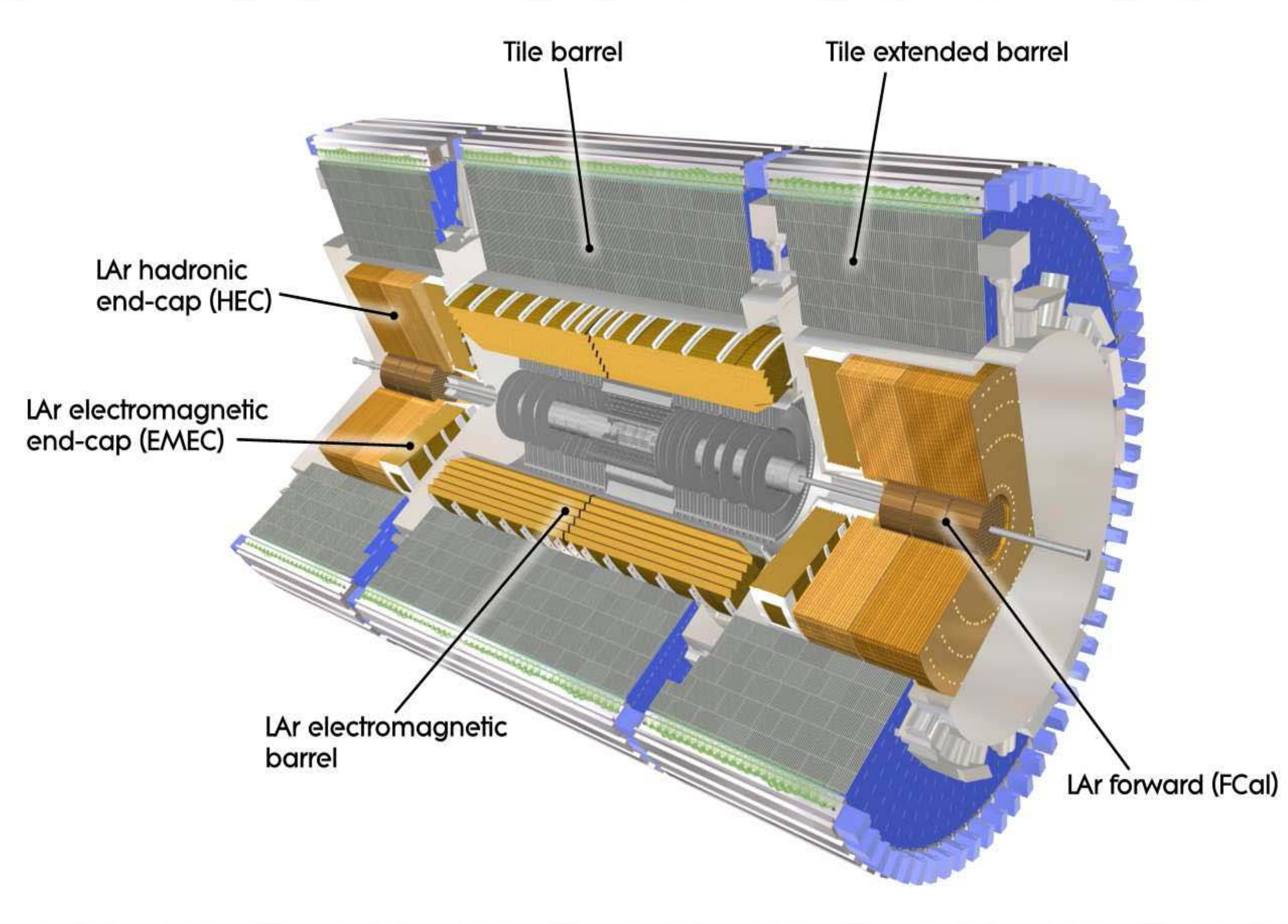
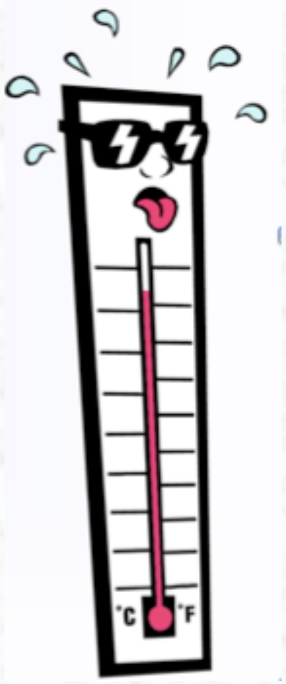
2.3 Energy measurement in calorimeters



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

2.3.1 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

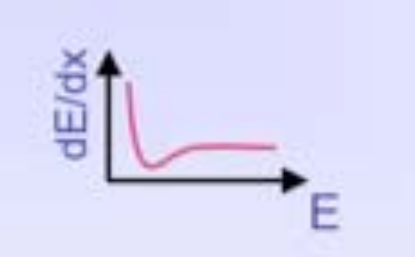
  worse for sampling calorimeters as compared to homogeneous calorimeters
- Uniformity of the energy response to different particles (e/h response)

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

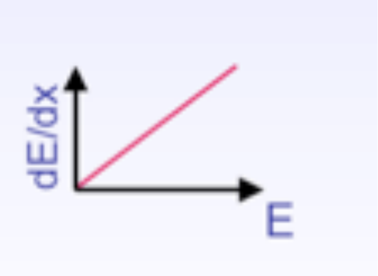
Overview of interaction processes of electrons and photons

Energy loss due to excitation and ionisation

Bethe Bloch formula



Bremsstrahlung



Cherenkov radiation

Photo effect

(dominant in ~ keV energy range)

Compton effect

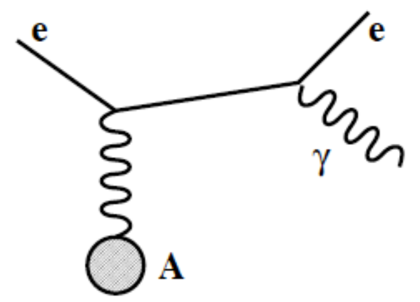
(dominant in MeV energy range)

Pair creation

(threshold energy $= 2\ m_e = 1{,}022$ MeV)

2.3.2 Energy loss due to bremsstrahlung

- Charged high energy 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



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

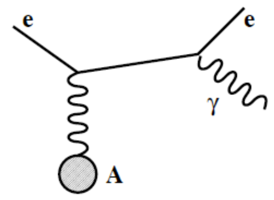
$$-\frac{dE}{dx}\Big|_{Brems} := \frac{1}{X_0} Q^2 E \qquad \Rightarrow \qquad E(x) = E_0 \; e^{-x/X_0}$$

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

- Important material constant: X_0 = radiation length

- Energy of the particle decreases exponentially as a function of the thickness x of the traversed material, due to bremsstrahlung;
(After $x=X_0$: $E(X_0) = E_0 / e = 0.37\ E_0$)

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



- Most important dependencies:

  - dE/dx ~ Z (Z+1)

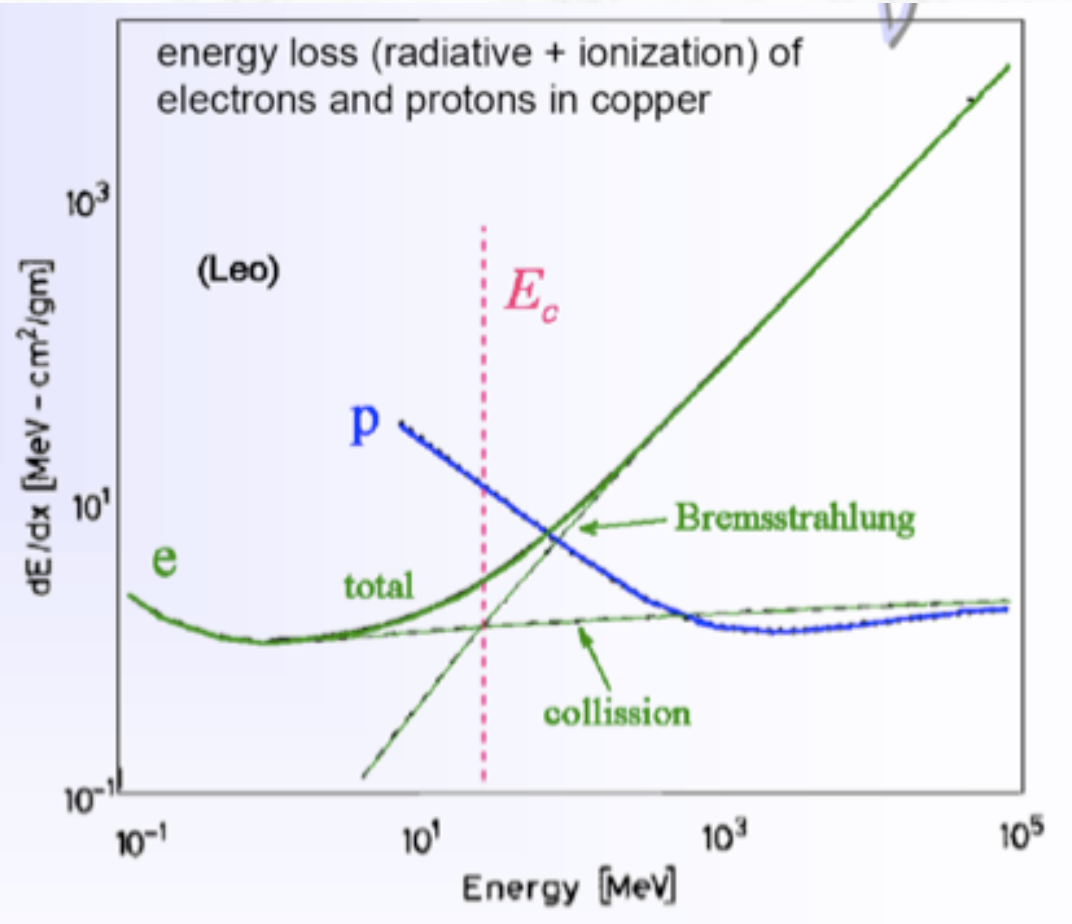
  - dE/dx ~ 1 / m^2 → $\left(\frac{dE}{dx}\right)_\mu / \left(\frac{dE}{dx}\right)_e \sim \frac{1}{40.000}$

  - dE/dx ~ E

Energy loss due to bremsstrahlung is important for electrons / positrons and for ultra high-energy muons (E > 1000 GeV)

- Critical energy is defined as: $-\frac{dE}{dx}\Big|_{ion}(E_c) = -\frac{dE}{dx}\Big|_{brems}(E_c)$

For electrons, one roughly finds: $E_c \approx (550\text{ MeV}) / Z$, $X_0 \approx 180\, A / Z^2$ (g/cm^2)

