3rd WORKSHOP ON PARTICLE PHYSICS

NATIONAL CENTRE FOR PHYSICS
(QUAID-I-AZAM UNIVERSITY)

Detectors for High Energy Physics

Lecture IV - Calorimetry

Gigi Rolandi – Cern – Geneva - Switzerland

http://rolandi.home.cern.ch/rolandi/

edit: F. Bedeschi, M. Diemoz, F. Gianotti, C. Joram, J. Virdee

Calorimetry

alorimetry:

nergy measurement by total absorption, combined with spatial reconstruction.

alorimetry is a "destructive" method Detector response $\propto$ E

alorimetry works both for

- ⇨ charged ($e^{\pm}$ and hadrons)
- ⇨ and neutral particles (n,γ)

asic mechanism: formation of

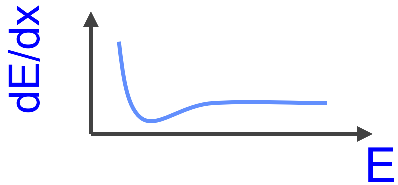
- ⇨ electromagnetic
- ⇨ or hadronic showers.

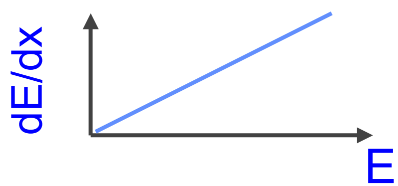
Finally, the energy is converted into ionization or excitation of the matter.

Basic electromagnetic interactions

e^+ / e^-

- Ionisation

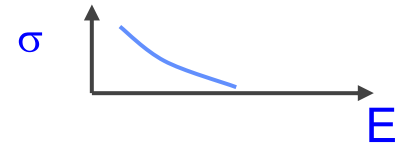


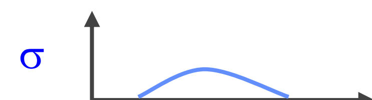


- Bremsstrahlung

γ

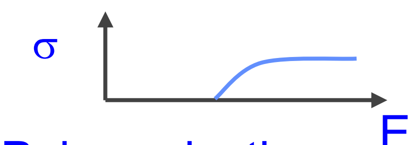
- Photoelectric effect





- Compton effect

E

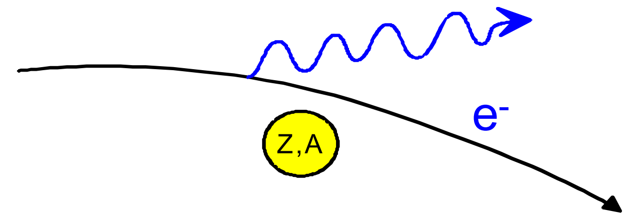


- Pair production

Energy loss by Bremsstrahlung

adiation of real photons in the
oulomb field of the nuclei of the absorber

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



ffect plays a role only for e± and ultra-relativistic μ (>1000 GeV)

or electrons:

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

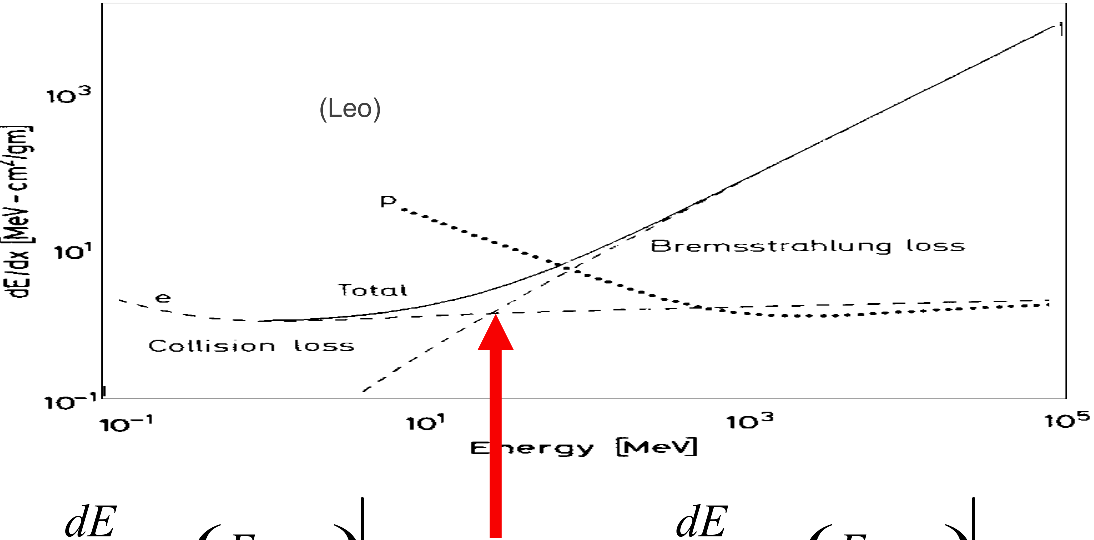
$$-\frac{dE}{dx} = \frac{E}{X_0}$$

$$E = E_0 e^{-x/X_0}$$

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

radiation length [g/cm²]

Critical energy



energy loss (radiative + ionization) of electrons and protons in copper

$$\frac{dE}{dx}(E_c)\Big|_{Brems} = \frac{dE}{dx}(E_c)\Big|_{ion}$$

or electrons

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

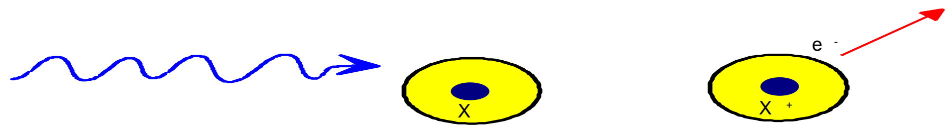
$$E_c \approx E_c^{elec}\left(\frac{m_\mu}{m_e}\right)^2$$

Ec(e-) in Fe(Z=26) = 22.4 MeV

Ec(m) in Fe(Z=26) ≈ 1 TeV

Photo-electric effect

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



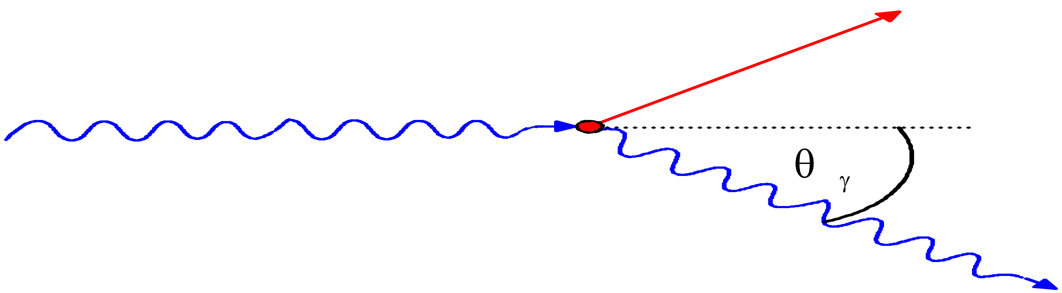
$$\gamma + \text{atom} \rightarrow \text{atom}^{+} + e^{-}$$

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

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

Compton scattering

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



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

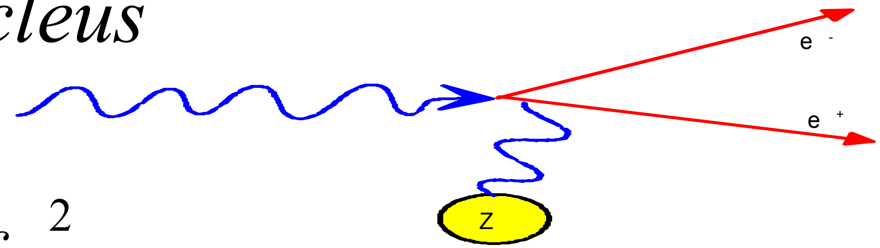
Assume electron as quasi-free.

Cross-section: Klein-Nishina formula, 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

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



nly possible if $E_{\gamma} \geq 2 m_{e} c^{2}$

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

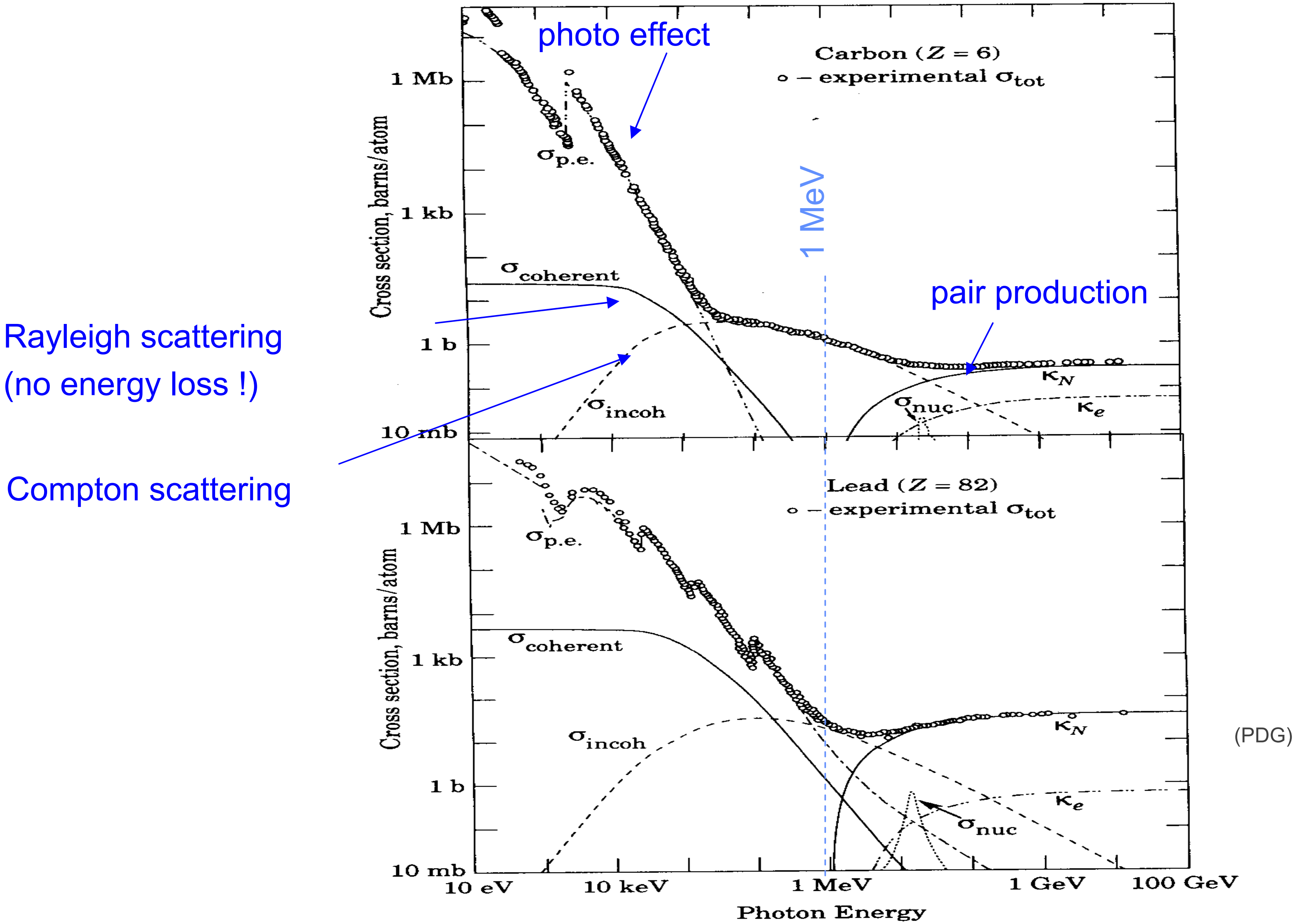
independent of energy !

