INFN Istituto Nazionale di Fisica Nucleare

Calorimetry in High-Energy Physics

(lecture 1 of 2)

Roberto Ferrari
INFN – Sezione di Pavia

Topics (lecture 1 of 2)

introduction to calorimetry

electromagnetic showers

hadronic showers

detector response and compensation

(by far not exhaustive)

Calorimetry

Name inherited from thermodynamics …

Calorimetry

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Q: does this make sense ?

Calorimetry

Name inherited from thermodynamics …

Q: does this make sense ?

possibly yes …

it works on O(100%) energy absorption

energy → heat

Calorimetry

Heat ?

Calorimetry

Heat ?

100 TeV ~ 4 10^{-9} Cal over tons of material!

Calorimetry

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not measurable!

Calorimetry

Heat ?

100 TeV ~ 4 10^{-9} Cal over tons of material!

not measurable!

→ use some secondary process

Calorimetry

Secondary processes ?

What ?

Calorimetry

Secondary processes ?

What ?

Typically:

Ionisation
Scintillation light emission
Cherenkov light emission

Take care :

Calorimetry

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only a very small fraction of the total energy goes
into the secondary process …

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(even orders of magnitude lower)

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… nevertheless :

Calorimetry

Take care :

only a very small fraction of the total energy goes
into the secondary process …

How much ?

$\ll 1 : 10^3$
(even orders of magnitude lower)

… nevertheless :

proportional to the total energy lost !

Calorimeters

massive detectors for both charged and neutral particles

→ *work as well for clusters of particles (i.e. jets)*

particles are ~ totally "absorbed"

absorption process known as "shower development"

typically divided into:

1) electromagnetic ("em") calorimeters

2) hadronic ("had") calorimeters

Calorimeters

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typically divided into:

1) electromagnetic ("em") calorimeters
2) hadronic ("had") calorimeters

last but not least:

(+) provide (local & global) trigger information
(++) provide particle ID capabilities

Calorimeters

Missing energy measurements :

4π (em & had) calorimetry coverage

["hermeticity"]

electromagnetic (em) showers

development driven by em interactions :

→ clean & ~ simple

→ long-range

→ depend on atomic properties

→ atomic number & atomic scale (~10^{-10} m)

hadronic (had) showers

development driven by nuclear interactions :

→ complex & ~ hard

→ short-range

→ depend on nuclear properties

→ density of nuclei & nuclear scale (~10^{-15} m)

well known for about a century …

atom → football field (electron clouds anywhere)

nucleus → 1 mm (static) sand grain at field center

well known for about a century …

atom → football field (electron clouds anywhere)

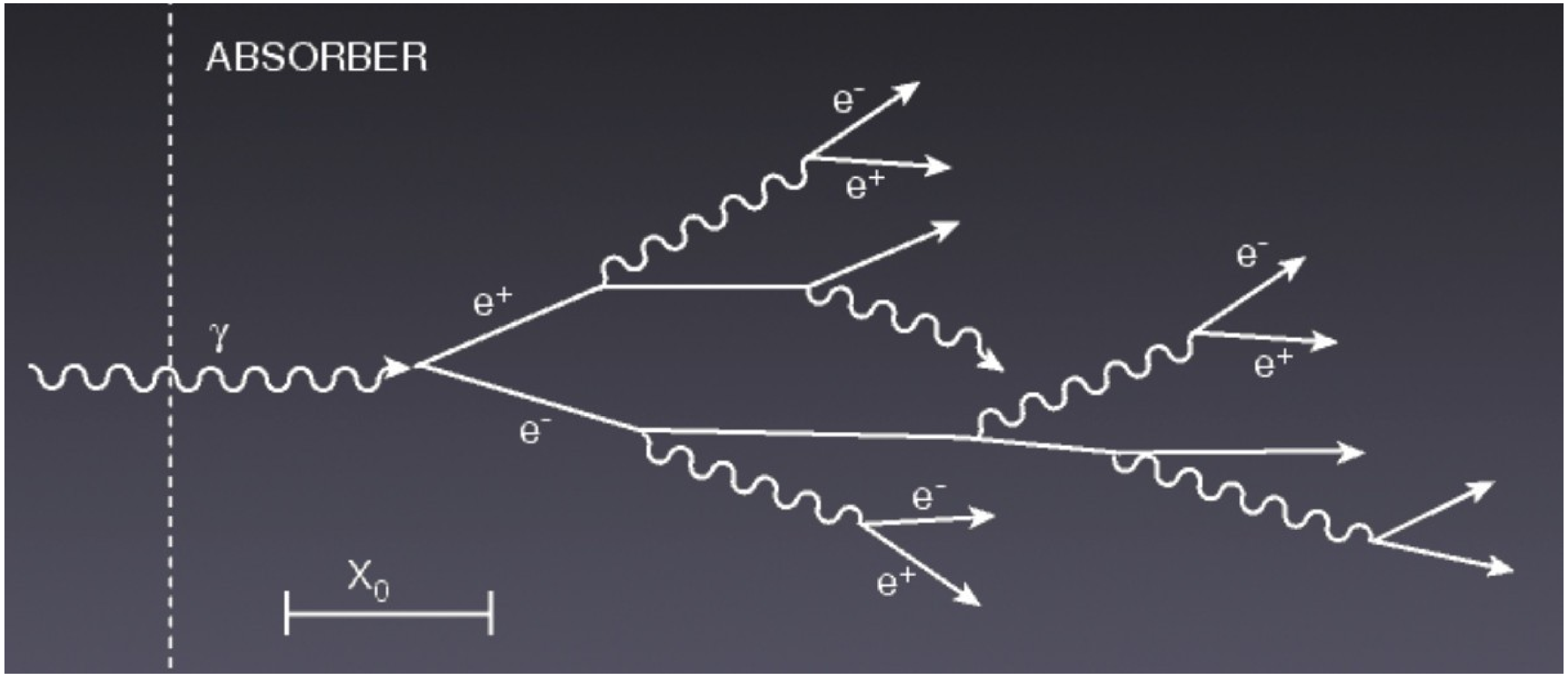
nucleus → 1 mm (static) sand grain at field center

→ *hadrons need to pass within ~10^{-15}m from nuclei to interact*

→ detectors (dimensions, materials) and performance
quite different

em showers

Cascade of (e^+,e^-,γ) → stochastic process w/ thousands particles



pair production, bremsstrahlung & ionisation

radiation length → X_0

X_0 : longitudinal development scale

$$-\left\langle \frac{dE}{dx} \right\rangle_{Brems} = \frac{E}{X_0}$$

1 X_0 : when <1-1/e> (~ 63.2%) of electron energy → brems.

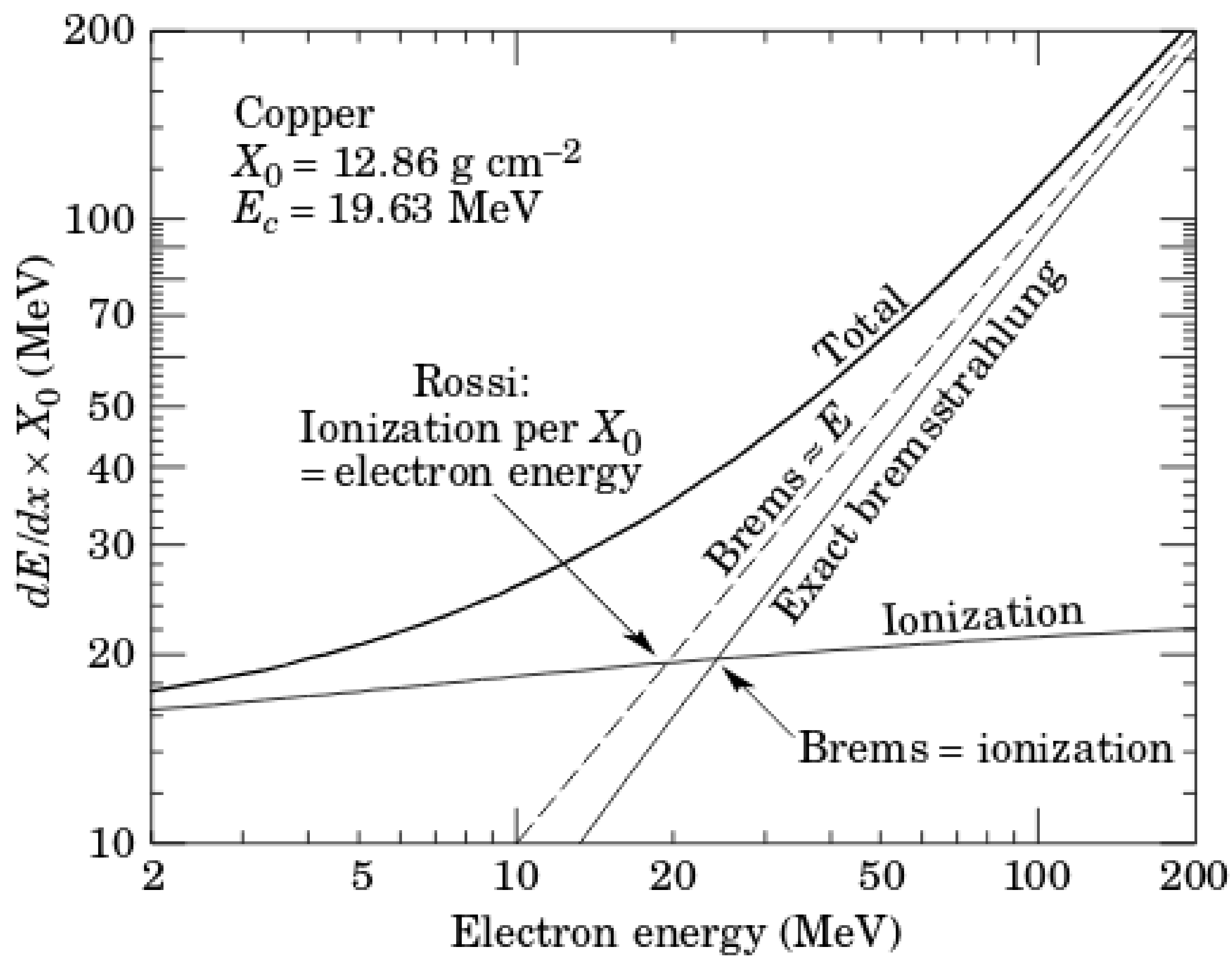
$$X_0 = \frac{1433A}{Z(Z+1)(11.4-\ln(Z))}\frac{\text{g}}{\text{cm}^2}$$

