6. Energiemessung

6.1 Messprinzip

6.2 Energiemessung mit Halbleiterdetektoren

6.3 Energiemessung in Kalorimetern

6.1 Messprinzip

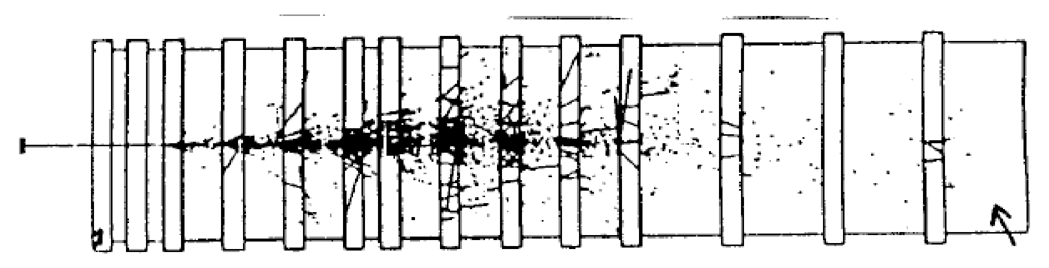
- Energiemessung kann dann durchgeführt werden, wenn Teilchen ihre Energie in Detektoren komplett deponieren

  - Niederenergiebereich: < ~1 MeV: Ionisationsdetektoren (α–Spektroskopie)
    Szintillatoren (γ – Spektroskopie)
    Halbleiterzähler (γ – Spektroskopie)

  - Hohe Energien: Elektromagnetische (für Elektronen, Photonen) und
    hadronische Kalorimeter (stark wechselwirkende Teilchen)

- Energie des Teilchens wird in ein elektrisches Signal (Ionisationsladung) oder in ein Lichtsignal (Szintillator- oder Cherenkov-Licht) umgewandelt
  Dieses Signal sollte proportional zur ursprünglichen Energie: $E = \alpha\, S$
  Kalibration → α [MeV / S]

- Die Energie kann auch stichprobenartig gemessen werden („*sampling* Detektor“); Dies funktioniert, solange die Proportionalität E ~ S erhalten bleibt



6.2 Energiemessung in Halbleiterdetektoren

- Durch Bildung von elektron-Loch-Paaren entstehen in Halbleitern freie Ladungsträger

- Kleiner W-Wert:

Silizium:	3.6 eV
Germanium:	2.8 eV
Gas (zum vergleich):	~30 eV
Szintillatoren:	~400 – 1000 eV (zur Erzeugung eines Photoelektrons)

→ enorme Vorteile in der erreichbaren Energieauflösung für Halbleiterdetektoren! (s. nächste Folie)

- Silizium und Germanium stellen die für Energiemessungen am häufigsten verwendeten Halbleiterzähler dar

Bandlücken:

Silizium:	1.14 eV
Germanium:	0.67 eV

→ geringe Bandlücke von Germanium erfordert Kühlung des Detektors, um thermisches Rauschen zu reduzieren

- Zur Ladungssammlung müssen Halbleiterzähler in Sperrrichtung betrieben werden (vgl. Kap. 5)

  → Dioden mit pn-Übergang in Sperrrichtung
  Verarmungszone

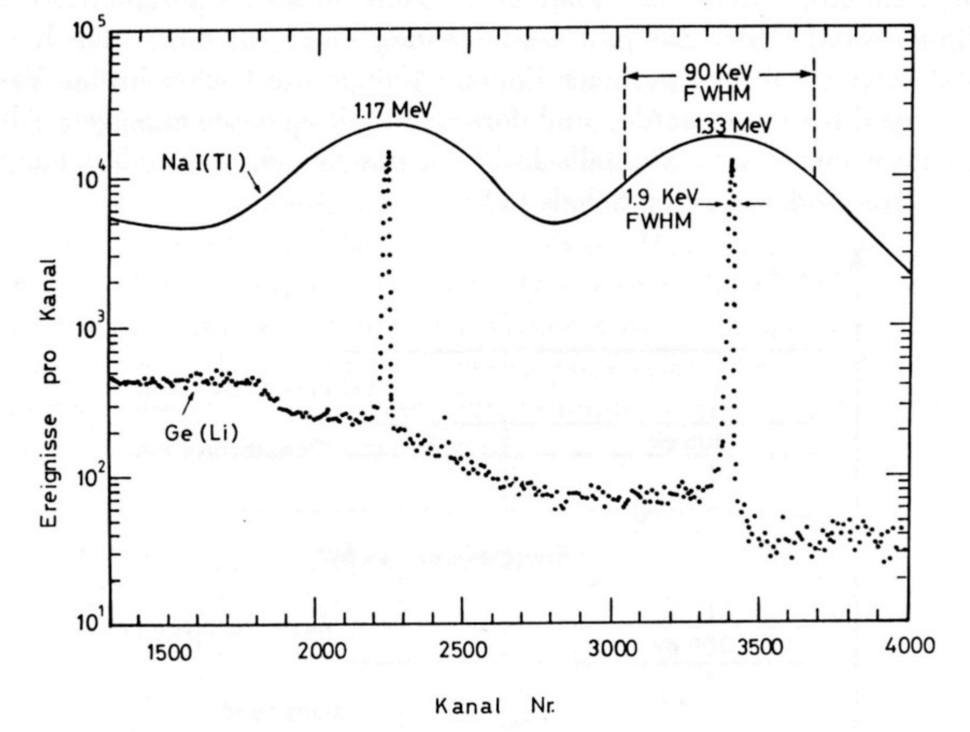
- Zur Energieauflösung: Die Zahl N der erzeugten freien Ladungsträger ist in Halbleiterdetektoren wesentlich größer;