$$\approx \frac{7}{9} \frac{A}{N_{A}} \frac{1}{X_{0}}$$

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

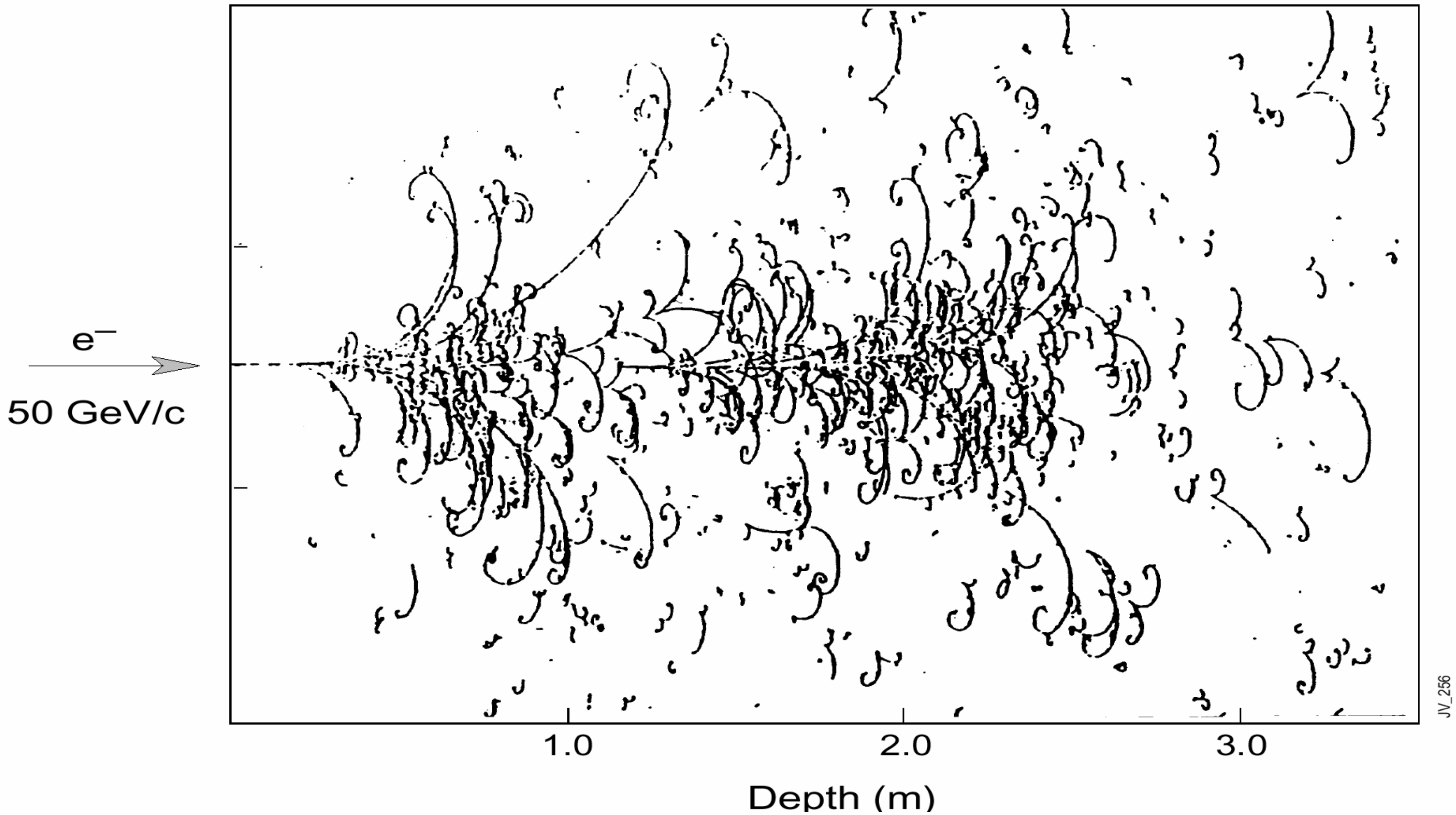
$$\lambda_{pair} = \frac{9}{7} X_{0}$$

Interaction of photons



lectromagnetic showers

A simple model



Big European Bubble Chamber filled with Ne:H_2 = 70%:30%, 3T Field, L=3.5 m, $X_0 \approx$34 cm, 50 GeV incident electron

lectromagnetic showers

A simple model

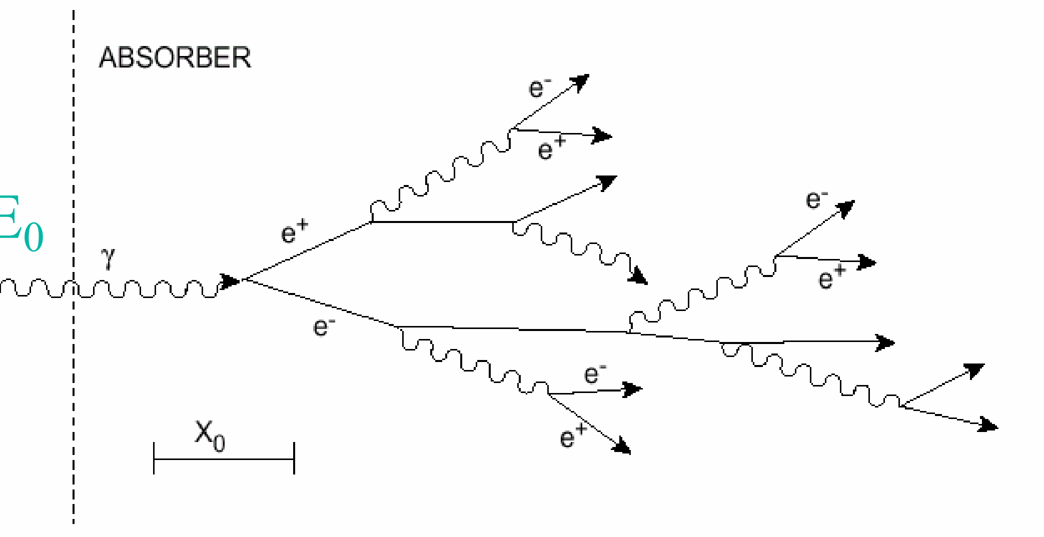
Above 1 GeV the dominant processes, bremsstrahlung for e^+ and e
and pair production for γ, become energy independent

Trough a succession of these energy loss mechanisms an electromagnetic cascade is propagated until the energy of charged secondaries has been degraded to the regime dominated by ionization loss (below Ec)

Below Ec a slow decrease in number of particles occurs as electrons are stopped and photons absorbed

lectromagnetic showers

A simple model



- In $1X_0$ an e loses about 2/3 of its
  a high energy γ has a probability of 7/9 of pair conversion
- Assume X_0 as a generation length
- In each generation the number of particle increases by a factor 2
  Until E>Ec

@$\Delta x = X_0$ $\gamma \rightarrow e+\ e-$ $E = E_0/2$ @$\Delta x = 2X_0$ $e \rightarrow \gamma\ e'$ $E' = E_0/4$

@$\Delta x = tX_0$ $N(t) = 2^t$ $E(t) = E_0 / 2^t$

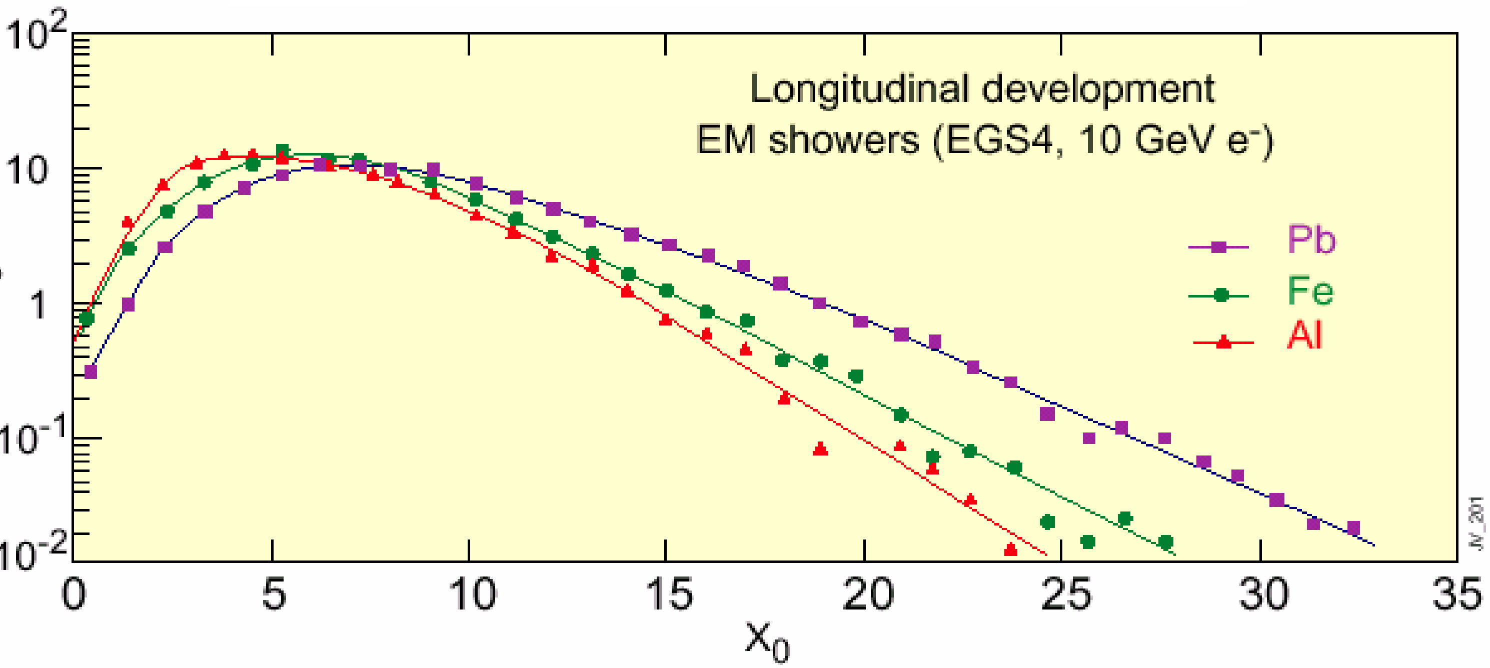
@ $t_{max}X_0$ (shower max) $E(t_{max}) = E_c$ $E_0 / 2^{t_{max}} = E_c$

