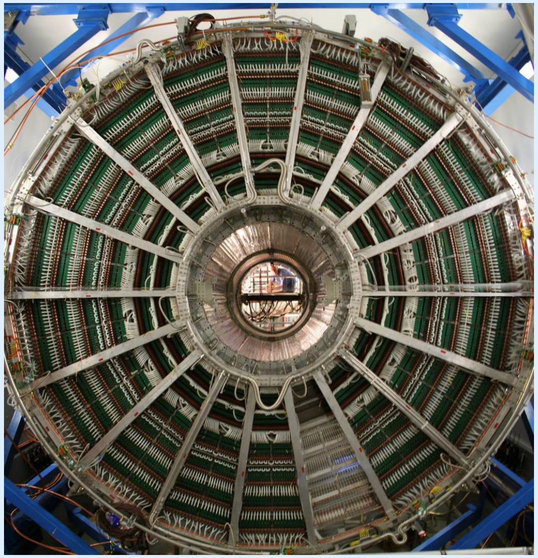

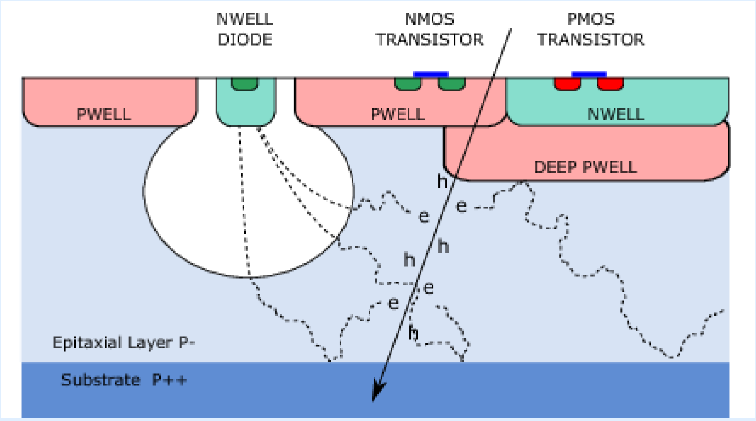

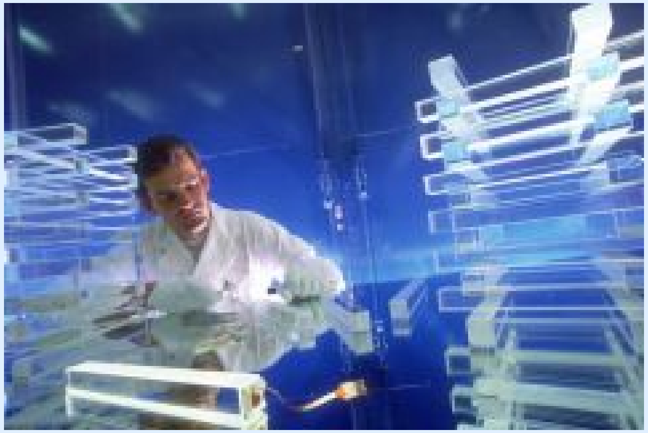

Hadronic calorimeters

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GSI and University of Heidelberg

SS2017, Heidelberg
July 12, 2017

Calorimetry

Experimental technique in nuclear and particle physics in which the detection of a particle and the measurement of its properties is based on ABSORPTION in the detector volume (partial or total)

This is a DESTRUCTIVE process:

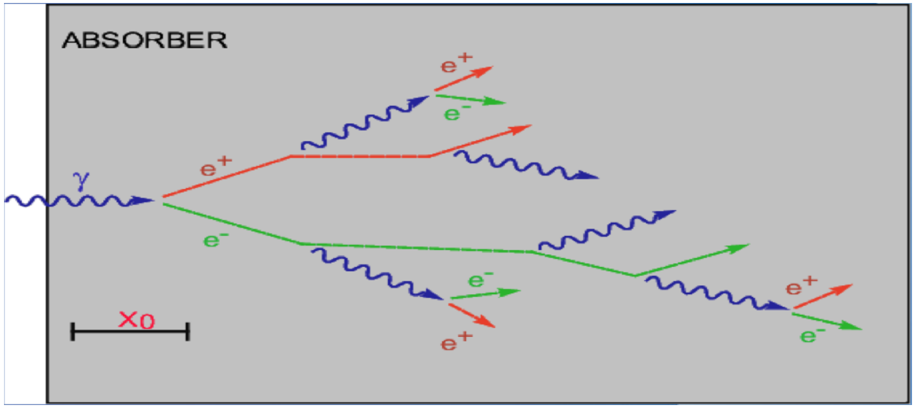
The particle's energy is converted in a detectable signal until the particle is absorbed

Another note: calorimetry is addressed also to neutral particle (not only charged one, see magnetic spectrometer)

Electromagnetic calorimeters - reminder

Electrons, positrons, photons

- $E > E_c$
  - Bremsstrahlung
  - Pair production
- $E < E_c$
  - Electrons, positrons stopped within X_0
  - Photons need another 7-9 X_0



Longitudinal containment (95%): $t_{max} + 0.08\ Z + 9.6\ X_0$

Transverse containment (95%): 2 x Moliere radius

Energy leakage: mostly by soft photons escaping the calorimeter at the sides (later leakage) or at the back (rear leakage)

Showers: em and hadronic

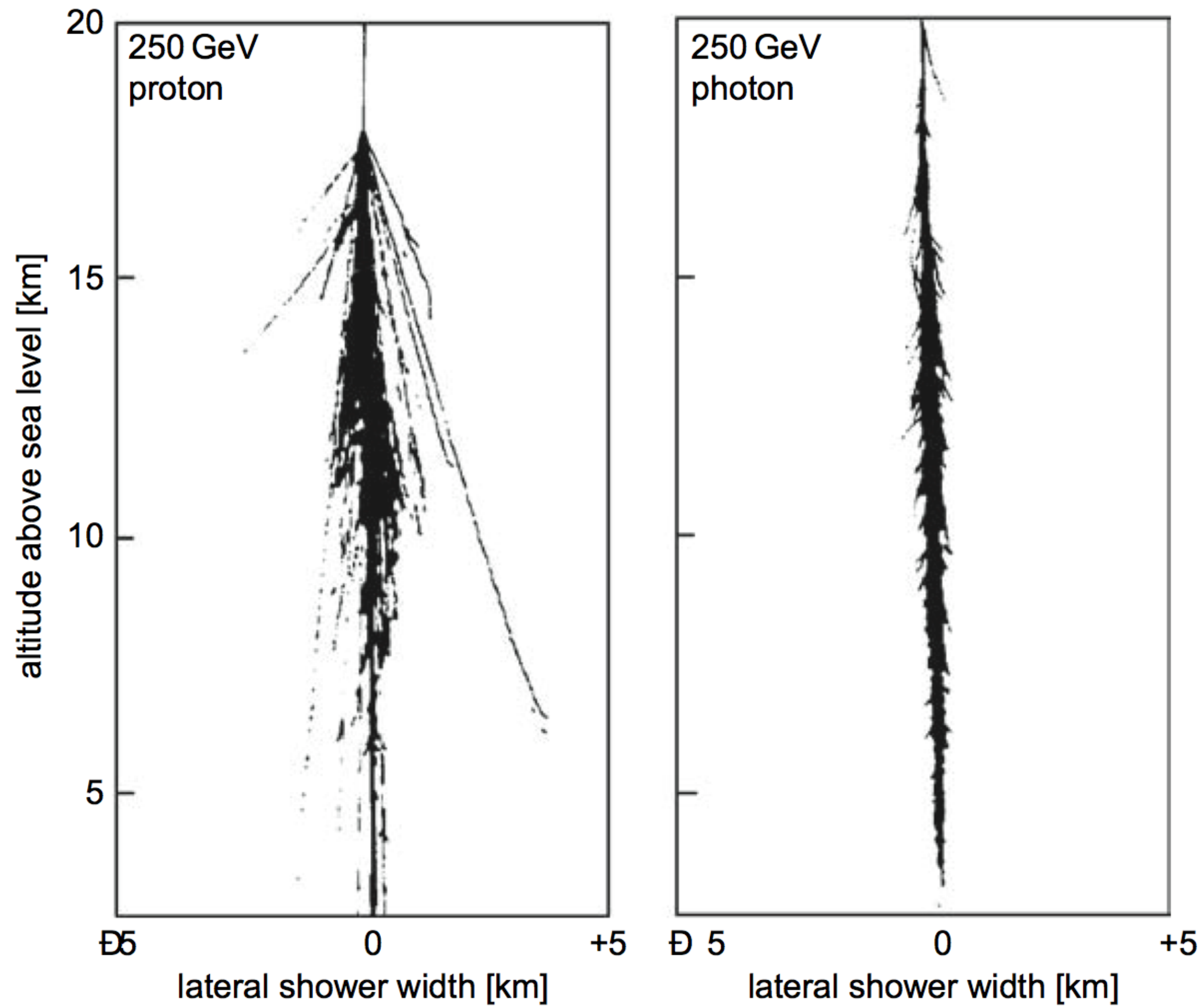


Fig. 8.16. Monte Carlo simulations of the different development of hadronic and electromagnetic cascades in the Earth's atmosphere, induced by 250 GeV protons and photons [51].

Hadronic calorimeters - outline

- **Hadronic showers**
  - Hadron interaction with matter
  - Shower development (longitudinal and lateral)
- **Hadronic calorimeters**
  - Sampling calorimeters
- **Compensation**
- **Particle identification**
- ATLAS hadronic calorimeters

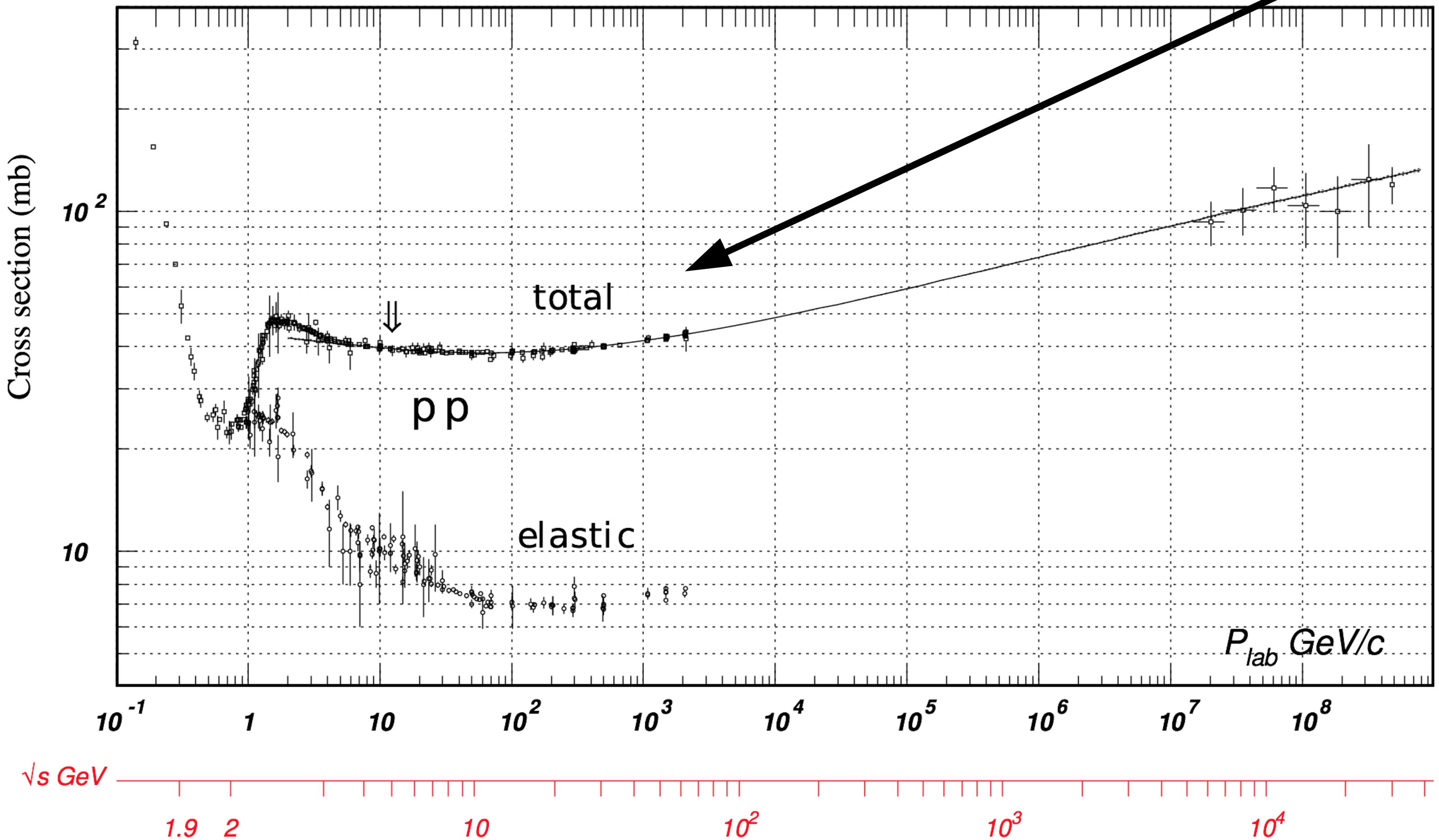
Interaction of hadrons with matter

As reference, consider the interaction of protons (with E ≥ 1 GeV) with a nucleon (e.g. another p) or a nucleus:

