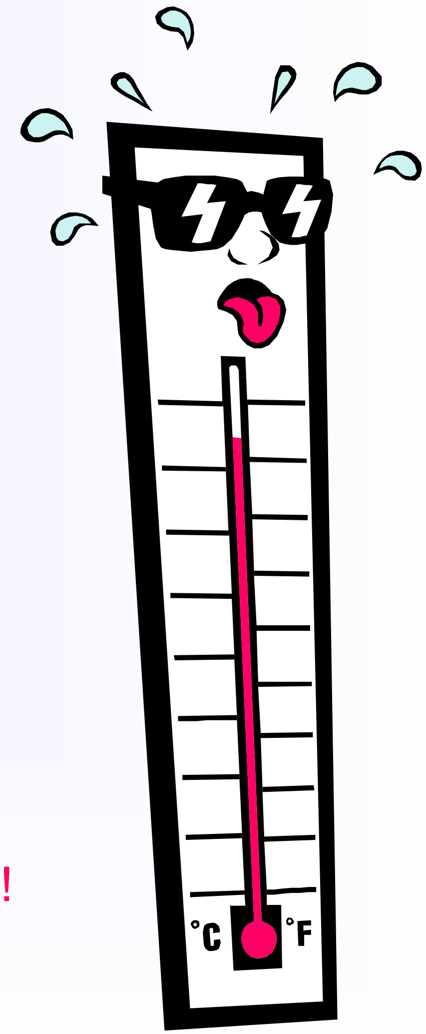
Outline

- **Lecture 1 - Introduction** — C. Joram, L. Ropelewski
- **Lecture 2 - Tracking Detectors** — L. Ropelewski, M. Moll
- **Lecture 3 - Scintillation and Photodetection** — C. D'Ambrosio, T. Gys
- **Lecture 4 – Calorimetry** — C. Joram
  - Calorimetry - Basic principles
    - Interaction of charged particles and photons
    - Electromagnetic cascades
    - Nuclear interactions
    - Hadronic cascades
  - Homogeneous calorimeters
  - Sampling calorimeters
- **Lecture 5 - Particle ID, Detector Systems** — C. Joram, C. D'Ambrosio

Calorimetry

Calorimetry = Energy measurement by total absorption, usually combined with spatial reconstruction.

latin: calor = heat



- LHC beam: Total stored beam energy
  $E = 10^{14}$ protons $\times$ $14 \cdot 10^{12}$ eV $\approx 1 \cdot 10^{8}$ J

- Which mass of water M_{water} could one heat up (ΔT = 100 K) with this amount of energy (c_{water} = 4.18 J g^{-1} K^{-1}) ?
  $M_{water} = E / (c\Delta T) =$ 239 kg

- What is the effect of a 1 GeV particle in 1 liter water (at 20° C)?
  $\Delta T = \mathrm{E} / (\mathrm{c} \cdot M_{water})$ = $3.8 \cdot 10^{-14}$ K !

There must be more sensitive methods than measuring ΔT !

Calorimetry

- Basic mechanism for calorimetry in paricle physics: formation of
  - ⇨ electromagnetic
  - ⇨ or hadronic showers.

- Finally, the energy is converted into ionization or excitation of the matter.

Charge

Scintillation light

Cerenkov light

- Calorimetry is a “destructive” method. The energy and the particle get absorbed!

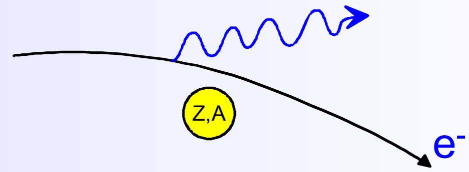
- Detector response $\propto$ E

- Calorimetry works both for
  - ⇨ charged ($e^{\pm}$ and hadrons) → Complementary information to p-measurement
  - ⇨ and neutral particles (n,γ) → Only way to get direct kinematical information for neutral particles

Interaction of charged particles

Energy loss by Bremsstrahlung

Radiation of real photons in the Coulomb field of the nuclei of the absorber medium



$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} z^2 \left(\frac{1}{4\pi\varepsilon_0} \frac{e^2}{mc^2} \right)^2 E \ln \frac{183}{Z^{1/3}} \propto \frac{E}{m^2}$$

Effect plays a role only for $e^{\pm}$ and ultra-relativistic μ (>1000 GeV)

For electrons: $$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 E \ln \frac{183}{Z^{1/3}}$$

$$-\frac{dE}{dx} = \frac{E}{X_0} \quad \Longrightarrow \quad E = E_0 e^{-x/X_0}$$

$$X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln \frac{183}{Z^{1/3}}}$$

radiation length [g/cm^2]

(divide by specific density to get X_0 in cm)

Interaction of charged particles

- **Critical energy E_c**

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

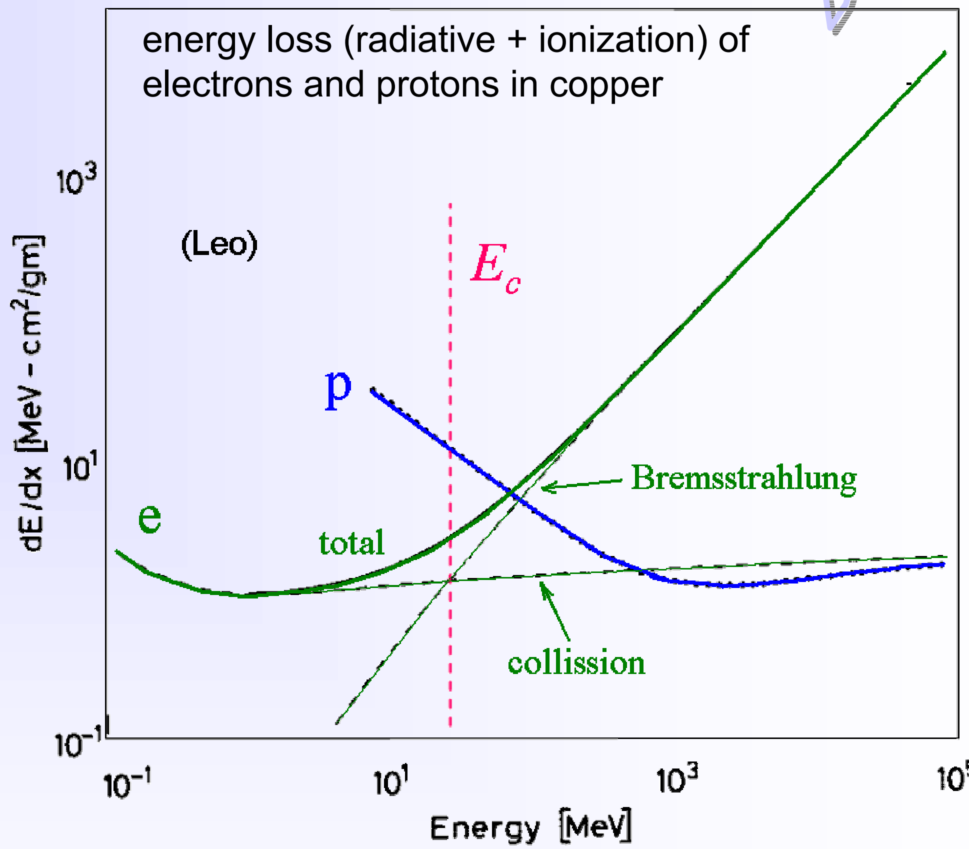
For electrons one finds approximately:

$$E_c^{solid+liq} = \frac{610 MeV}{Z+1.24} \qquad E_c^{gas} = \frac{710 MeV}{Z+1.24}$$

$E_c(e^-)$ in Cu(Z=29) = 20 MeV

For muons $E_c \approx E_c^{elec}\left(\frac{m_\mu}{m_e}\right)^2$

$E_c(\mu)$ in Cu $\approx$ 1 TeV

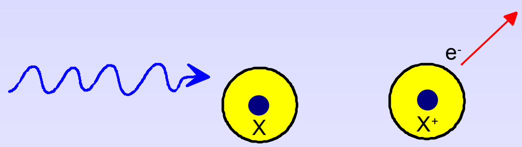


Unlike electrons, muons in multi-GeV range can traverse thick layers of dense matter.
Find charged particles traversing the calorimeter ? → most likely a muon → Particle ID

Interaction of photons

In order to be detected, a photon has to create charged particles and / or transfer energy to charged particles

- **Photo-electric effect:** (already met in photocathodes of photodetectors)



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

Only possible in the close neighborhood of a third collision partner → photo effect releases mainly electrons from the K-shell.