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

$$N(t_{max}) = 2\,E_0/E_c - 1$$

lectromagnetic showers

Parametrization



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

arametrization of energy deposition $N_{tot} \propto E_0/E_c$ $t_{max} = 1.4 \ln(E_0/E_c)$

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

E_c α 1/Z ➡

- shower max
- shower tail

Transverse shower profile

- Multiple scattering make electrons move away from shower axis
- Photons with energies in the region of minimal absorption can travel far away from shower axis

Molière radius sets transverse shower size, it gives the average lateral deflection of critical energy electrons after traversing $1X_0$

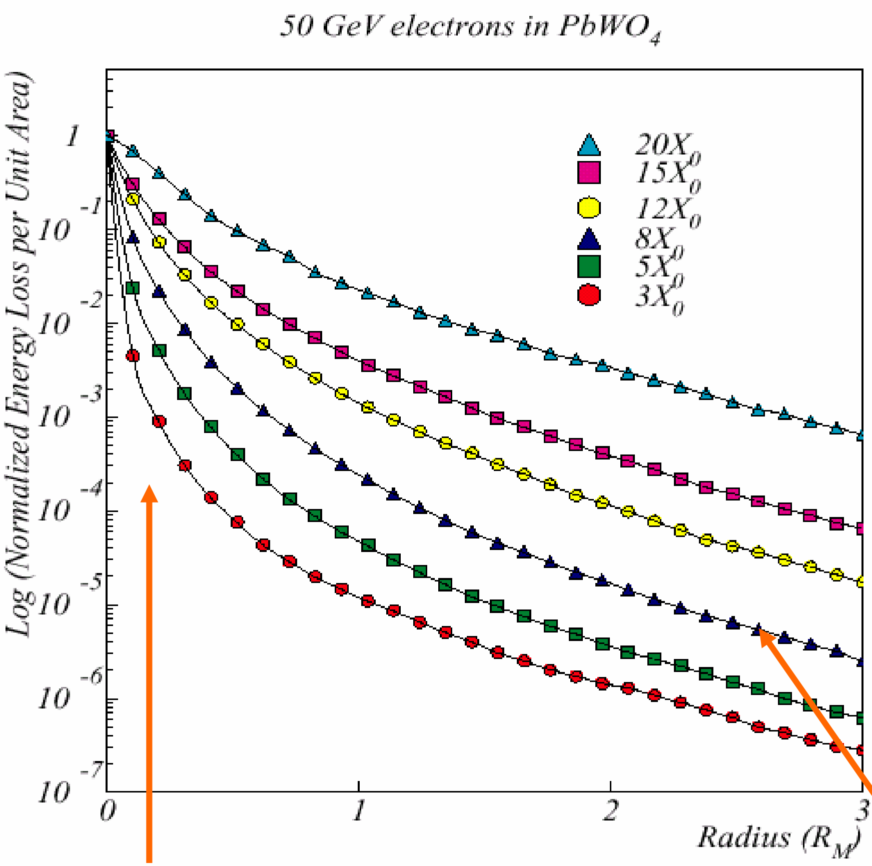
$$R_M = \frac{21\,\mathrm{MeV}}{E_C} X_0$$

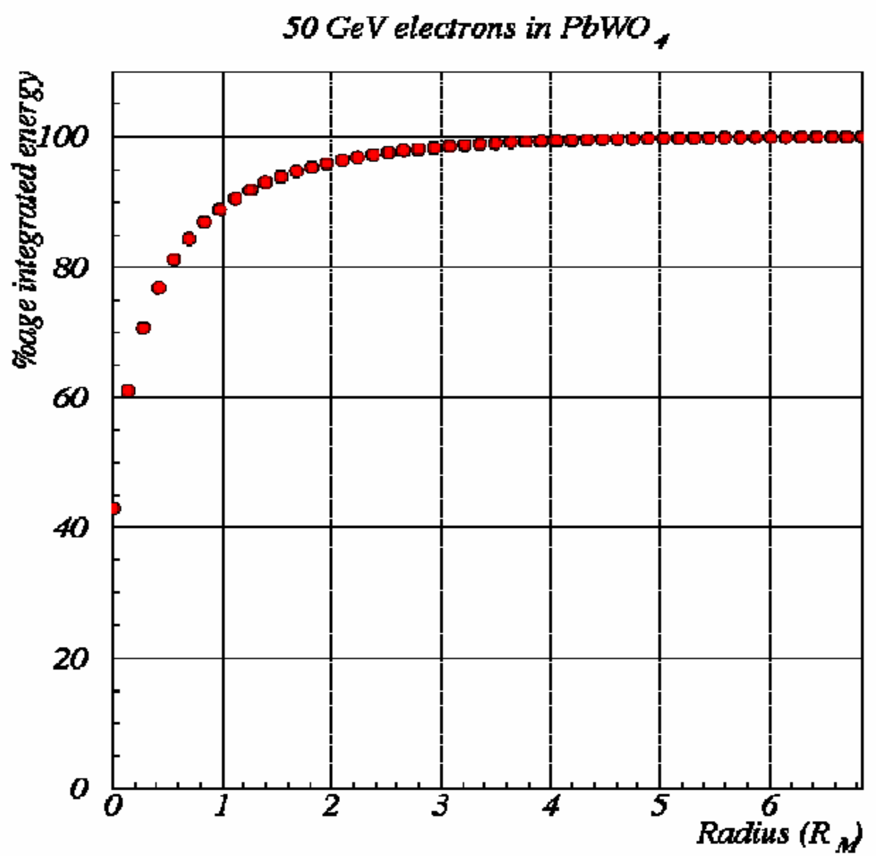
$$R_M \propto \frac{X_0}{E_C} \propto \frac{A}{Z} \left(Z >> 1\right)$$

75% E_0 within $1R_M$, 95% within $2R_M$, 99% within $3.5R_M$

lectromagnetic showers

Parametrization





Central core: multiple scattering

Peripheral halo: propagation of less attenuated photons, widens with depth of of the shower

The energy deposited in the calorimeters is converted to active detector response

- $E_{vis} \leq E_{dep} \leq E_0$

Main conversion mechanism

- Cerenkov radiation from e
- Scintillation from molecules
- Ionization of the detection medium

Different energy threshold E_s for signal detectability

lectromagnetic calorimeters

Intrinsic limit

Detectable signal is proportional to the total track length of e+ and e-
in the active material, intrinsic limit on energy resolution is given by the
fluctuations in fraction of initial energy that generates detectable signal

$$N_{tot} \propto \frac{E_0}{E_C}$$

Total track length

$$T_0 = N_{tot} X_0 \approx \frac{E_0}{E_C} X_0$$

Detectable track length $T_r = f_s T_0$
f_s fraction of N_{tot} with $E > E_s$
Fluctuations in track length:
Poisson process

$$\frac{\sigma(E)}{E} \propto \frac{\sigma(T_r)}{T_r} \propto \frac{1}{\sqrt{T_r}} \propto \frac{1}{\sqrt{E_0}}$$

Calorimeter types

Homogeneous calorimeters:

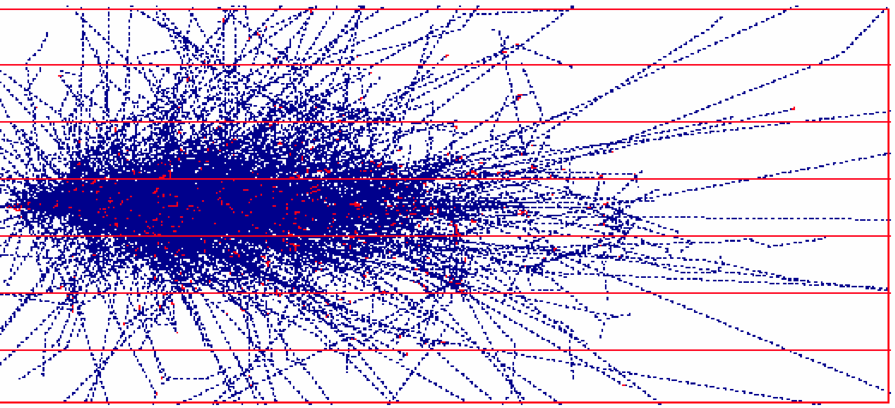
- ⇨ Detector = absorber
- ⇨ good energy resolution
- ⇨ limited spatial resolution (particularly in longitudinal direction)
- ⇨ only used for electromagnetic calorimetry

Sampling calorimeters:

- ⇨ Detectors and absorber separated $\rightarrow$ only part of the energy is sampled.
- ⇨ limited energy resolution
- ⇨ good spatial resolution
- ⇨ used both for electromagnetic and hadron calorimetry

lectromagnetic calorimeters

Homogeneous calorimeters: all the energy is deposited in the active medium. Absorber ≡ active medium