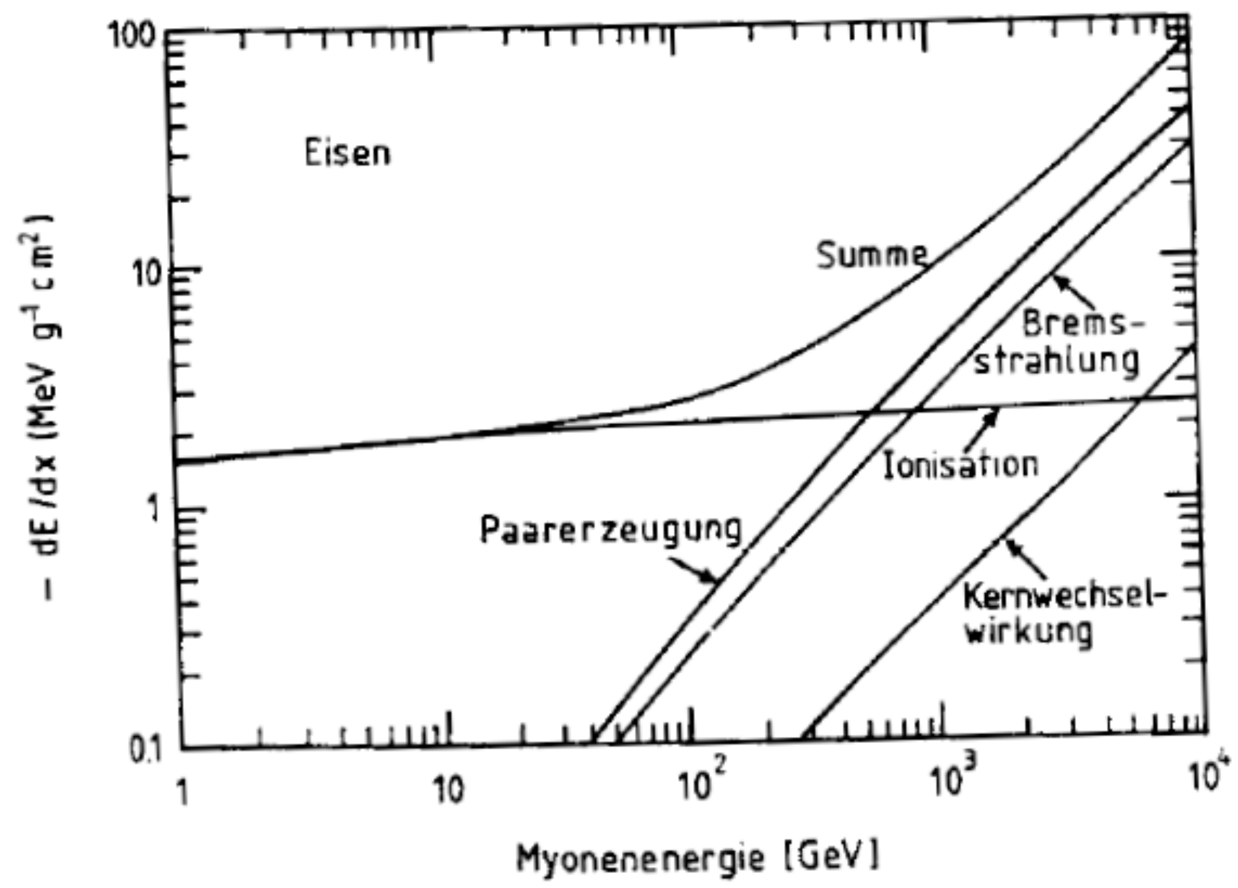


Critical energies in copper (Z = 29):

E_c (e) ≈ 20 MeV

$E_c(\mu)$ ≈ 1 TeV

- Muons with energies in the 10 - 100 GeV range are able to penetrate thick layers of matter, e.g. calorimeters;
- Can also be used for particle / 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	A	$X_0[g/cm^2]$	$X_0/\varrho\ [cm]$	$E_c[MeV]$
Wasserstoff	1	1.01	63	700000	350
Helium	2	4.00	94	530000	250
Lithium	3	6.94	83	156	180
Kohlenstoff	6	12.01	43	18.8	90
Stickstoff	7	14.01	38	30500	85
Sauerstoff	8	16.00	34	24000	75
Aluminium	13	26.98	24	8.9	40
Silizium	14	28.09	22	9.4	39
Eisen	26	55.85	13.9	1.76	20.7
Kupfer	29	63.55	12.9	1.43	18.8
Silber	47	109.9	9.3	0.89	11.9
Wolfram	74	183.9	6.8	0.35	8.0
Blei	82	207.2	6.4	0.56	7.40
Luft	7.3	14.4	37	30000	84
SiO_2	11.2	21.7	27	12	57
Wasser	7.5	14.2	36	36	83

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

2.3.3 Interactions of photons

In order to be detected, photons must transfer their energy to charged particles

- Photo electric effect
- Compton scatteraing
- Pair creation

Photo electric effect:

$$\gamma + \text{atom} \rightarrow \text{atom}^{+} + e^{-}$$

- Only possible in the close neighborhood of a third collision partner
  release of electrons from the inner shells (K, L, ..) of atoms

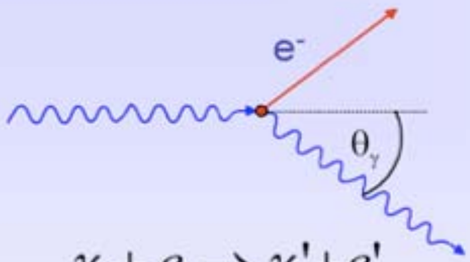
- The cross section shows a strong modulation if $E_{\gamma} \approx E_{bin}$

$$\sigma^{K}_{photo} = \left(\frac{32}{\varepsilon^{7}}\right)^{\frac{1}{2}} \alpha^{4} Z^{5} \sigma^{e}_{Th} \qquad \varepsilon = \frac{E_{\gamma}}{m_{e}c^{2}} \qquad \sigma^{e}_{Th} = \frac{8}{3}\pi r_{e}^{2} \quad \text{(Thomson)}$$

At high energies (ε>>1)

$$\sigma^{K}_{photo} = 4\pi r_{e}^{2} \alpha^{4} Z^{5} \frac{1}{\varepsilon} \qquad \boxed{\sigma_{photo} \propto Z^{5}}$$

Compton scattering:

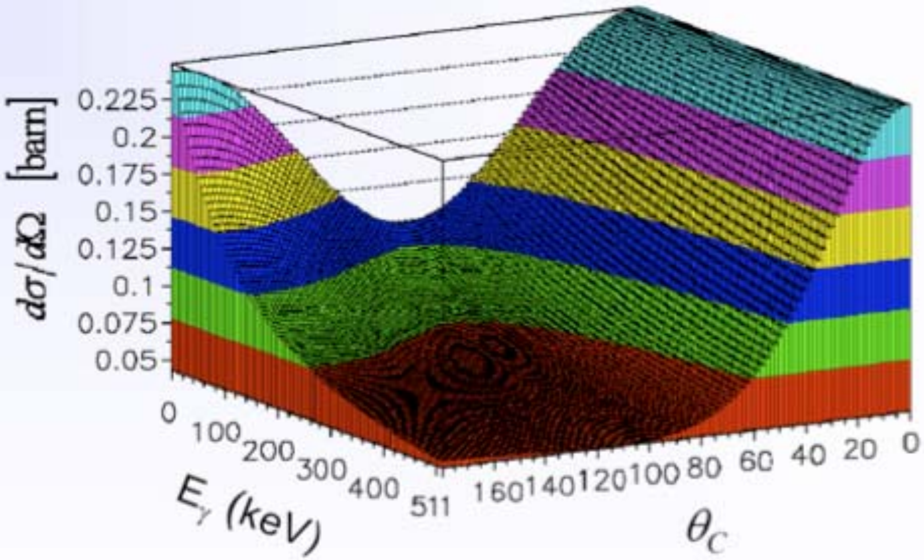


$$E'_\gamma = E_\gamma \frac{1}{1+\varepsilon(1-\cos\theta_\gamma)}$$

$$E_e = E_\gamma - E'_\gamma$$

$$\gamma + e \rightarrow \gamma' + e'$$

Compton cross-section (Klein-Nishina)



Assume electron as quasi-free.

Klein-Nishina $\frac{d\sigma}{d\Omega}(\theta,\varepsilon)$ →

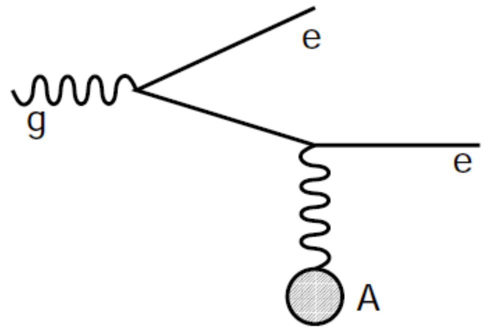
At high energies approximately

$$\sigma_c^e \propto \frac{\ln\varepsilon}{\varepsilon}$$

Atomic Compton cross-section:

$$\sigma_c^{atomic} = Z \cdot \sigma_c^e$$

Pair production: $\gamma + (A) \rightarrow e^+ e^- + (A)$



- Only possible in the close neighborhood of a collision partner (atomic nucleus)
- Threshold energy: $E_\gamma > 2\, m_e\, c^2 = 1.022$ MeV
- Cross section (high energy approximation):

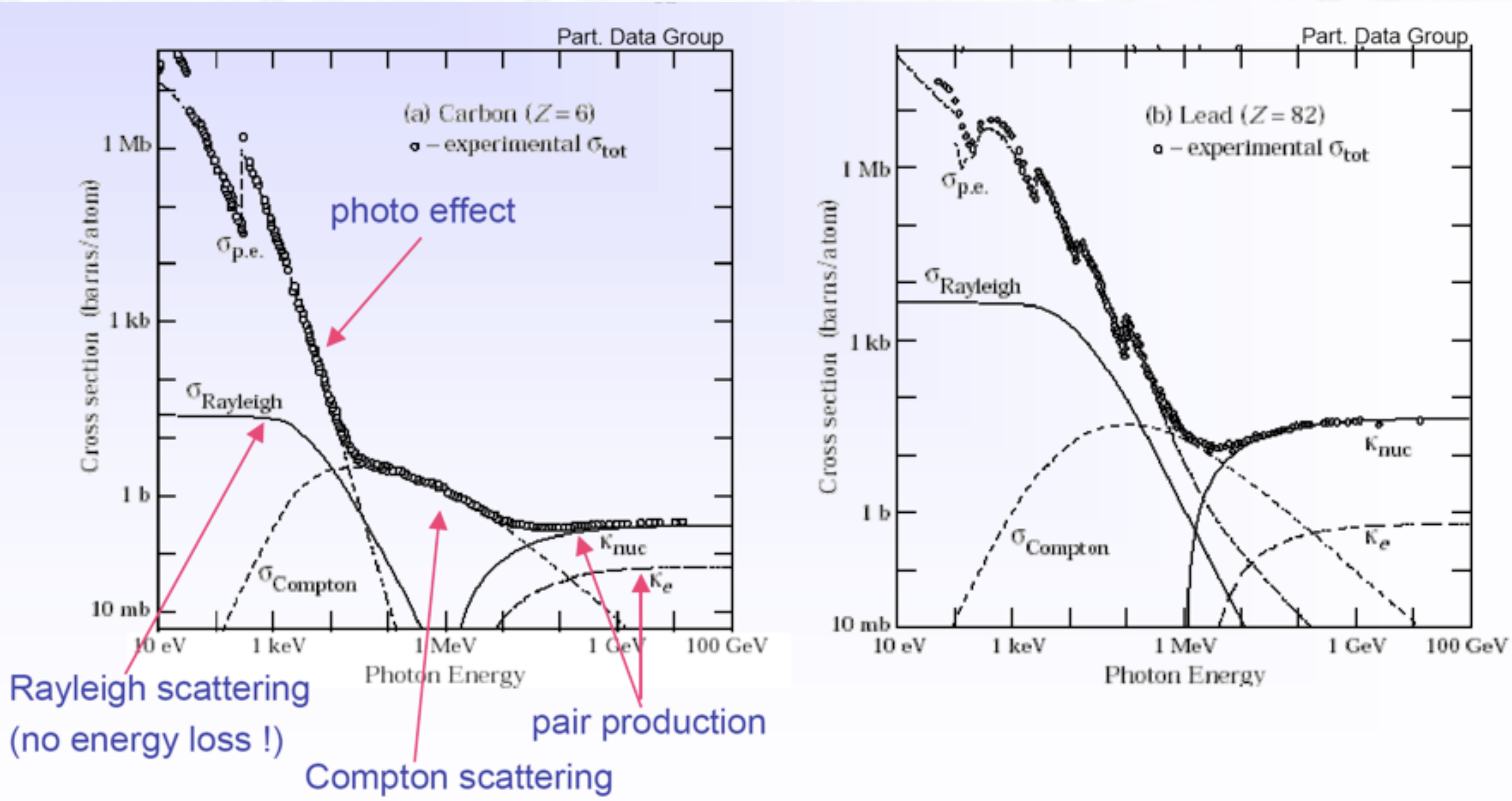
$$\sigma_{Paar} = 4\alpha r_e^2 Z^2 \left(\frac{7}{9} \ln \frac{183}{Z^{1/3}} - \frac{1}{54} \right) \approx \frac{7}{9} \cdot \frac{A}{N_L} \cdot \frac{1}{X_0}$$

$$\Rightarrow \mu_{Paar} = \frac{7}{9} \cdot \frac{1}{X_0}$$

- After traversing a material thickness of 9/7 X_0, the photon intensity –due to pair creation- is decreased by 1/e
  .or.
- For high photon energies, pair production occurs after traversing a material thickness corresponding to one radiation length with a probability of