$E \sim N$

→ die relativen „statistischen“ Schwankungen in der Zahl der erzeugten Ladungsträger und damit der „statistische“ Anteil der Energieauflösung sind in Halbleiterzählern wesentlich kleiner

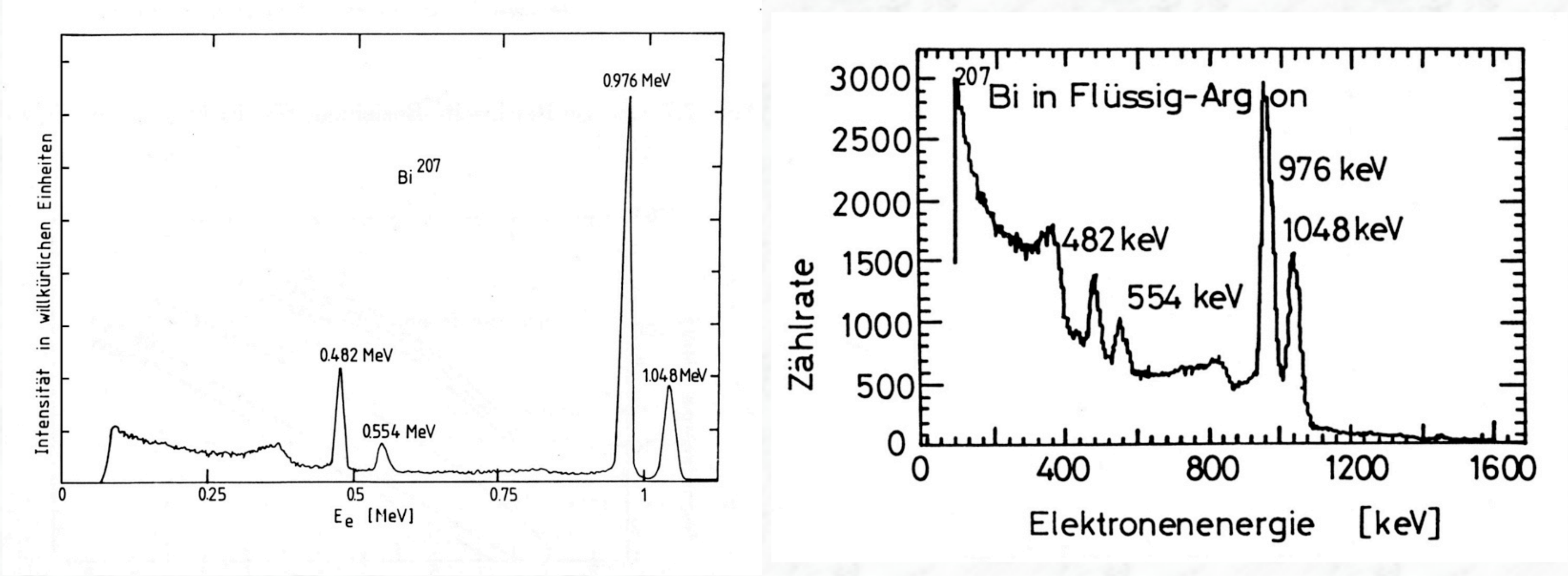
$$\Delta E / E \sim \sqrt{N} / N = 1 / \sqrt{N}$$

$$(\Delta E / E)_{HLZ} / (\Delta E / E)_{Szintll} = (\sqrt{E} / 700\ \mathrm{eV}) / (\sqrt{E} / 3\ \mathrm{eV}) = 6\ 10^{-2}$$



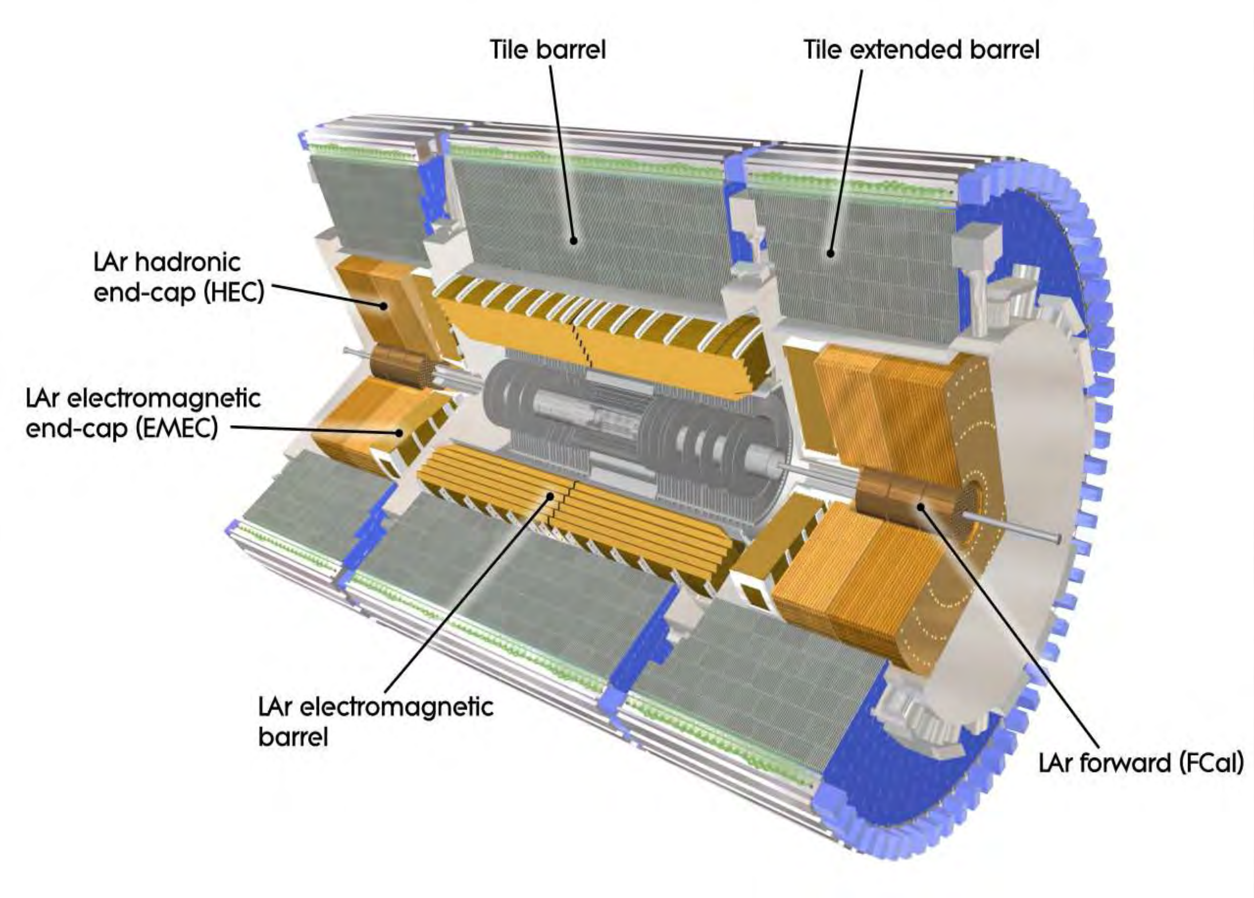
Vergleich des ^{60}Co- γ-Spektrums, aufgenommen mit einem NaJ(Tl)-Szintillator und einem Ge-Halbleiterdetektor [Ref. C. Grupen]

