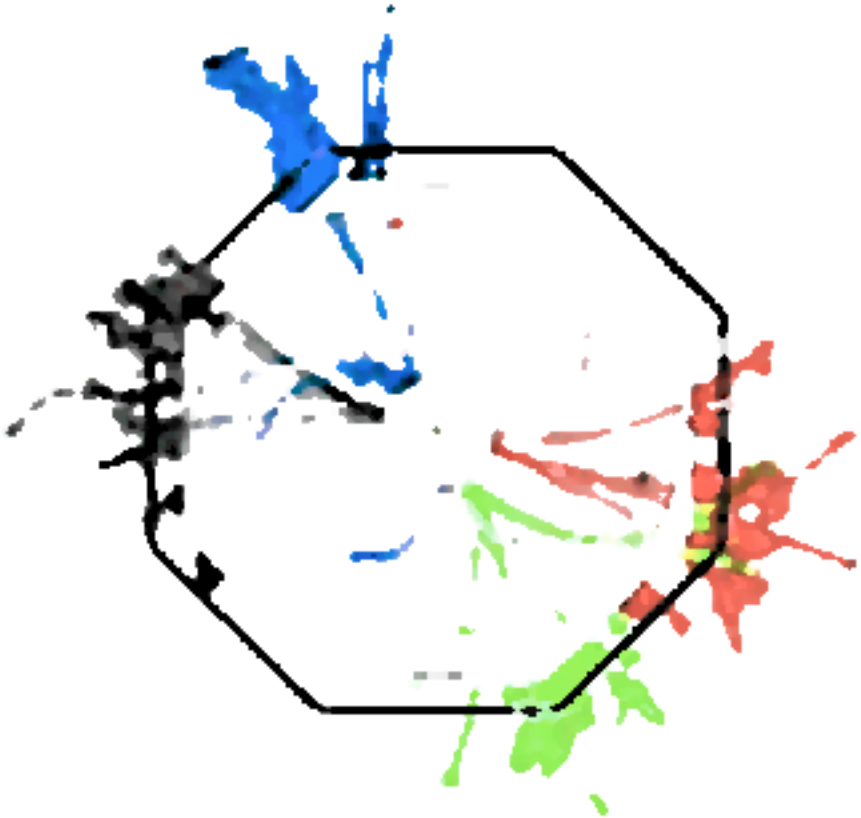

Calorimeters
- Part I -

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Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Outline

- Lecture 1 – Basics of calorimetry for HEP
  - Signal generation
  - Electromagnetic and hadronic processes
  - Sampling vs homogeneous calorimeters
  - 4D shower development
  - Signal detection
  - Response linearity and energy resolution
- Lecture 2 – Modern calorimeter systems (Martin Aleksa)
- Lecture 3 – Particle flow calorimeters (Katja Krüger)

Key questions:

- What is a calorimeter used for (in HEP)?

  Measure particle energy

- Of which particles is possible to measure the energy ?

  Stable charged and neutral particles with sufficiently long lifetime of $c\tau > 500\mu m$:

  $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$, K^0, n, γ

- How is the energy of a particle measured?

  Total absorption (destructive process) / conversion into measurable signal

  (NB. issue of muons)

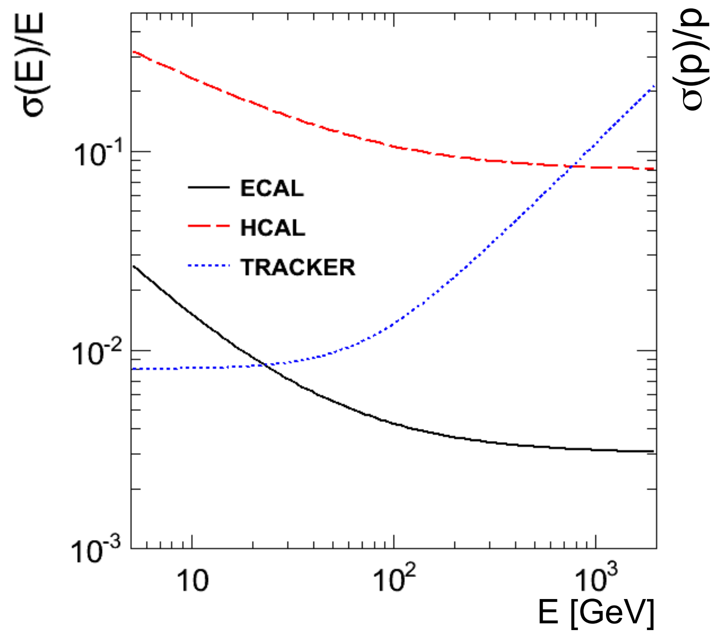
- What is the basic assumption in this method?

  $S = aE$

why calorimeters?

- Measure *charged + neutral* particles

- Performance of calorimeters *improves with energy* and is ~constant over 4π (Magn. Spectr. anisotropy due to B field)



Calorimeter: $\frac{\sigma_E}{E} \sim \frac{1}{\sqrt{E}}$

e.g. ATLAS:

$\frac{\sigma_E}{E} \approx \frac{0.1}{\sqrt{E}}$

i.e. σ_E/E = 1% @ 100 GeV

Gas detector: $\frac{\sigma_p}{p} \sim p$

e.g. ATLAS:

$\frac{\sigma_p}{p} \approx 5 \cdot 10^{-4} \cdot p_t$

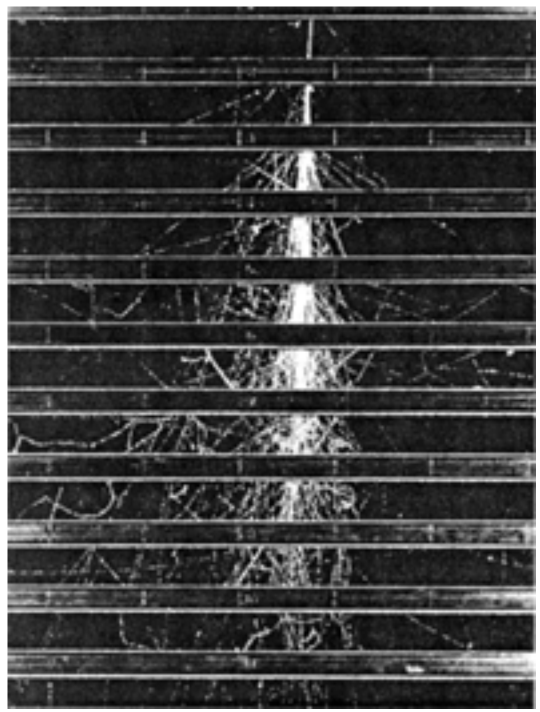
i.e. σ_p/p = 5% @ 100 GeV

- Obtain information *fast* (<100ns feasible) recognise and select interesting events in real time (*trigger*)

Signal generation

1. A particle deposits its full energy in the calorimeter media

2. The energy is converted into a measurable signal



Signal generation

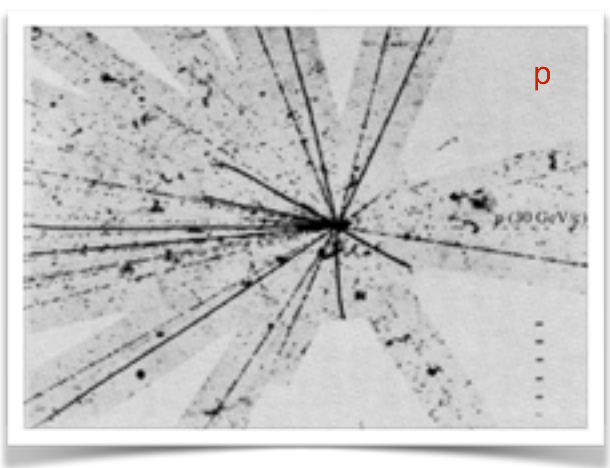
1. A particle deposits its full energy in the calorimeter media

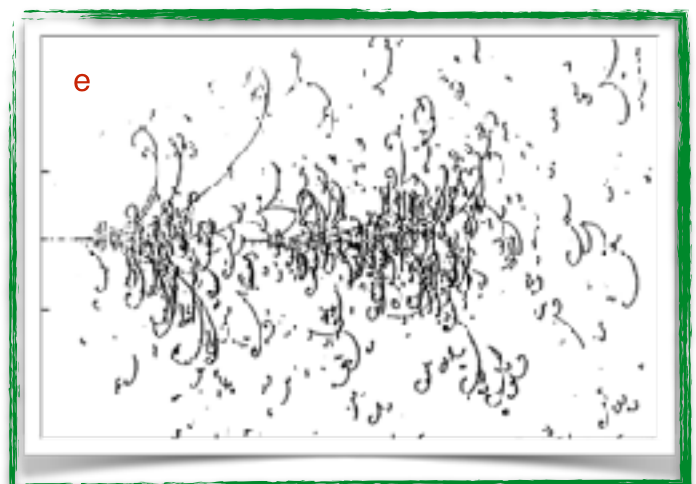
Interaction of particles & matter:

Process are particle & energy dependent

It depends on the kind of material the calorimeter is made of

Analytical description exists for electromagnetic (EM) processes but not for hadronic (HAD) processes





Electromagnetic Showers

Dominant processes at high energies (E > few MeV) :

Photons : Pair production

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

$$= \frac{7}{9}\frac{A}{N_A X_0}$$

[X_0: radiation length]
[in cm or g/cm^2]

Absorption coefficient:

$$\mu = n\sigma = \rho\frac{N_A}{A}\cdot\sigma_{\text{pair}} = \frac{7}{9}\frac{\rho}{X_0}$$

X_0 = radiation length in [g/cm^2]

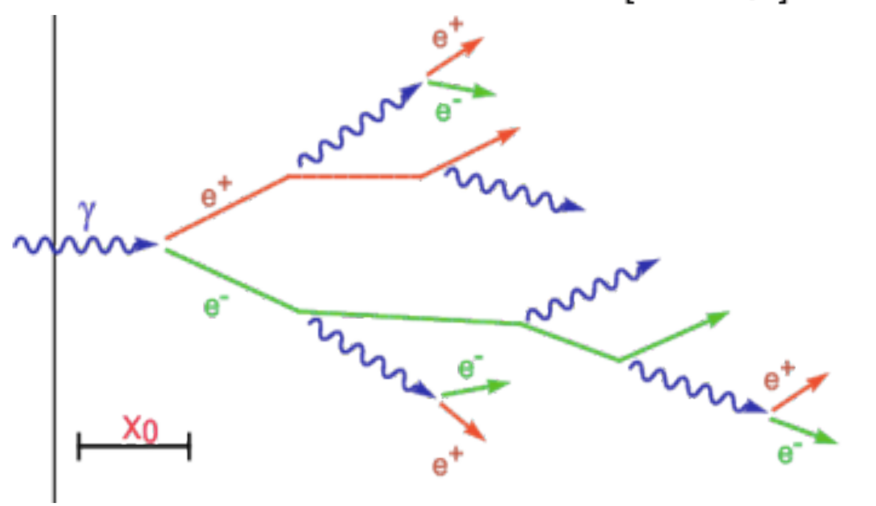
$$X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln\frac{183}{Z^{1/3}}}$$

Electrons : Bremsstrahlung

$$\frac{dE}{dx} = 4\alpha N_A\,\frac{Z^2}{A} r_e^2 \cdot E\ \ln\frac{183}{Z^{\frac{1}{3}}} = \frac{E}{X_0}$$

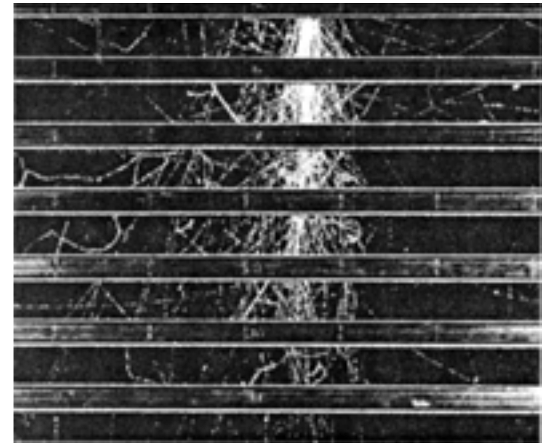
$$\rightarrow\ E = E_0 e^{-x/X_0}$$

After passage of one X_0 electron has only (1/e)th of its primary energy ...
[i.e. 37%]



Electromagnetic Showers

Cloud chamber photo of electromagnetic cascade between spaced lead plates.