Cross section shows strong modulation if $E_\gamma \approx E_{shell}$

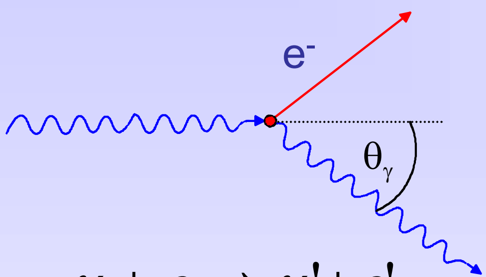
$$\sigma^K_{photo} = \left(\frac{32}{\varepsilon^7}\right)^{\frac{1}{2}} \alpha^4 Z^5 \sigma^e_{Th} \qquad \varepsilon = \frac{E_\gamma}{m_e c^2} \qquad \sigma^e_{Th} = \tfrac{8}{3}\pi r_e^2 \quad \text{(Thomson)}$$

At high energies (ε>>1)

$$\sigma^K_{photo} = 4\pi r_e^2 \alpha^4 Z^5 \frac{1}{\varepsilon} \qquad \boxed{\sigma_{photo} \propto Z^5}$$

Interaction of photons

- **Compton scattering:**



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

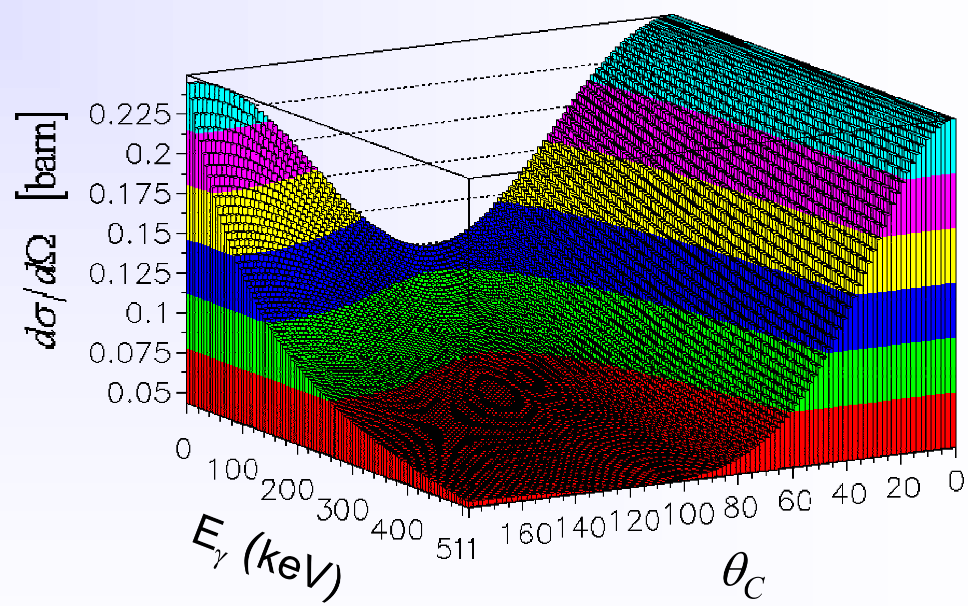
$$E_e = E_\gamma - E'_\gamma$$

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

Assume electron as quasi-free.

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

Compton cross-section (Klein-Nishina)



At high energies approximately

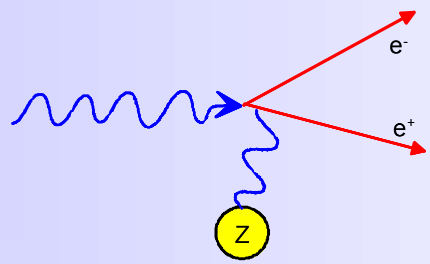
$$\sigma_c^e \propto \frac{\ln\varepsilon}{\varepsilon}$$

Atomic Compton cross-section:

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

Interaction of photons

Pair production



$$\gamma + nucleus \rightarrow e^+e^- + nucleus$$

Only possible in the Coulomb field of a nucleus (or an electron) if $E_\gamma \geq 2m_ec^2$

Cross-section (high energy approximation)

$$\sigma_{pair} \approx 4\alpha r_e^2 Z^2 \left(\frac{7}{9} \ln \frac{183}{Z^{\frac{1}{3}}} \right)$$

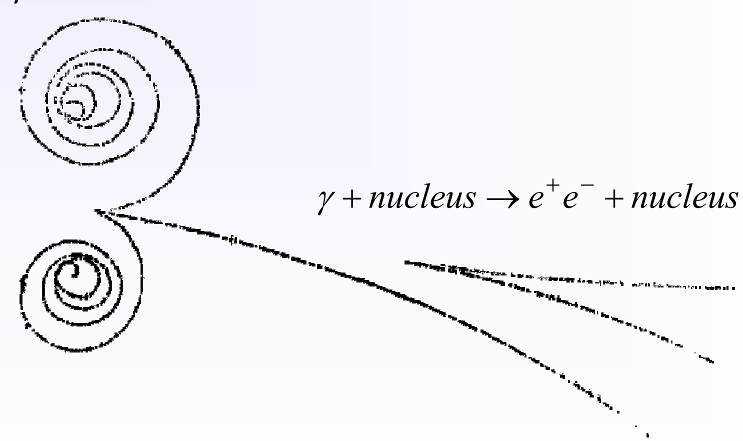
independent of energy !

$$\approx \frac{7}{9} \frac{A}{N_A} \frac{1}{X_0}$$

$$\approx \frac{A}{N_A} \frac{1}{\lambda_{pair}}$$

$$\lambda_{pair} = \frac{9}{7} X_0$$

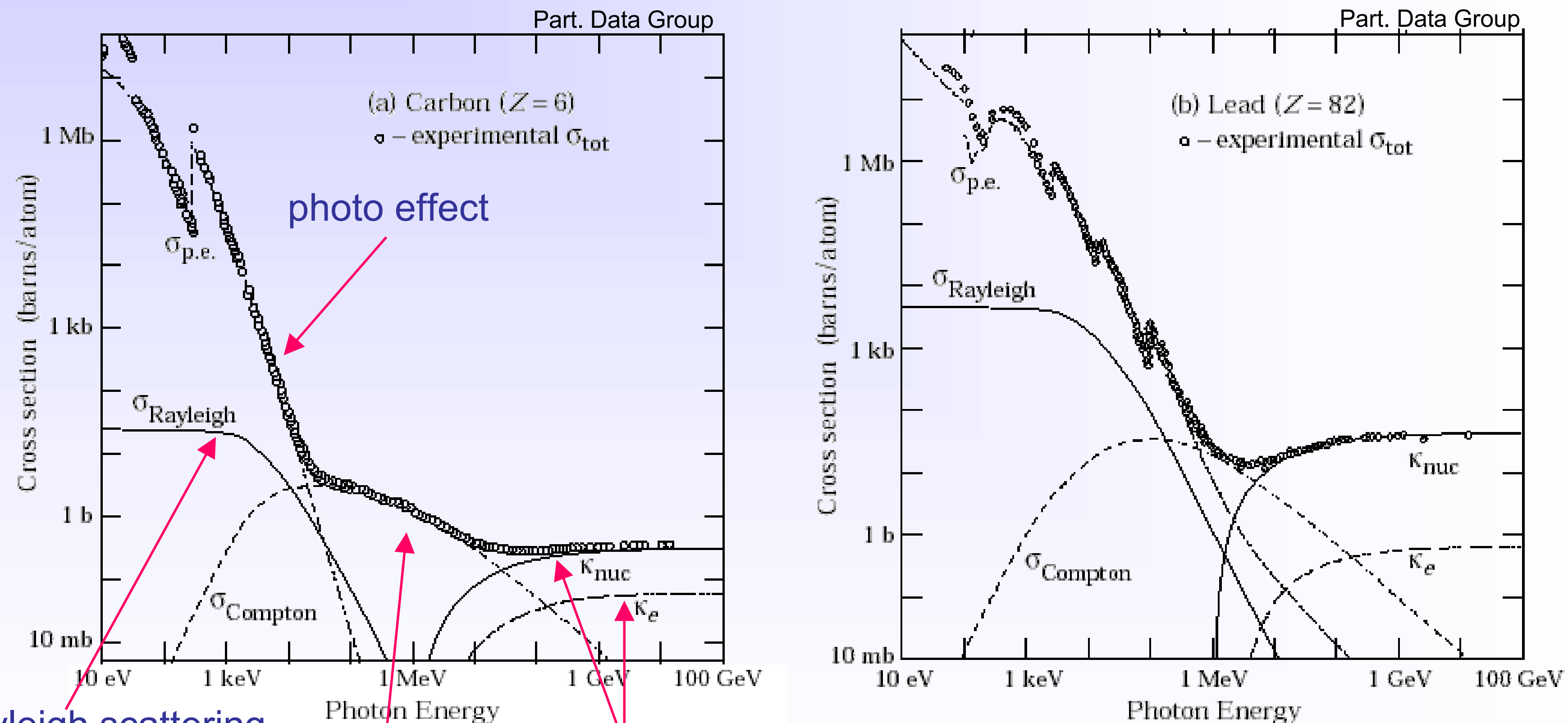
Energy sharing between e+ and e- becomes asymmetric at high energies.



Interaction of photons

In summary: $I_\gamma = I_0 e^{-\mu x}$

μ: mass attenuation coefficient $\mu_i = \frac{N_A}{A}\sigma_i \quad \left[cm^2/g\right]$ $\quad \mu = \mu_{photo} + \mu_{Compton} + \mu_{pair} + \ldots$



Rayleigh scattering (no energy loss !)

