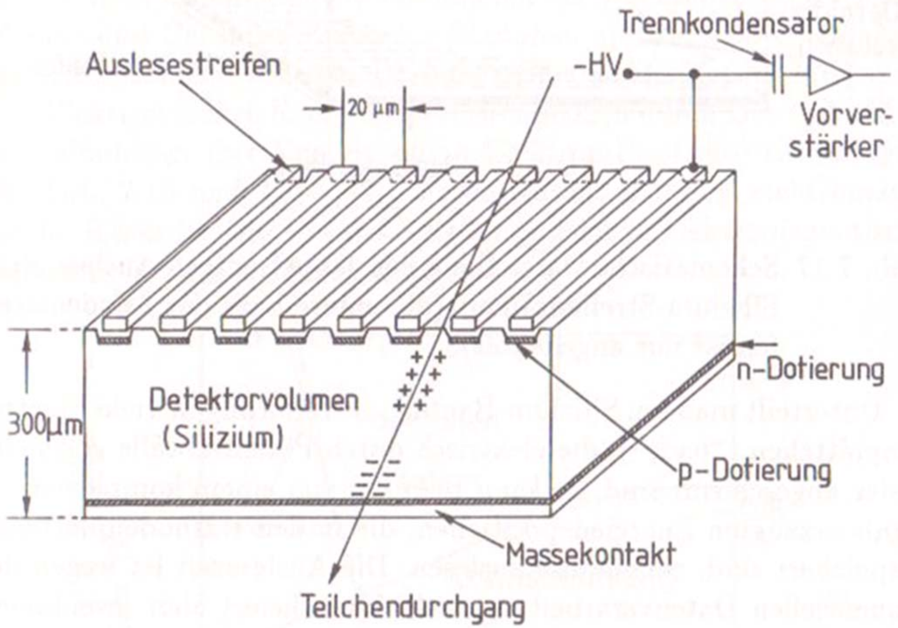
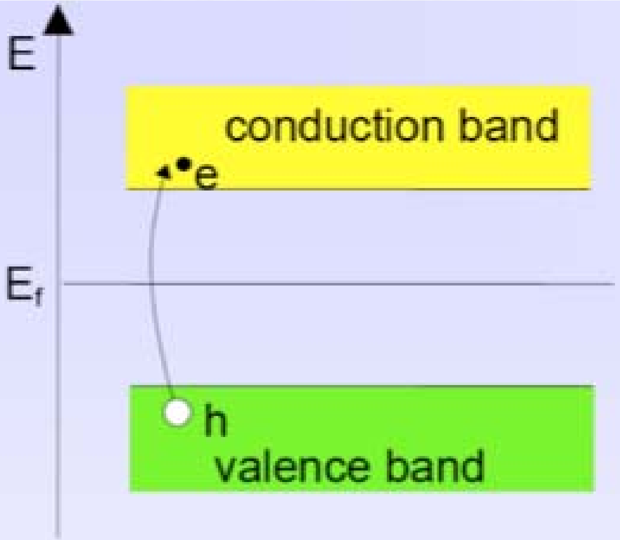


Abb. 7.16 Schematische Darstellung des Aufbaus eines Silizium-Streifenzählers. Jeder Auslesestreifen liegt auf negativer Hochspannung. Die Streifen sind untereinander kapazitiv gekoppelt (nicht maßstabsgetreu, nach [284]).

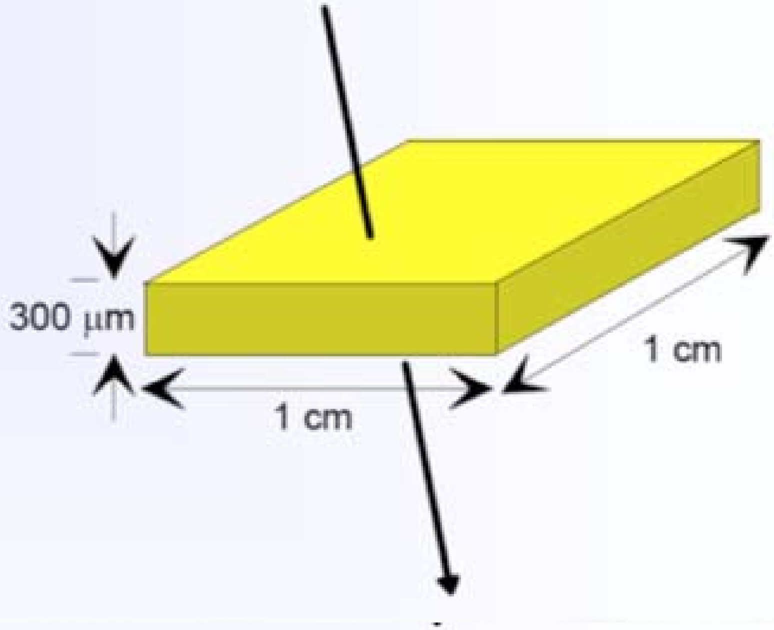
How to obtain a signal



In a pure intrinsic (undoped) semiconductor the electron density *n* and hole density *p* are equal.

$n = p = n_i$ For Silicon: $n_i \approx 1.45 \cdot 10^{10}\ \mathrm{cm}^{-3}$

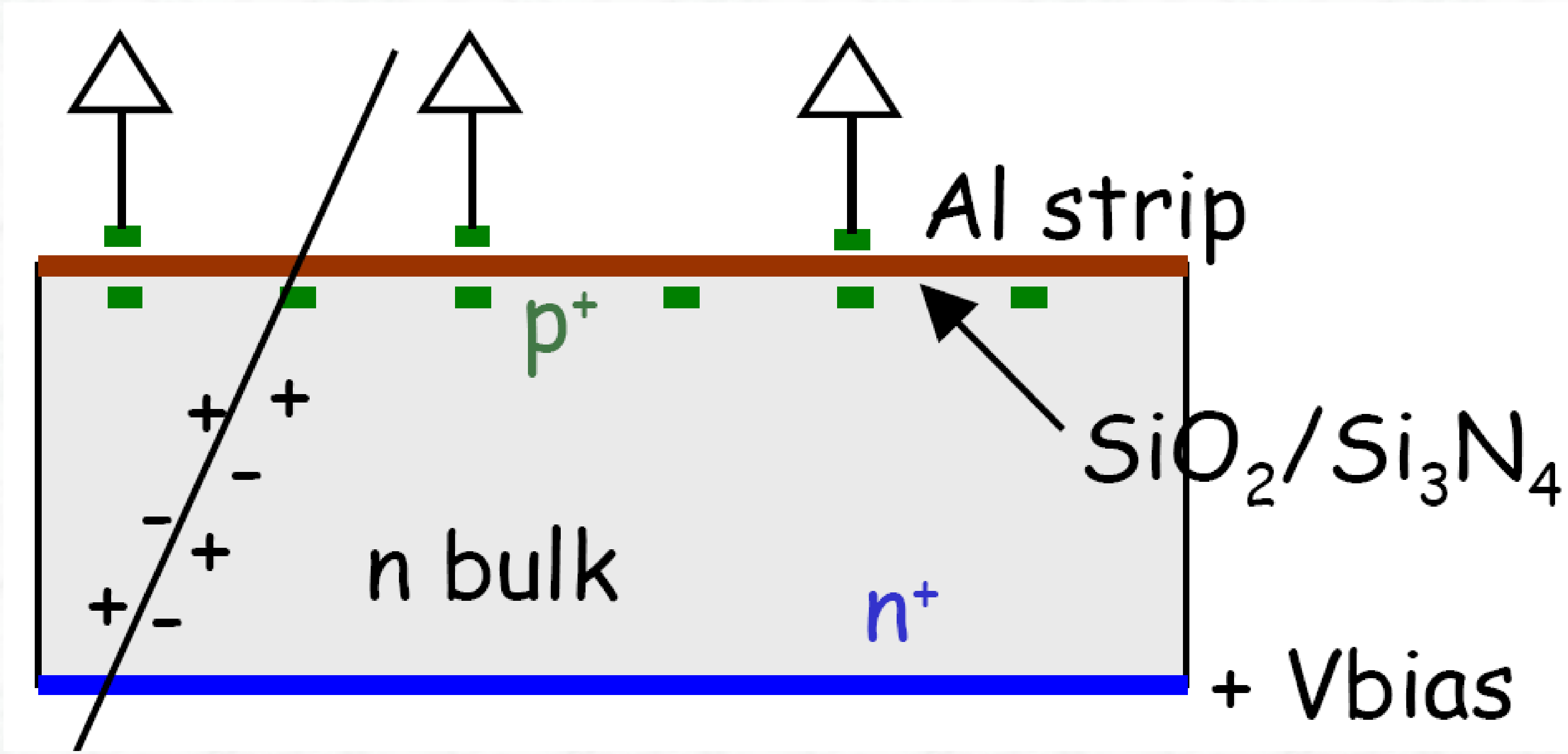
4.5 $\cdot 10^8$ free charge carriers in this volume, but only 3.2 $\cdot 10^4$ e-h pairs produced by a M.I.P.

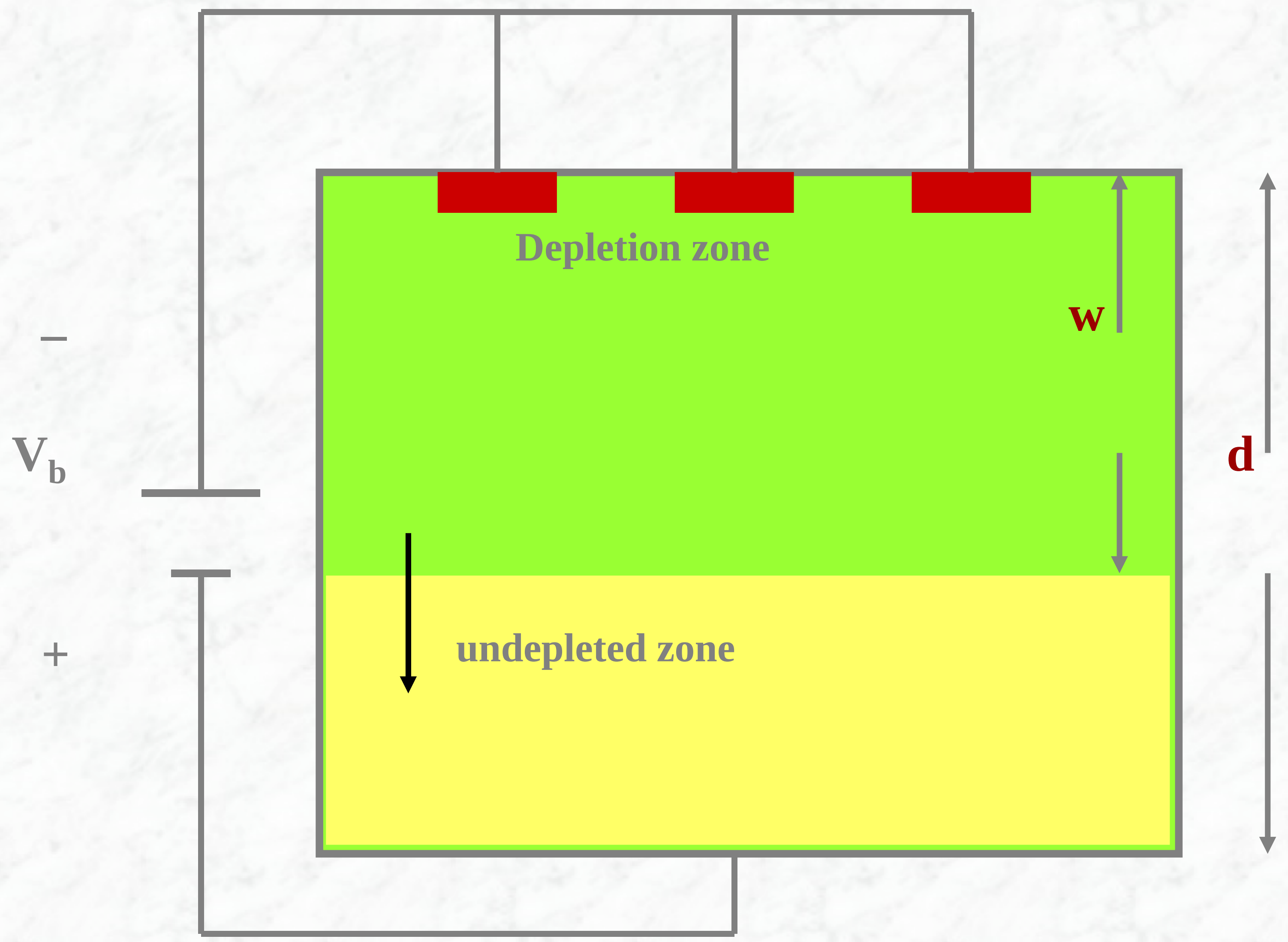


⇒ Reduce number of free charge carriers, i.e. deplete the detector

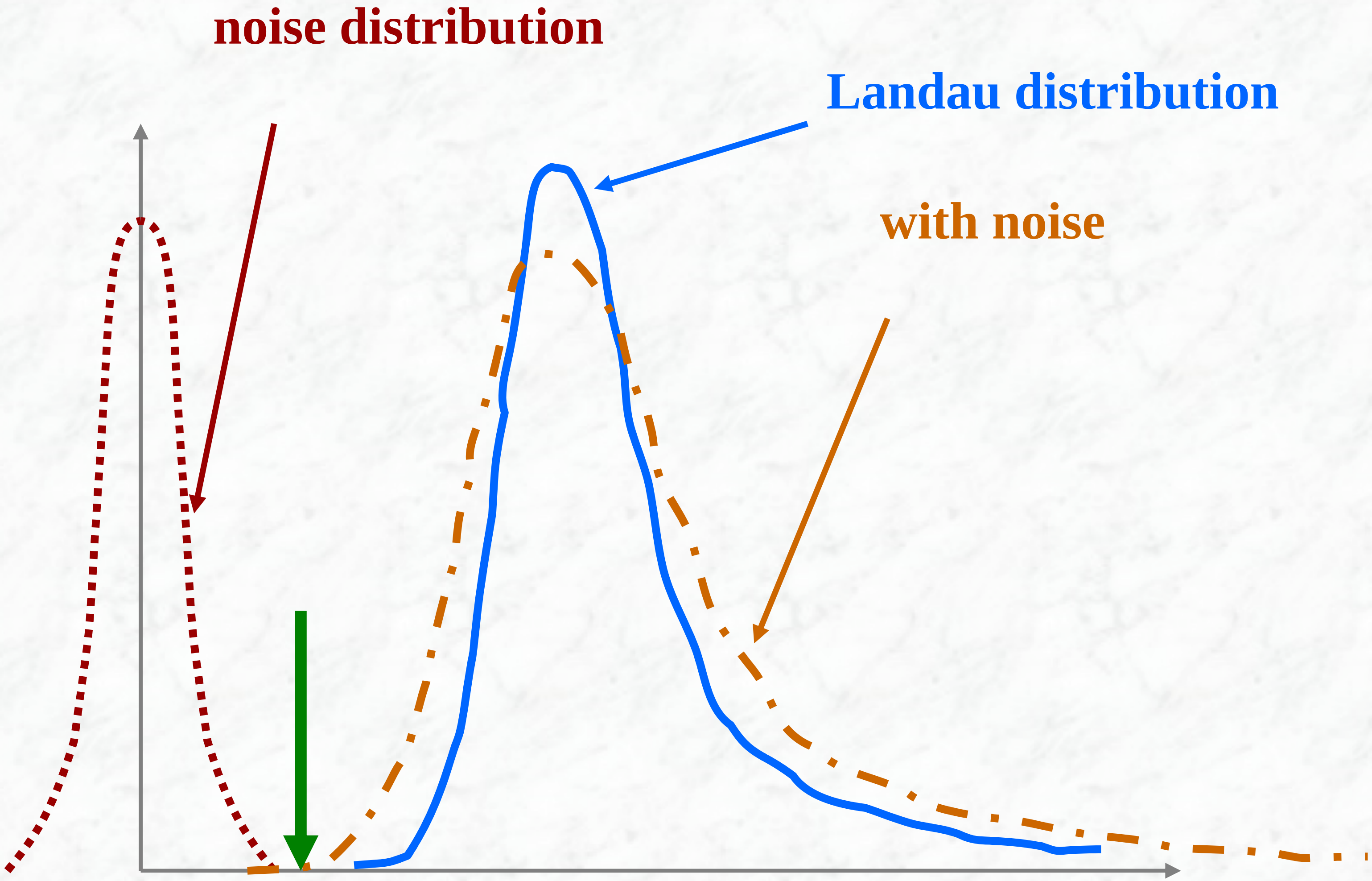
⇒ **Most detectors make use of reverse biased p-n junctions**