Pic: MIT cosmic ray group

An alternating sequence of interactions leads to a cascade

Simplified shower model [Heitler]

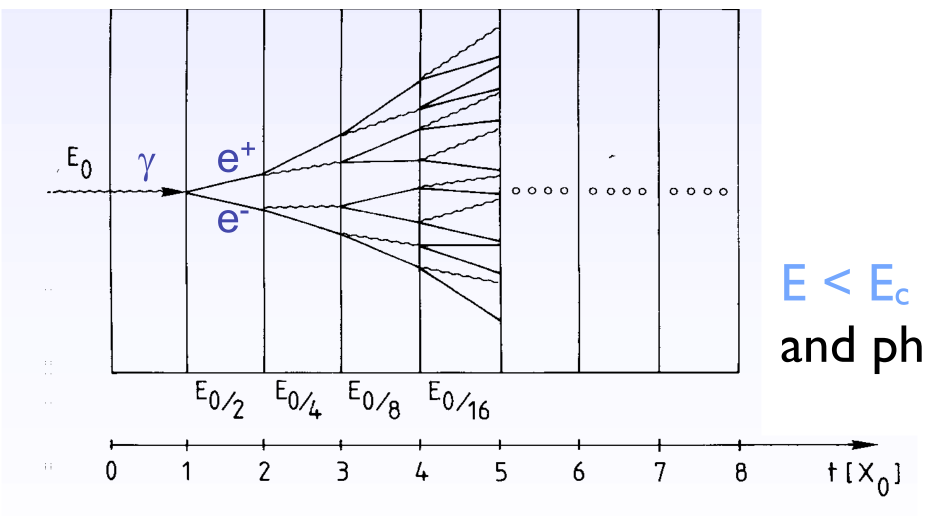
$E > E_c$: shower development governed by X_0

e⁻ loses energy via Bremsstrahlung

γ pair production with *mean free path* $9/7\ X_0$

Number of particles doubles every X_0 of material,

till the particles energy reaches E_c



$$N_{\text{max}} = 2^{t_{\text{max}}} = \frac{E_0}{E_c}$$

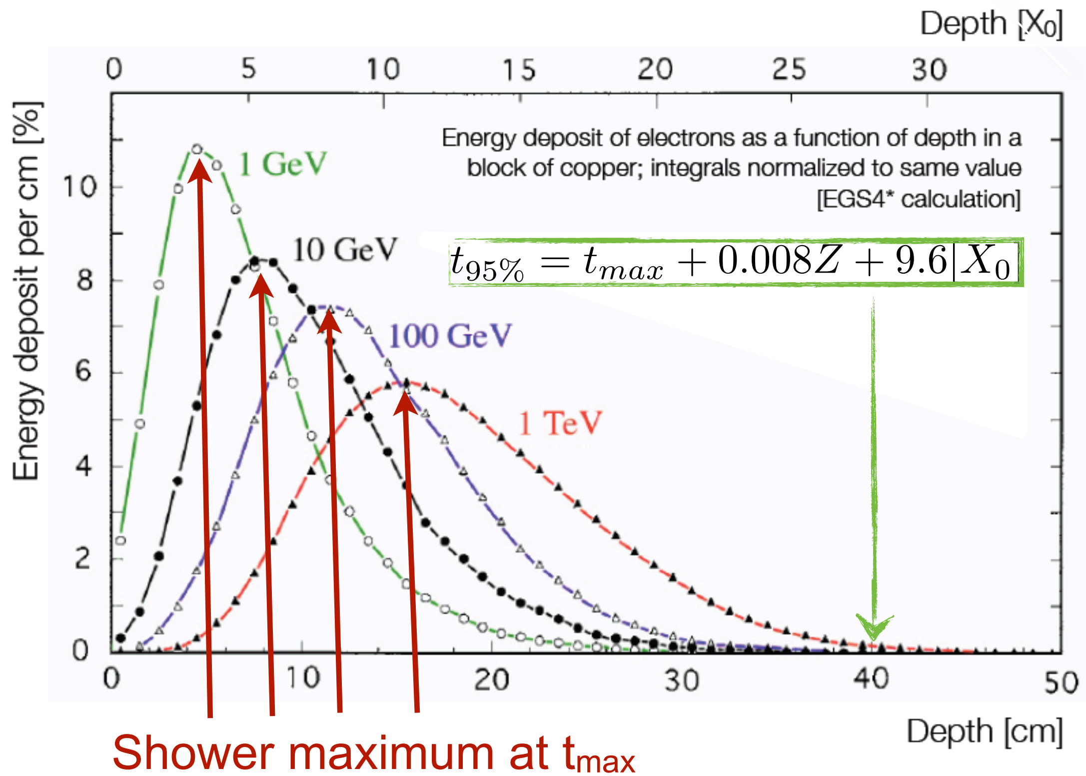
$E < E_c$: energy loss only via ionization/excitation and photo- absorption

EM Shower Properties

- Shower continues until energy of particles below critical energy

$$t_{max} = \frac{\ln \frac{E_0}{E_c}}{\ln 2} \qquad N_{max} \simeq \frac{E_0}{E_c}$$

Key feature in calorimetry:
Shower increases longitudinally with the logarithm of the incident particle energy
➡ Calorimeters can be compact



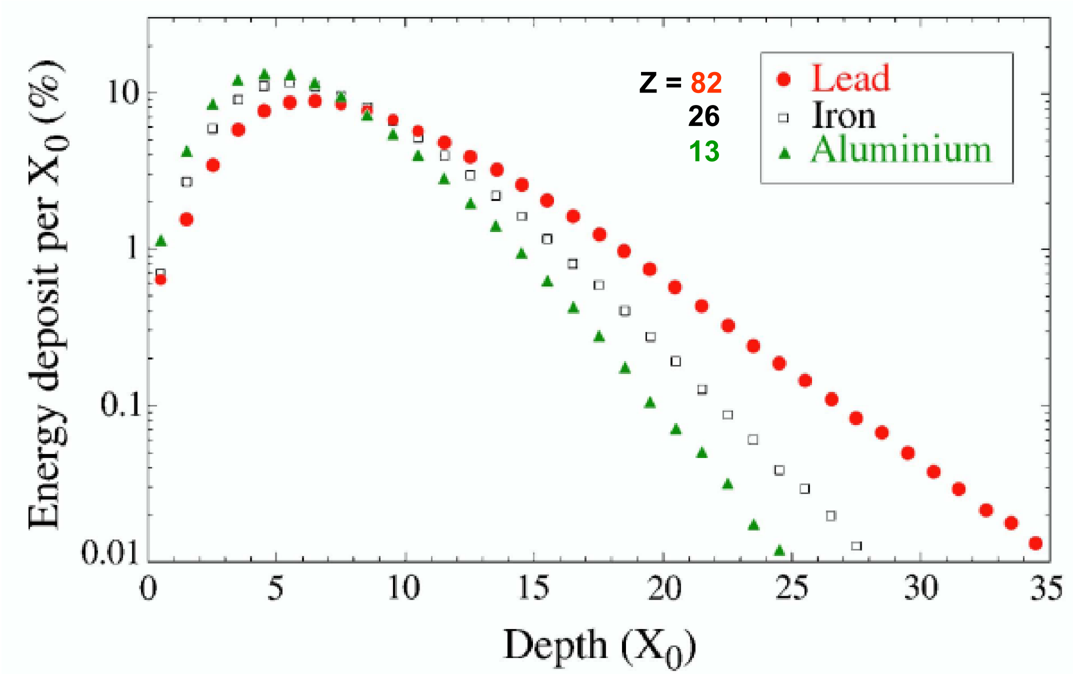
Some numbers: $E_c \approx 10$ MeV, $E_0 = 1$ GeV ➔ $t_{max} = \ln 100 \approx 4.5$; $N_{max} = 100$ $t_{95\%} \sim 10\ X_0$
$E_0 = 100$ GeV ➔ $t_{max} = \ln 10000 \approx 9.2$; $N_{max} = 10000$ $t_{95\%} \sim 20\ X_0$

	Szint.	LAr	Fe	Pb	W
X_0(cm)	34	14	1.76	0.56	0.35

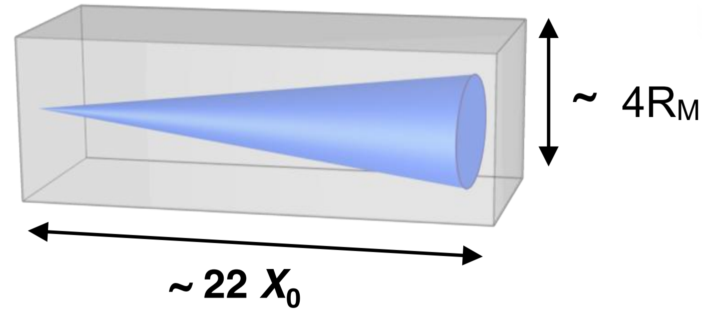
➔ 100 GeV electron contained in 16 cm Fe or 5 cm Pb

EM shower - a more complex reality

- Shower maximum depends slightly on material
- After maximum the shower decays via ionization and Compton scattering
- The process is slower for high-Z materials NOT proportional to X_0