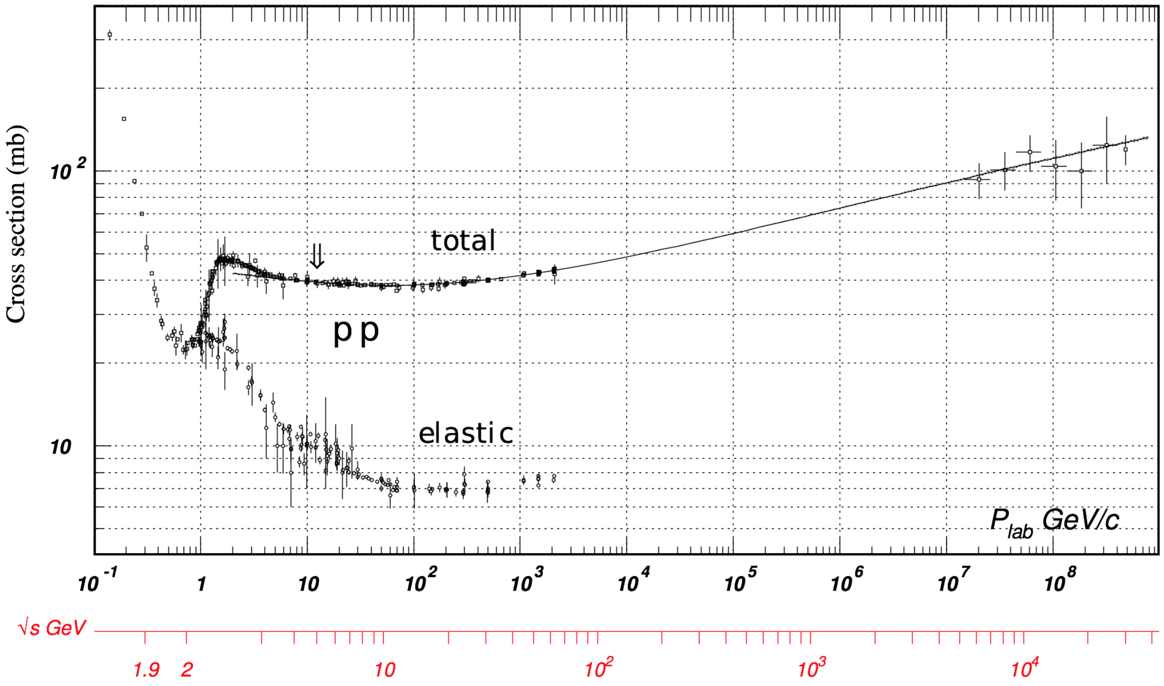
Elastic	$p + N \rightarrow p + N$	σ_{el}
Inelastic	$p + N \rightarrow X$	σ_{inel}

$$\sigma_{tot} = \sigma_{el} + \sigma_{inel}$$

grows weakly with $\sqrt{s}$



Interaction of hadrons with matter



$\sqrt{s}$ (GeV)	σ_{tot} for pp (mb)
5	40
100	50
10000	100

- Elastic cross section ~ 10 mb
- At high energy there is also a diffractive contribution (similar to elastic)
- Majority of σ_{tot} is due to the **inelastic** component σ_{inel}

- Proton-nucleus: σ_{tot} (pA) ≃ σ_{tot} (pp) · $A^{2/3}$

Hadronic interaction length

Average nuclear interaction length: $\lambda_W = \frac{A}{N_A \rho \sigma_{tot}}$

For inelastic processes → absorption: $\lambda_A = \frac{A}{N_A \rho \sigma_{inel}}$

$$N(x) = N_0 \exp\left(-\frac{x}{\lambda_A}\right)$$

$$\lambda_A \simeq 35 \frac{g}{cm^2} \cdot A^{\frac{1}{3}} \quad \text{for } Z \geqslant 15 \text{ and } \sqrt{s} \simeq 1-100\,\text{GeV}$$

	C	Ar (lq)	Fe	U	scint.
λ_A (cm)	38.8	85.7	16.8	11.0	79.5
X_0 (cm)	19.3	14.0	1.76	0.32	42.4

$\lambda_A \gg X_0$!!

→ hadronic calorimeters are larger ("thicker") than electromagnetic ones

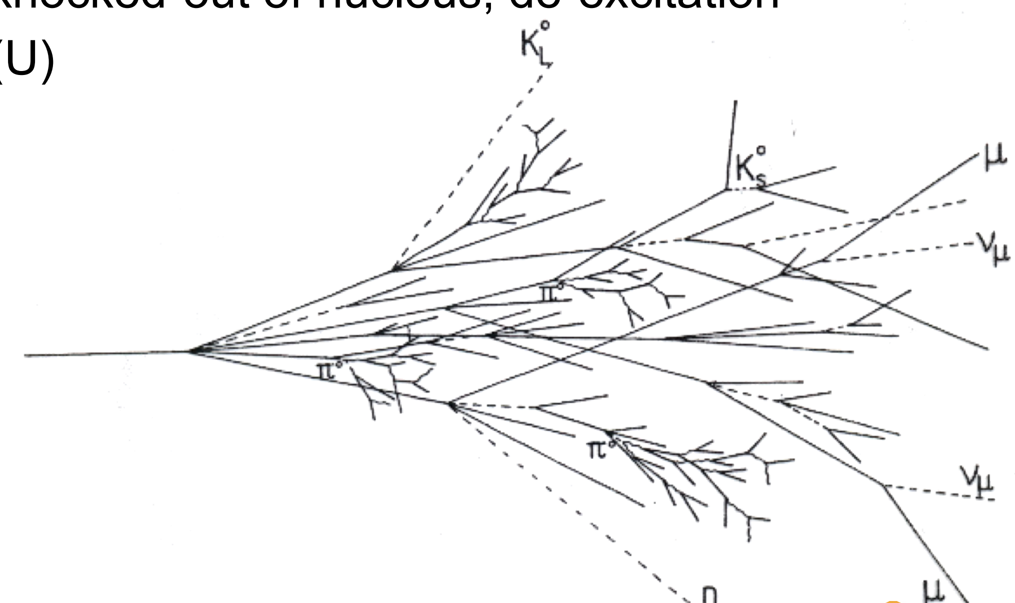
For 95% containment:
Typical longitudinal size: 9 λ_A
Typical transverse size: 1 λ_A

Hadronic shower

- p + nucleus → $\pi^+ + \pi^- + \pi^0$ .... + nucleus*
  - ↳ nucleus 1 + n, p, α
  - ↳ nucleus 2 + 5 p,n
  - ↳ fission
- Secondary particles undergo further inelastic collisions with similar cross sections, until they fall below the pion production threshold
- Sequential decays:
  - $\pi^0 \to \gamma\gamma \to$ electromagnetic shower
  - Fission fragments → β-decay, γ-decay
  - Nuclear spallation: individual nucleons knocked-out of nucleus, de-excitation
  - Neutron capture → nucleus* → fission (U)

At every "step" about 1/3 of deposited energy goes into em shower

- Mean number of secondary particles $\propto \ln E$. Typical transverse momentum $\langle p_T \rangle \sim 350$ MeV/c
- Mean inelasticity (fraction of E in secondary particles) ≃ 50%



Shower development

Extremely rough analytic description (**fluctuations are huge**):

Similarly to em showers, but important differences!!!

Variable: $t = x/\lambda_A$ depth in units of interaction length

$E_{thr} = 290$ MeV (diff!)

$$E(t) = \frac{E}{\langle n \rangle^t}$$

$$E(t_{max}) = E_{thr} \quad \rightarrow \quad E_{thr} = \frac{E}{\langle n \rangle^{t_{max}}}$$

$$\langle n \rangle^{t_{max}} = \frac{E}{E_{thr}} \quad \text{or} \quad t_{max} = \frac{\ln E/E_{thr}}{\ln \langle n \rangle}$$

Compared to em shower:

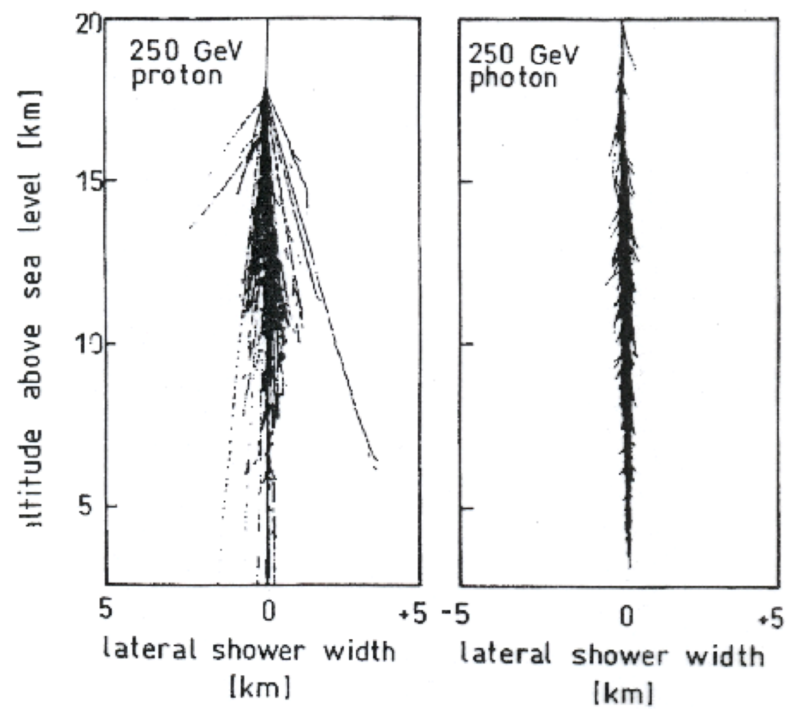
- Number of particles in hadronic shower lower by a factor E_{thr}/E_c
- Intrinsic resolution worse by factor $\sqrt{E_{thr}/E_c}$

Shower development

Significant variations and fluctuations of the energy sharing!!