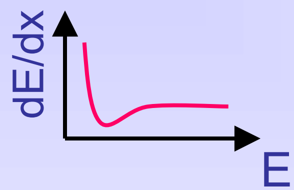
pair production

Compton scattering

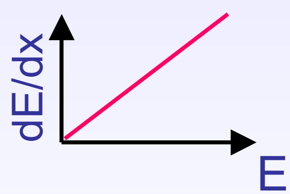
Reminder: basic electromagnetic interactions

e^+ / e^-

- Ionisation

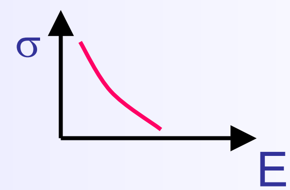


- Bremsstrahlung

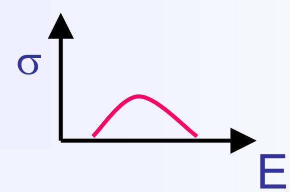


γ

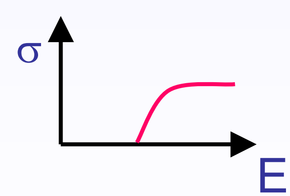
- Photoelectric effect



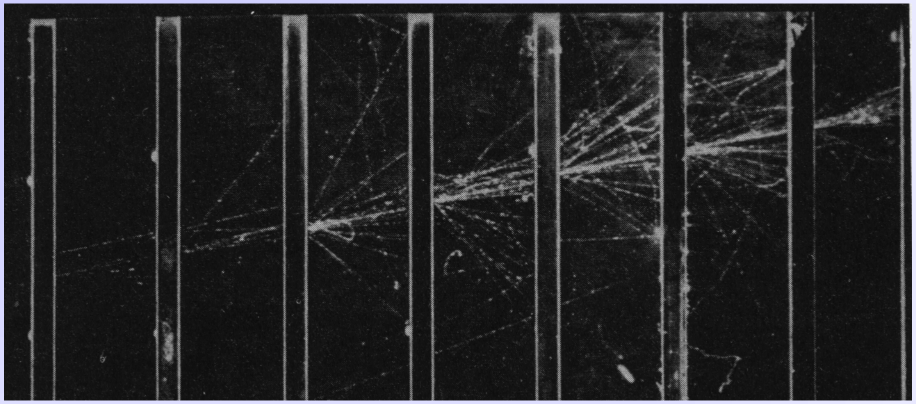
- Compton effect



- Pair production

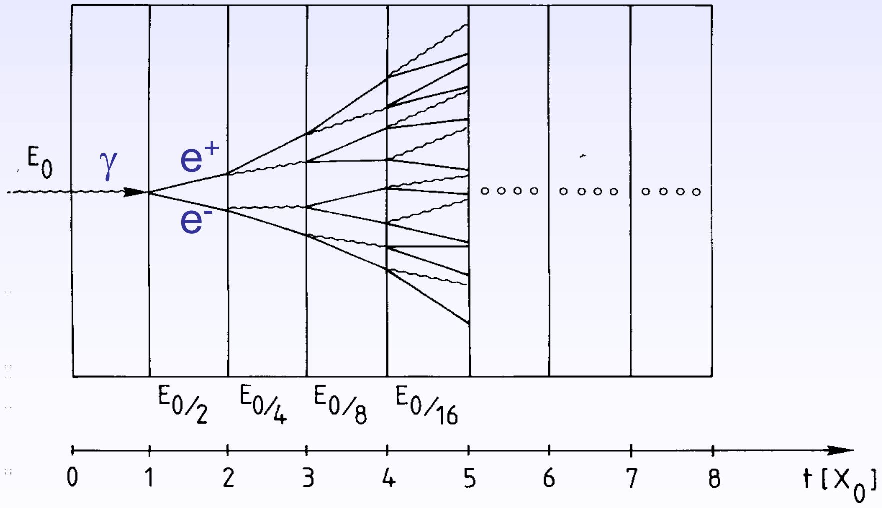


Electromagnetic cascades (showers)



Electron shower in a cloud chamber with lead absorbers

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.

Electromagnetic cascades

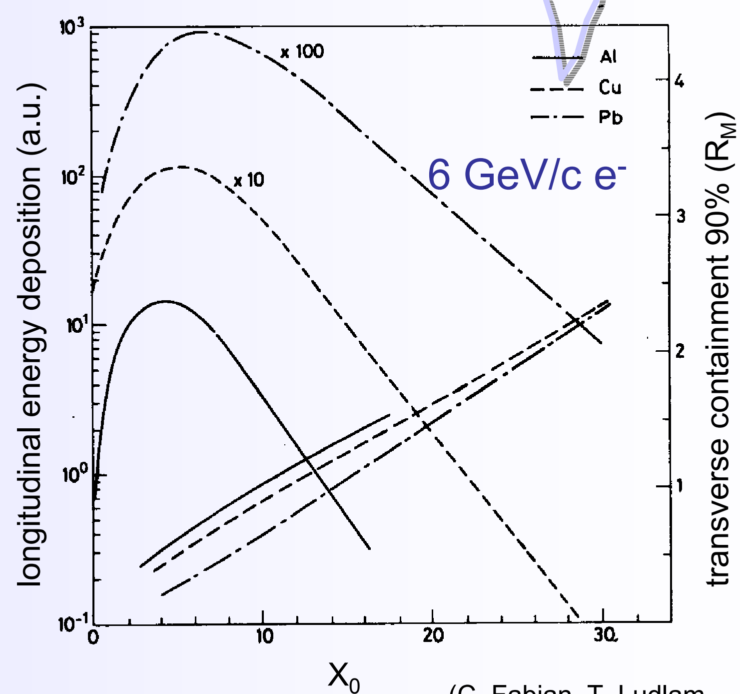
Longitudinal shower development

$$\frac{dE}{dt} \propto t^{\alpha} e^{-t}$$

Shower maximum at $t_{\max} = \ln \frac{E_0}{E_c} \frac{1}{\ln 2}$

95% containment $t_{95\%} \approx t_{\max} + 0.08Z + 9.6$

Size of a calorimeter grows only logarithmically with E_0



(C. Fabjan, T. Ludlam, CERN-EP/82-37)

Transverse shower development

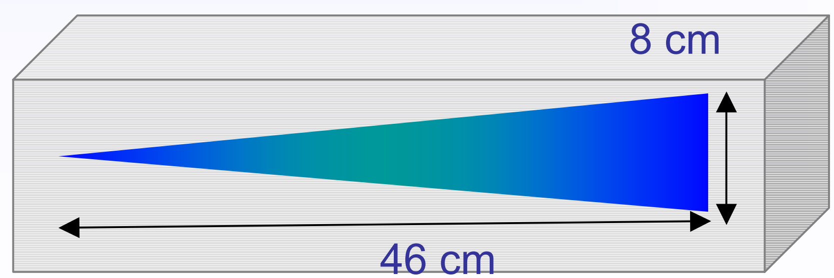
95% of the shower cone is located in a cylinder with radius 2 R_M

Molière radius $R_M = \frac{21\,\mathrm{MeV}}{E_c} X_0 \quad [g/cm^2]$

Example: E_0 = 100 GeV in lead glass

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

X_0 ≈ 2 cm, R_M = 1.8·X_0 ≈ 3.6 cm



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Energy resolution of a calorimeter

$N^{total} \propto \frac{E_0}{E_c}$ total number of track segments

$T \propto \frac{E_0}{E_c} X_0$ total track length

$T_{det} = F(\xi) T \qquad \zeta \propto \frac{E_{cut}}{E_c}$ detectable track length (above energy E_{cut})

$\frac{\sigma(E)}{E} \propto \frac{\sigma(T_{det})}{T_{det}} \propto \frac{1}{\sqrt{T_{det}}} \propto \frac{1}{\sqrt{E_0}}$ holds also for hadron calorimeters

More general: $$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

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

stochastic term
(see above)

'constant term'

- inhomogenities
- bad cell inter-calibration
- non-linearities

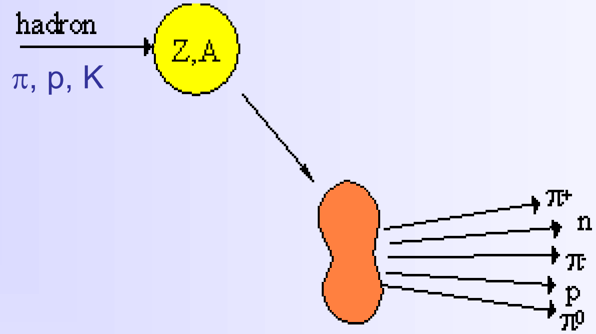
↓ Quality factor !

'noise term'

- Electronic noise
- radioactivity
- pile up

Nuclear Interactions

The interaction of energetic hadrons (charged or neutral) with matter is determined by inelastic nuclear processes.