$$P = 1 - e^{-7/9} = 0.54$$

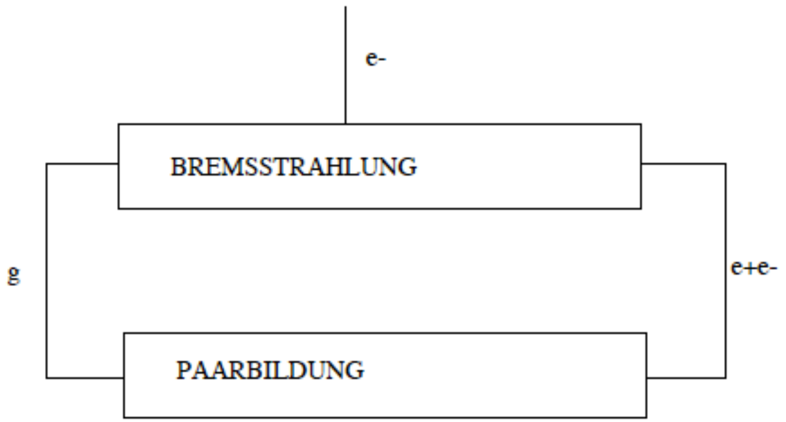
Photon interaction cross sections

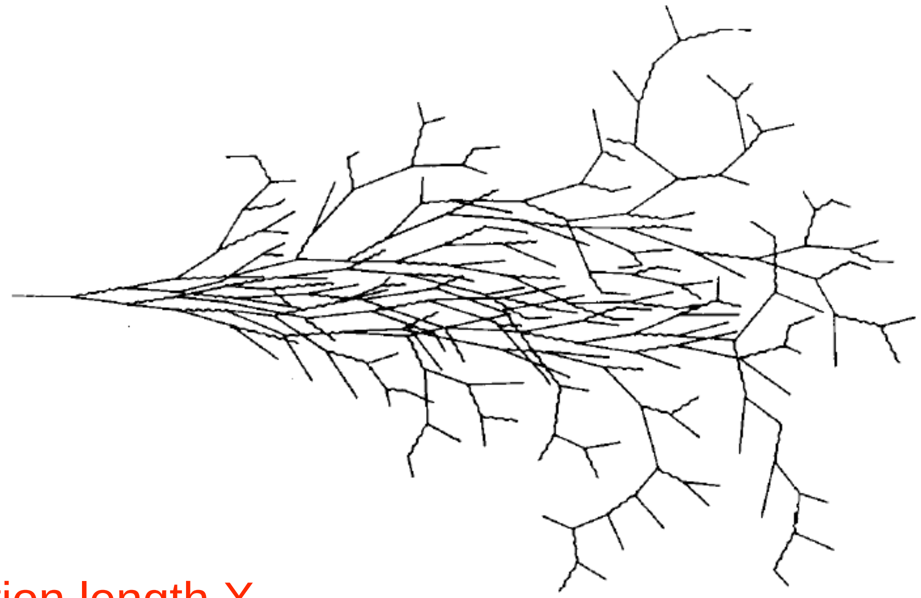


2.3.4 Electromagnetic calorimeters

- 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



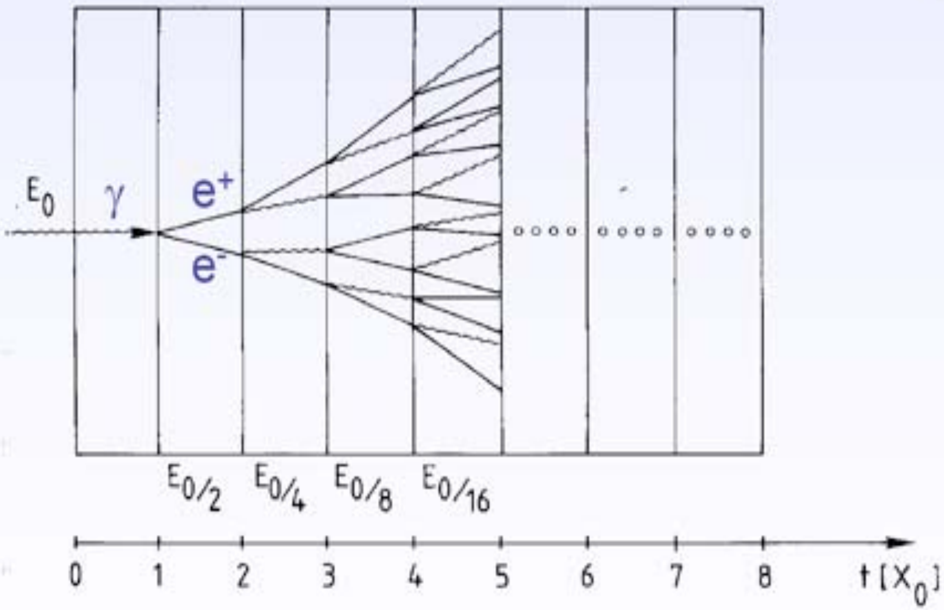


- Characteristic interaction length: radiation length X_0

- 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

Longitudinal shower profile

Simple qualitative model



- Consider only Bremsstrahlung and (symmetric) pair production.
- Assume: $X_0 \sim \lambda_{pair}$

$$N(t) = 2^t \qquad E(t)/\,particle = E_0 \cdot 2^{-t}$$

Process continues until $E(t)<E_c$

$$N^{total} = \sum_{t=0}^{t_{max}} 2^t = 2^{(t_{max}+1)} - 1 \approx 2 \cdot 2^{t_{max}} = 2\frac{E_0}{E_c}$$

$$t_{max} = \frac{\ln E_0/E_c}{\ln 2}$$

After $t = t_{max}$ the dominating processes are ionization, Compton effect and photo effect absorption of energy.

Shower depth (shower maximum) scales logarithmically with particle energy !

→ size of calorimeters growth only logarithmically with energy.

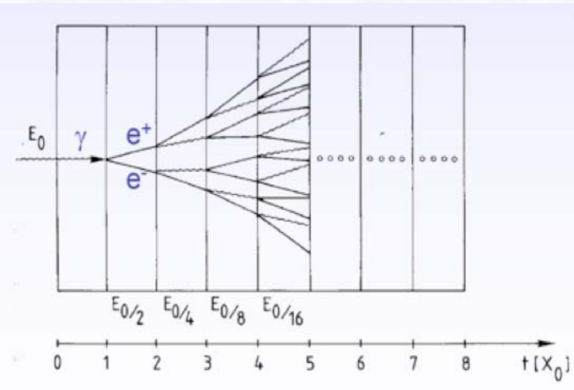
Longitudinal shower parametrization

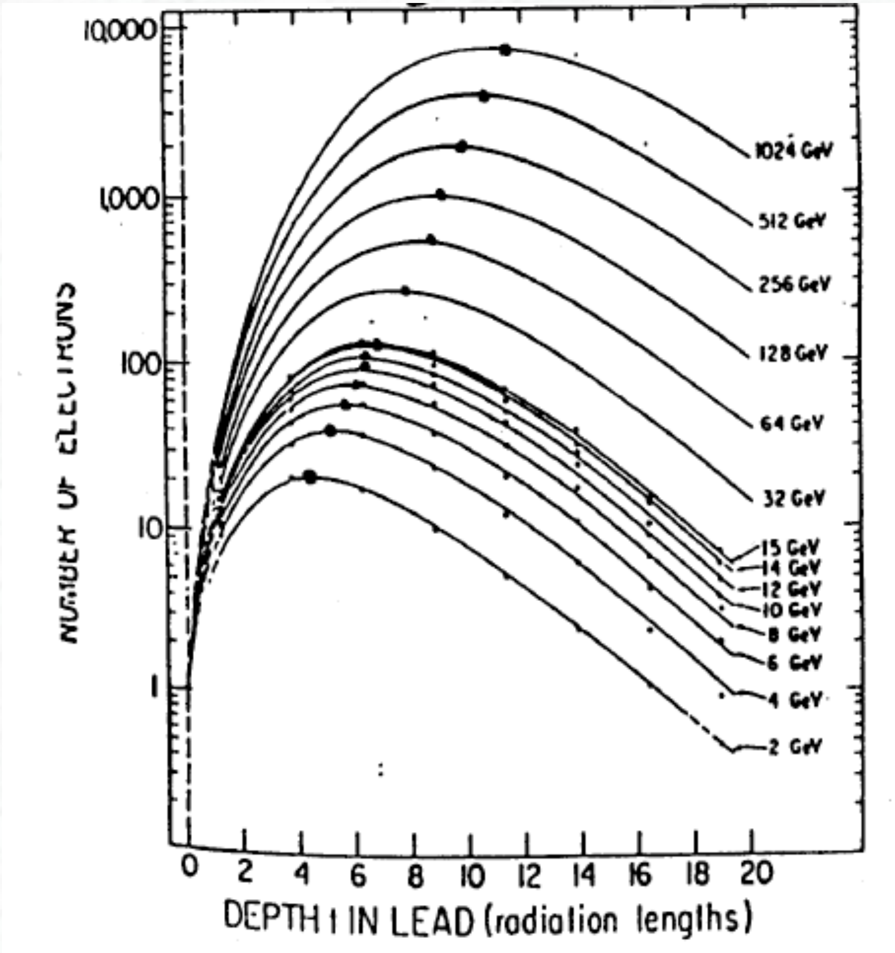
$$\frac{dE}{dt} = const \cdot t^a \cdot e^{-bt}$$

Shower depth (shower maximum) scales logarithmically with particle energy !

→ size of calorimeters growth only logarithmically with energy.

can be derived using a simple shower model (see exercises)





Lateral shower profile:

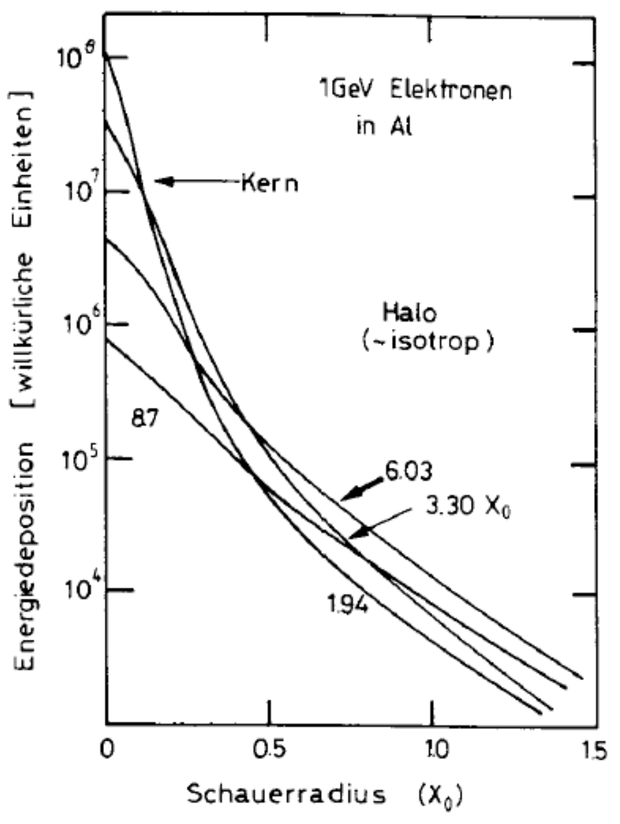
- The lateral shower profile is dominated by two processes:
  - multiple Coulomb scattering
  - relatively long free path length of low energy photons

- It is characterized by the so-called Molière radius ρ_M

$$\rho_M = \frac{21\text{MeV}}{E_C} X_0 \approx 7 \frac{A}{Z} \left[\frac{g}{cm^2}\right]$$

- About 95% of the shower energy are contained within a cylinder with radius r = 2 ρ_M

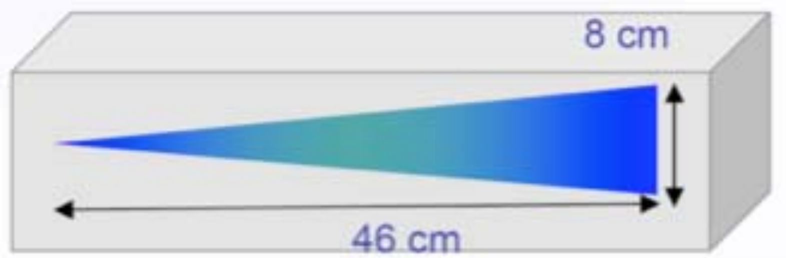
in general well collimated !