X_0 [g/cm^2] ~ Z^{-1}

critical energy → E_c

E_c : when bremsstrahlung takes over ionisation

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



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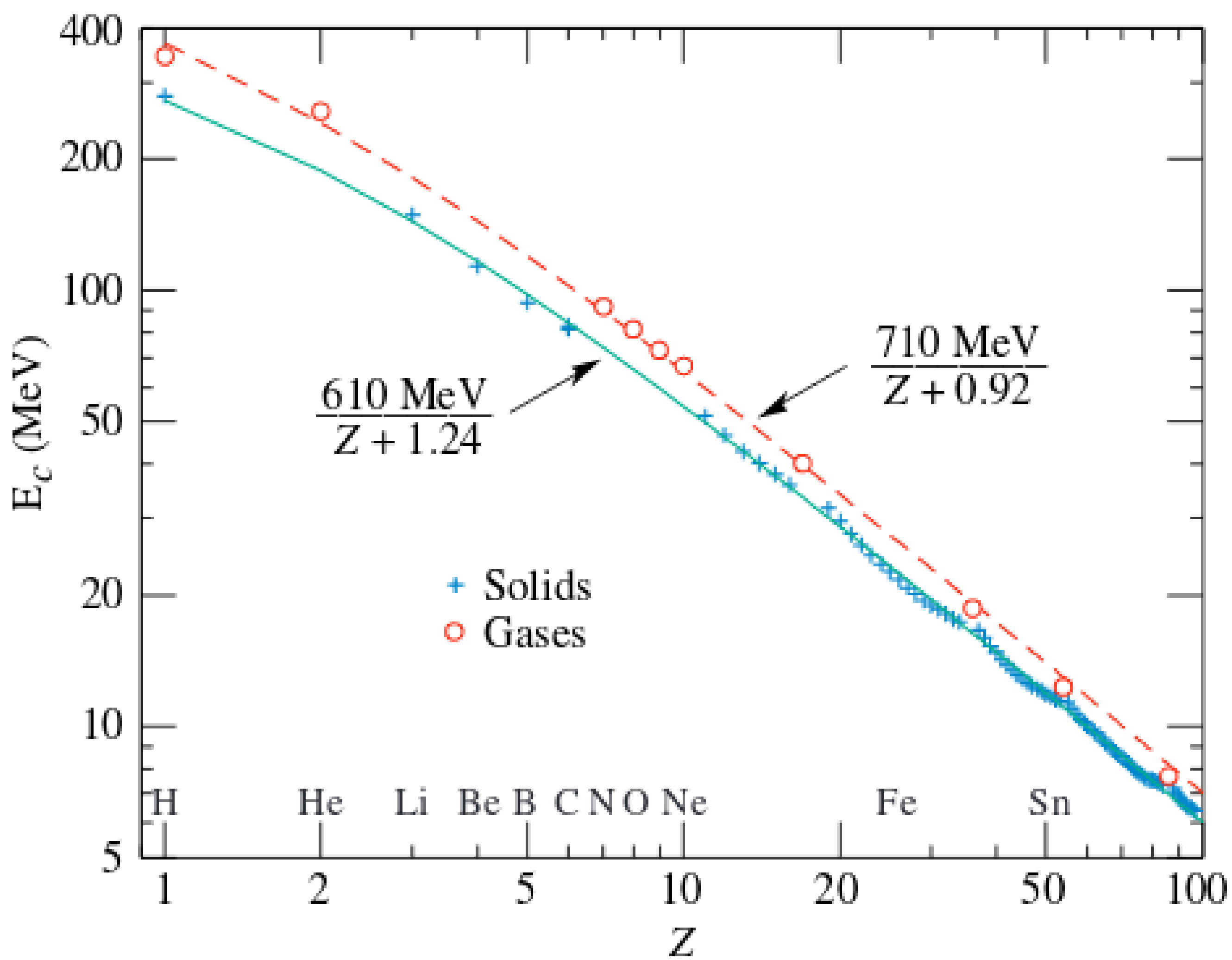


E_c [MeV] ~ Z^{-1}

Molière radius → R_M

lateral spread ~ driven by multiple scattering

R_M : radius of cylinder containing 90% of shower energy (95% in $2 \times R_M$)

$$R_M = E_s \frac{X_0}{E_c}$$

where :

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

→ R_M [g/cm^2] ~ independent of Z

compound materials

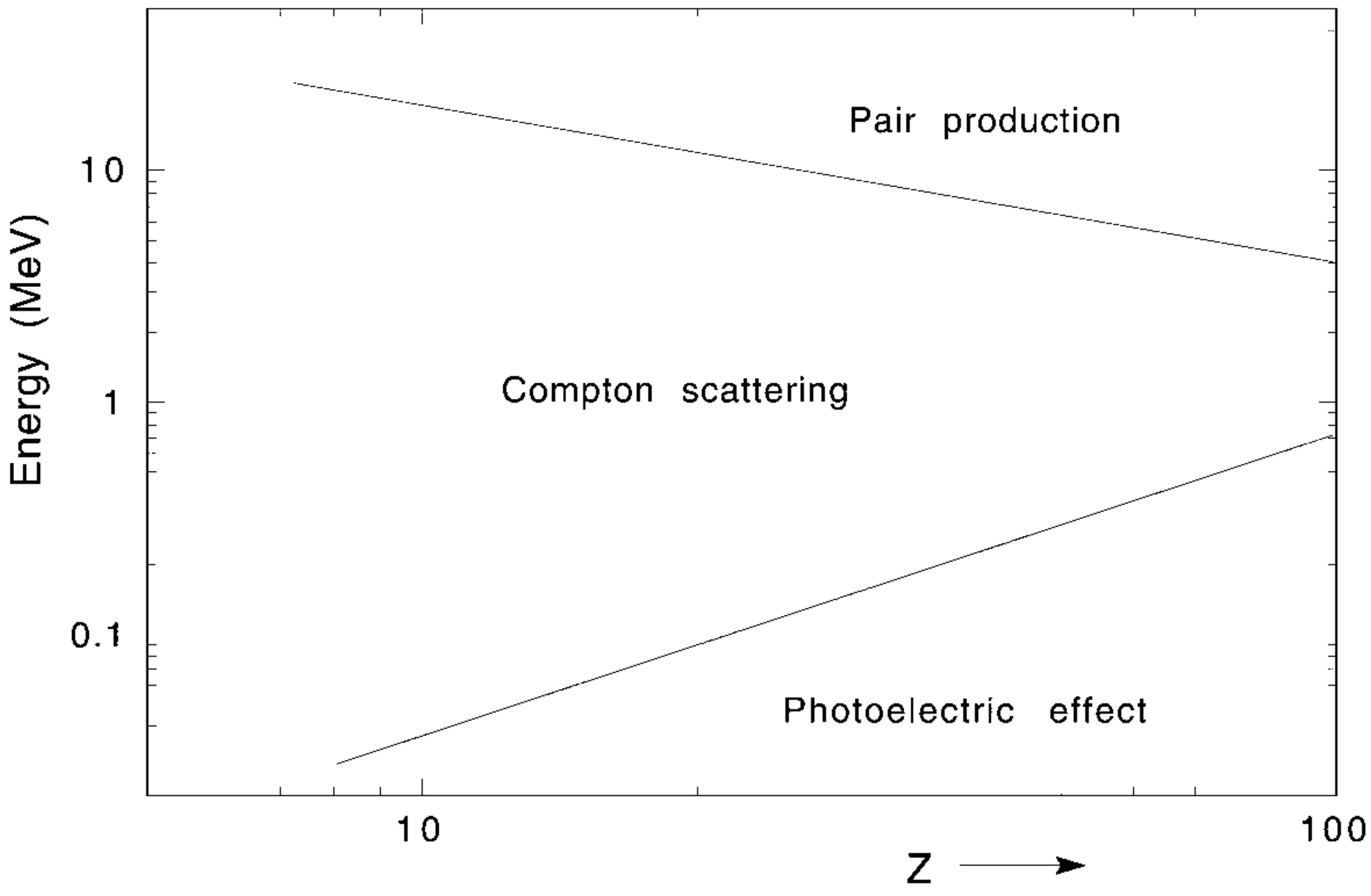
$$1/X_0 = \sum w_j/X_j$$

where : w_j = fraction by weight of j_{th} element

same for R_M :

$$\frac{1}{R_M} = \frac{1}{E_s}\sum\frac{w_j E_{cj}}{X_j} = \sum\frac{w_j}{R_{Mj}}$$