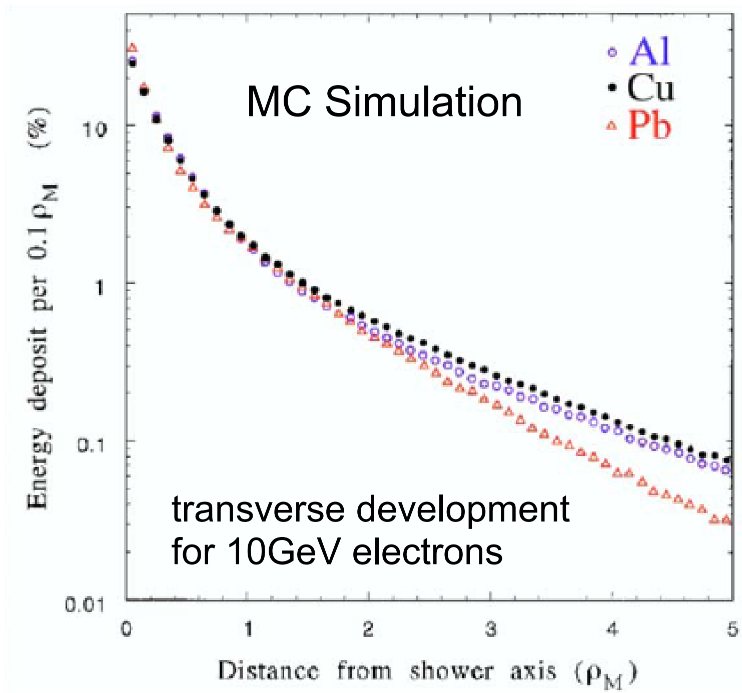


EM Shower Properties



- Longitudinal development governed by the radiation length X_0

- Lateral spread due to electron undergoing multiple Coulomb scattering [Molière theory]:
 95% of the shower cone is located in a cylinder with radius 2 R_M



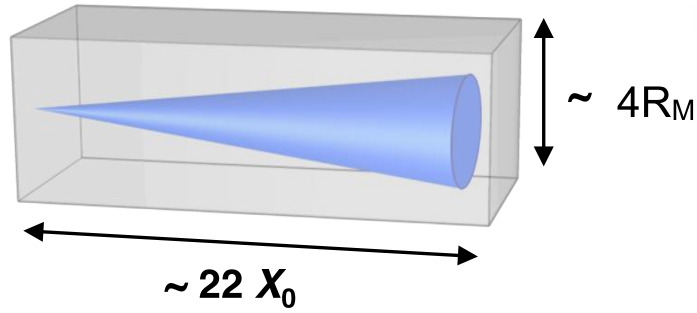
$$R_M = \frac{E_s}{E_c} X_0 \approx \frac{21MeV}{E_c} X_0$$

$$E_s = \sqrt{\frac{4\pi}{\alpha}}(m_e c^2) = 21.2 \text{ MeV}$$

[Scale Energy]

- Lateral width scales with the **Molière radius R_M**
- Important parameter for shower separation

Example



electron with E_0 = 100 GeV
in lead glass E_c = 11.8 MeV
$X_0 \approx$ 2 cm

$$t_{max} = \frac{\ln \frac{E_0}{E_c}}{\ln 2}$$ ~ 13 X_0 = 26 cm

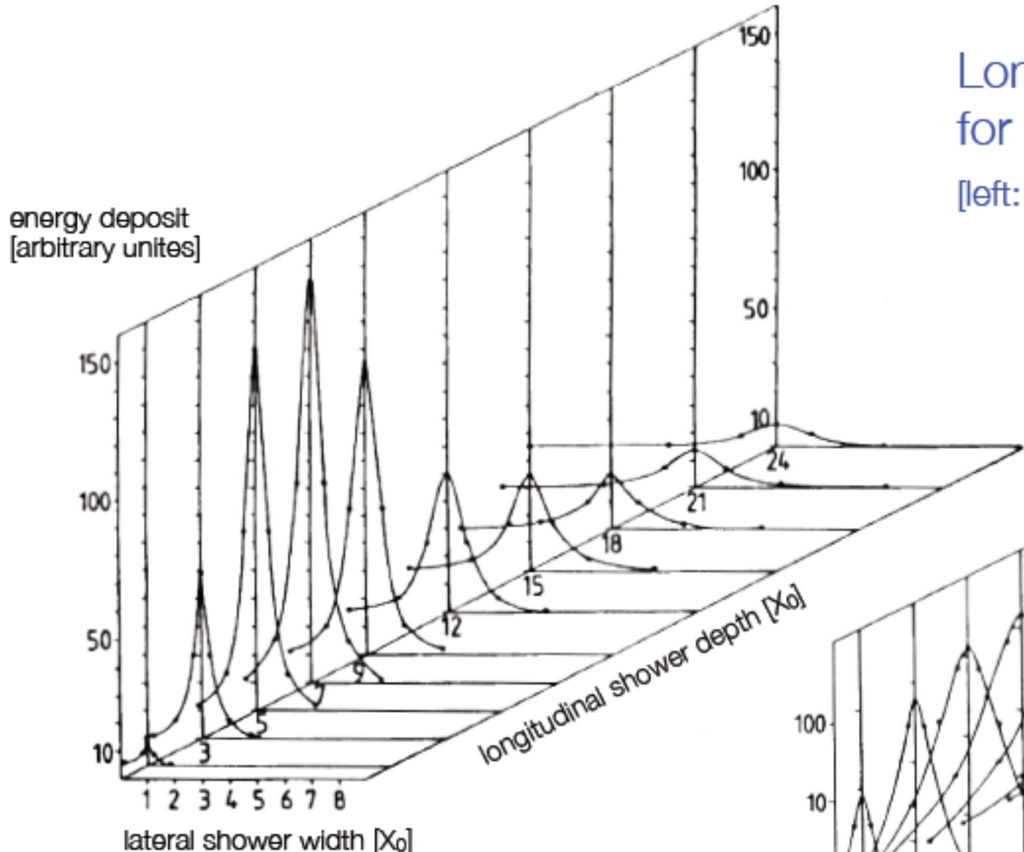
$$t_{95\%} = t_{max} + 0.008Z + 9.6[X_0]$$ ~ 23 X_0 = 46 cm

$$N_{\max} = 2^{t_{\max}} = \frac{E_0}{E_c}$$ ~ 8000

$$R_M = \frac{E_s}{E_c} X_0 \approx \frac{21MeV}{E_c} X_0$$ ~ 3.6 cm

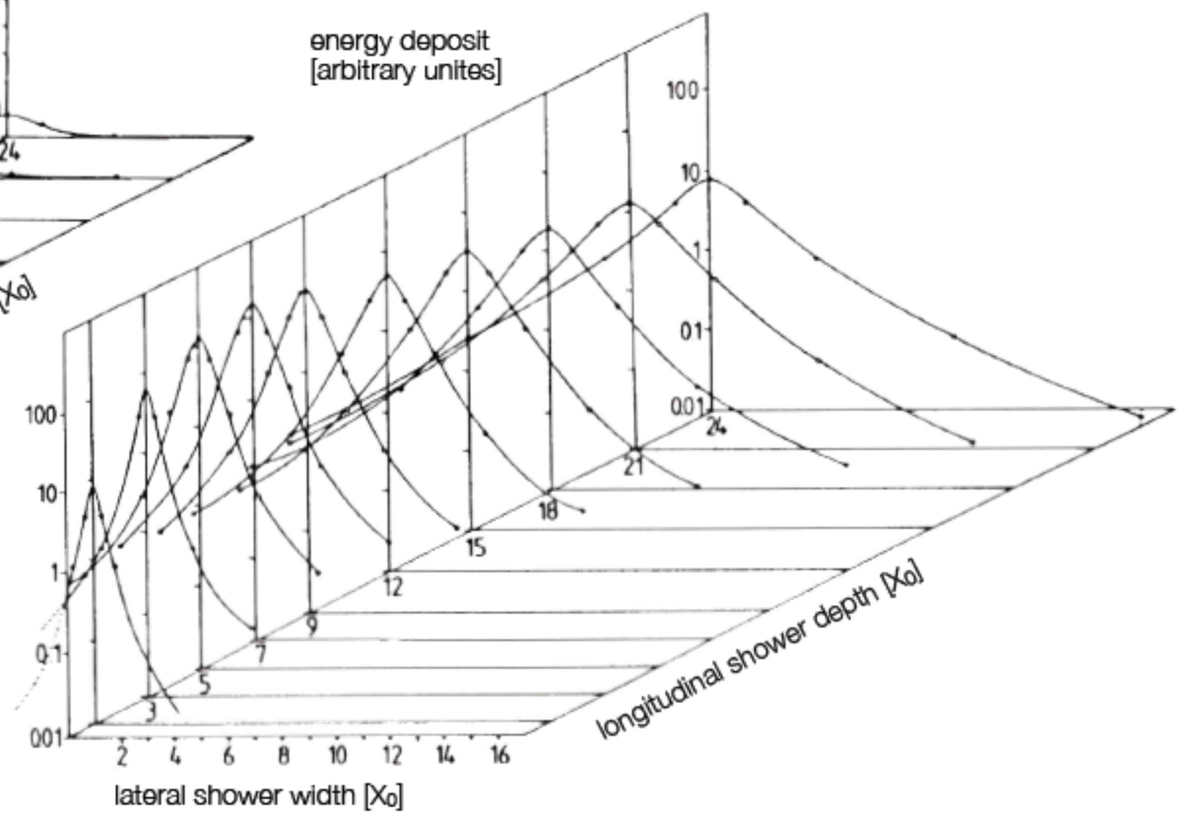
$R(95\%) = 2\, R_M$ ~ 7.2 cm

3D development of EM showers



Longitudinal and transversal shower profile for a 6 GeV electron in lead absorber ...

[left: linear scale; right: logarithmic scale]



Note: time development of EM processes is instantaneous from the detector point of view

Signal generation

1. A particle deposits its full energy in the calorimeter media

2. The energy is converted into a measurable signal (charge / light / sound / heat)

⇩

- The most used materials:
  - gases / semiconductors / scintillators
- ... but also:
  - Cherenkov radiators / water - ice / antennas / metals or liquids ...

Principle of energy conversion

COST:

- semiconductors: dE/dx or photo-absorption + drift of e-h — eV per e-hole pair
- gases: dE/dx or photo-absorption + charge diffusion — 20-40 eV per e-ion pair
- scintillators: dE/dx or photo-absorption + light emission — 400-1000 eV per photon

⇨ generated charges or photons yield the measurable signal:
statistical process = the more the better !

Historically

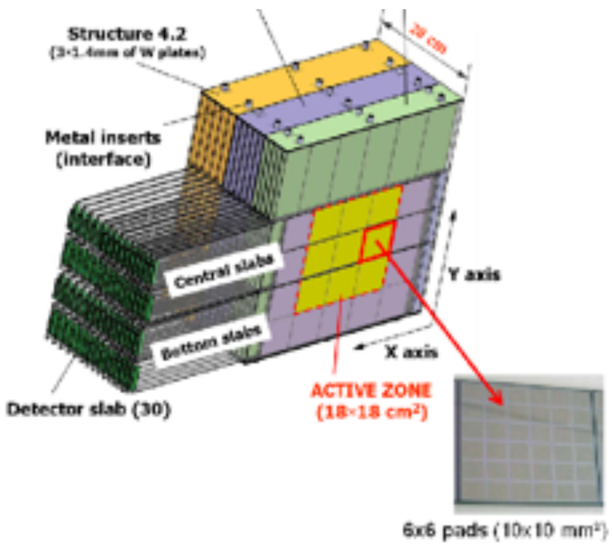
- semiconductors & gas mainly used in tracker detectors
  ➔ p measurement (+ dE/dx)

- scintillators (organic/inorganic) mainly used in calorimeters
  ➔ E measurement

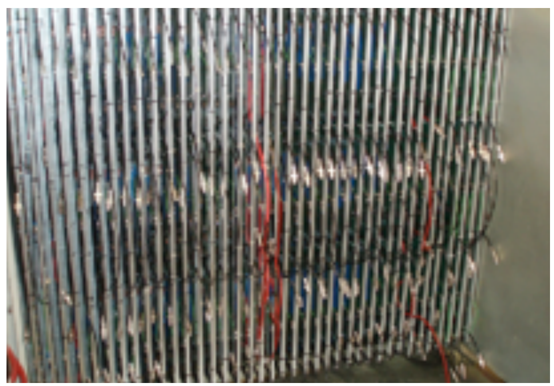
- ... but exceptions exist

as detector developer be open minded and daring !