Einige Beispiele von gemessenen Elektron-Spektren



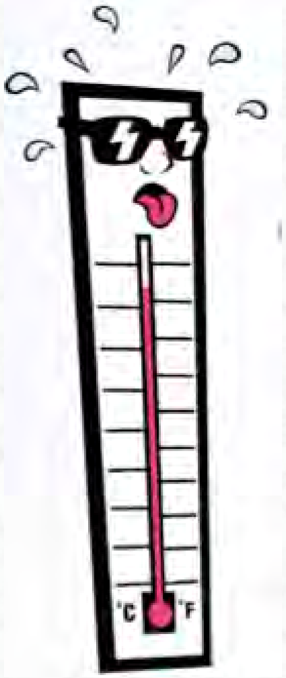
Gemessene Spektren von ^{207}Bi Konversionselektronen mit einem Si(Li) Halbleiterzähler (links) und einem Flüssig-Argon-Ionisationsdetektor (rechts) [Ref. C. Grupen]

6.3 Energiemessung in Kalorimetern



Kalorimetersystem des ATLAS-Experiments

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 $\sim 10^{8}$ J

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

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

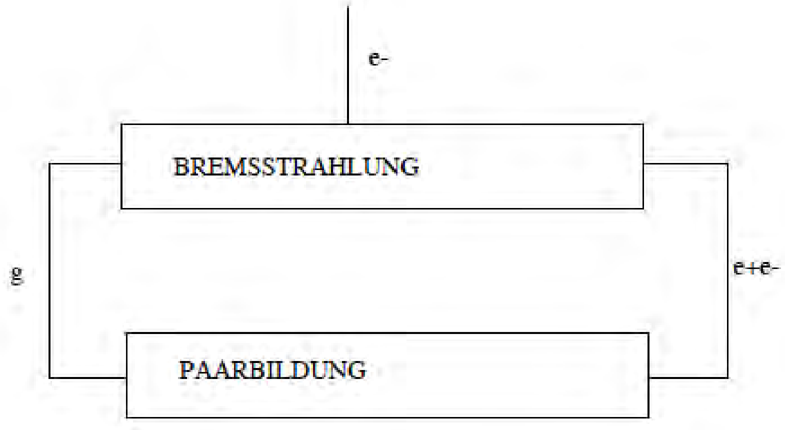
  worse for sampling calorimeters as compared to homogeneous calorimeters
- Uniformity of the energy response to different particles (e/h response)

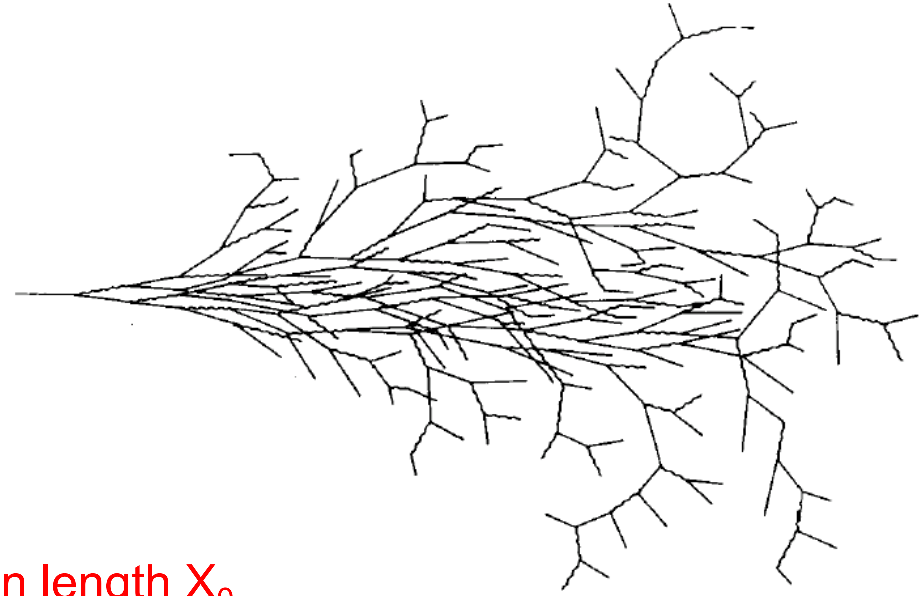
  in general: response of calorimeters is different to so called electromagnetic particles (e, γ) and hadrons (h)