Excitation and finally break-up of nucleus $\rightarrow$ nucleus fragments + production of secondary particles.

multiplicity $\propto \ln(E)$

$p_t \approx 0.35$ GeV/c

For high energies (>1 GeV) the cross-sections depend only little on the energy and on the type of the incident particle (π, p, K…).

$$\sigma_{inel} \approx \sigma_0 A^{0.7} \qquad \sigma_0 \approx 35\ mb$$

In analogy to X_0 a hadronic absorption length can be defined

$$\lambda_a = \frac{A}{N_A \sigma_{inel}} \propto A^{\frac{1}{4}} \quad \text{because } \sigma_{inel} \approx \sigma_0 A^{0.7}$$

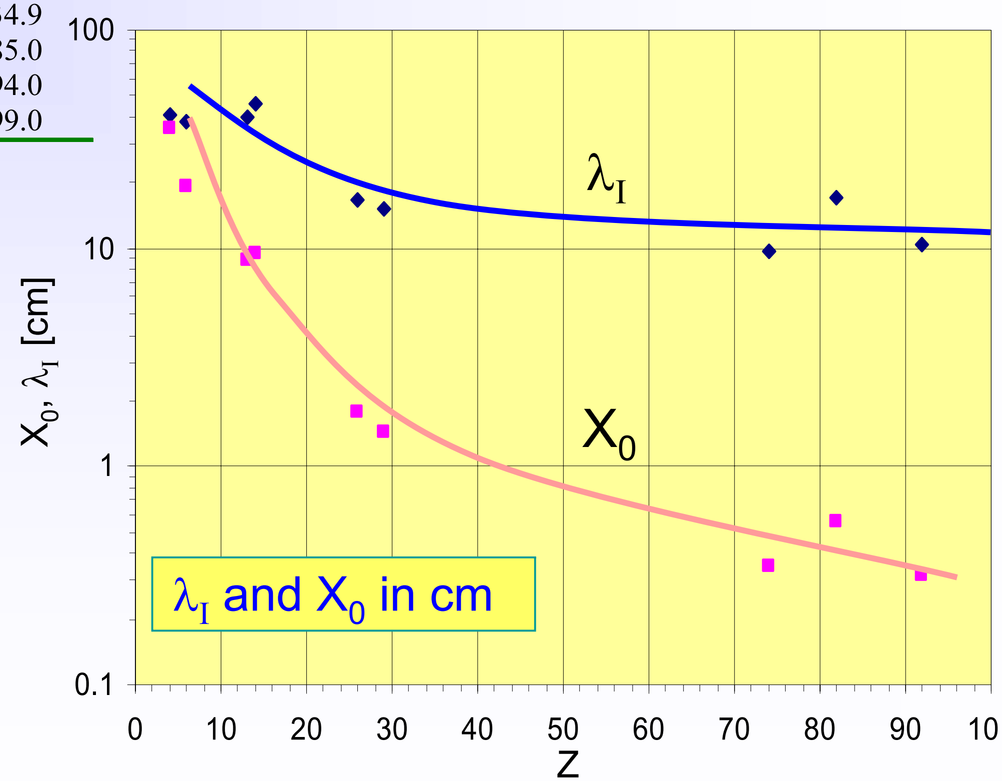
similarly a hadronic interaction length

$$\lambda_I = \frac{A}{N_A \sigma_{total}} \propto A^{\frac{1}{3}} \qquad \lambda_I < \lambda_a$$

Interaction of charged particles

Material	Z	A	ρ [g/cm^3]	X_0 [g/cm^2]	λ_I [g/cm^2]
Hydrogen (gas)	1	1.01	0.0899 (g/l)	63	50.8
Helium (gas)	2	4.00	0.1786 (g/l)	94	65.1
Beryllium	4	9.01	1.848	65.19	75.2
Carbon	6	12.01	2.265	43	86.3
Nitrogen (gas)	7	14.01	1.25 (g/l)	38	87.8
Oxygen (gas)	8	16.00	1.428 (g/l)	34	91.0
Aluminium	13	26.98	2.7	24	106.4
Silicon	14	28.09	2.33	22	106.0
Iron	26	55.85	7.87	13.9	131.9
Copper	29	63.55	8.96	12.9	134.9
Tungsten	74	183.85	19.3	6.8	185.0
Lead	82	207.19	11.35	6.4	194.0
Uranium	92	238.03	18.95	6.0	199.0

For Z > 6: $\lambda_I > X_0$



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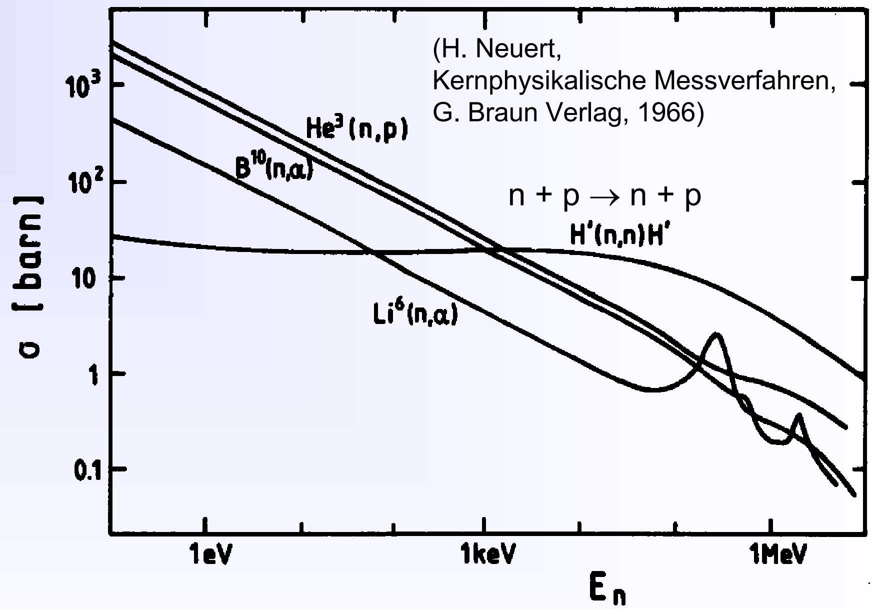
Interaction of neutrons and neutrinos

Interaction of neutrons

Neutrons have no charge, i.e. their interaction is based only on strong (and weak) nuclear force. To detect neutrons, we have to create charged particles.
Possible neutron conversion and elastic reactions …

$n + {}^{6}Li \rightarrow \alpha + {}^{3}H$
$n + {}^{10}B \rightarrow \alpha + {}^{7}Li$
$n + {}^{3}He \rightarrow p + {}^{3}H$
} $E_n < 20$ MeV

$n + p \rightarrow n + p$ $E_n < 1$ GeV



E_n
- high energy
- 100 MeV
- fast
- 100 keV
- epithermal
- 10^{-1} eV
- 10^{-2} eV — thermal
- 10^{-3} eV
- cold
- ultracold

In addition there are …

- neutron induced fission $E_n \approx E_{th} \approx 1/40$ eV
- inelastic reactions → hadronic cascades (see below) $E_n > 1$ GeV

Interaction of neutrons and neutrinos

Interaction of neutrinos

Neutrinos interact only weakly → tiny cross-sections. For their detection we need again first a charged particle. Possible detection reactions:

$\nu_\ell + n \rightarrow \ell^- + p \qquad \ell = e, \mu, \tau$

$\bar{\nu}_\ell + p \rightarrow \ell^+ + n \qquad \ell = e, \mu, \tau$

The cross-section for the reaction $\nu_e + n \rightarrow e^- + p$ is of the order of 10^{-43} cm^2 (per nucleon, $E_\nu \approx$ few MeV).

→ detection efficiency $\varepsilon_{\det} = \sigma \cdot N^{surf} = \sigma \cdot \rho \frac{N_A}{A} d$

1 m Iron: $\varepsilon_{\det} \approx 5 \cdot 10^{-17}$

1 km water: $\varepsilon_{\det} \approx 6 \cdot 10^{-15}$

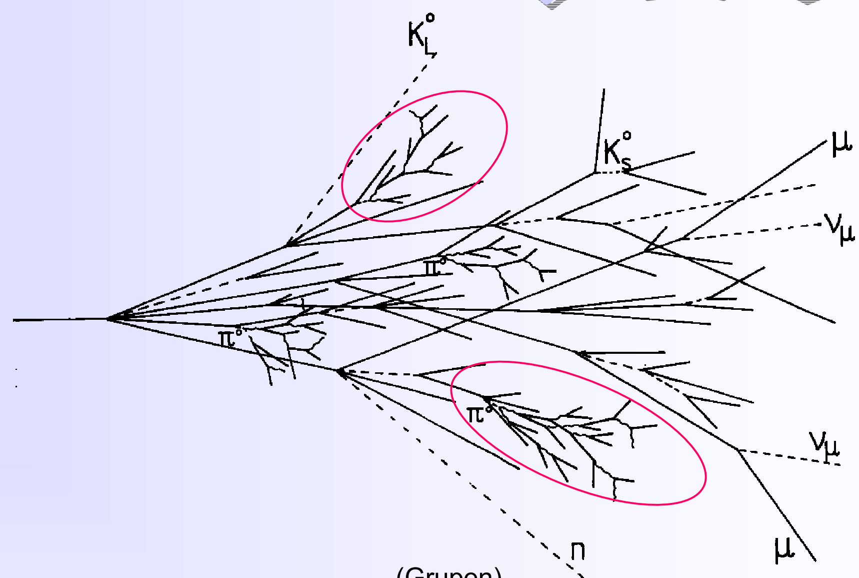
Neutrino detection requires big and massive detectors (ktons - Mtons) and very high neutrino fluxes (e.g. 10^{20} ν / yr).