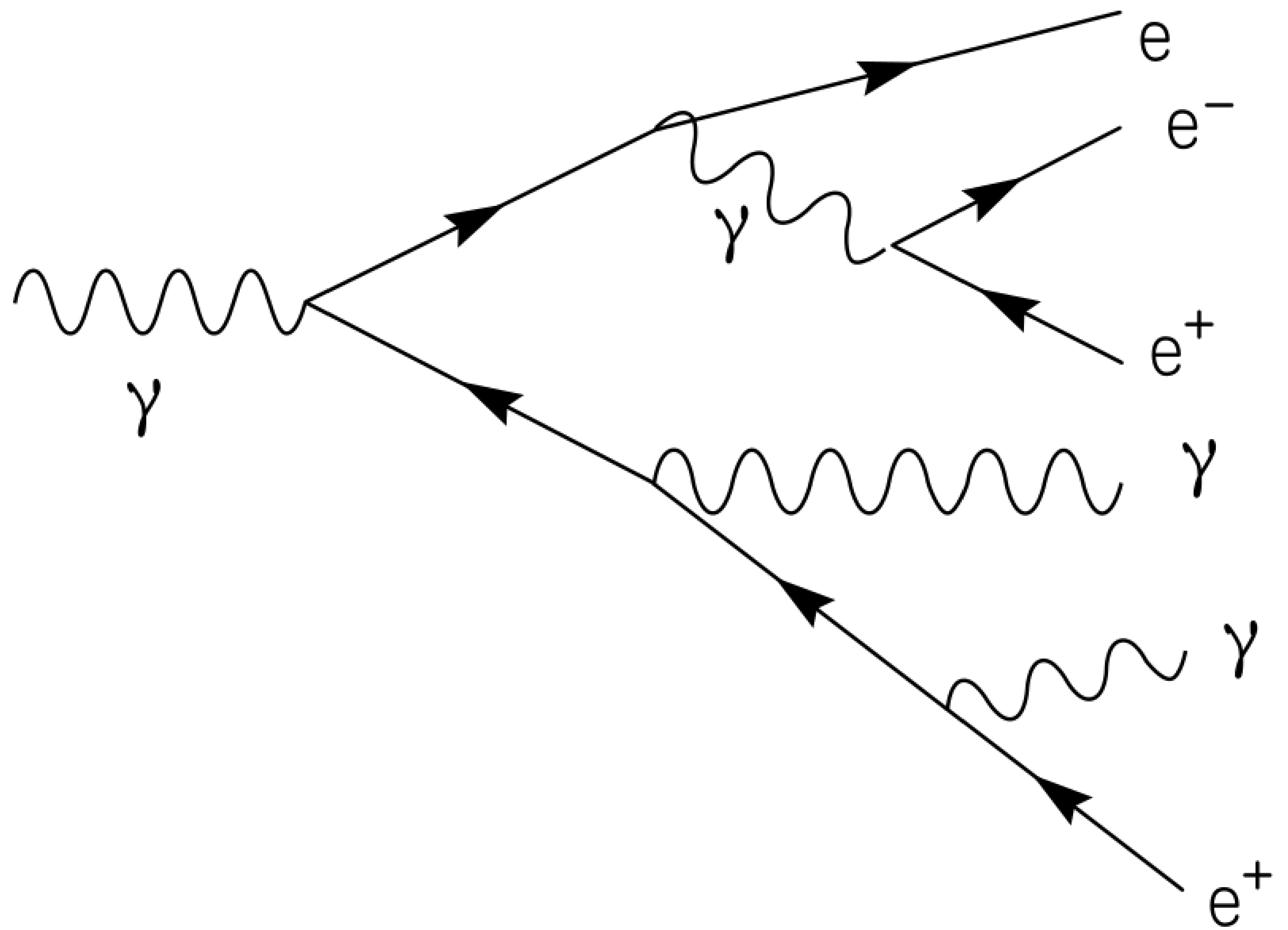
photons



High-energy photons → mean free path (pair production) ~ $\frac{9}{7} X_0$

at first pair production → 2 electron showers

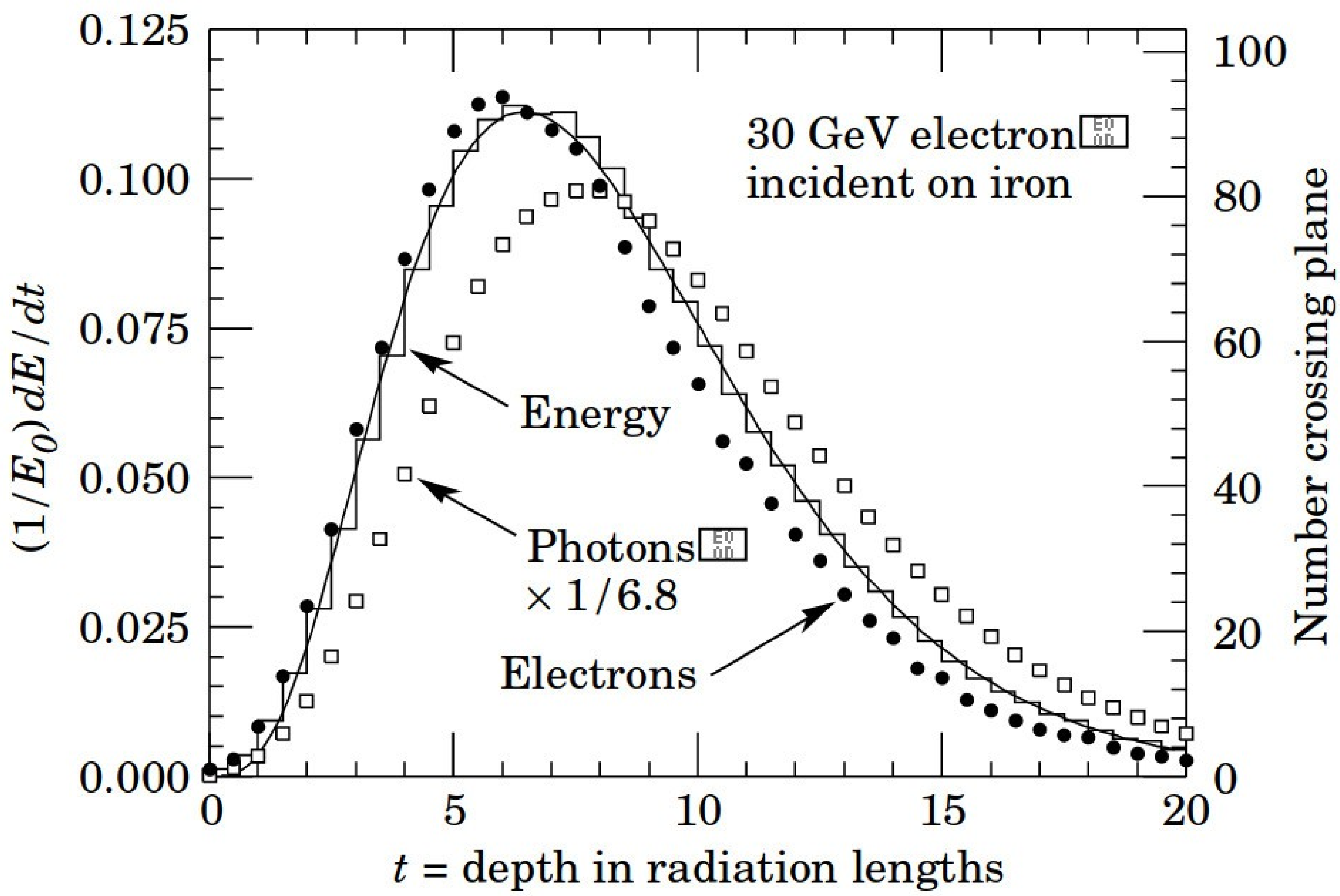
photon showers



em shower:

electrons emit photons
photons produce e^+e^- pairs

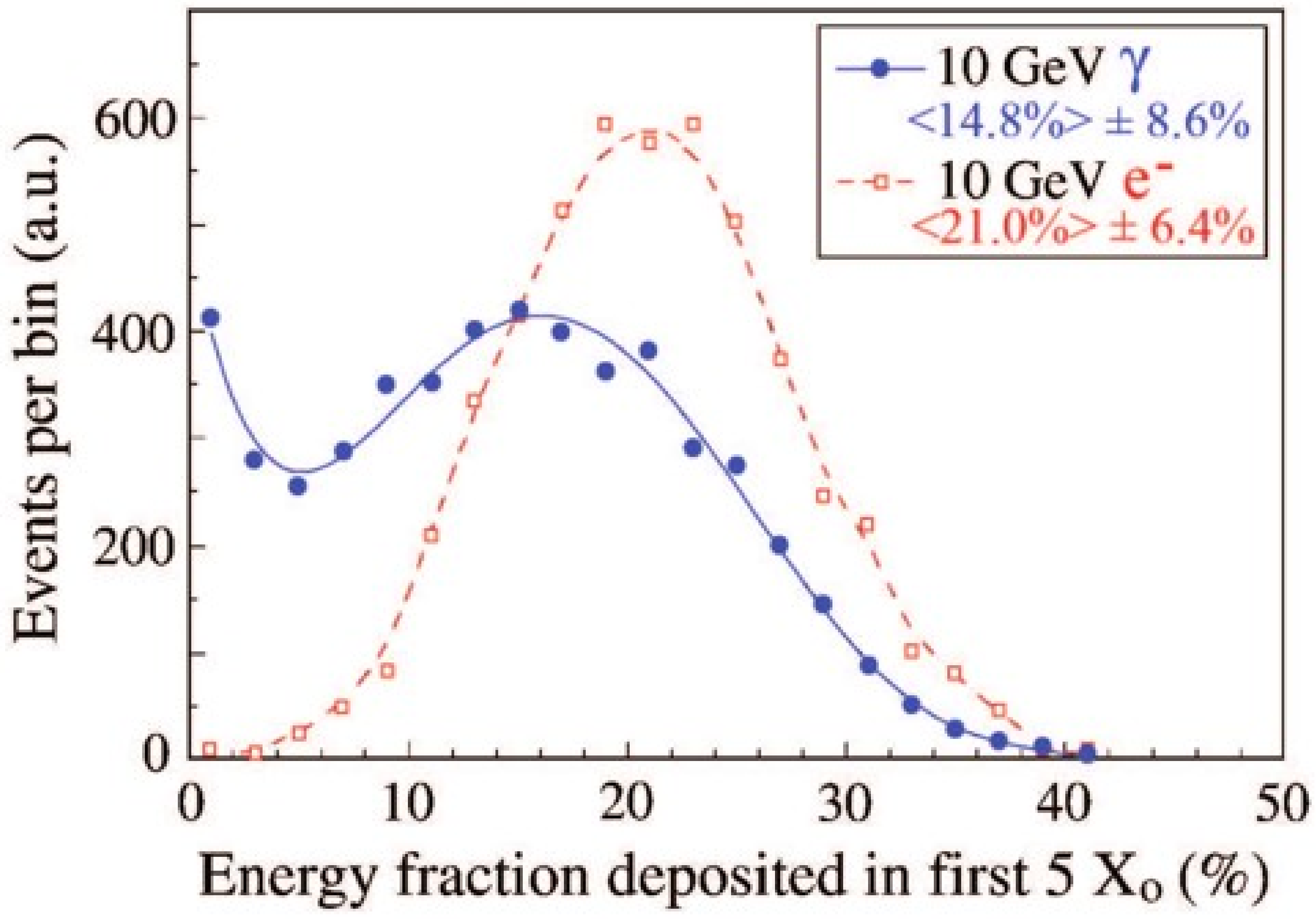
em shower development



1) fractional energy deposition per X_0

2) number of e and photons (E > 1.5 MeV) crossing planes

electron vs. γ initiated showers



… one more parameter

shower maximum (shower depth):

where multiplication process ~ stops

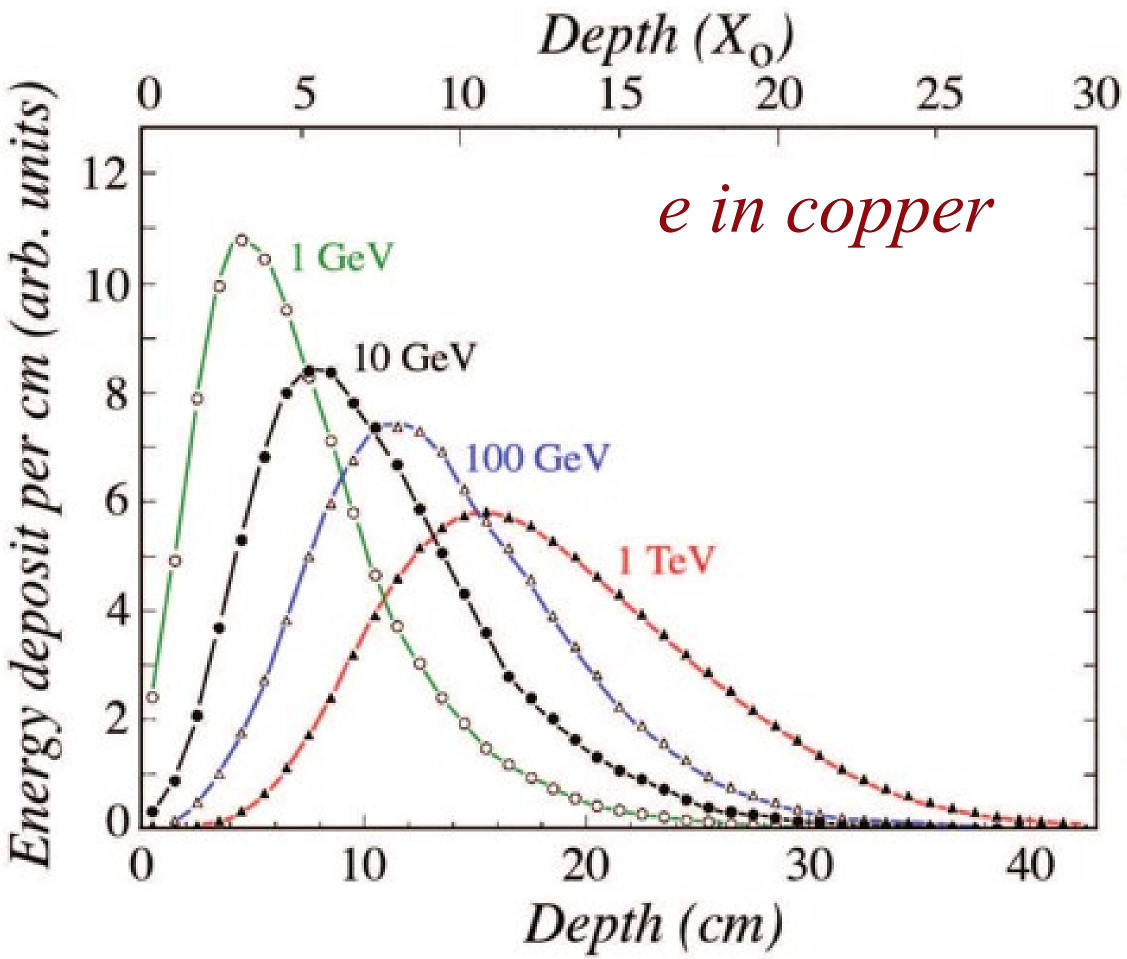
$$X = X_0 \frac{\ln(E_0 / E_c)}{\ln 2}$$

X ~ 1 / Z , ~ log(E)

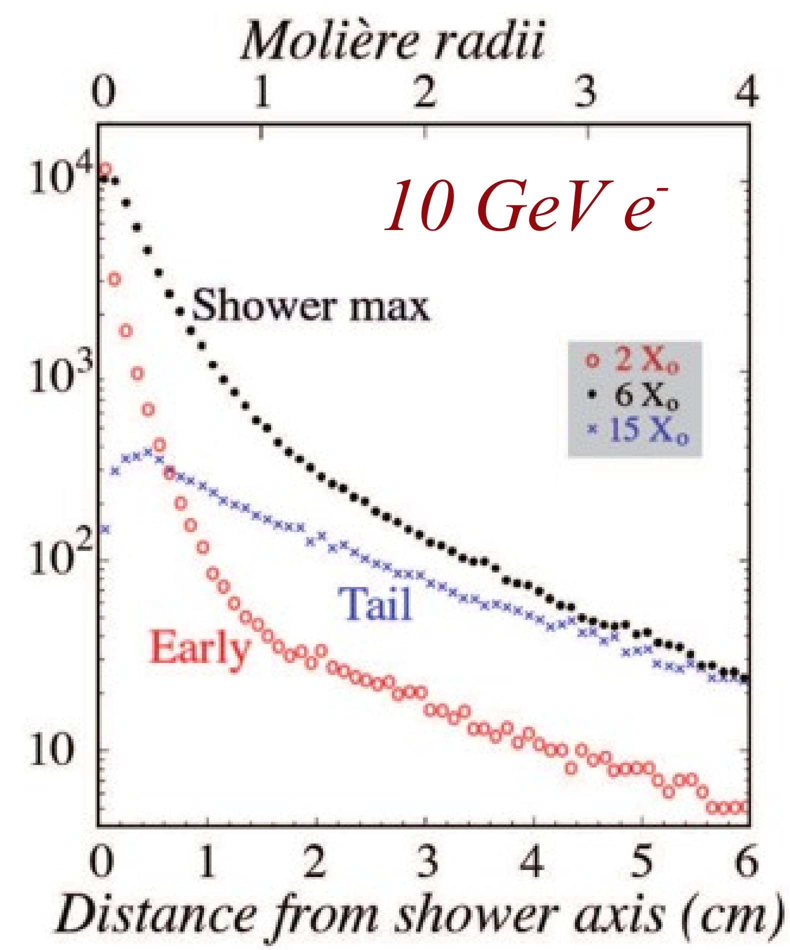
shower longitudinal dimension mildly grows as log(E)