Schematic Si-Detector

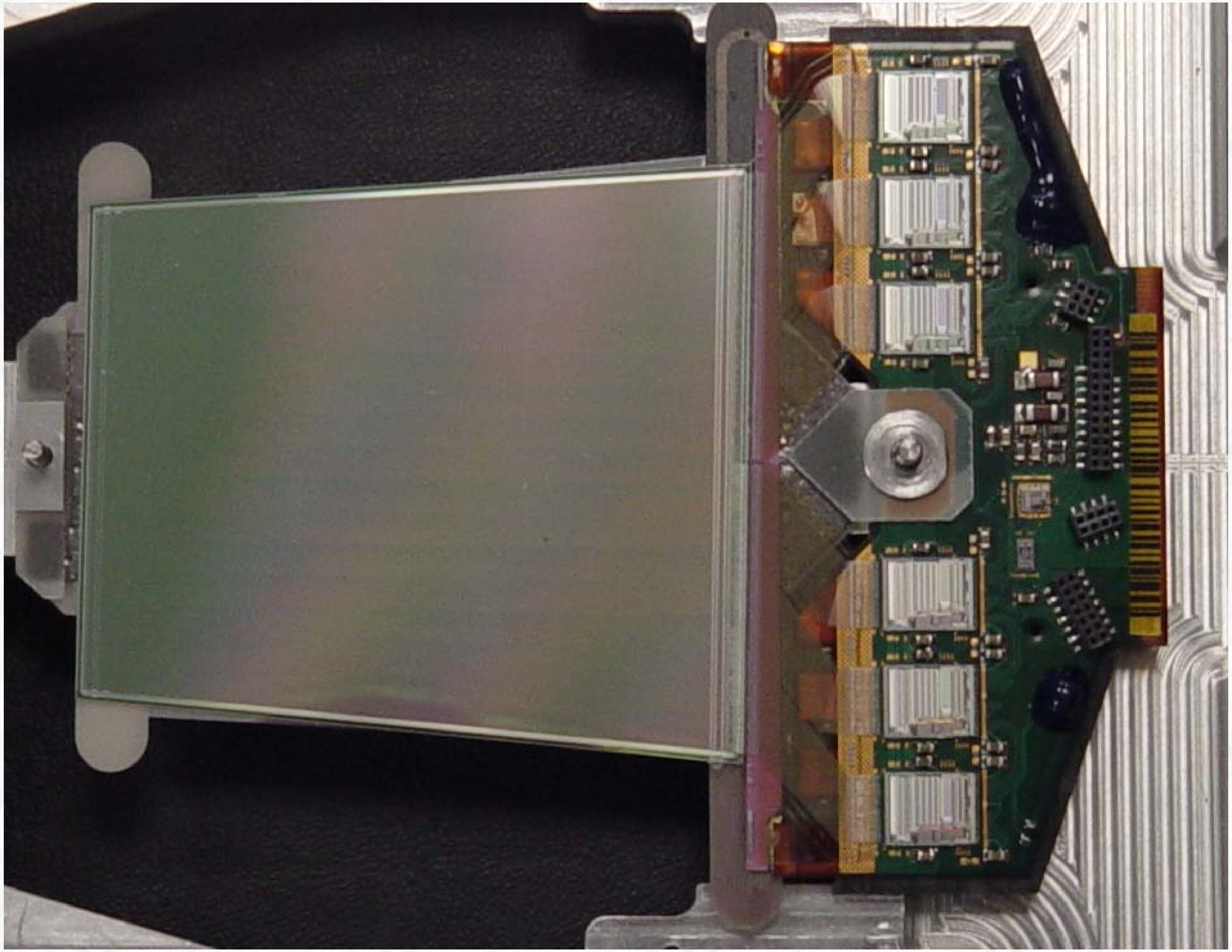



Depletion zone
w
d
−
V_b
+
undepleted zone

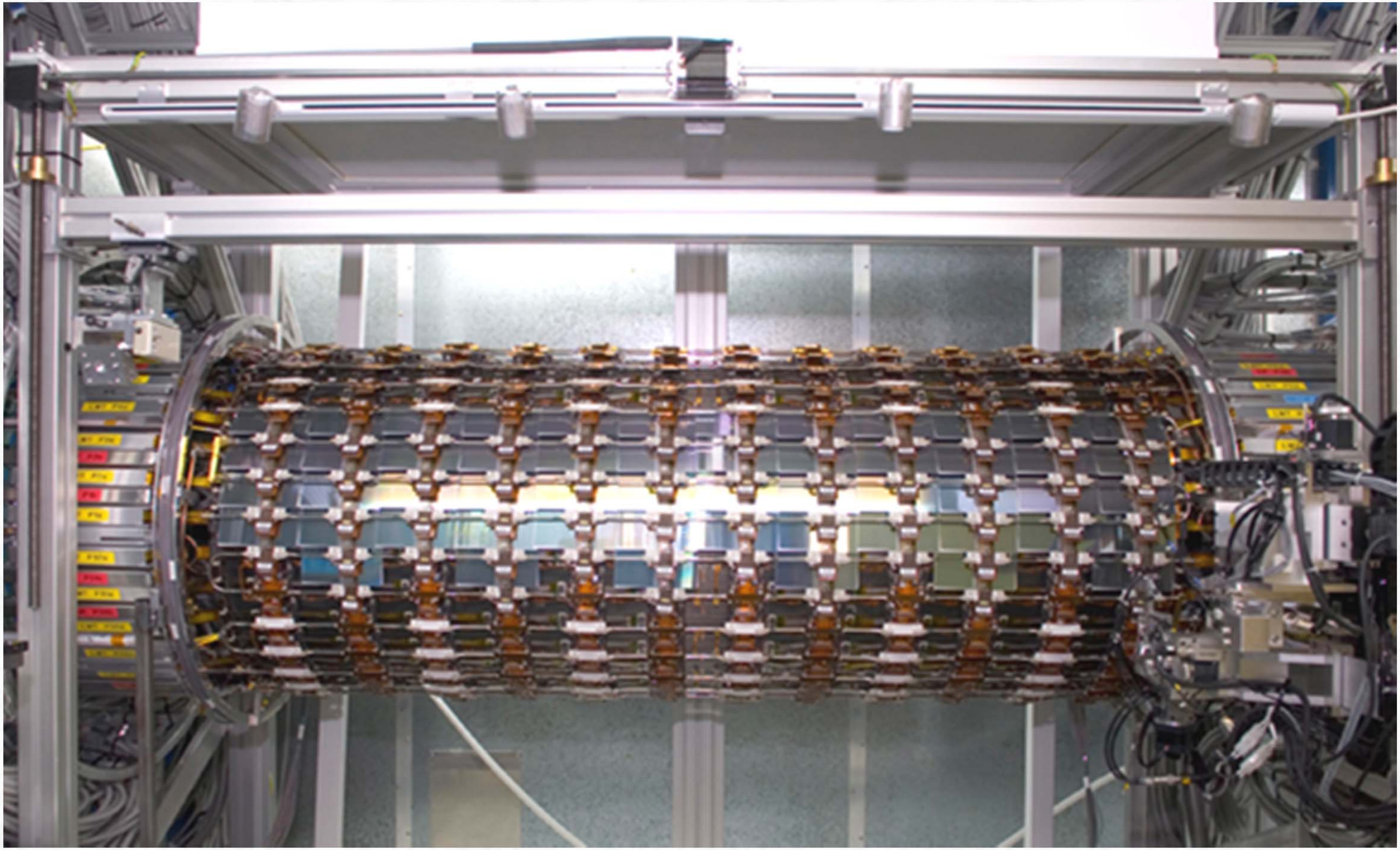
Signal, Noise and S/N Cut



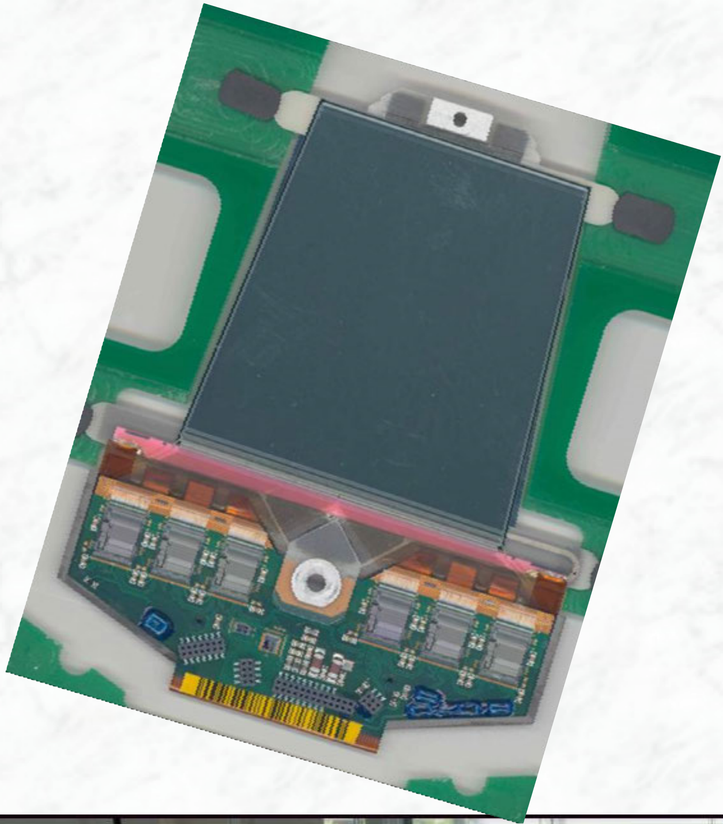
Example: ATLAS Module

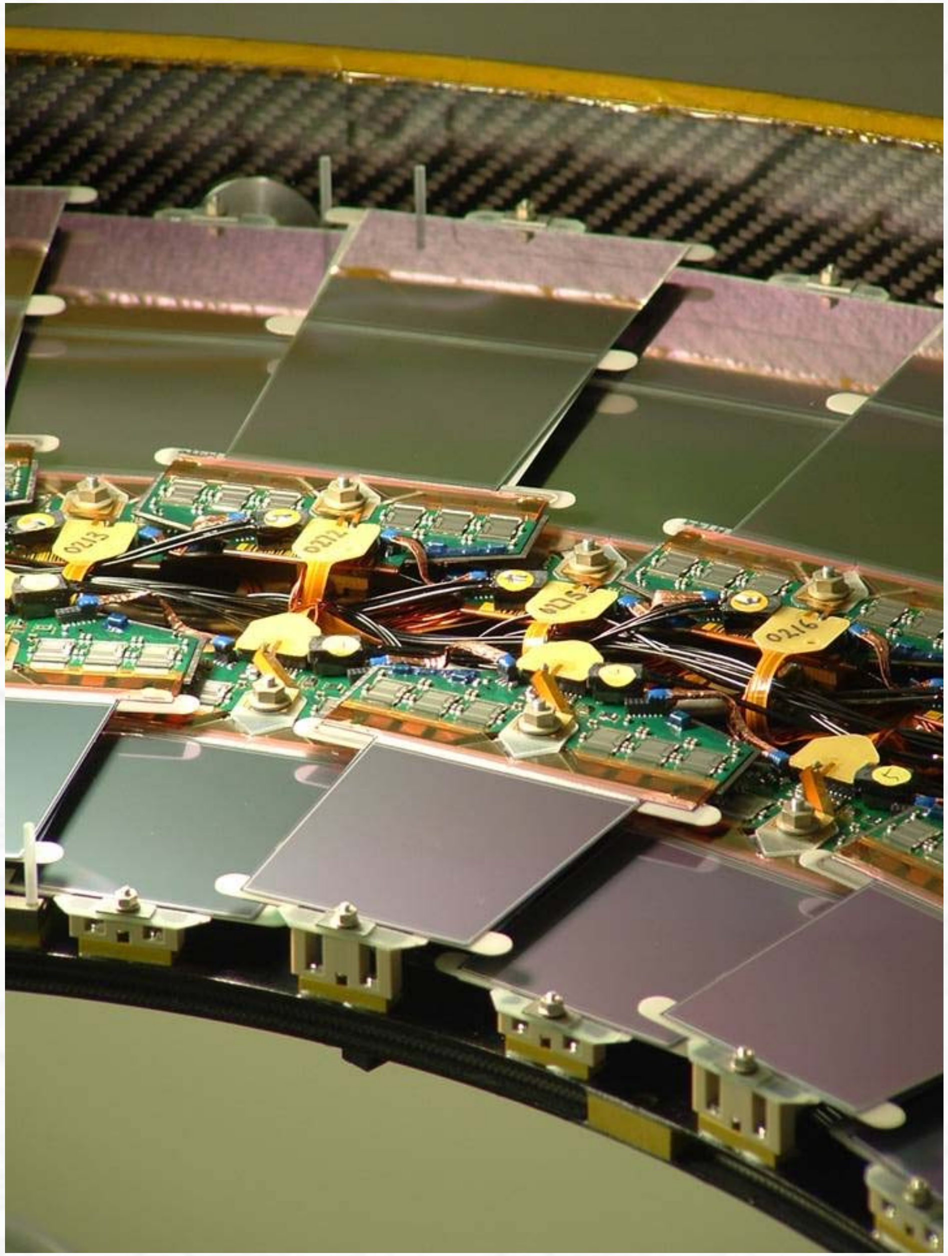


ATLAS Barrel detector



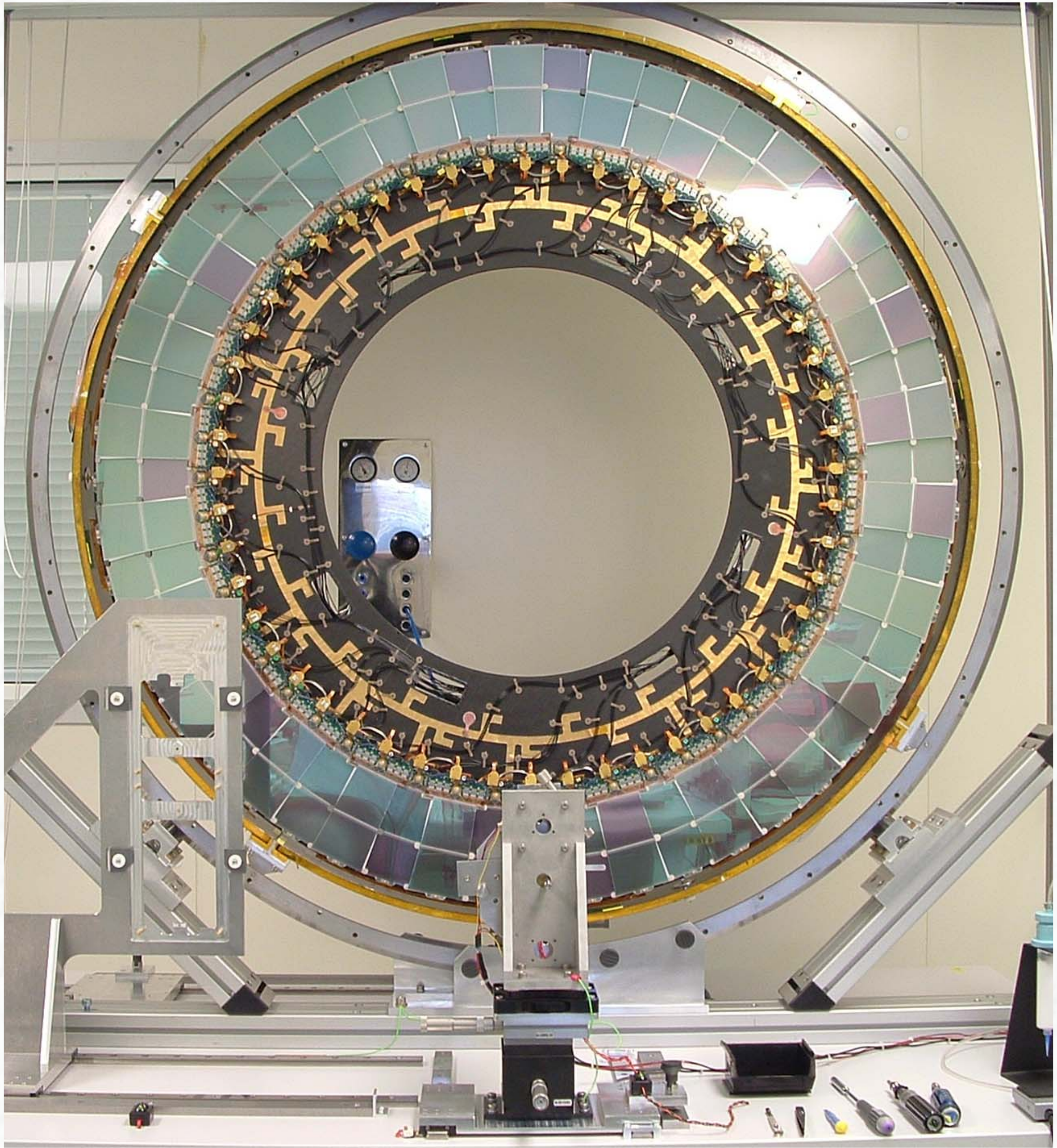
SemiConductor Tracker (SCT)