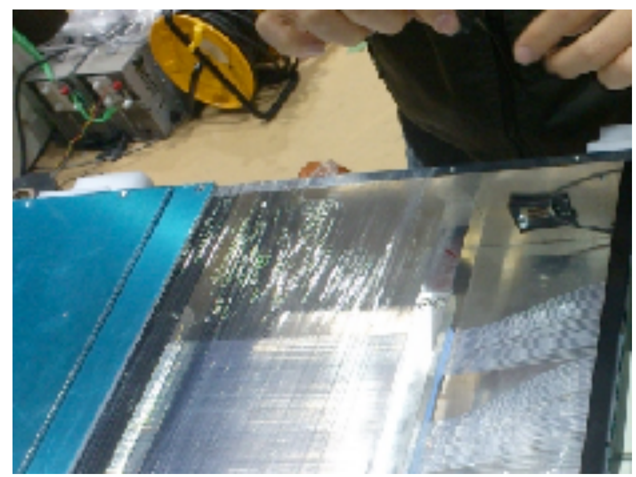
Silicon - ECAL



Gas readout for HCAL



Fiber tracker

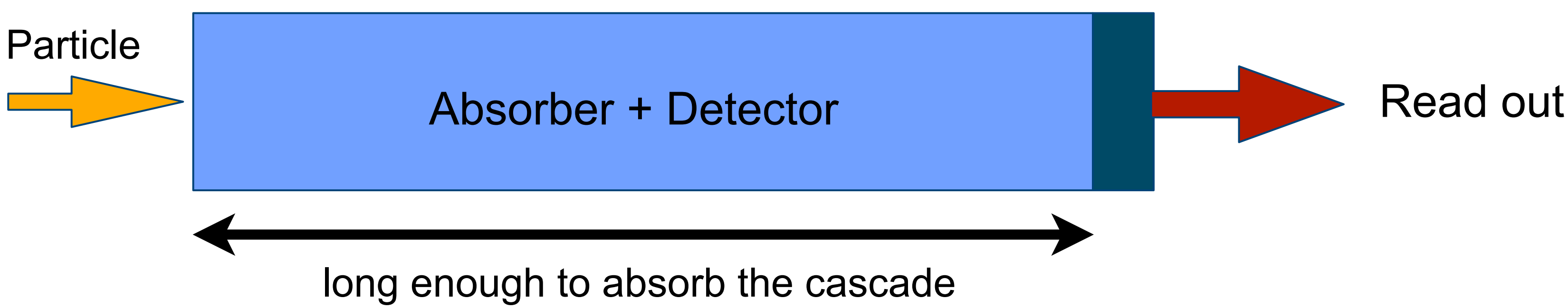


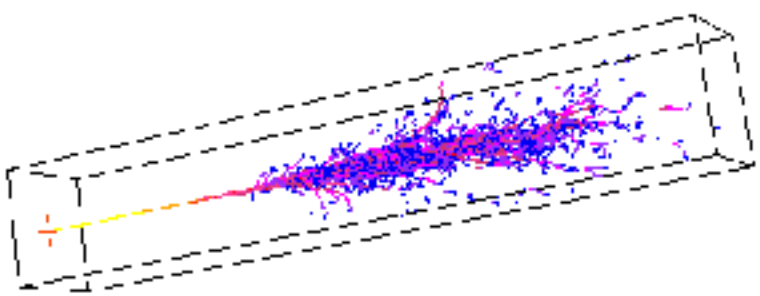
Calorimeter Types

- Most commonly used: Homogeneous and Sampling Calorimeter

Homogeneous Calorimeter

- The absorber material is active; all deposited energy is converted into signal
- Pro: very good energy resolution
- Contra: segmentation difficult, selection of material is limited, expensive





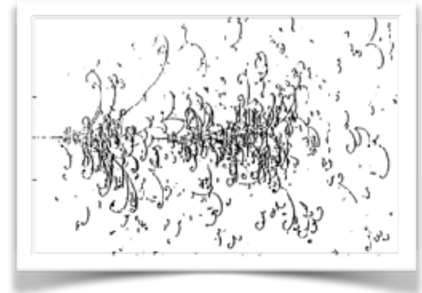
Pic: Cornell

Example: CMS electromagnetic calorimeter

design not suitable for hadronic calorimeters

Calorimeter Types

- Most commonly used: Homogeneous and Sampling Calorimeter



Homogeneous Calorimeter

Pro: very good energy resolution - **why ?**

- Detectable signal is proportional to the total track length of e+ and e- in the active material
- Intrinsic limit on σ(E)/E due to fluctuations in the fraction (f_s) of initial energy that generates detectable signal, or the detectable portion of track

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

$T_r = f_s T_0$

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

E_C = critical energy (ionization = Bremsstrahlung)

$$\frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{f_s}} \sqrt{\frac{E_C}{X_0}} \propto \frac{1}{\sqrt{f_s}} \sqrt{\frac{Z}{A}}$$

- minimize Z/A
- maximize f_s

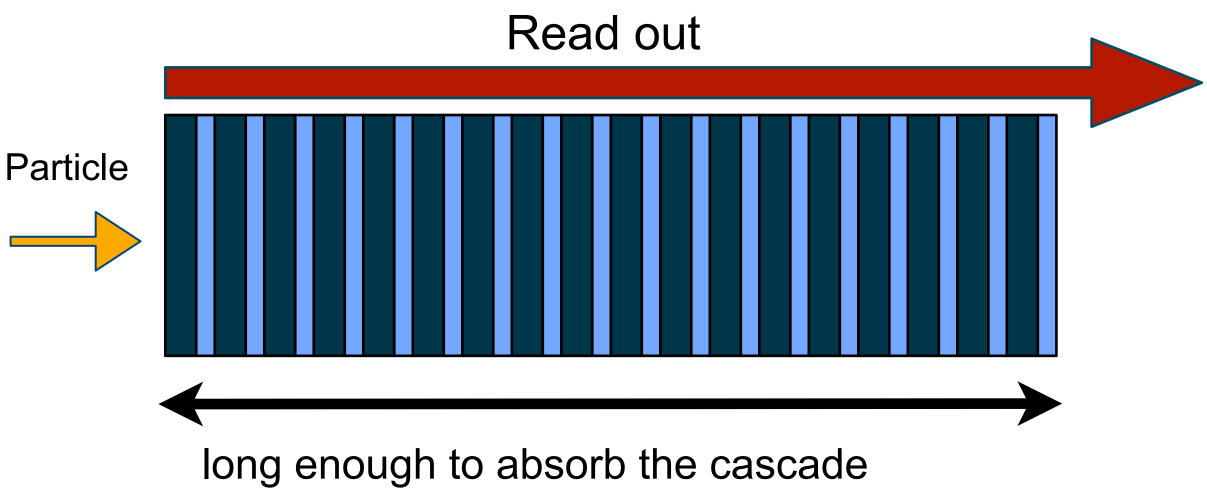
$$f_s = \frac{E_0 - N_{max} E_{th}}{E_0}$$

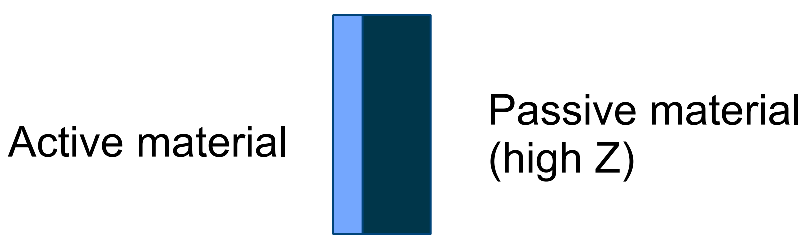
- Homogeneous calorimeter all e+e- over threshold produce signal
  i.e. scintillating crystals E_s~eV, 10^2-10^4 γ/MeV ➔ σ(E)/E ~ 1-3% / √E

Calorimeter Types

Sampling Calorimeter

- A structure of passive and active material; a fraction (**Sampling Fraction, f_S**) of the deposited energy is detected (1-5%)
- Pro: Segmentation, compact detectors by the usage of dense materials (W, U)
- Contra: Energy resolution is limited by fluctuations





Example: ZEUS Uranium Calorimeter,
ATLAS electromagnetic calorimeter
ATLAS / CMS hadronic calorimeters, ...

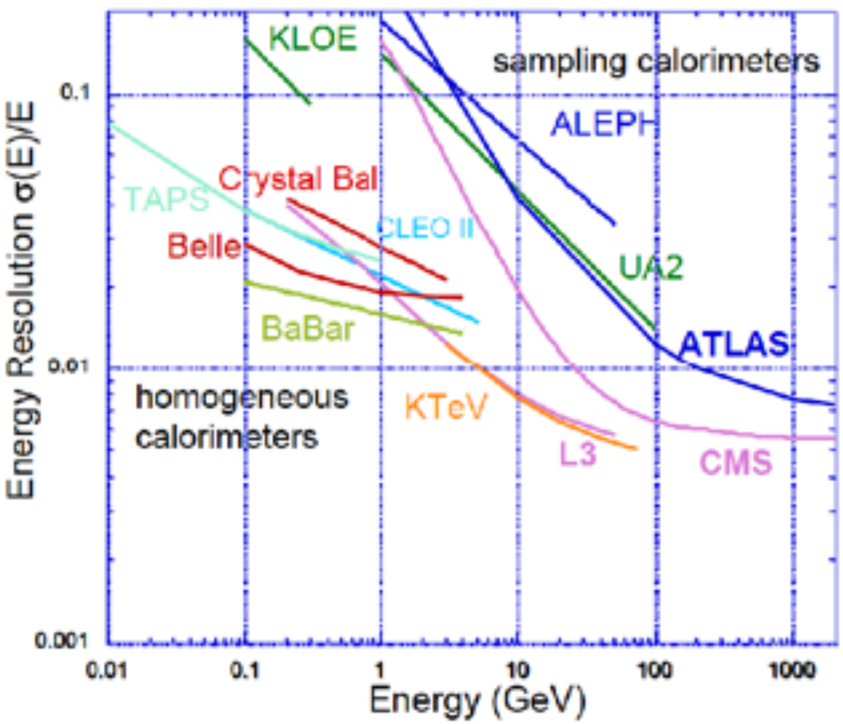
Calorimeter Types

Sampling Calorimeter

- A structure of passive and active material; a fraction (**Sampling Fraction, f_S**) of the deposited energy is detected (1-5%)