Example: E_0 = 100 GeV in lead glass

E_c=11.8 MeV $\rightarrow t_{max} \approx 13$, $t_{95\%} \approx 23$

$X_0 \approx 2$ cm, $R_M = 1.8 \cdot X_0 \approx 3.6$ cm



2.3.5 Hadronic calorimeter showers

Geladene und neutrale Hadronen können aufgrund der starken Wechselwirkung mit den Detektormaterialien (insbesondere Kalorimetern) wechselwirken.

relevant: inelastische Wechselwirkungen, charakterisiert durch die hadronische Wechselwirkungslänge λ_{had}
$\Rightarrow$ mehrere Sekundärteilchen (Meson-Produktion),
Multiplizität $\sim \ln E$

Schwächung eines Hadronenstrahls aufgrund der inelastischen WW:

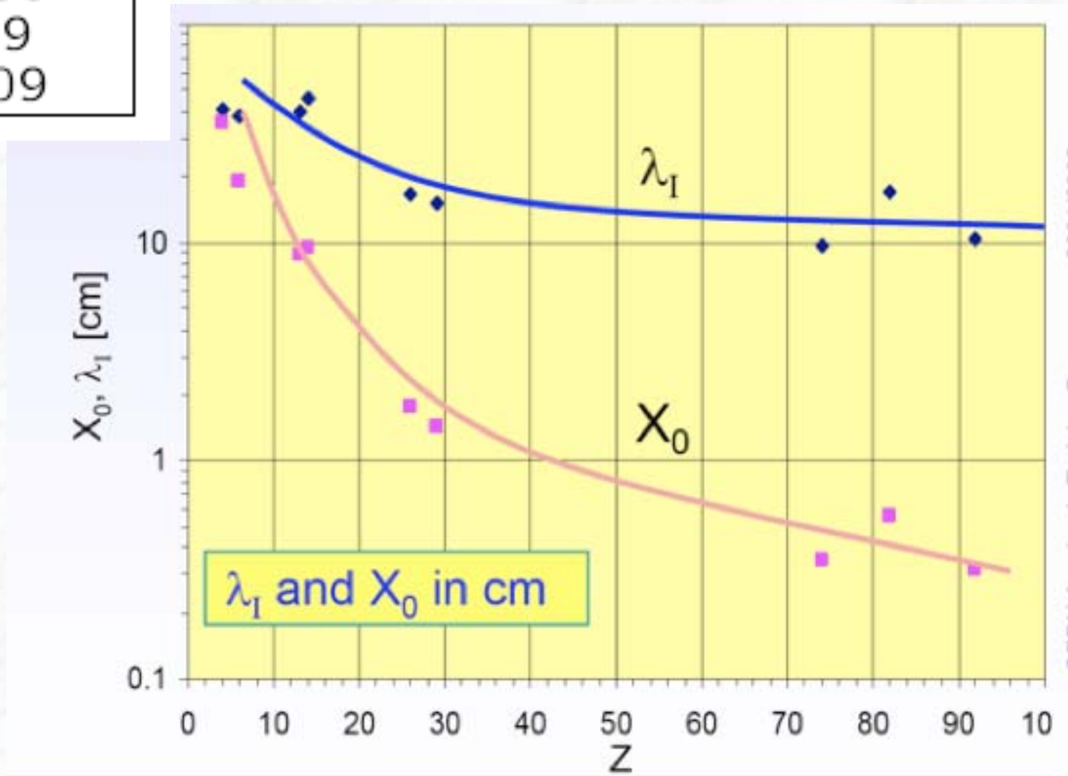
$$I(x) = I_0 \, e^{-x/\lambda_{had}}$$

Zusammenhang mit dem inelastischen Wirkungsquerschnitt σ_{inel}:

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

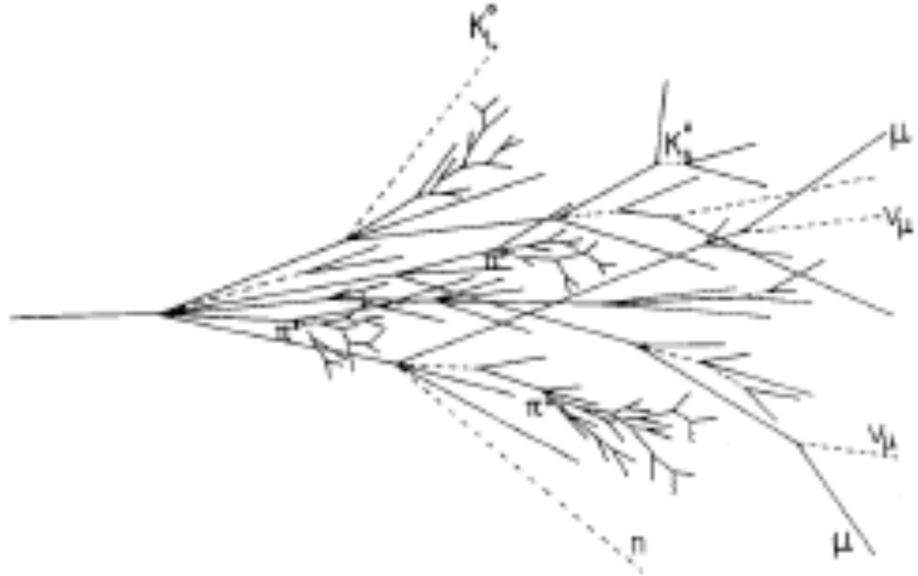
useful approximation: $\lambda_{had} \approx 35\ A^{1/3}$ (cm)

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



- Schauer, die von Hadronen (aufgrund der starken Wechselwirkung) initiiert werden, werden als hadronische Schauer bezeichnet.

- hadronische Schauer sind wesentlich komplexer als el.magn. Schauer; grundlegende WW: inelastische hadronische Wechselwirkung



  - ⇒ mehrere Sekundärteilchen (Meson-Produktion) Multiplizität $\sim$ ln E

  - π^0 Komponenten, $\pi^0 \rightarrow \gamma\gamma$ ⇒ el.magn. Subschauer
    Der el.magn. Anteil f_{em} nimmt mit wachsender Energie zu (Bremsstrahlung): $f_{em} = 0.1 \cdot lnE$ (E in GeV, 10 GeV < E < 100 GeV)

- Atomkerne werden teilweise aufgebrochen oder verbleiben in angeregten Zuständen

  Kernbindungsenergie muß vom Primär- oder Sekundärteilchen aufgebracht werden

  ⇒ kein Beitrag zur sichtbaren Energie

  Angeregte Kerne geben Energie ab ⇒ γ-Strahlung ⇒ el.magn. Subschauer

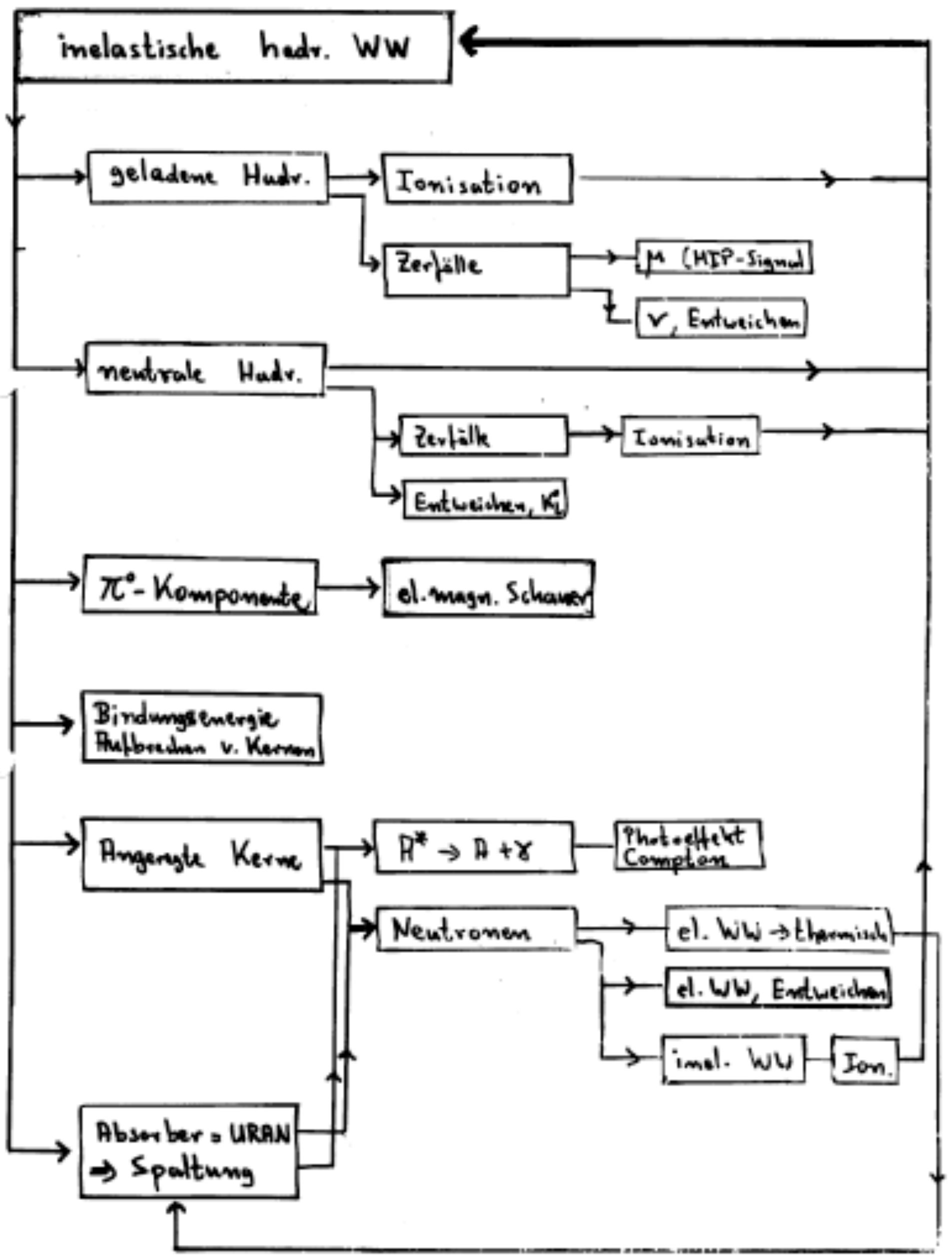
- Neutronen:
  Wechselwirkung ist stark abhängig von der Energie der Neutronen, Extremfälle:

  * Kernreaktionen, z.B. Kernspaltung

  * Austritt aus Kalorimeter (elastische Streuung) ohne inel. WW

- Zerfälle von Teilchen (langsame Teilchen am Schauerende), z.B.: $\pi \to \mu\nu_\mu$

Hadronisches Schauermodell



2.3.6 Layout and readout of calorimeters

Prinzipiell unterscheidet man zwischen sog. homogenen Kalorimetern und Sampling-Kalorimetern