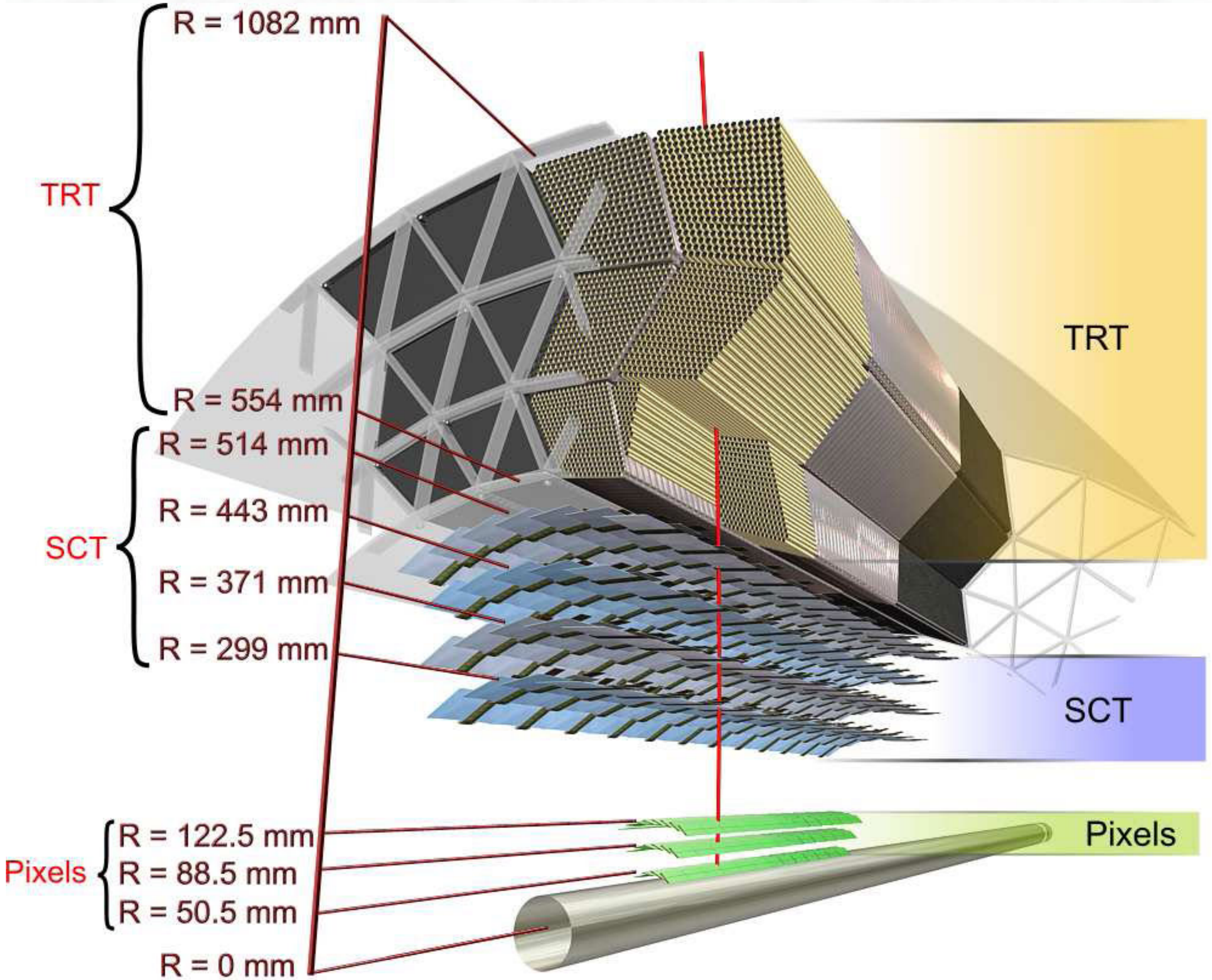


Module fabrication in Freiburg

SCT Endcap



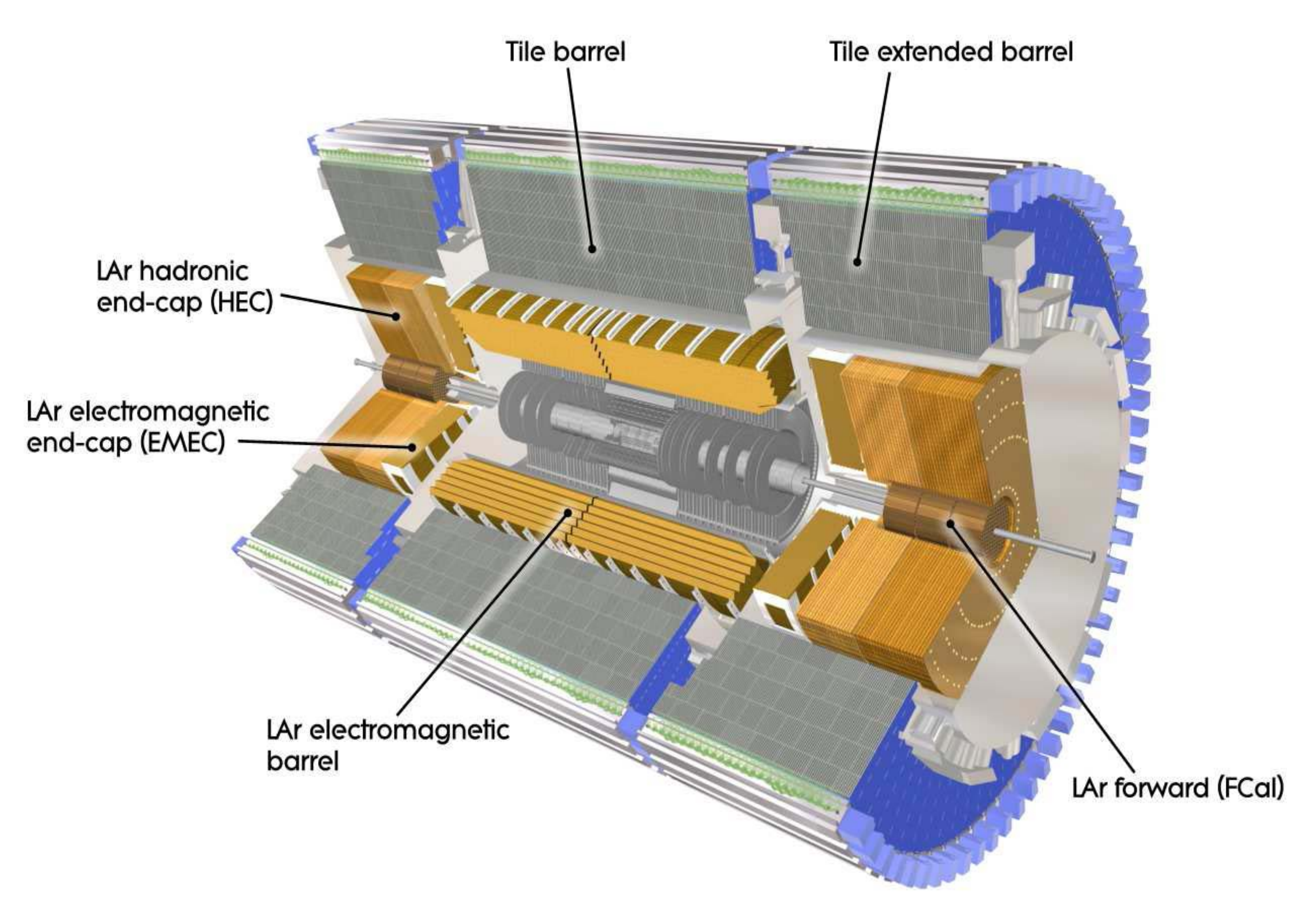
The ATLAS Inner Detector



	R- ϕ accuracy	R or z accuracy	# channels
Pixel	10 μm	115 μm	80.4M
SCT	17 μm	580 μm	6.3M
TRT	130 μm		351k

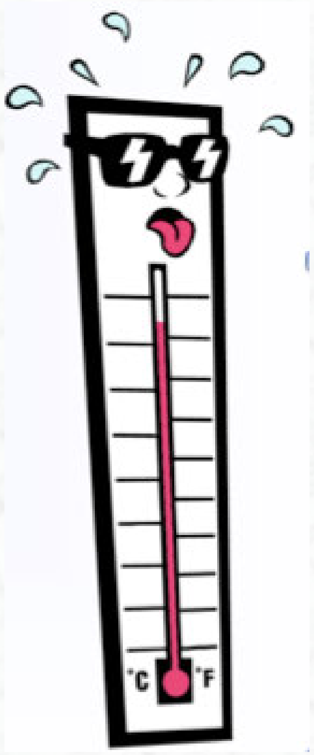
$$\sigma/p_T \sim 0.05\%\ p_T \oplus 1\%$$

2.5 Energy measurement in calorimeters



Calorimetry: = Energy measurement by total absorption, usually combined with spatial information / reconstruction

latin: calor = heat



However: calorimetry in particle physics does not correspond to measurements of ΔT

- The temperature change of 1 liter water at 20 °C by the energy deposition of a 1 GeV particle is $3.8\ 10^{-14}$ K !

- LHC: total stored beam energy
  $E = 10^{14}$ protons • 14 TeV ~ 10^{8} J

  If transferred to heat, this energy would only suffice to heat a mass of 239 kg water from 0° to 100° C
  [$c_{Water} = 4.18\ \mathrm{J\ g^{-1}\ K^{-1}}$, $m = \Delta E / (c_{Water}\ \Delta T)$]

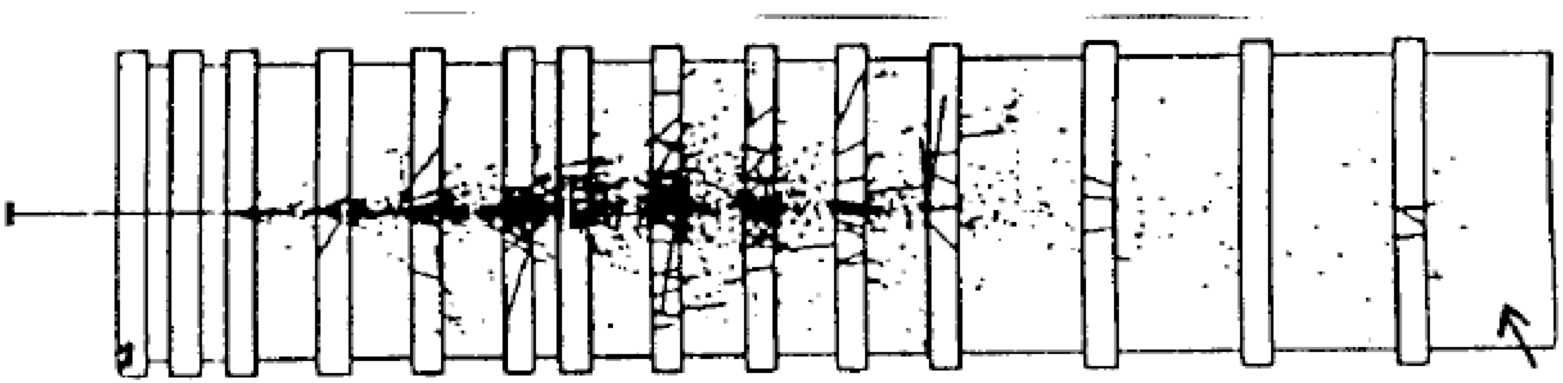
2.5.1 Concept of a particle physics calorimeter

- Primary task: measurement of the total energy of particles

- Energy is transferred to an electrical signal (ionization charge) or to a light signal (scintillators, Cherenkov light)
  This signal should be proportional to the original energy: $E = \alpha S$
  Calibration procedure → α [GeV / S]

  Energy of primary particle is transferred to new particles,
  → cascade of new, lower energy particles

- Layout: block of material in which the particle deposits its energy
  (absorber material (Fe, Pb, Cu,…)
  + sensitive medium (Liquid argon, scintillators, gas ionization detectors,..)



Important parameters of a calorimeter:

- Linearity of the energy measurement

- Precision of the energy measurement (resolution $\Delta E / E$)
  in general limited by fluctuations in the shower process

  worse for sampling calorimeters as compared to homogeneous calorimeters

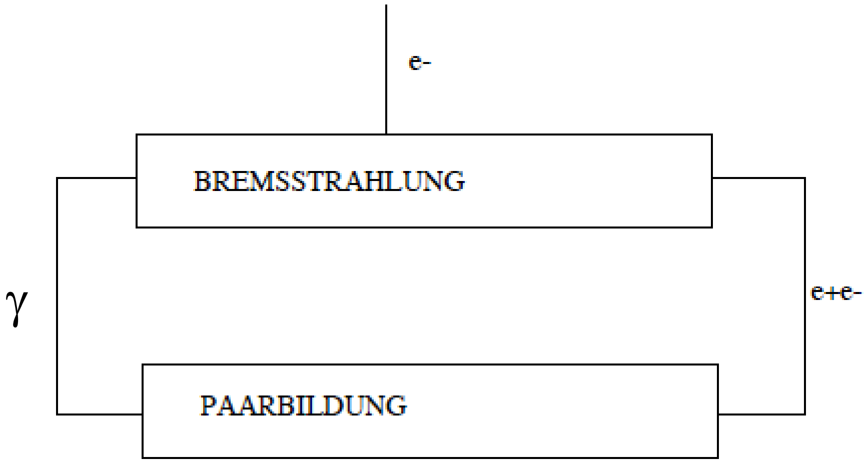
- Uniformity of the energy response to different particles (e/h response)

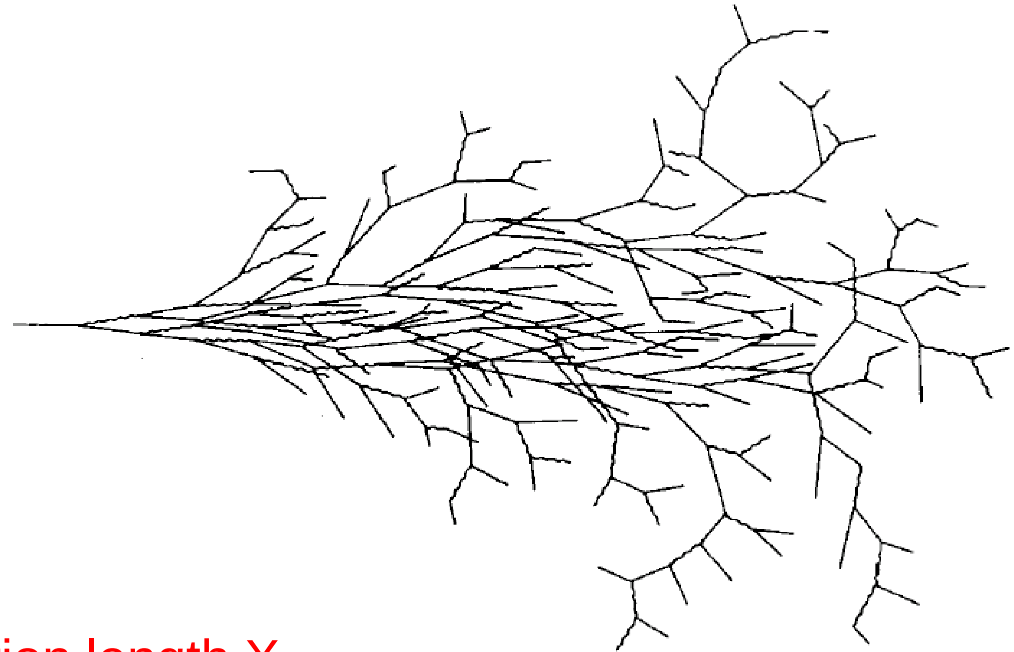
  in general: response of calorimeters is different to so-called electromagnetic particles (e, γ) and hadrons (h) (see later)

2.5.2 Electromagnetic and hadronic showers

- Particle showers created by electrons/positrons or photons are called electro-magnetic showers (only electromagnetic interaction involved)

- Basic processes for particle creation: bremsstrahlung and pair creation





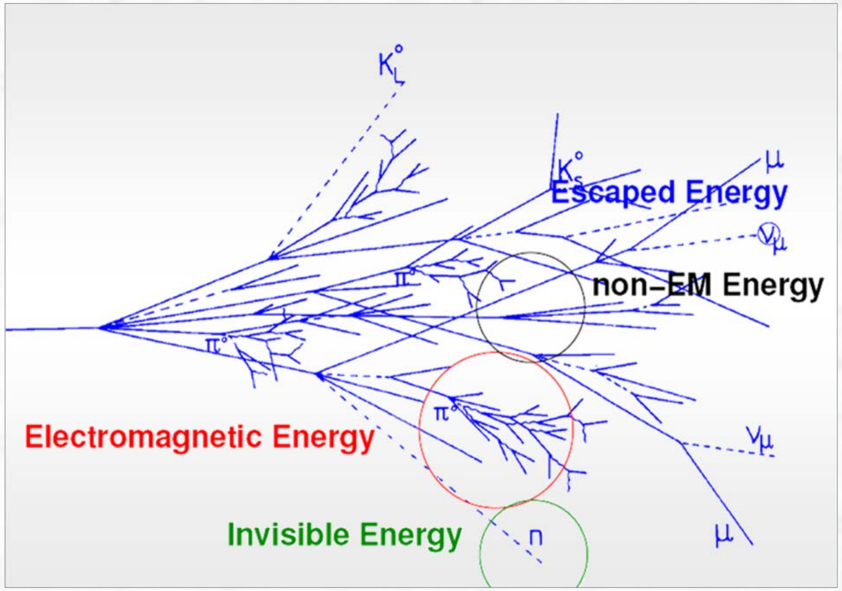
- Characteristic interaction length: radiation length X_0

- Number of particles in the shower increases, until a critical energy E_c is reached; For $E < E_c$ the energy loss due to ionization and excitation dominates, the number of particles decreases, due to stopping in material

Hadronic showers

- Hadrons initiate the shower by inelastic hadronic interactions; (strong interaction, showers are called hadronic showers)

- Hadronic showers are much more complex then electromagnetic showers



- Several secondary particles, meson production, multiplicity ~ ln(E)

- π^0 components, $\pi^0 \rightarrow \gamma\gamma$, electromagnetic sub-showers;
  The fraction of the electromagnetic component grows with energy,
  $f_{EM} = 0.1 \ln E$ (E in GeV, in the range 10 GeV < E < 100 GeV)

- During the hadronic interactions atomic nuclei are broken up or remain in exited states

  The corresponding energy (excitation energy, binding energy) comes from original particle energy
  → no or only partial contribution to the visible energy

- In addition, there is an important neutron component

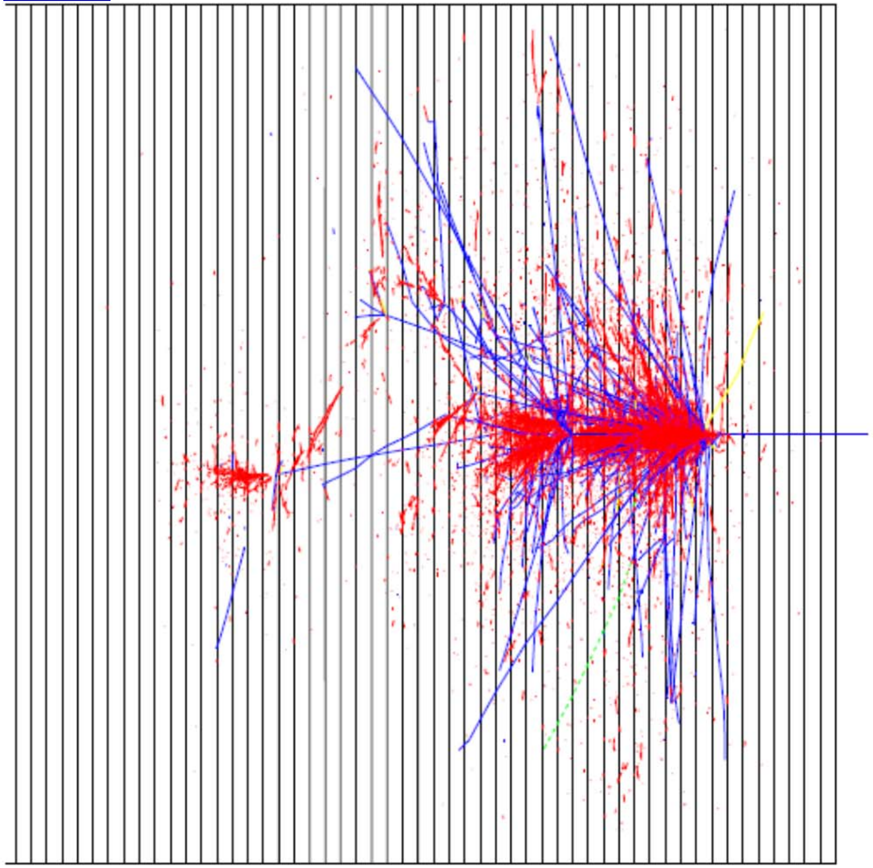
  The interaction of neutrons depends strongly on their energy;
  Extreme cases:
  - Nuclear reaction, e.g. nuclear fission → energy recovered
  - Escaping the calorimeter (undergo only elastic scattering, without inelastic interaction)

- Decays of particles (slow particles at the end of the shower)
  e.g. $\pi \rightarrow \mu \, \nu_\mu$ → escaping particles → missing energy

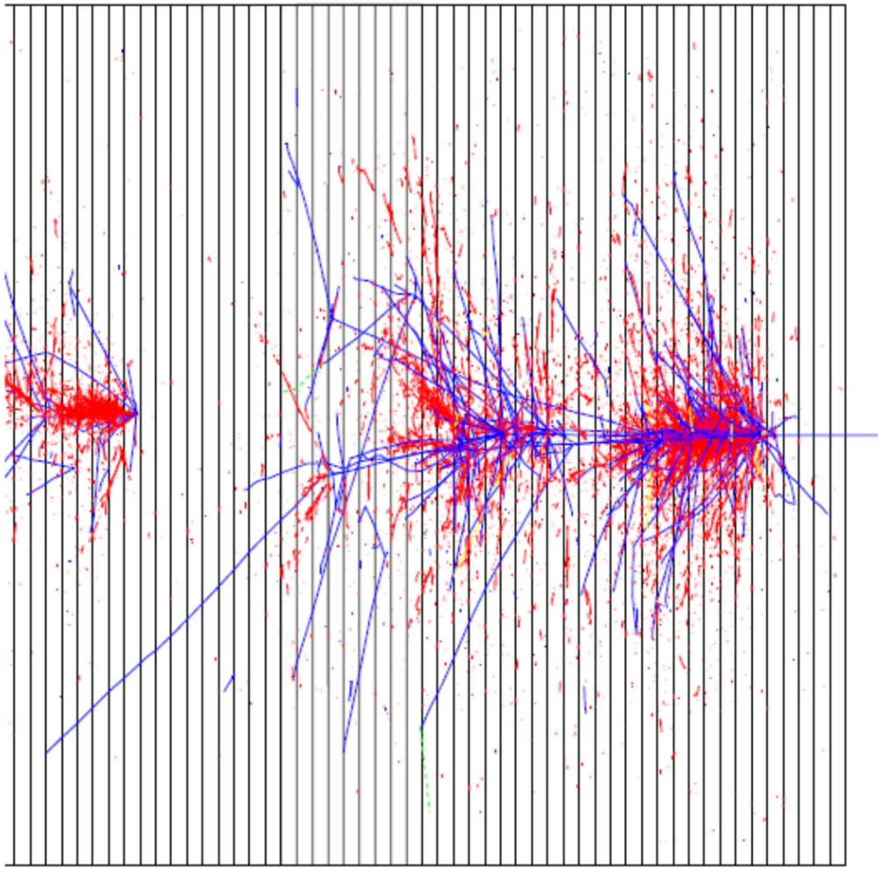
These energy loss processes have important consequences:
in general, the response of the calorimeter to electrons/photons and hadrons is different ! The signal for hadrons is non-linear and smaller than the e/γ signal for the same particle energy

Two hadronic showers in a sampling calorimeter

1.