6.3.1 Electromagnetic showers

- Particle showers created by electrons/positrons or photons are called electromagnetic 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 the 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

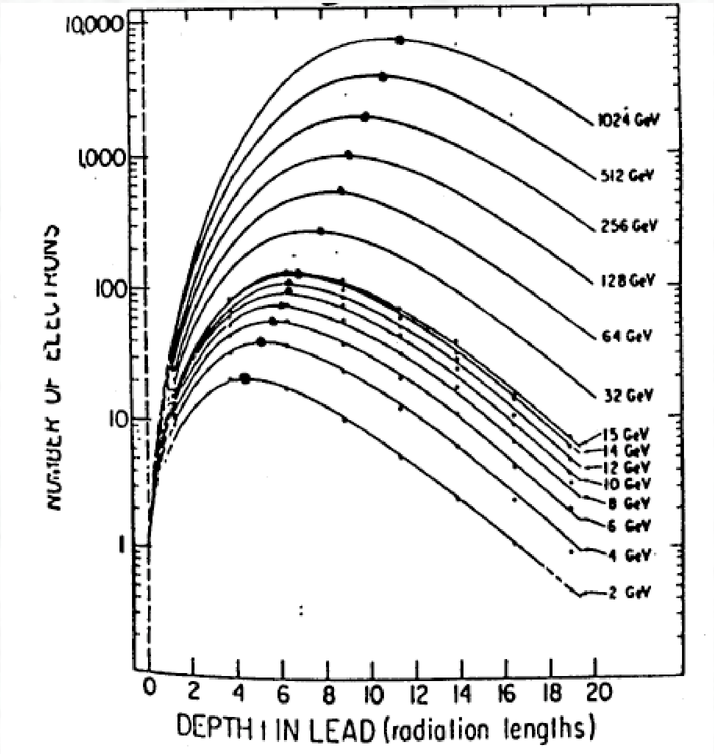
Longitudinal shower parametrization (t [X_0] = thickness in units of X_0)

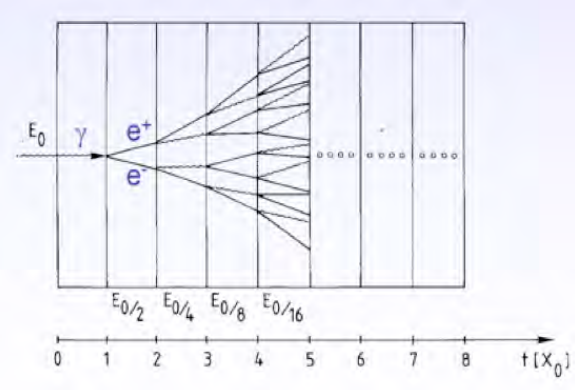
$$\frac{dE}{dt} = const \cdot t^a \cdot e^{-bt}$$

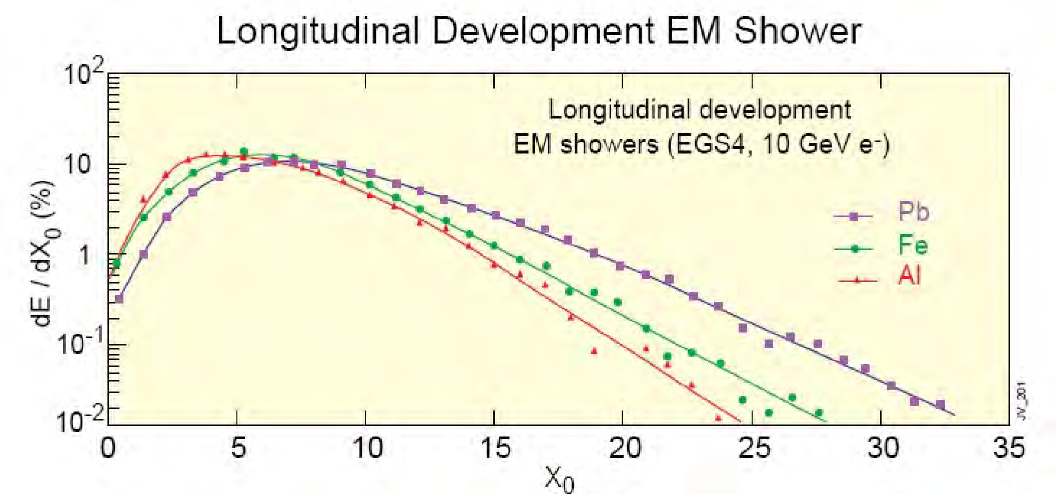
Shower depth (shower maximum) scales logarithmically with particle energy !

→ size of calorimeters growth
only logarithmically with energy.

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







Lateral shower profile:

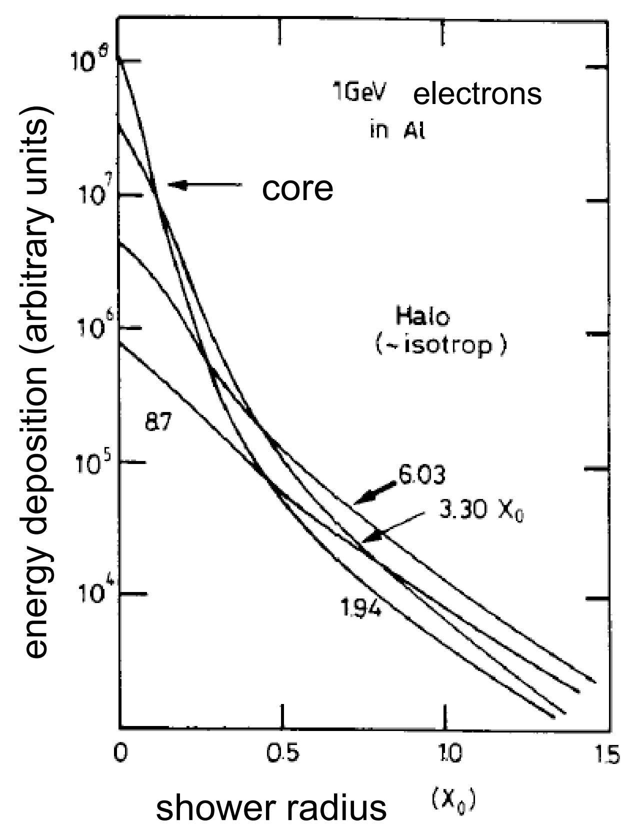
- The lateral shower profile is dominated by two processes:
  - Multiple Coulomb scattering
  - Relatively long free path length of low energy photons