In collider experiments fully hermetic detectors allow to detect neutrinos indirectly:

- sum up all visible energy and momentum.
- attribute missing energy and momentum to neutrino.

Hadronic cascades

Various processes involved.
Much more complex than
electromagnetic cascades.



(Grupen)

A hadronic shower contains two components:

hadronic **+** **electromagnetic**

- charged hadrons p, $\pi^{\pm}$, $K^{\pm}$,
- nuclear fragmets ….
- breaking up of nuclei (binding energy)
- neutrons, neutrinos, soft γ's, muons

neutral pions $\to 2\gamma$

$\to$ electromagnetic cascades

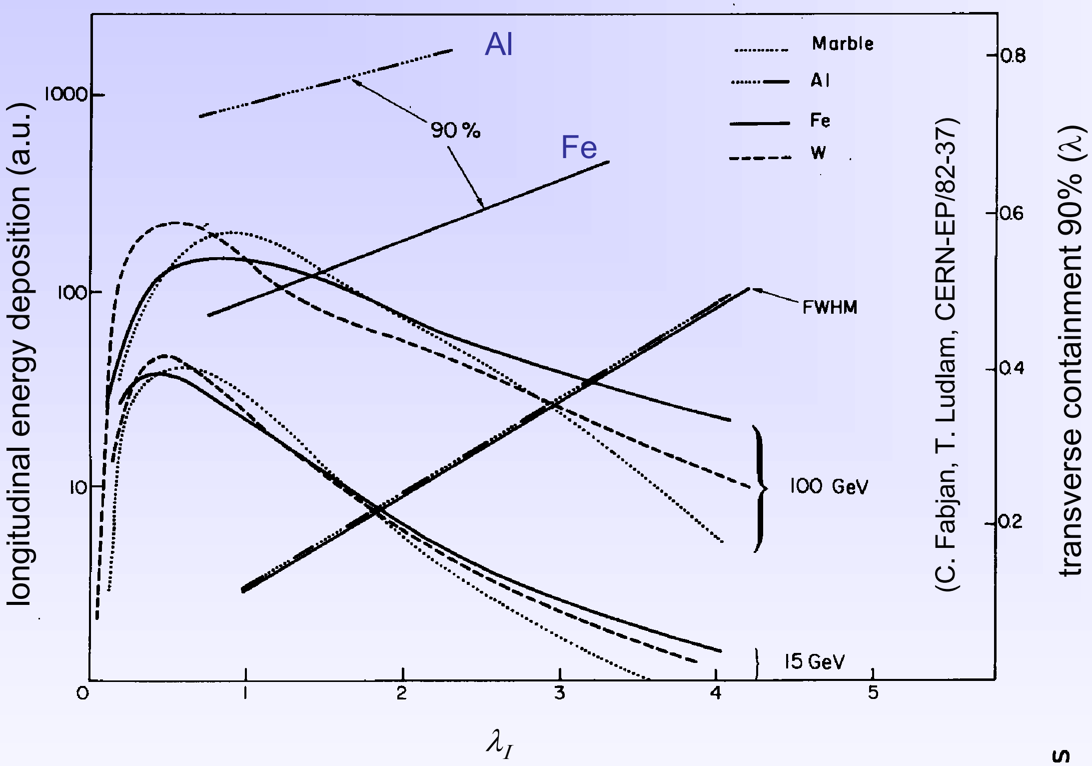
$$n(\pi^0) \approx \ln E(GeV) - 4.6$$

example $E = 100$ GeV: $n(\pi^0) \approx 18$

invisible energy $\to$ large energy fluctuations $\to$ limited energy resolution

Hadronic cascades

- Longitudinal shower development



$$t_{\max}[\lambda_I] \approx 0.2 \ln E[GeV] + 0.7$$
$$t_{95\%}[cm] \approx a \ln E + b$$

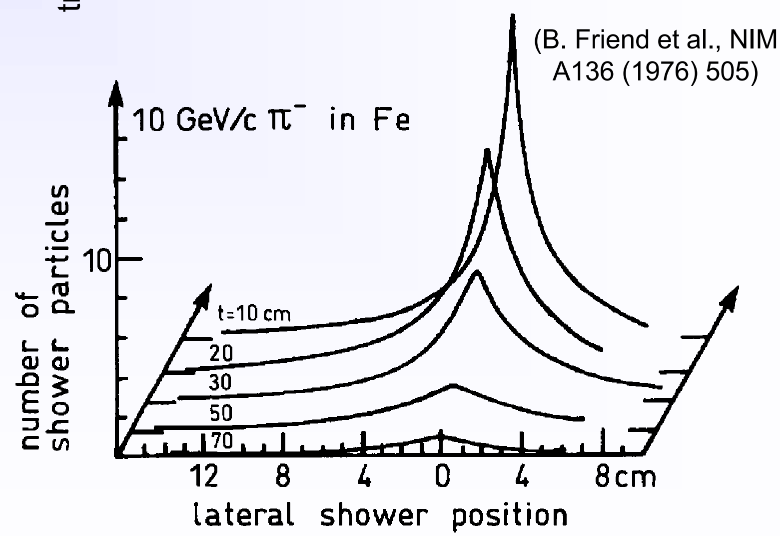
Ex.: 100 Gev in iron (λ_i =16.7 cm)

a = 9.4, b = 39

→ t_{max} = 1.6 λ_i = 27 cm

→ $t_{95\%}$ = 4.9 λ_i = 80 cm

- Laterally shower consists of core + halo.
  95% containment in a cylinder of radius λ_I.



Hadronic showers are much longer and broader than electromagnetic ones !

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Hadronic cascades

The concept of compensation

A hadron calorimeter shows in general different efficiencies for the detection of the hadronic and electromagnetic components ε_h and ε_e.

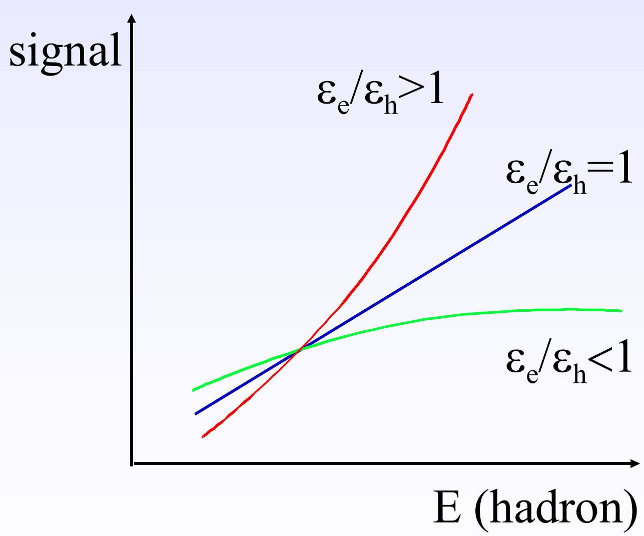
$$R_h = \varepsilon_h E_h + \varepsilon_e E_e$$

ε_h: hadron efficiency
ε_e: electron efficiency

The fraction of the energy deposited hadronically depends on the energy (remember n(π^0))

$$\frac{E_h}{E} = 1 - f_{\pi^0} = 1 - k \ln E \ (GeV) \qquad k \approx 0.1$$

→ Response of calorimeter to hadron shower becomes non-linear



Energy resolution degraded !

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} + b \cdot \left| \frac{\varepsilon_e}{\varepsilon_h} - 1 \right|$$

(Schematically after Wigmans R. Wigmans NIM A 259 (1987) 389)