shower development

longitudinal profiles

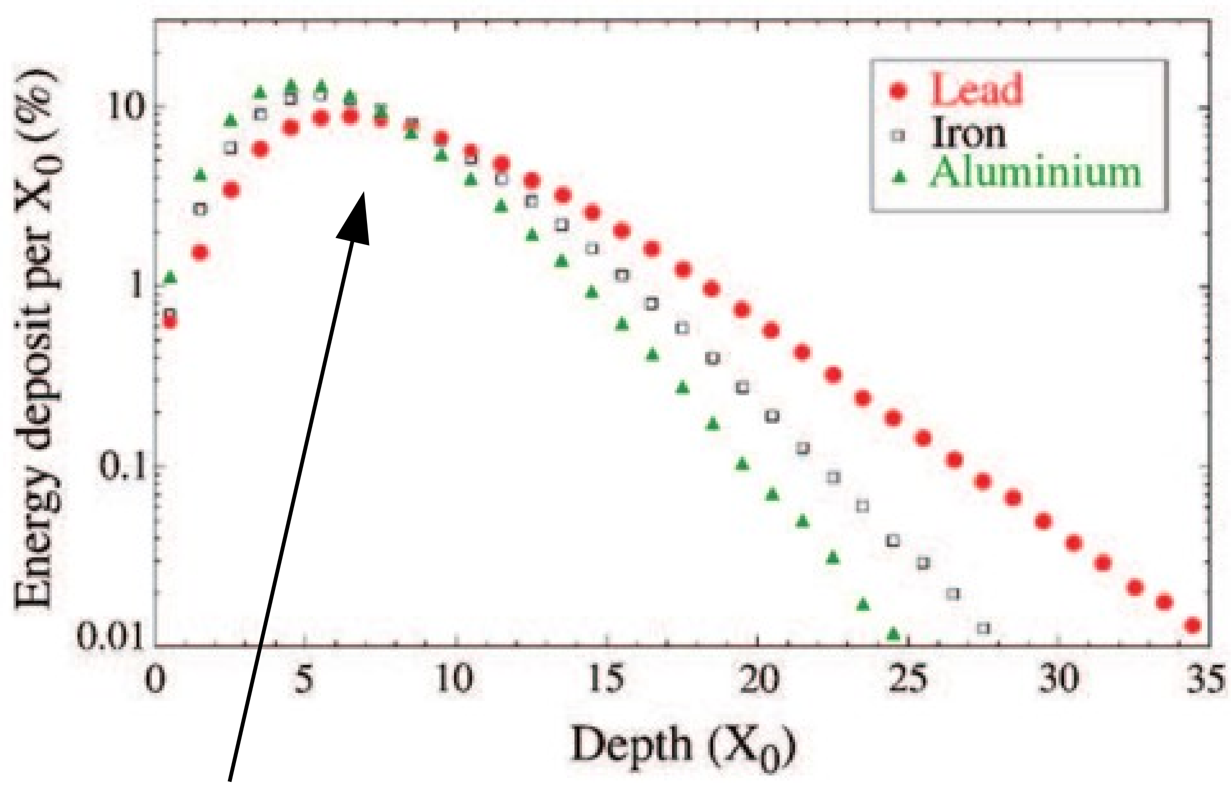


lateral profiles

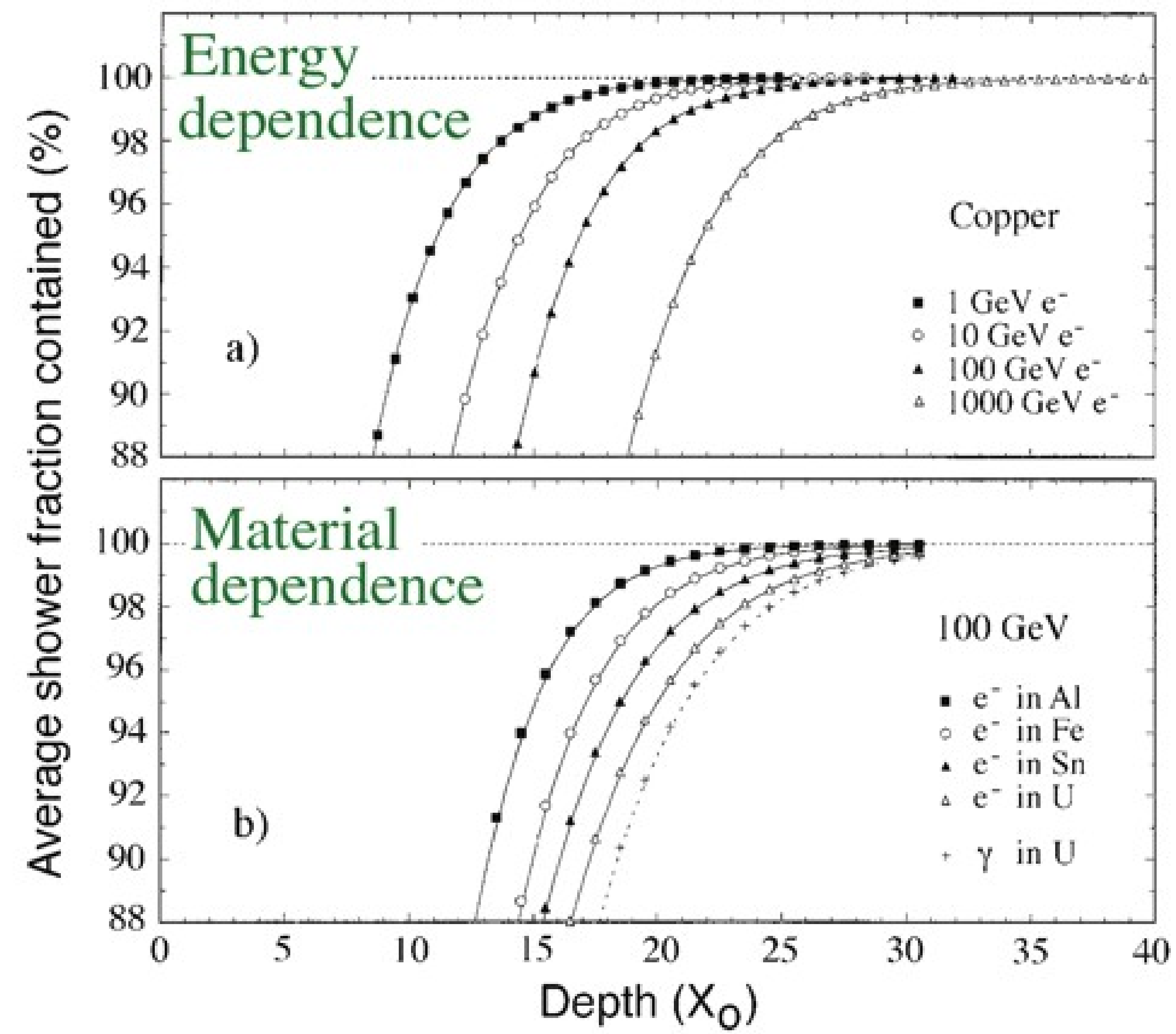


after shower maximum, lateral spread dominated by isotropic processes (Compton scattering, photelectric effect)

scaling violations



longitudinal profiles (10 GeV e^-)



as well due to low-energy phenomena (Compton scattering, photoelectric effect) dominating after shower maximum

energy response

total shower length L $\propto$ total energy = E

signal S (mainly due to low-energy particles) $\propto$ L $\propto$ E

$\rightarrow$ linearity

fluctuations :

a 40 GeV shower equivalent to 2 × 20 GeV showers

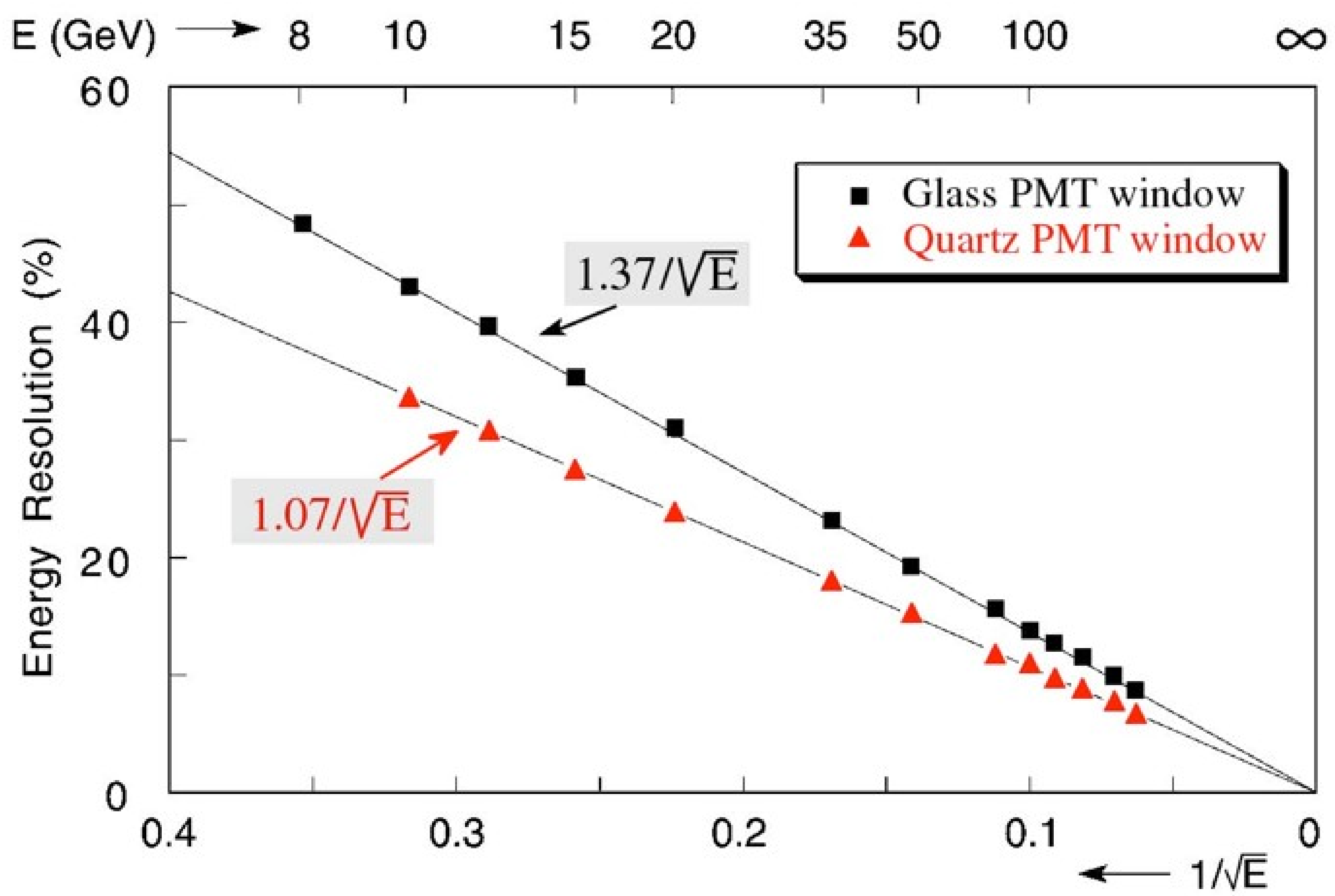
$\rightarrow$ independent fluctuations

$\rightarrow \sigma(E) \propto \sqrt{E}$

stochastic term :