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

$$T_r = f_s T_0 = f_s N_{tot} X_0^{abs} \approx f_s \frac{E}{E_C^{abs}} X_0^{abs}$$



Resolution scales with absorber thickness $t_{abs} = d/X_0$

$$\frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{N_r}} \propto \frac{1}{\sqrt{f_s}} \sqrt{\frac{E_C t_{abs}}{E}}$$

σ(E)/E ~ 10-20% / √E

➔ Each system optimised to the energy range & physics of interest for the experiment

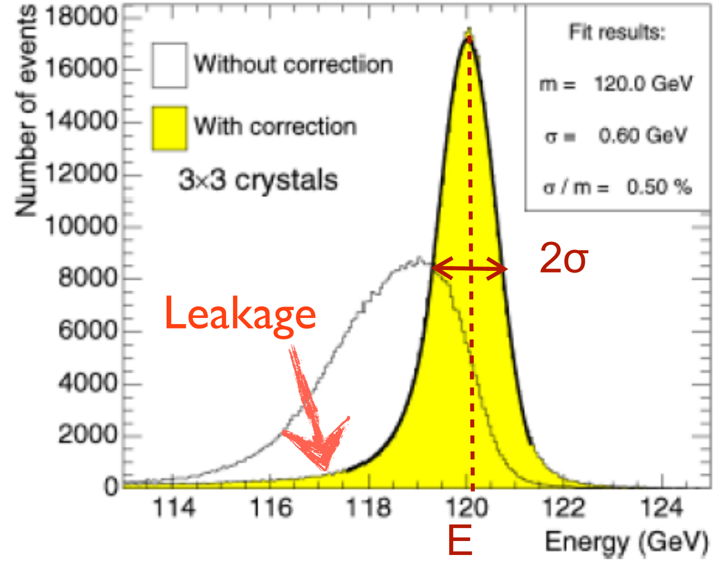
Energy resolution

- The **energy resolution** is parametrized as:

$$\frac{\sigma(E)}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + \left(\frac{b}{E}\right)^2 + c^2}$$

or

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



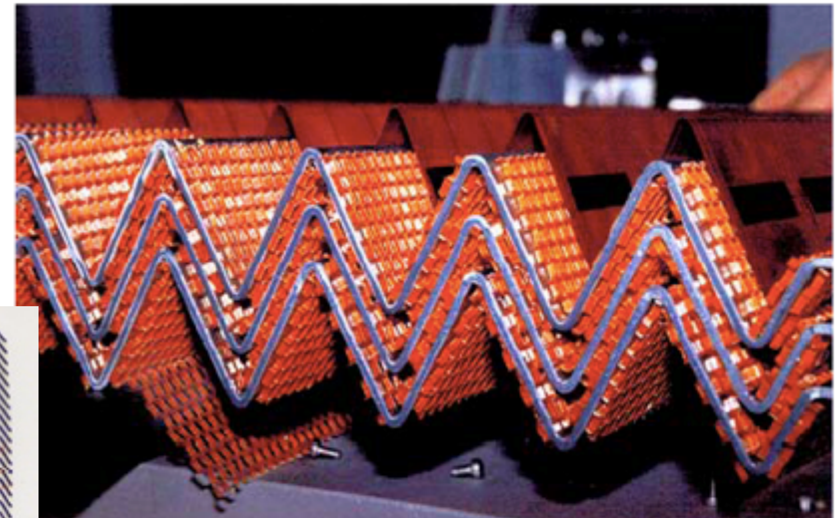
- Stochastic term **a**
  - $E \propto N \rightarrow \sigma \propto 1/\sqrt{N}$: all statistical effects contribute

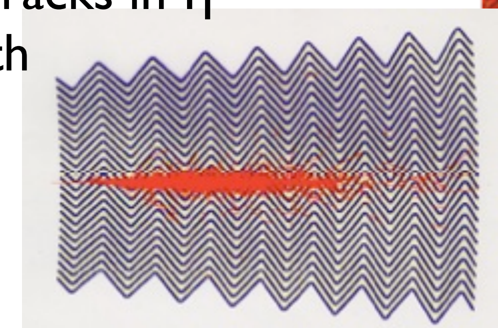
    i.e. intrinsic and sampling fluctuations, photoelectron statistics
- Noise term **b** (energy independent term) relevant at low E
  - Electronic noise, radioactivity
- Constant term **c** (linearly dependent of energy) dominates at high E
  - inhomogeneities, calibration uncertainties, radiation damage, (leakage), ...

Examples of electromagnetic calorimeters

ATLAS EM barrel calorimeter

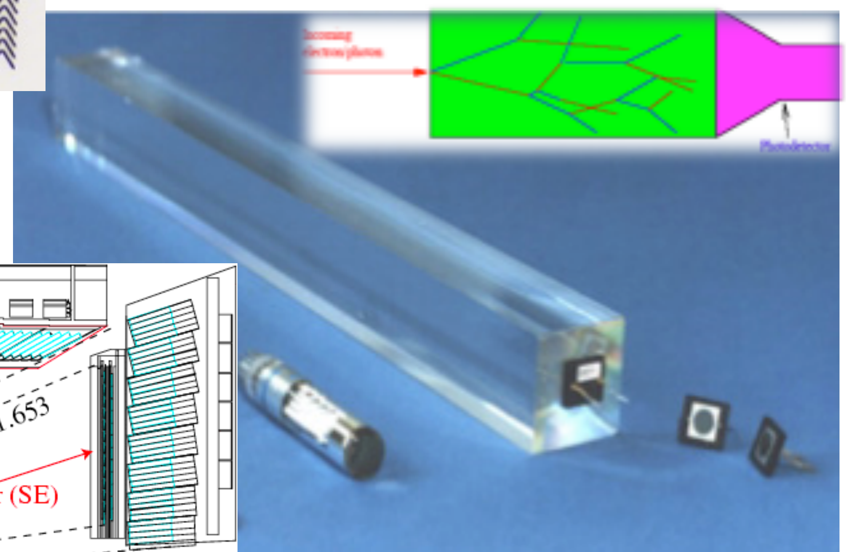
- Honeycomb spacers position the electrodes between the lead absorber plates
- Liquid Argon at 90°K flows through.
- Radiation resistant, no cracks in η
- Accordion structure with Pb-LAr sampling

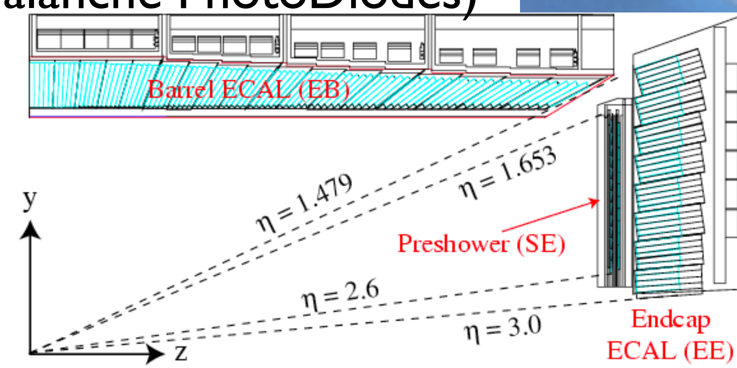




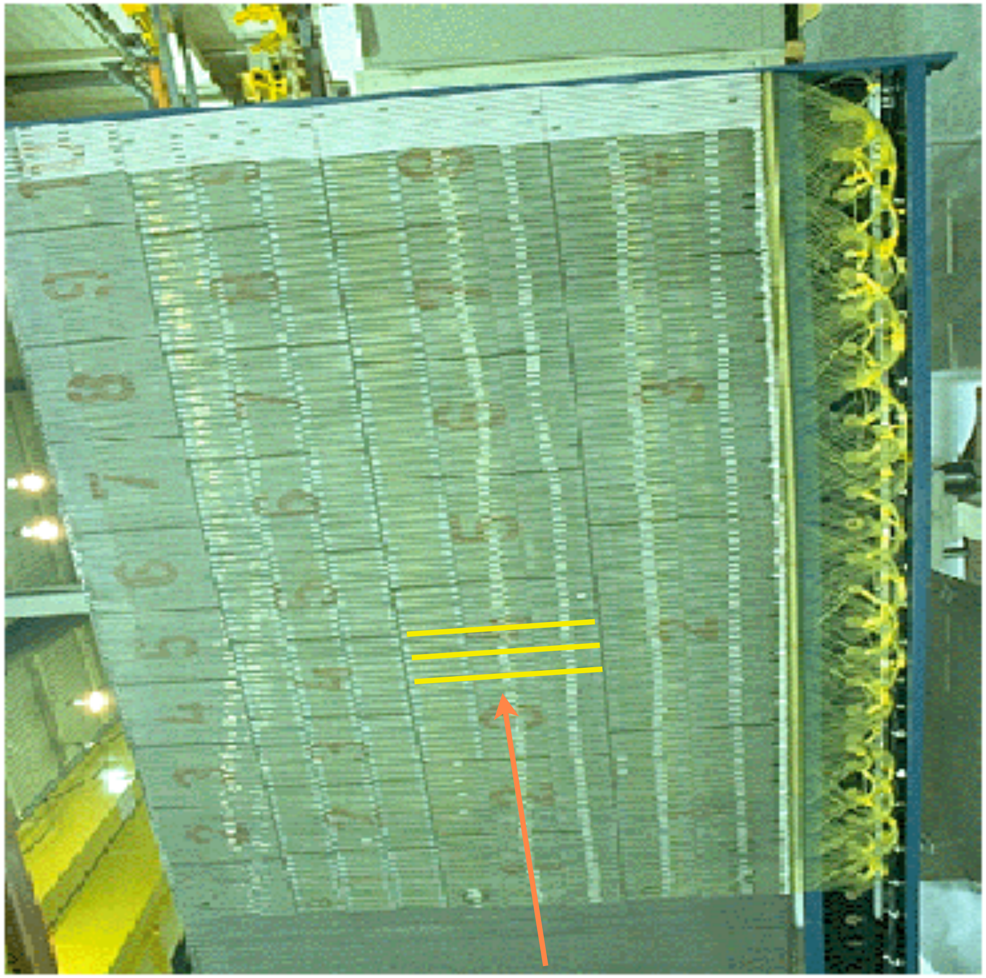
CMS EM barrel calorimeter

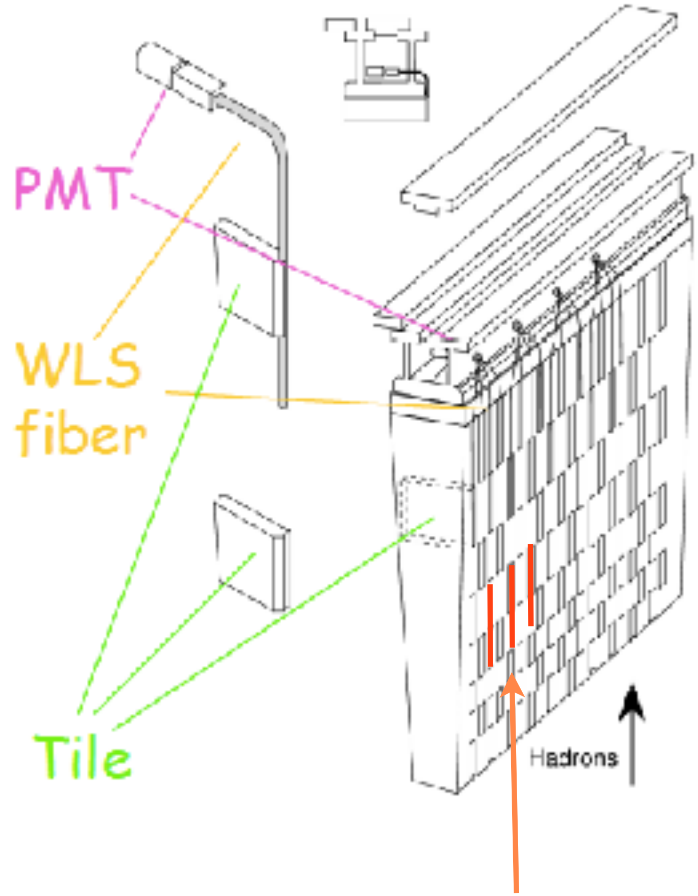
- PbWO4 crystals (230x22x22 mm³)
- Read out by APD (Avalanche PhotoDiodes)
- Homogeneous