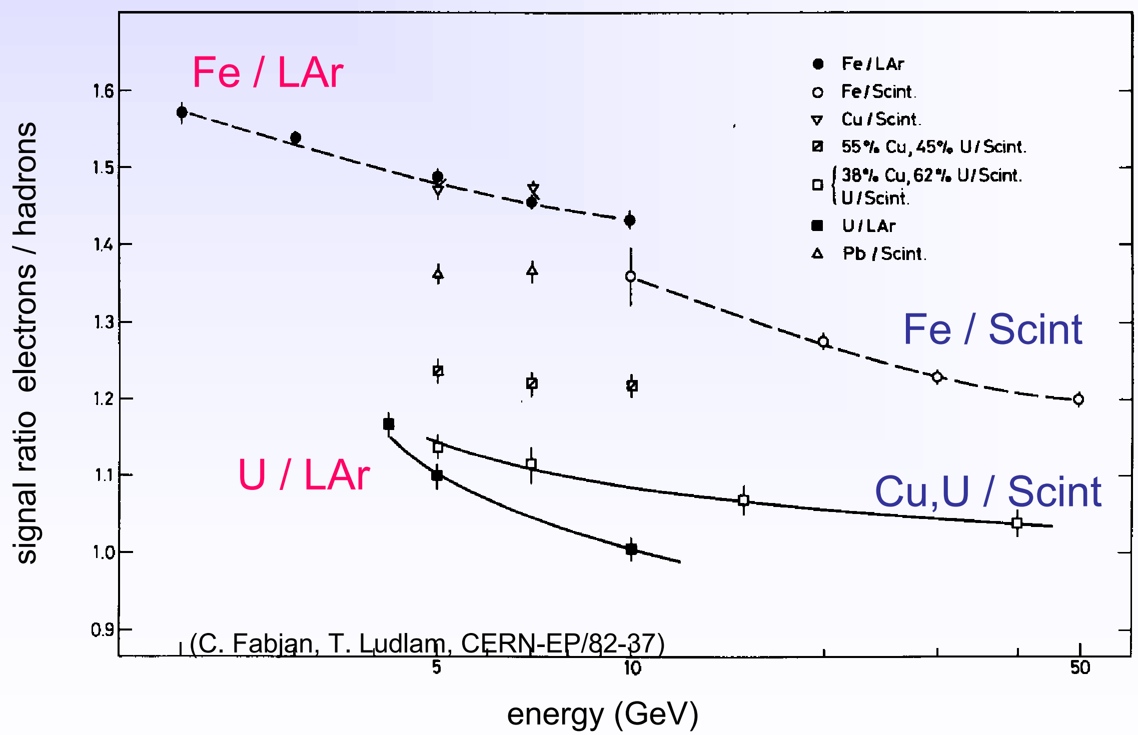
Hadronic cascades

- **How to achieve compensation?**

increase ε_h : use Uranium absorber $\rightarrow$ amplify neutron and soft γ component by fission + use hydrogeneous detector $\rightarrow$ high neutron detection efficiency

decrease ε_e : combine high Z absorber with low Z detectors. Suppressed low energy γ detection ($\sigma_{photo} \propto Z^5$)

offline compensation : requires detailed fine segmented shower data $\rightarrow$ event by event correction.



Calorimeter types

Homogeneous calorimeters: Detector = absorber

- ⇨ good energy resolution
- ⇨ limited spatial resolution (particularly in longitudinal direction)
- ⇨ only used for electromagnetic calorimetry

Two main types:

1. Scintillators

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 36	310 310	10^3	Slightly hygroscopic
BaF_2	4.87	2.03	10^4 (0.13)	0.6 620	220 310	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)

* Relative light yield: rel. to NaI(Tl) readout with PM (bialkali PC)

2. Cherenkov devices

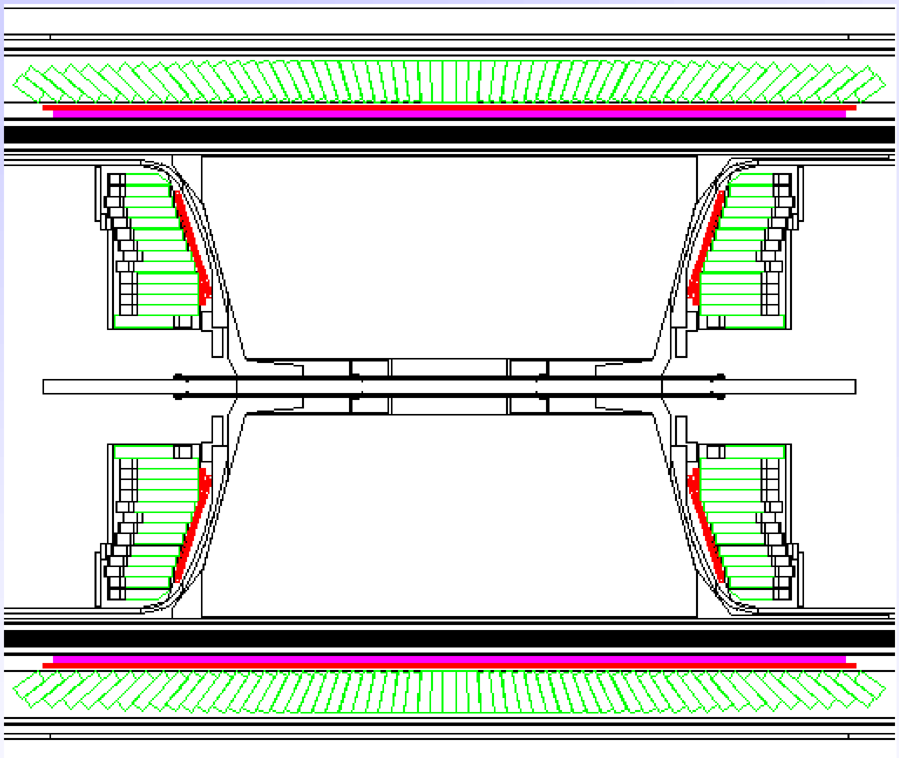
Material	Density [g/cm^3]	X_0 [cm]	n	Light yield [p.e./GeV] (rel. p.e.*)	λ_{cut} [nm]	Rad. Dam. [Gy]	Comments
SF-5 Lead glass	4.08	2.54	1.67	600 (1.5×10^{-4})	350	10^2	
SF-6 Lead glass	5.20	1.69	1.81	900 (2.3×10^{-4})	350	10^2	
PbF_2	7.66	0.95	1.82	2000 (5×10^{-4})		10^3	Not available in quantity

In both cases the signal consists of photons. Readout via photomultiplier, -diode/triode, APD, HPD

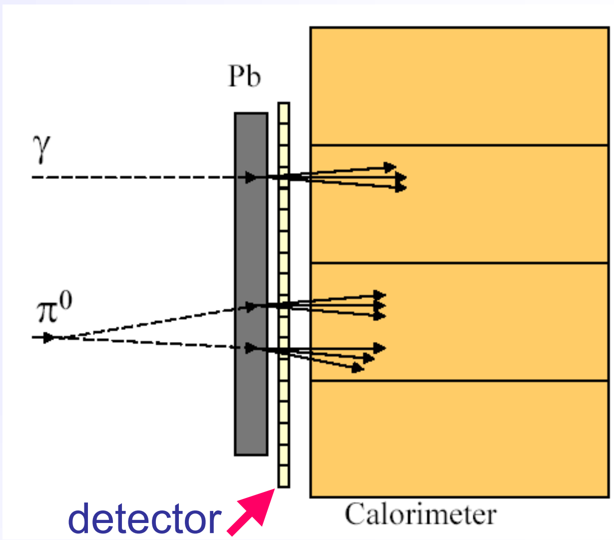
Example ECAL - homogeneous

OPAL Barrel + end-cap electromagnetic calorimeter: lead glass + pre-sampler

(OPAL collab. NIM A 305 (1991) 275)



Principle of pre-sampler or pre-shower detector



$\approx$10500 blocks (10 x 10 x 37 cm^3, 24.6 X_0), PM (barrel) or PT (end-cap) readout.

$$\sigma(E)/E = 0.06/\sqrt{E} \oplus 0.002$$

Spatial resolution (intrinsic) $\approx$ 11 mm at 6 GeV

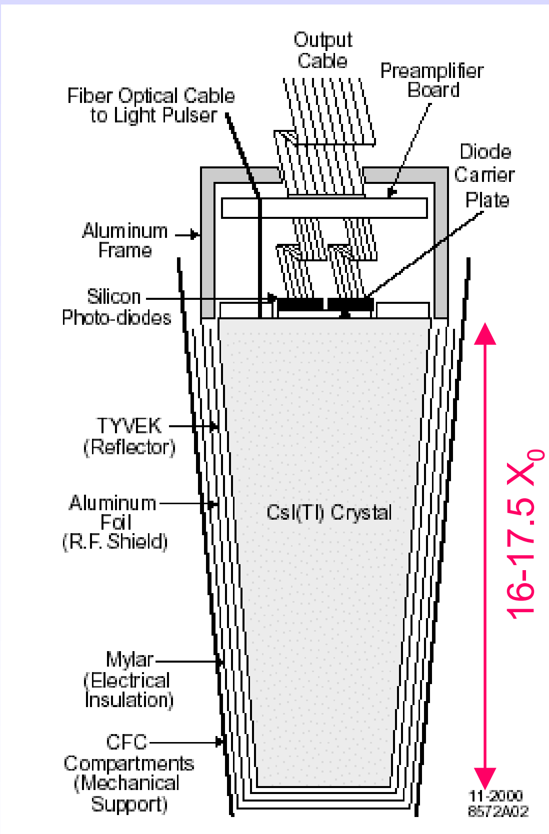
Sample first part of shower with high granularity. Useful for γ/π^0, e/γ, $e/\pi^\pm$ discrimination.

Usually gas or, more recently, Si detectors.