homogene Kalorimeter: Absorbermaterial = aktives (sensitives) Medium

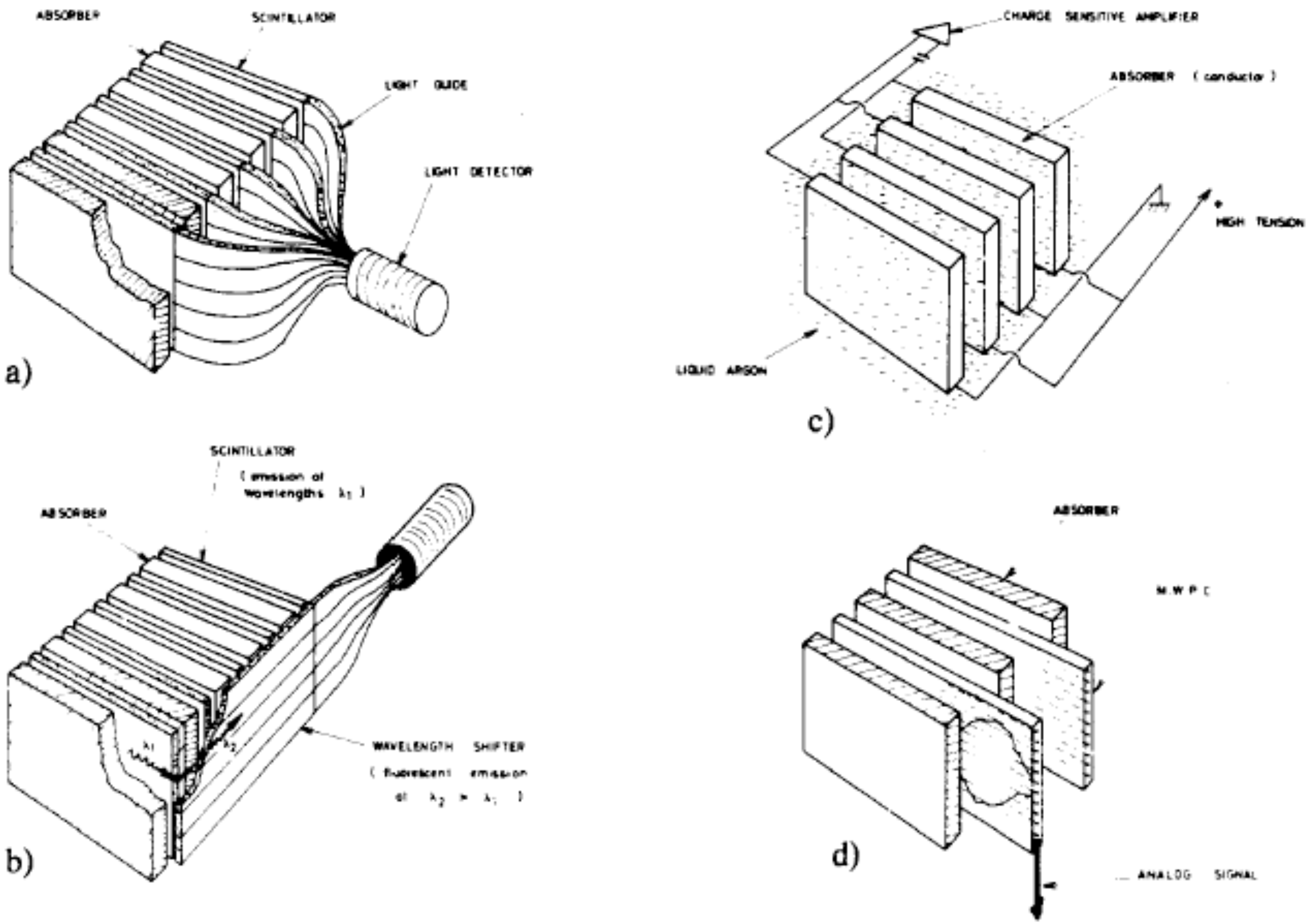
Beispiele:

- NaJ oder andere Kristalle (Szintillationslicht)
- Bleiglas (Cherenkovlicht)
- Flüssig-Argon oder Flüssig-Krypton Kalorimeter (Ionisationsladung)

Sampling-Kalorimeter: Absorption und hadr. Wechselwirkungen finden hauptsächlich in eingebrachten Materialien mit hohem Z statt (passives Medium, Absorber)

Signal wird im sog. aktiven Medium erzeugt; nur ein Teil der Energie trägt zum meßbaren Signal bei.

Beispiele für Sampling Kalorimeter



a) Szintillatoren, optisch an Photomultiplier gekoppelt
b) Szintillatoren, Wellenlängenschieber-Auslese
c) Ionisationsladung in Flüssigkeiten
d) Ionisationsladung in Vieldrahtproportionalkammern

2.3.7 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 of 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 constant term (determines at high energies)

    important contributions to b 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 $1/\sqrt{E}$

Beispiele für erreichte el. magn. Energieauflösungen bei großen Detektorsystemen:

Experiment	Kalorimeter	α	β	γ
L3	BGO	$< 2.0\%$	0.3 %	
BaBar (*)	CsI (Tl)	(*)1.3%	2.1 %	0.4 MeV
OPAL	Bleiglas	(**) 5% (++) 3%		
NA48	Flüssig Krypton	3.2%	0.5%	125 MeV
UA2	Pb/Szintillator	15%	1.0%	-
ALEPH	Pb/Prop.kammern	18%	0.9%	-
ZEUS	U/Szintillator	18%	1.0%	-
H1	Pb/Flüssig - Argon	11.0%	0.6%	154 MeV
D0	U/Flüssig - Argon	15.7%	0.3%	140 MeV

(*) Skalierung entsprechend $E^{-1/4}$ anstatt $E^{-1/2}$
vorläufiger Wert, Daten vom Jahr 2000
(**) at 10 GeV
(++) at 45 GeV

hadronische Energieauflösungen:

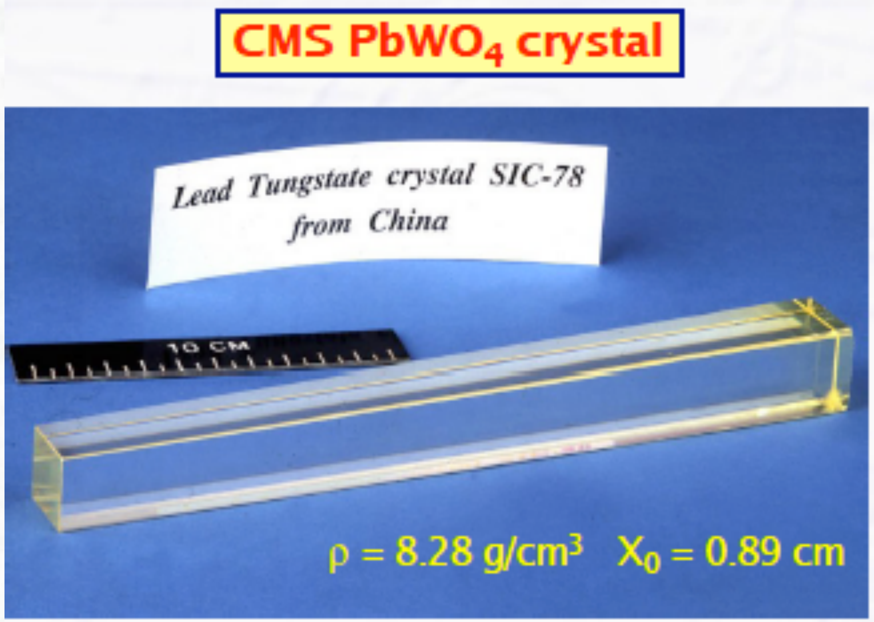
Experiment	Kalorimeter	α	β	γ
ALEPH	Fe/Streamer Rohre	85%		-
ZEUS (*)	U/Szintillator	35%	2.0%	-
H1 (+)	Fe/Flüssig - Argon	51%	1.6%	900 MeV
D0	U/Flüssig - Argon	41%	3.2%	1380 MeV

(*) compensating calorimeter
(+) weighting technique

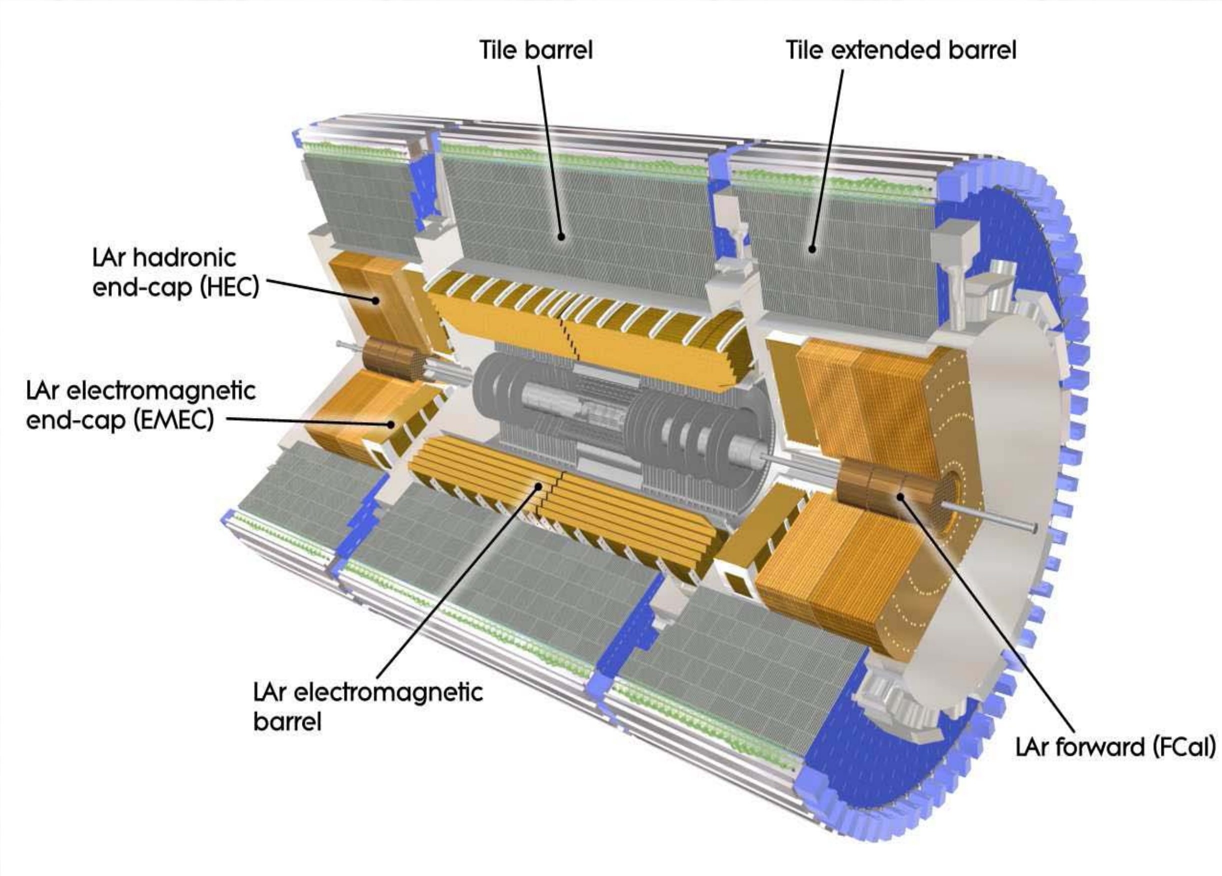
- i. Allg. ist die Energieantwort für Kalorimeter für e/γ und Hadronen verschieden; Ein Maß hierfür ist das sogenannte e/h Verhältnis

- In sog. "kompensierenden Kalorimetern" wird versucht, durch phys. Effekte die hadronischen Verluste auszugleichen, d.h e/h in die Nähe von 1 zu bringen (z.B. Energiegewinn aus Uranspaltung (Neutronen) oder Energieübertrag von Neutronen an Protonen (Wasserstoff in Szintillatoren)

2.3.8 The ATLAS and CMS calorimeters



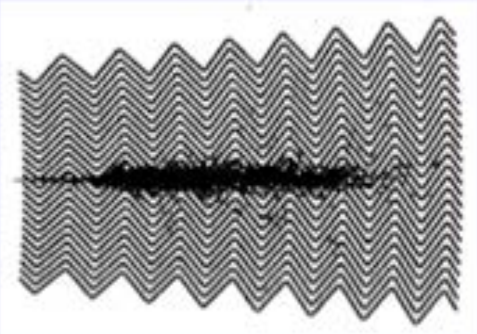
The ATLAS calorimeter system



- Liquid argon electromagnetic
- Liquid argon hadron calorimeter in the end-caps and forwards regions
- Scintillator tile hadron calorimeter in the barrel and extended end-cap region

ATLAS electromagnetic Calorimeter

Accordion geometry absorbers immersed in Liquid Argon



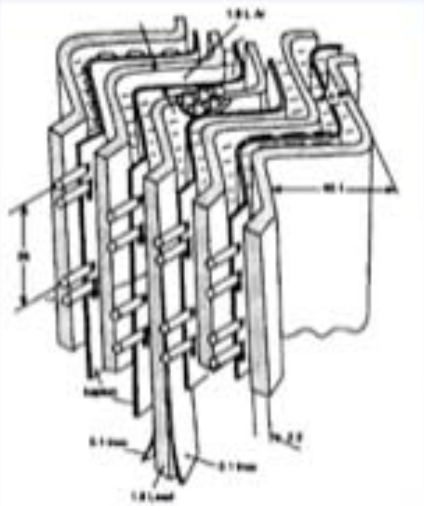
Liquid Argon (90K)

+ lead-steal absorbers (1-2 mm)

+ multilayer copper-polyimide readout boards

→ Ionization chamber.

