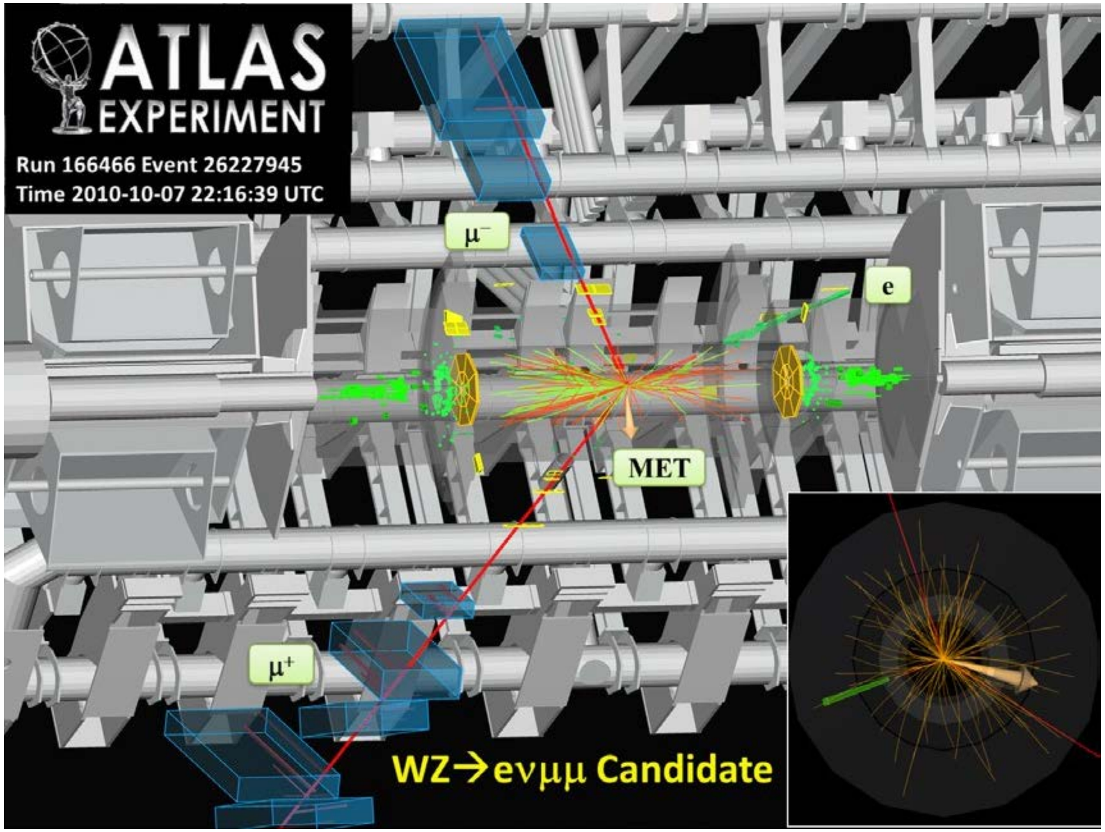
7. Particle Detectors

-a short introduction-



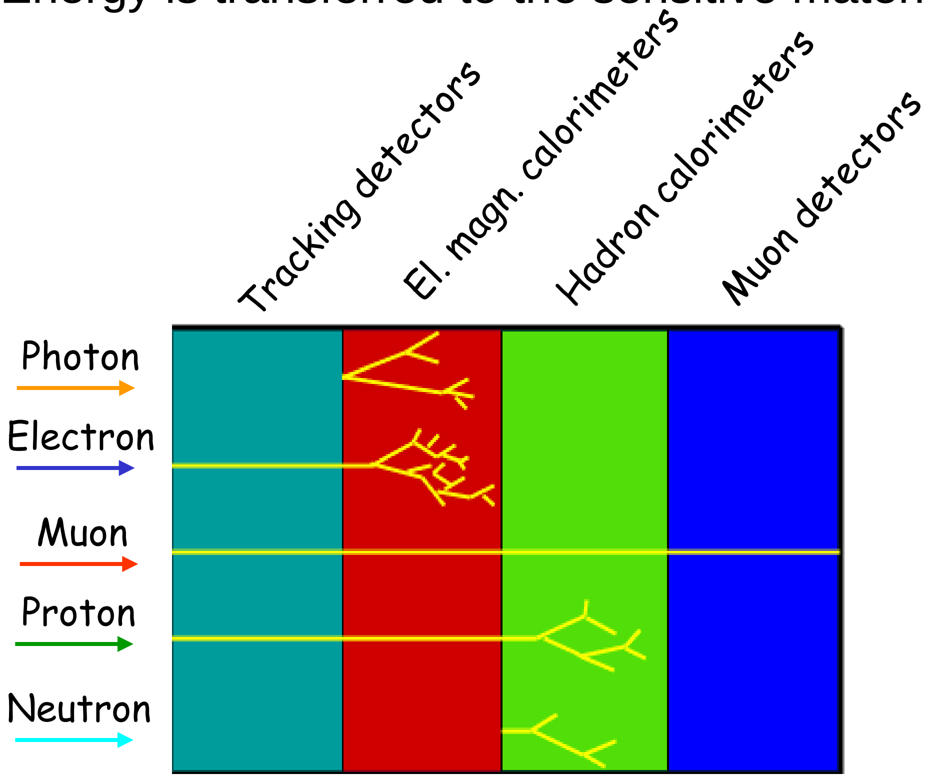
Prof. K. Jakobs
Physikalisches Institut
Universität Freiburg / Germany

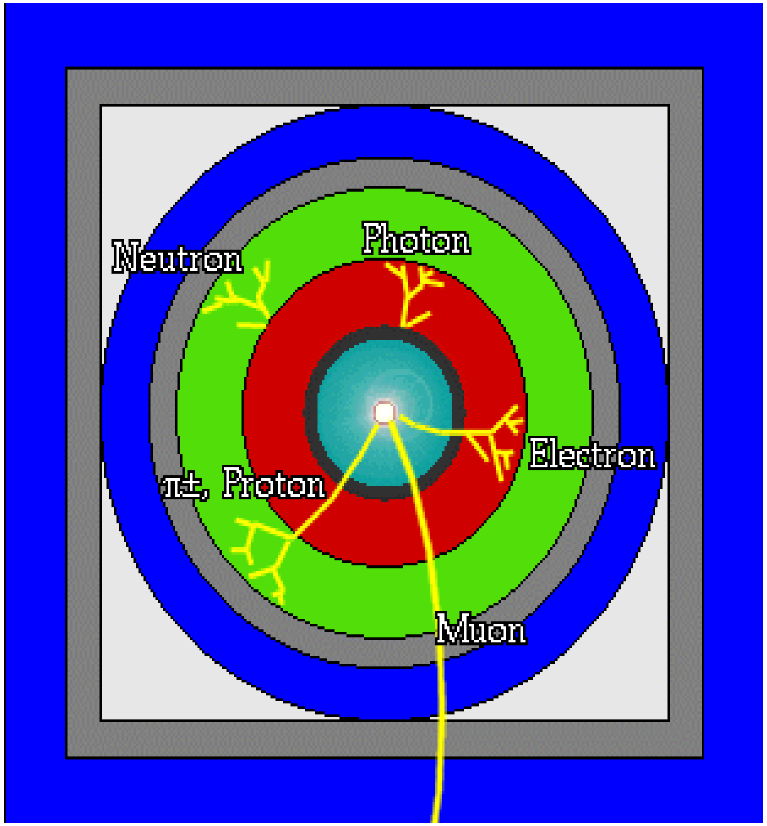
7.1 Detection principle

- 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

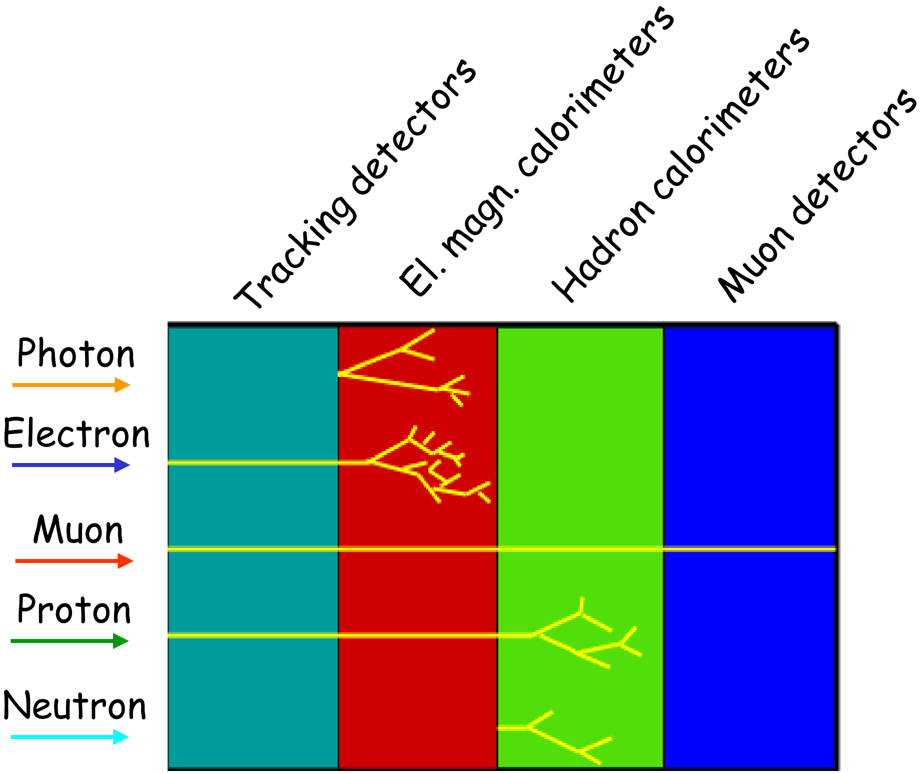


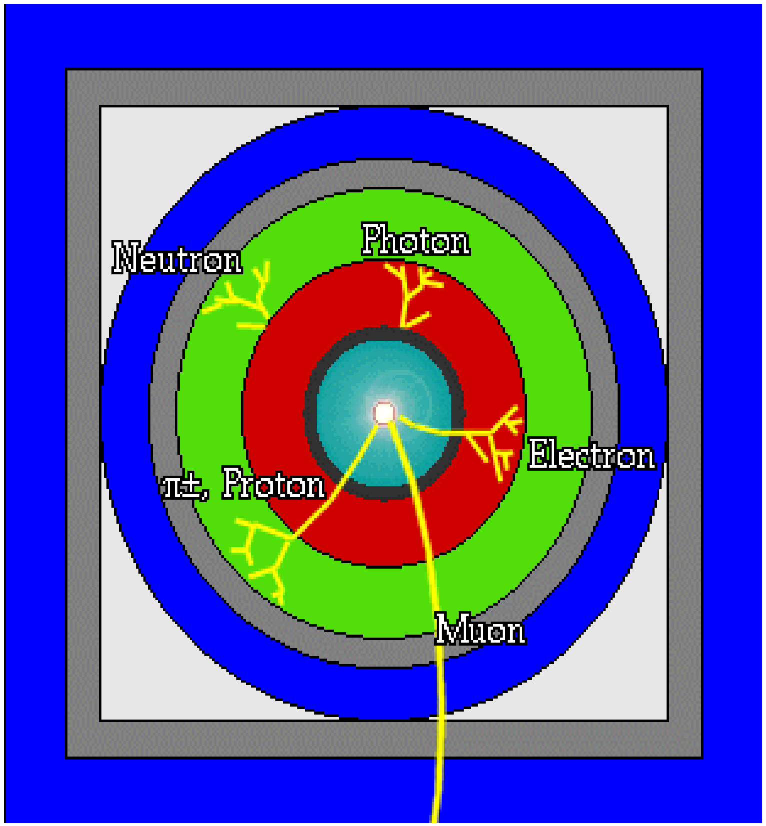


Detection principle (cont.)

(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



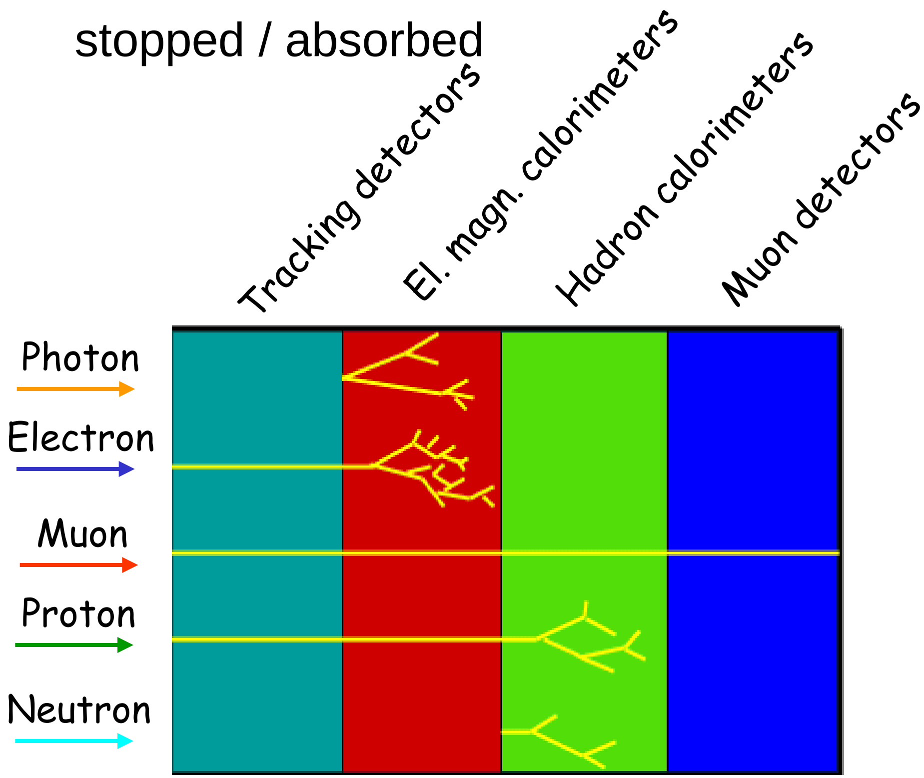


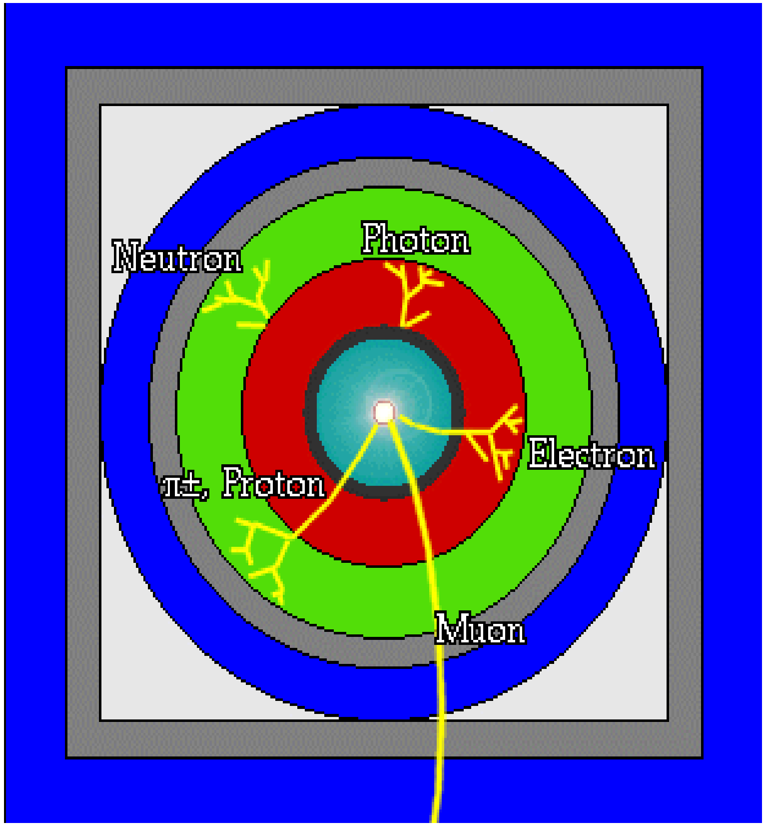
(ii) Calorimeters: measure the energy of the particles, particles are stopped, their full energy is deposited, part of it is transferred to a detector medium

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

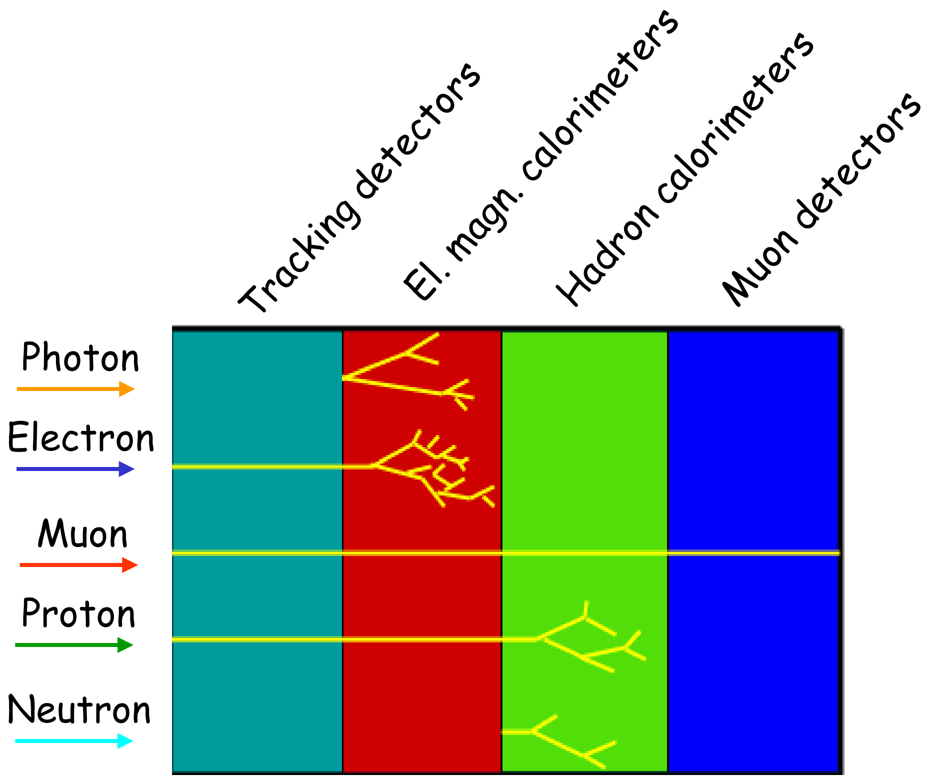


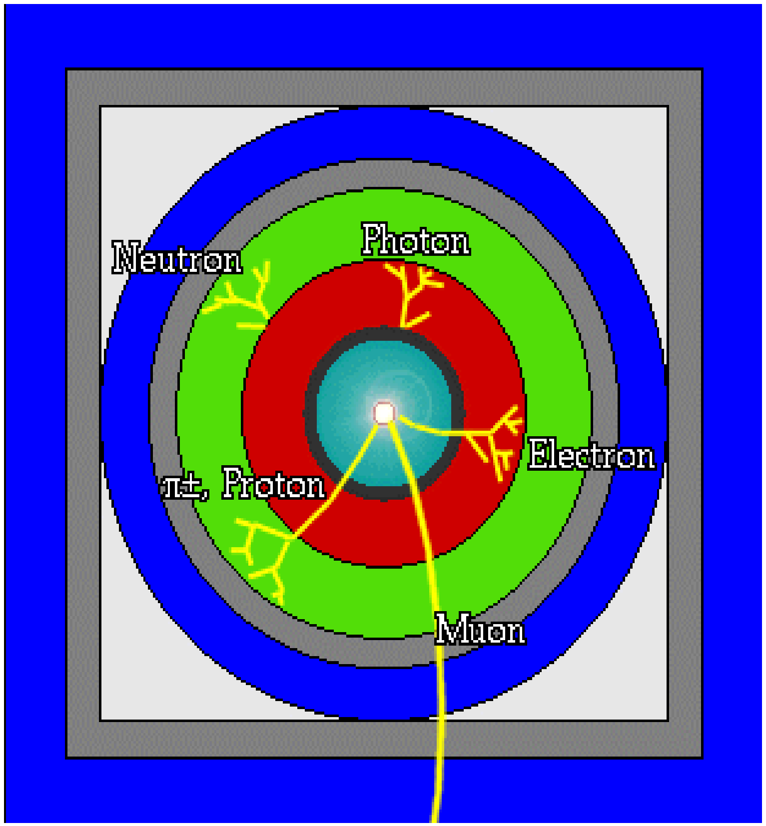


Detection principle

(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





Detection principle

(iv) How to detect neutrinos?