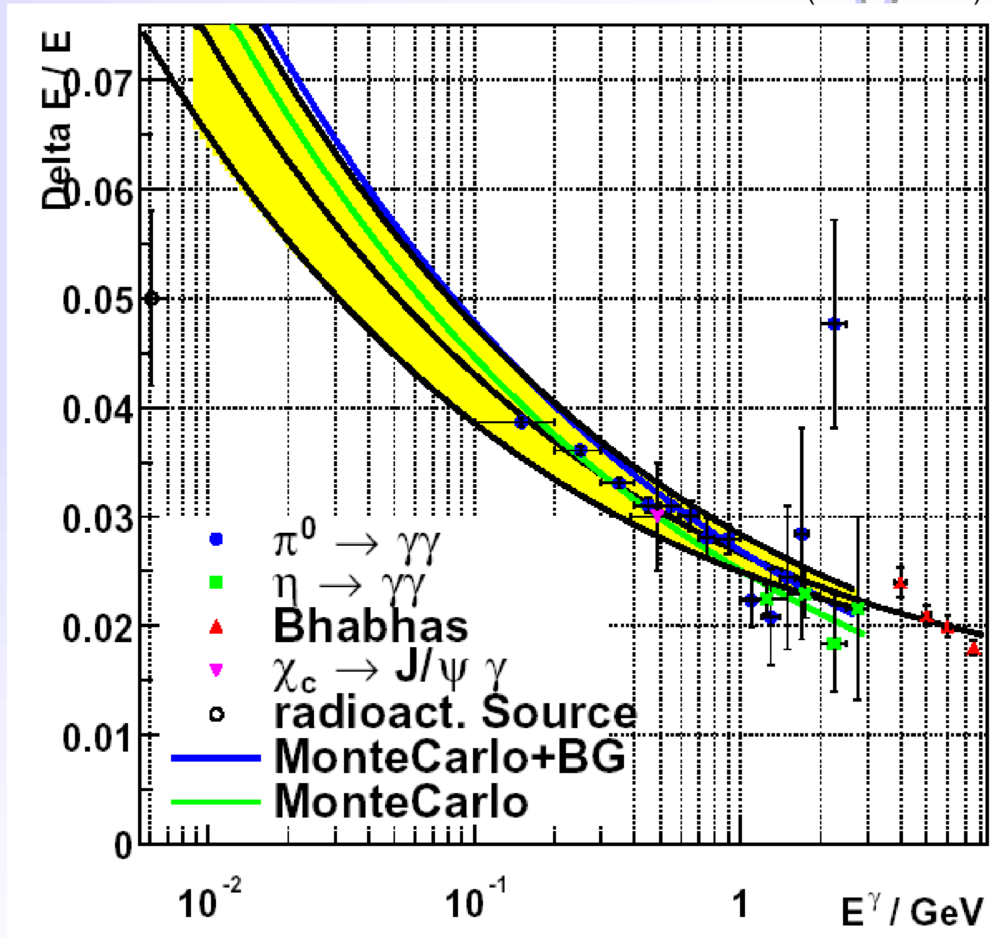
Example ECAL - homogeneous

BABAR (SLAC)

6580 CsI(Tl) crystals with
Si-PD readout



M. Kocian et al. (CALOR 2002)



$$\frac{\sigma_E}{E} = \frac{\sigma_1}{\sqrt[4]{E}} \oplus \sigma_2$$

$$\sigma_1 = (2.30 \pm 0.03 \pm 0.3)\%$$

$$\sigma_2 = (1.35 \pm 0.08 \pm 0.2)\%$$

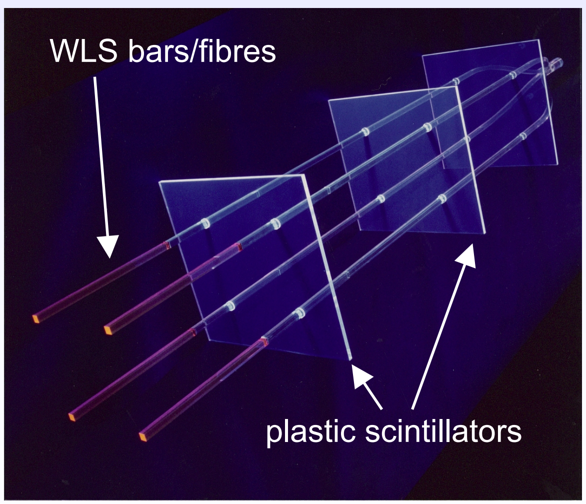
resolution drops only with $\sqrt[4]{E}$!

CERN Academic Training Programme 2004/2005

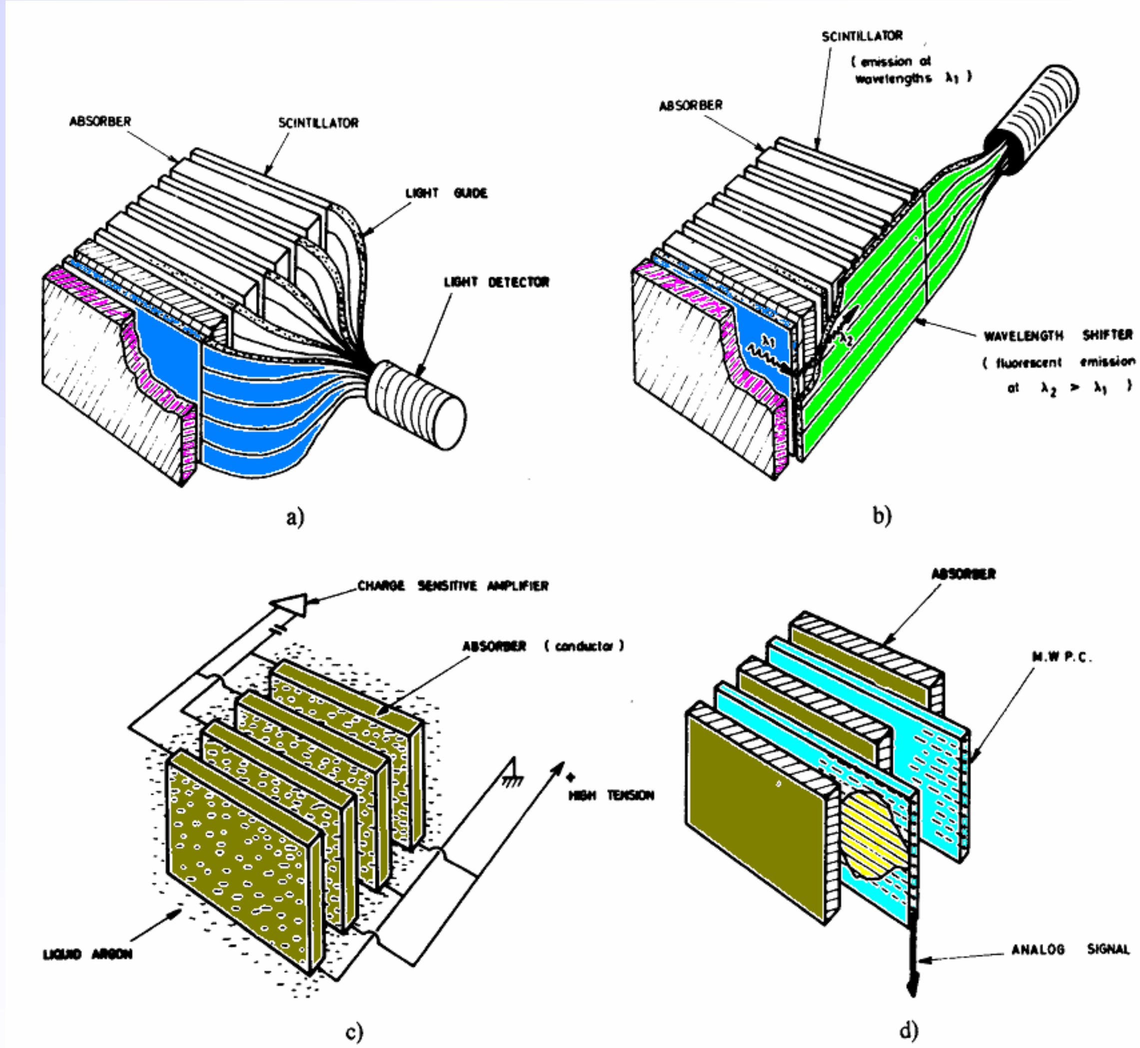
Sampling calorimeters

- **Sampling calorimeters** = Absorber + detector (gaseous, liquid, solid)

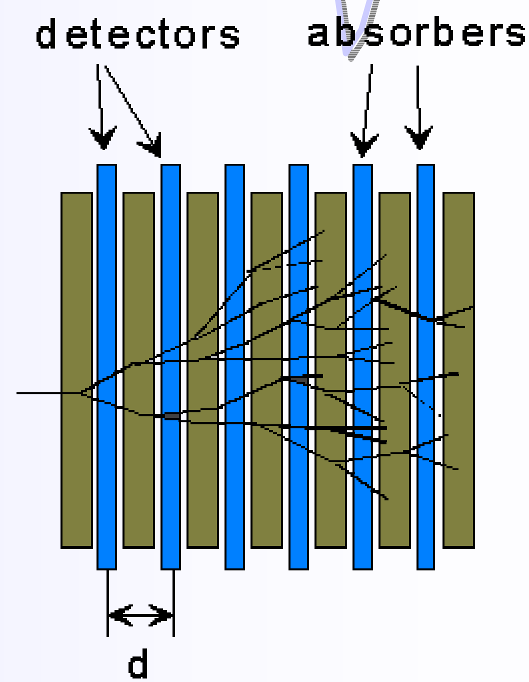
  - MWPC, streamer tubes
  - warm liquids (TMP = tetra-methylpentane, TMS = tetra-methylsilane)
  - cryogenic noble gases: mainly LAr (Lxe, LKr)
  - scintillators, scintillation fibres, silicon detectors