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

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

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

in general well collimated !



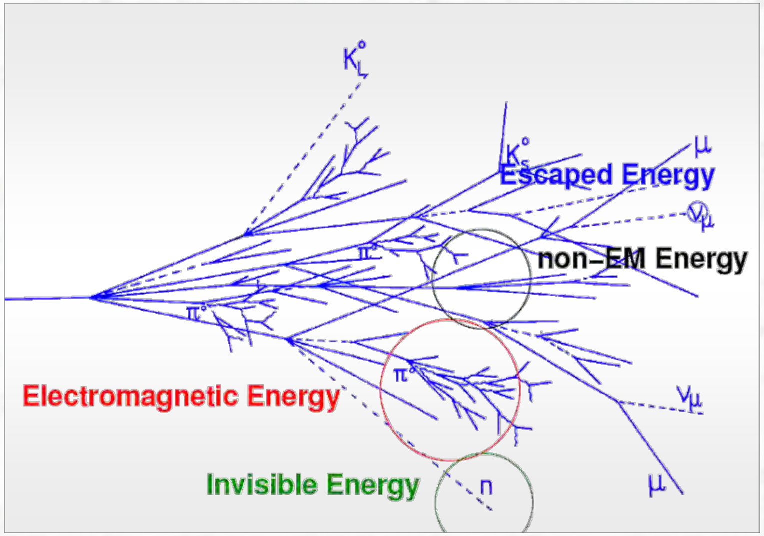
Example: E_0 = 100 GeV in lead glass

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

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

6.3.2 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

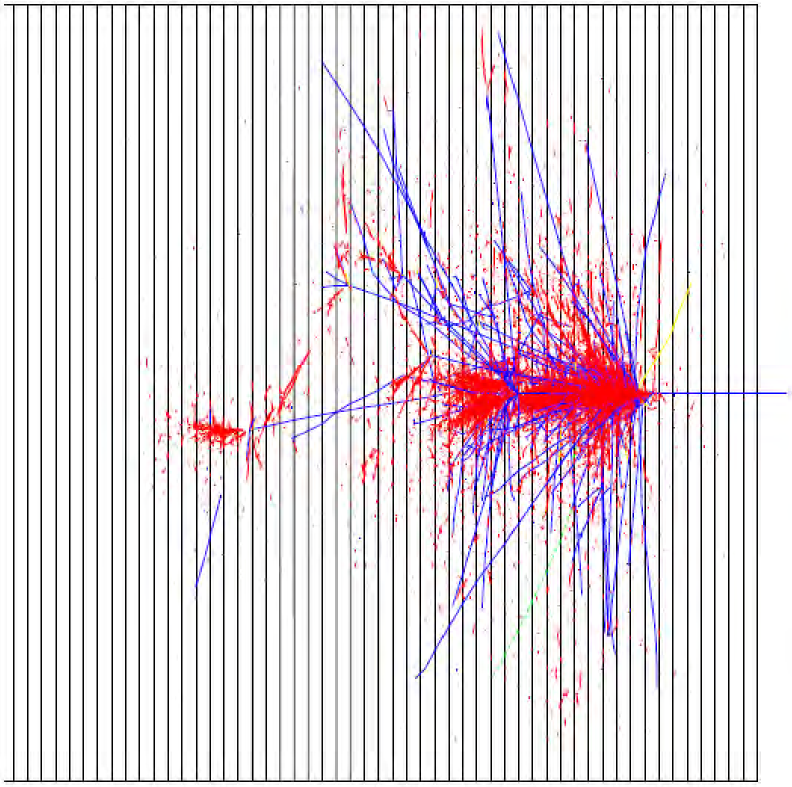
  The interaction of neutrons depends strongly on their energy;
  Extreme cases:
    - Nuclear reaction, e.g. nuclear fission → energy recovered
    - Escaping the calorimeter (undergo only elastic scattering, without inelastic interaction)

- 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

1.