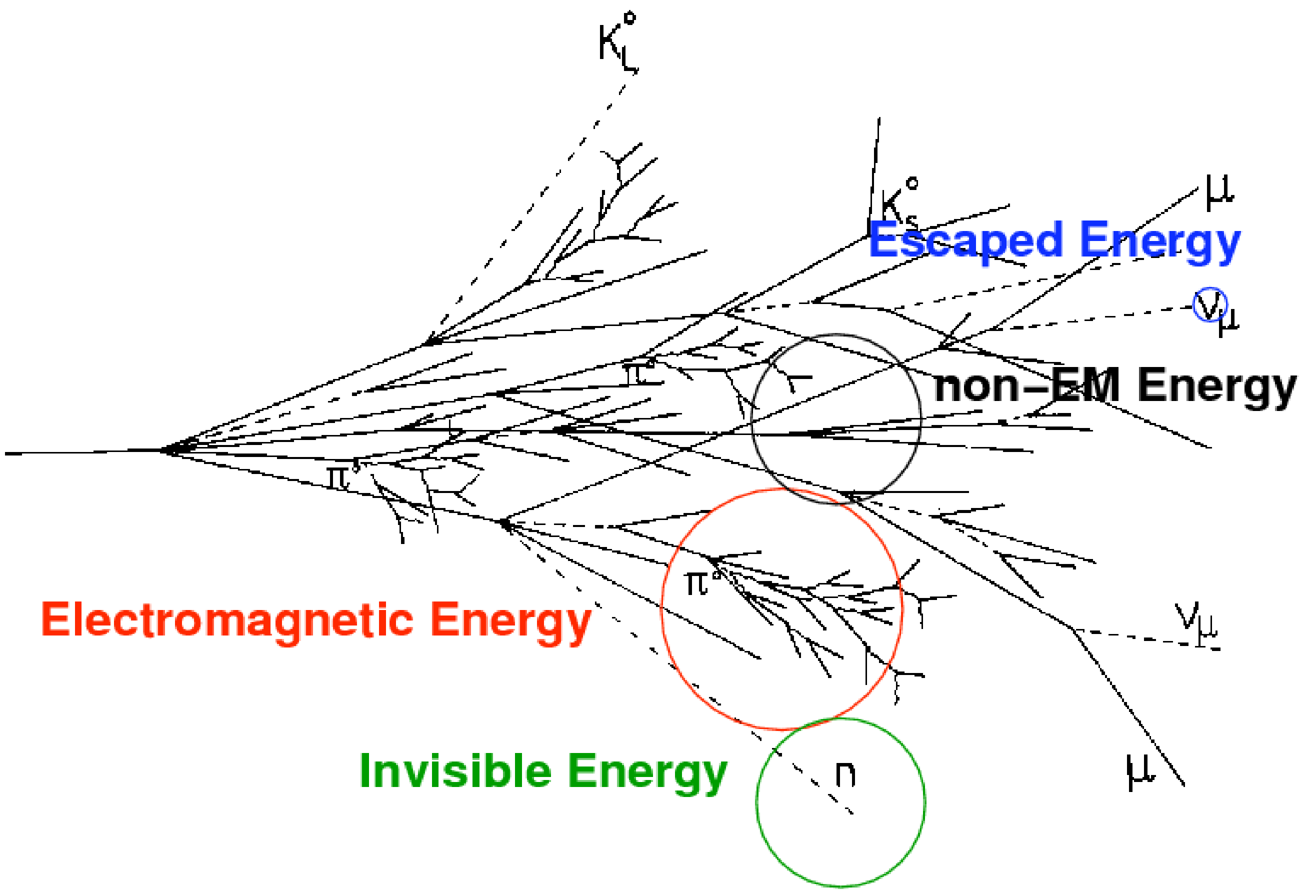
- Part of energy is invisible

  Neutron capture leads to fission → release of binding energy
- Variation in SPATIAL distribution of energy deposition ($\pi^{\pm} \leftrightarrow \pi^0$)
- Electromagnetic fraction grows with E: $f_{em} \simeq f_{\pi 0} \propto \ln[E(\mathrm{GeV})]$
- Energetic hadrons contribute to electromagnetic fraction by e.g. $\pi + p \rightarrow \pi^0 + n$, but very rarely the opposite happens (a 1 GeV π^0 travels 0.2 μm before it decays)
- Below pion production threshold, mainly dE/dx by ionization



Monte-Carlo simulated air showers

Shower development



Shower development

Deposition of energy:

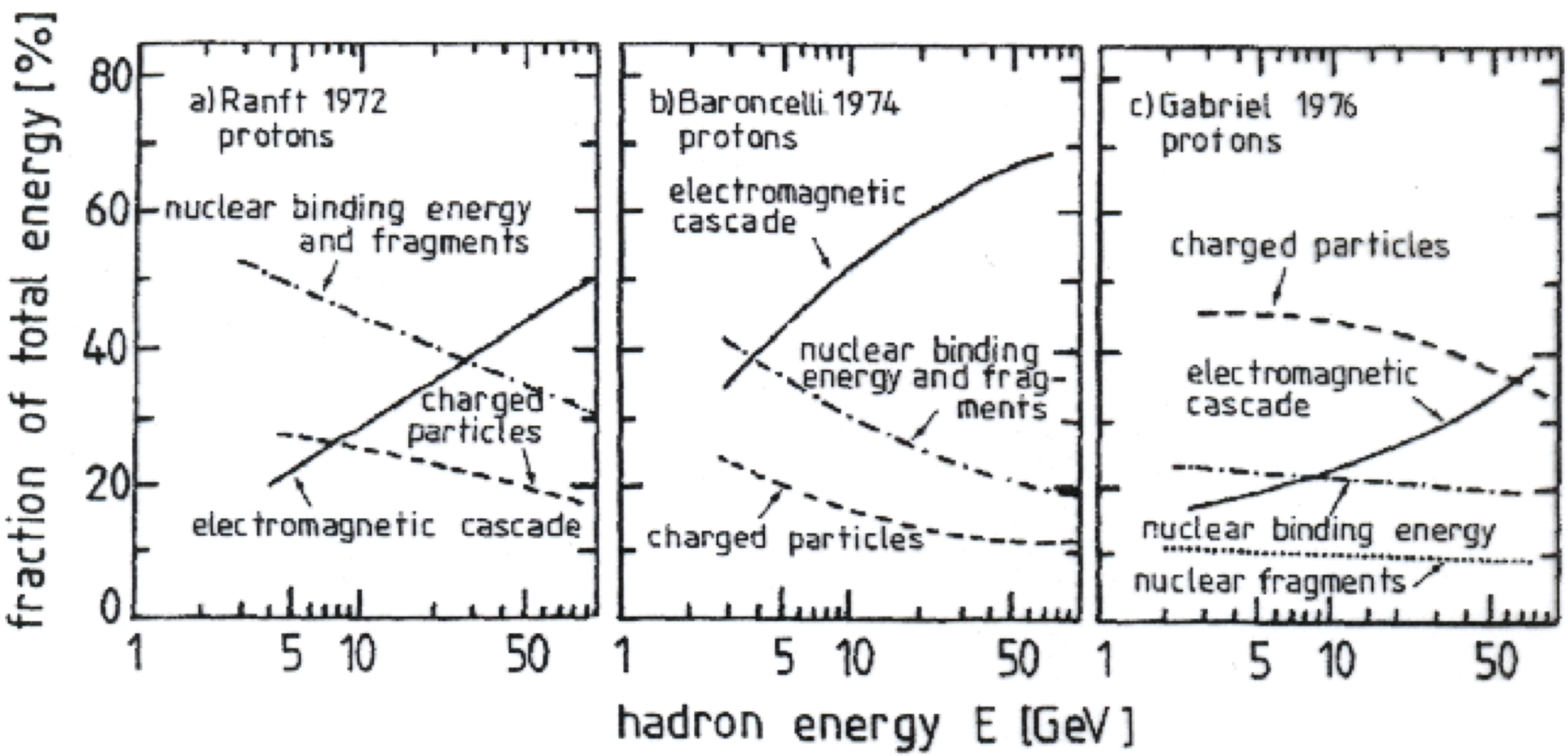
- Electromagnetic fraction (e, π^0, η^0) ~ 30%
  however π^0 production is subject to large fluctuations!
- Ionization energy by charged hadrons (p,π,K) up to 40%
- Invisible fraction of energy ~ 30 – 40 %
  - Hadrons break up nuclear bonds
    → nuclear binding energy
    → short-range nuclear fragments mostly absorbed before detector layers
  - Long-lived or stable neutral particles escape: neutrons, K^0_L, neutrinos
  - Muons created as decay products of pions and kaons deposit very little part of their energy

Because of the invisible energy fraction and the large fluctuations, the energy resolution is significantly worse compared to the em case

Shower development

Shower simulations via intra- and inter-nuclear cascade models
(e.g. GEISHA, CALOR, etc)

Common features, but significant variations! Need to tune to measured data



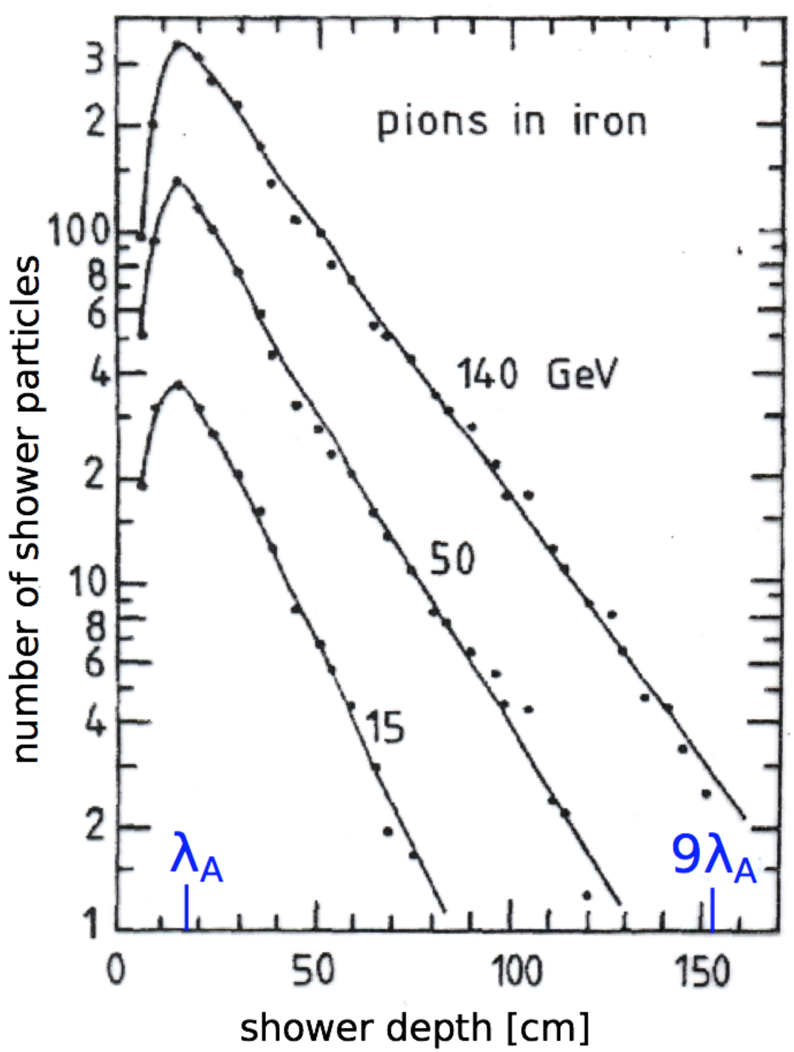
Longitudinal shower development

- Strong peak near hadronic interaction length
- Followed by exponential decrease
- Shower depth:

  $t_{max} \simeq 0.2 \ln E(\mathrm{GeV}) + 0.7$

  95% of energy in $L_{95} = t_{max} + \lambda_{att}$

  where $\lambda_{att} \simeq E^{0.3}$ (E in GeV, λ_{att} in units of λ_A)



Example: 350 GeV $\pi^{\pm}$

$t_{max} = 1.9$ $\quad\quad$ $L_{95} = 1.9 + 5.8$

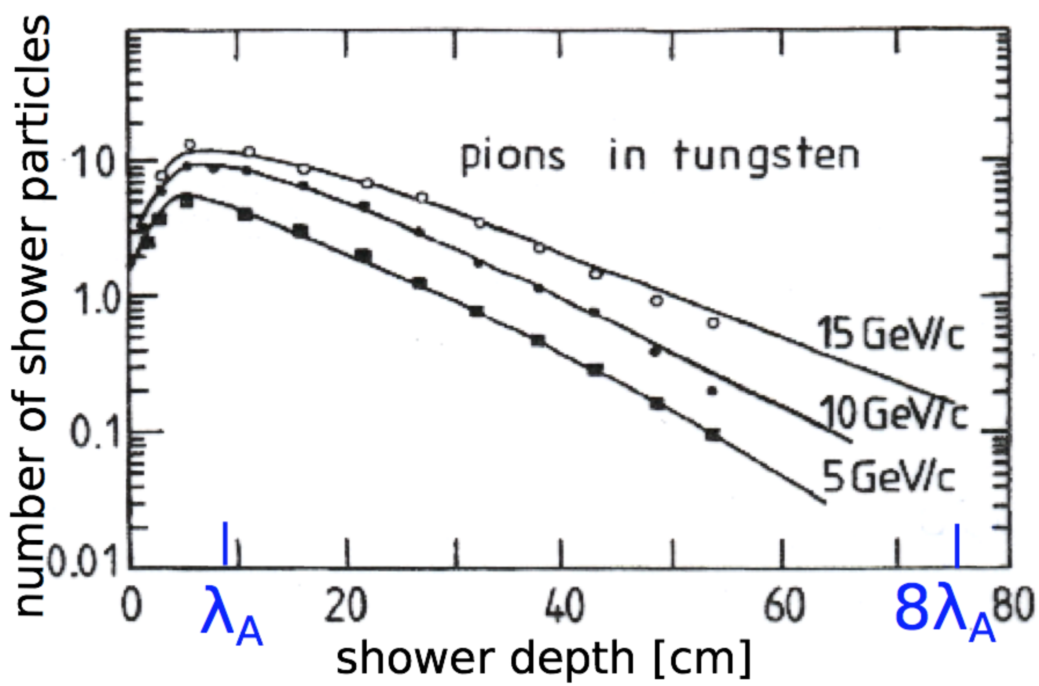
Need about 8 λ_A to contain 95% of energy