$\sigma(E)/E = a/\sqrt{E}$ $\rightarrow$ improves as $E^{-1/2}$

energy resolution



quartz : better UV light transmittance

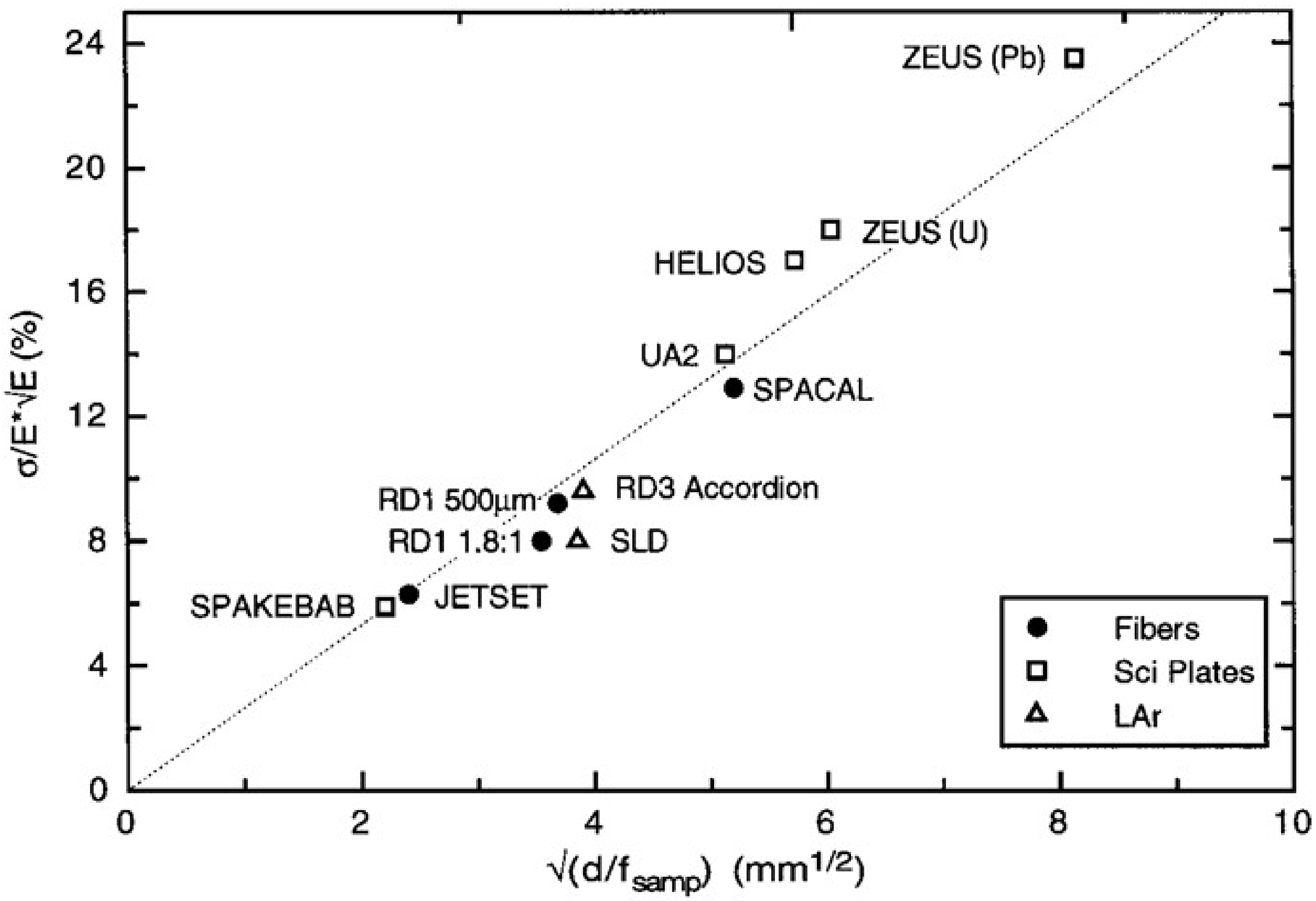
sampling calorimeters

usually sandwich of active (e.g. scintillator plates) and passive elements (e.g. lead plates)

→ impact on resolution ?

sampling fraction : fraction of energy lost in the active medium (by a minimum ionising particle)

sampling fluctuations



(rough) rule of thumb : $a_{\text{samp}} = 2.7\% \sqrt{d/f_{\text{samp}}}$

d [mm] = thickness of each active layer

em resolution ?

1) homogeneous: 100% of shower track sampled in active medium

→ resolution $\sigma/E \sim O(1\%)/\sqrt{E(GeV)}$

2) sampling: only part (<~5%) of track sampled in active medium

→ resolution $\sigma/E \sim O(10\%)/\sqrt{E(GeV)}$

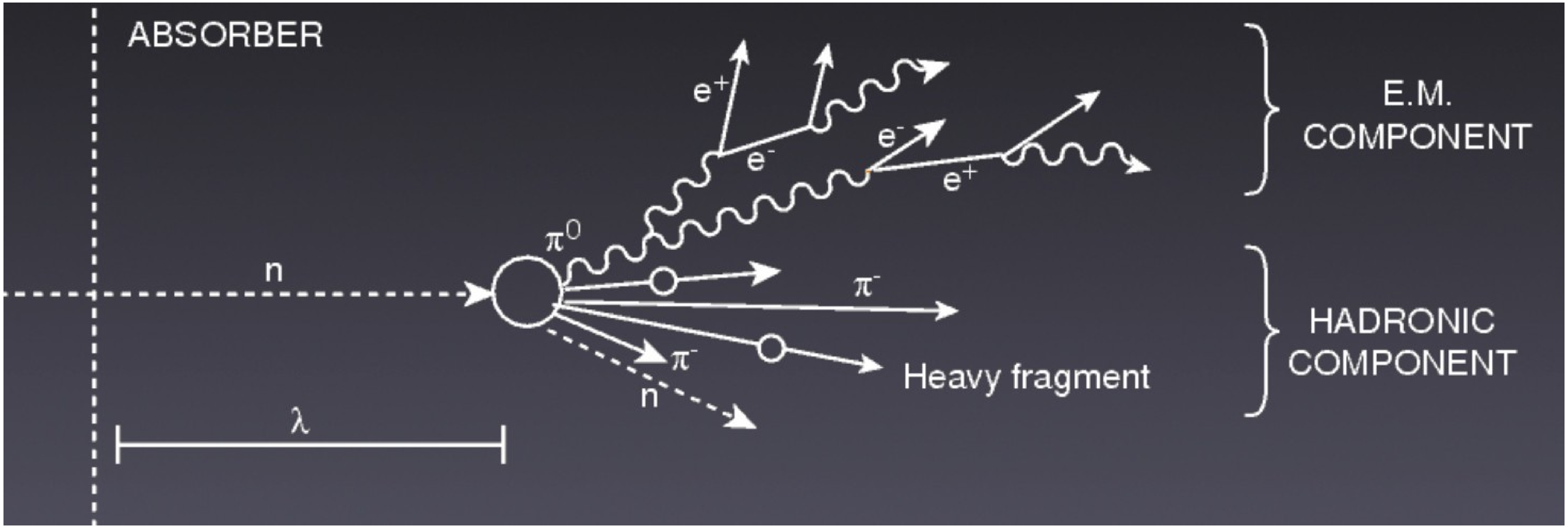
* "typical" values for high-energy physics

real em calorimeters

Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/\mathrm{E}^{1/4}$	1983
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	16–$18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5$ GeV	1998
$PbWO_4$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
Lead glass (OPAL)	$20.5X_0$	$5\%/\sqrt{E}$	1990
Liquid Kr (NA48)	$27X_0$	$3.2\%/\sqrt{E} \oplus 0.42\% \oplus 0.09/E$	1998
Scintillator/depleted U (ZEUS)	20–$30X_0$	$18\%/\sqrt{E}$	1988
Scintillator/Pb (CDF)	$18X_0$	$13.5\%/\sqrt{E}$	1988
Scintillator fiber/Pb spaghetti (KLOE)	$15X_0$	$5.7\%/\sqrt{E} \oplus 0.6\%$	1995
Liquid Ar/Pb (NA31)	$27X_0$	$7.5\%/\sqrt{E} \oplus 0.5\% \oplus 0.1/E$	1988
Liquid Ar/Pb (SLD)	$21X_0$	$8\%/\sqrt{E}$	1993
Liquid Ar/Pb (H1)	20–$30X_0$	$12\%/\sqrt{E} \oplus 1\%$	1998
Liquid Ar/depl. U (DØ)	$20.5X_0$	$16\%/\sqrt{E} \oplus 0.3\% \oplus 0.3/E$	1993
Liquid Ar/Pb accordion (ATLAS)	$25X_0$	$10\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996

hadronic calorimetry

π^0, η^0 production → hadronic showers develop 2 main components:



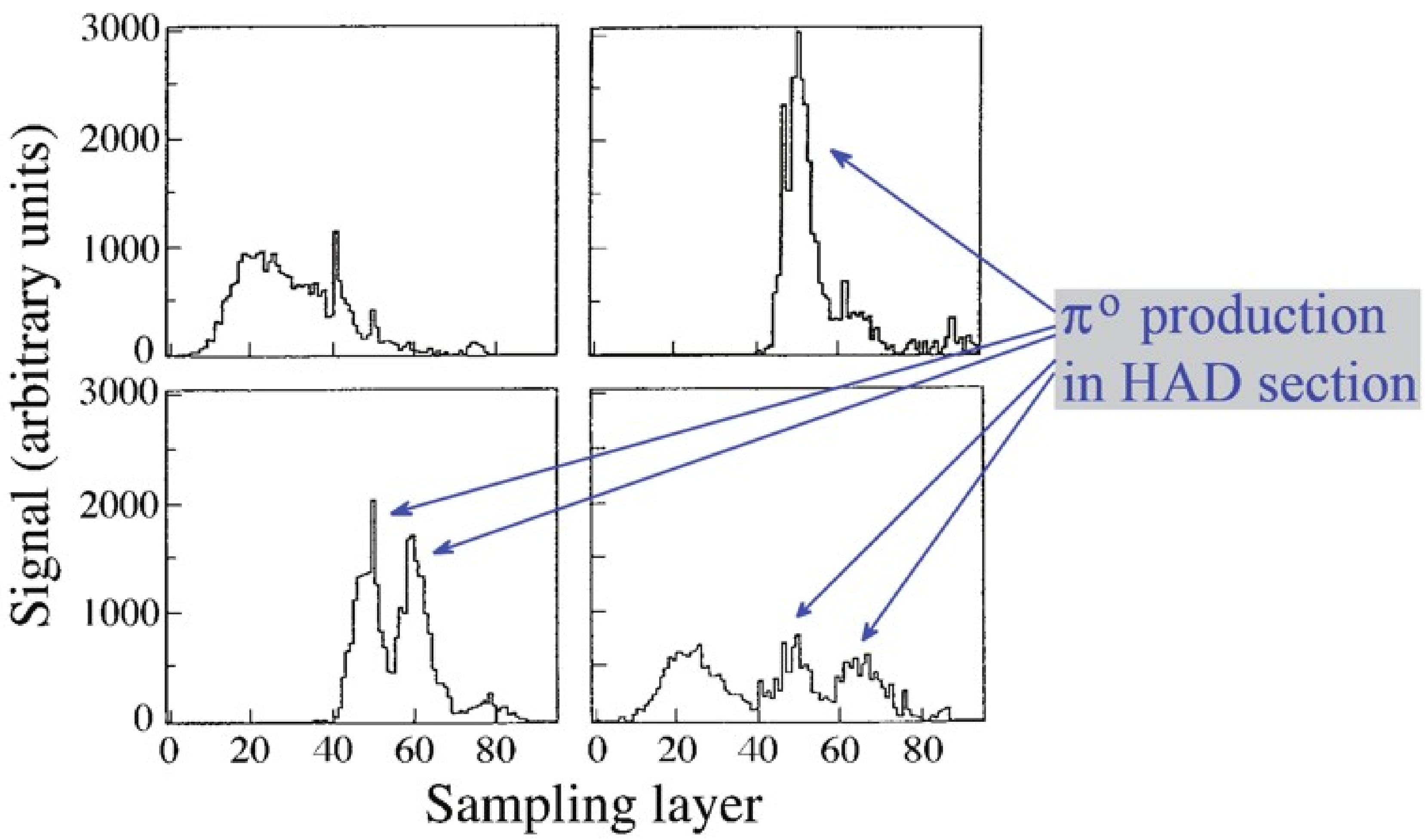
h component: p, n, $\pi^{\pm}$, nuclear fission, … delayed photons, …

dimension scale : $\lambda_I \sim 35\ g/cm^2 \cdot A^{1/3}$

hadronic shower development

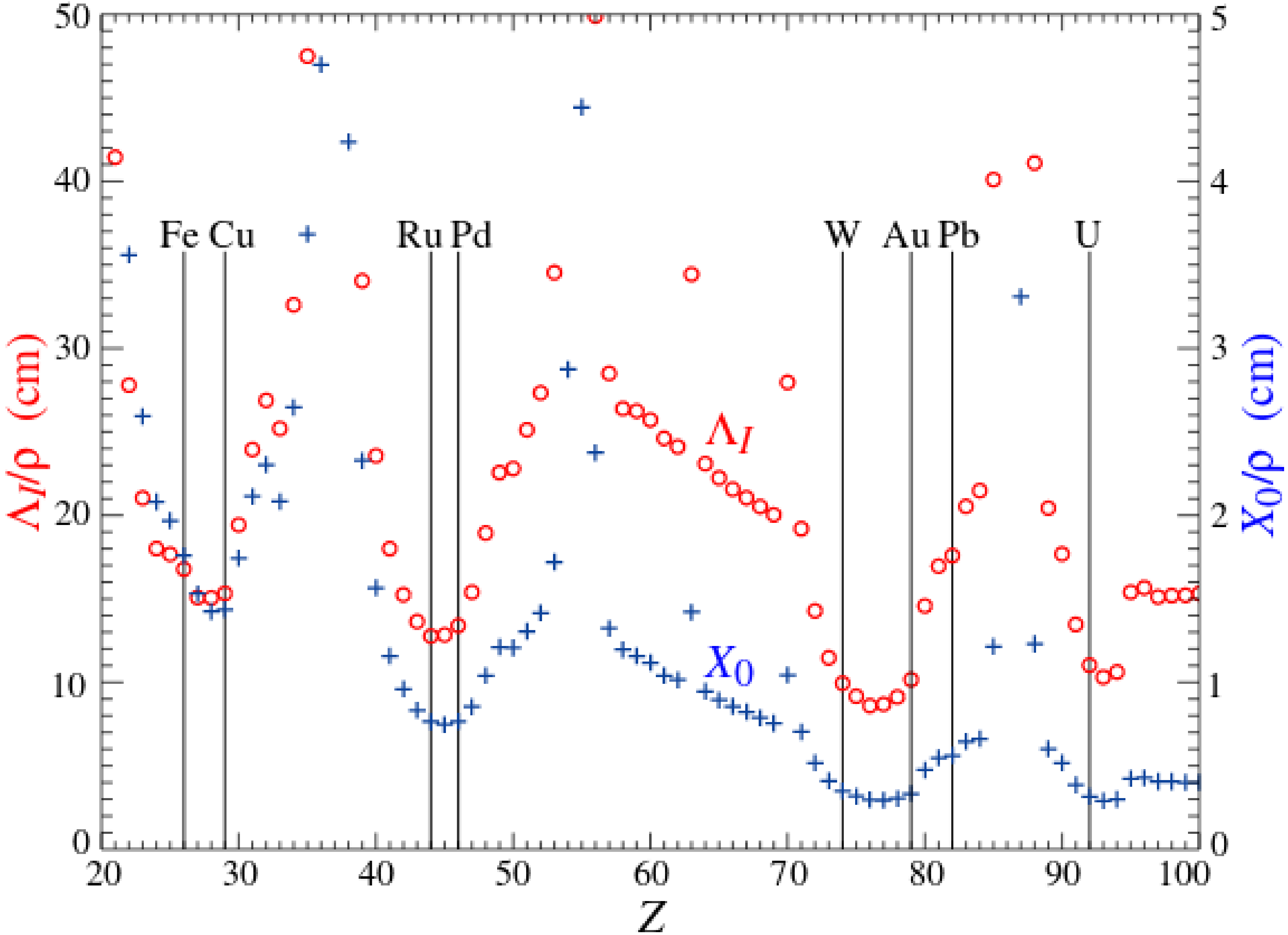
on average equivalent to em showers with X_0 and R_M replaced by λ_I (nuclear interaction length) … but :

single showers by 170 GeV pions



… much much larger event-by-event fluctuations !