Examples of hadronic calorimeters





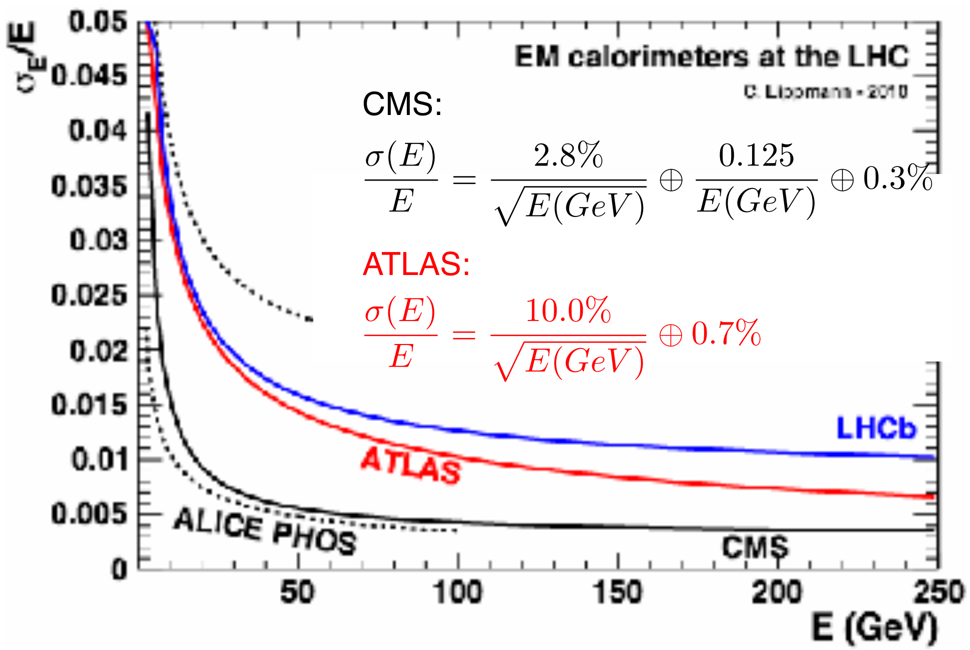
CMS: Brass/scintillator
longitudinal orientation

ATLAS: Fe/scintillator
vertical orientiation

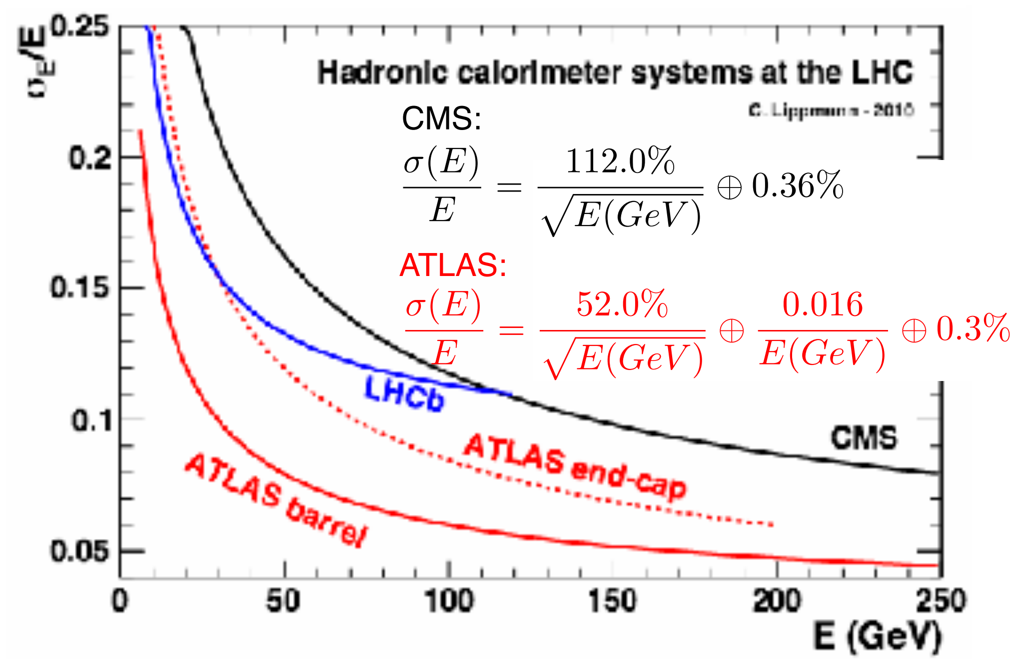
Resolution comparison

Reported energy resolutions for single particles from test beam measurements:

electrons



pions



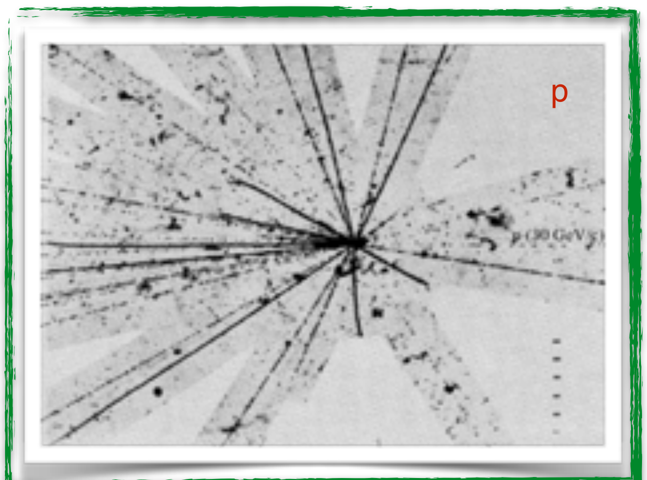
Material upstream the calorimeter degrades E resolution performance:
loss of energy in tracker / support structure / cables /cooling / readout electronics

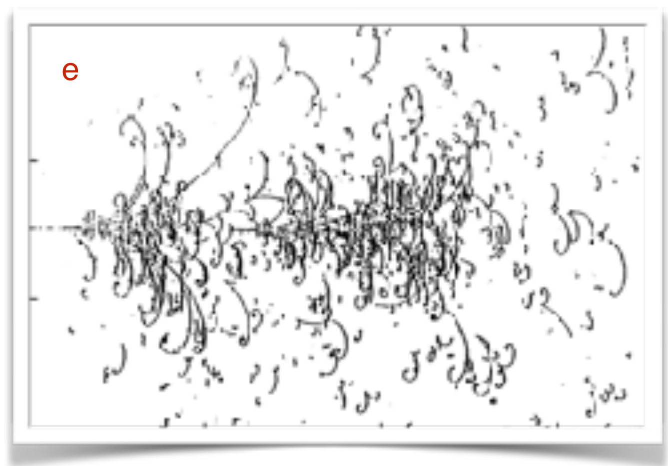
Why are hadronic calorimeters worse than EM ones?
Signal generation

1. A particle deposits its full energy in the calorimeter media

Interaction of particles & matter:

Process are particle & energy dependent
It depends on the kind of material the calorimeter is made of
Analytical description exists for electromagnetic (EM) processes but not for hadronic (HAD) processes





Hadronic shower

Extra complication: ***The strong interaction*** with detector material.

Produced in nuclear collisions:

high energetic secondary hadrons [O(GeV)]

electromagnetically decaying particles (π_0,η) initiate EM showers

spallation p/n and nuclear excitation from soft nuclear processes [O(MeV)]

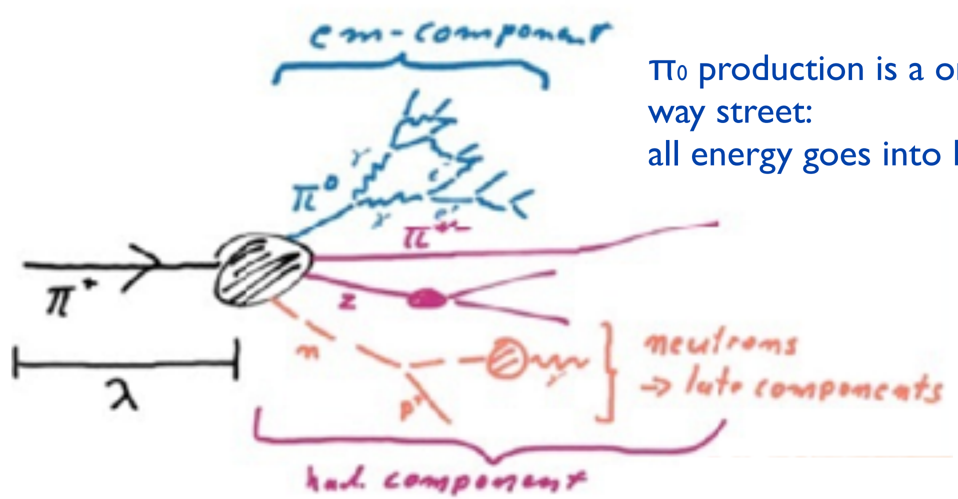
part of the energy is invisible: binding energy of nuclei, ν, μ, soft γ's

Different scale: hadronic interaction length $\lambda_l = \frac{A}{N_A \sigma_{total}}$

σ_{tot} = total cross section for nuclear processes

	λ_I	X_0
Polystyren	81.7 cm	43.8 cm
PbWO	20.2 cm	0.9 cm
Fe	16.7 cm	1.8 cm
W	9.9 cm	0.35 cm

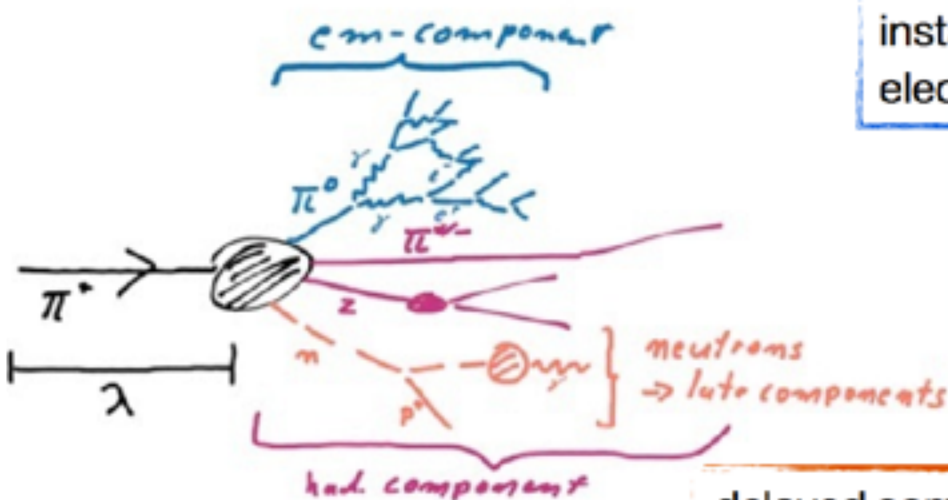
Compare X_0 for high-Z materials, we see that the size needed for hadron calorimeters is large compared to EM calorimeters.