Need about 11 λ_A to contain 99% of energy

Longitudinal shower development

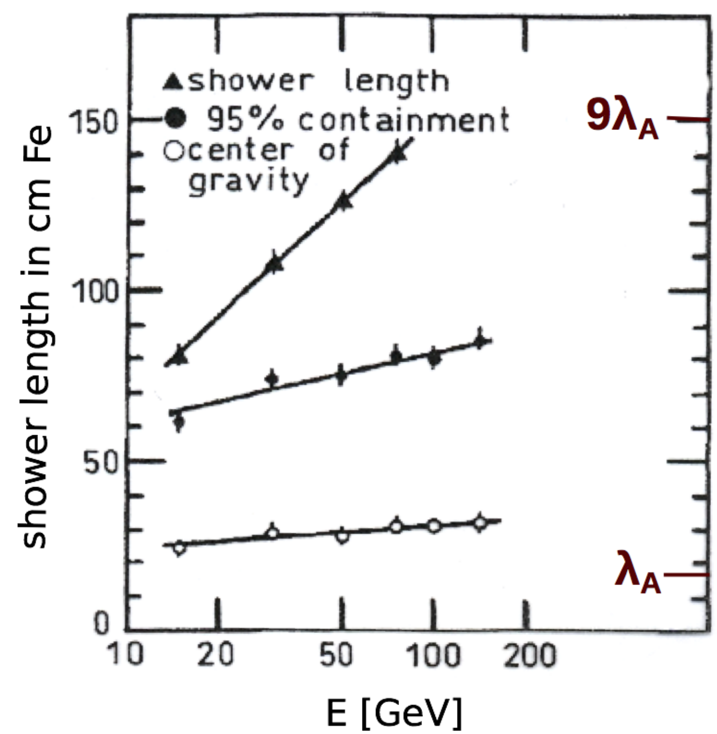
Rather sharp peak close to λ_A

Pions in tungsten:



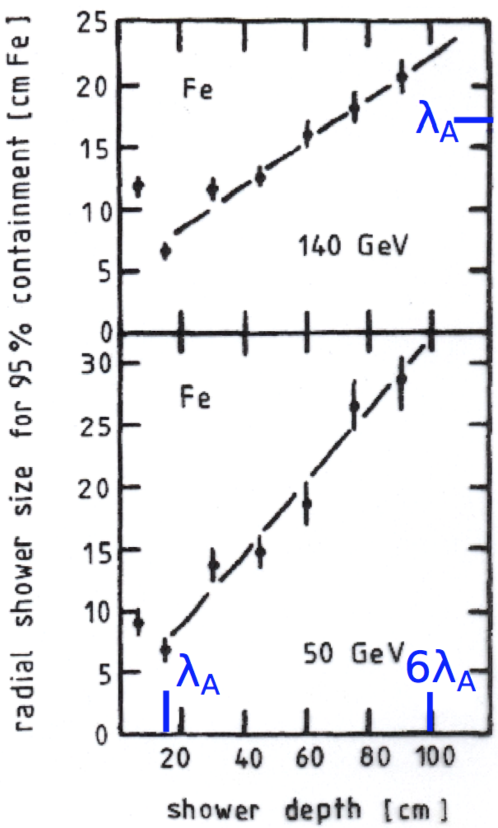
Different definitions:

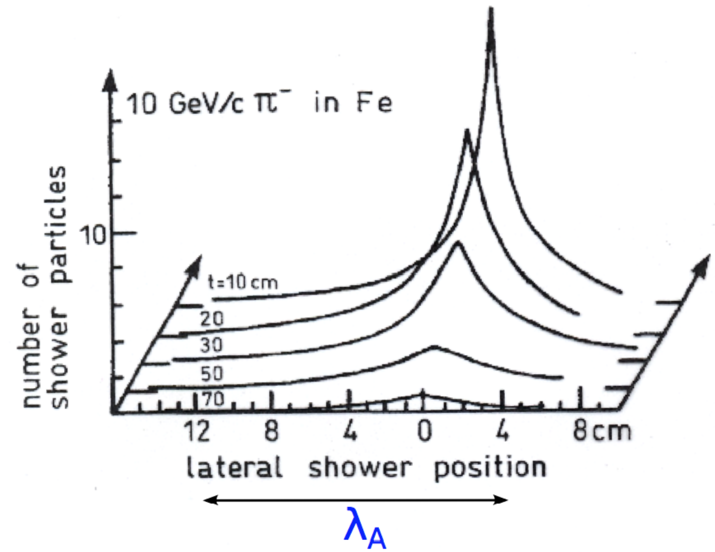
- length of hadron cascade ≡ one particle or less left
- 95% of energy
- Center of gravity

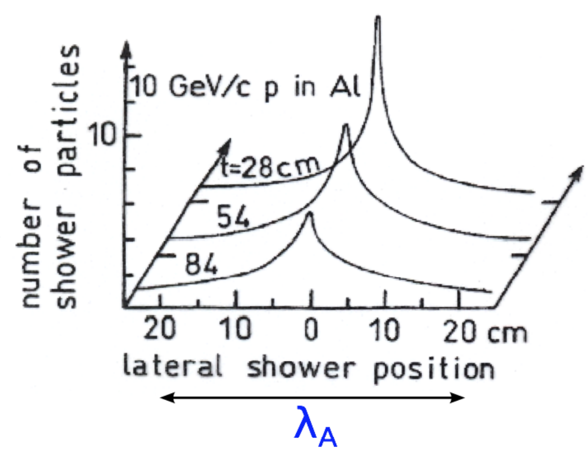


Lateral shower development

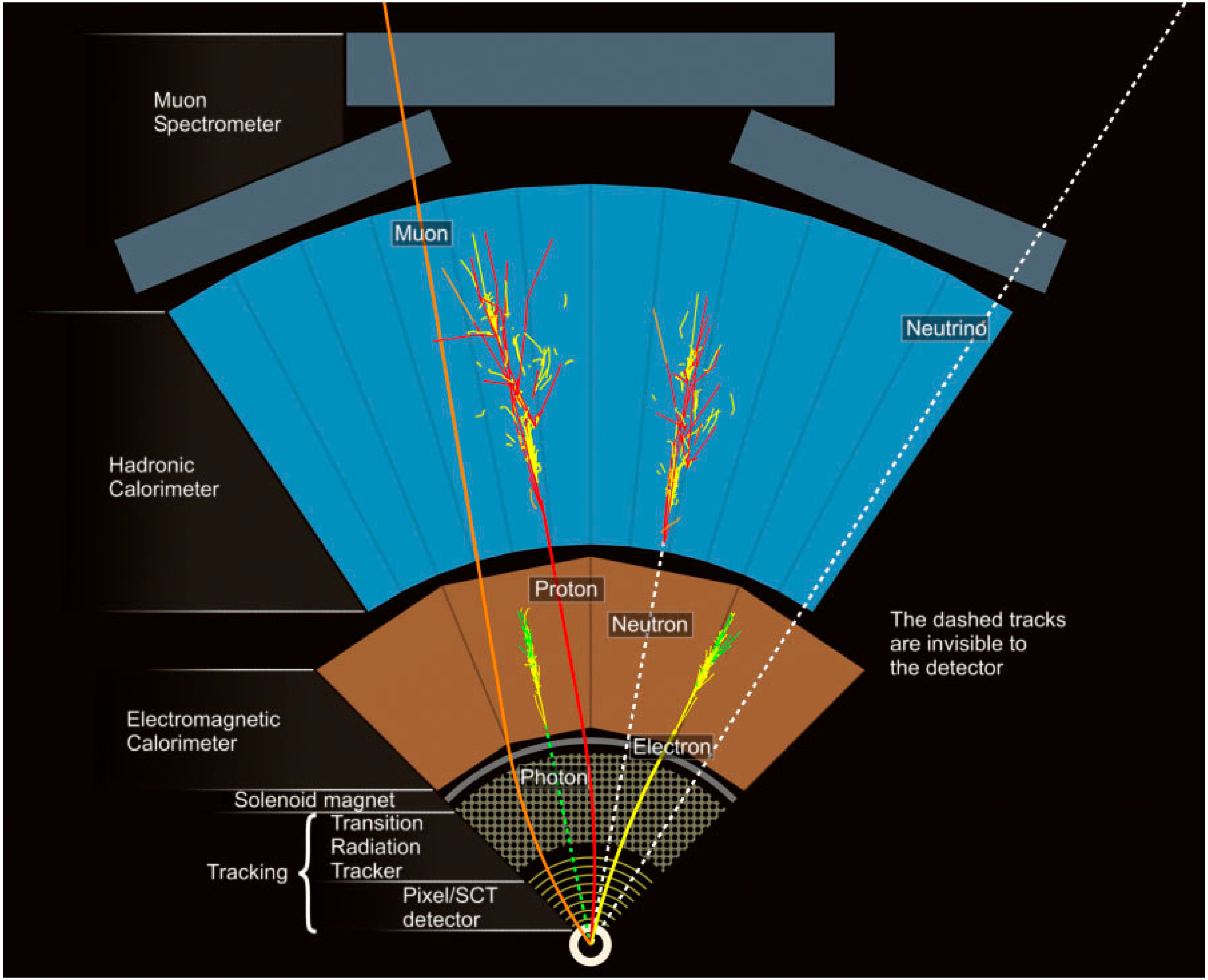
- Typical transverse momentum for secondary hadrons $\langle p_T \rangle \sim 350$ MeV/c
- Lateral extent at shower maximum $R_{95} \simeq \lambda_A$ (sizably larger than em!!)
- Relatively well defined core with $R \simeq R_M$ (electromagnetic component) + exponential decay (hadronic component with large transverse momentum transfers in nuclear interactions)







Hadronic calorimeters



Hadronic calorimeters

Homogeneous calorimeter that could measure entire visible energy loss generally would be too large and expensive to realize. In all cases fluctuations of invisible component make this expense not worth.

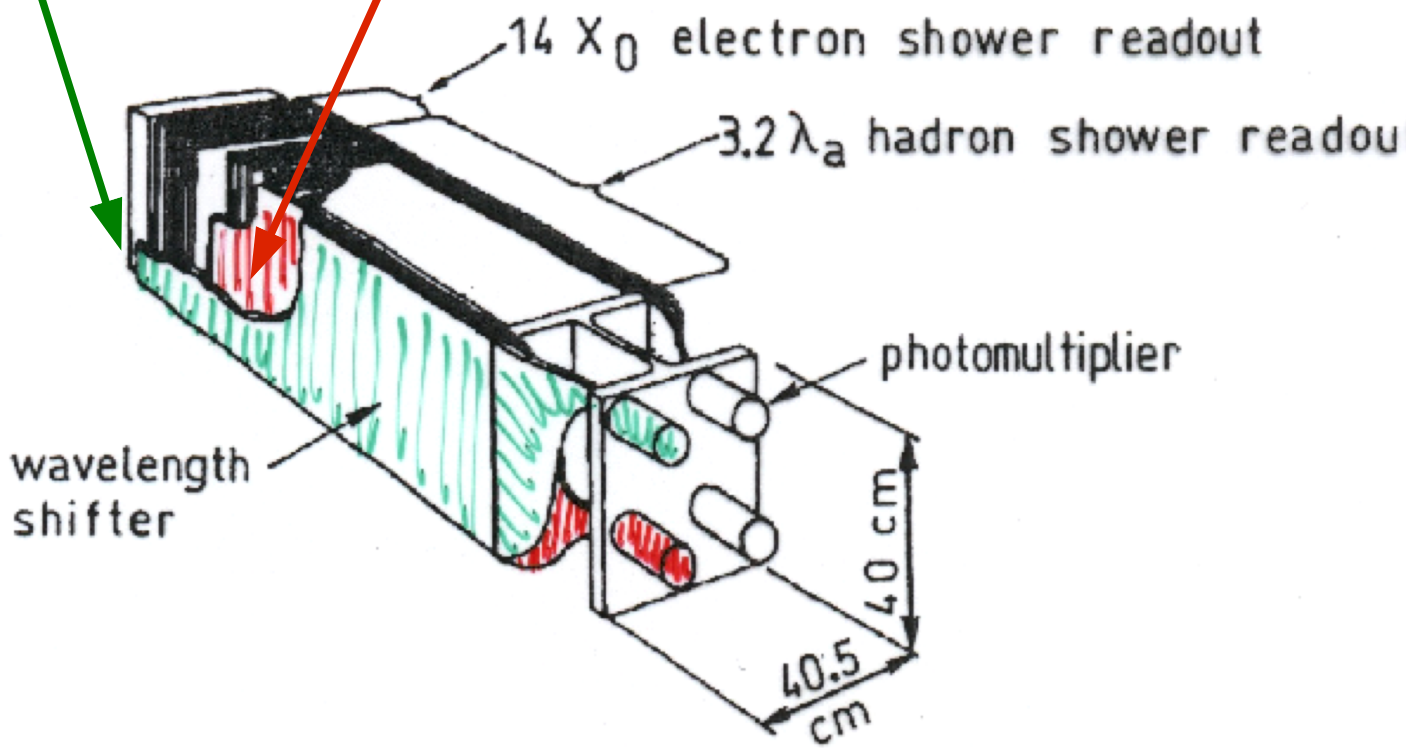
→ most common: **sampling calorimeters!**

- Alternating layers of passive absorber (Fe, Pb, U) + sampling elements (scintillator, liquid Ar or Xe, MPWCs, layers of proportional tubes, streamer tubes, Geiger-Mueller tubes, ..)