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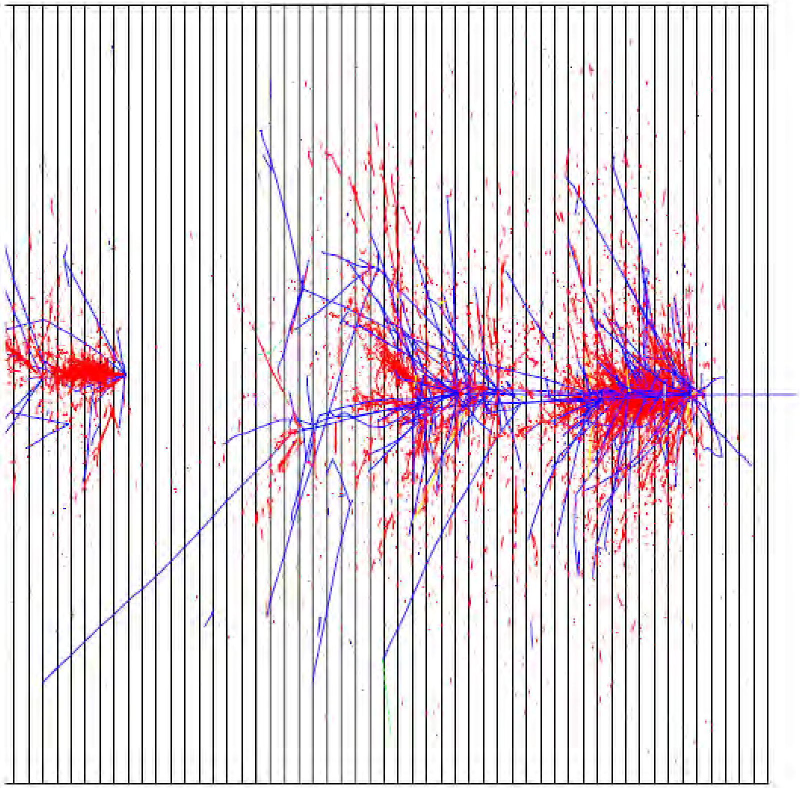


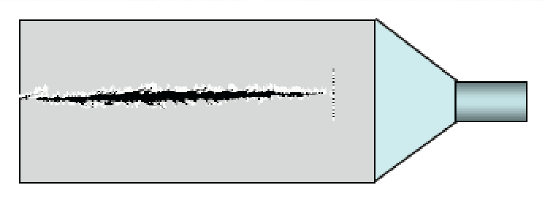
Red: electromagnetic component
Blue: charged hadron component

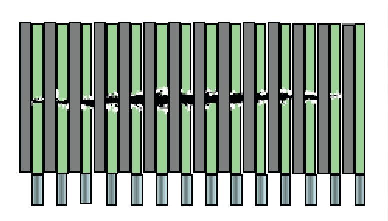
Hadronic showers show very large fluctuations from one event to another
→ the energy resolution is worse than for electromagnetic showers

6.3.3 Layout and readout of calorimeters

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

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

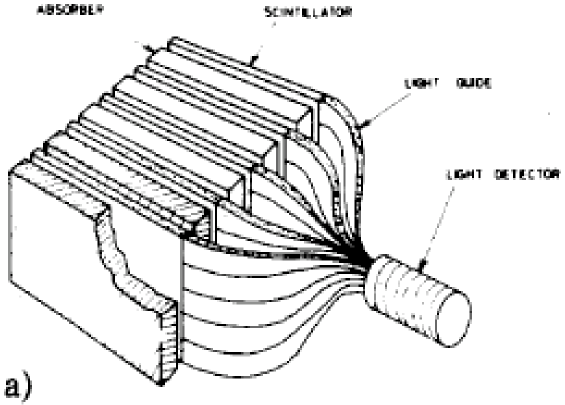




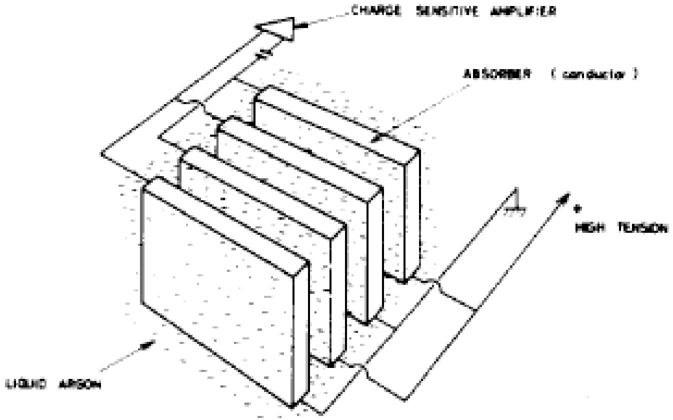
- Examples for homogeneous calorimeters:
    - NaJ or other crystals (Scintillation light)
    - Lead glass (Cherenkov light)
    - Liquid argon or liquid krypton calorimeters (Ionization charge)

- 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

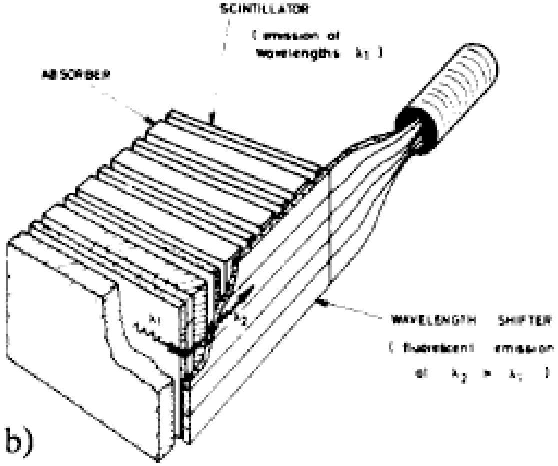
Examples for sampling calorimeters



a)



c)



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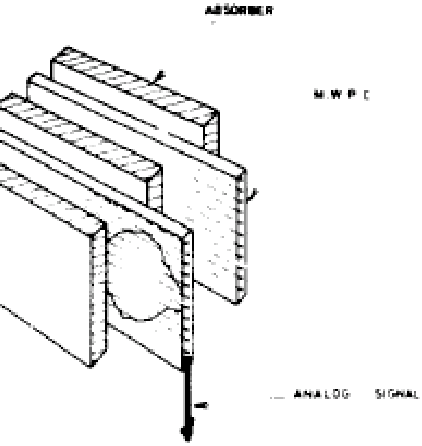


d)

(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

6.3.4 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:

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

- 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:

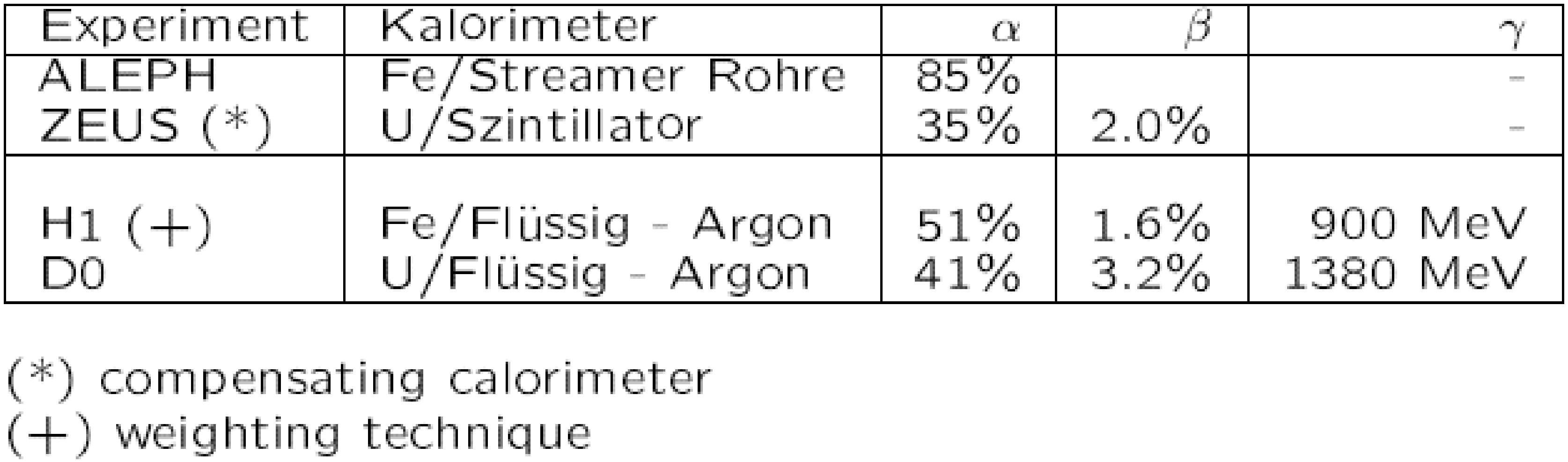
Experiment	Calorimeter	α	β	γ
L3	BGO	< 2.0%	0.3%	
BaBar	CsI (Tl)	(*) 1.3%	2.1%	0.4 MeV
OPAL	Lead glass	(**) 5% (++) 3%		
NA48	Liquid krypton	3.2%	0.5%	125 MeV
UA2	Pb /Szintillator	15%	1.0%	
ALEPH	Pb / Prop.chamb.	18%	0.9%	
ZEUS	U / Szintillator	18%	1.0%	
H1	Pb / Liquid argon	11.0%	0.6%	154 MeV
D0	U /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

homogeneous calorimeters (L3, BaBar, OPAL, NA48)

sampling calorimeters (UA2, ALEPH, ZEUS, H1, D0)

(*) scaling according to $E^{-1/4}$ rather than $E^{-1/2}$
(**) at 10 GeV
(++) at 45 GeV

hadronic energy resolutions:



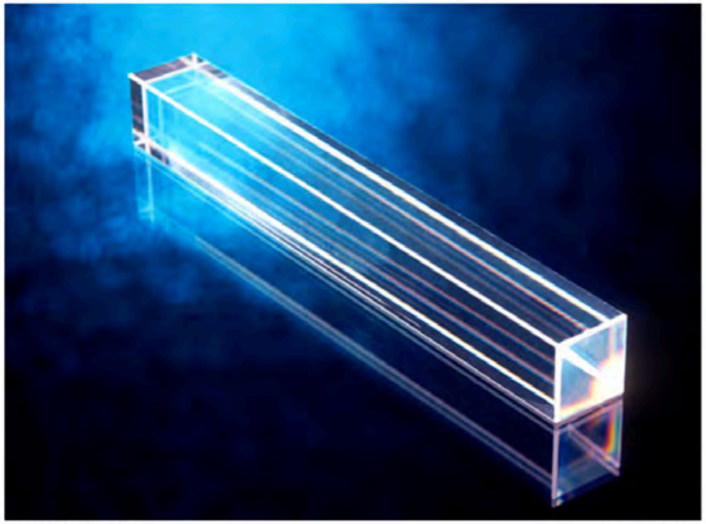
Experiment	Kalorimeter	α	β	γ
ALEPH	Fe/Streamer Rohre	85%		-
ZEUS (*)	U/Szintillator	35%	2.0%	-
H1 (+)	Fe/Flüssig - Argon	51%	1.6%	900 MeV
D0	U/Flüssig - Argon	41%	3.2%	1380 MeV

(*) 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)