- Excellent energy resolution
- No information on longitudinal shower shape
- Cost

All e+e- over threshold produce a signal

$$\frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{E}}$$

Compare processes with different energy threshold

Scintillating crystals

$$E_s \cong \beta E_{gap} \sim eV$$

$$\approx 10^2 \div 10^4 \gamma / MeV$$

$$\sigma / E \sim (1 \div 3)\% / \sqrt{E(GeV)}$$

Lowest possible limit

Cherenkov radiators

$$\beta > \frac{1}{n} \rightarrow E_s \sim 0.7 MeV$$

$$\approx 10 \div 30 \ \gamma / MeV$$

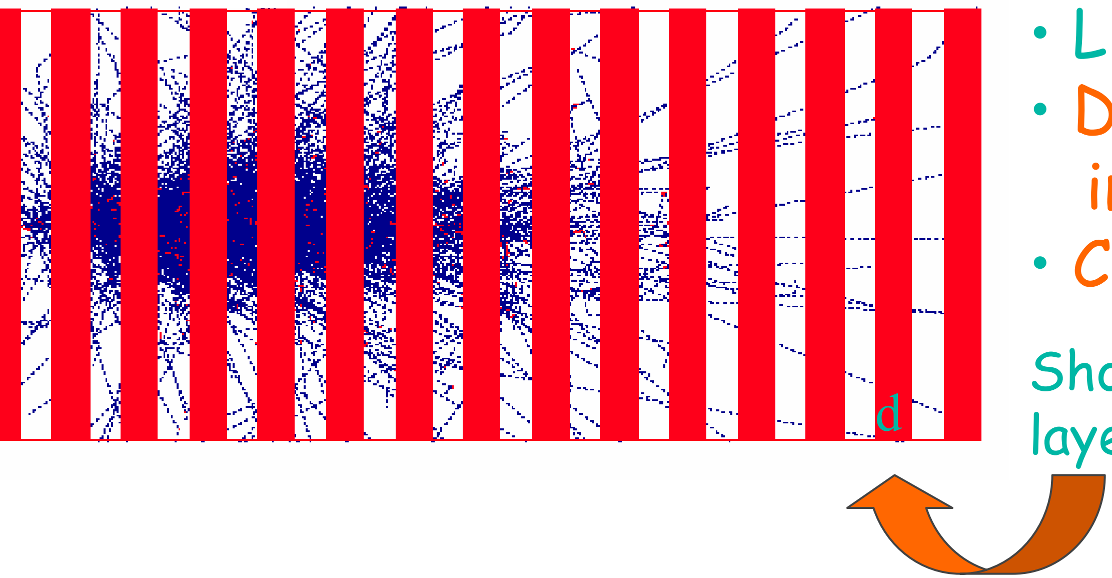
$$\sigma / E \sim (10 \div 5)\% / \sqrt{E(GeV)}$$

Crystal Calorimeters: 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	10 10	≈440 ≈530	10^4	light yield =f(T)

lectromagnetic calorimeters

ampling calorimeters: shower is sampled by layers of active edium (low-Z) alternated with dense radiator (high-Z) material.

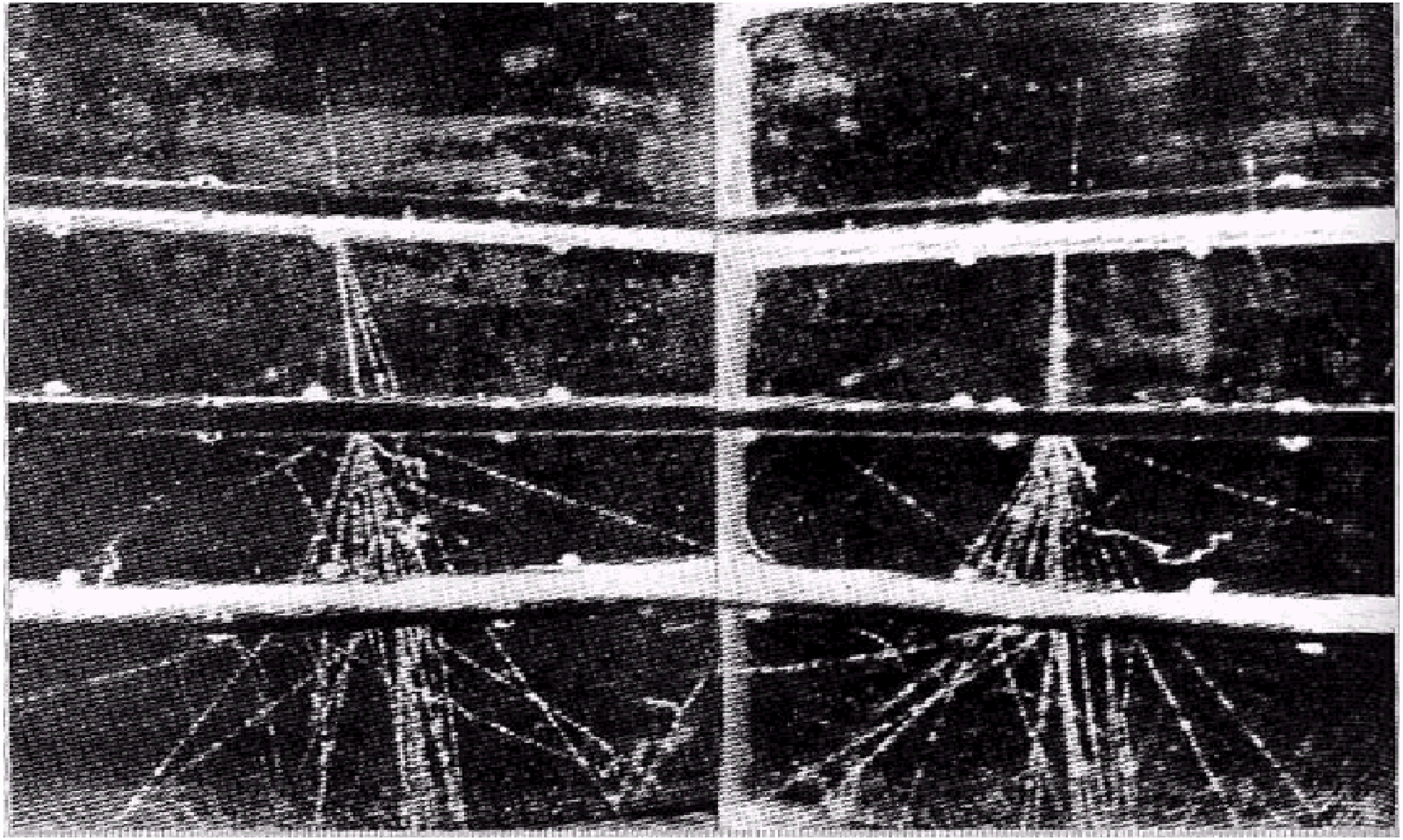


- Limited energy resolution
- Detailed shower shape information
- Cost

Shower generator separates active layers by a distance d

only a fraction of the shower energy is dissipated in the active medium
energy resolution is dominated by fluctuations in energy deposited in active layers: sampling fluctuations

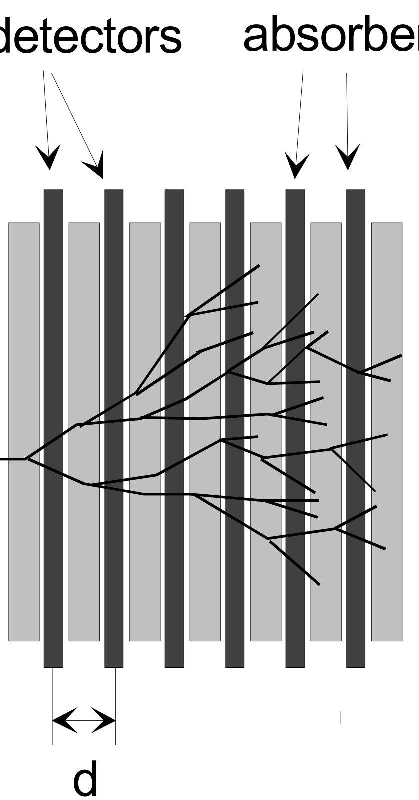
ampling electromagnetic showers



Cloud chamber photograph of e.m. shower developing in lead plates (thickness from top down 1.1, 1.1, 0.13 X_0) exposed to cosmic radiation

lectromagnetic calorimeters

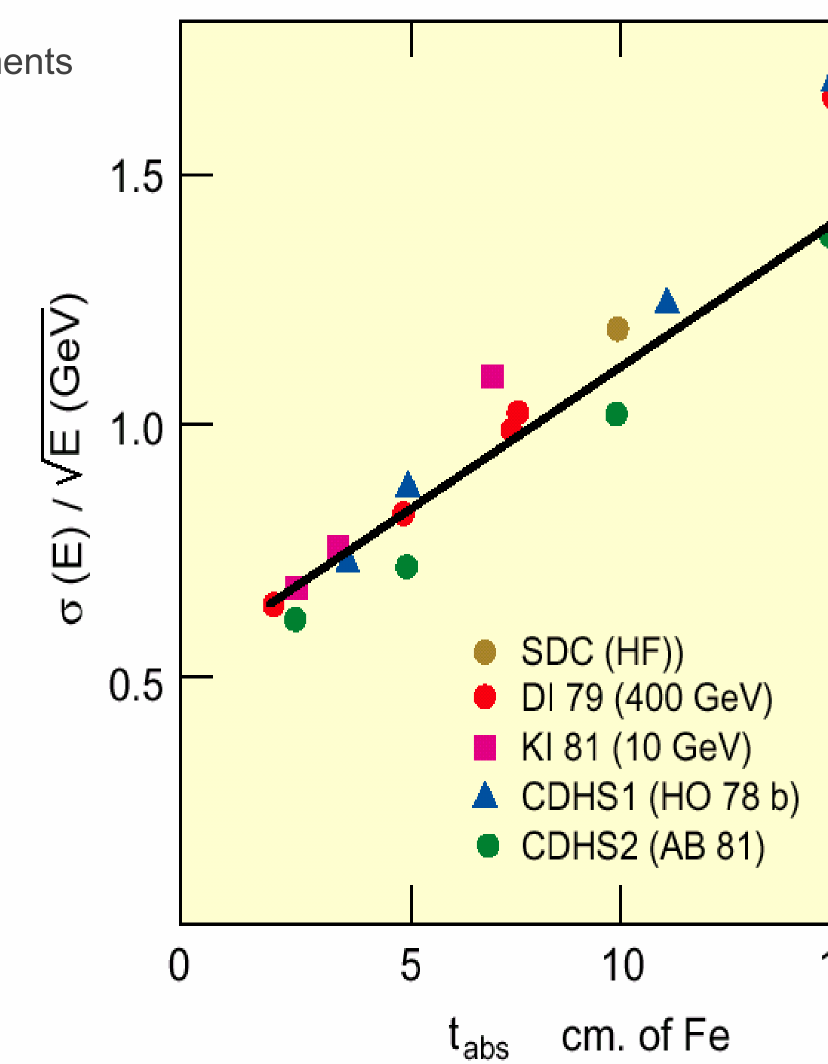
Energy resoluti



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

$$= F(\xi)\frac{E}{E_c}X_0\frac{1}{d}$$

$$\frac{\sigma(E)}{E} \propto \frac{\sqrt{N}}{N} \propto \sqrt{\frac{1}{E}} \cdot \sqrt{\frac{d}{X_0}}$$