'Shashlik' readout



Sampling calorimeters



Sampling fluctuations

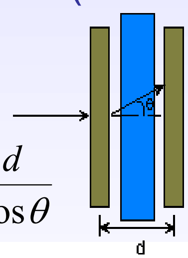
$$N = \frac{T_{det}}{d}$$ Detectable track segments

$$= F(\xi)\frac{E}{E_c}\frac{X_0}{d} \quad \Rightarrow \quad \frac{\sigma(E)}{E} \propto \frac{\sqrt{N}}{N} \propto \frac{1}{\sqrt{F(\xi)}}\sqrt{\frac{E_c}{E}}\sqrt{\frac{d}{X_0}}$$

Pathlength fluctuations + Landau fluctuations

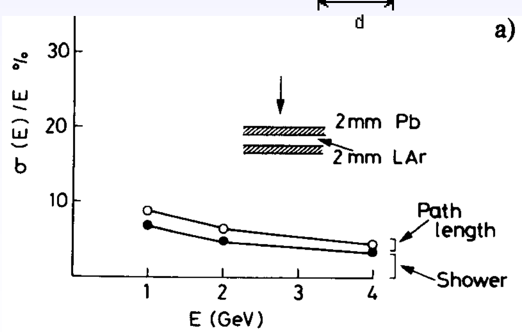
wide spread angular distribution of (low energy) $e^{\pm}$

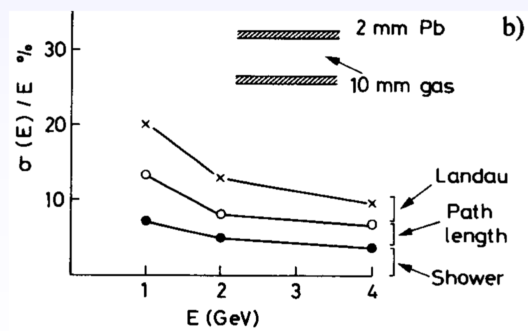
$$d_{eff} = \frac{d}{\cos\theta}$$



In thin gas detector layers the deposited energy shows typical Landau tails

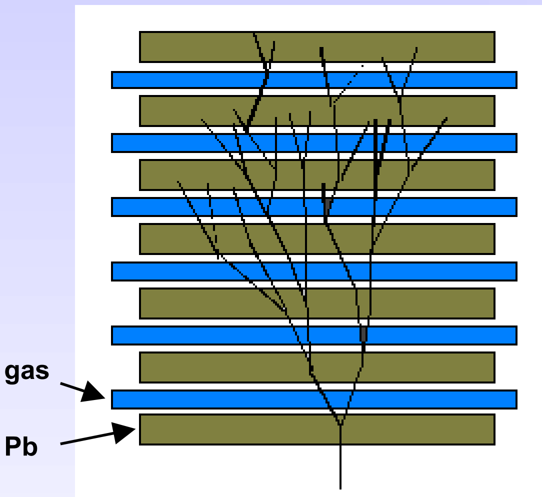
(C. Fabjan, T. Ludlam, CERN-EP/82-37)



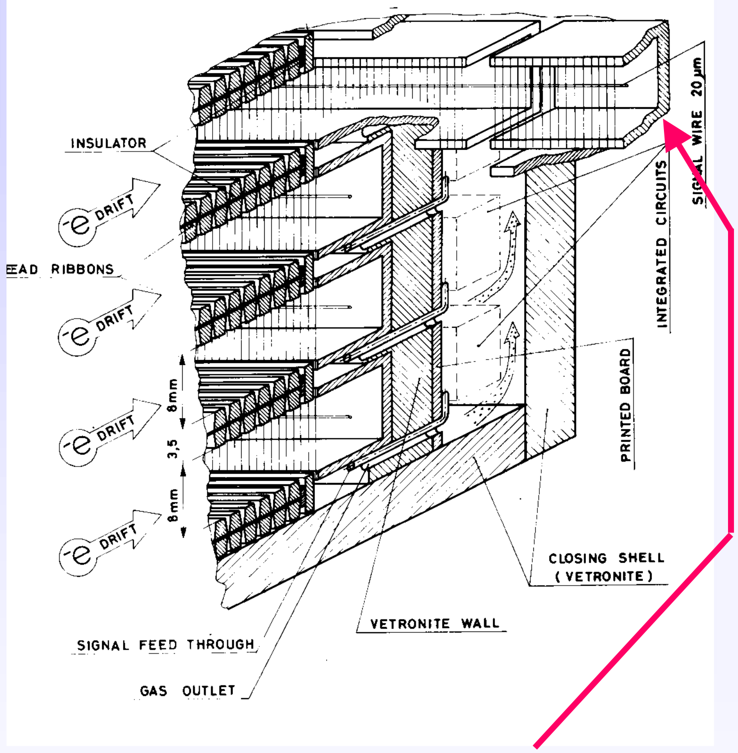


Example ECAL - sampling

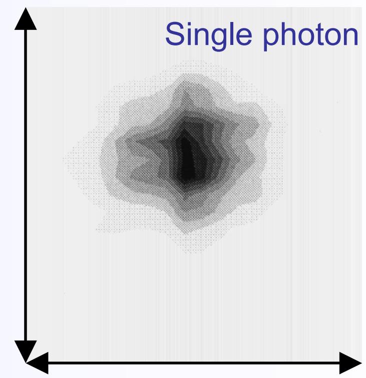
Example of a sampling ECAL: DELPHI High Density Projection Chamber (HPC)



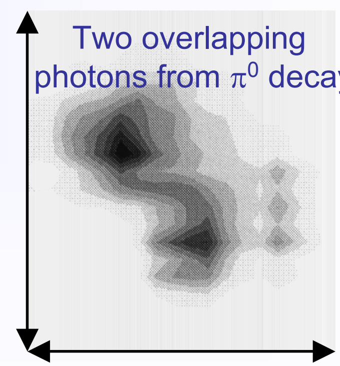
(H.G. Fischer and O. Ullaland, IEEE NS-27 (1980), 38)



Transversal charge distribution in the DELPHI HPC



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



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

Segmented cathodes + drift times ('TPC')
$\rightarrow$ full 3D reconstruction of shower

$$\sigma(E)/E = 0.32/\sqrt{E} \oplus 0.043 \qquad \sigma_\varphi = 1.7\ \text{mrad}, \sigma_\theta = 1.0\ \text{mrad}$$

(HPC was placed behind massive RICH detector !)

(A. Algeri et al. CERN-PPE/95-04)

Example ECAL - sampling

ATLAS electromagnetic Calorimeter

Accordion geometry absorbers immersed in Liquid Argon

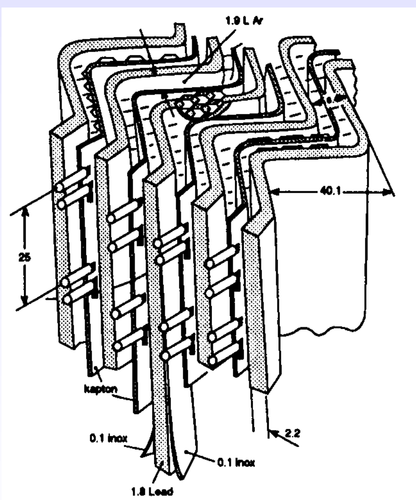
Liquid Argon (90K)

+ lead-steal absorbers (1-2 mm)

+ multilayer copper-polyimide readout boards

$\rightarrow$ Ionization chamber.

1 GeV E-deposit $\rightarrow$ 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

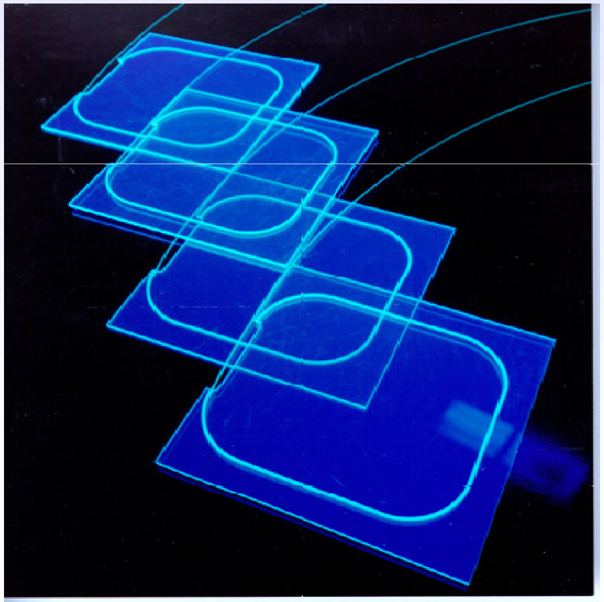
Example HCAL - sampling

CMS Hadron calorimeter

Brass absorber + plastic scintillators

2 x 18 wedges (barrel)
+ 2 x 18 wedges (endcap)
~ 1500 T absorber
5.8 λ_i at $\eta = 0$.

Scintillators fill slots and are read out via WLS fibres by HPDs (B = 4T!)



Test beam resolution for single hadrons

$$\frac{\sigma_E}{E} = \frac{65\%}{\sqrt{E}} \oplus 5\%$$