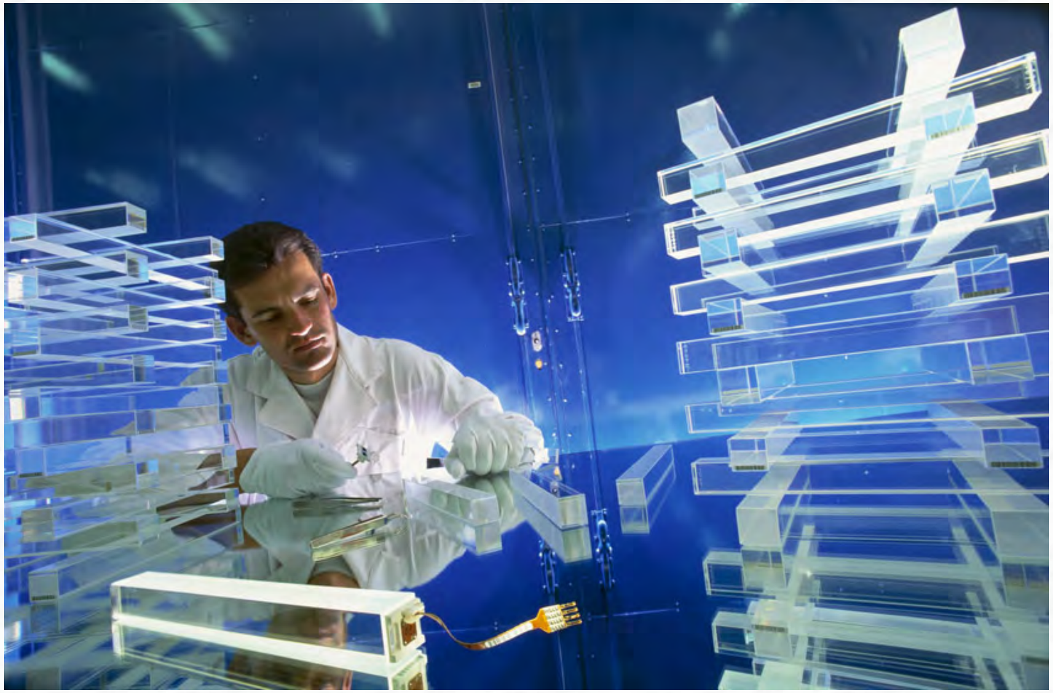
  physical processes: - energy recovery from nuclear fission, initiated
  by slow neutrons (uranium calorimeters)
  - transfer energy from neutrons to protons (same mass)
  use hydrogen enriched materials / free protons

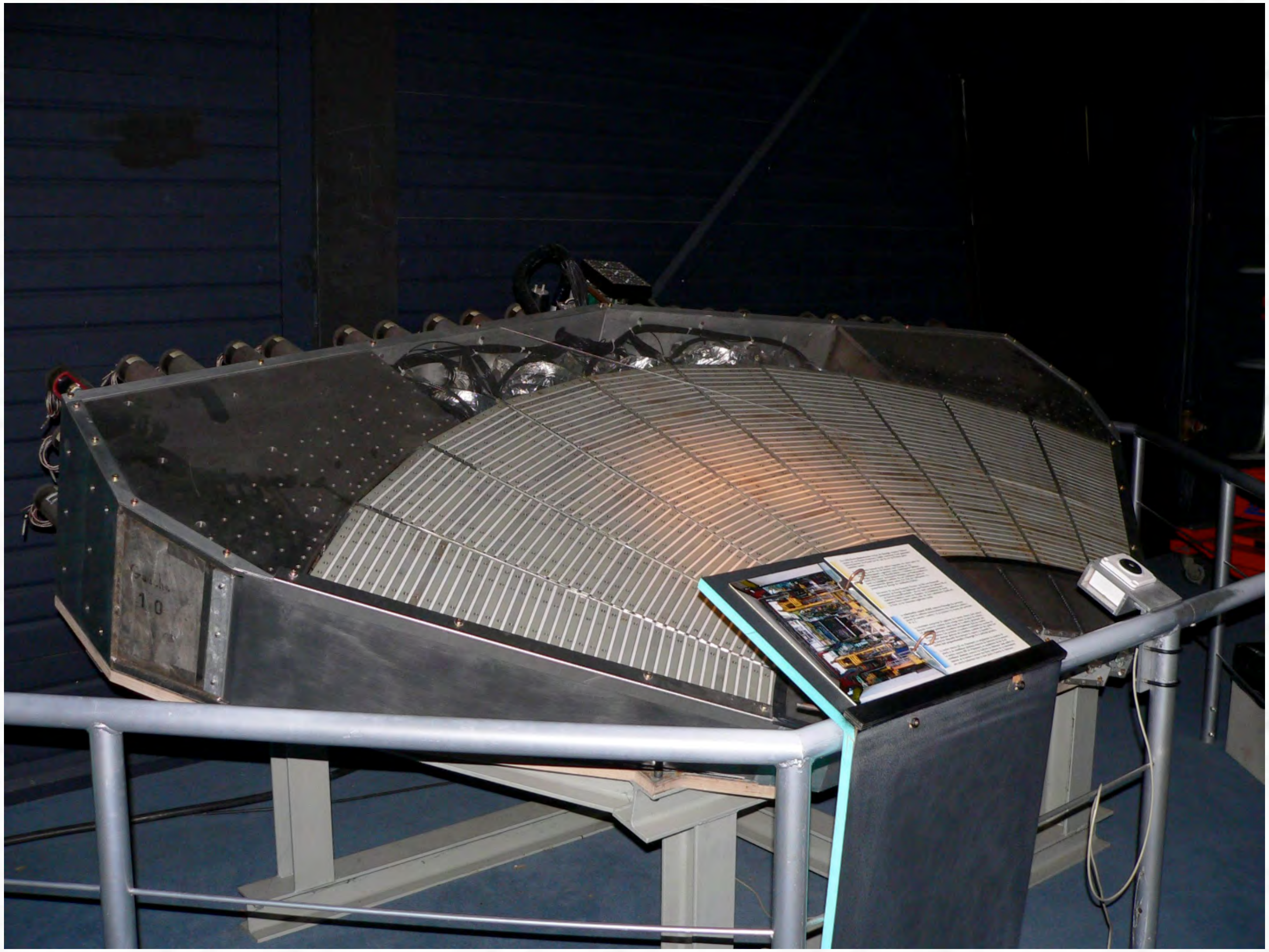


Blei-Wolframat Kristall

Quelle: CERN

Blei-Wolframat-Szintillatorkristalle zur Energiemessung im CMS-Experiment am LHC





Kalorimeter des UA2-Experiments mit Plastikszintillatoren als aktivem Material