lectromagnetic calorimeters

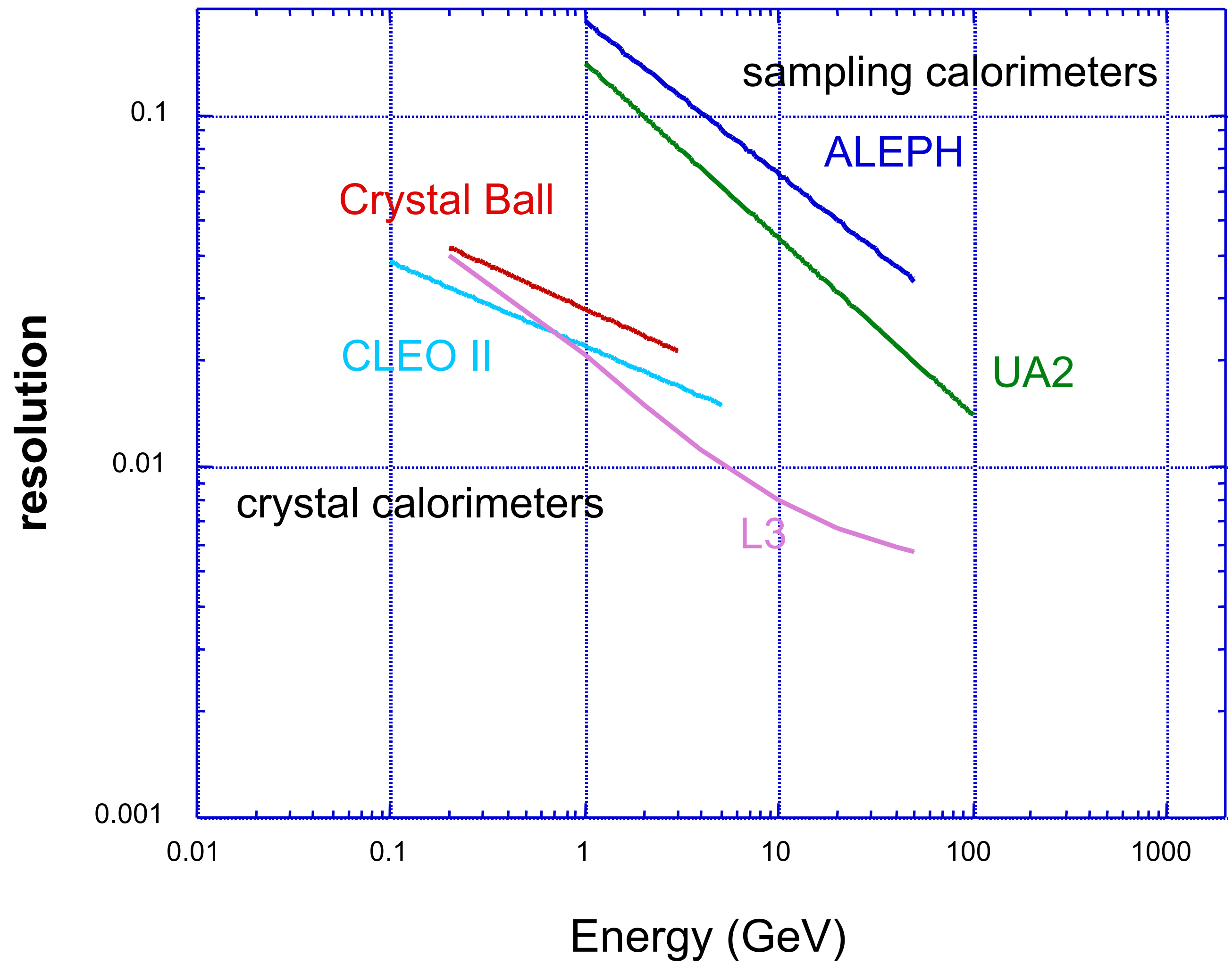
Energy resolution of a calorimeter can be parametrised as

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

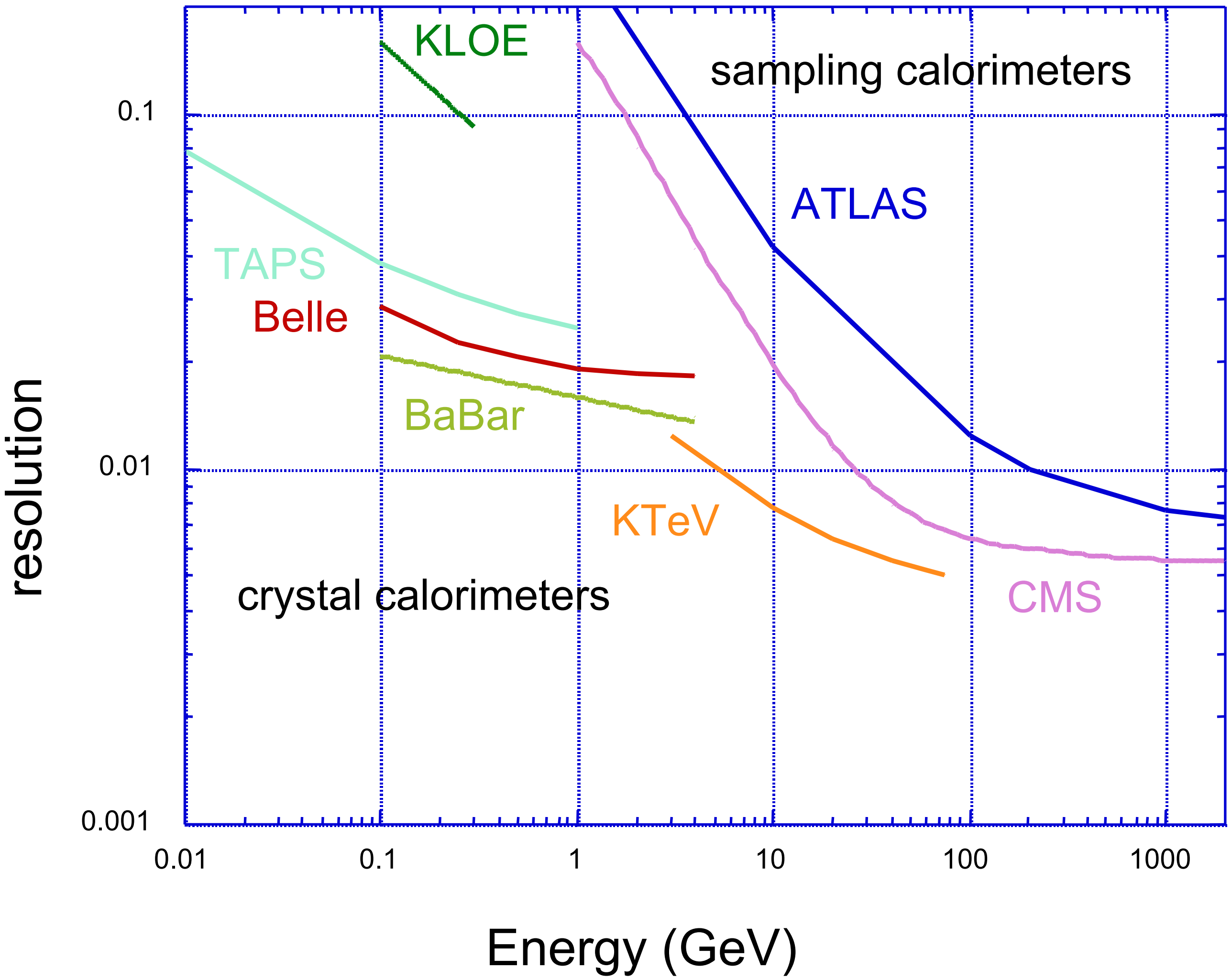
$\oplus$ means quadratic sum

- a the *stocastic term* accounts for any kind of Poisson-like fluctuations
  - natural merit of homogeneous calorimeters
  - several contributions add to the "intrinsic one"
- b the *noise term* responsible for degradation of low energy resolution
  - mainly the energy equivalent of the electronic noise
  - contribution from pileup: the fluctuation of energy entering the measurement area from sources other than the primary particle
- c the *constant term* dominates at high energy
  - its relevance is strictly connected to the small value of a
  - it is mostly dominated by the stability of calibration
  - contributions from energy leakage, non uniformity of signal generation and/or collection, loss of energy in dead materials,…

assic calorimeters



odern calorimeters

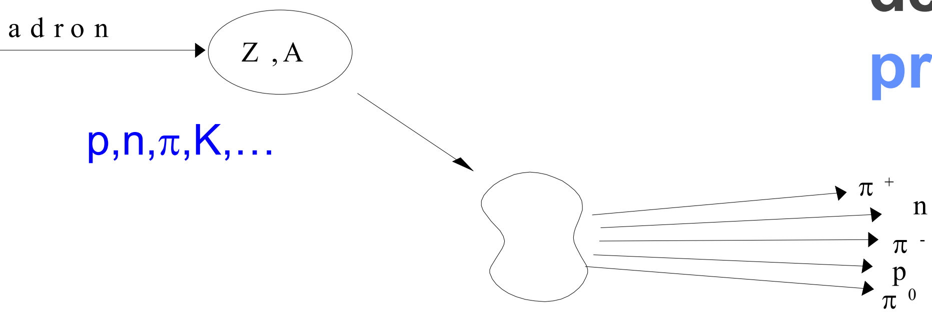


uclear Interactions

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

multiplicity $\propto \ln(E)$

$p_t \approx 0.35$ GeV/c



citation and finally breakup up nucleus → nucleus fragments + oduction of secondary particles.