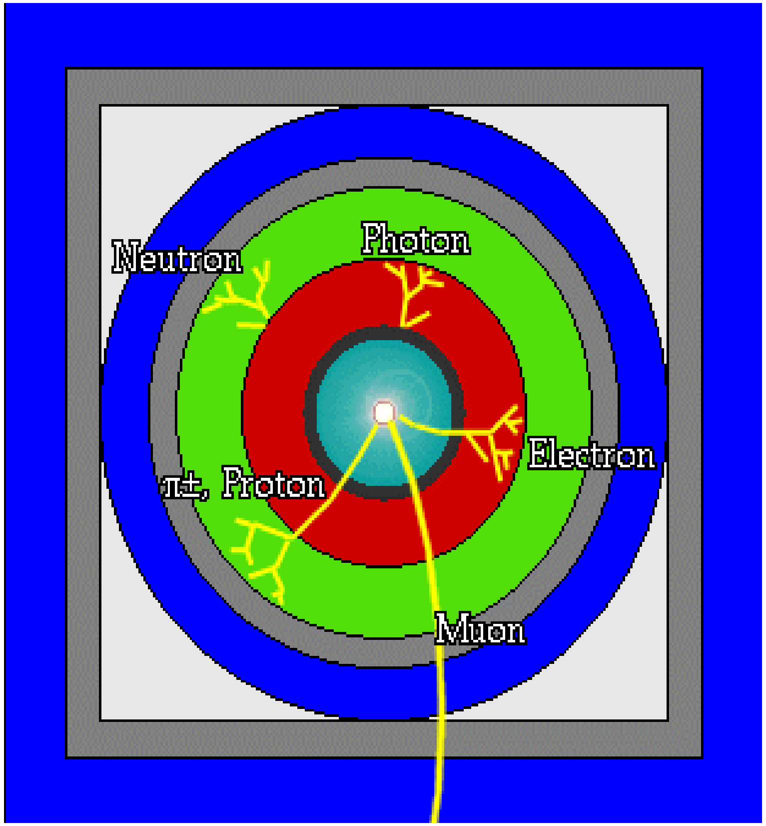
- Neutrinos interact only weakly, i.e. via the weak interaction, with the detector material

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

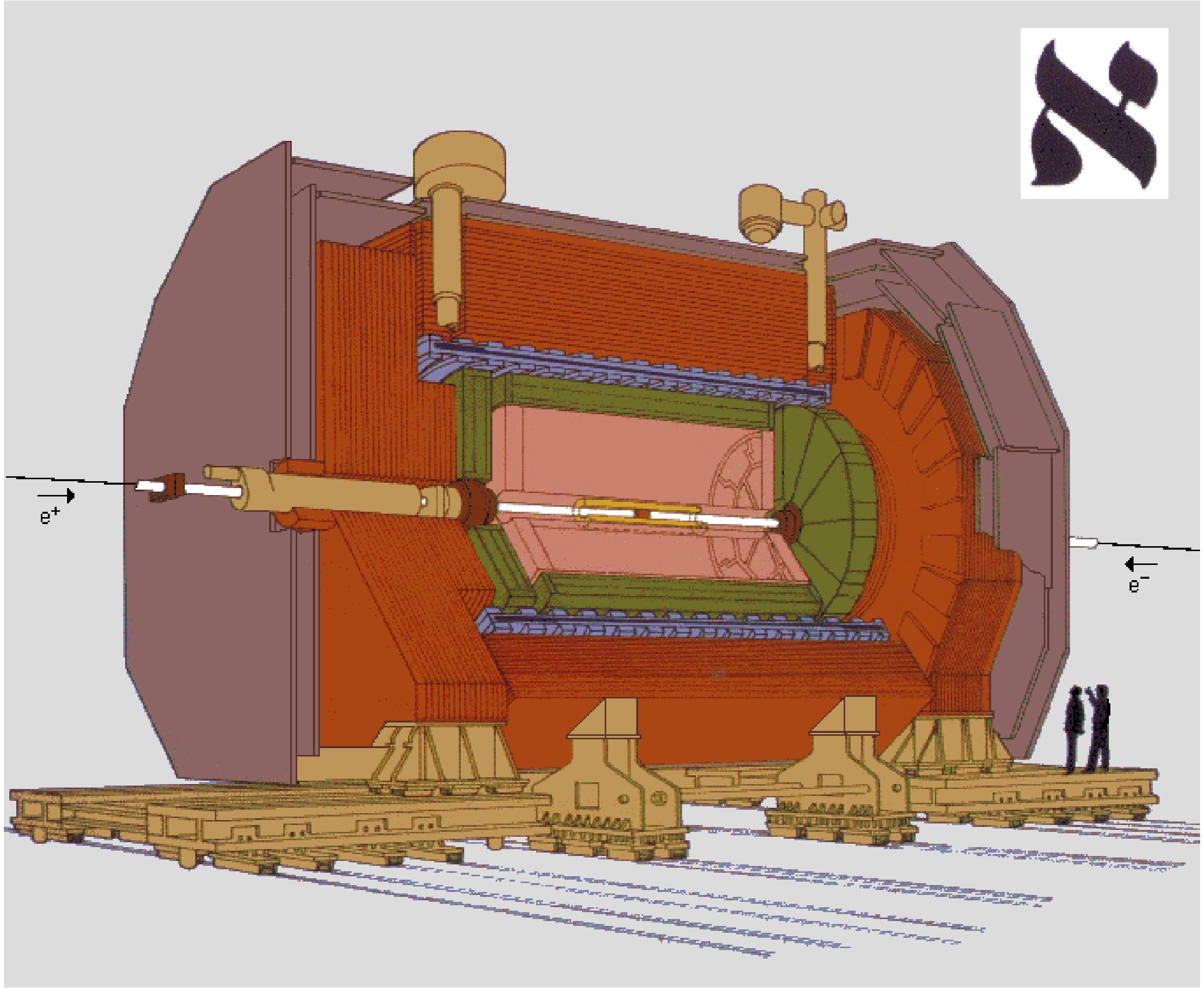
- They carry away energy and momentum

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

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



A typical particle detector
-ALEPH at LEP (~1990) as an example-



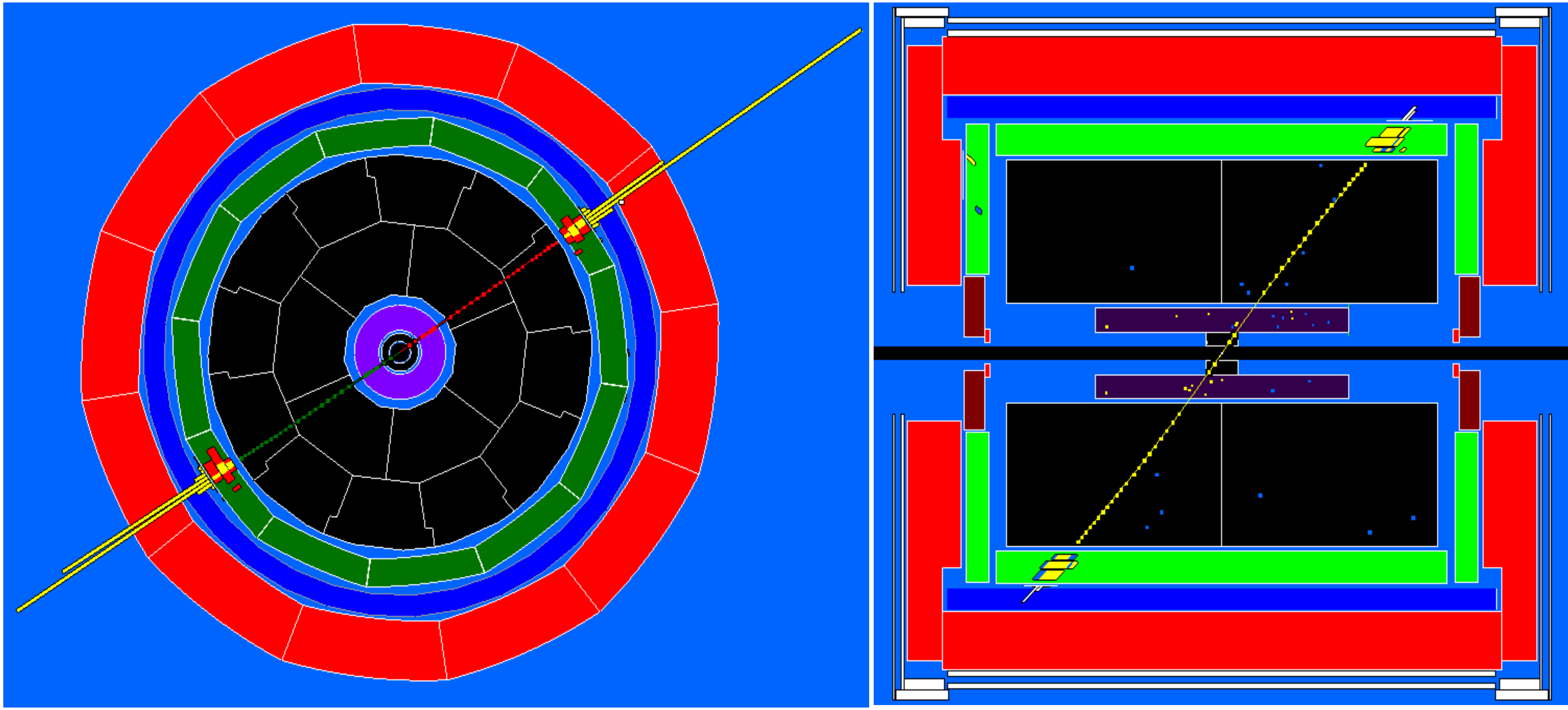
1. Central region:
   large tracking detector
2. Electromagnetic part of the calorimeter
3. Superconducting coil, high currents
   → high solenoidal magnetic field
4. Hadronic part of the calorimeter
5. Muon detector system

A few collision events recorded with the ALEPH detector at LEP

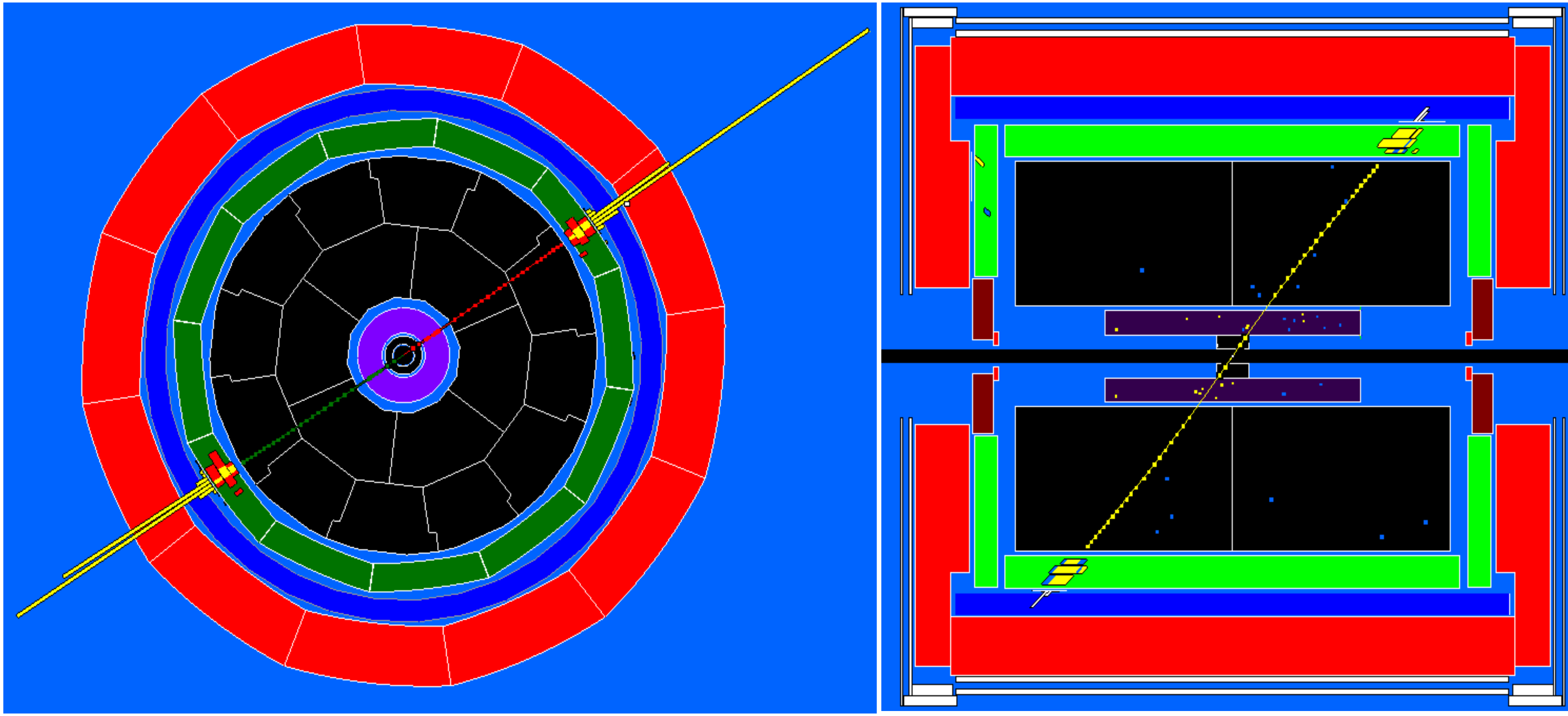
Initial state: $e^+ e^-$ collisions

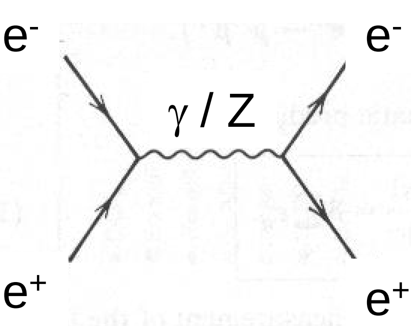
centre-of-mass energy $\sqrt{s}$ = 91 GeV

What process has occurred here ?

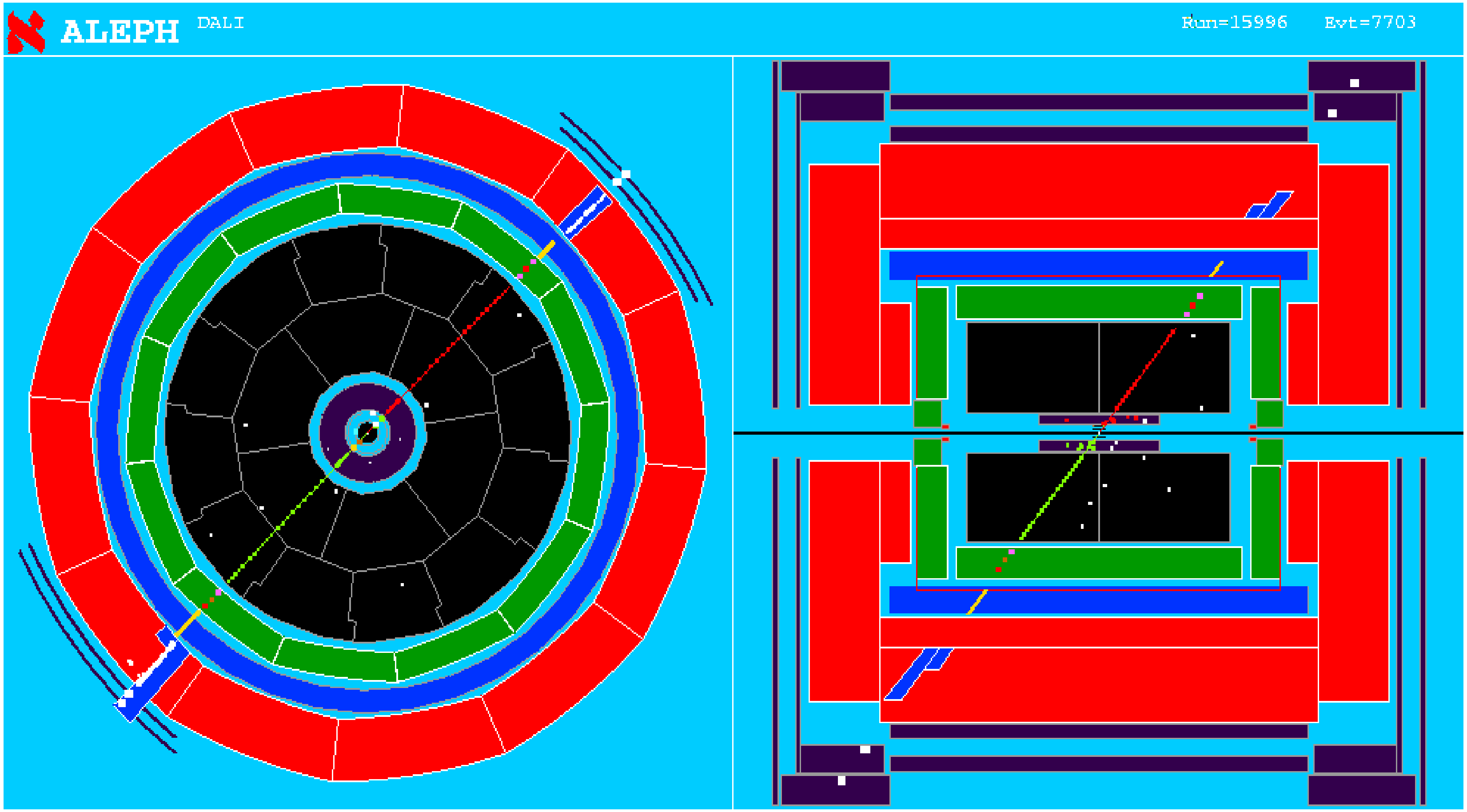


What process has occurred here ?