2.



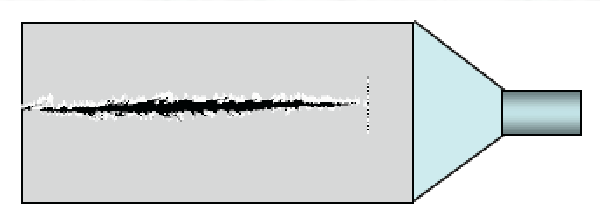
Red: electromagnetic component
Blue: charged hadron component

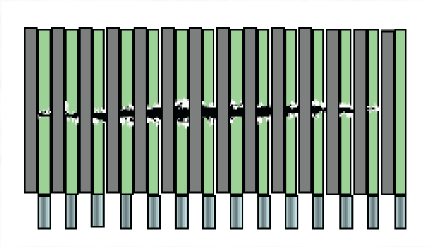
Hadronic showers show large fluctuations from one event to another
→ the energy resolution is worse than for electromagnetic showers

2.5.3 Layout and readout of calorimeters

- In general, one distinguishes between homogenous calorimeters and sampling calorimeters

For homogeneous calorimeters: absorber material = active (sensitive) medium



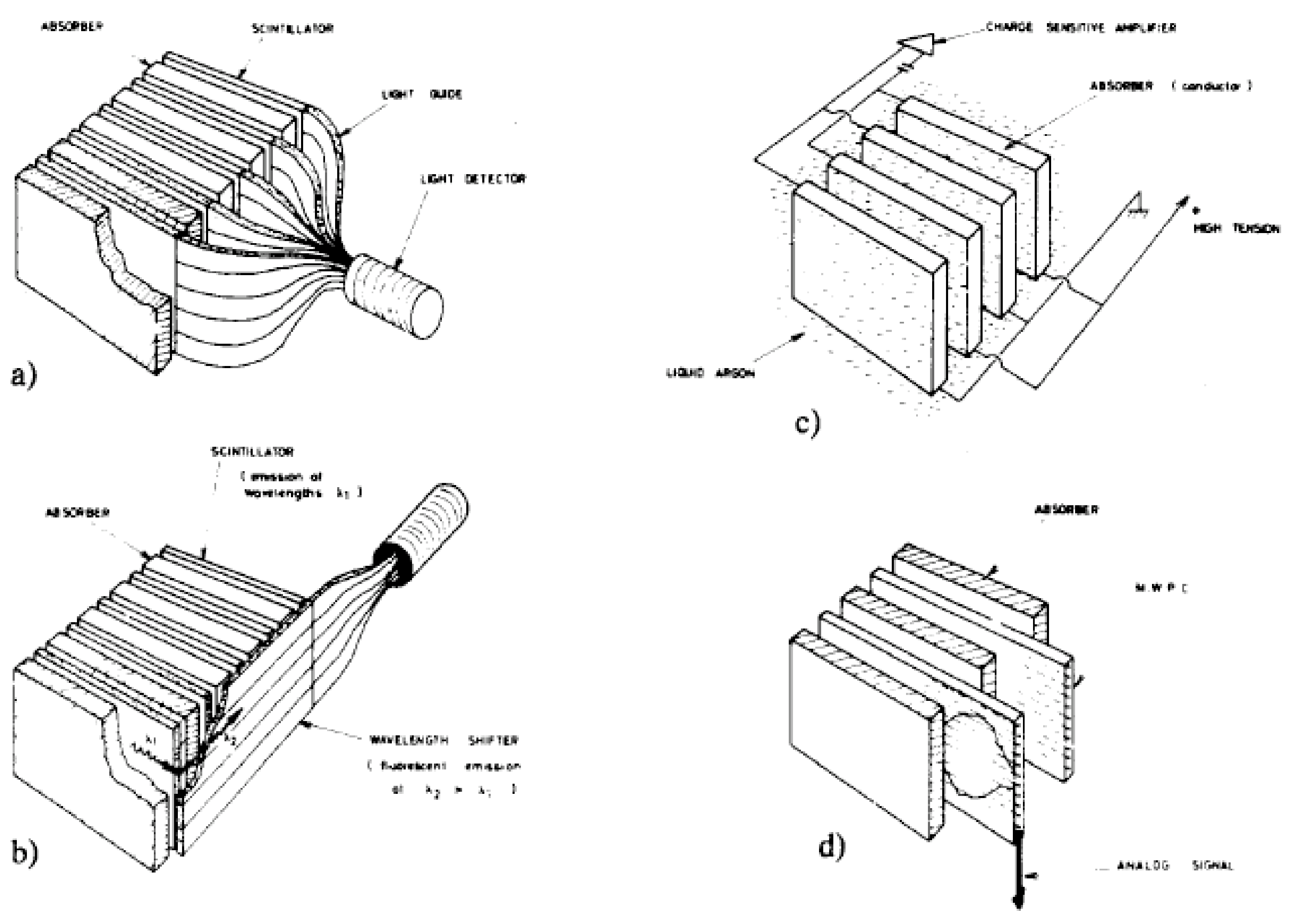


- Examples for homogeneous calorimeters:
  - NaJ or other crystals (Scintillation light)
  - Lead glass (Cherenkov light)
  - Liquid argon or liquid krypton calorimeters (Ionization charge)

- Sampling calorimeters: absorption and hadronic interactions occur mainly in dedicated absorber materials (dense materials with high Z, passive material)

  Signal is created in active medium, only a fraction of the energy contributes to the measured energy signal

Examples for sampling calorimeters



(a) Scintillators, optically coupled to photomultipliers
(b) Scintillators, wave length shifters, light guides
(c) Ionization charge in liquids
(d) Ionization charge in multi-wire proportional chambers

2.5.4 Energy resolution of calorimeters

- The energy resolution of calorimeters depends on the fluctuations of the measured signal (for the same energy E_0),
  i.e. on the fluctuation of the measured signal delivered by charged particles.

  Example: Liquid argon, ionization charge: $Q \sim \langle N \rangle \langle T_0 \rangle \sim E_0$

  where: $\langle N \rangle$ = average number of produced charge particles, $\sim E_0 / E_c$

  $\langle T_0 \rangle$ = average track length in the active medium

  For sampling calorimeters only a fraction f of the total track length (the one in the active medium) is relevant;
  Likewise, if there is a threshold for detection (e.g. Cherenkov light)

- The energy resolution is determined by statistical fluctuations:
  - Number of produced charged particles (electrons for electromagnetic showers)
  - Fluctuations in the energy loss (Landau distribution of Bethe-Bloch sampling)

- For the resolution one obtains:

$$\frac{\Delta E}{E} = \frac{\Delta Q}{Q} \propto \frac{\sqrt{N}}{N} \propto \frac{\alpha}{\sqrt{E}}$$

- The energy resolution of calorimeters can be parametrized as:

$$\boxed{\frac{\Delta E}{E} = \frac{\alpha}{\sqrt{E}} \oplus \beta \oplus \frac{\gamma}{E}}$$

- α is the so called stochastic term (statistical fluctuations)

- β is the constant term (dominates at high energies)

  important contributions to β are:
  - stability of the calibration (temperature, radiation, ….)
  - leakage effects (longitudinal and lateral)
  - uniformity of the signal
  - loss of energy in dead material
  - ….

- γ is the noise term (electronic noise,..)

- Also angular and spatial resolutions scale like $1/\sqrt{E}$

Examples for energy resolutions seen in electromagnetic calorimeters in large detector systems:

Experiment	Calorimeter	α	β	γ
L3	BGO	< 2.0%	0.3%	
BaBar	CsI (Tl)	(*) 1.3%	2.1%	0.4 MeV
OPAL	Lead glass	(**) 5% (++) 3%		
NA48	Liquid krypton	3.2%	0.5%	125 MeV
UA2	Pb /Scintillator	15%	1.0%	
ALEPH	Pb / Prop.chamb.	18%	0.9%	
ZEUS	U / Scintillator	18%	1.0%	
H1	Pb / Liquid argon	11.0%	0.6%	154 MeV
D0	U / Liquid argon	15.7 %	0.3%	140 MeV

homogeneous calorimeters

sampling calorimeters

(*) scaling according to $E^{-1/4}$ rather than $E^{-1/2}$

(**) at 10 GeV

(++) at 45 GeV

hadronic energy resolutions:

Experiment	Kalorimeter	α	β	γ
ALEPH	Fe/Streamer Rohre	85%		-
ZEUS (*)	U/Szintillator	35%	2.0%	-
H1 (+)	Fe/Flüssig - Argon	51%	1.6%	900 MeV
D0	U/Flüssig - Argon	41%	3.2%	1380 MeV

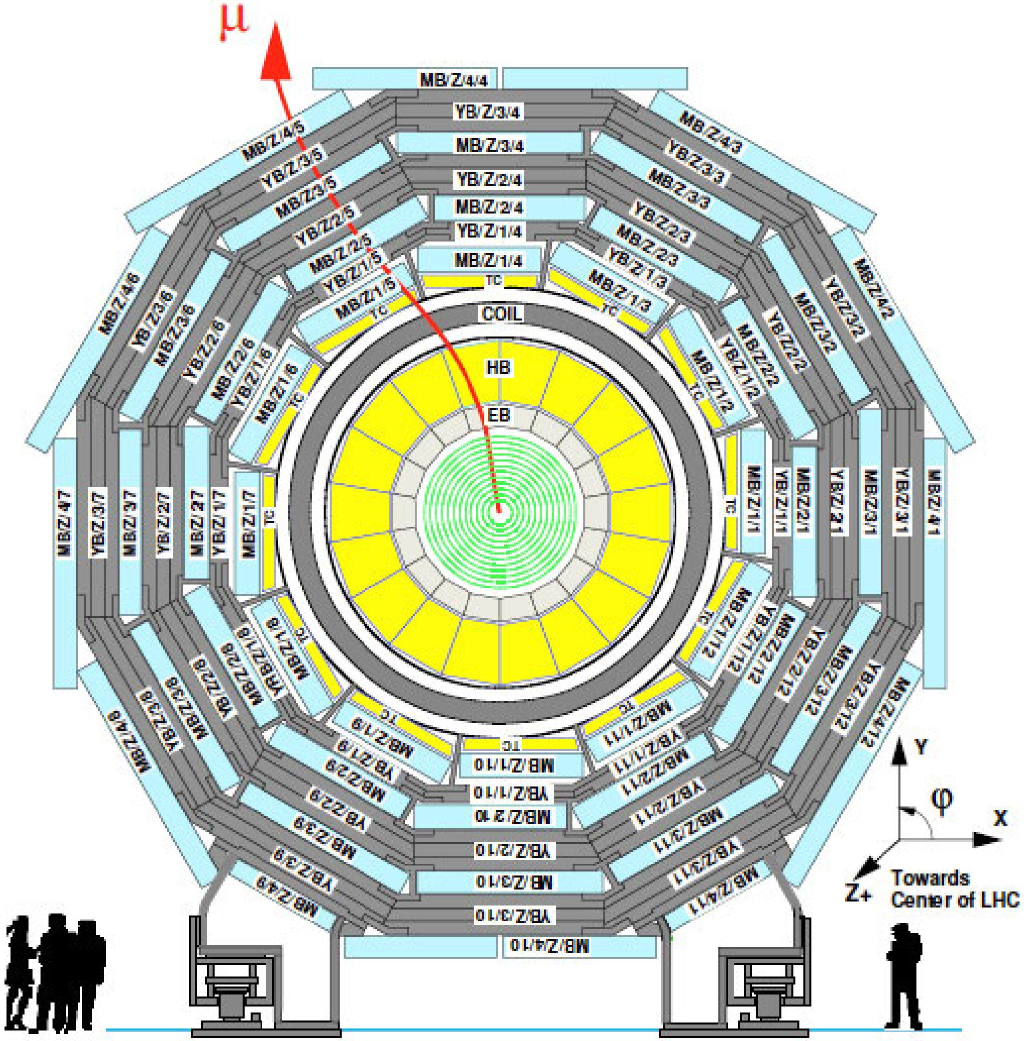
(*) compensating calorimeter
(+) weighting technique

- In general, the energy response of calorimeters is different for e/γ and hadrons; A measure of this is the so-called e/h ratio

- In so-called "compensating" calorimeters, one tries to compensate for the energy losses in hadronic showers (→ and bring e/h close to 1)

  physical processes: - energy recovery from nuclear fission, initiated by slow neutrons (uranium calorimeters)
  - transfer energy from neutrons to protons (same mass) use hydrogen enriched materials / free protons

2.6 Measurements of muons

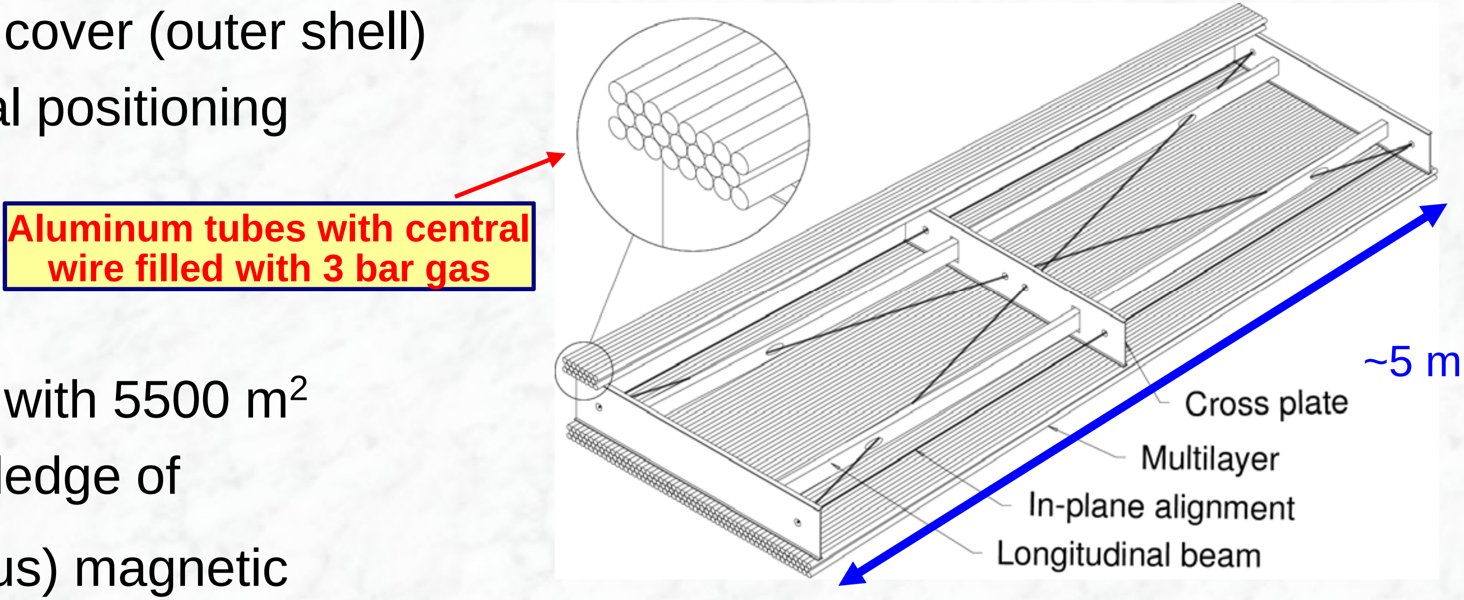


Muon Detectors

- 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 is 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 over time