- Also spaghetti or shish kebab calorimeter: absorber with scintillating fibers embedded

Hadronic calorimeters

Frequently electron and hadron calorimeters are integrated in a single detector. Here: iron-scintillator calorimeter with separate wavelength-shifter readout for electrons and for hadrons (two components can be separated)



Energy resolution

- Intrinsic contributions
  - Leakage and its fluctuations
  - Fluctuations of electromagnetic portion
  - Heavily ionizing particles with $dE/dx \gg (dE/dx)_{\text{min.ion.}} \rightarrow$ saturation

all scale like $1/\sqrt{E}$ as statistical processes

- Sampling fluctuations
  - Dominate in em calorimeter, are nearly completely negligible in hadronic ones: d_{abs} = thickness of one absorber layer

$$\sigma_{\text{sample}}/S \propto \sqrt{d_{abs}/E}$$

- Other contributions:
  - Noise: $\sigma_E/E = C/E$
  - Inhomogeneities: σ_E/E = constant

Add in quadrature:

$$\boxed{\frac{\sigma_E}{E} = \frac{A}{\sqrt{E}} \oplus B \oplus \frac{C}{E}}$$

A: 0.5 – 1.0 (record 0.35)
B: 0.03 – 0.05
C: 0.01 – 0.02

Quality of a calorimeter

… is based on the following criteria:

Limitations imposed by the complicated structure of the hadronic shower, with its very large fluctuations

- Linear response: signal $\propto$ E

  often linearity is not over large range

- Energy resolution $$\frac{\sigma_E}{E} = \frac{\text{const}}{\sqrt{E}}$$

  fluctuations make things deviate from optimal resolution

- Signal independent from particle species

  response to electromagnetic and hadronic components can be very different relative to each other → e/h issue

e/h (or e/π) issue → compensation

Generally the response to electromagnetic and hadronic energy deposition is different!

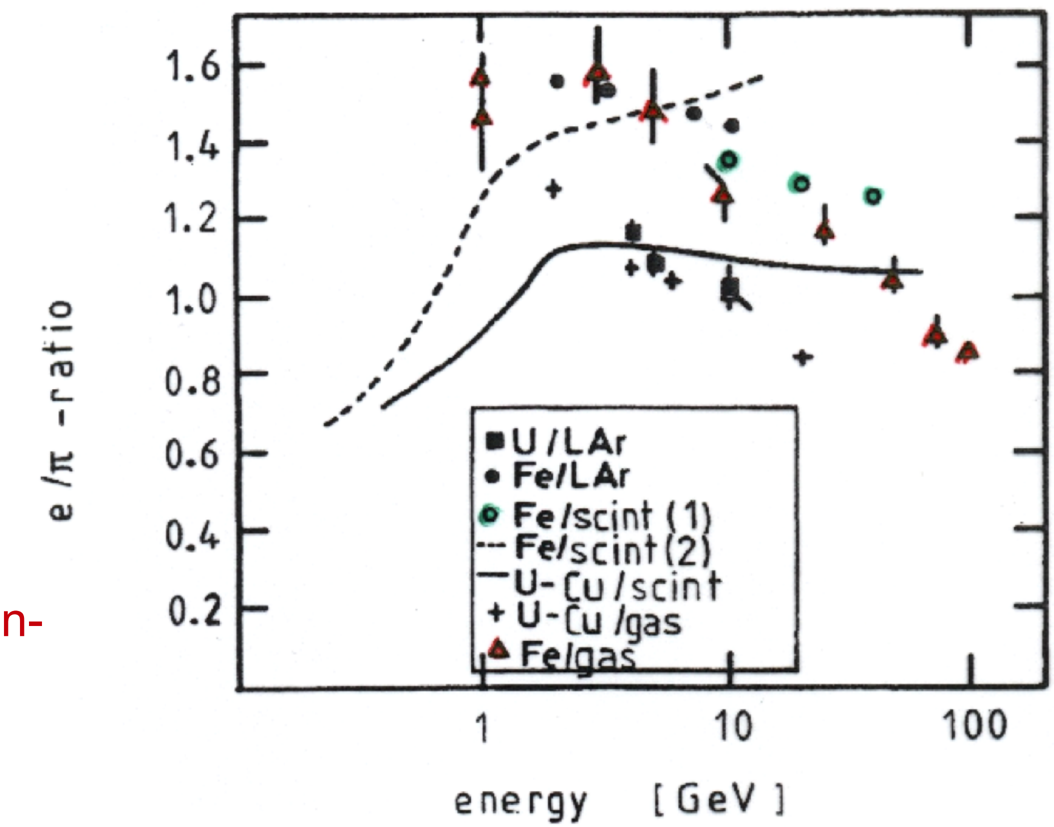
Usually the electromagnetic component has higher weight, since the hadronic shower has an invisible component → **e / h > 1 !!!** **(*)**

This is a serious limitation to the measurement of the total energy flow in an event!

Optimization:

"Compensation"

"Overcompensation" (e / h < 1)



(*) ratio of energy deposits of an electron-initiated shower compared to that of a hadron-initiated shower for the same initial energy of electrons and hadrons

Compensation

How to get from e/h > 1 to e/h ≃ 1?

It is important to understand the contributions to the signal: only that allows to reach an optimization

Let's consider an incident particle i with energy E(i):

Visible energy: $E_v(i) = E_{dep}(i) – E_{nv}(i)$ nv = invisible

Define visible fraction:

$$a(i) = \frac{E_v(i)}{E_v(i) + E_{nv}(i)}$$

Compensation

Compare various signals to those of a minimum ionizing particle:

Electron $$\frac{e}{mip} = \frac{a(e)}{a(mip)}$$

Hadronic shower component $$\frac{h_i}{mip} = \frac{a(h_i)}{a(mip)}$$

Electron signal $$S(e) = k \cdot E \cdot \frac{e}{mip}$$

Hadronic signal $$S(h_i) = k \cdot E \cdot \left[f_{em} \frac{e}{mip} + (1-f_{em}) \frac{h_i}{mip}\right]$$

Constant k is determined by calibration

f_{em}: fraction of primary energy of a hadron deposited in form of electromagnetic energy $\approx$ ln (E / 1 GeV)

Compensation

In case: $$\frac{e}{mip} \neq \frac{h_i}{mip} \quad \rightarrow \quad \frac{S(h_i)}{E} \neq \text{constant!}$$

$$\frac{S(e)}{S(h_i)} = \frac{e/mip}{f_{em}(e/mip) + (1-f_{em})(h_i/mip)}$$

So, in case

- Worsening of resolution
- S/E not constant!

Goal: aim for $$\frac{e}{mip} = \frac{h_i}{mip} \quad \rightarrow \quad \frac{S(e)}{S(h_i)} = 1$$

Compensation

Hadronic shower component has various contributions:

$$\frac{h_i}{mip} = f_{ion}\frac{ion}{mip} + f_n\frac{n}{mip} + f_\gamma\frac{\gamma}{mip} + f_b\frac{b}{mip}$$

f_{ion} fraction of hadronic component in charged particles, ionizing: $\pi^\pm$, p, $\mu^\pm$

f_n fraction of neutrons

f_γ fraction of photons

f_b fraction of nuclear binding energy

Example: 5 GeV proton

	Fe	U
f_{ion}	57%	38%
f_γ	3%	2%
f_n	8%	15%
f_b	32%	45%

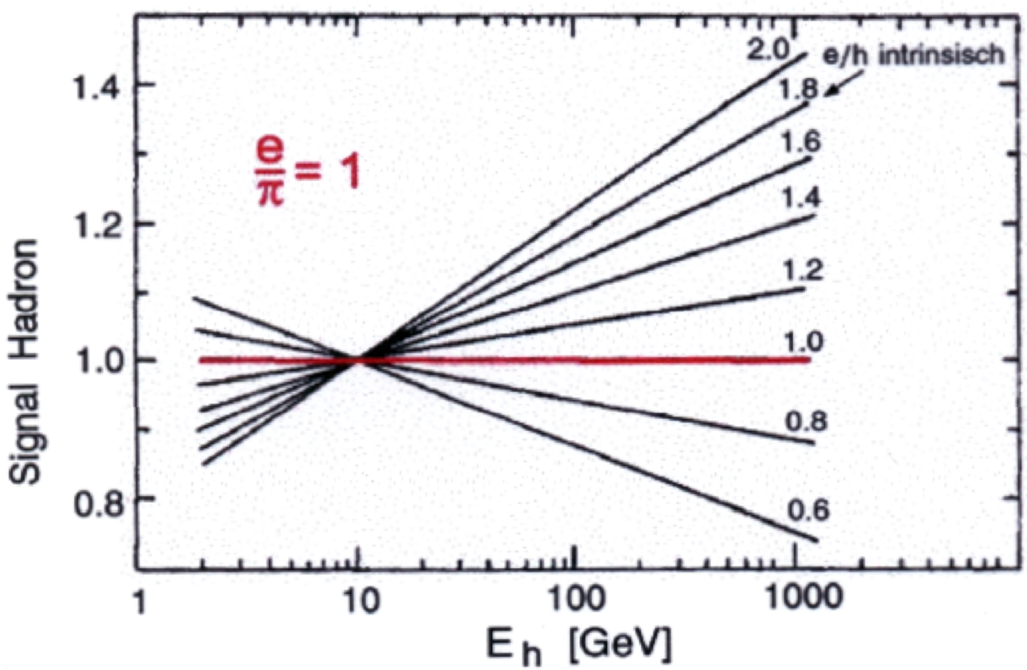
← dominated by spallation products (protons)

} strongly correlated

Compensation

	Fe/Sci	Fe/Ar	U/Sci	U/Ar	determined by
ion/mip	0.83	0.88	0.93	1.0	d_{act}
n/mip	0.5-2	0	0.8 - 2.5	0	d_{act}/d_{abs}
γ*/mip*	0.7	0.95	0.4	0.4	d_{abs}
e/mip	0.9	0.95	0.55	0.55	d_{abs}

Increase h_i/mip via increase of f_n, f_γ (materials) and n/mip, γ/mip (layer thickness)



hadron signal in different sampling calorimeters

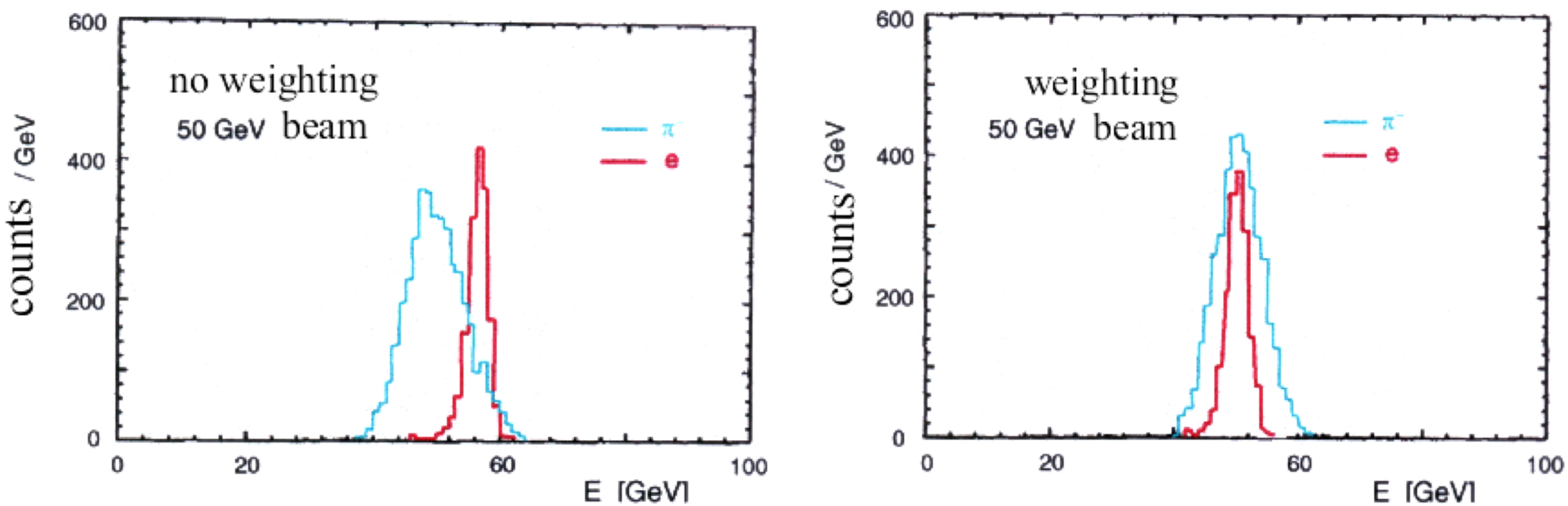
Software compensation

Consider the layers of active components of the calorimeter:

- Identify the layers with particularly large Ev → π0 contribution
- Assign SMALL WEIGHT to these layers!