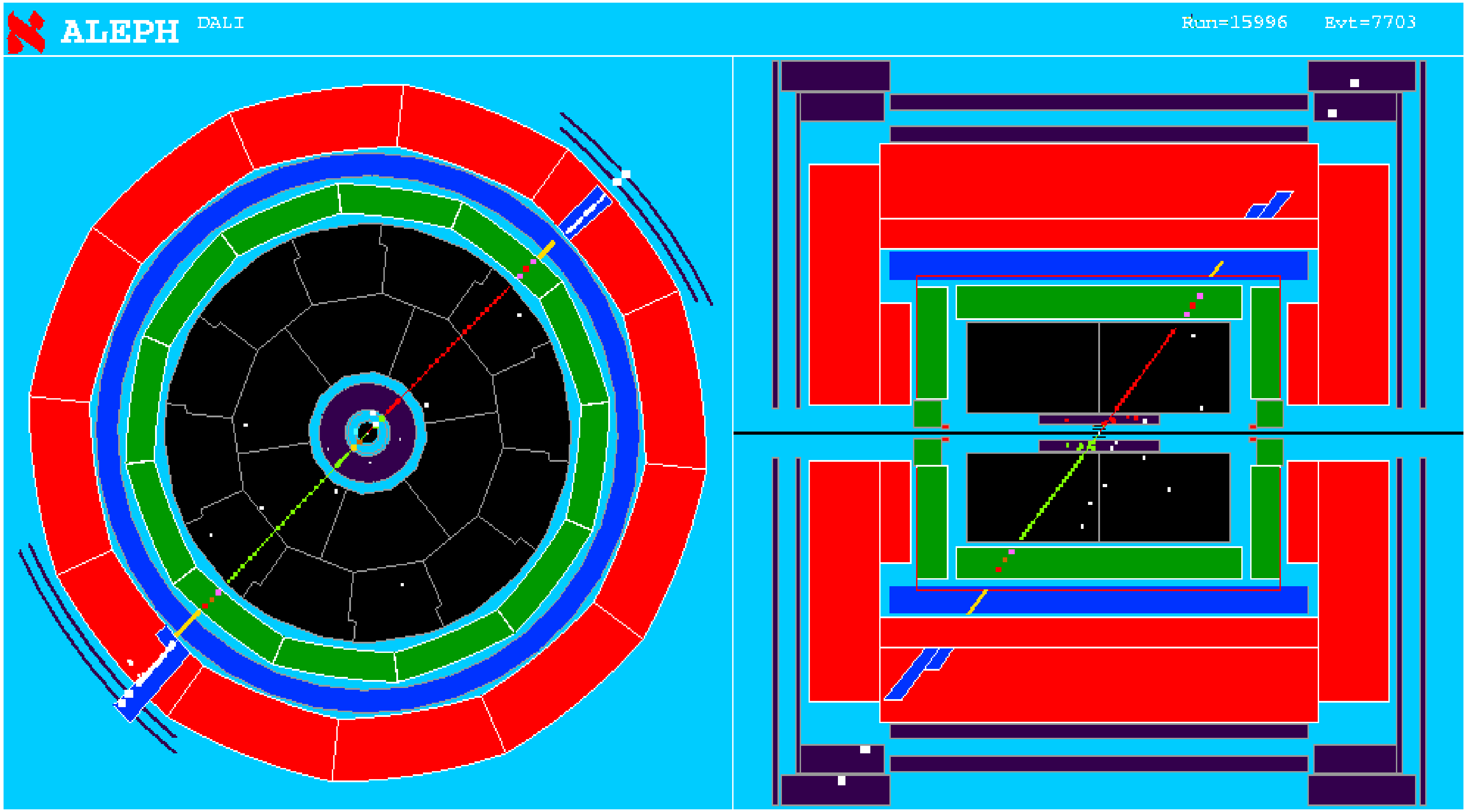


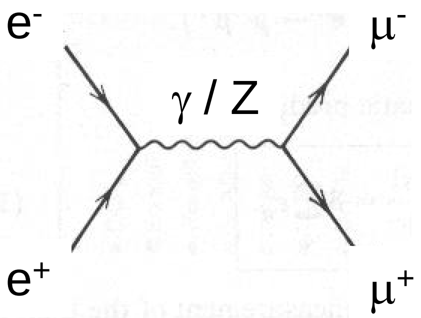


What process has occurred here ?

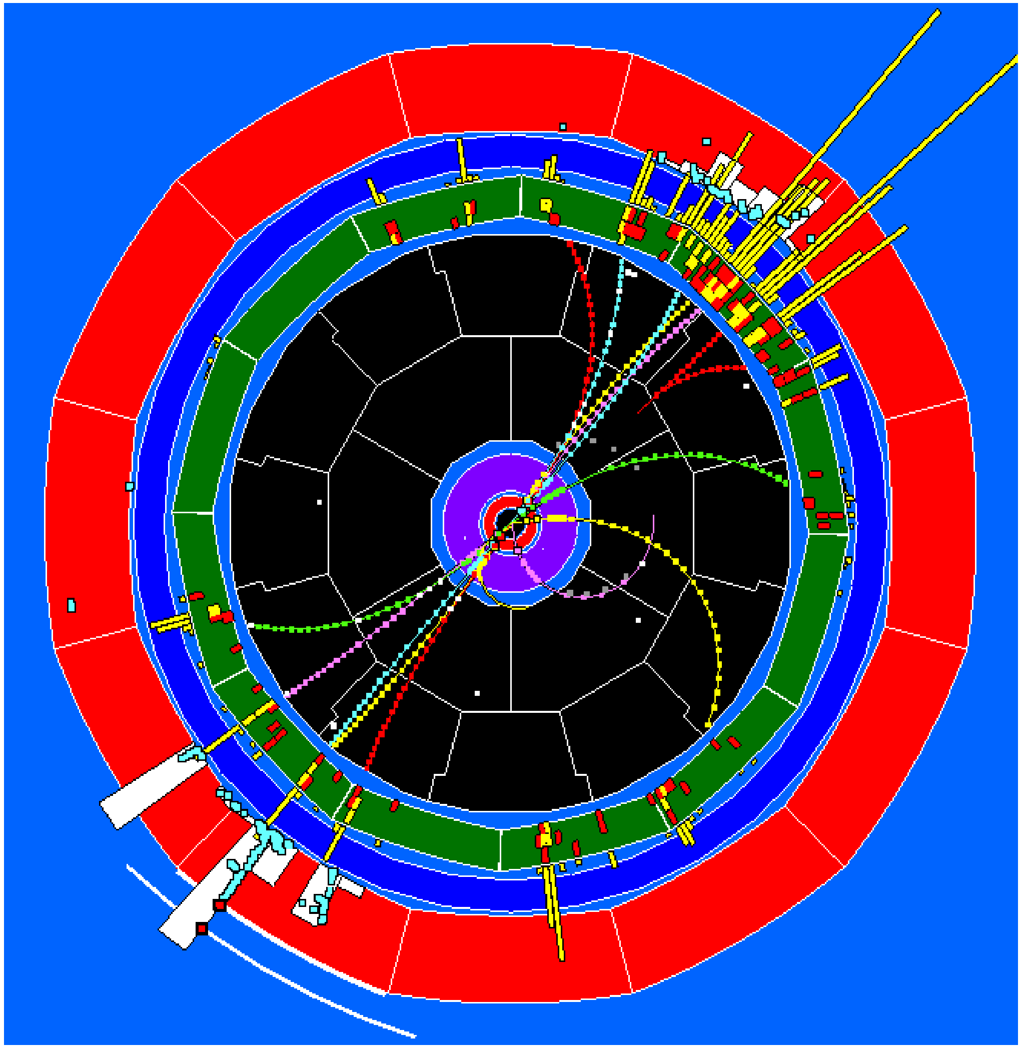


What process has occurred here ?

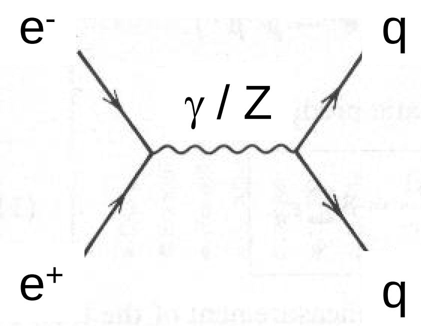


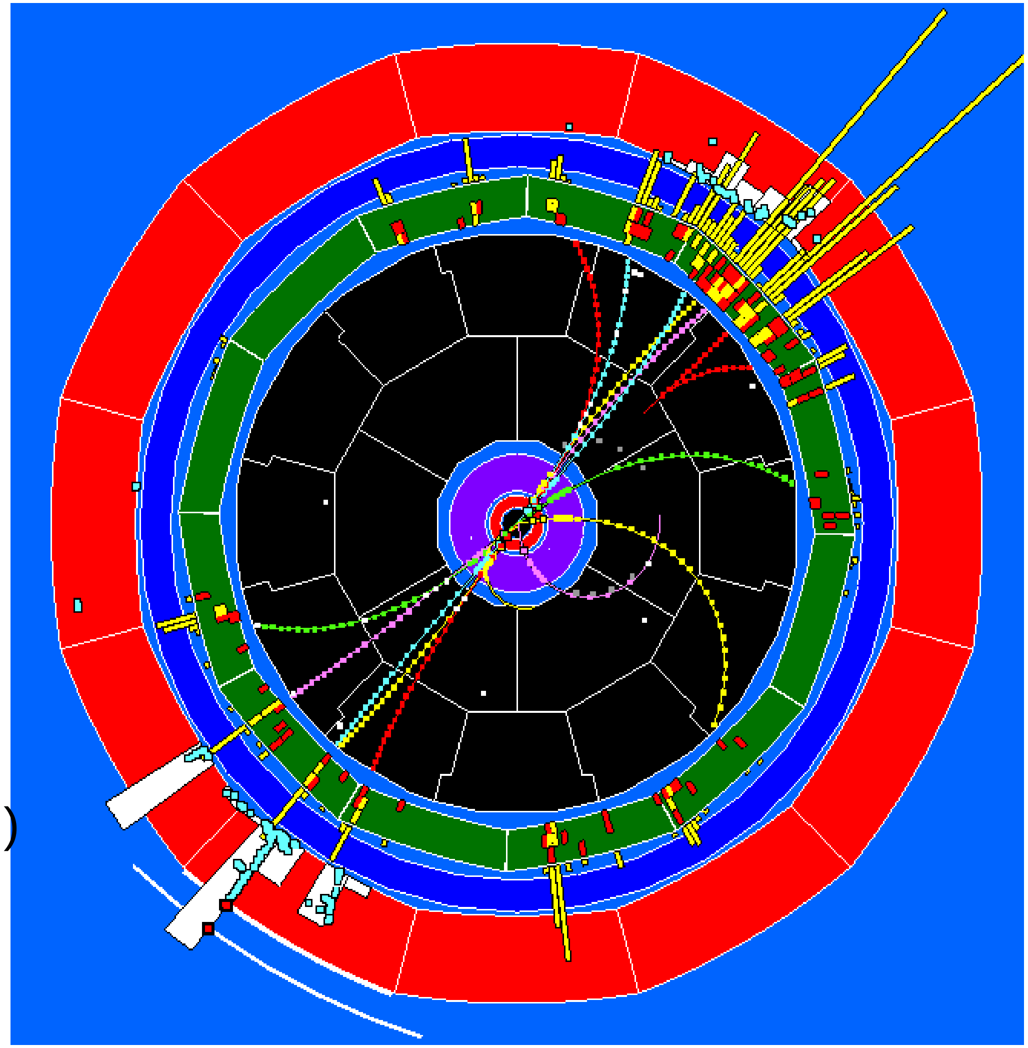


What process has occurred here ?



What process has occurred here ?





- Production of a quark-antiquark pair in the final state

- Quarks cannot exist as "free particles" and undergo fragmentation into final state hadrons ($\pi^\pm$, π^0, $K^\pm$, K^0, p, n, …,$B^\pm$,B^0,….)

•Depending on their lifetime, these particles decay inside the detector

prompt decays: e.g.	$\pi^0 \rightarrow \gamma\gamma$	$\tau = 8.4 \cdot 10^{-17}$ s	$c\tau = 25.1$ nm
medium lifetime: B-hadrons:	$B^0 \rightarrow D^0 \pi^+\pi^-$	$\tau = 1.55 \cdot 10^{-12}$ s	$c\tau = 464$ μm
"stable" particles:	$\pi^\pm$	$\tau = 2.6 \cdot 10^{-8}$ s	$c\tau = 7.8$ m

7.2 Introduction to Detector Physics

- Detection through interaction of the 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	

7.2.1 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: $T^{\max} = \dfrac{2 m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e / m_0 + (m_e / m_0)^2}$

  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

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

z: atomic number of incident particle

Z: atomic number of absorber

I : energy needed for ionization

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

δ ($\beta\gamma$): density effect correction to inoization energy loss

$x = \rho s$, surface density or mass thickness, with unit g/cm^2, where 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).

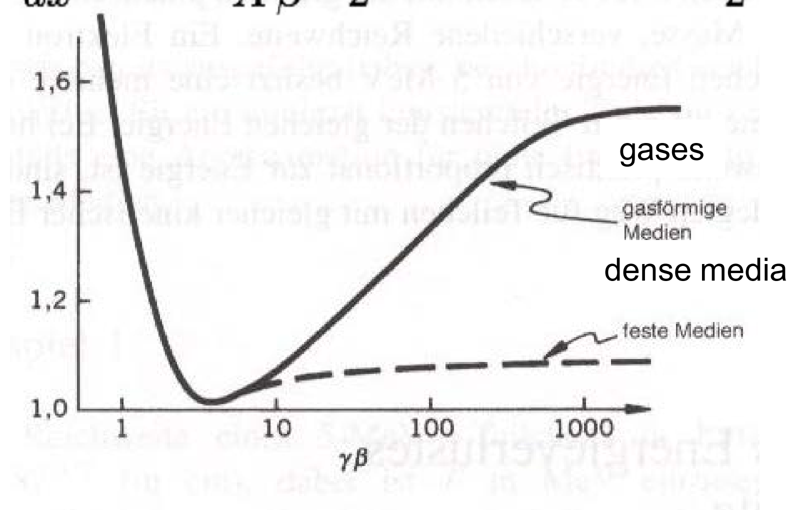
Hans Bethe (1906-2005)

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.

Important features / dependencies:

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



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

- depends quadratically on the charge and velocity of the particle: $\sim z^2/\beta^2$

- 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:

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

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

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

Examples of Mean Energy Loss

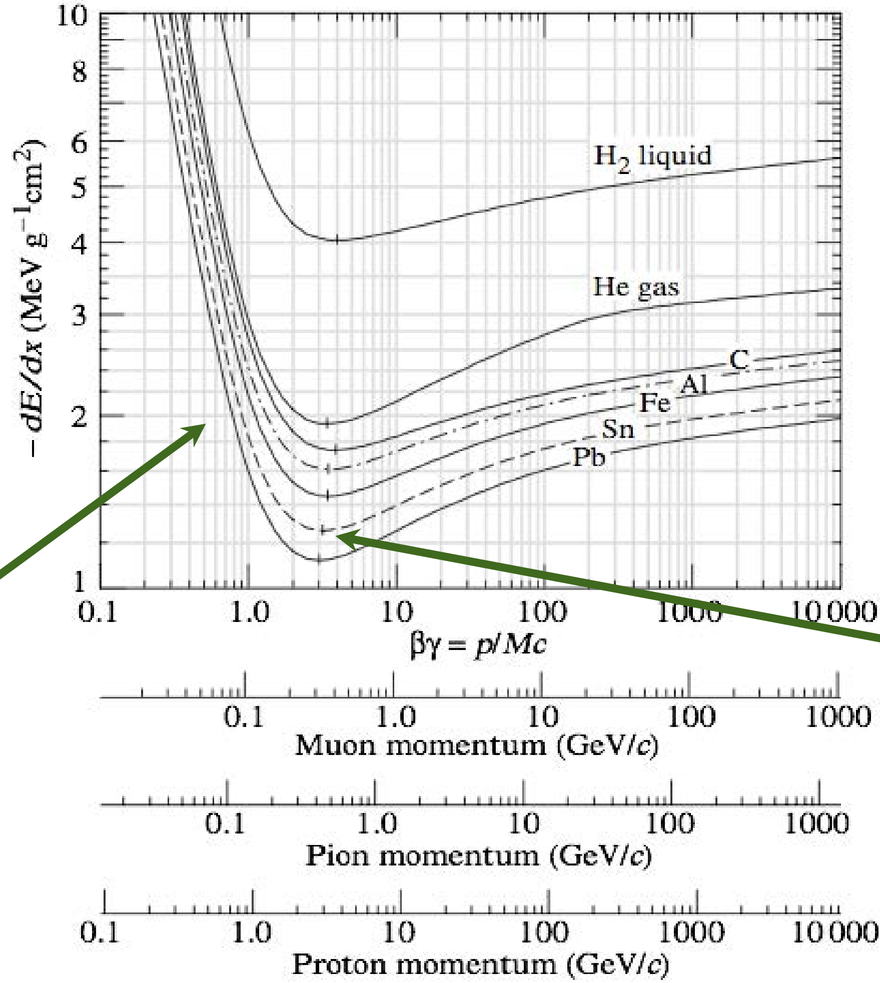


Figure 27.3: Mean energy loss rate in liquid (bubble chamber) hydrogen, gaseous helium, carbon, aluminum, iron, tin, and lead. Radiative effects, relevant for muons and pions, are not included. These become significant for muons in iron for $\beta\gamma \gtrsim 1000$, and at lower momenta for muons in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

$1/\beta^2$

Bethe-Bloch formula:

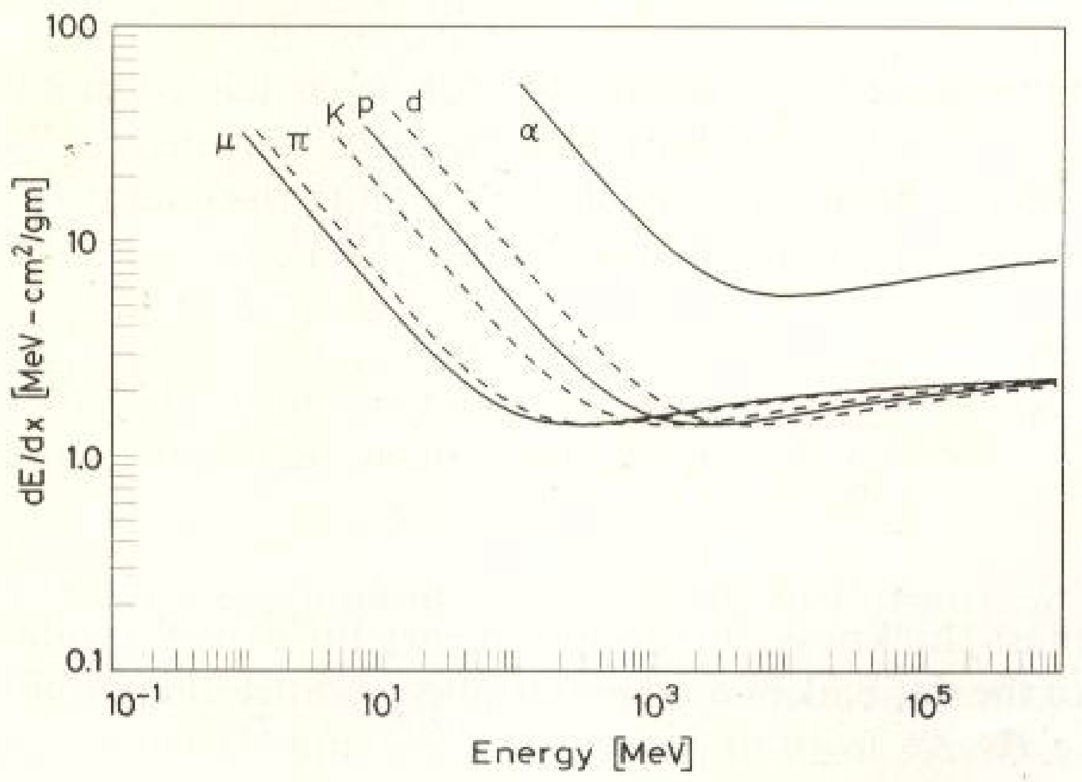
$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} [\frac{1}{2} \ln f(\beta) - \beta^2 - \frac{\delta(\beta\gamma)}{2}]$$