π_0 production is a one way street: all energy goes into EM

The structure of hadronic showers

- hadronic showers have a complex structure also in time



instantaneous, detected via energy loss of electrons and positrons in active medium

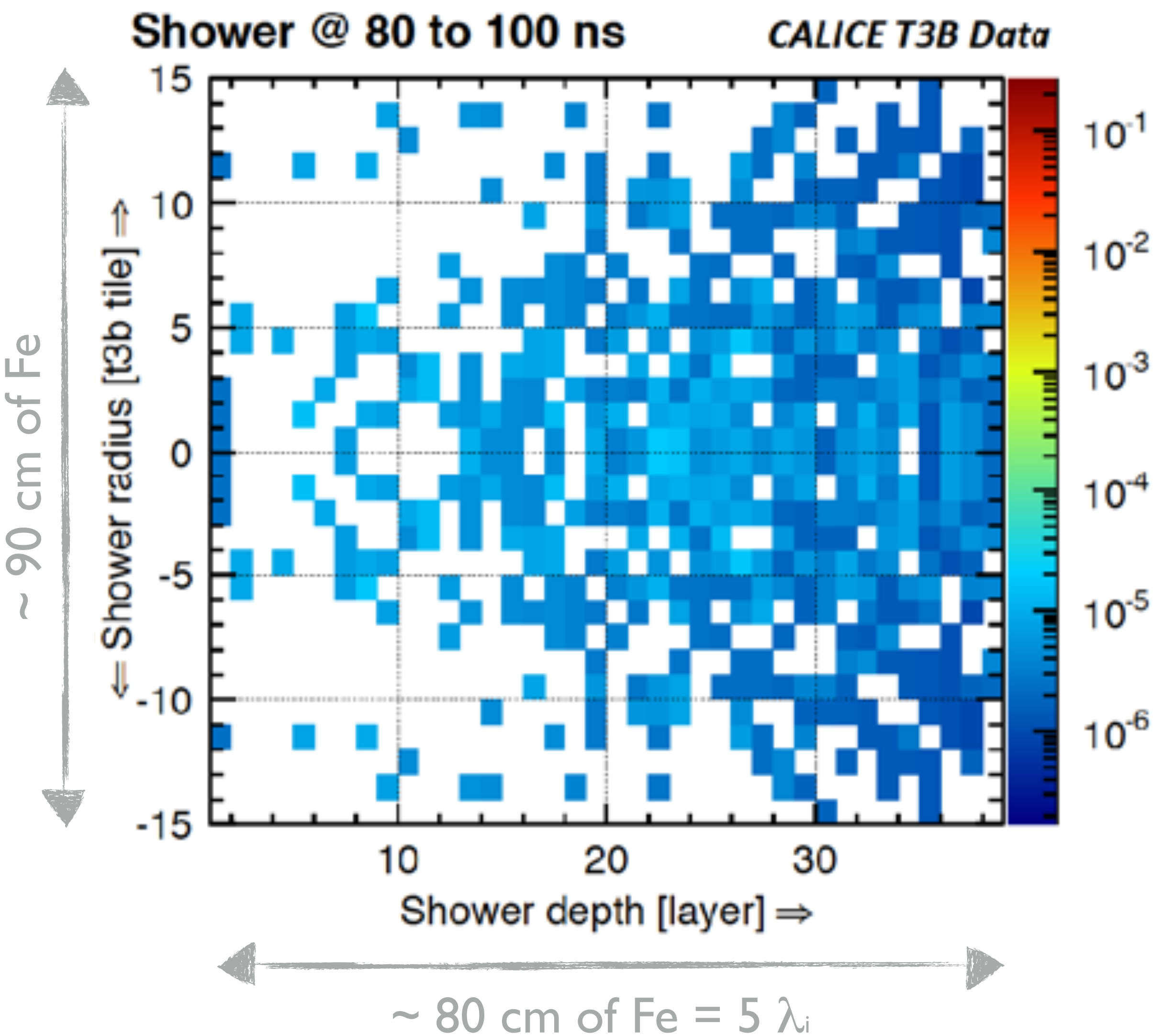
instantaneous component: charged hadrons detected via energy loss of charged hadrons in active medium

f_{EM} = fraction of primary hadron energy deposited via EM processes

delayed component:
- neutrons from evaporation and spallation
- photons, neutrons, protons from nuclear de-excitation following neutron capture
- momentum transfer to protons in hydrogenous active medium from slow neutrons

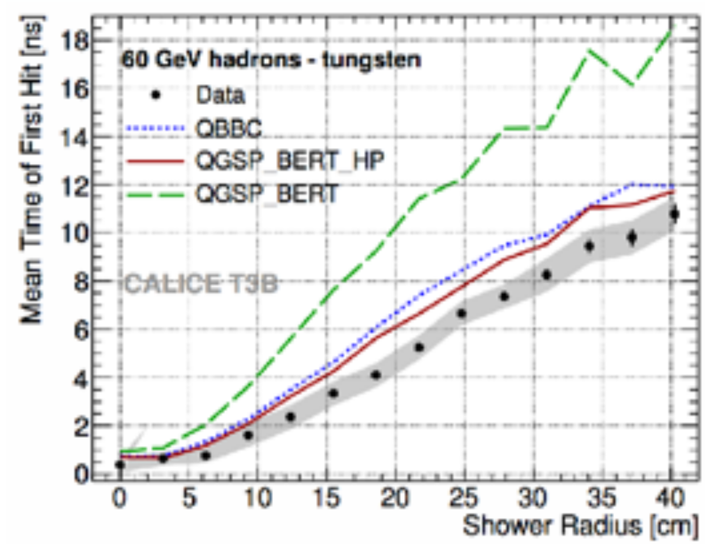
- Importance of delayed component strongly depends on target nucleus
- Sensitivity to time structure depends on the choice of active medium

4D development of HAD showers



C. Adloff et al. (CALICE), JINST 9 (2014) P0702

- 60 GeV pion shower in a highly segmented Fe/scint calo.
- 5 λ_i not sufficient for longitudinal containment (~11 λ_i necessary)
- Significant portion of energy deposited at t > 25 ns
- Not always well described in MC



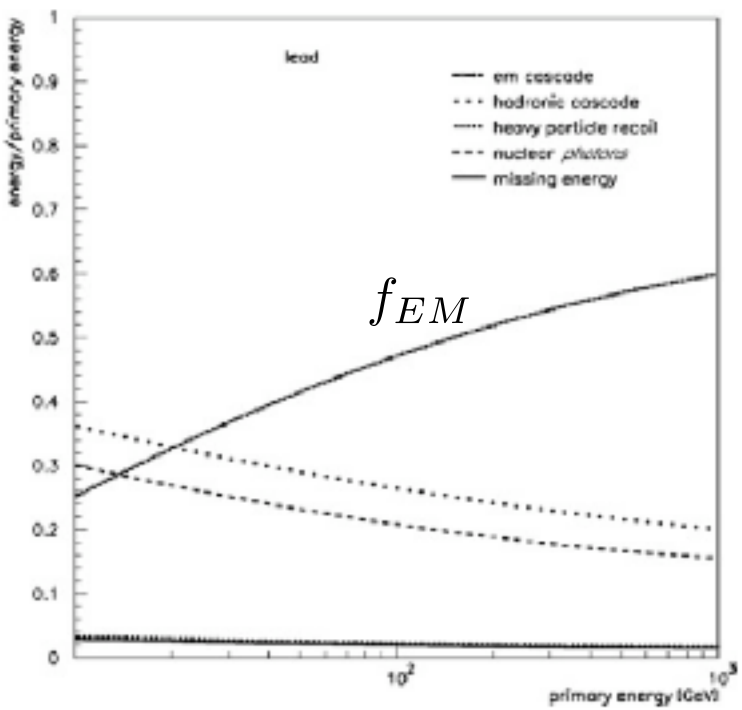
Hadronic calorimeter

The concept of compensation

- A hadron calorimeter shows in general different response to hadronic and electromagnetic shower components

$$R_h = eE_e + hE_h$$

- The fraction of the energy deposited hadronically depends on the energy



$$\frac{E_h}{E} = 1 - f_{EM} = 1 - klnE(GeV) \quad k \approx 0.1$$

C. Fabjan, F. Gianotti, Rev. Mod. Phys. 75, 1243 (2003)

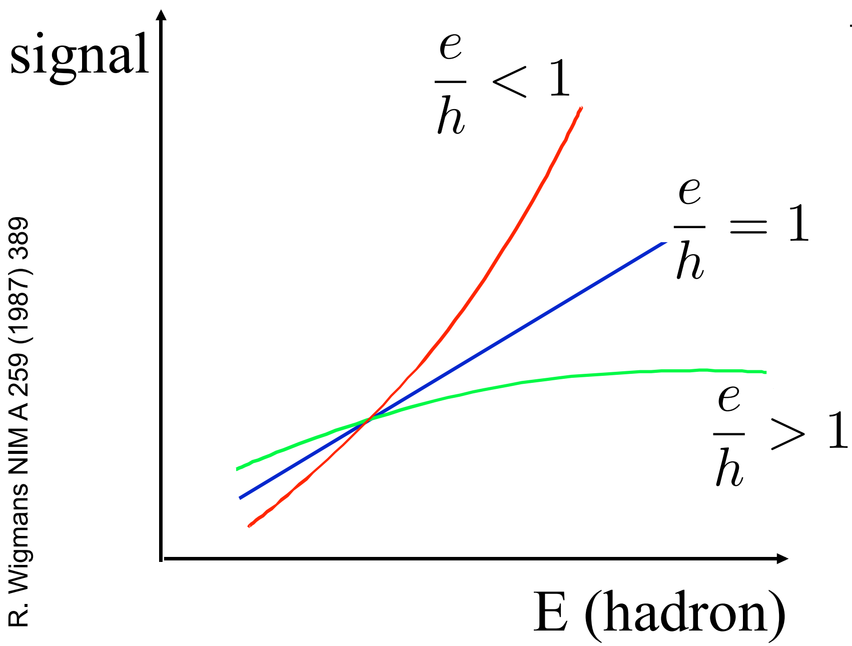
Hadronic calorimeter

The concept of compensation

- A hadron calorimeter shows in general different response to hadronic and electromagnetic shower components