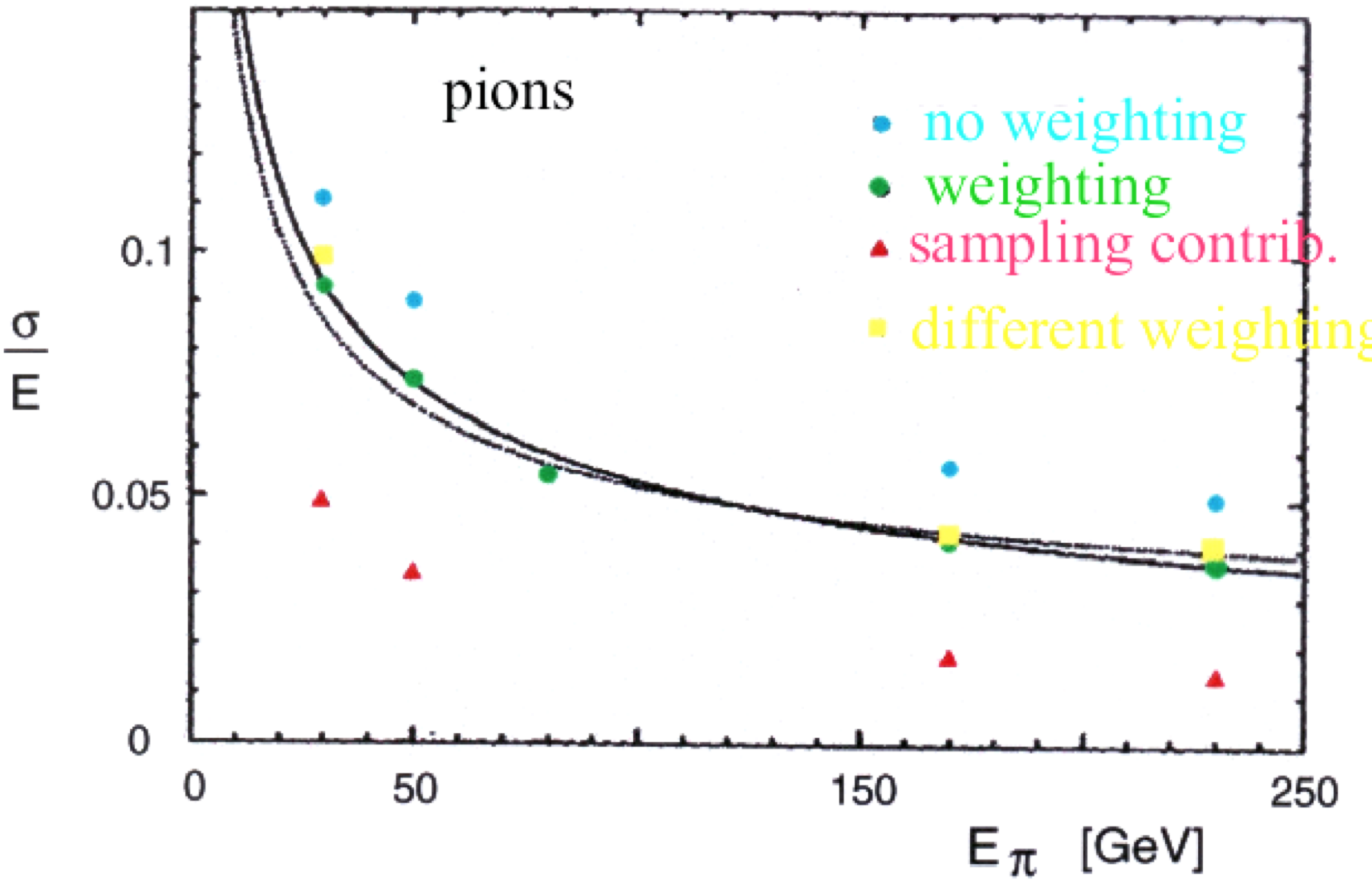
$w_i^* = w_i\,(1 - cw_i)$ w_i = measured, deposited energy

c = weight factor



Software compensation

Energy resolution of non-compensating liquid-Ar calorimeter



overall response more Gaussian improved resolution, improved linearity

Hardware compensation

Essential if one wants to trigger!

Increase of h/mip or decrease of e/mip. Possibilities:

- Increase of hadronic response via fission and spallation of ^{238}U

  $\rightarrow$ increase of $\frac{\text{ion}}{\text{mip}}$ or $\frac{n}{\text{mip}}$

- Increase of neutron detection efficiency in active material: high proton content

  $Z=1 \rightarrow$ increase of $\frac{n}{\text{mip}}$

- Reduction of e/mip via high Z absorber and suitable choice of $\frac{d_{abs}}{d_{act}}$

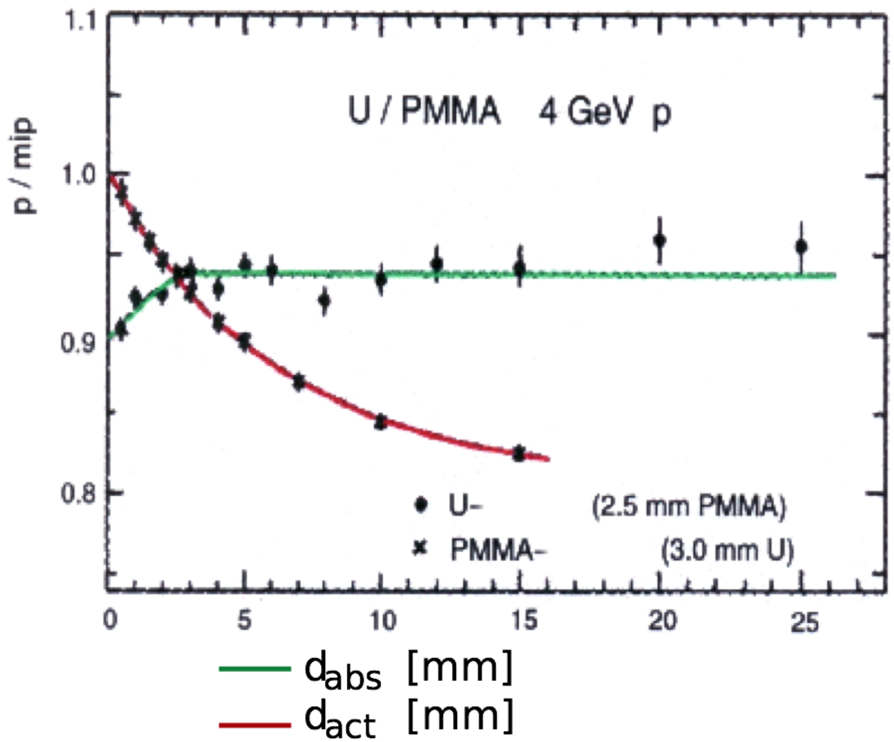
  increase of Z_{abs} $\rightarrow$ decrease of $\frac{e}{\text{mip}}$ $\leftarrow$ increase of d_{abs}

- Long integration time $\rightarrow$ sensitivity to γ capture after neutron thermalization

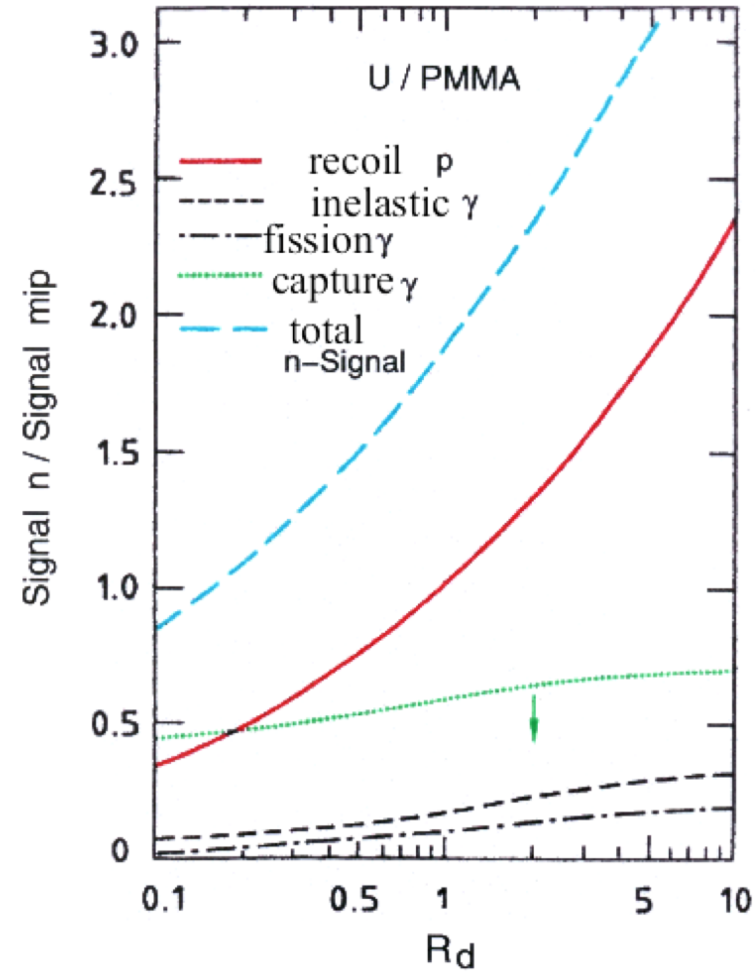
  $\rightarrow$ t long $\rightarrow$ increase of $\frac{n}{\text{mip}}$

Hardware compensation

calorimeter response to protons



calorimeter response to neutrons



variation of plate thickness ↔ variation of response p/mip

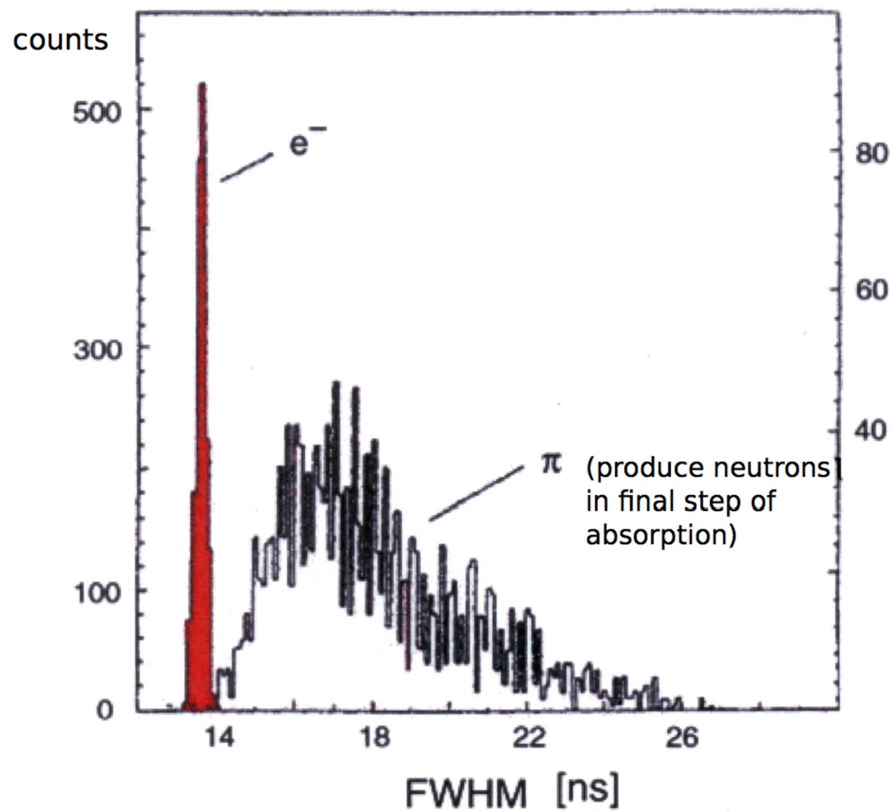
variation of contributions vs. $R_d = d_{abs}/d_{act}$

Time structure of showers

In em showers, all components cross the detector within few ns (speed ~ 30 cm/ns)

In hadronic showers, the component due to neutrons is delayed: they need to slow down before they produce a visible signal