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

PDG 2008

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

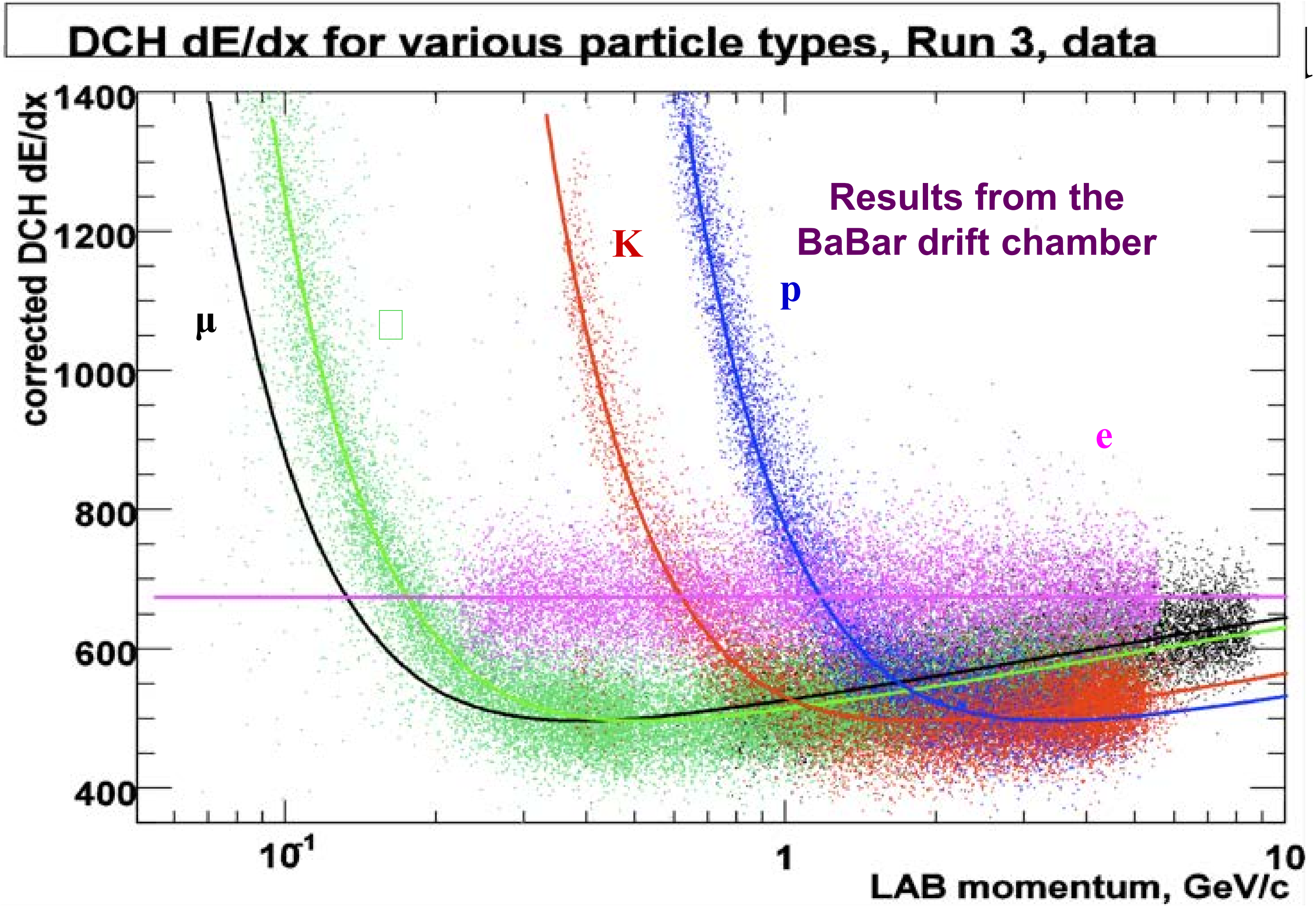


$$\beta\gamma = \frac{p}{E}\frac{E}{m} = \frac{p}{m}$$

- 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,E → particle ID

Example: BaBar experiment at SLAC



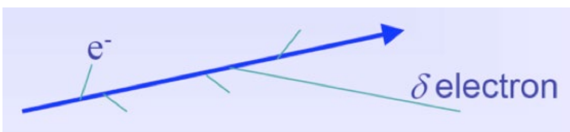
A simultaneous measurement of dE/dx and momentum p can provide particle identification. Works well in the low momentum range (< ~1 GeV)

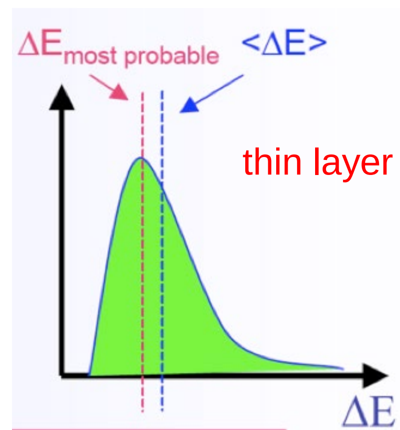
Fluctuations in Energy Loss

- A real detector (limited granularity) cannot measure <dE/dx>;
- It measures the energy ΔE deposited in layers of finite thickness Δx;

- Repeated measurements → sampling from an energy loss distribution

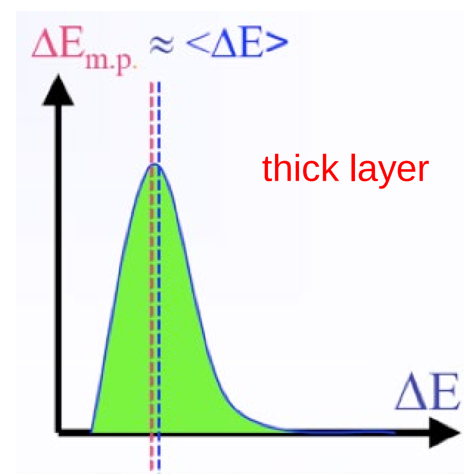
- For thin layers or low density materials, the energy loss distribution shows large fluctuations towards high losses, so called Landau tails.

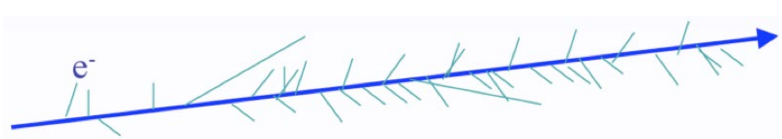




Example: Silicon sensor, 300 μm thick,
ΔE_{mip} ~82 keV, <ΔE> ~115 keV

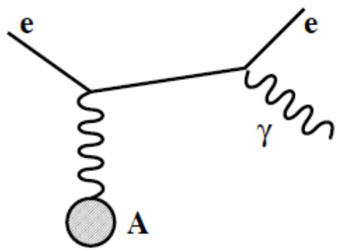
- For thick layers and high density materials, the energy loss distribution shows a more Gaussian-like distribution (many collisions, Central Ilimit theorem)





7.2.2 Energy loss due to bremsstrahlung

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



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

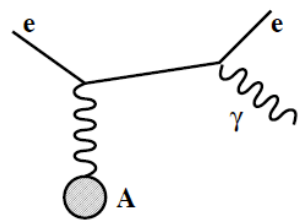
where: Q, m = electric charge and mass of the particle,
α = fine structure constant
A,Z = atomic number, number of protons of the material
N_A= Avogardo's number

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

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

note 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

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



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)

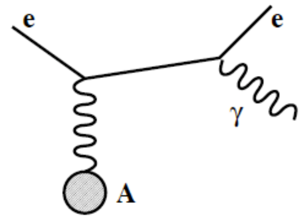
  This is the reason for the strong difference in bremsstrahlung energy loss between electrons and muons

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

- 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



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

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

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

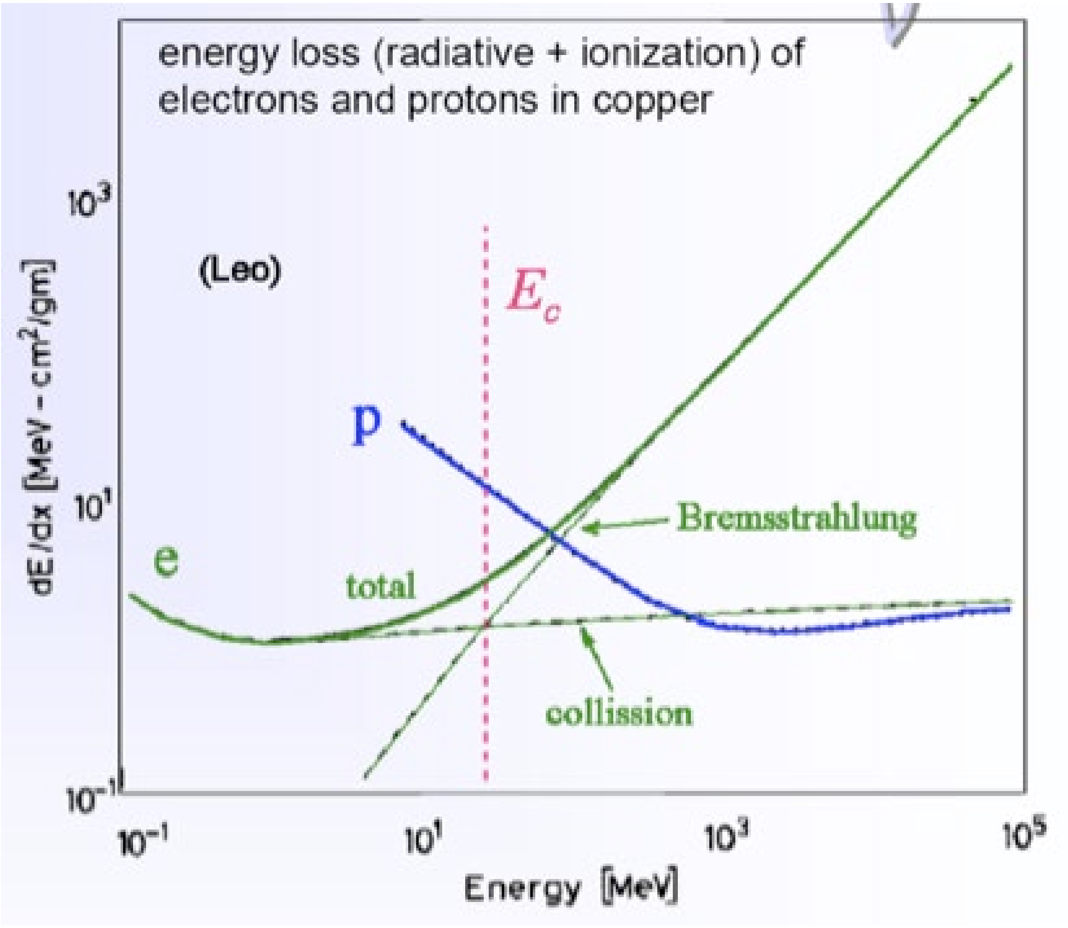
- Continuous 1/E energy loss spectrum, mainly soft radiation, with hard tail
- One defines the critical energy, as the energy where the energy loss due to ionization and bremsstrahlung are equal

$$-\left.\frac{dE}{dx}\right|_{ion} (E_c) = -\left.\frac{dE}{dx}\right|_{brems} (E_c)$$

useful approximations for electrons: (heavy elements)

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

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

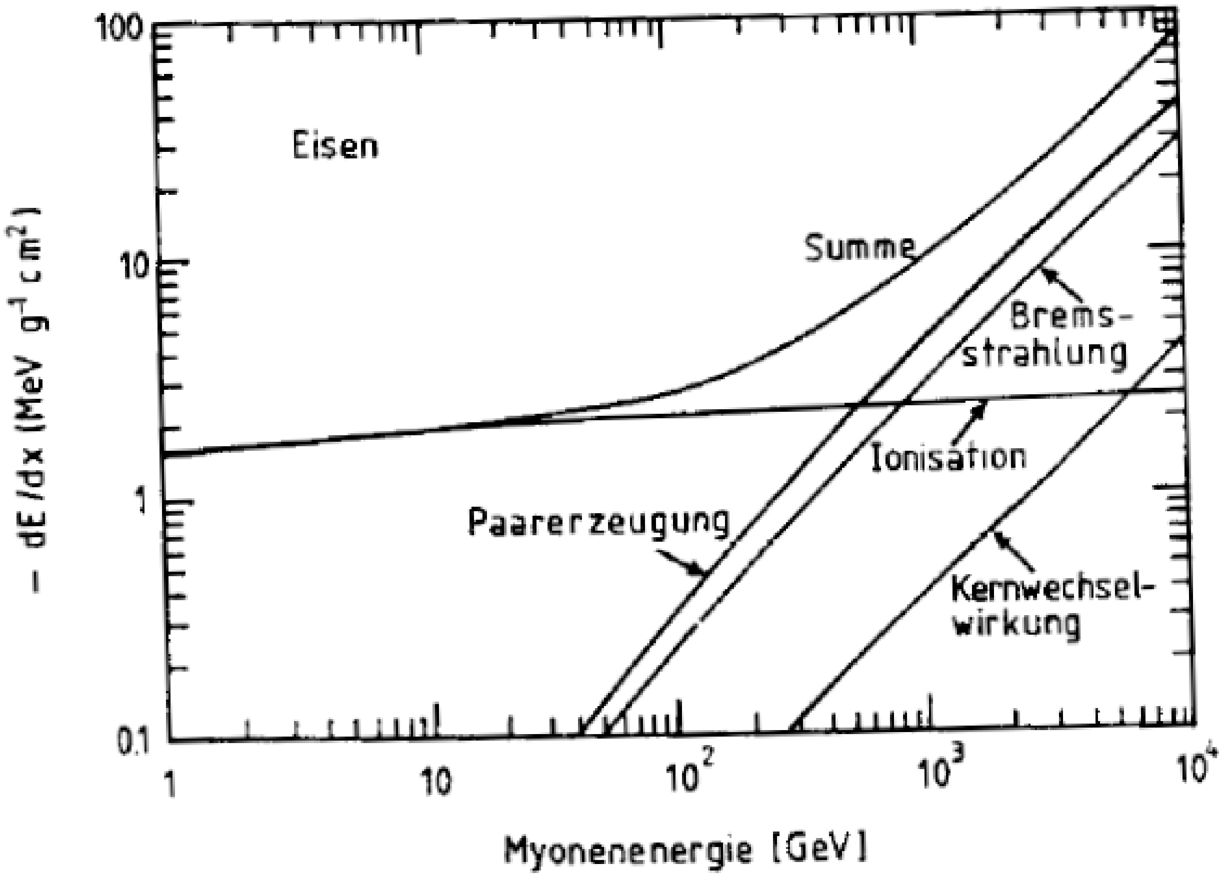


Critical energies in copper (Z = 29):

E_c (e) ≈ 20 MeV

$E_c(\mu)$ ≈ 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 μ (A) → μ e^+e^- (A) becomes important

Material	Z	X_0 (cm)	E_c (MeV)
H_2 Gas	1	700000	350
He	2	530000	250
Li	3	156	180
C	6	18.8	90
Fe	26	1.76	20.7
Cu	29	1.43	18.8
W	74	0.35	8.0
Pb	82	0.56	7.4
Air	7.3	30000	84
SiO_2	11.2	12	57
Water	7.5	36	83

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

7.2.3 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

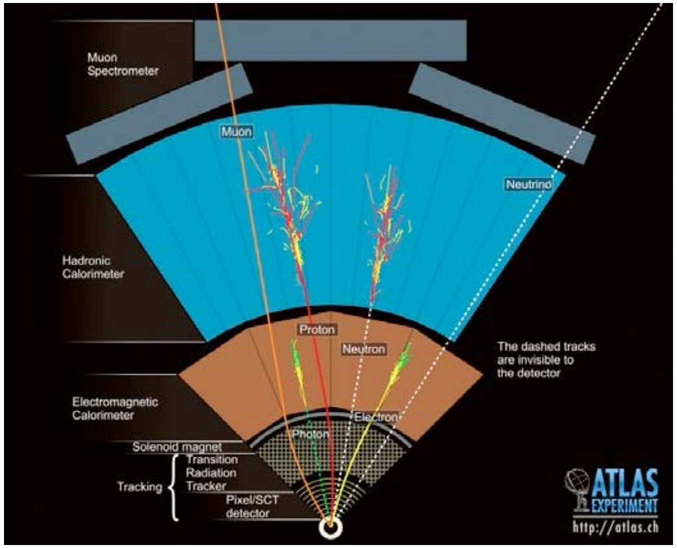
- The hadronic interaction length is a material constant and is linked to the inelastic interaction cross section σ_{inel}

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

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

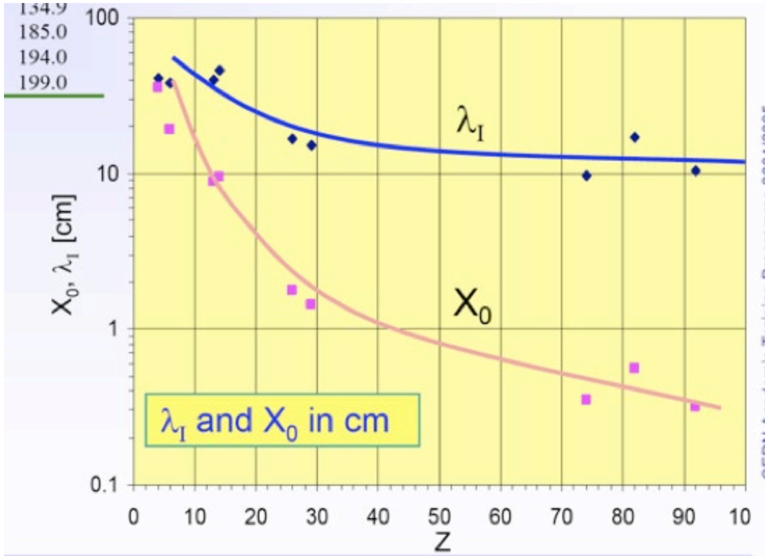
Some values for radiation and hadronic absorption lengths:

Material	X_0 (cm)	λ_{had} (cm)
H_2 Gas	865	718
He	755	520
Be	35.3	40.7
C	18.8	38.1
Fe	1.76	16.76
Cu	1.43	15.06
W	0.35	9.59
Pb	0.56	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 the hadronic calorimeters

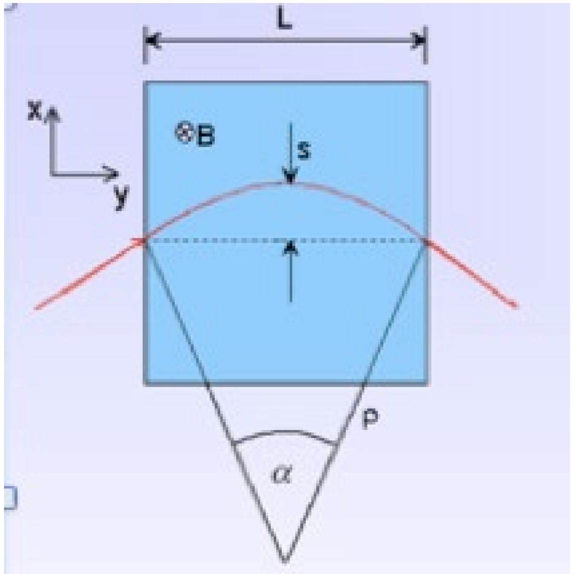


7.3 Basics on Momentum measurement

- 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)



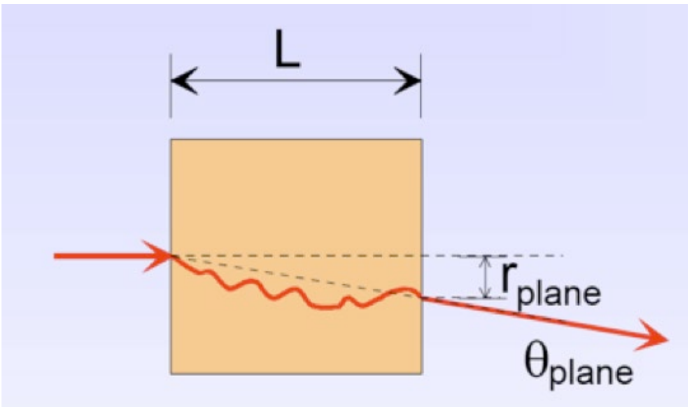
For N equidistant measurements, the momentum resolution is described by the Gluckstern formula (1963):

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

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

Momentum measurement (cont.)