$$R_h = eE_e + hE_h$$

- The fraction of the energy deposited hadronically depends on the energy



$$\frac{E_h}{E} = 1 - f_{EM} = 1 - k ln E(GeV) \quad k \approx 0.1$$

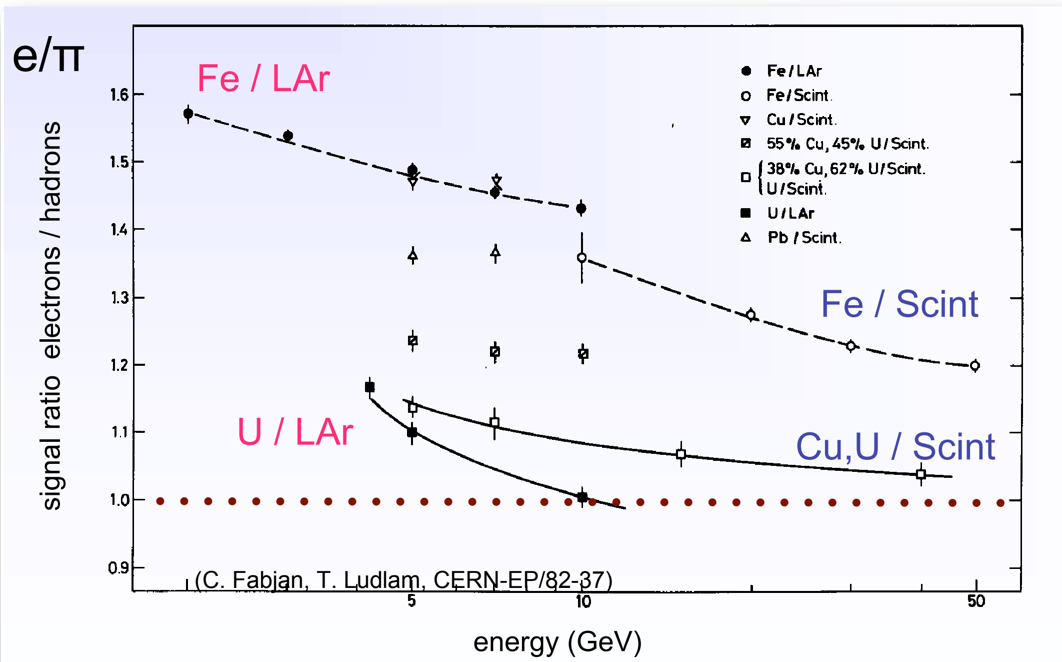
Response of calorimeter to hadron shower becomes non-linear

Energy resolution degrades

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} + d\left(\frac{e}{h} - 1\right)$$

Improved Energy Resolution: Compensation

- The detector parameter e/h is defined by geometry and material
- Typically to reach compensation (e/h = 1), the hadron signal has to be increased, by:
  - enhance sensitivity to slow neutrons, i.e. H-enriched scintillator, more $n + p \rightarrow n + p$
  - increasing of the neutron activity by use of a special absorber i.e. Uranium
  - choosing the right sampling-fraction ...



but:

careful with amount of material in front of calorimeter!

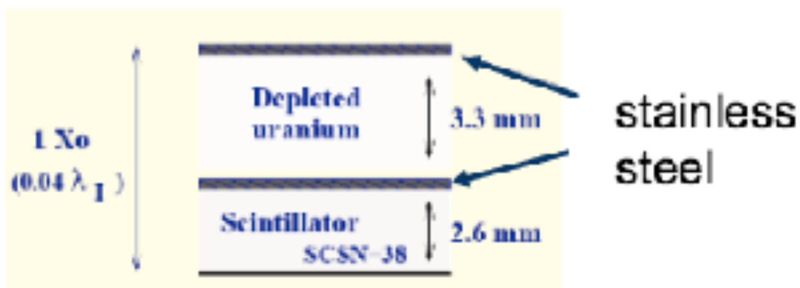
$$\frac{e}{\pi} = \frac{e}{h} \cdot \frac{1}{1 + f_{em}(e/h-1)}$$

Compensating calorimeters - The ZEUS example

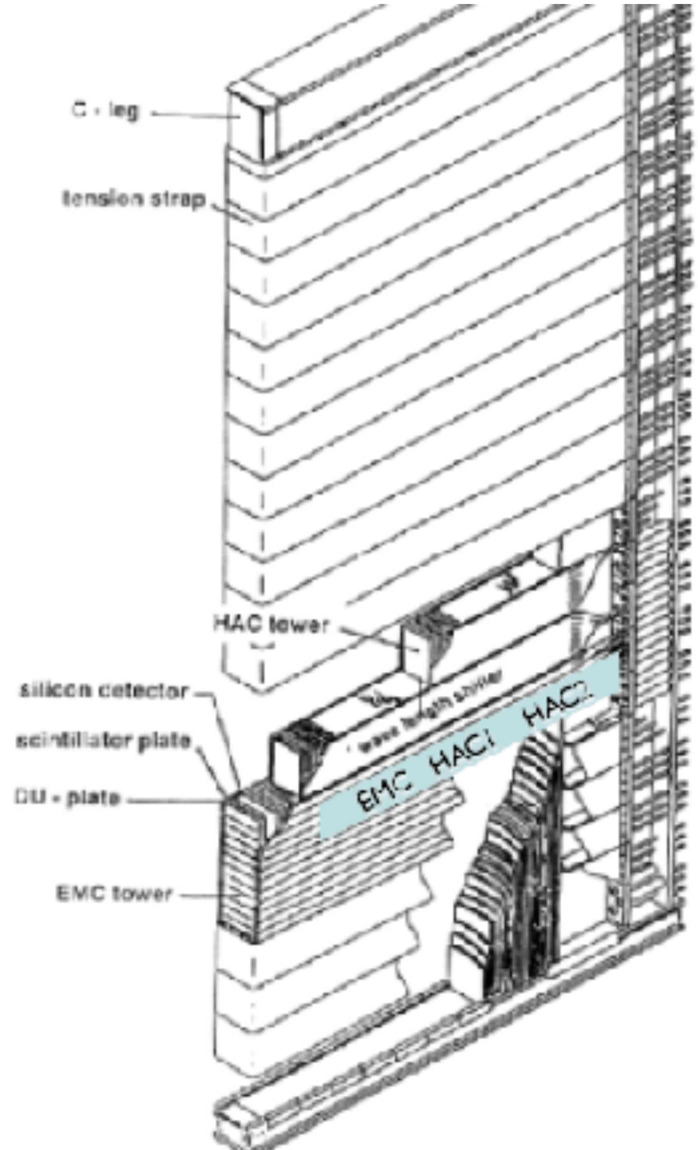
Highly-segmented, uranium scintillator sandwich calorimeter r/o by 12,000 photomultiplier tubes:

- compensation
- high Z material = compact size
- natural radioactivity provides means of calibration

Layers:



proper choice of active and passive thicknesses gives compensation (e/h = 1.0)



3m x 5m x 0.2m, 12tons
total of 80 modules

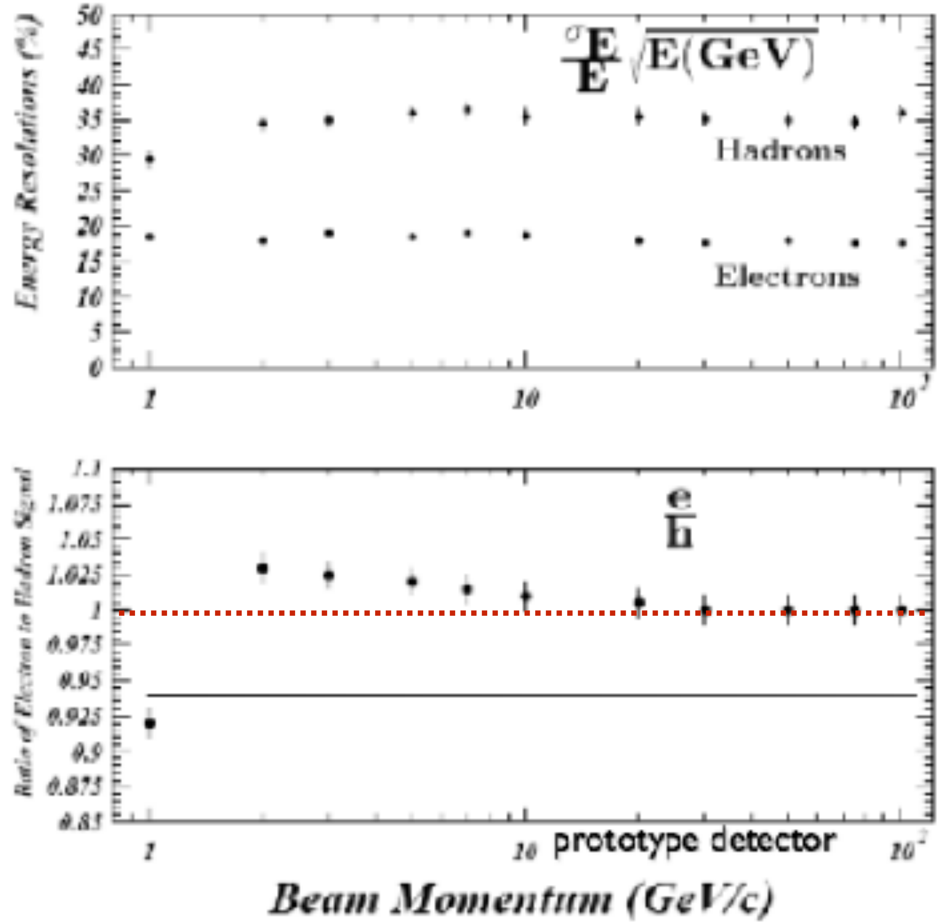
Compensating calorimeters - The ZEUS example

Highly-segmented, uranium scintillator sandwich calorimeter r/o by 12,000 photomultiplier tubes

Electrons: $\frac{\sigma(E)}{E} = \frac{18\%}{\sqrt{E(GeV)}}$

Hadrons: $\frac{\sigma(E)}{E} = \frac{35\%}{\sqrt{E(GeV)}}$

Best hadronic resolution ever !!



proper choice of active and passive thickness gives compensation (e/h = 1.0)

Summary

Calorimeters serve to measure the energy of charged and neutral particles

Electromagnetic Calorimeters

- to measure electrons and photons through their EM interactions.

Hadron Calorimeters

- to measure hadrons through their strong and EM interactions.

Two types of calorimeters classified into:

Homogeneous Calorimeters

- only one material for two tasks, energy degradation and signal generation.

Sampling Calorimeters

- alternating layers of absorber material to degrade the energy of the incident particle, and active material that provides the detectable signal.

Energy resolution

- dominated by fluctuations