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

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

In analogy to X0 a **hadronic absorption length** can be defined

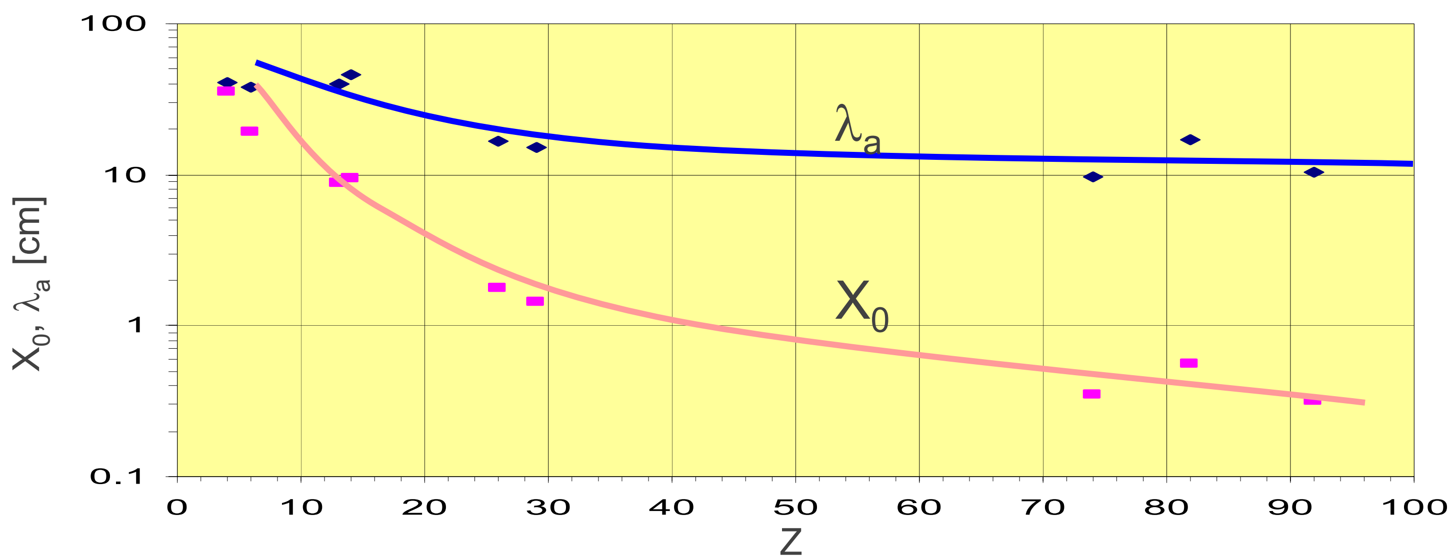
$$\lambda_a = \frac{A}{N_A \sigma_{inel}}$$

nteraction of charged particles

Material	Z	A	ρ [g/cm³]	X_0 [g/cm²]	λ_a [g/cm²]
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

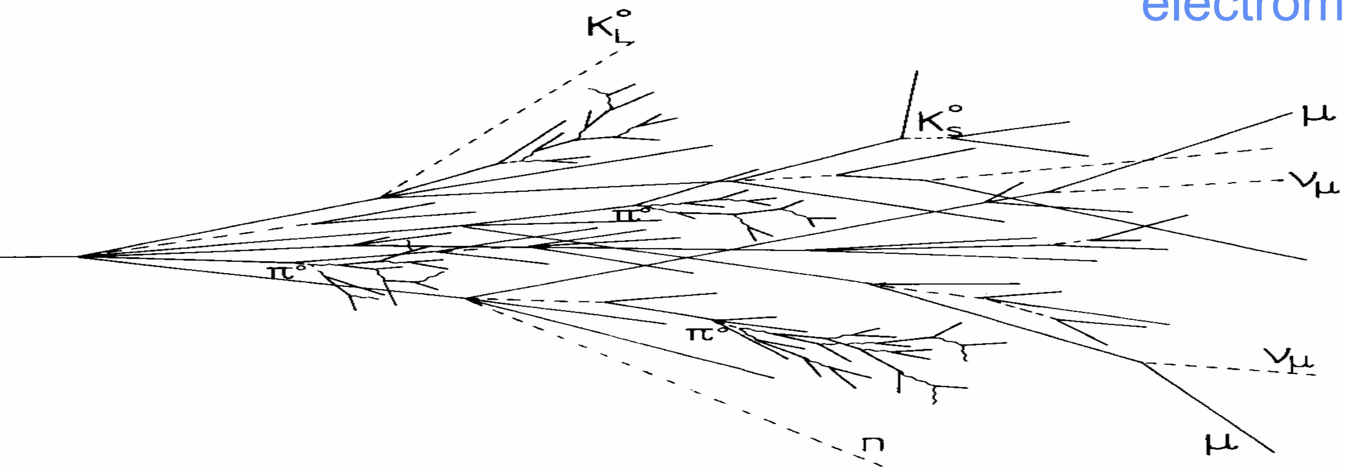
For Z > 6: $\lambda_a > X_0$

λ_a and X_0 in cm



Hadronic cascades

Various processes involved. Muc
more complex than
electromagnetic cascades.



Hadronic + electromagnetic component

(Grupen)

charged pions, protons, kaons ….
Breaking up of nuclei (binding energy),
neutrons, neutrinos, soft γ's
muons …. → invisible energy

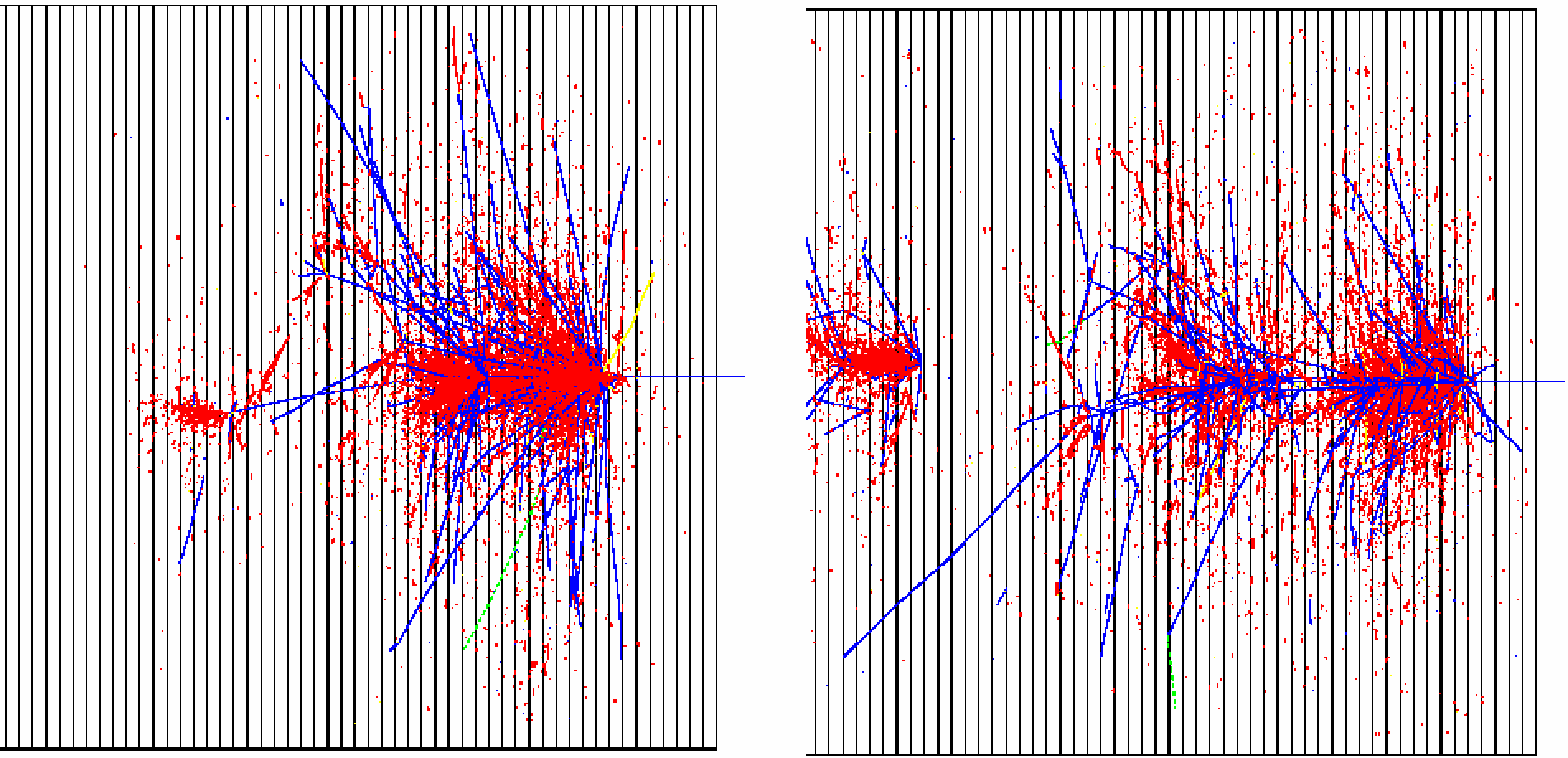
neutral pions → 2γ → electromagnetic cascade