1 GeV E-deposit → 5 x10^6 e^-

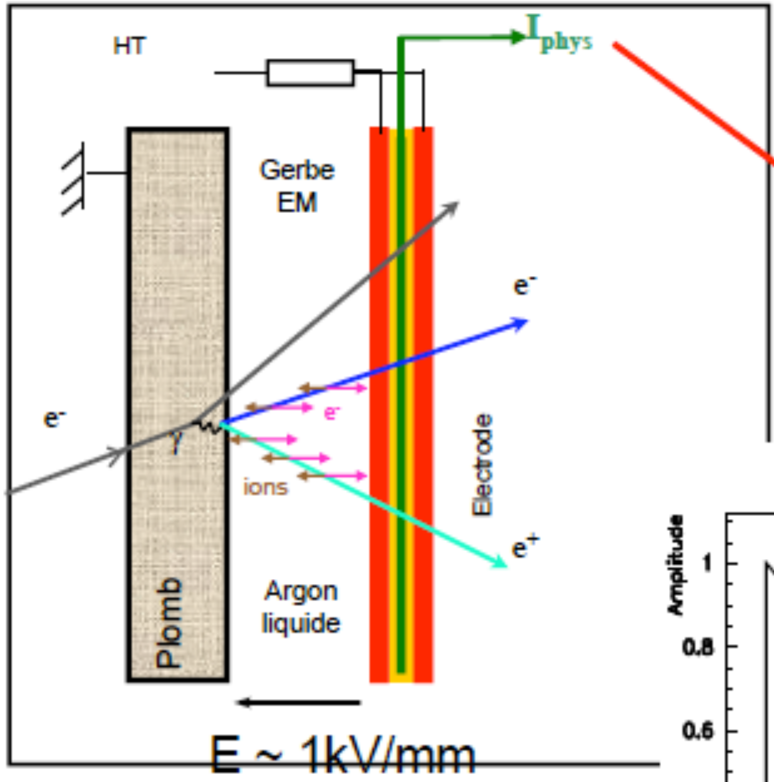


- Accordion geometry minimizes dead zones.
- Liquid Ar is intrinsically radiation hard.
- Readout board allows fine segmentation (azimuth, pseudo-rapidity and longitudinal) acc. to physics needs

Test beam results $\sigma(E)/E = 9.24\%/\sqrt{E} \oplus 0.23\%$

Spatial resolution ≈ 5 mm / √E

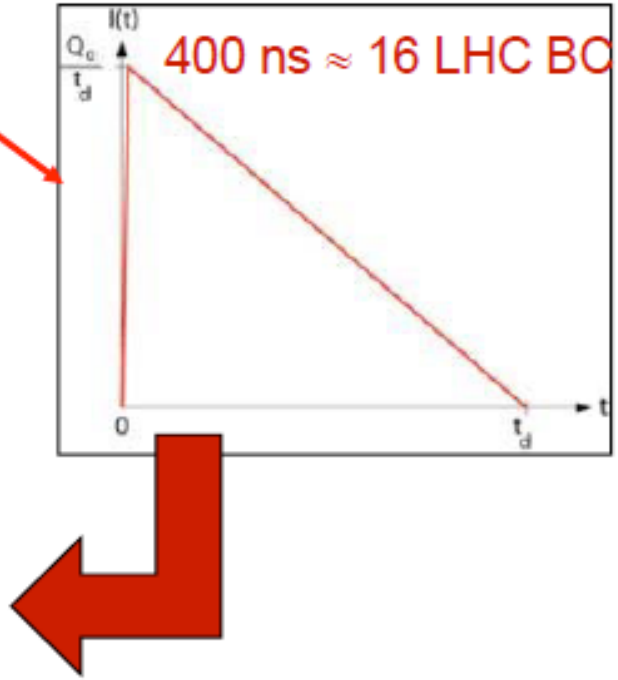
Signal formation in a Liquid argon calorimeter and pulse shaping:

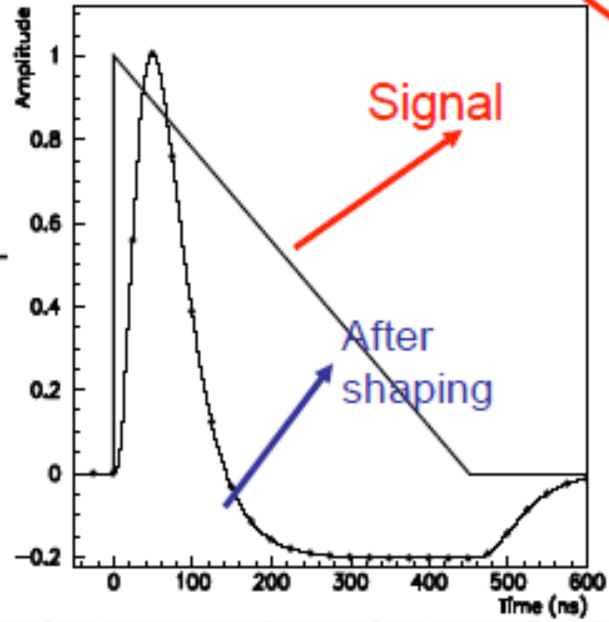


Signal is given from collection of released electrons

Drift velocity depends on electron mobility and applied field. In ATLAS :

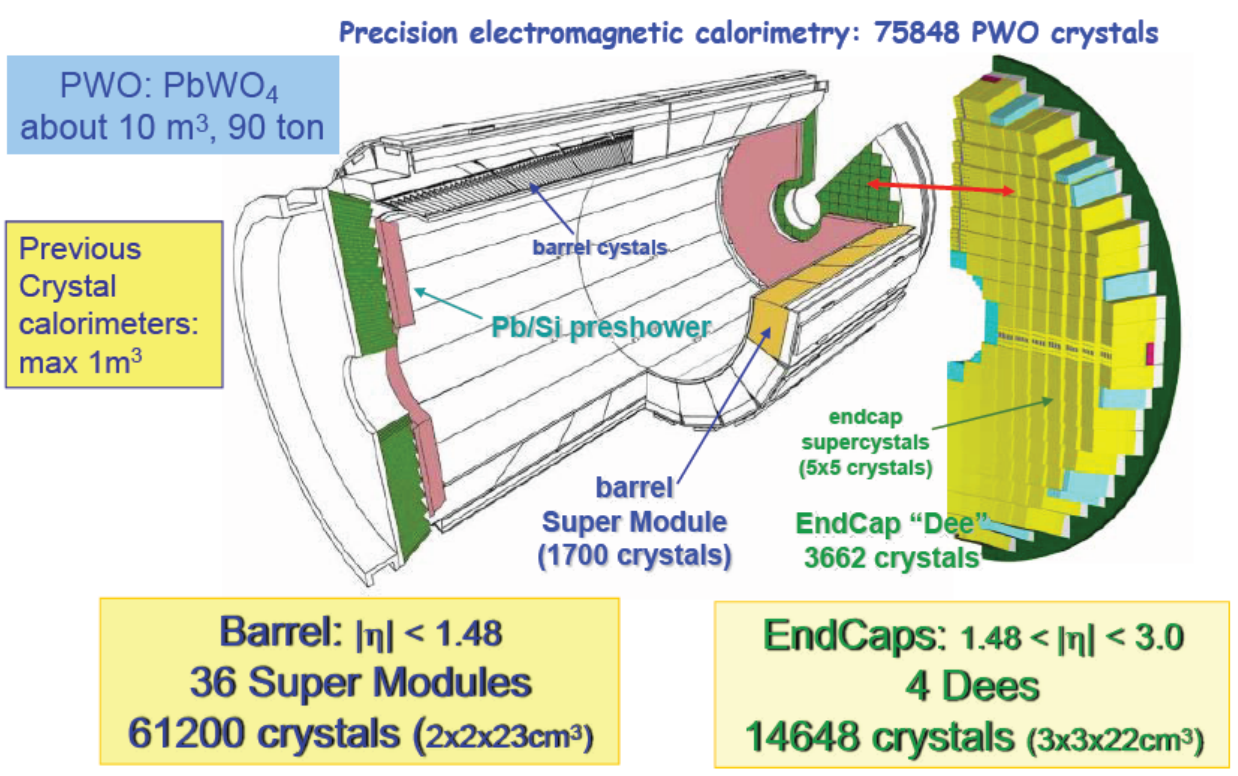
LAr gap 2 mm, ΔV = 2kV





Instead of total charge (integrated current) measure the initial current I_0, (via electronic signal shaping), which is also proportional to the energy released

The CMS calorimeter system

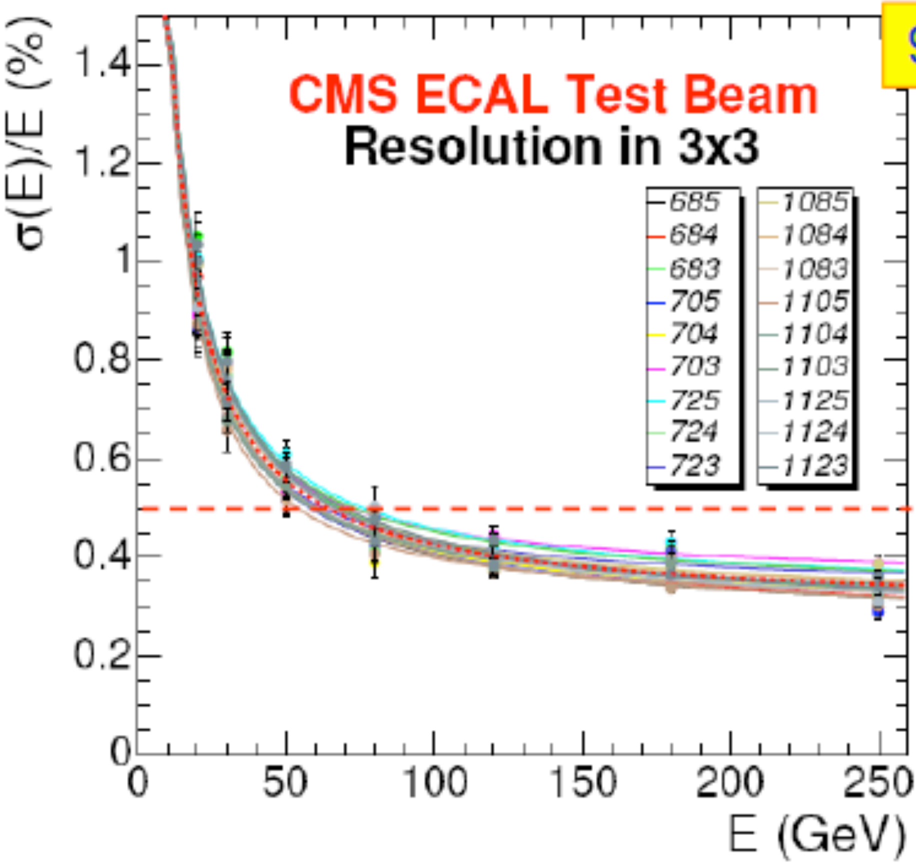


- $PbWO_4$ crystal
  el. magn calorimeter
  (homogeneous)

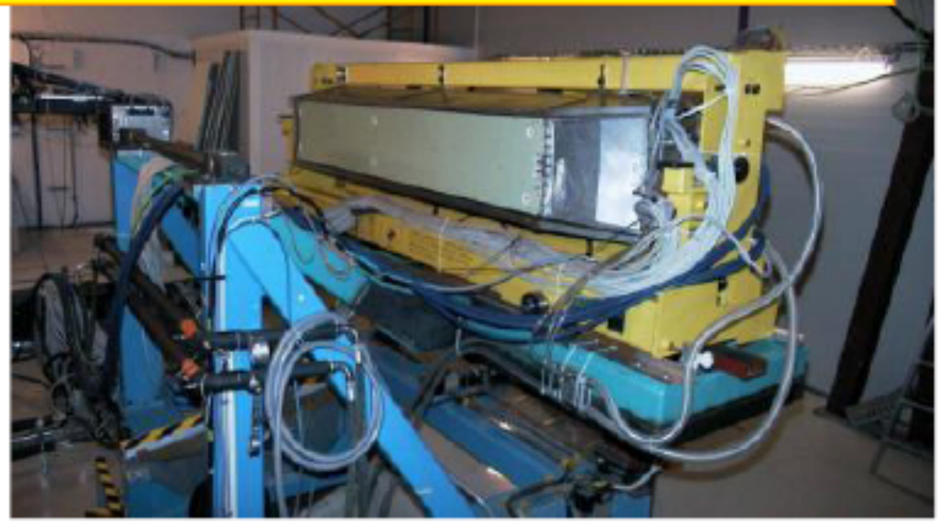
- Hadron calorimeter
  integrated in return yoke