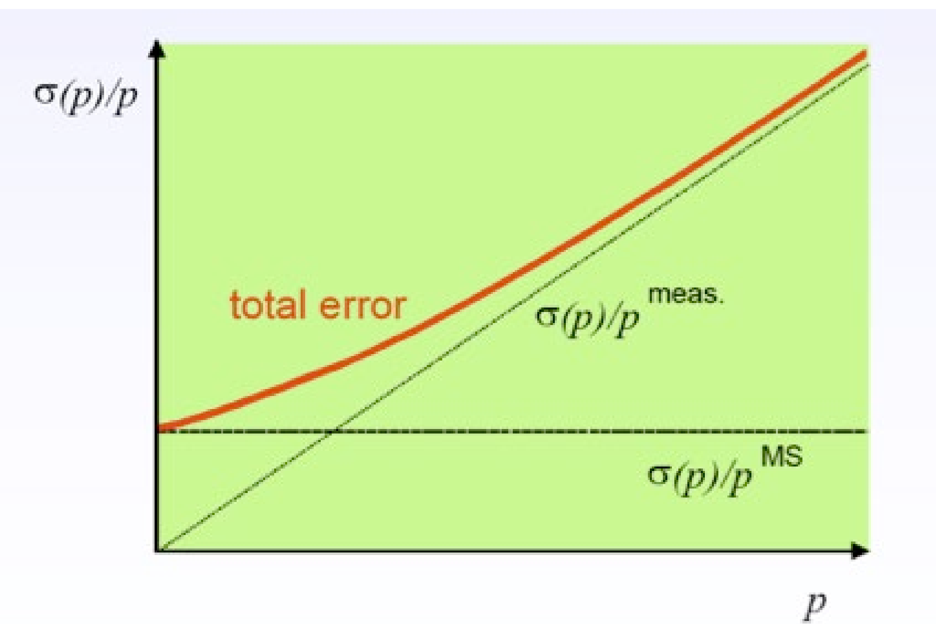
- Degradation of the resolution due to Coulomb multiple scattering (no ionization, elastic scattering on nuclei, change of direction)



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

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

where X_0 = radiation length of the material (characteristic parameter, see calorimeter section)



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

7.4 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)

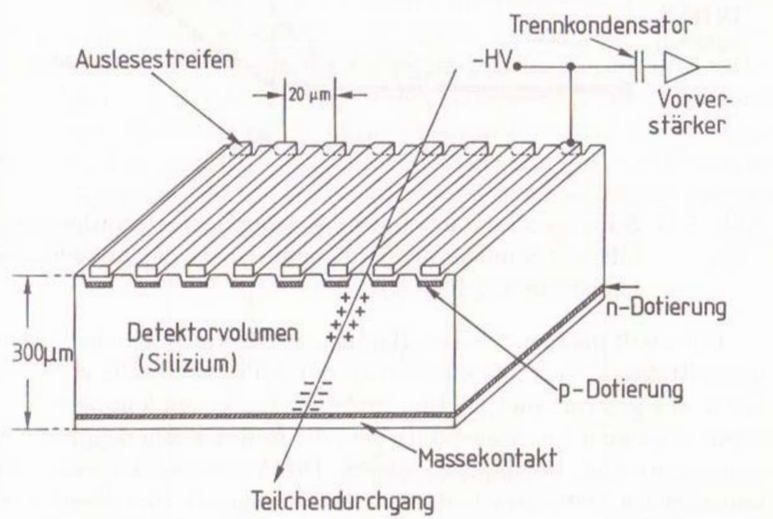
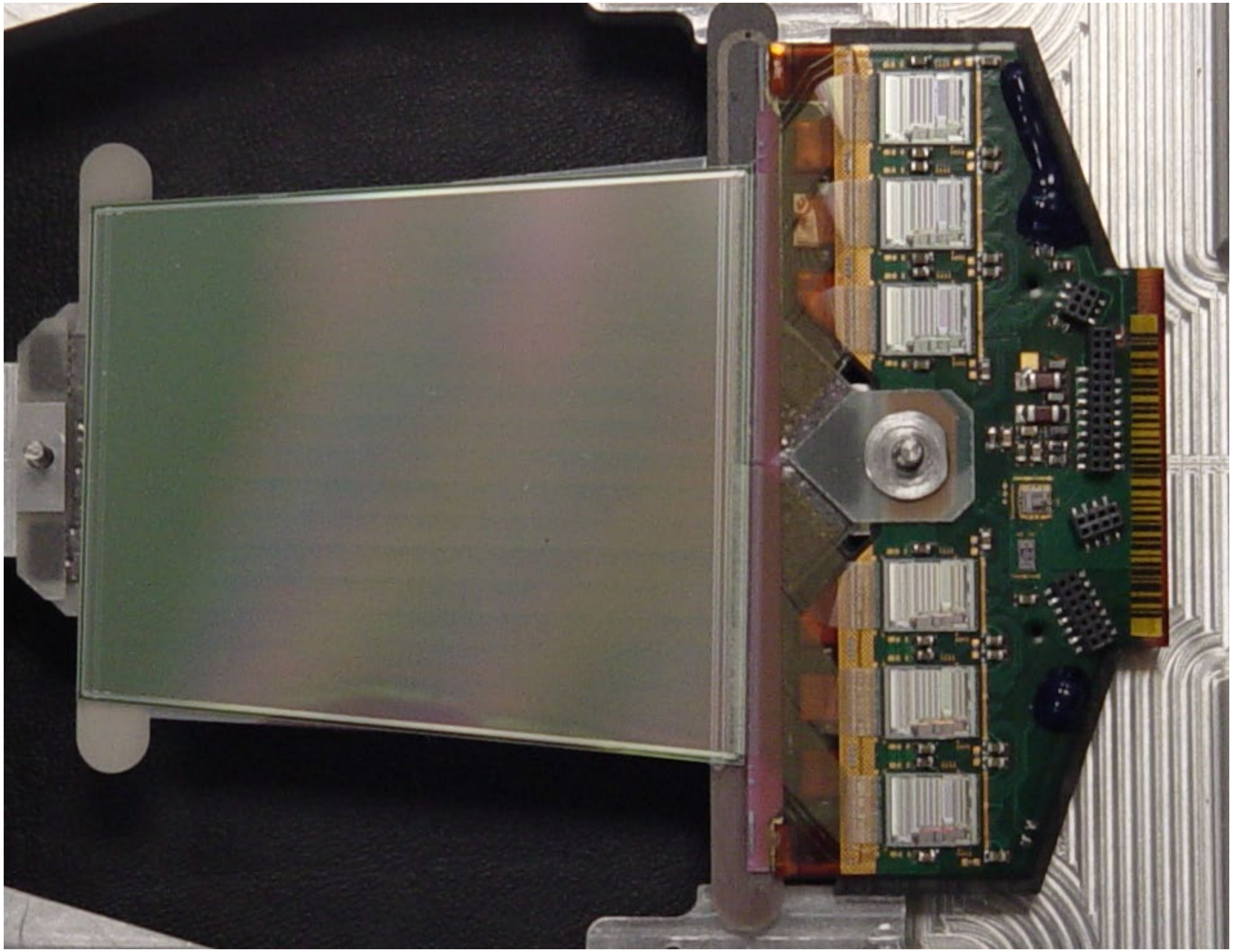
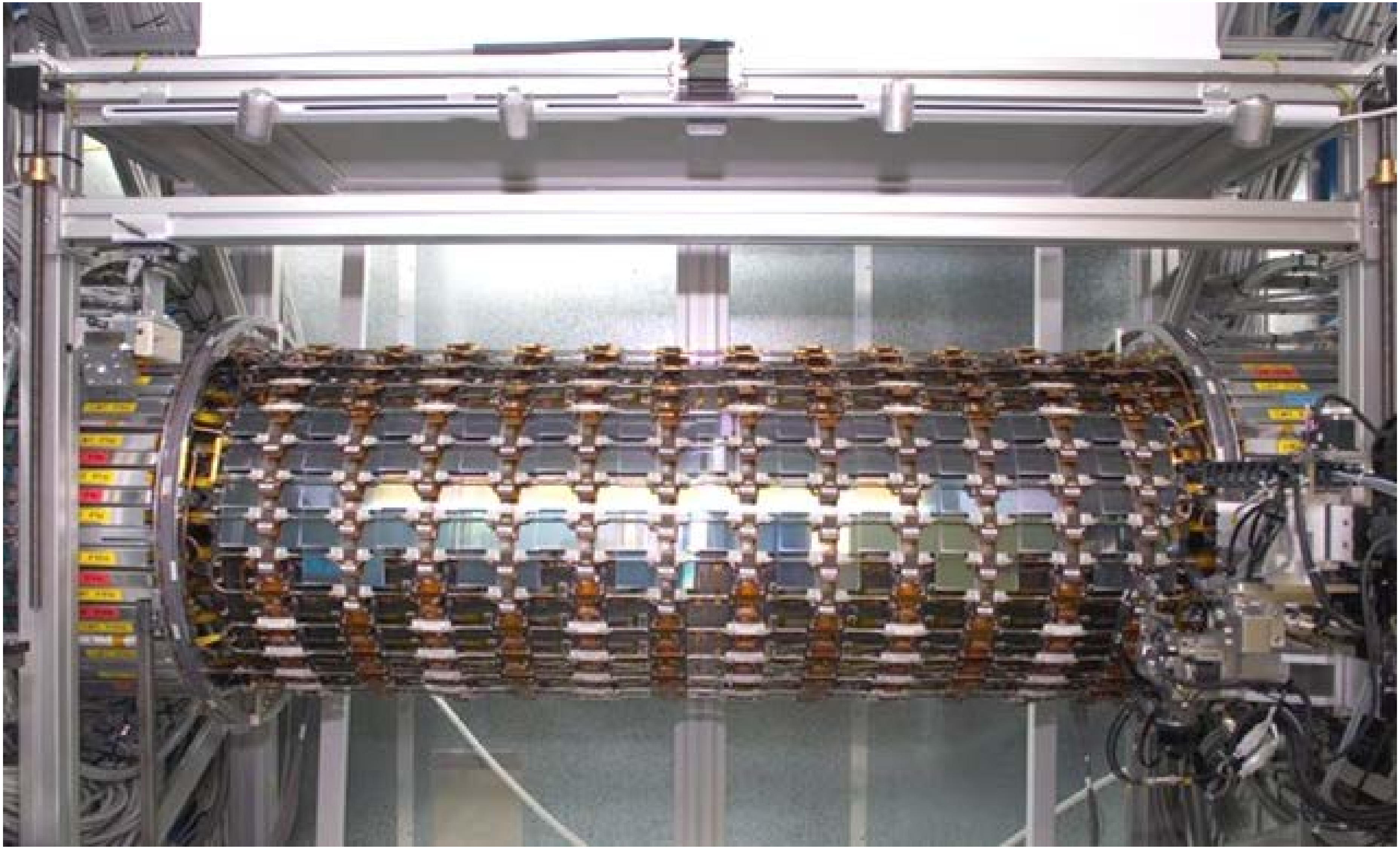


Abb. 7.16 Schematische Darstellung des Aufbaus eines Silizium-Streifenzählers. Jeder Auslesestreifen liegt auf negativer Hochspannung. Die Streifen sind untereinander kapazitiv gekoppelt (nicht maßstabsgetreu, nach [284]).