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

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

Large energy fluctuations → limited energy resolution

150 GeV Pion Showers in Cu



Hadron shower not as well behaved as an em one

red - e.m. component
blue - charged hadrons

Hadron calorimeter are always sampling calorimeters

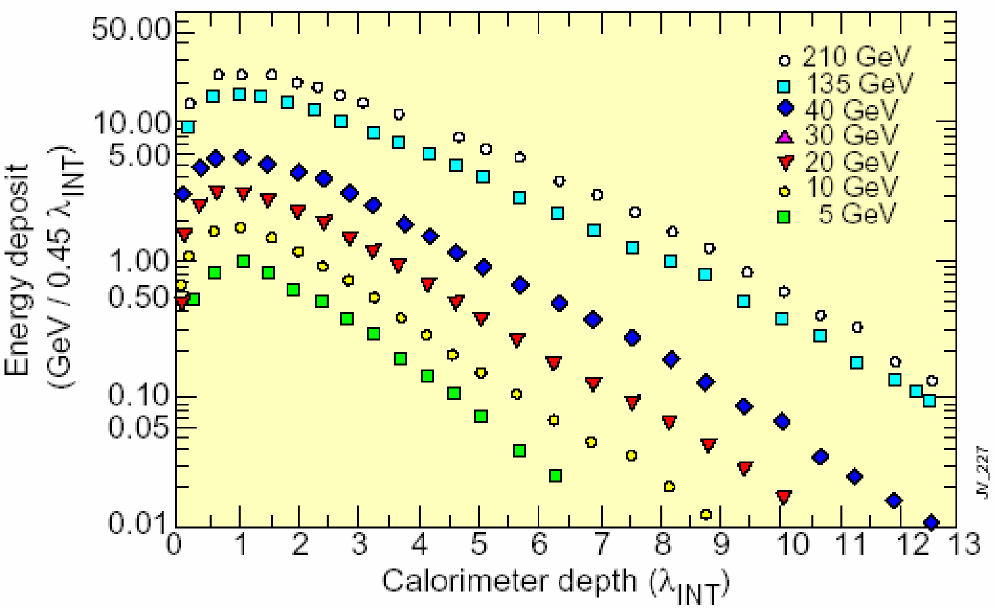
Hadronic Cascade: Profiles

Hadron shower profiles for single $\pi^{\pm}$

Longitudinal

- sharp peak from π^0's produced in the 1st interaction
- followed by a more gradual falloff with a characteristic scale of λ.

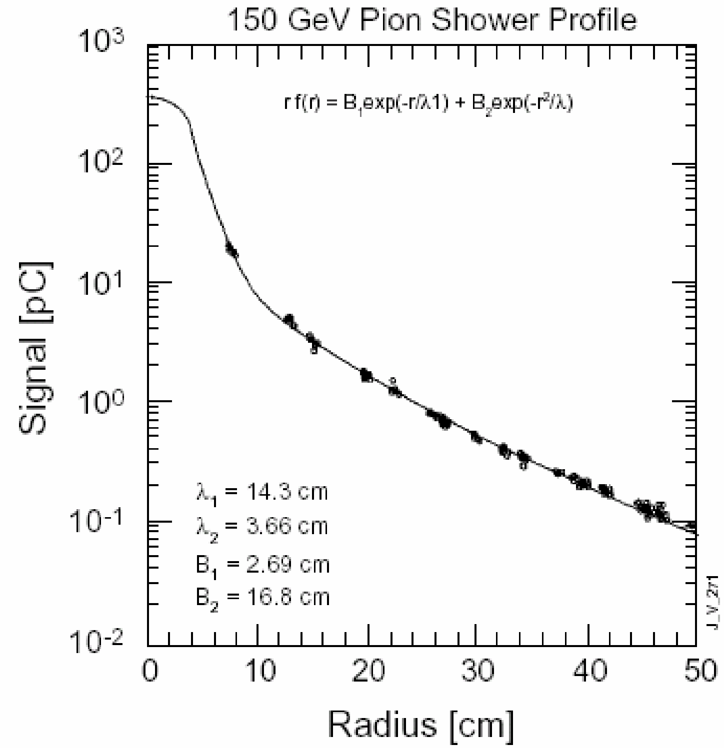
WA78 : 5.4λ of 10mm U / 5mm Scint + 8λ of 25mm Fe / 5mm Scint



Approx. 10 λ required to contain 99% of the energy of ≈ 200 GeV pions

Lateral

- Secondaries produced with $\langle p_t \rangle$ ~ 300 MeV
-approx. energy lost in ≈ 1 λ in most materials.
- Characteristic transverse scale is $r_\pi \approx \lambda$.
- Pronounced core, caused by the π^0 component,

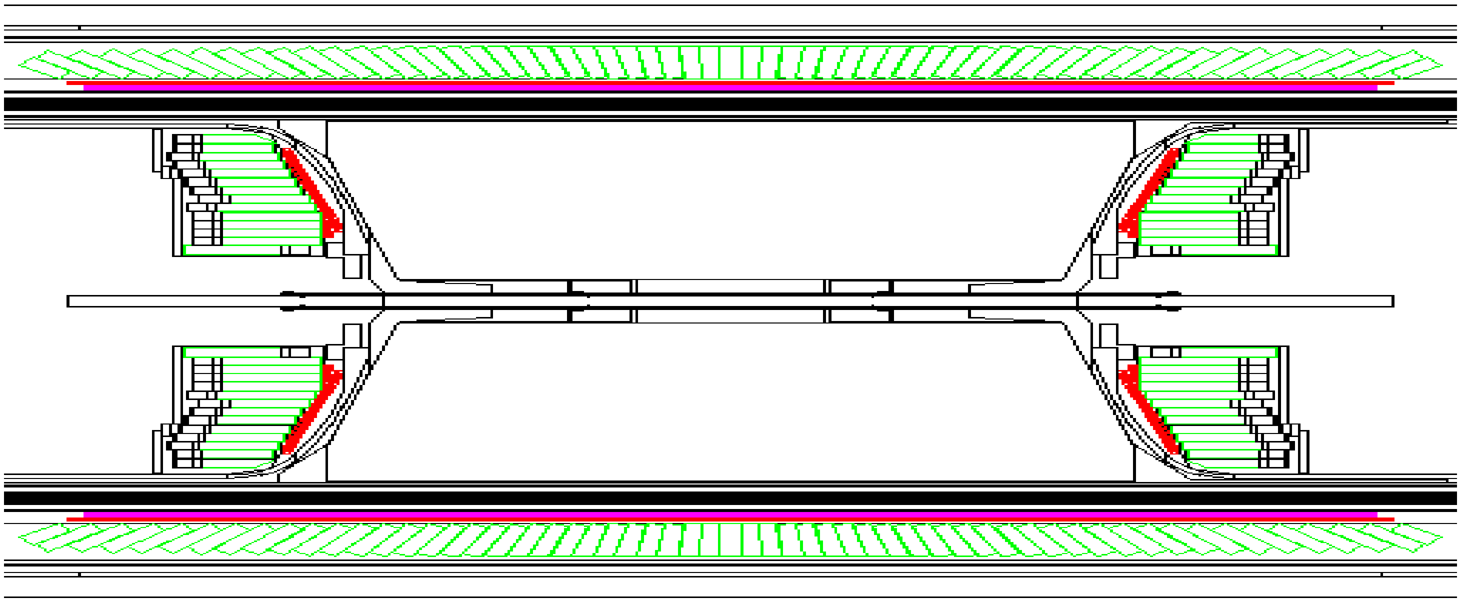


Transverse radius for 95% containment is $R_{0.95} \approx 1\ \lambda$

Homogeneous calorimeters

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

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



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

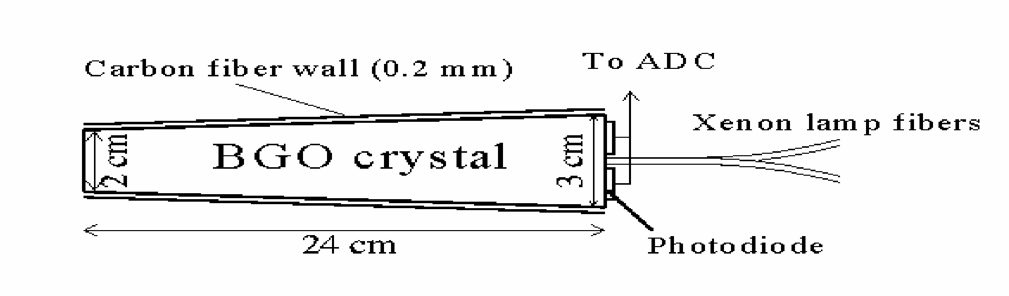
$$\sigma(E)/E = 0.06/\sqrt{E} \oplus 0.002$$

Spatial resolution (intrinsic) ≈ 11 mm at 6 GeV

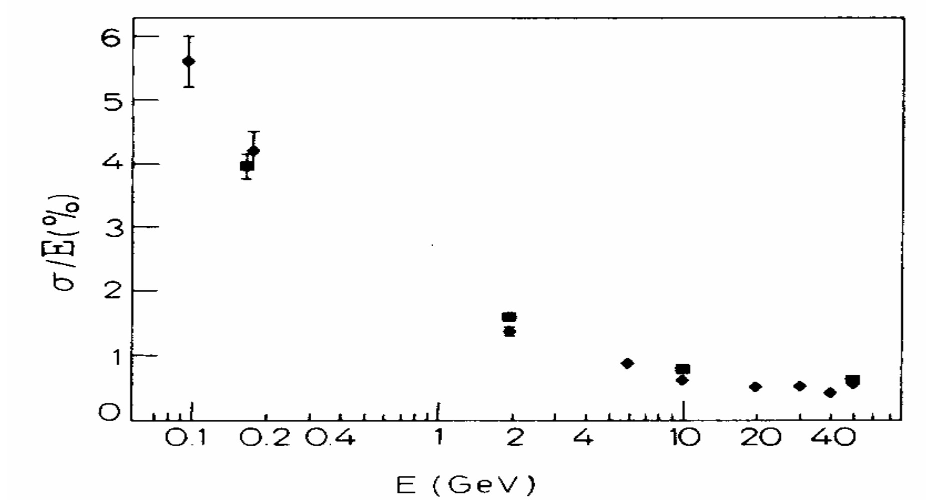
Homogeneous calorimeters

BGO E.M. Calorimeter in L3

(L3 collab. NIM A 289 (1991) 53



1000 crystals, 21.4 X_0, temperature
monitoring + control system
ight output -1.55% / ºC