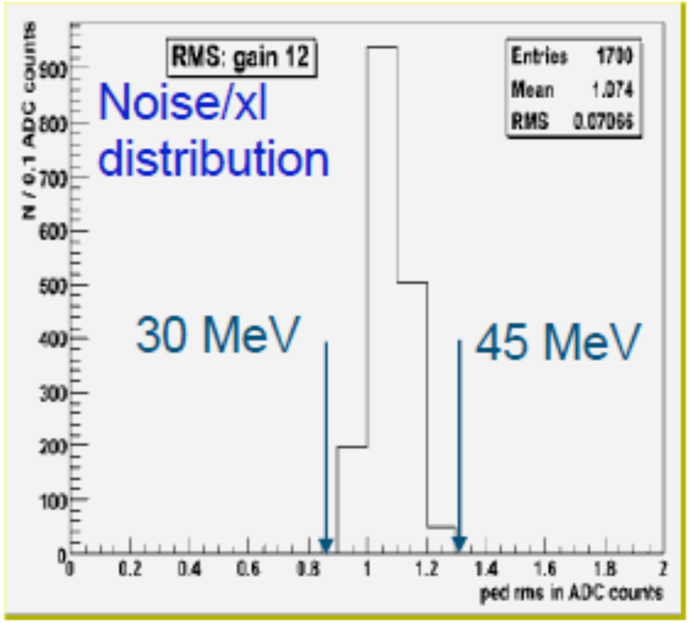
CMS el.magnetic calorimeter: crystal $PbWO_4$

Scintillator	Density $[g/cm^3]$	X_0 [cm]	Light Yield γ/MeV (rel. yield*)	τ_1 [ns] λ_1 [nm]	Rad. Dam. [Gy]	Comments
NaI (Tl)	3.67	2.59	4×10^4	230 415	≥10	hydroscopic, fragile
CsI (Tl)	4.51	1.86	5×10^4 (0.49)	1005 565	≥10	Slightly hygroscopic
CSI pure	4.51	1.86	4×10^4 (0.04)	10 310 36 310	10^3	Slightly hygroscopic
BaF_2	4.87	2.03	10^4 (0.13)	0.6 220 620 310	10^5	
BGO	7.13	1.13	8×10^3	300 480	10	
$PbW0_4$	8.28	0.89	≈100	440 broad band 530 broad band	10^4	light yield =f(T)



9 Super Modules 1700 xl on test beam





$$\frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E(\mathrm{GeV})}} \oplus \frac{125}{E(\mathrm{MeV})} \oplus 0.3\%$$

Local resolution

Comparison between ATLAS and CMS calorimeters

CMS	ATLAS
Homogeneous calorimeter made of 75000 **$PbWO_4$ scintillating crystals** + PS FW	**Sampling LAr-Pb**, 3 Longitudinal layers + PS
•Very compact R_M=2.0cm	•R_M=7.3cm
• Excellent energy resolution	•Good energy resolution
• Fast << 100 ns	•Not so fast (450 ns), requires shaping
• High granularity	• High granularity
•No longitudinal segmentation	• Longitudinally segmented
•No angular measurement	•Angular measurement
•Radiation tolerance : needs follow up	• Radiation resistance
•Room Temperature	•Cryogenic detector (cryostat)
•T sensitive 5%/°K	•T sensitive 5%/°K
•Requires uniformisation by calibration	•Instrinsically uniform

2.4 The ATLAS and CMS muon systems

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)

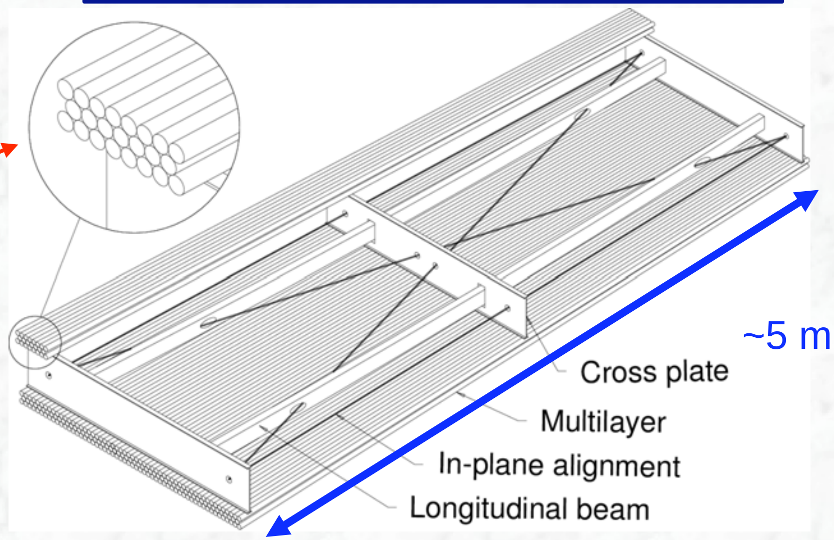
- Challenge for muon detectors
  - large surface to cover (outer shell)
  - keep mechanical positioning over time

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

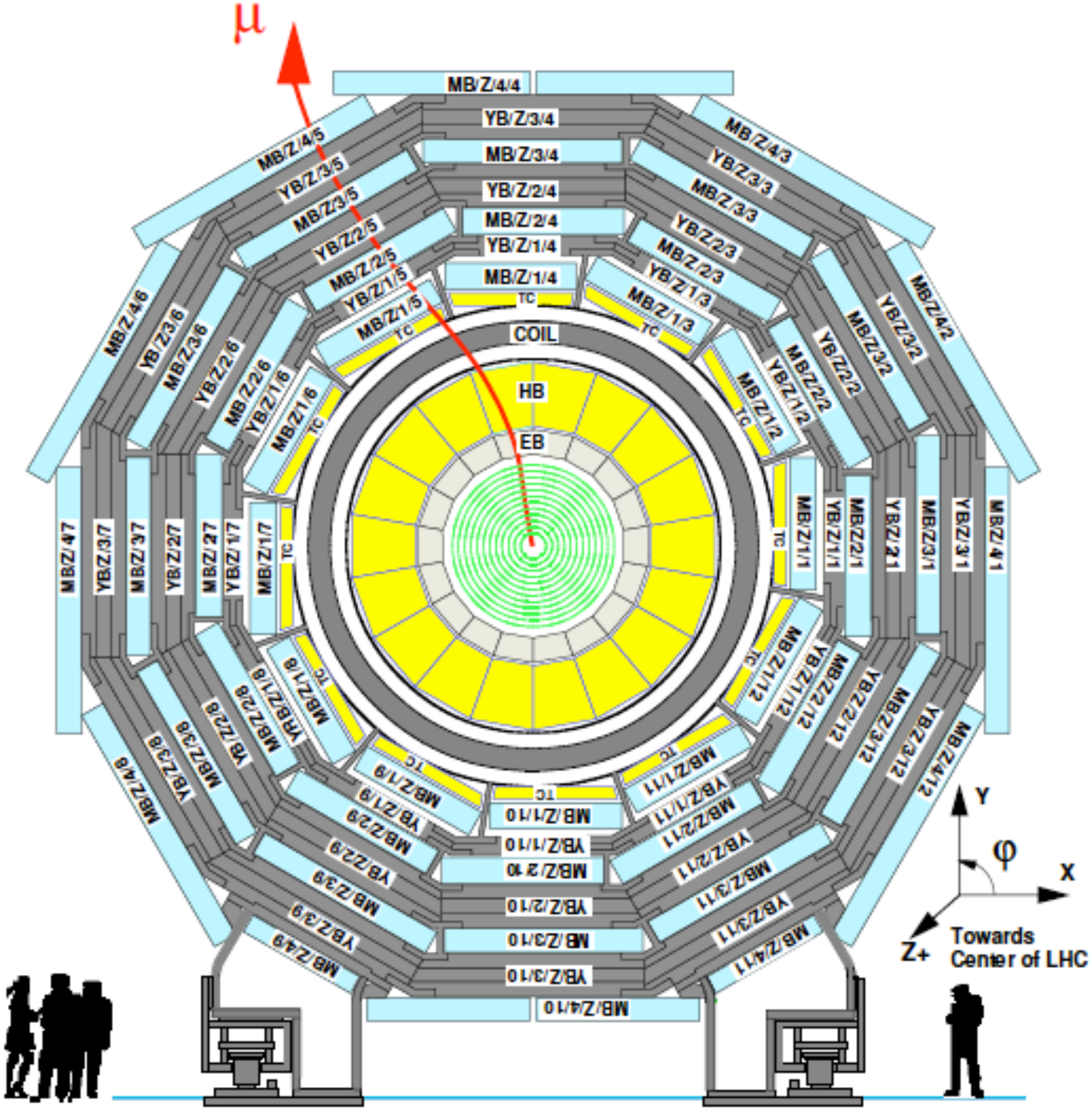
    (inhomogeneous) magnetic field needed