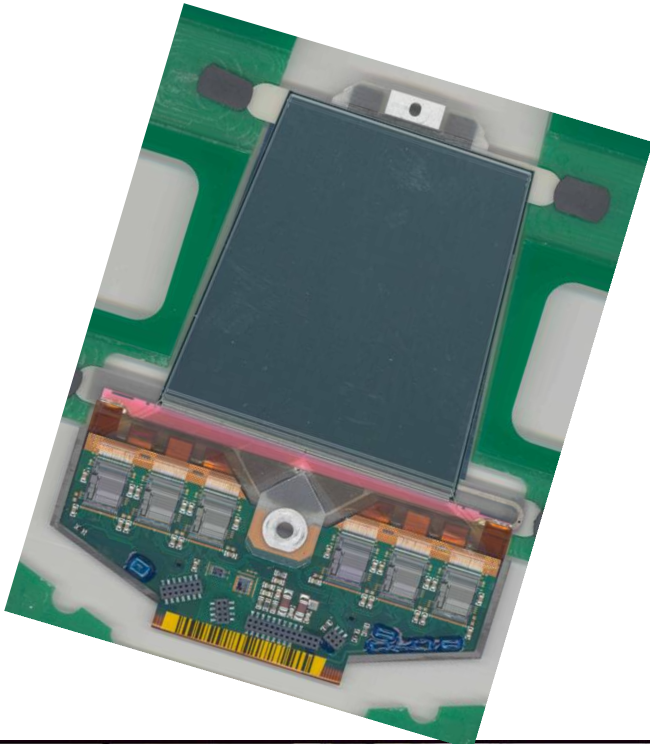
Example: ATLAS Module

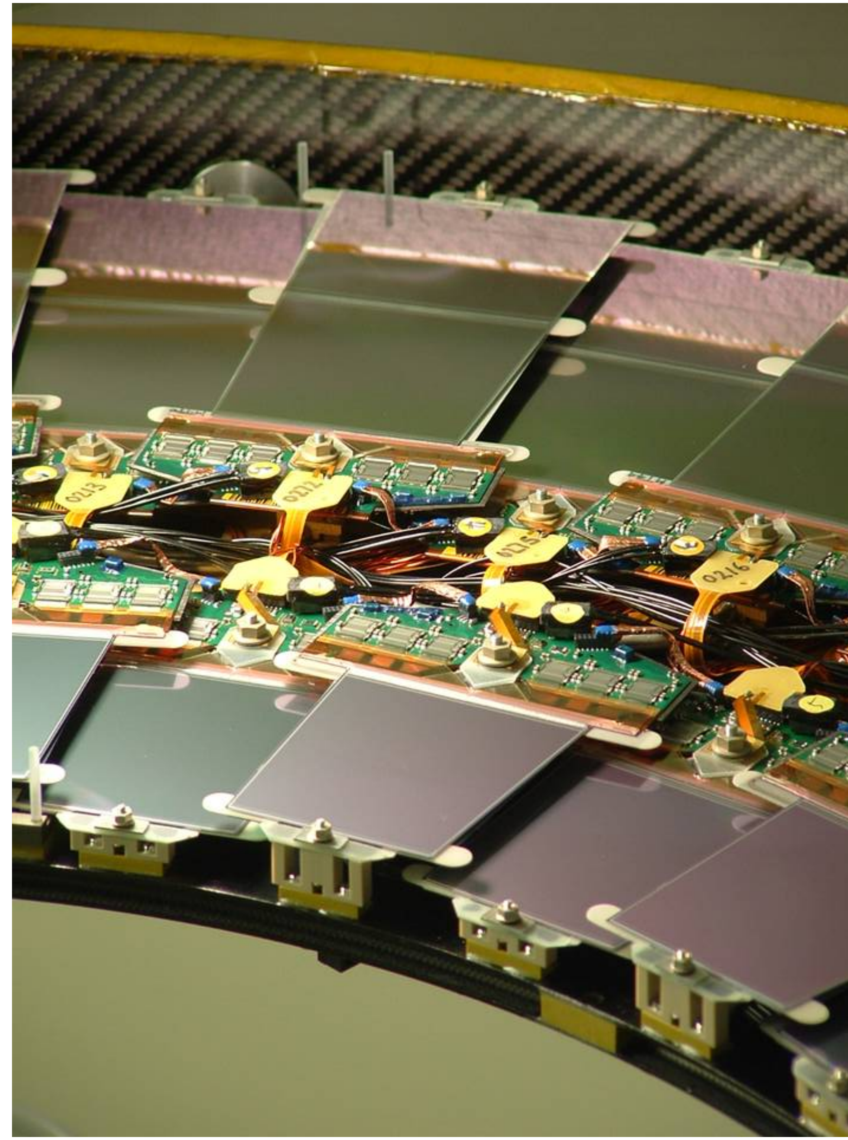


ATLAS Barrel detector



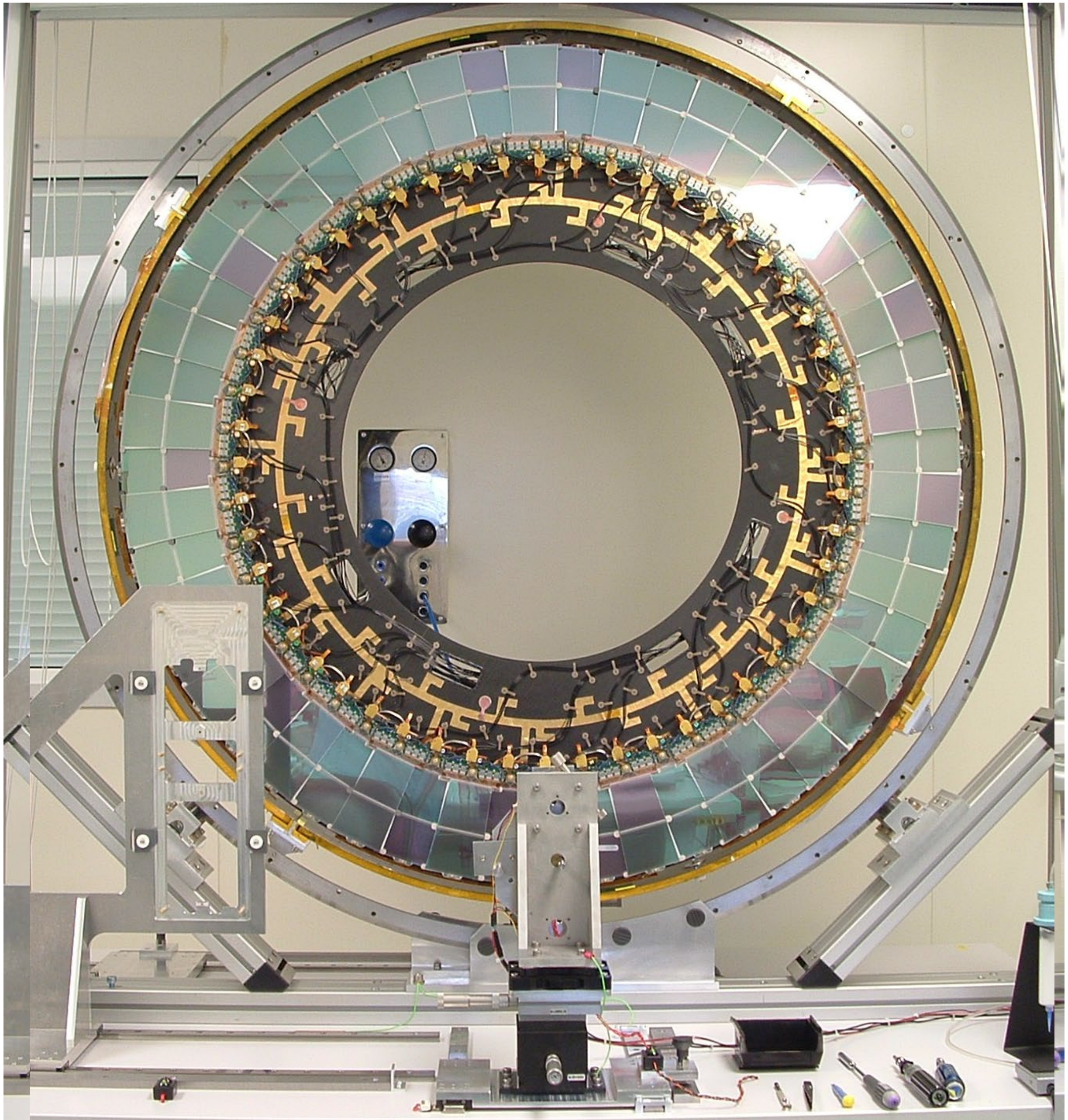
SemiConductor Tracker



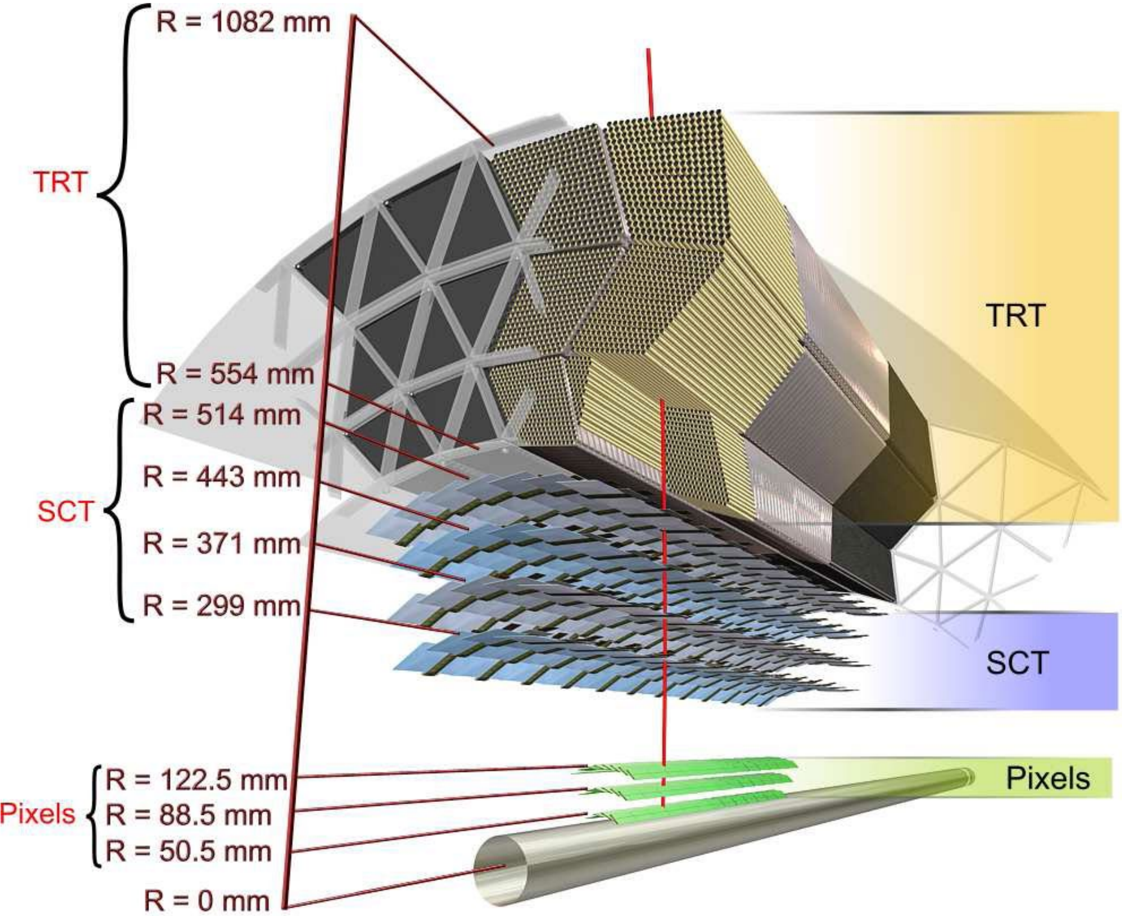


Module fabrication in Freiburg

SCT Endcap



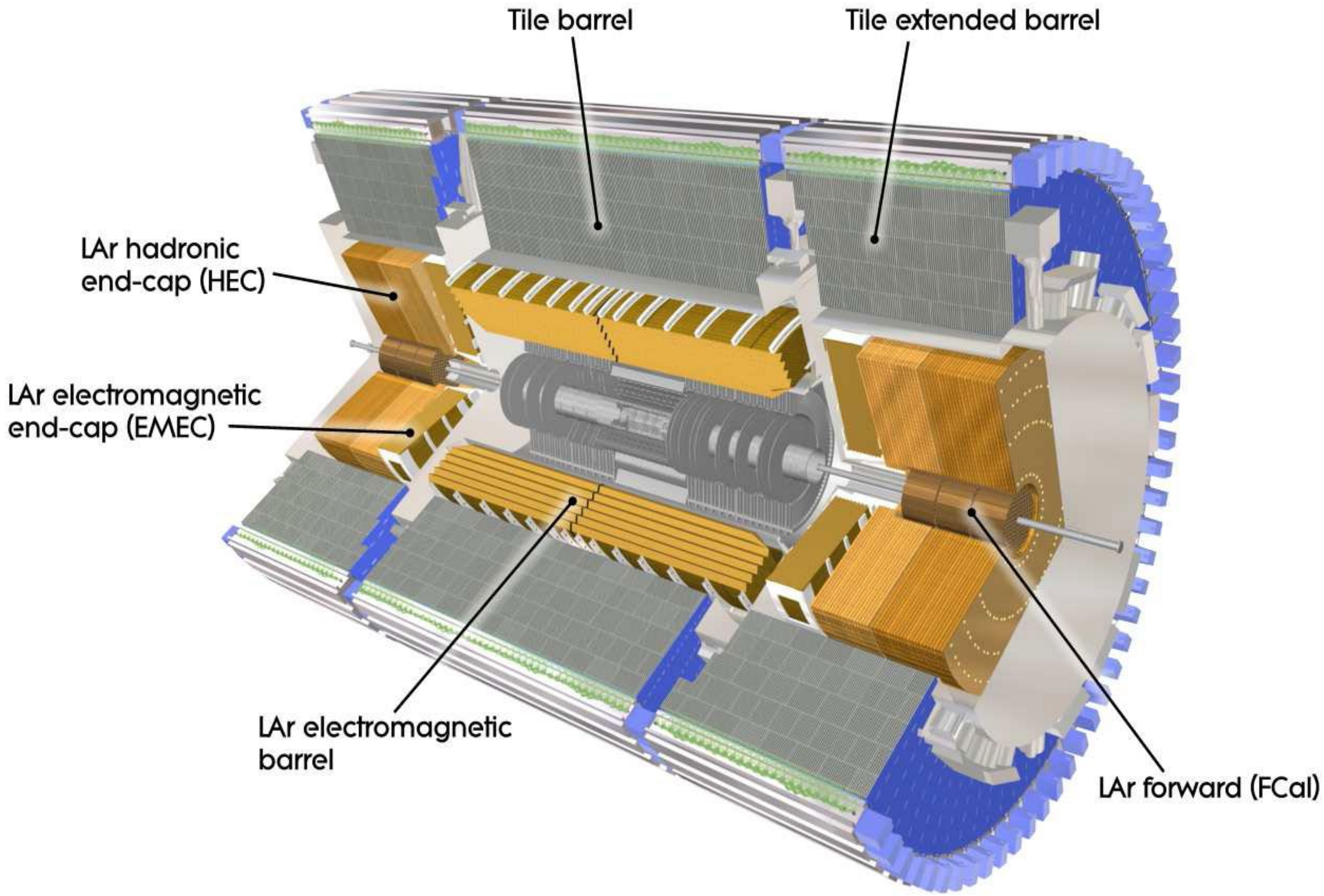
The ATLAS Inner Detector



	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**

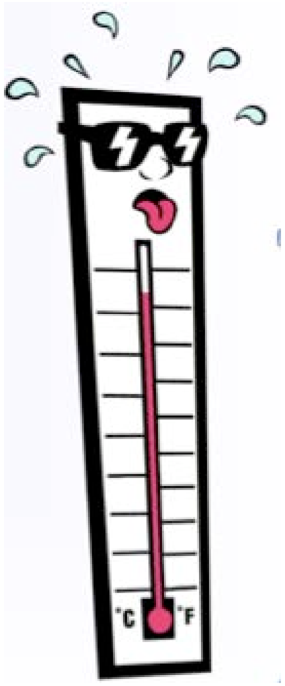
$$\sigma/p_T \sim 0.05\%\ p_T \oplus 1\%$$

7.5 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
  [$c_{Water} = 4.18\ \mathrm{J\ g^{-1}\ K^{-1}}$, $m = \Delta E / (c_{Water}\ \Delta T)$]

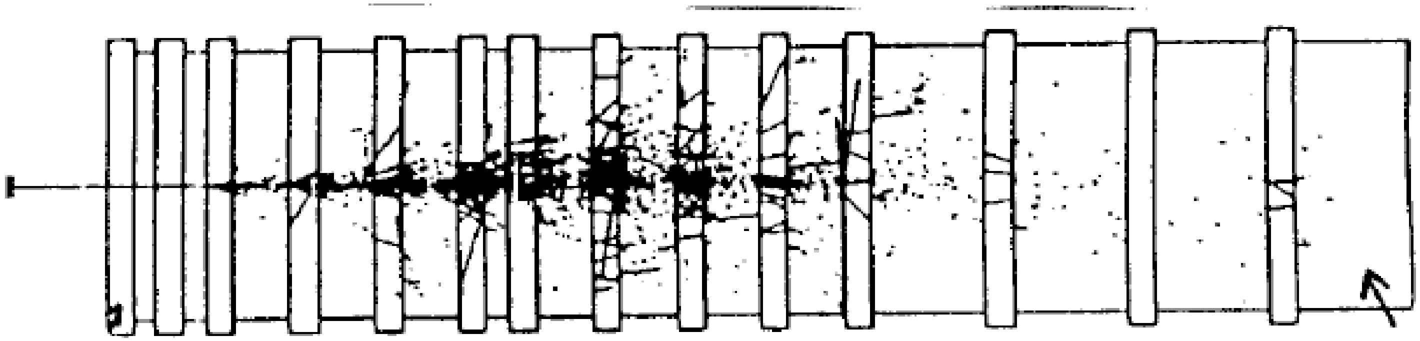
7.5.1 Concept of a particle physics calorimeter

- 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

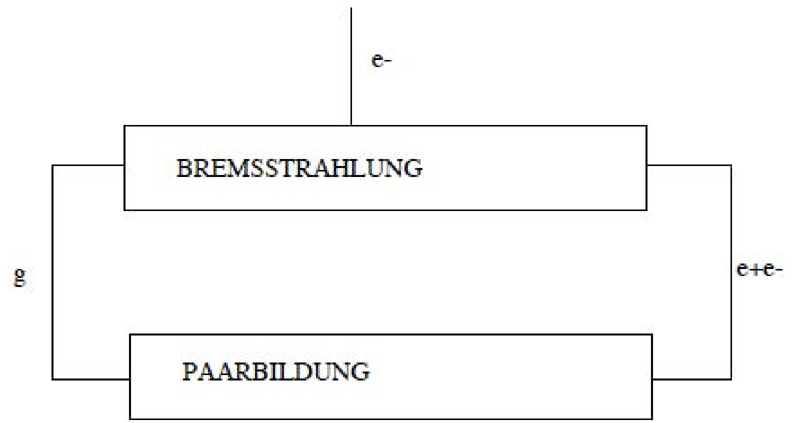
- Uniformity of the energy response to different particles (e/h response)

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

7.5.2 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



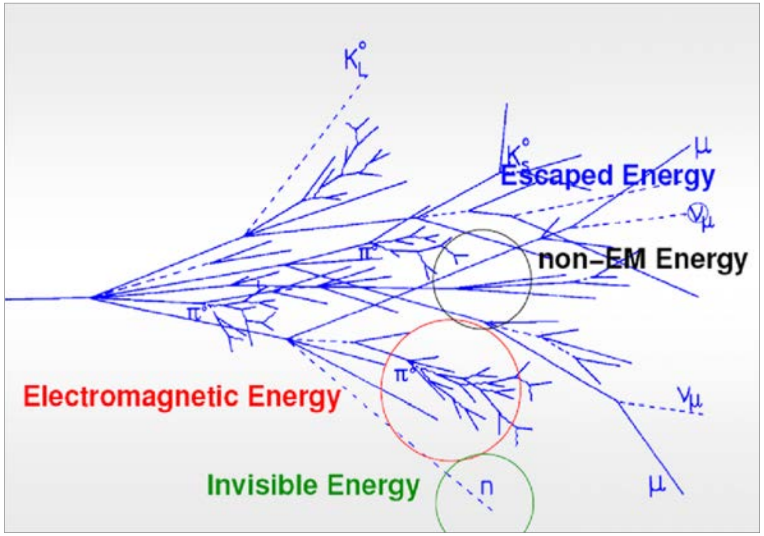
- Characteristic interaction length: radiation length X_0

- 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 their energy shower by inelastic hadronic interactions; (strong interaction responsible, 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

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

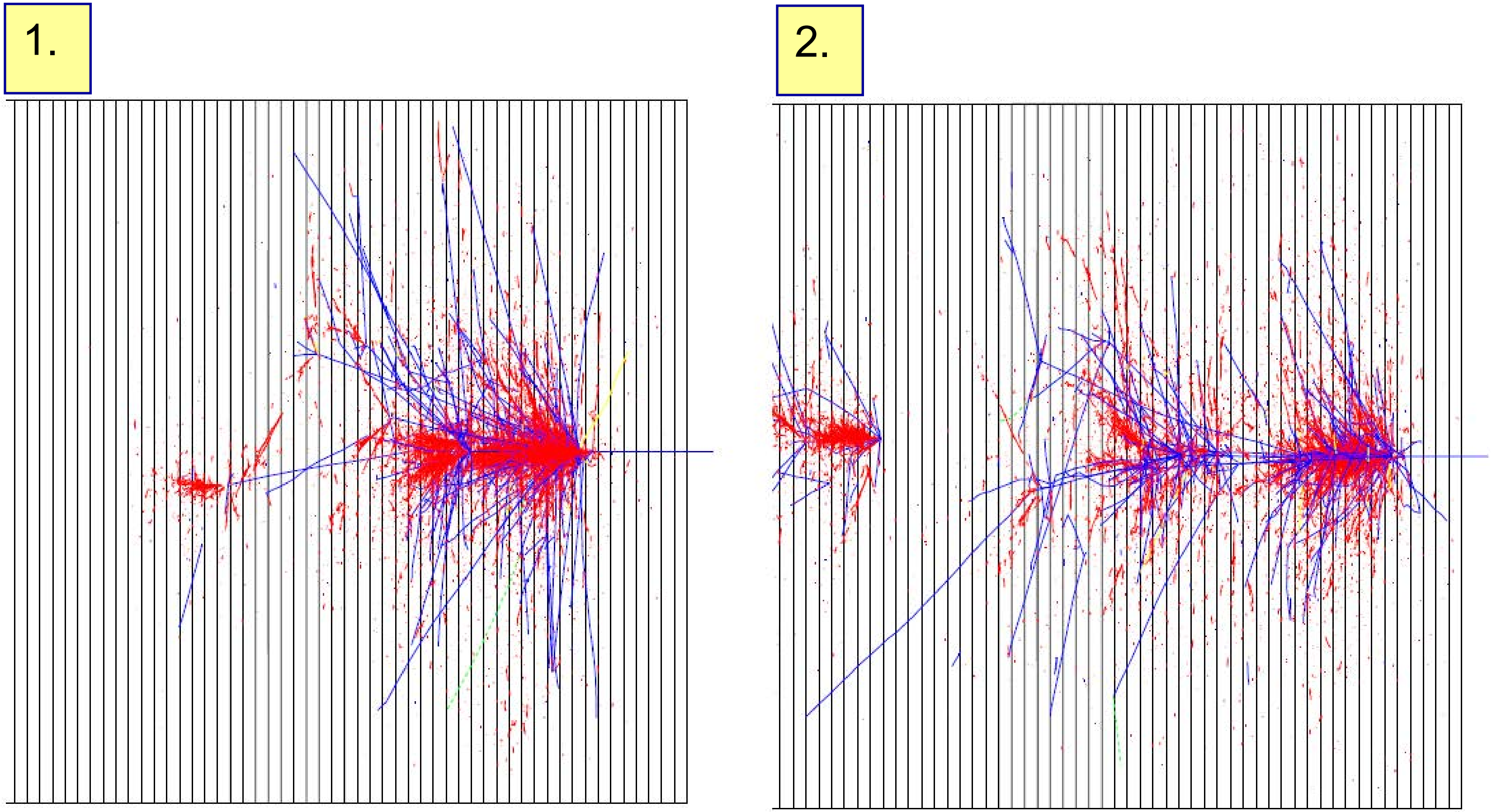
- In addition, there is an important neutron component