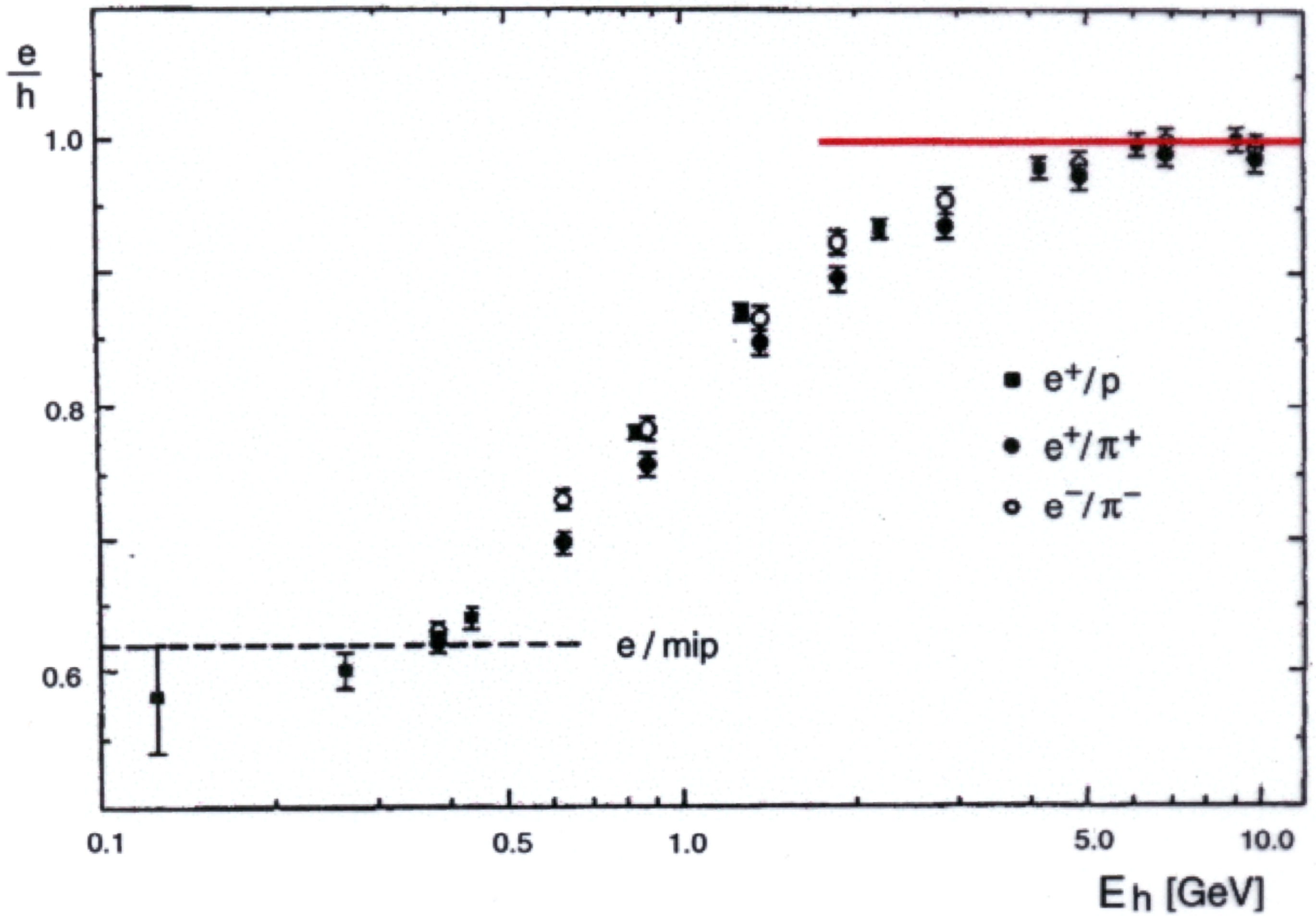
signal width for 80 GeV e and π in spaghetti calorimeter



Size of signal depends on integration time → a variation of the integration time of the electronics can enhance the hadronic signal (used in the ZEUS calorimeter)

ZEUS calorimeter

U (3 mm) + Scintillator (2.5 mm)



measured ratio of electron/pion signals at (ZEUS) for $E \geq 3$ GeV nearly compensated

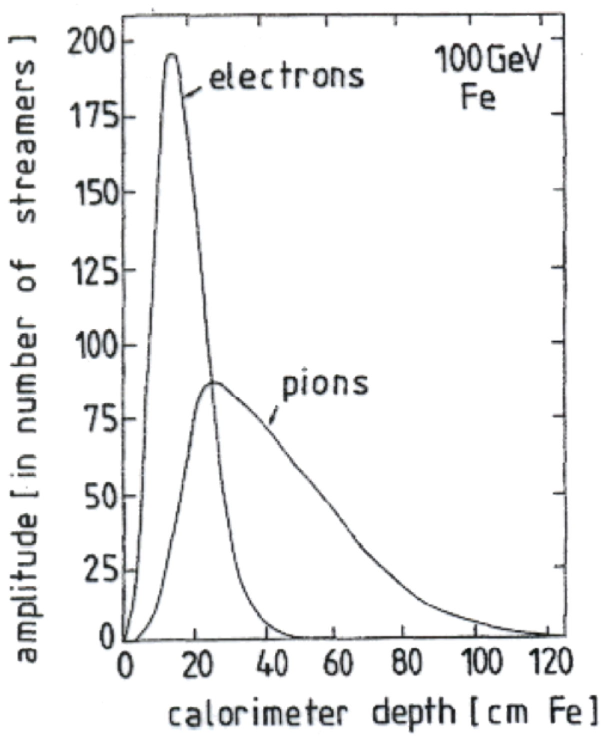
ZEUS calorimeter

Particle identification: e / π

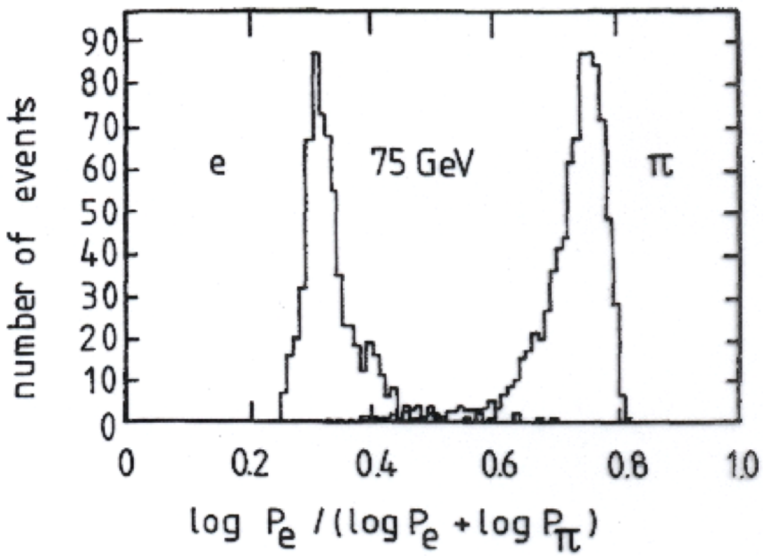
Electron/pion: hadron showers are deeper and wider and start later!

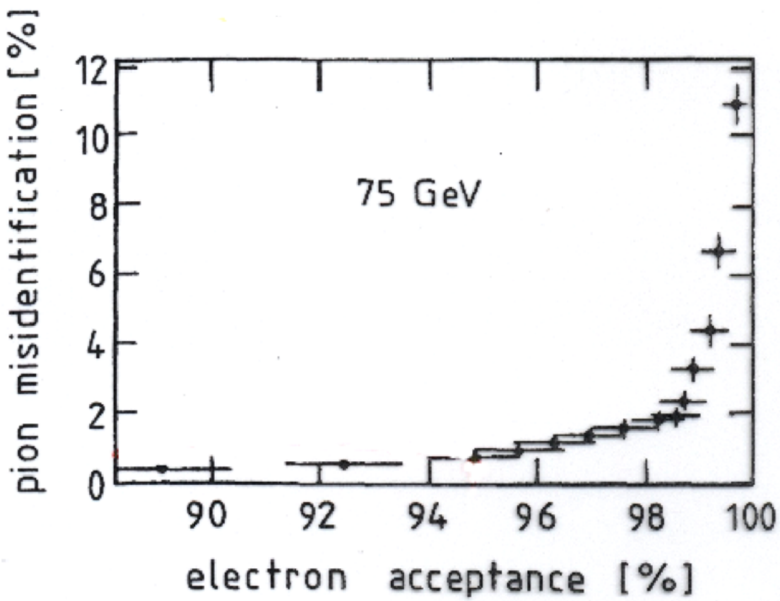
- Difference in transverse and longitudinal shower extent
- Signal for electron is faster