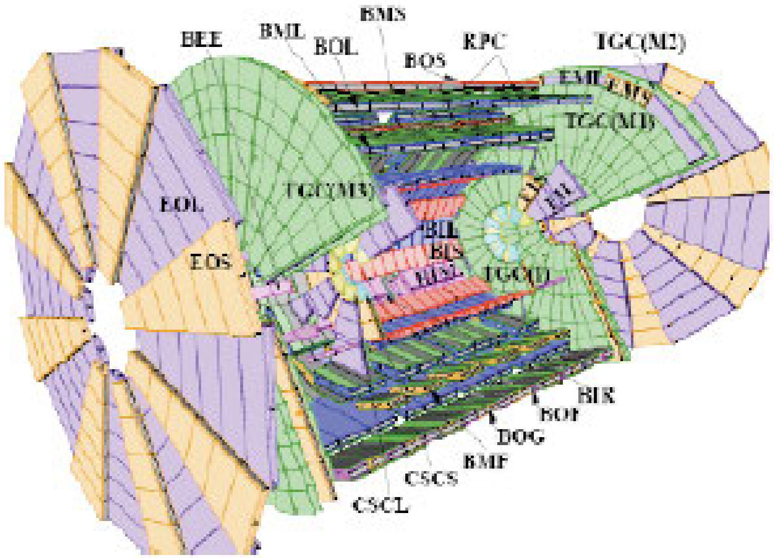
ATLAS Muon Detector Elements



- ATLAS
  - 1200 chambers with 5500 m^2
  - also good knowledge of

    (inhomogeneous) magnetic field needed

ATLAS muon system



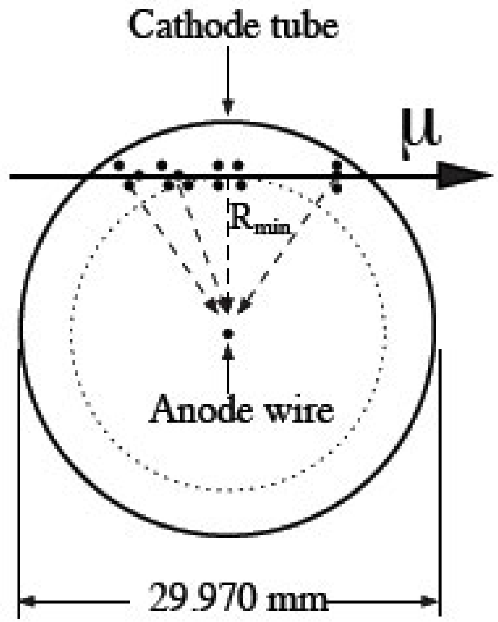
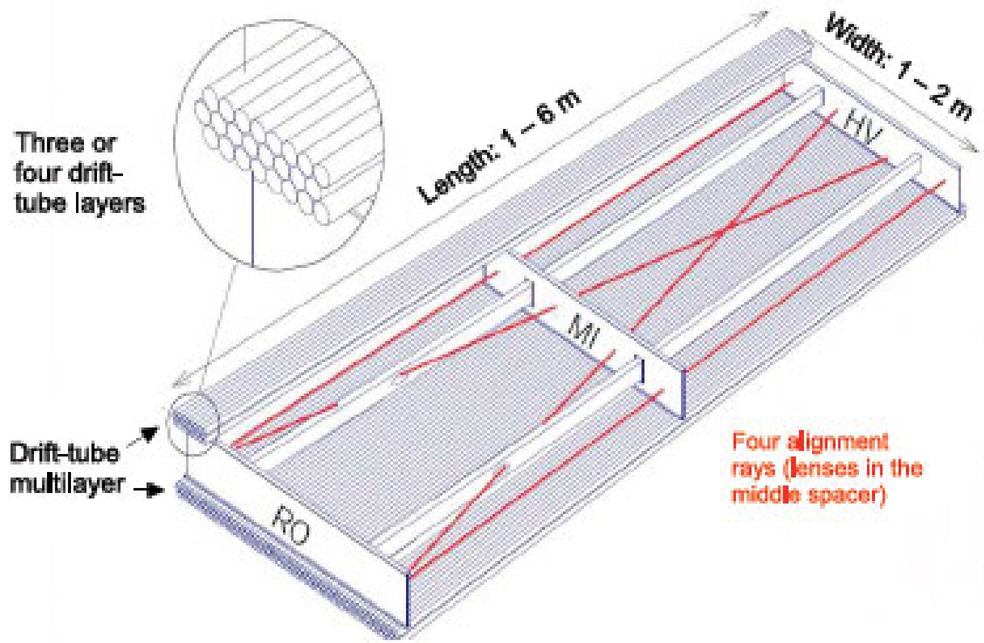
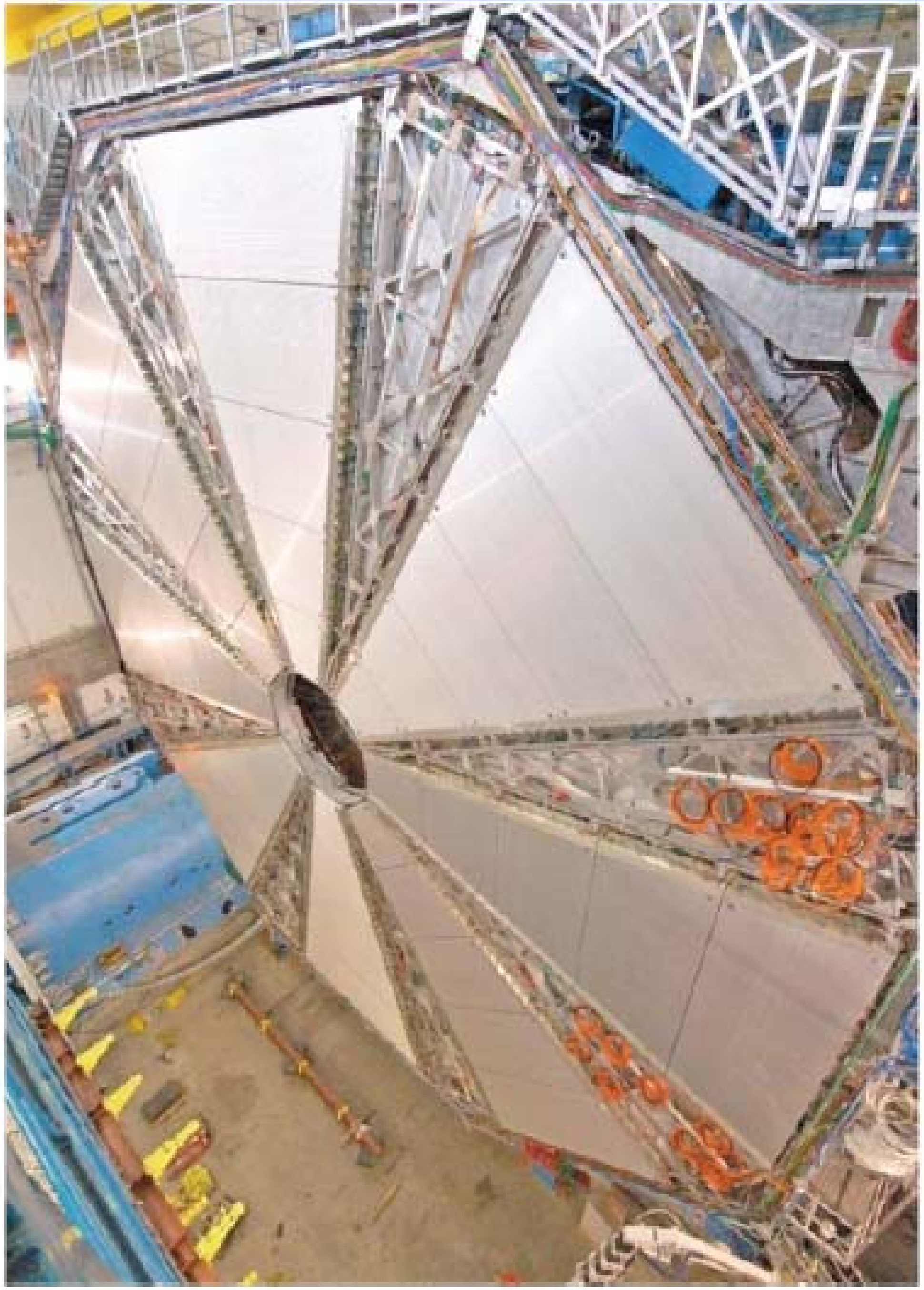


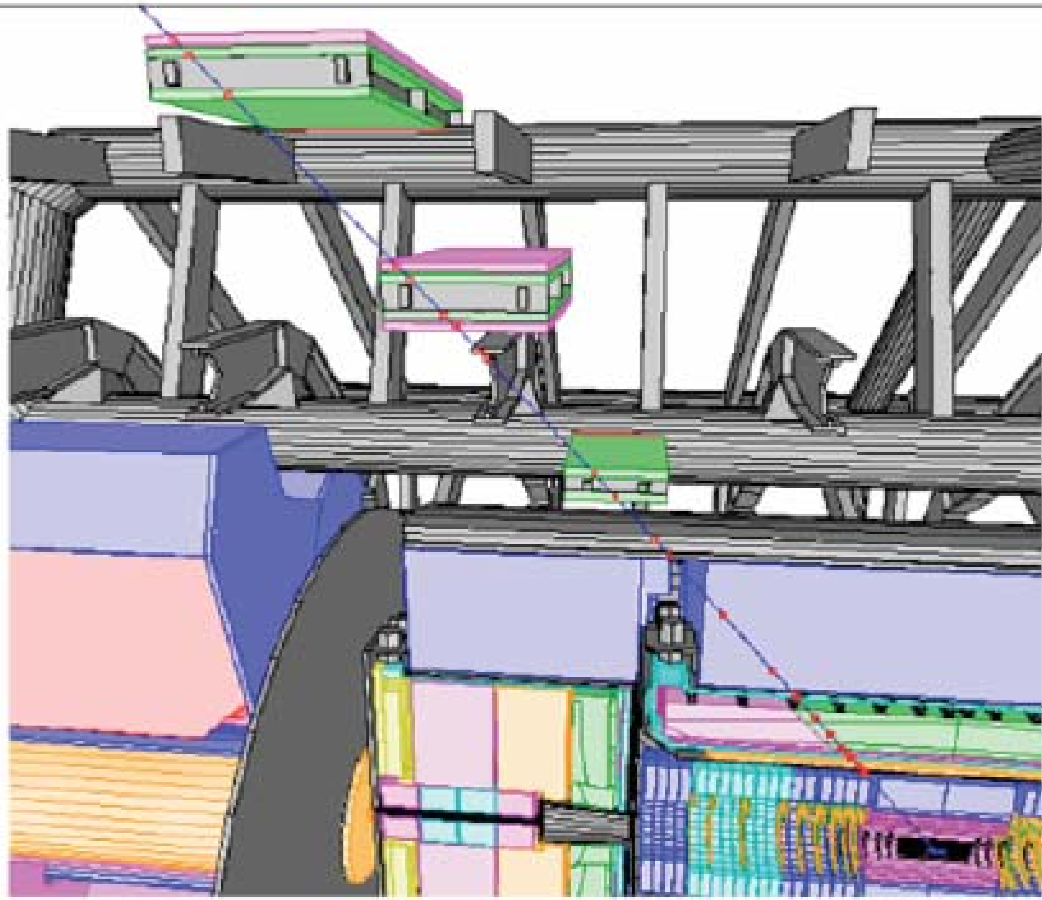
Table 6.2: Main MDT chamber parameters.

Parameter	Design value
Tube material	Al
Outer tube diameter	29.970 mm
Tube wall thickness	0.4 mm
Wire material	gold-plated W/Re (97/3)
Wire diameter	50 μm
Gas mixture	$Ar/CO_2/H_2O$ (93/7/$\leq$ 1000 ppm)
Gas pressure	3 bar (absolute)
Gas gain	2 x 10^4
Wire potential	3080 V
Maximum drift time	$\sim$ 700 ns
Average resolution per tube	$\sim$ 80 μm

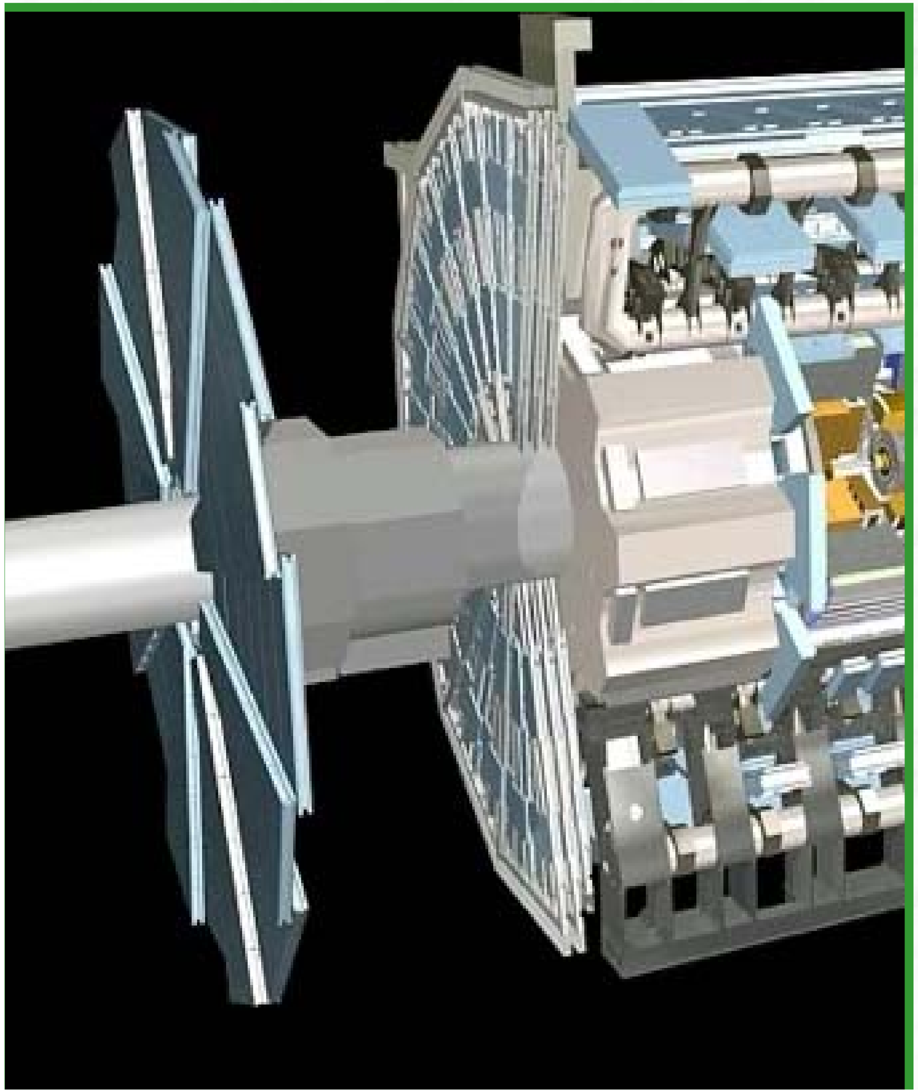


ATLAS muon system

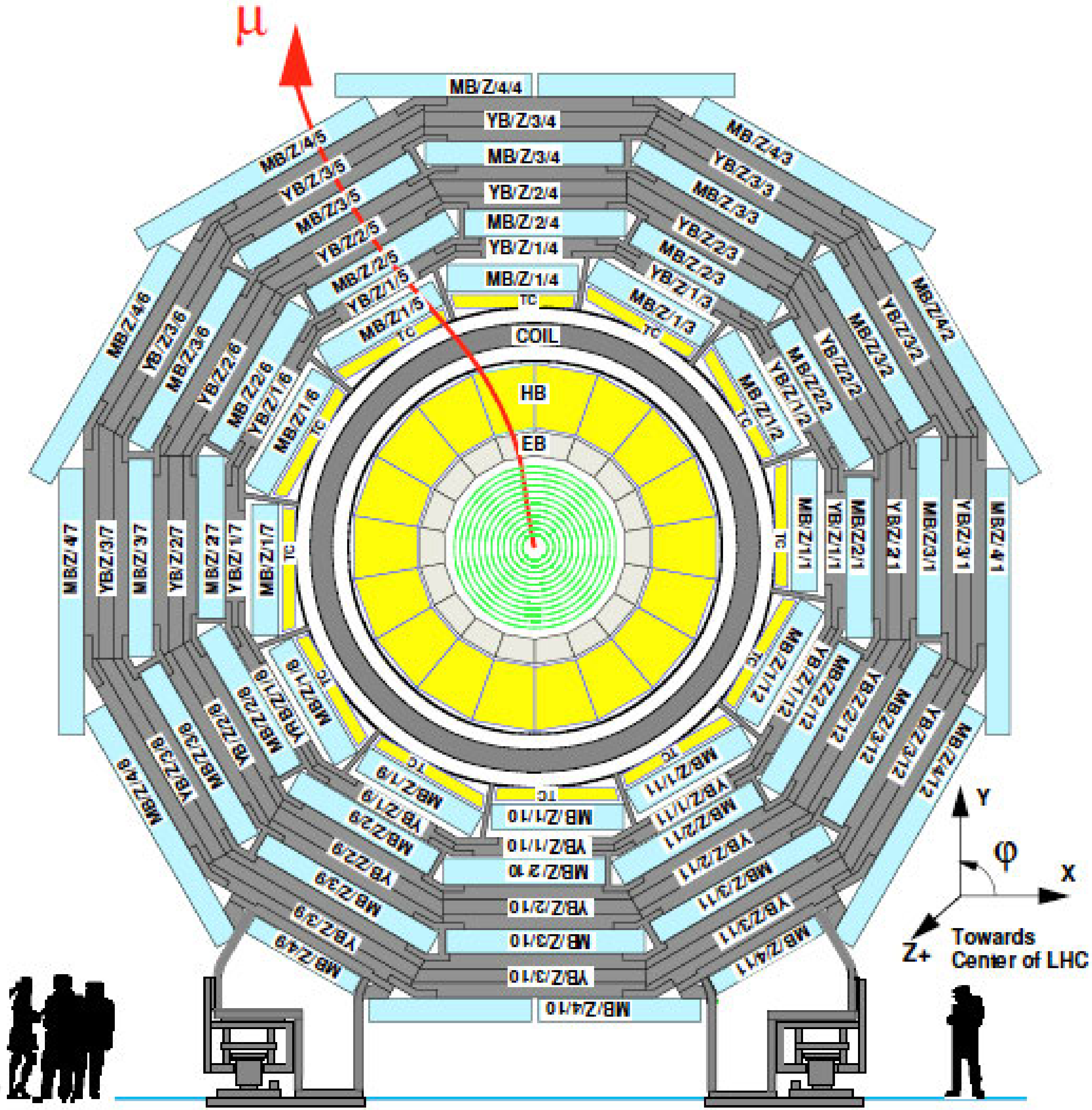




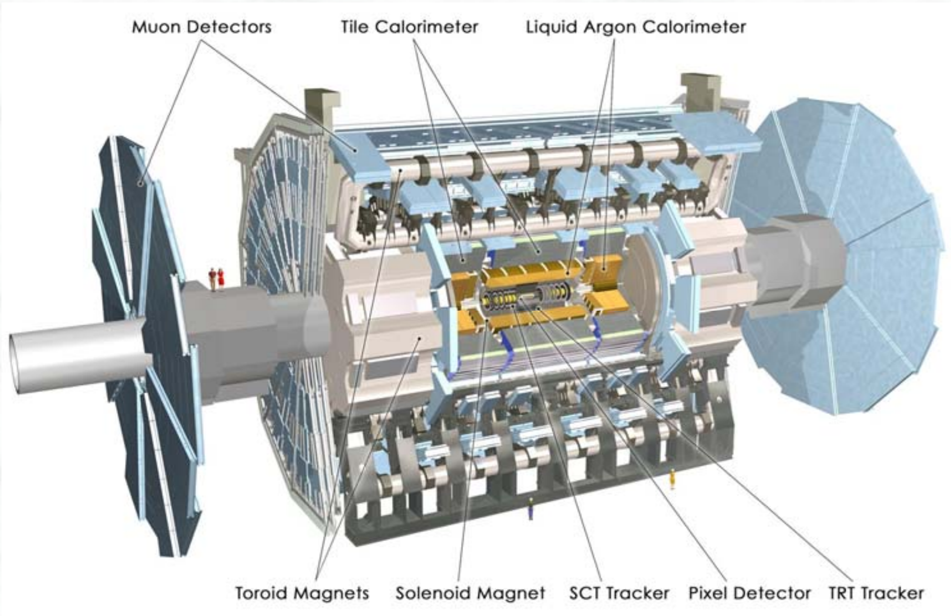
Muon detector system
In the forward region