  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



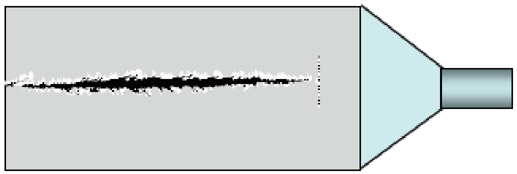
Red: electromagnetic component
Blue: charged hadron component

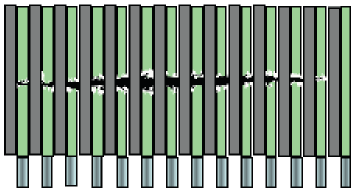
Hadronic showers show very large fluctuations from one event to another
→ the energy resolution is worse than for electromagnetic showers

7.5.3 Layout and readout of calorimeters

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

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

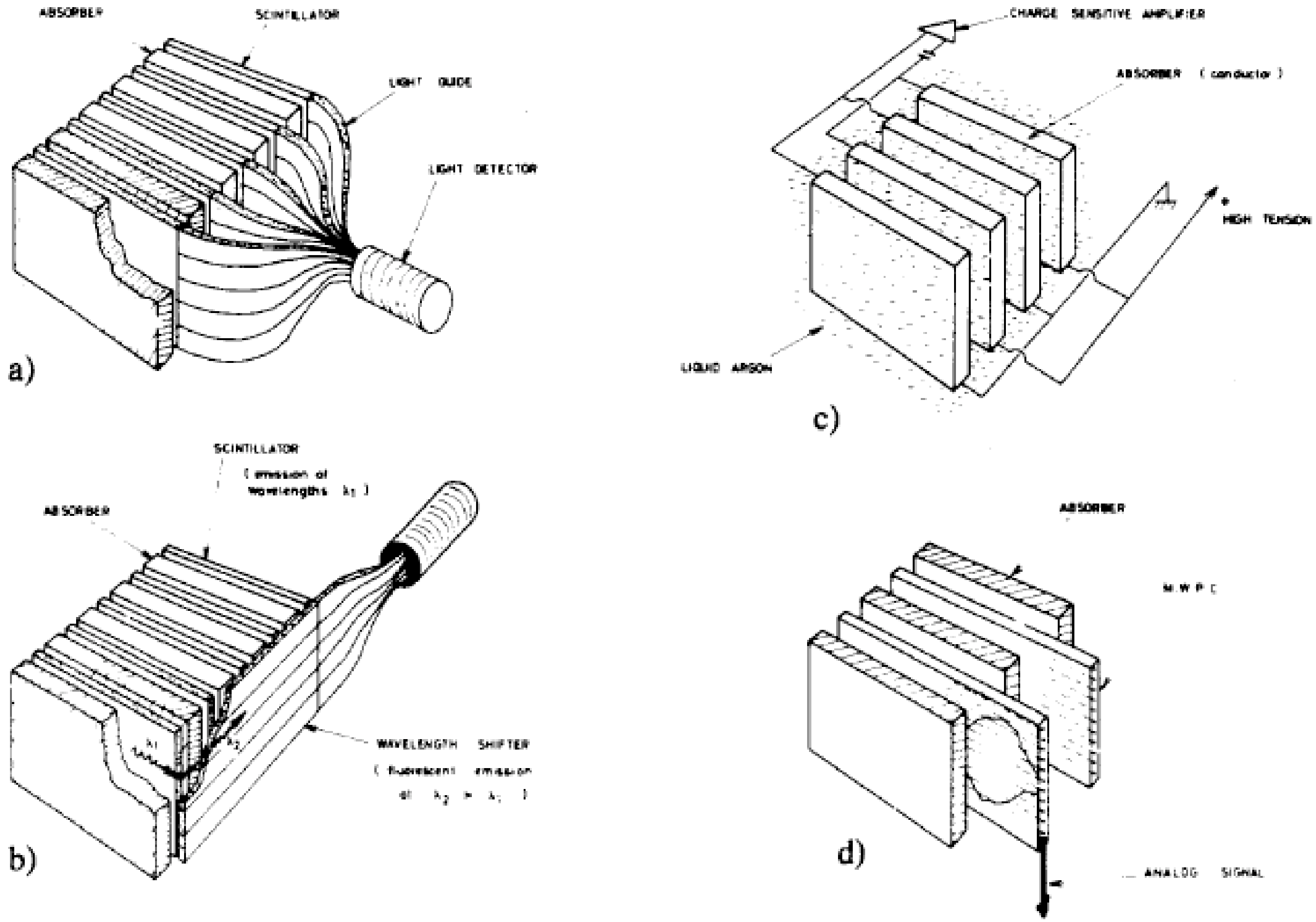




- Examples for homogeneous calorimeters:
  - NaJ or other crystals (Scintillation light)
  - Lead glass (Cherenkov light)
  - Liquid argon or liquid krypton calorimeters (Ionization charge)

- 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

7.5.4 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: $Q = \langle N \rangle \langle T_0 \rangle \sim E_0$
  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:

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

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

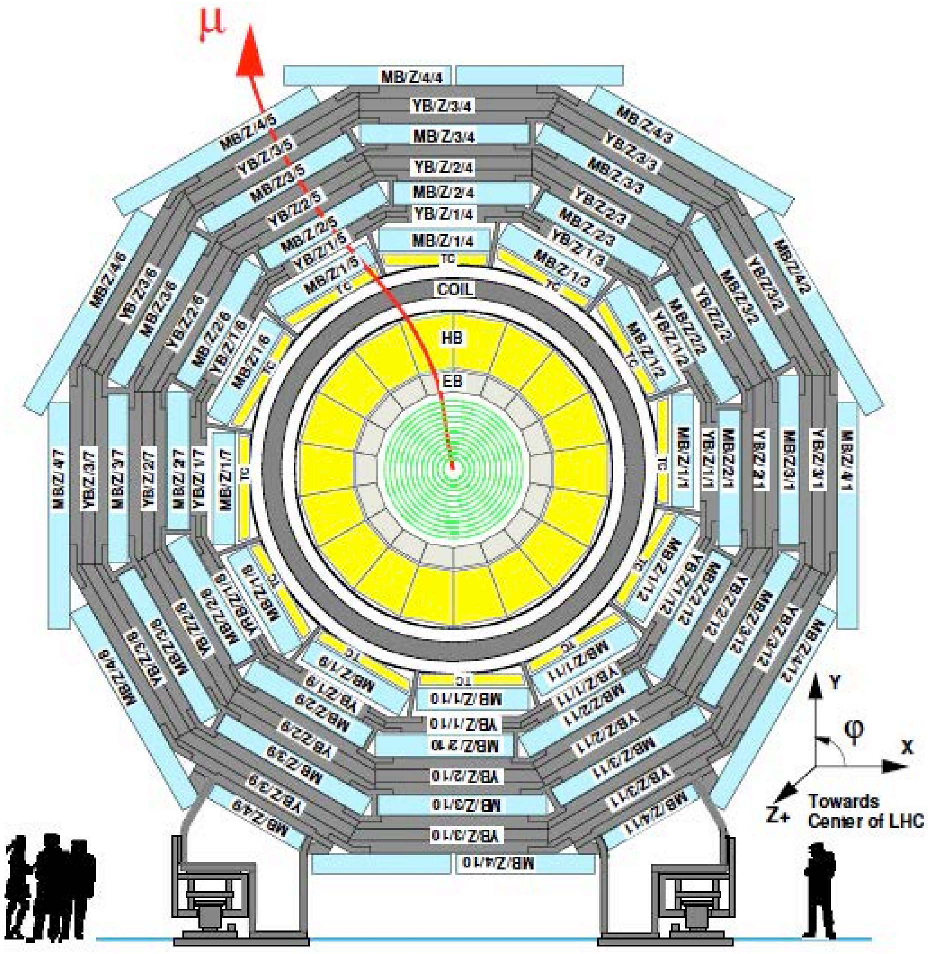
(*) compensating calorimeter
(+) weighting technique

- 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

7.6 Measurements of muons



Muon Detectors

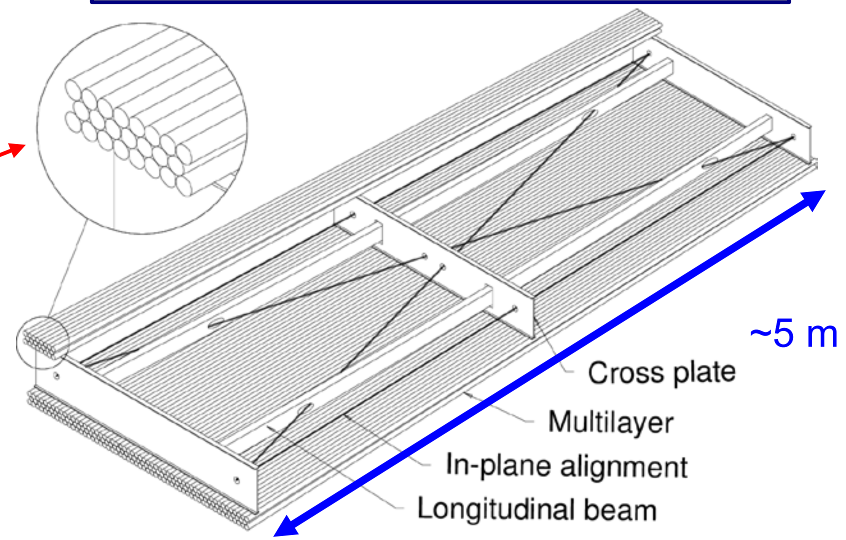
- Muon detectors are tracking detectors (e.g. wire chambers)
  - they form the outer shell of the (LHC) detectors
  - they are not only sensitive to muons (but to all charged particles)!
  - just by "definition": if a particle has reached the muon detector, it's considered to be a muon (all other particles should have been absorbed in the calorimeters)

- Challenge for muon detectors
  - large surface to cover (outer shell)
  - keep mechanical positioning over time

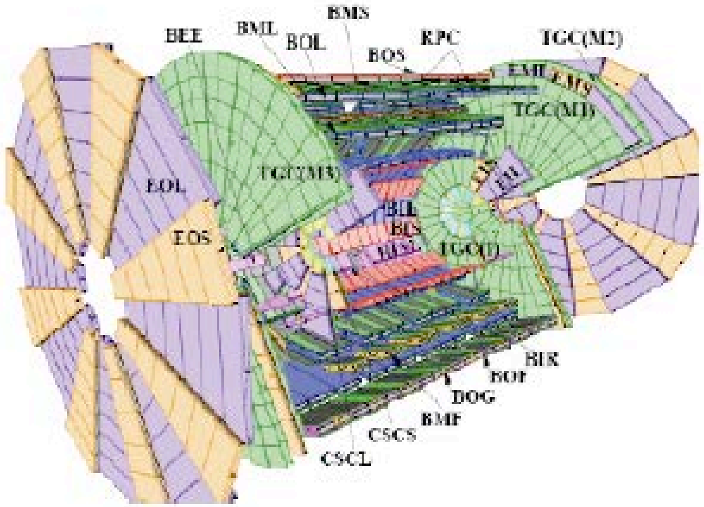
- ATLAS
  - 1200 chambers with 5500 m^2
  - also good knowledge of (inhomogeneous) magnetic field needed

ATLAS Muon Detector Elements

Aluminum tubes with central wire filled with 3 bar gas



ATLAS muon system



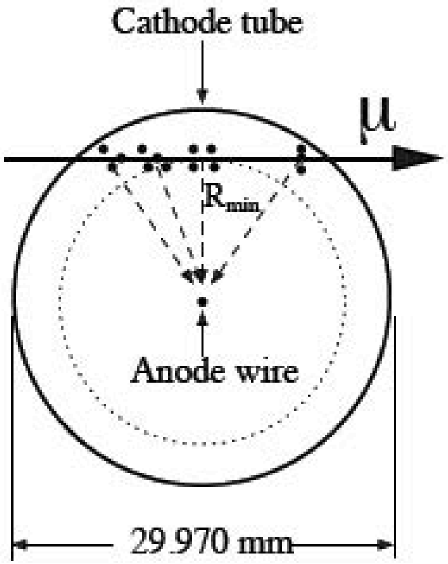
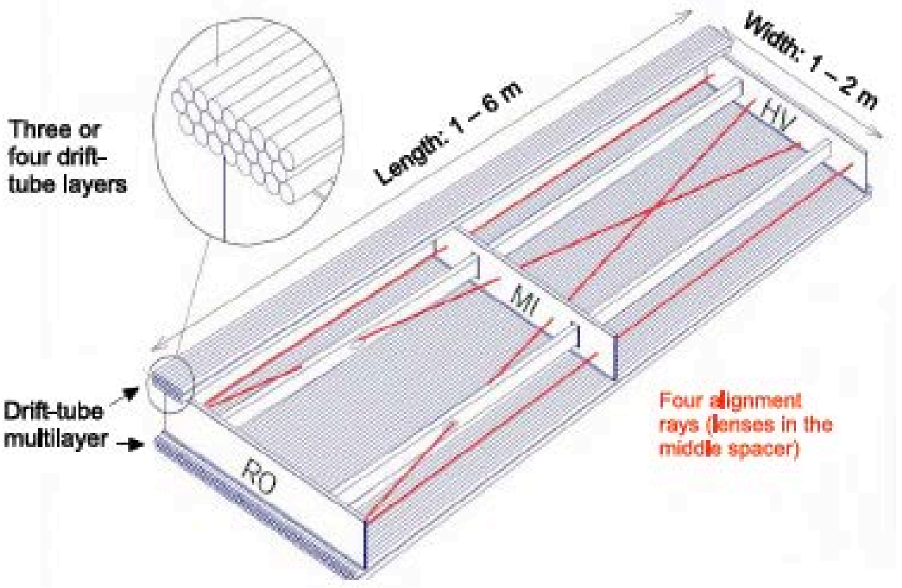
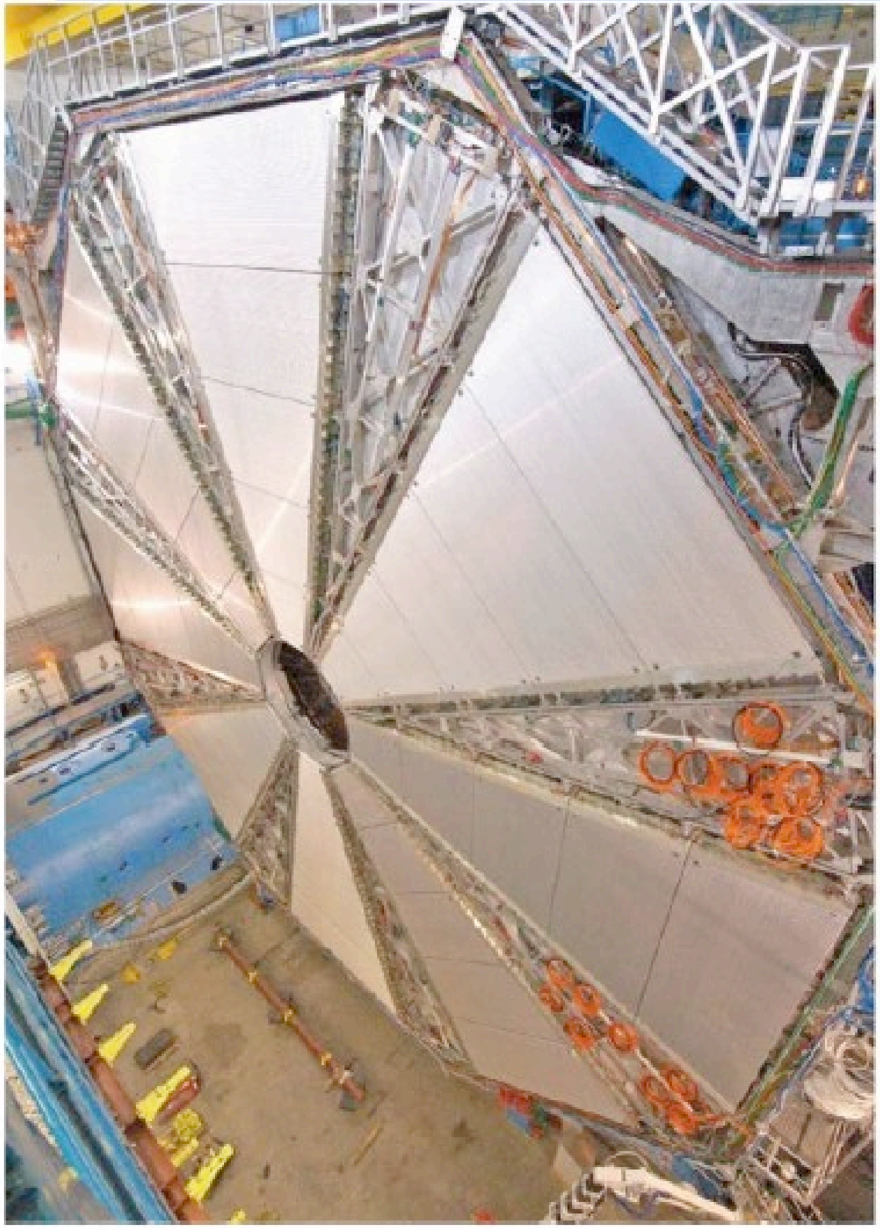


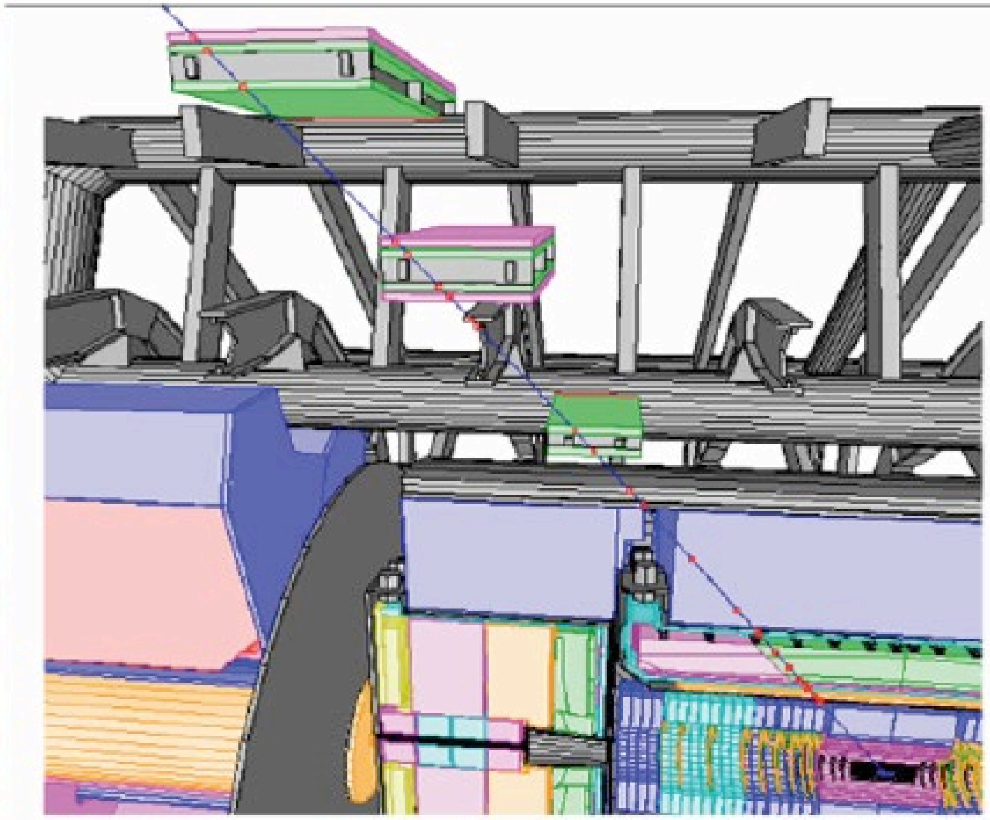
Table 6.2: Main MDT chamber parameters.