ATLAS Muon Detector Elements

Aluminum tubes with central wire filled with 3 bar gas

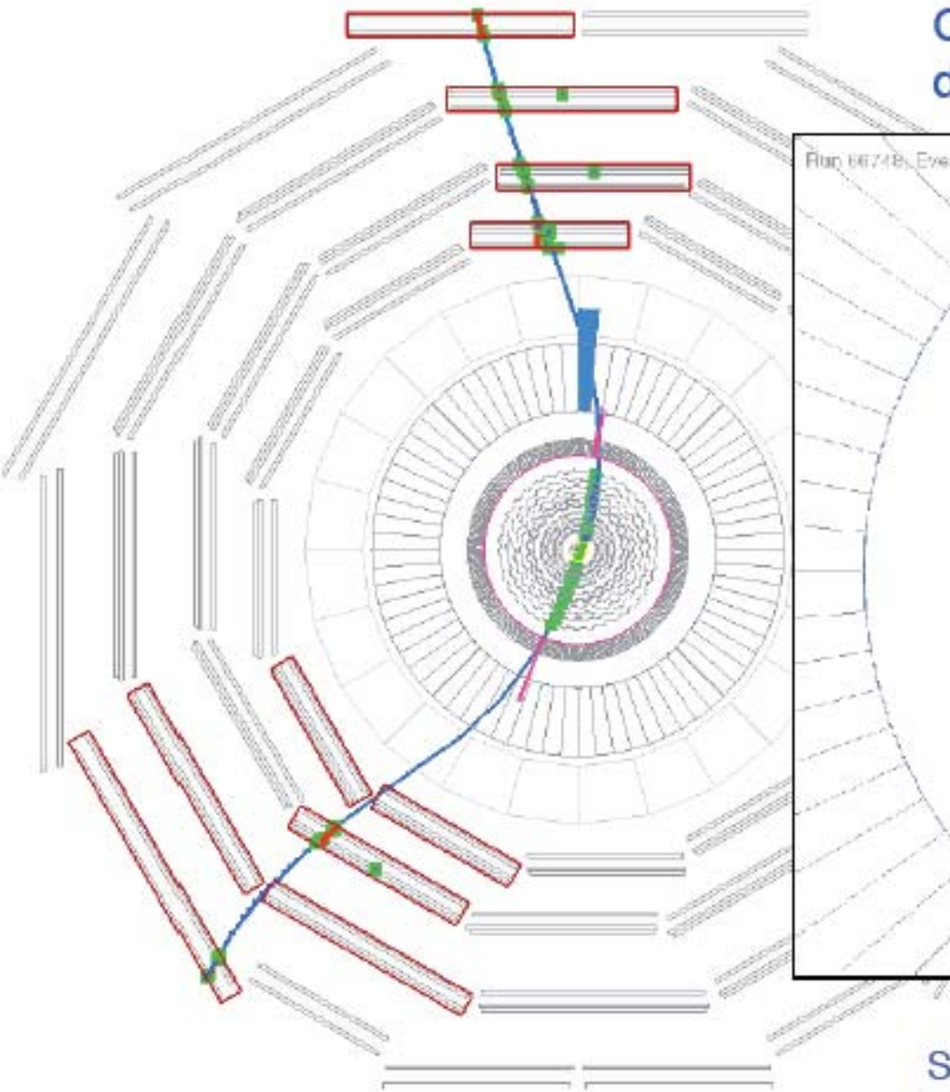


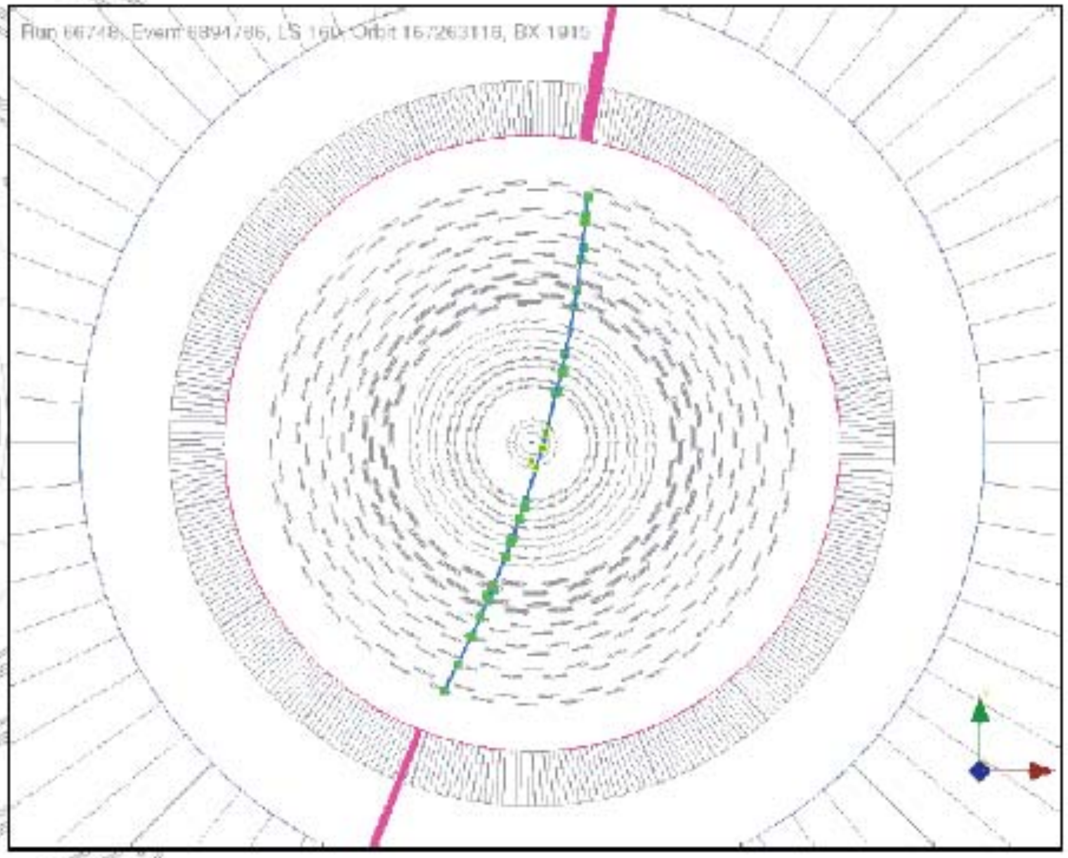
CMS Muon system



Cosmic muon event in CMS

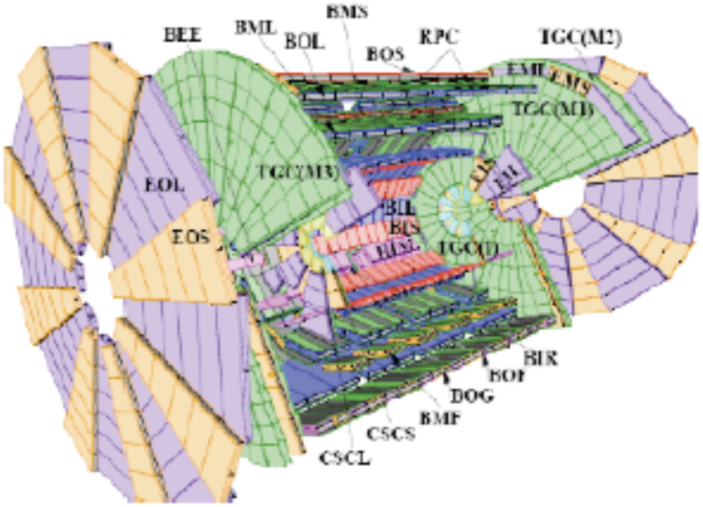
Cosmic Muons measured in all CMS sub-detectors including Pixel detector.





Several hundred million cosmics have been recorded.

ATLAS muon system



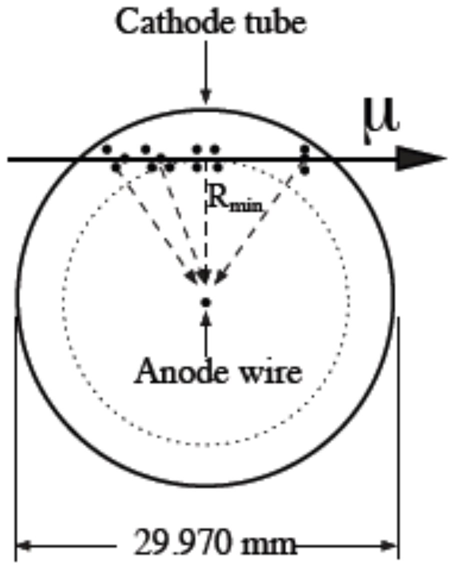
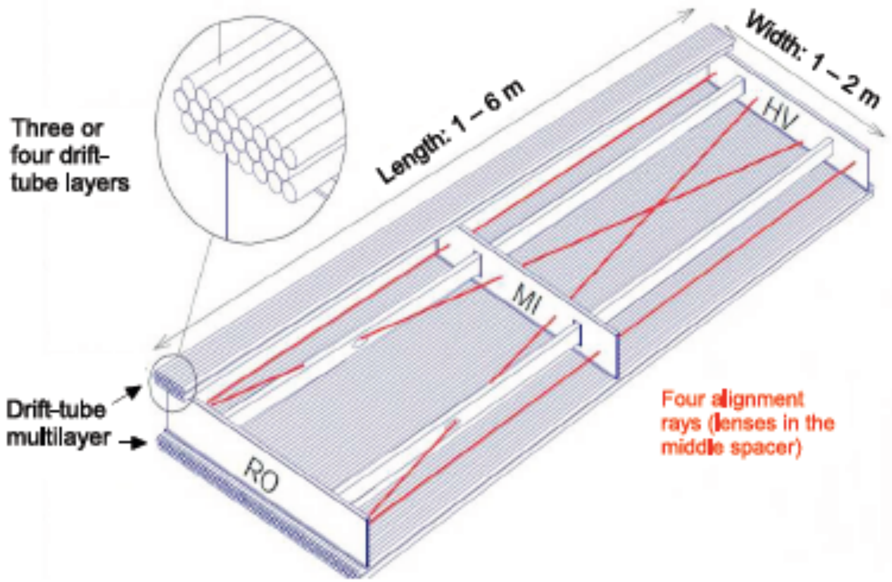
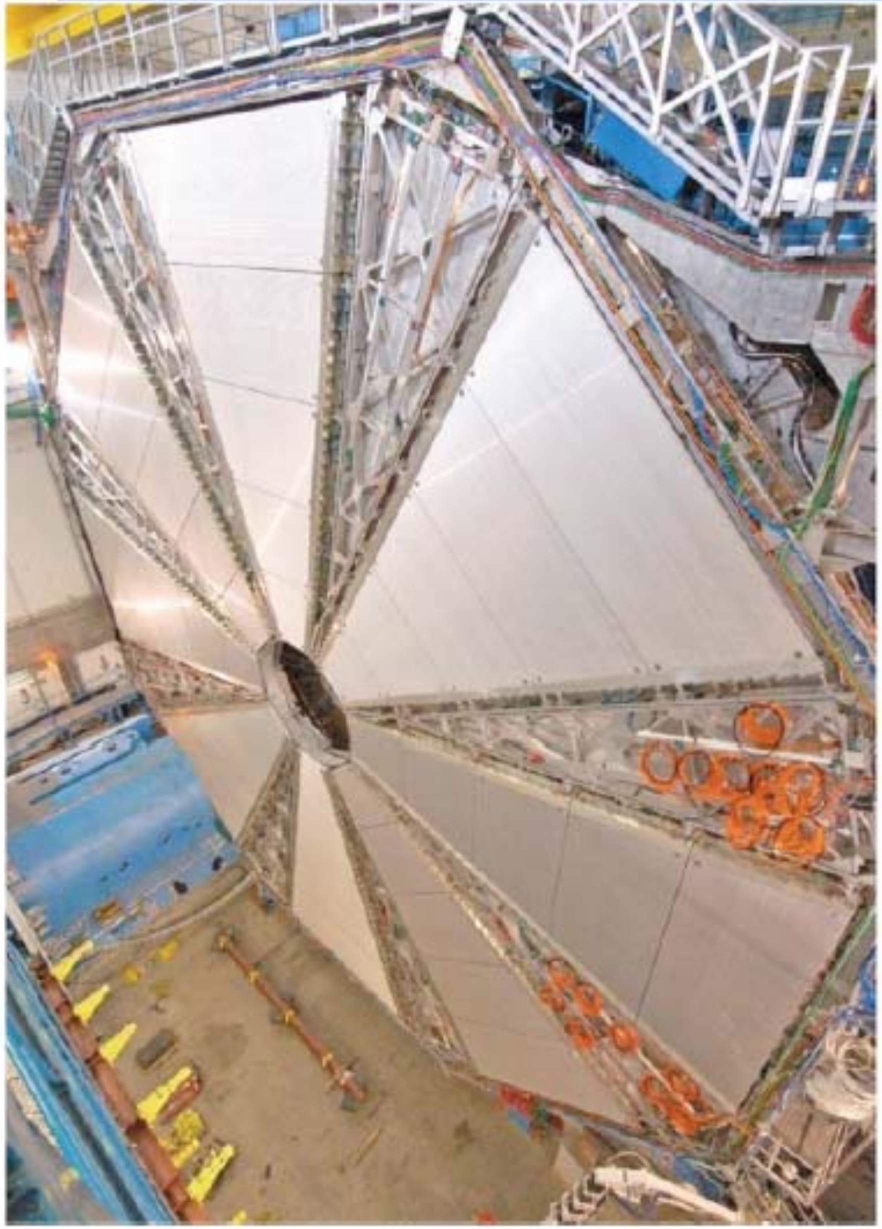


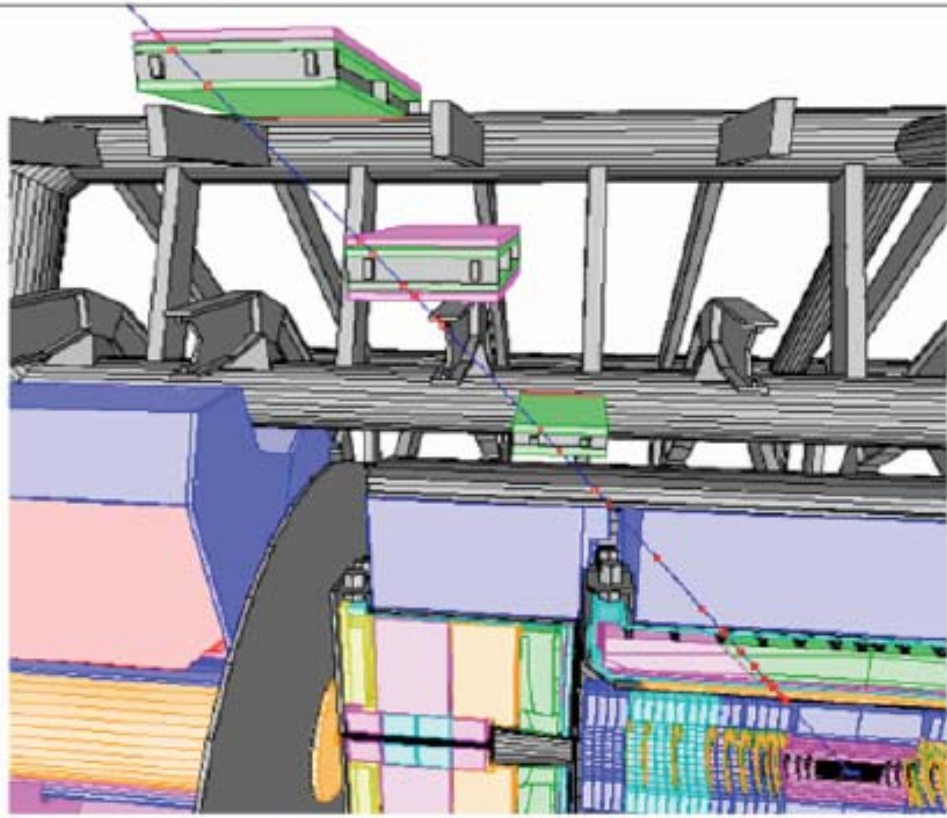
Table 6.2: Main MDT chamber parameters.

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