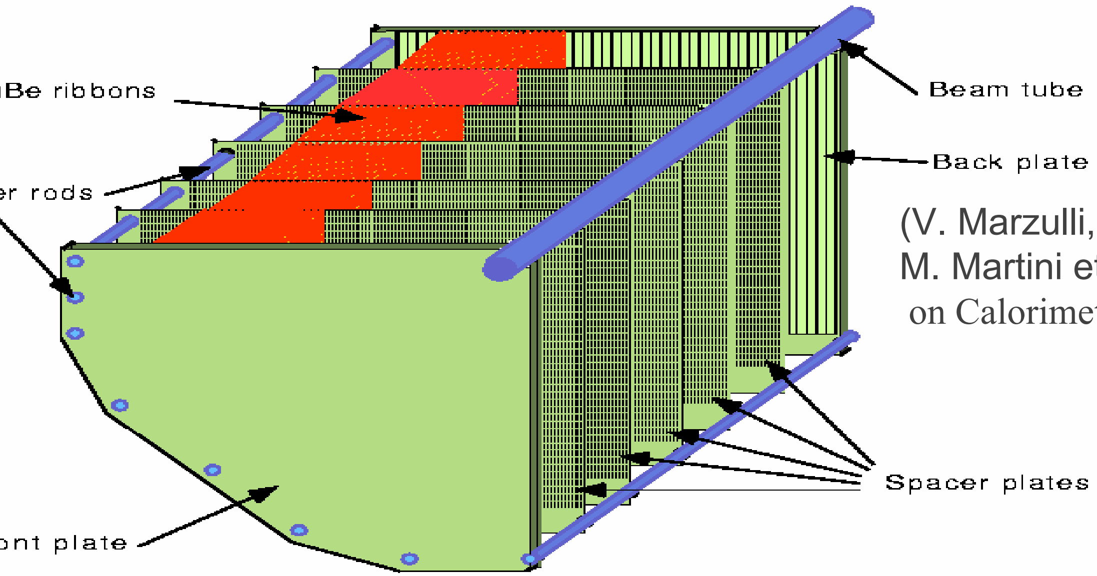


σ_E/E < 1% for E > 1 GeV
spatial resolution < 2 mm
(E >2 GeV)

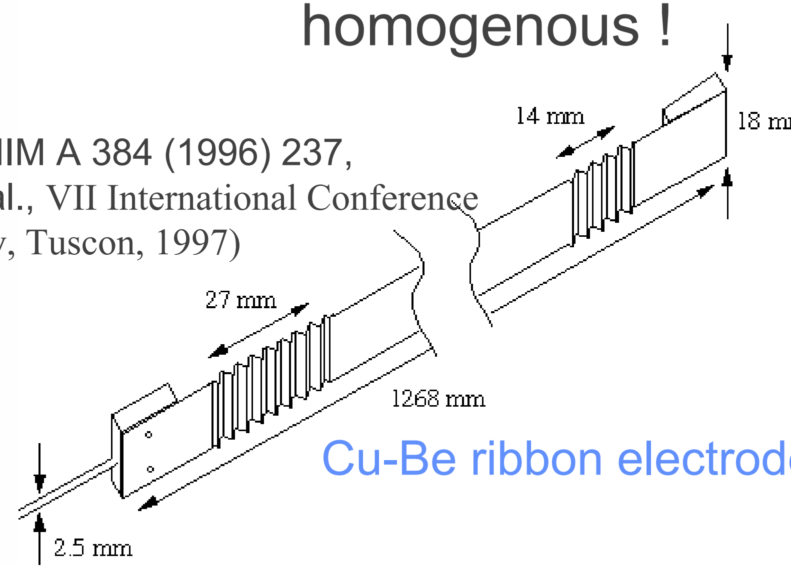
Partly test beam results !

Homogeneous calorimeters

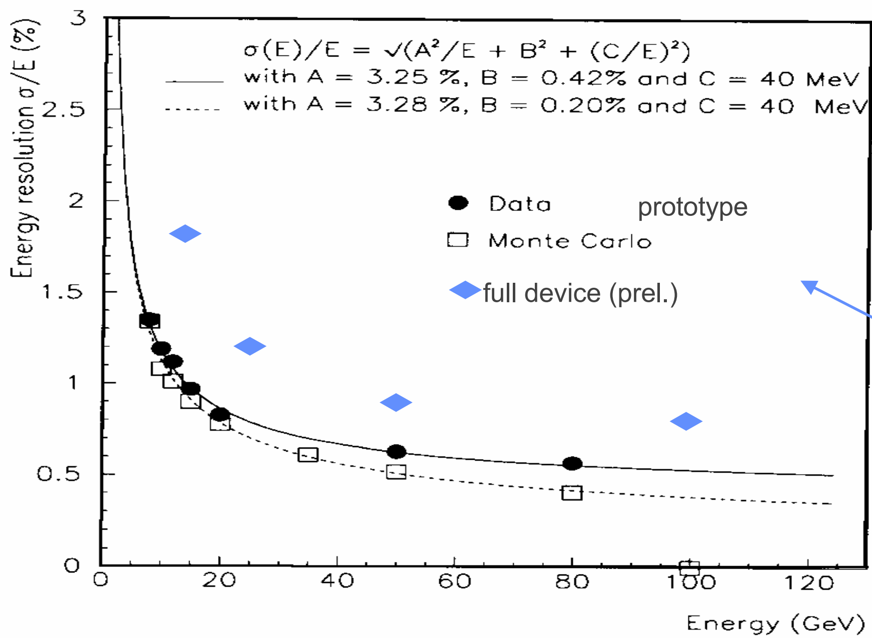
NA48: LKr Ionisation chamber (T = 120 K)no metal absorbers ~ quas homogenous !



(V. Marzulli, NIM A 384 (1996) 237,
M. Martini et al., VII International Conference on Calorimetry, Tuscon, 1997)



Cu-Be ribbon electrod

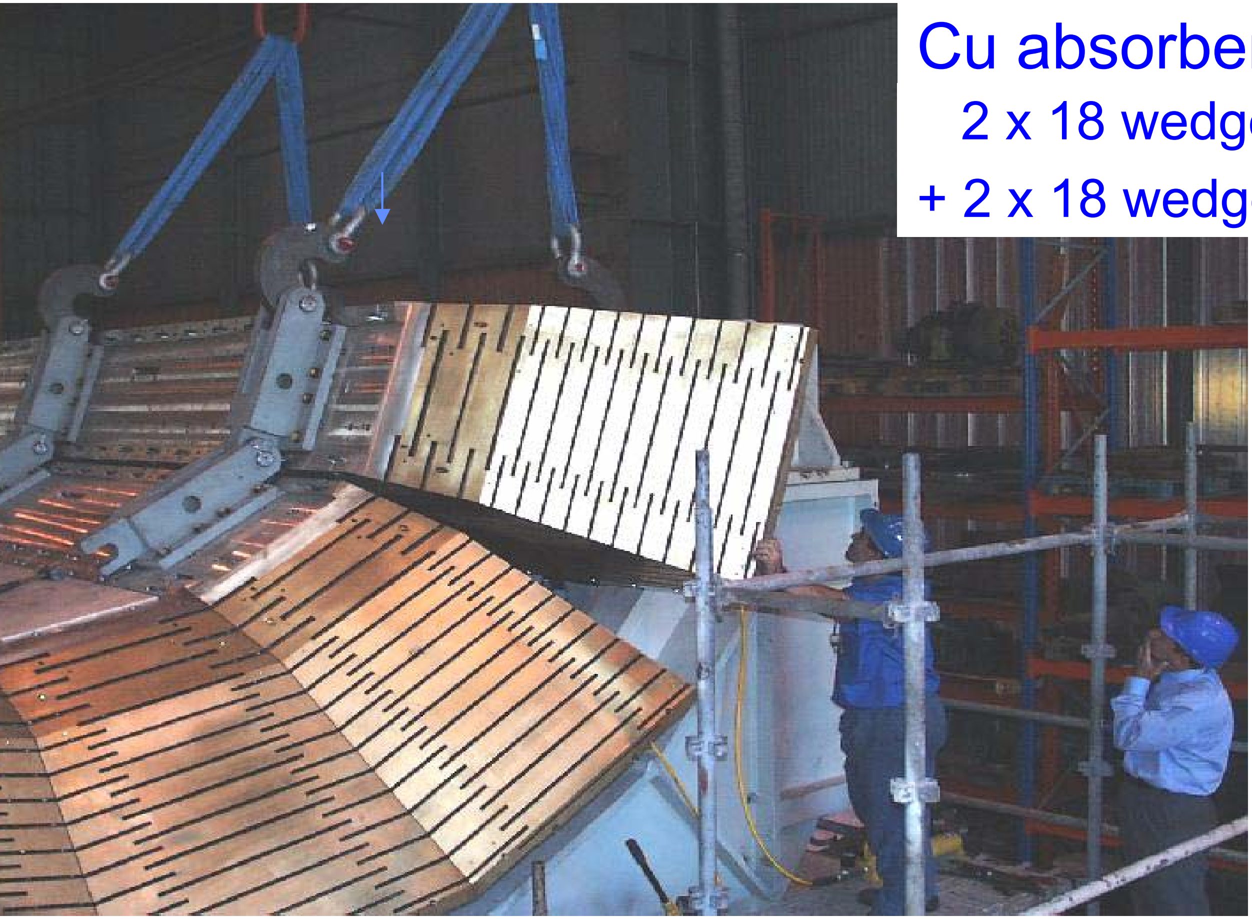


$\sigma_{x,y} \leq 1$ mm
$\sigma_t \approx 230$ ps

97 run: reduced performance due to proble with blocking capacitors → lower driftfield: 1 kV/cm rather than 5 kV/cm

ampling calorimeters

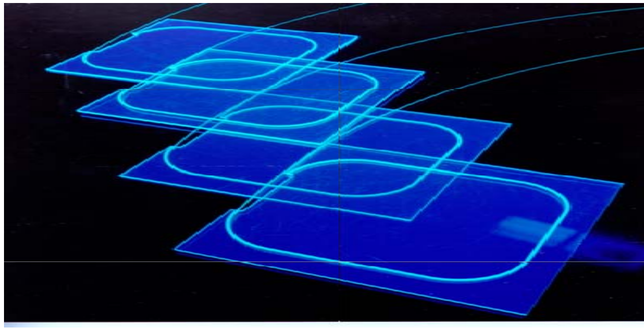
CMS Hadron calorimeter



Cu absorber + scintillators

2 x 18 wedges (barrel)

+ 2 x 18 wedges (endcap) ≈ 1500 T absorb



Scintillators fill slots and are read out via fibres by HPDs

st beam resolution for
ngle hadrons

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