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

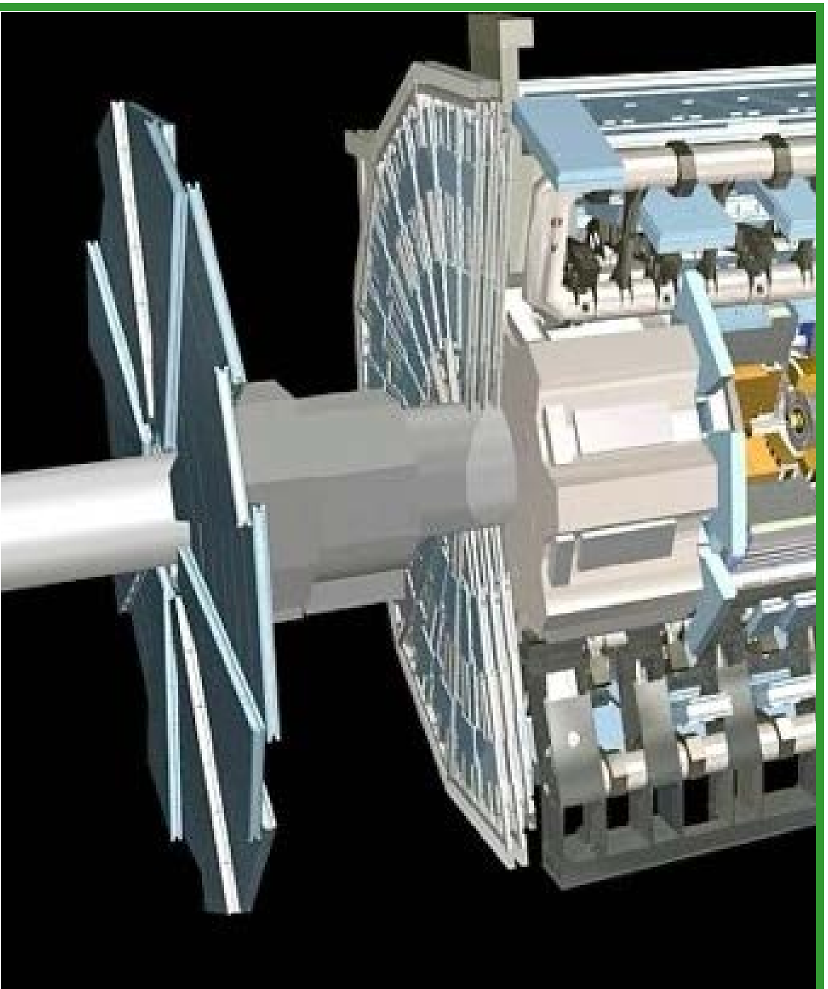


ATLAS muon system

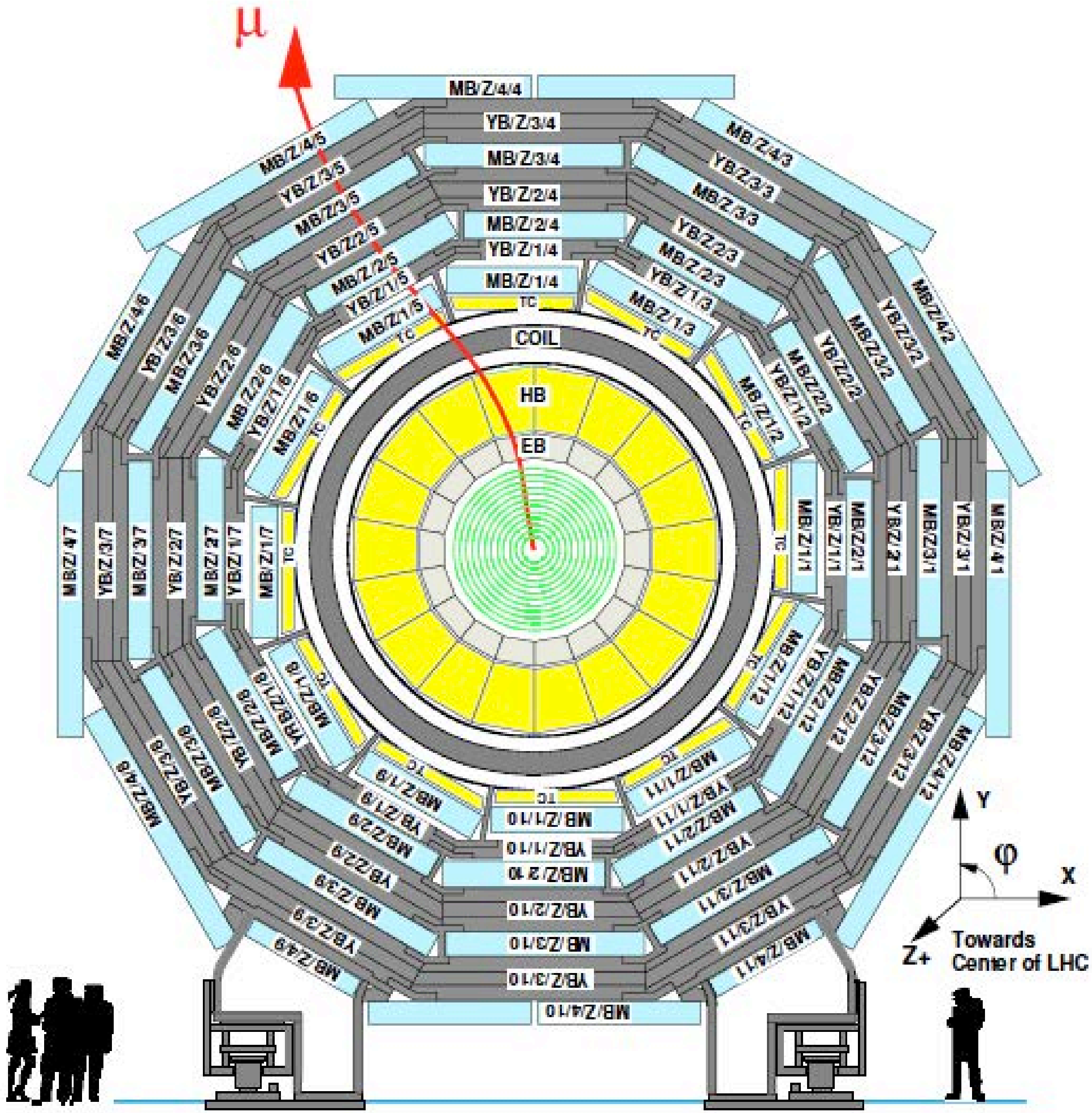




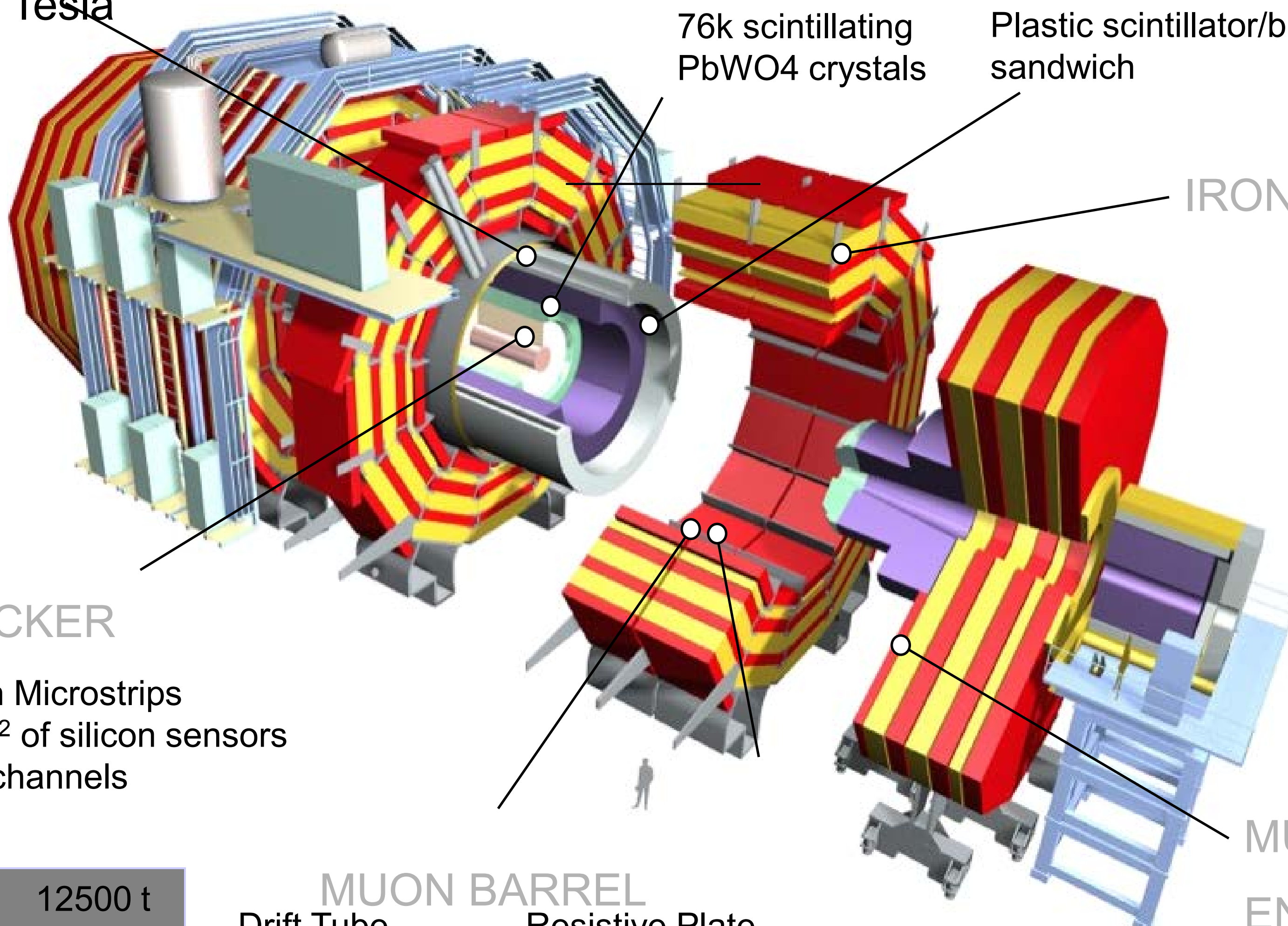
Muon detector system
In the forward region



CMS Muon system



CMS



Superconducting Coil, 4 Tesla

CALORIMETERS

ECAL
76k scintillating PbWO4 crystals

HCAL
Plastic scintillator/brass sandwich

IRON YOKE

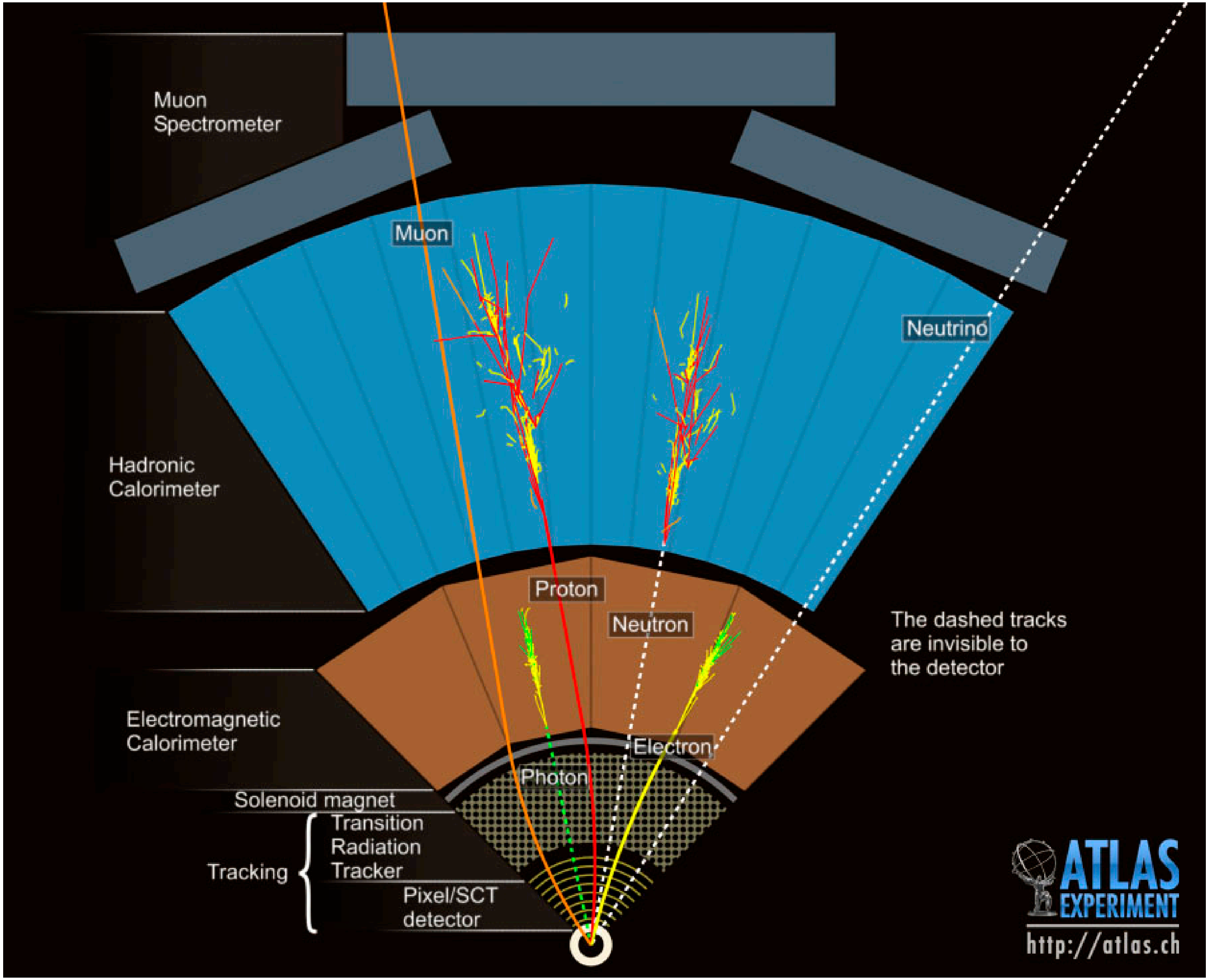
TRACKER
Pixels
Silicon Microstrips
210 m^2 of silicon sensors
9.6M channels

MUON BARREL
Drift Tube Chambers (**DT**)
Resistive Plate Chambers (**RPC**)

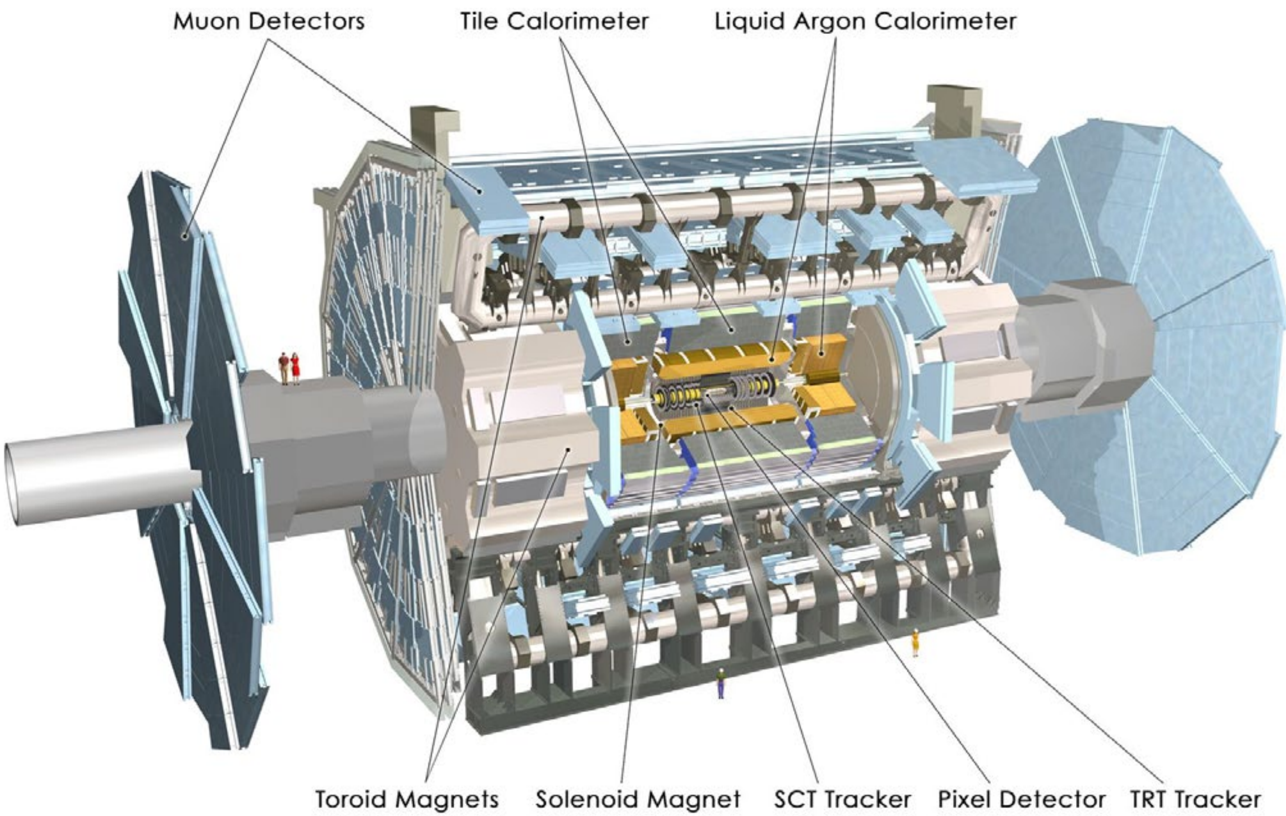
MUON ENDCAPS
Cathode Strip Chambers (**CSC**)
Resistive Plate Chambers (**RPC**)

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

Layers of the ATLAS detector



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