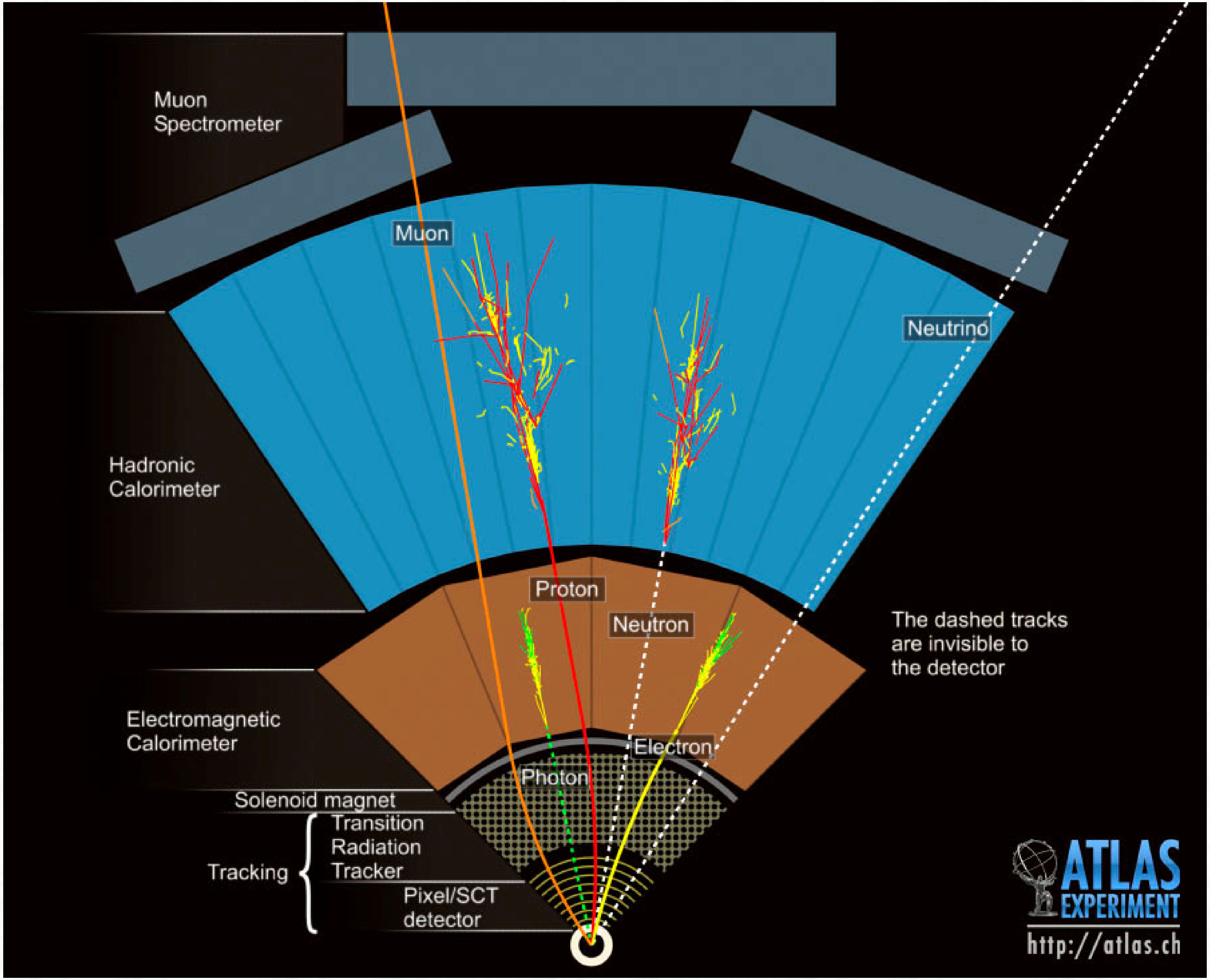
CMS Muon system



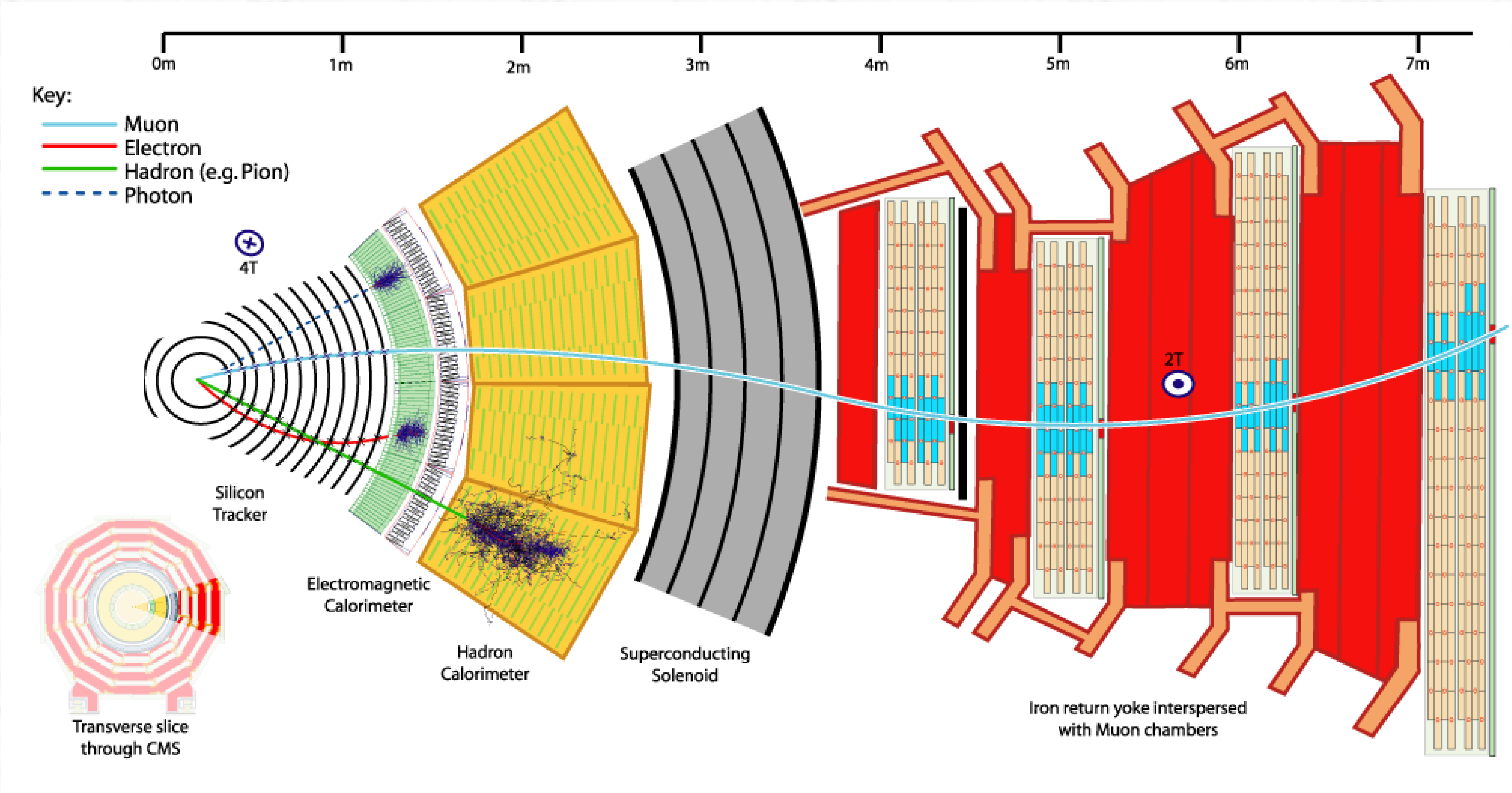
2.7 Important differences between the ATLAS and CMS detectors



The ATLAS detector concept

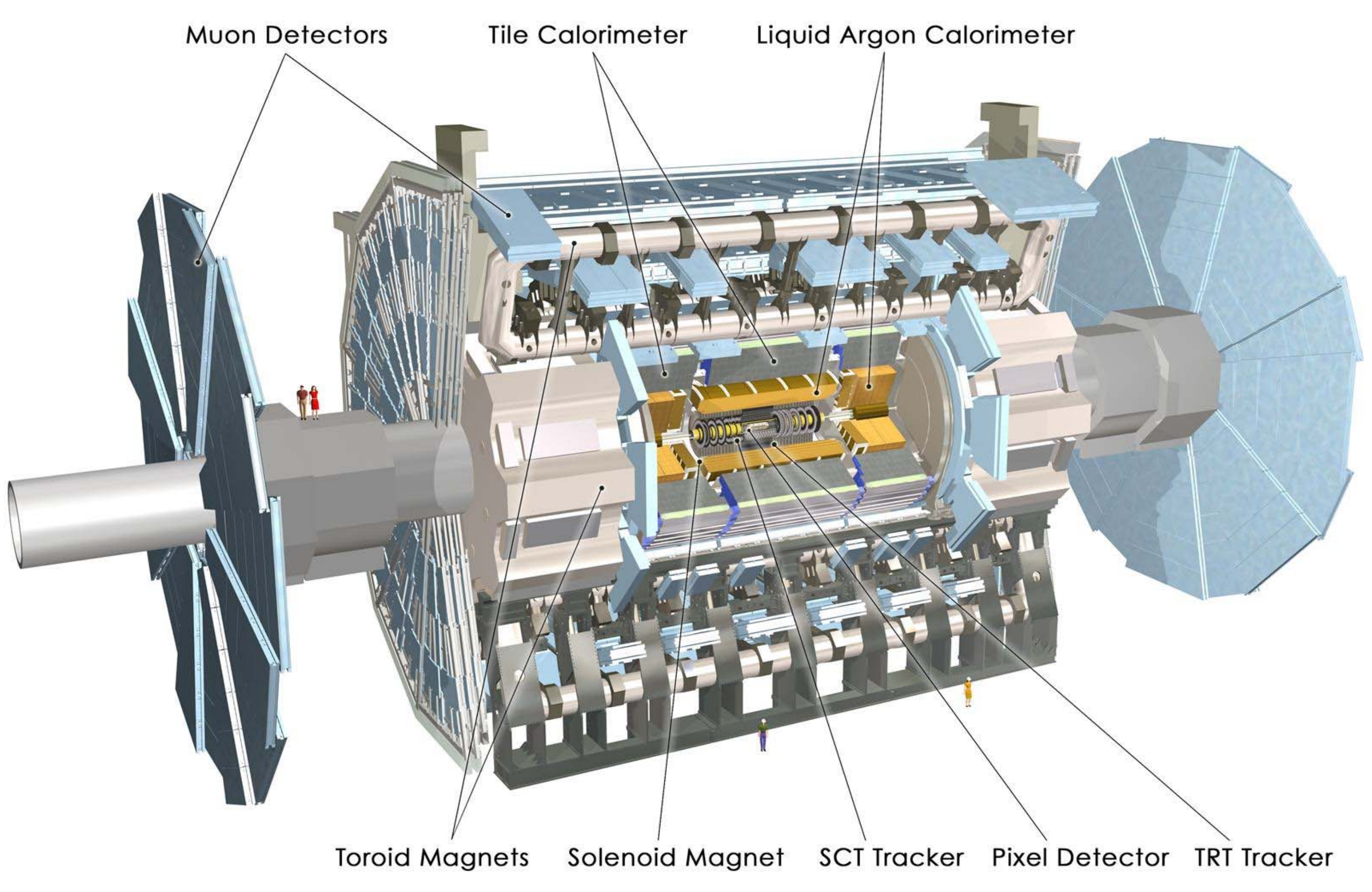


The CMS detector concept



Tracker **Calorimeter** **Coil** **Muon Detector and iron return yoke**

The ATLAS experiment



- Solenoidal magnetic field (2T) in the central region (momentum measurement)

  High resolution silicon detectors:
  - 6 Mio. channels (80 μm x 12 cm)
  - 100 Mio. channels (50 μm x 400 μm)

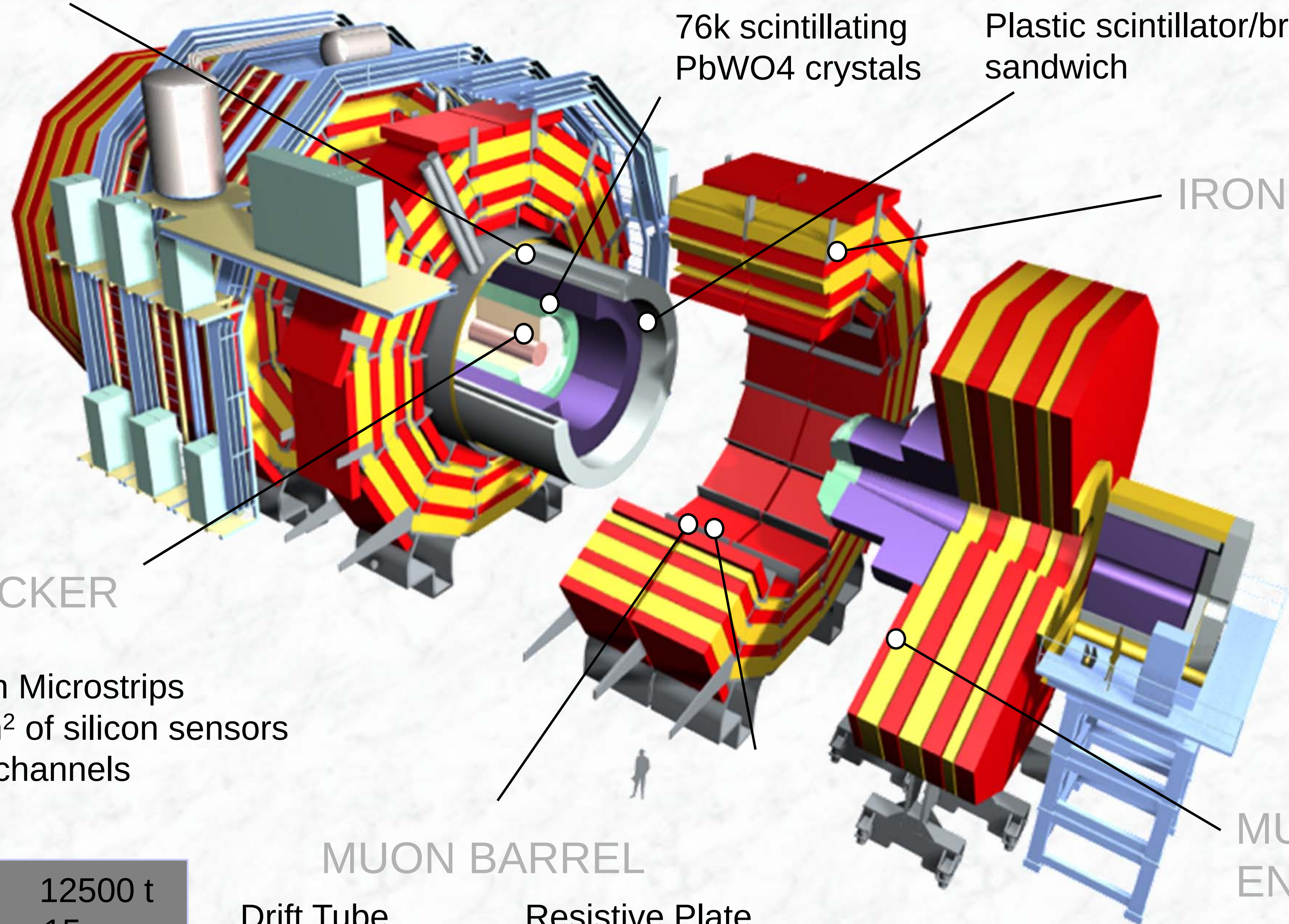
  space resolution: ~ 15 μm

- Energy measurement down to 1º to the beam line

- Independent muon spectrometer (supercond. toroid system)

Diameter	25 m
Barrel toroid length	26 m
End-cap end-wall chamber span	46 m
Overall weight	7000 Tons

The CMS experiment



Total weight	12500 t
Overall diameter	15 m
Overall length	21.6 m

How large are ATLAS and CMS?

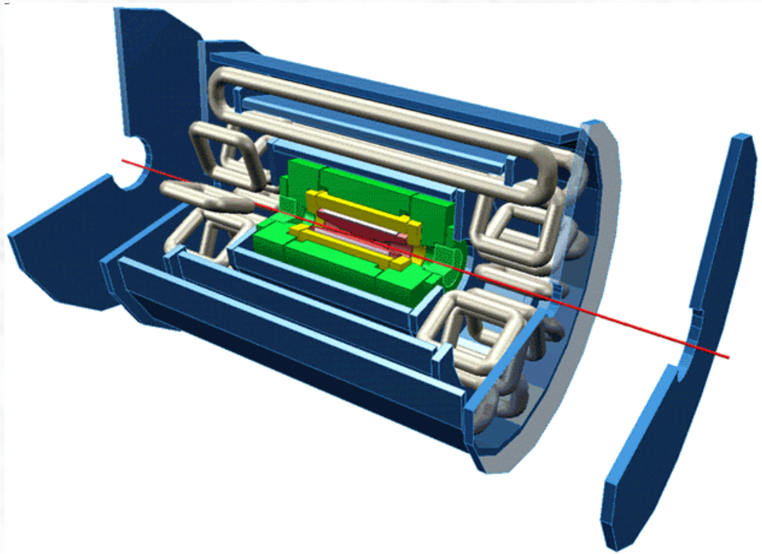
Size of detectors:

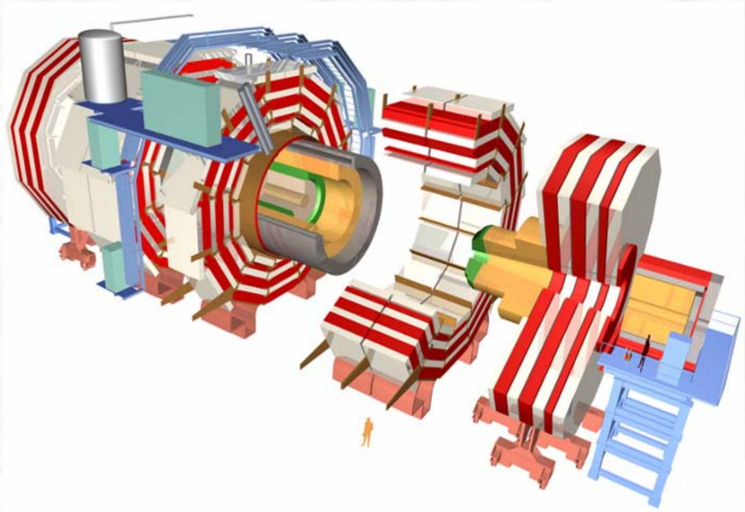
- Volume: 20 000 m^3 for ATLAS
- Weight: 12 500 tons for CMS
- 66 to 80 million pixel readout channels near vertex
- 200 m^2 of active silicon for CMS tracker
- 175 000 readout channels for ATLAS LAr EM calorimeter
- 1 million channels and 10 000 m^2 area of muon chambers
- Very selective trigger/DAQ system
- Large-scale offline software and worldwide computing (GRID)

Time-scale:

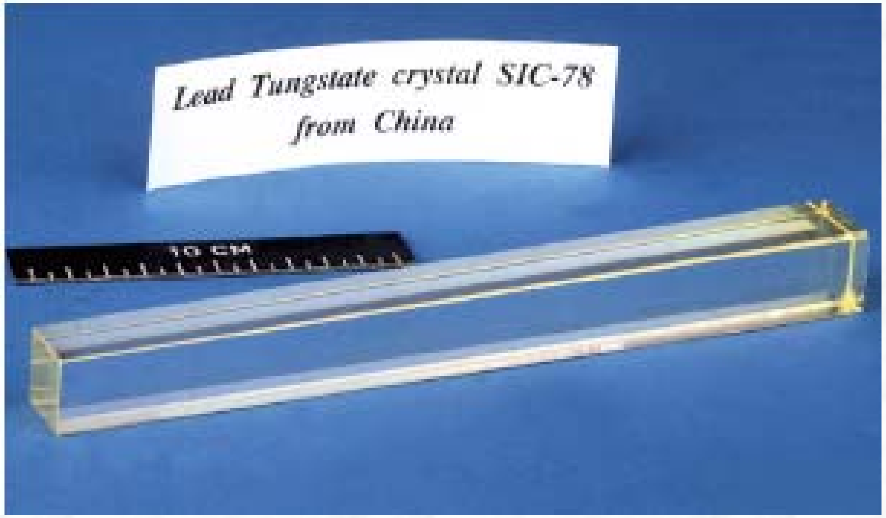
More than 25 years from first conceptual studies (Lausanne 1984)
to solid physics results in 2011