→ PID based on likelihood analysis



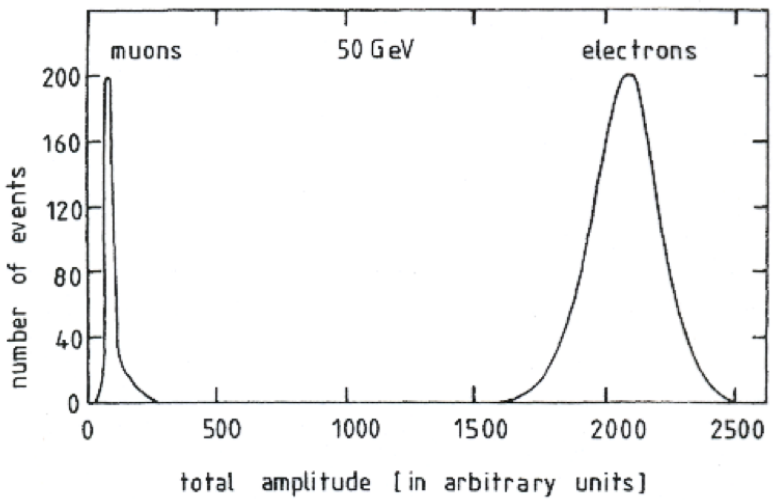
streamer tube calorimeter

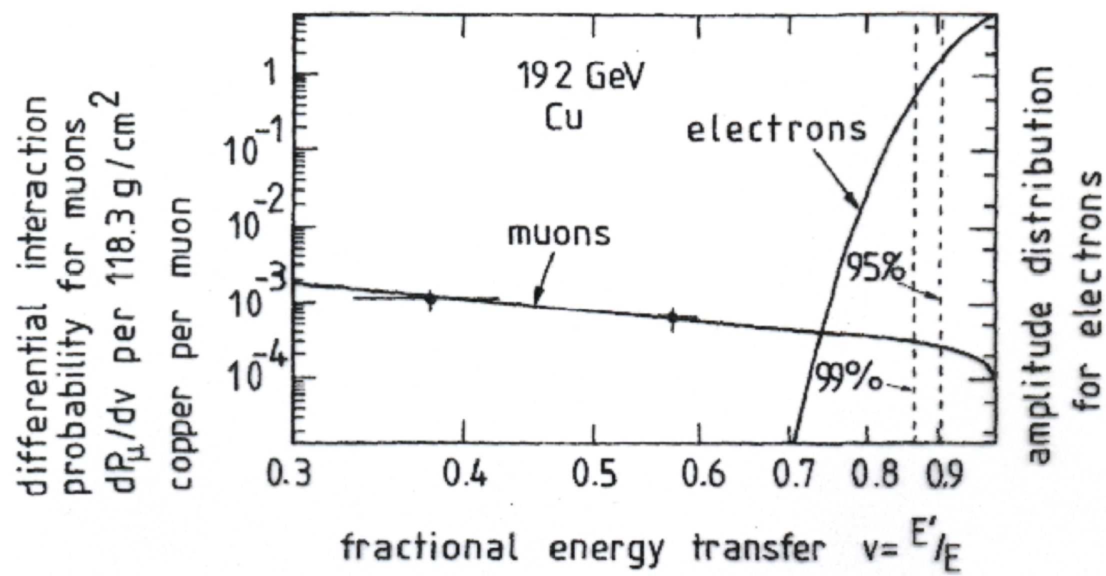




Particle identification: μ / e

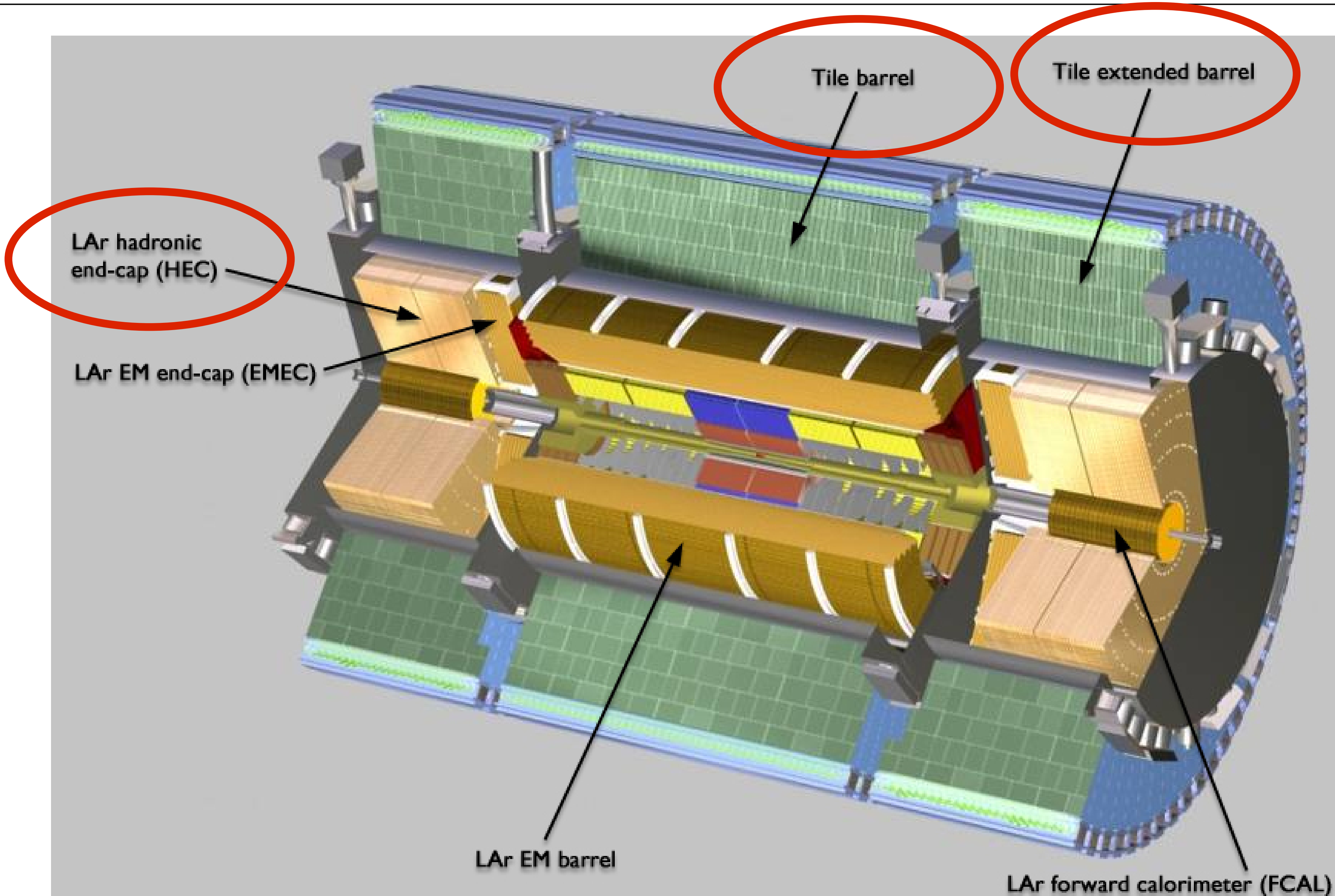
low energy loss for muon



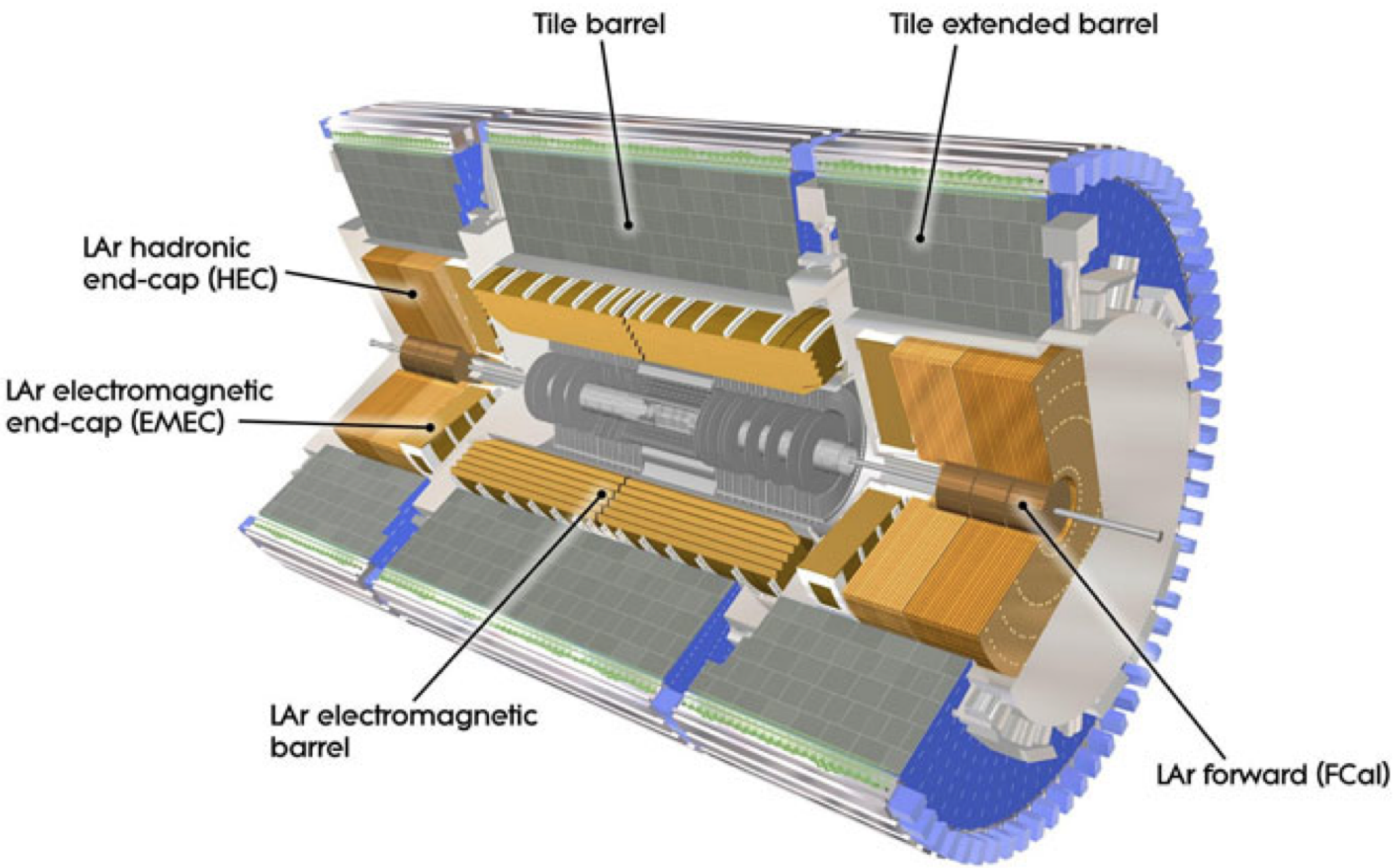


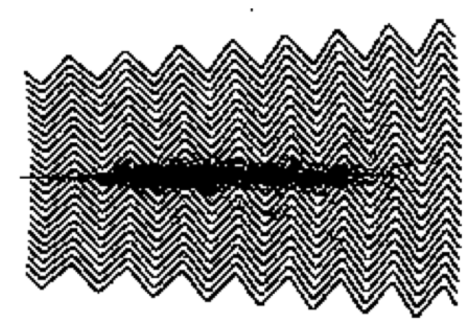
for 95% electron efficiency muon probability $1.7 \cdot 10^{-5}$

ATLAS hadronic calorimeters



ATLAS hadronic calorimeters





accordion-shaped layers of Pb absorber in liquid Ar as sensitive material (ionization measured in intermediate electrodes)

hadronic tile calorimeters:
steel sheets and scintillator tiles read out with scintillating fibers radially along outside faces into PMTs

ATLAS hadronic calorimeters

$$\frac{\sigma_E}{E} = \frac{A}{\sqrt{E}} \oplus B \oplus \frac{C}{E}$$

ATLAS hadronic calorimeter $A \simeq 0.50, \; B \simeq 0.033, \; C = 0.018$

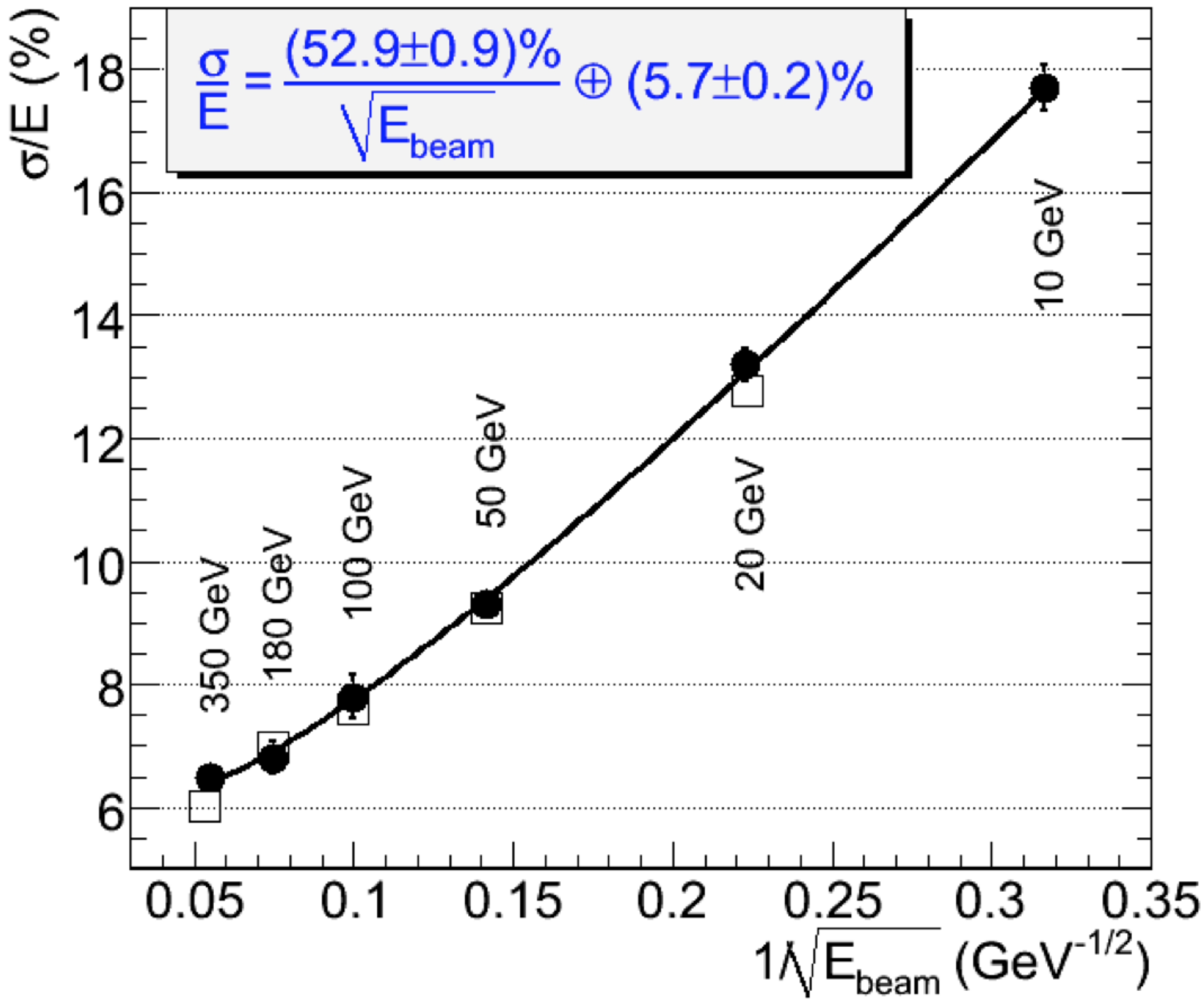
hadronic shower in ATLAS

- visible EM $\sim$ (50%)
  - $e, \; \gamma, \; \pi^0$
- visible non-EM $\sim$ (25%)
  - ionization of $\pi, \; p, \; \mu$
- invisible $\sim$ (25%)
  - nuclear break-up
  - nuclear excitation
- escaped $\sim$ (2%)

$$E = 1000 \text{ GeV} \quad \rightarrow \quad \frac{\sigma_E}{E} = 0.04$$

$$\frac{\sigma_p}{p} = 1.00$$

ATLAS hadronic calo: pion energy resolution



Calibration and monitoring of calorimeters

The pulse height A_i measured in an event from a certain (ith) element of the calorimeter is related to the energy E_i deposited in that element by

$$E_i = \alpha_i (A_i - P_i)$$

where P_i is the pedestal (i.e. the origin of the scale) and α_i is the calibration coefficient.

To keep good performance of the calorimeter, the following procedures are usually carried out:

- Pedestal determination by providing a trigger from a pulser without any signal at the input of the ADC ("random trigger events")
- Electronics channel control by test pulses applied to the input of the electronics chain
- Monitoring of the stability of the calibration coefficients α_i
- Absolute energy calibration, i.e. determination of the α_i values

Calibration and monitoring of calorimeters

Calibration by:

- Measure of a few modules of the final calorimeter in test beams of known particles (e, π, etc.) of known energy

  → intercalibration of all modules in the final calorimeter

- Use of very high energy muons from cosmic rays (might not manage to cover ALL modules, at all angles)

- Use of physical signals (e.g. decays, etc.)