	ATLAS	CMS
Magnetic field	2 T solenoid + toroid: 0.5 T (barrel), 1 T (endcap)	4 T solenoid + return yoke
Tracker	Silicon pixels and strips + transition radiation tracker $\sigma/p_T \approx 5 \cdot 10^{-4} p_T + 0.01$	Silicon pixels and strips (full silicon tracker) $\sigma/p_T \approx 1.5 \cdot 10^{-4} p_T + 0.005$
EM calorimeter	Liquid argon + Pb absorbers $\sigma/E \approx 10\%/\sqrt{E} + 0.007$	$PbWO_4$ crystals $\sigma/E \approx 3\%/\sqrt{E} + 0.003$
Hadronic calorimeter	Fe + scintillator / Cu+LAr (10λ) $\sigma/E \approx 50\%/\sqrt{E} + 0.03$ GeV	Brass + scintillator (7 λ + catcher) $\sigma/E \approx 100\%/\sqrt{E} + 0.05$ GeV
Muon	$\sigma/p_T \approx$ 2% @ 50GeV to 10% @ 1TeV (Inner Tracker + muon system)	$\sigma/p_T \approx$ 1% @ 50GeV to 10% @ 1TeV (Inner Tracker + muon system)
Trigger	L1 + HLT (L2+EF)	L1 + HLT (L2 + L3)





Important differences I:

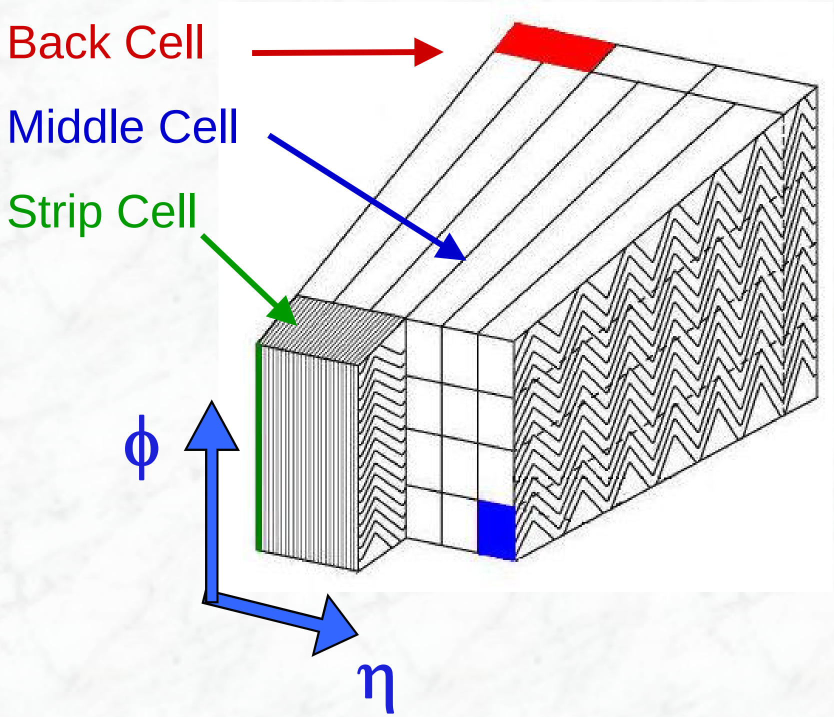


- In order to maximize the sensitivity for **$H \rightarrow \gamma\gamma$ decays**, the experiments need to have an excellent e/γ identification and resolution

---

- CMS: has opted for a high resolution $PbWO_4$ crystal calorimeter
  - higher intrinsic resolution

- ATLAS: Liquid argon calorimeter
  - high granularity and longitudinally segmentation (better e/γ ID)
  - electrical signals, high stability in calibration & radiation resistant

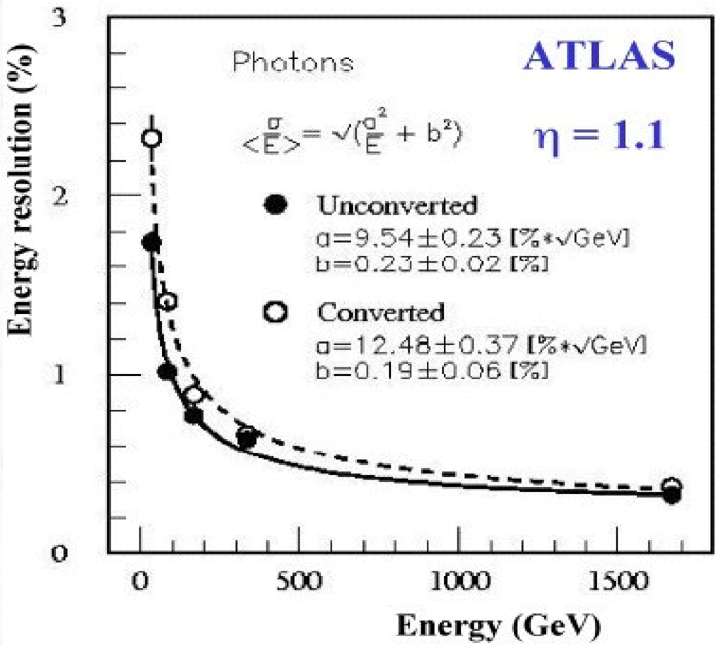


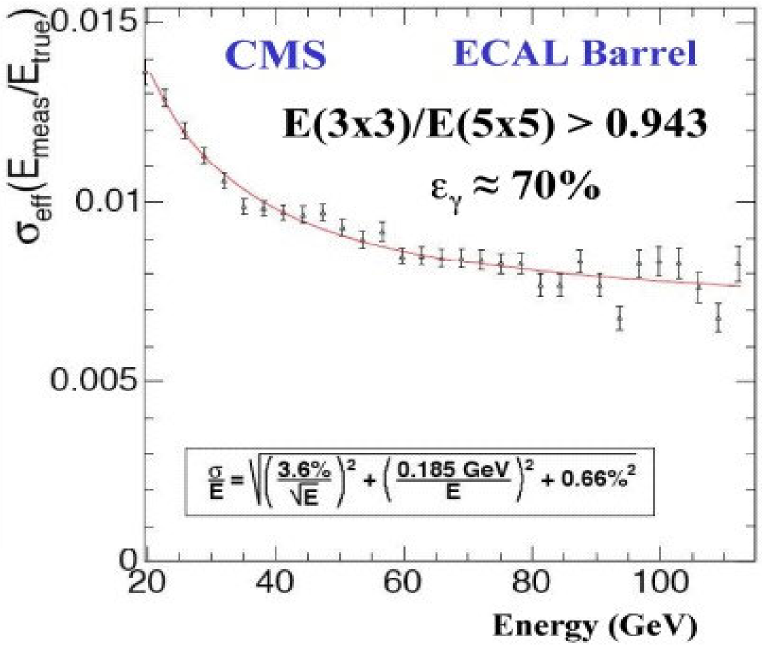
ATLAS/CMS: e/γ resolutions

Photons at 100 GeV

ATLAS: 1-1.5% energy resol. (all γ)

CMS: 0.8% energy resol. (ε_γ ~ 70%)

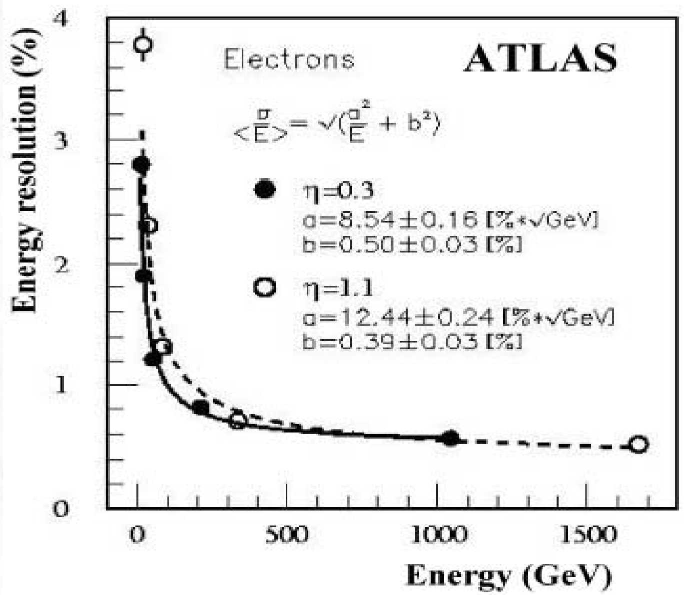


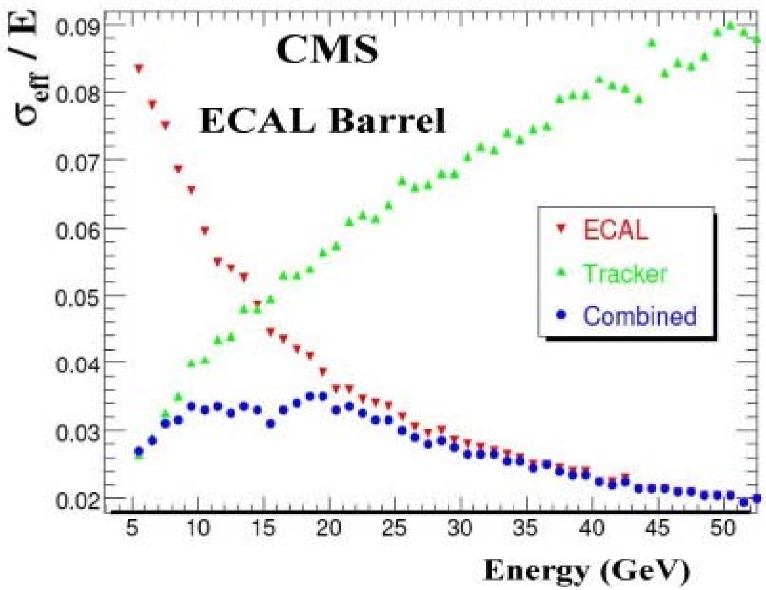


Electrons at 50 GeV

ATLAS: 1.3-2.3% energy resol. (use EM calo only)

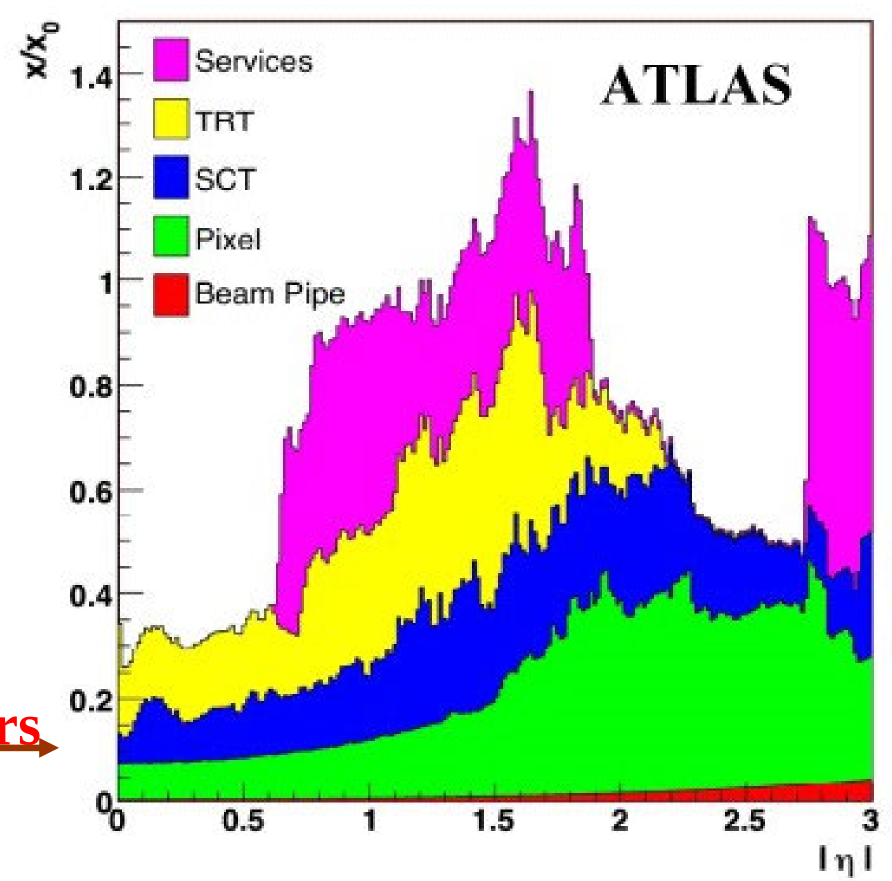
CMS: ~ 2.0% energy resol. (combine EM calo and tracker)





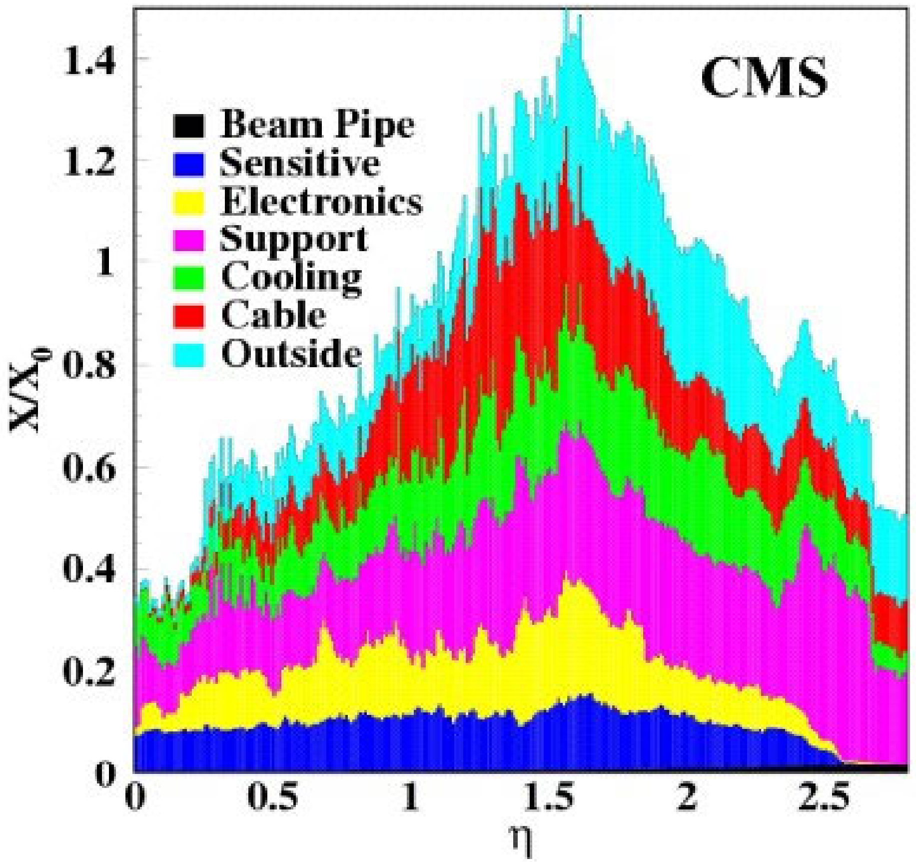
Amount of material in ATLAS and CMS inner trackers

Weight: 4.5 tons



LEP detectors

Weight: 3.7 tons

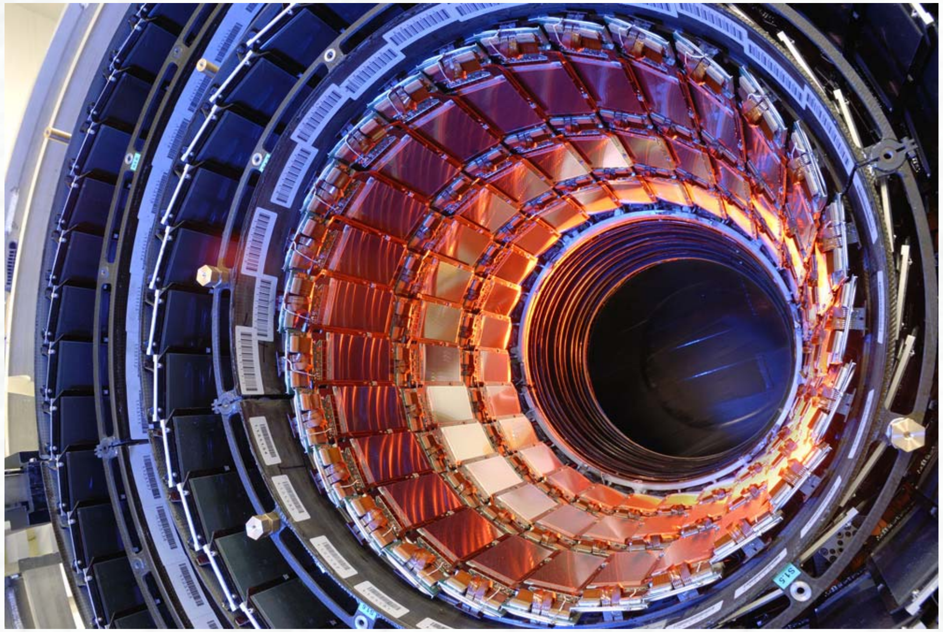


- Active sensors and mechanics account each only for ~ 10% of material budget
- Need to bring 70 kW power into tracker and to remove similar amount of heat
- Very distributed set of heat sources and power-hungry electronics inside volume: this has led to complex layout of services, most of which were not at all understood at the time of the TDRs

Important differences II:

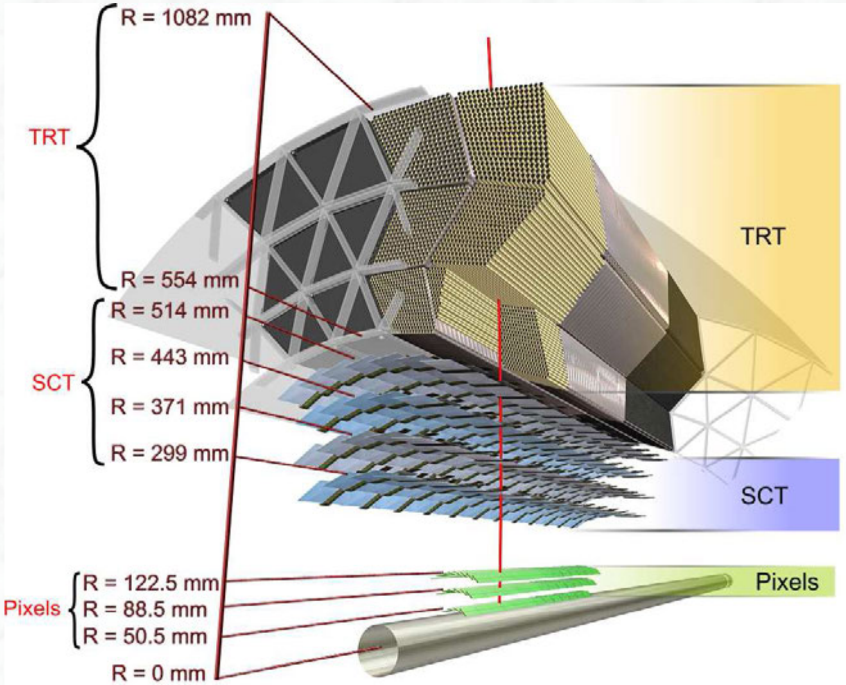
- Inner detectors / tracker

Both use solenoidal fields
ATLAS: 2 Tesla
CMS: 4 Tesla



- CMS: full silicon strip and pixel detectors
  - high resolution, high granularity

- ATLAS: Silicon (strips and pixels)
  + Transition Radiation Tracker
  - high granularity and resolution close to interaction region
  - "continuous" tracking at large radii



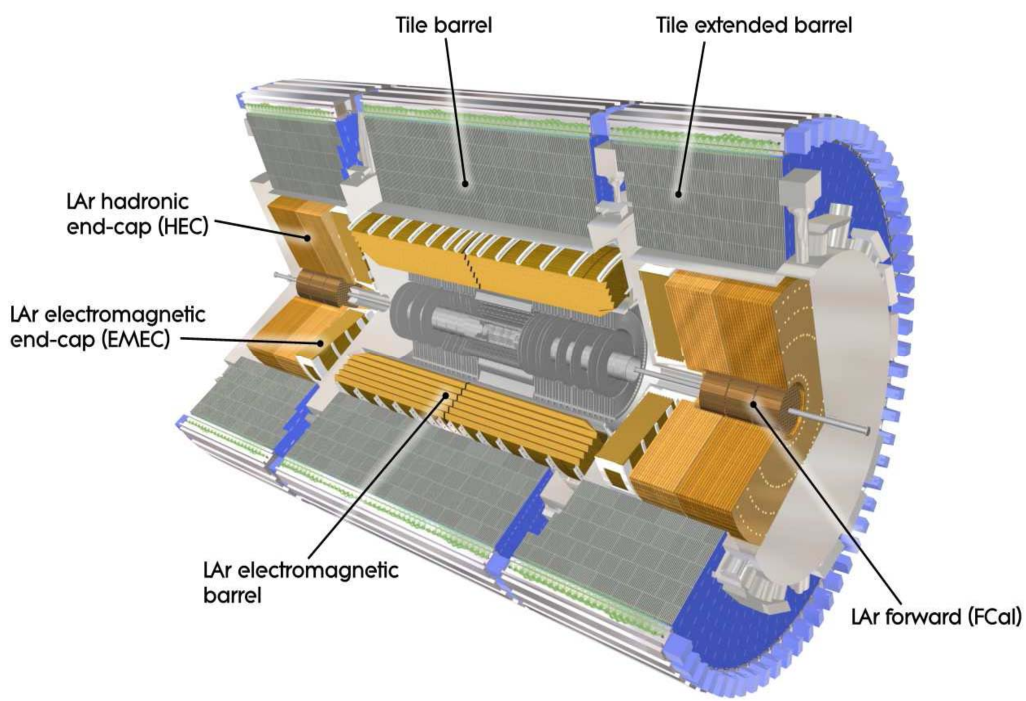
Important differences III:

- Coil / Hadron calorimeters

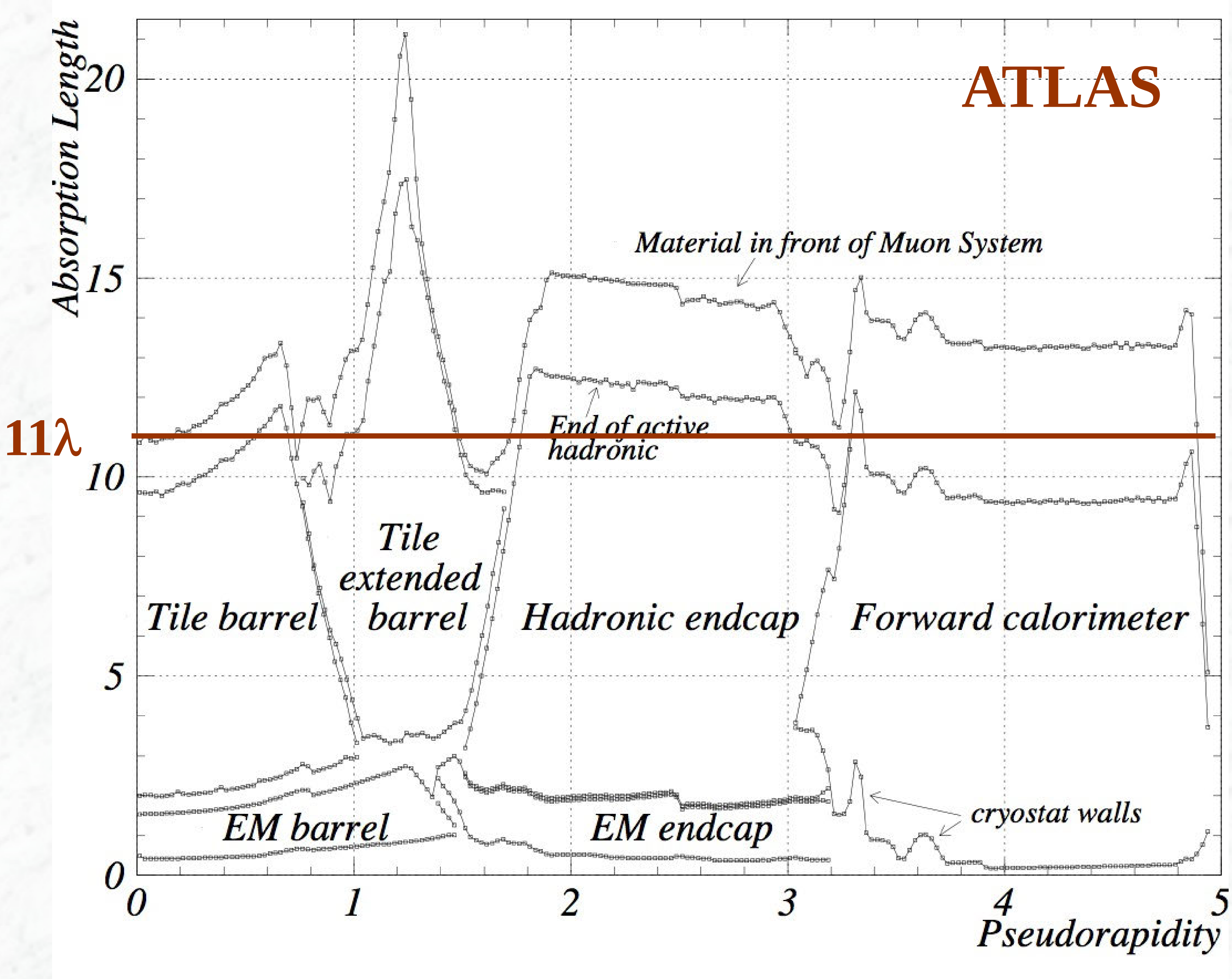
- CMS: electromagnetic calorimeter and part of the hadronic calorimeter (7λ) inside the solenoidal coil + tail catcher, return yoke

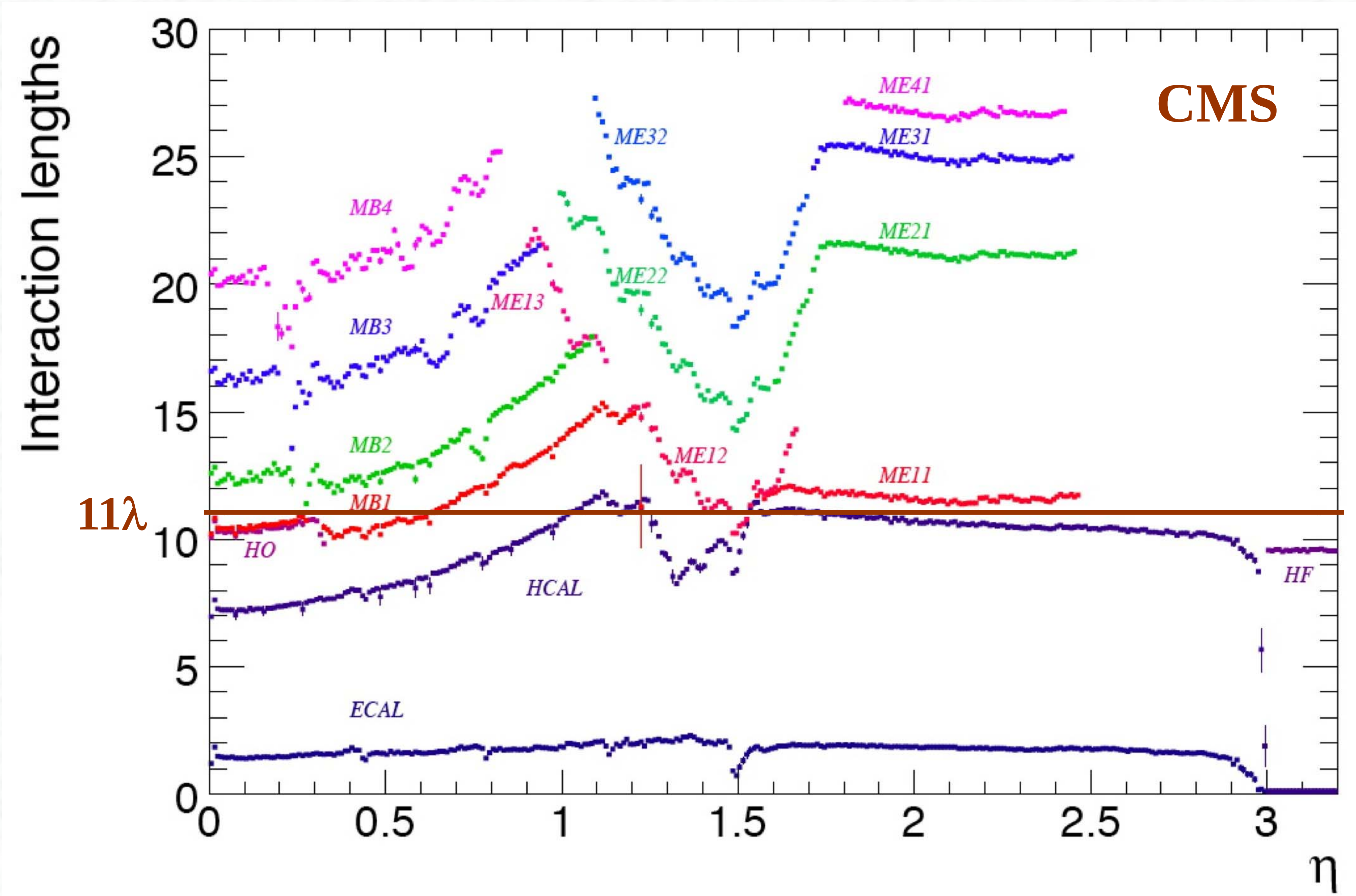
  good for e/γ resolution
  bad for jet resolution

- ATLAS: calorimetry outside coil



Hadronic absorption length of the calorimeters




CMS
11λ
Interaction lengths
η
MB4
MB3
MB2
MB1
HO
ME13
ME32
ME22
ME12
ME41
ME31
ME21
ME11
HCAL
HF
ECAL
0
5
10
15
20
25
30
0
0.5
1
1.5
2
2.5
3

Main performance parameters of the different hadronic calorimeter components of the ATLAS and CMS detectors, as measured in test beams using charged pions in both stand-alone and combined mode with the ECAL

	ATLAS					
	Barrel LAr/Tile		End-cap LAr		CMS	
	Tile	Combined	HEC	Combined	Had. barrel	Combined
Electron/hadron ratio	1.36	1.37	1.49			
Stochastic term	$45\%/\sqrt{E}$	$55\%/\sqrt{E}$	$75\%/\sqrt{E}$	$85\%/\sqrt{E}$	$100\%/\sqrt{E}$	$70\%/\sqrt{E}$
Constant term	1.3%	2.3%	5.8%	$< 1\%$		8.0%
Noise	Small	3.2 GeV		1.2 GeV	Small	1 GeV

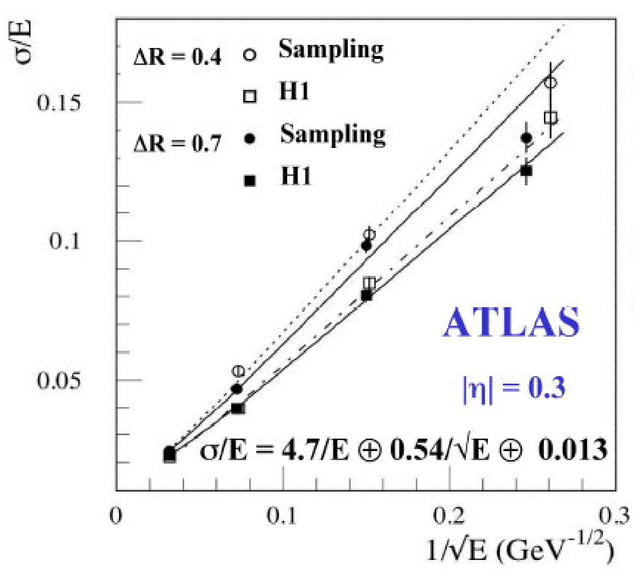
The measured electron/hadron ratios are given separately for the hadronic stand-alone and combined calorimeters when available, and for the contributions (added quadratically except for the stand-alone ATLAS tile calorimeter) to the pion energy resolution from the stochastic term, the local constant term, and the noise are also shown, when available from published data.

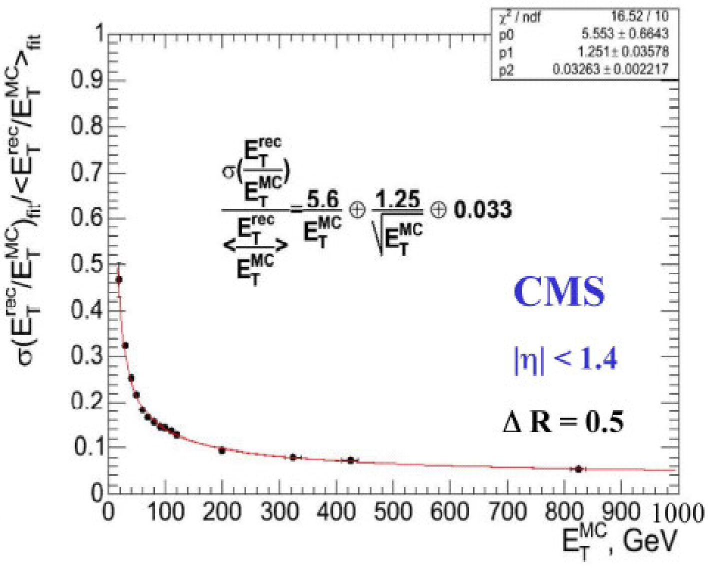
Biggest difference in performance perhaps for hadronic calorimetry

Jets at 1000 GeV

ATLAS: ~ 2%
energy resolution
CMS: ~ 5%
energy resolution,

But expect sizable
improvement using tracks
(especially at lower E)



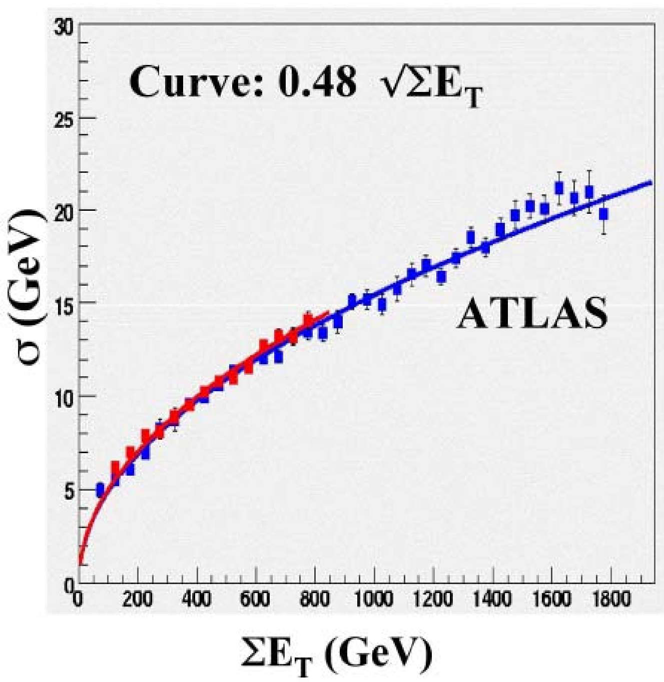


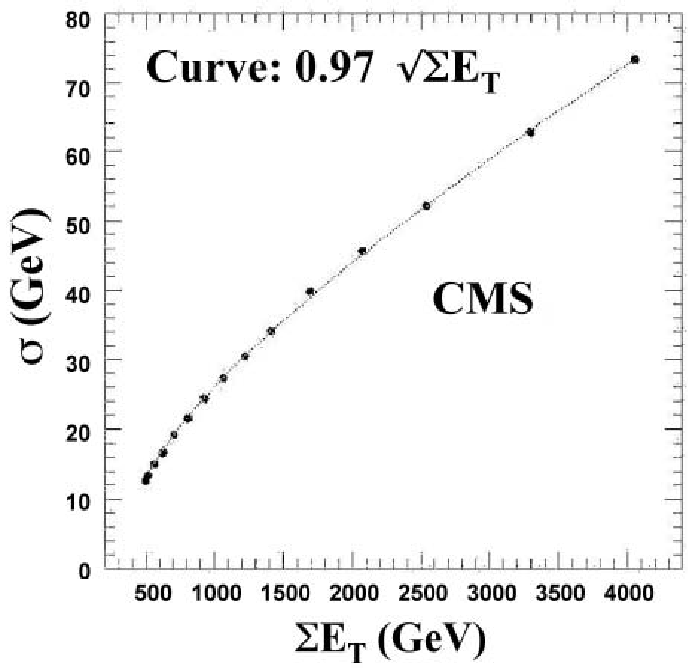
E_T^{miss} at ΣE_T = 2000 GeV

ATLAS: σ ~ 20 GeV

CMS: σ ~ 40 GeV

This may be important for
high mass H/A $\rightarrow \tau\tau$





<u>Important differences IV</u>:

- Muon spectrometer

- ATLAS: independent muon spectrometer;
  → excellent stand-alone capabilities

- CMS: superior combined momentum resolution in the central region;
  limited stand-alone resolution and trigger capabilities
  (multiple scattering in the iron)