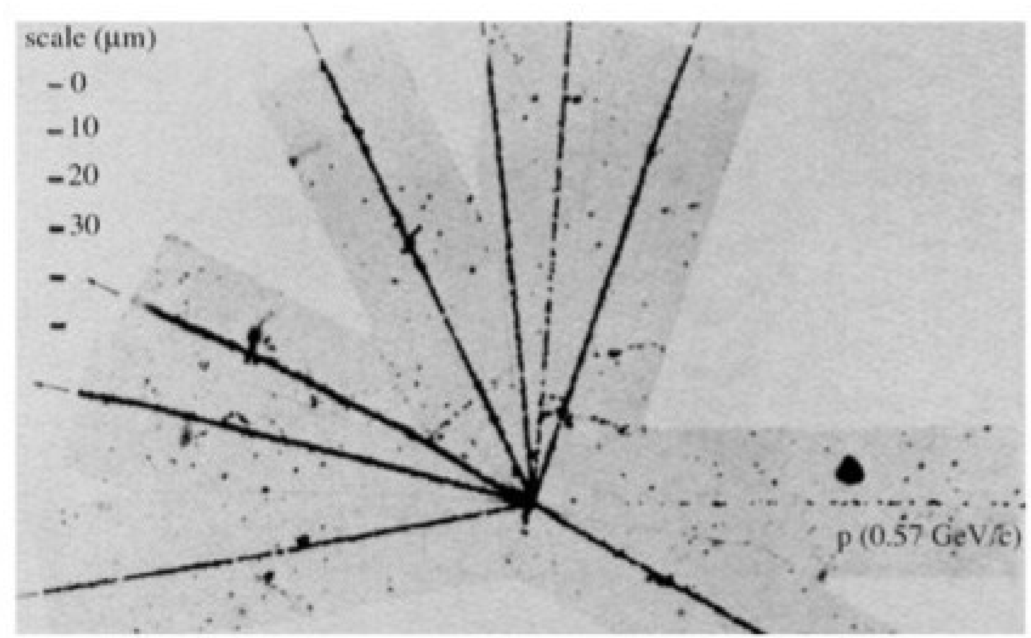
radiation vs. interaction length



→ a factor > ~10 in λ_I/X_0 ratio

hadronic shower components

- *Electromagnetic component*
  - electrons, photons
  - neutral pions → 2 γ
- *Hadronic (non-em) component*
  - charged hadrons $\pi^{\pm}$,$K^{\pm}$ (20%)
  - nuclear fragments, p (25%)
  - neutrons, soft γ's (15%)
  - break-up of nuclei (*"invisible"*) (40%)



many components w/ large fluctuations in relative yield

1. large non-gaussian fluctuations in energy sharing em/non-em
2. increase of em component with energy
3. large, non-gaussian fluctuations in "invisible" energy losses

electromagnetic fraction f_{em}

energy fraction carried by π^0 (mainly) and η^0

f_{em}, on average, *large and energy dependent*

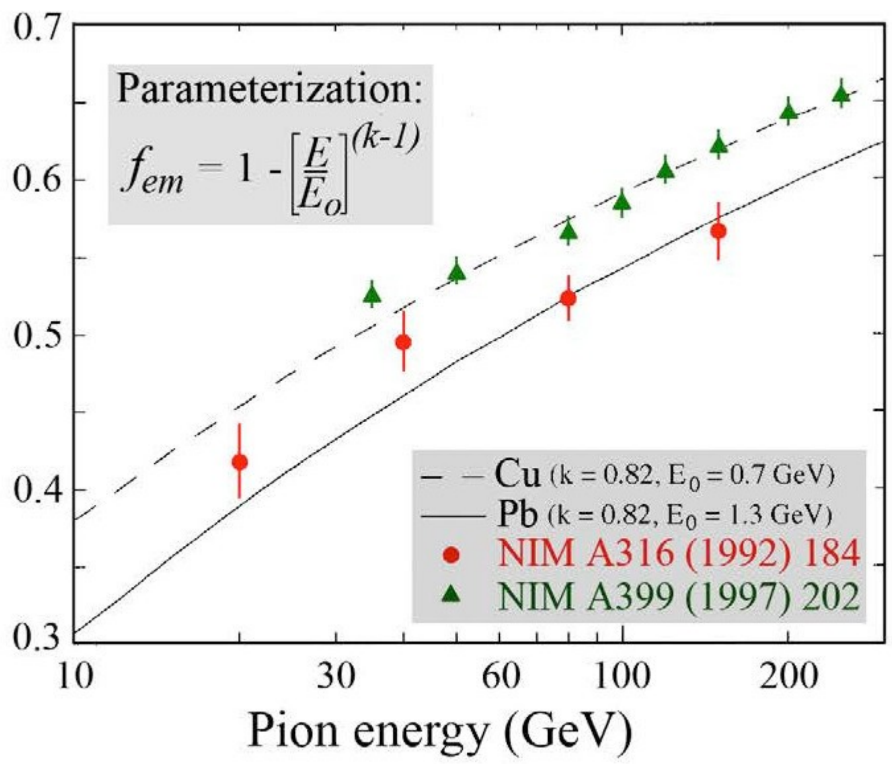
fluctuations in f_{em} *large and non-poissonian*

$$\langle f_{em} \rangle = 1 - \left(E / E_0 \right)^{(k-1)}$$

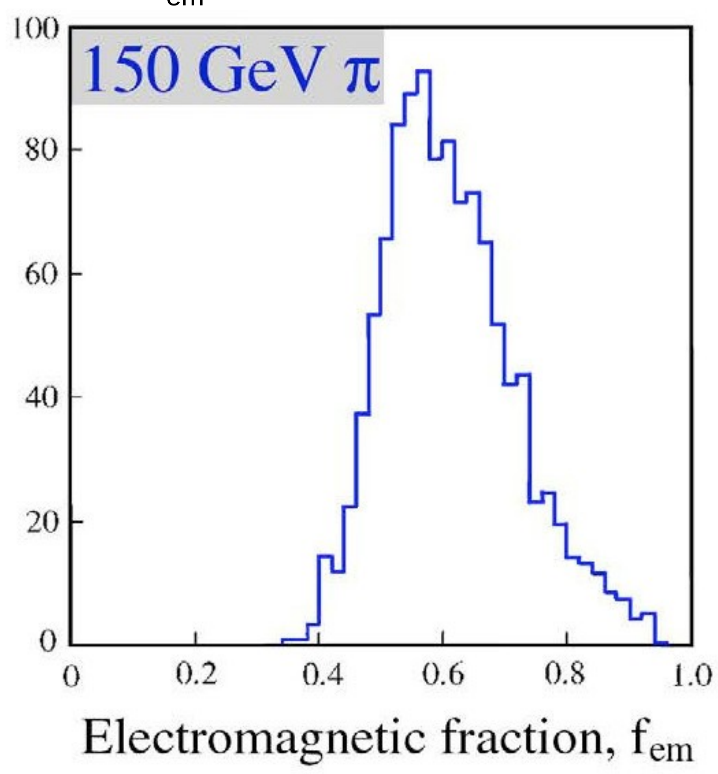
E_0 = average energy to produce a π^0

(k-1) related to average multiplicity

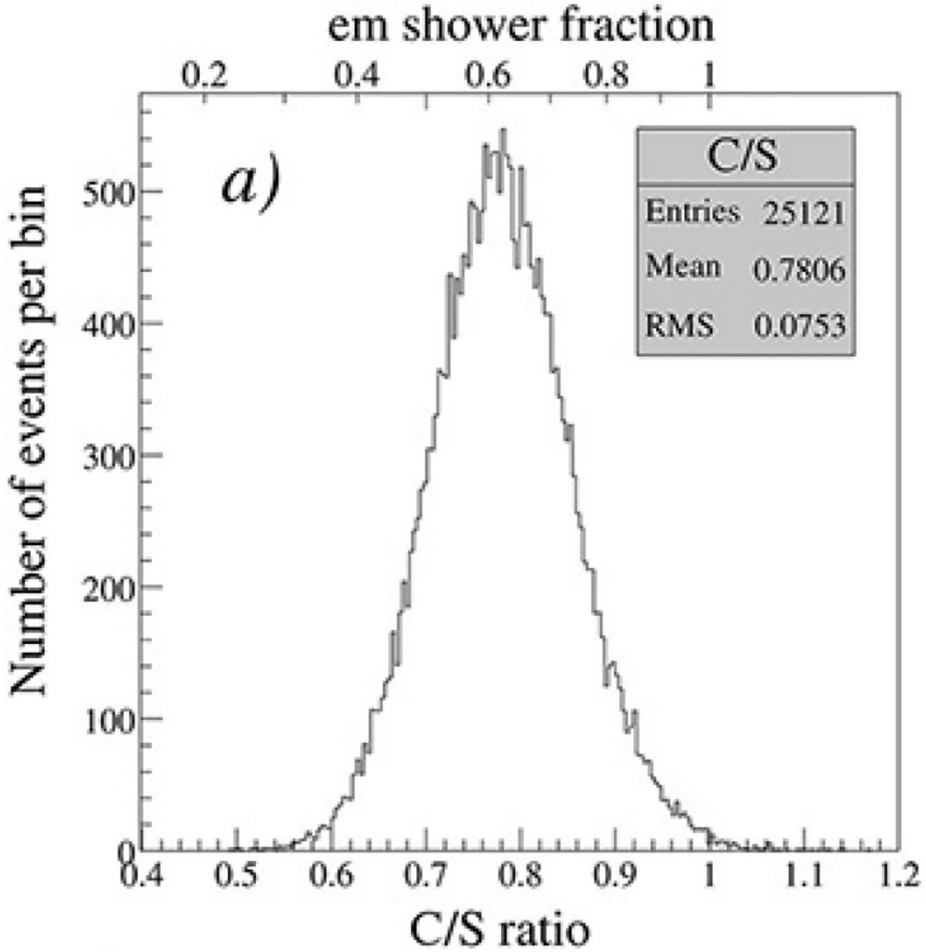
< f_{em} > vs. pion energy



f_{em} for 150 GeV pions

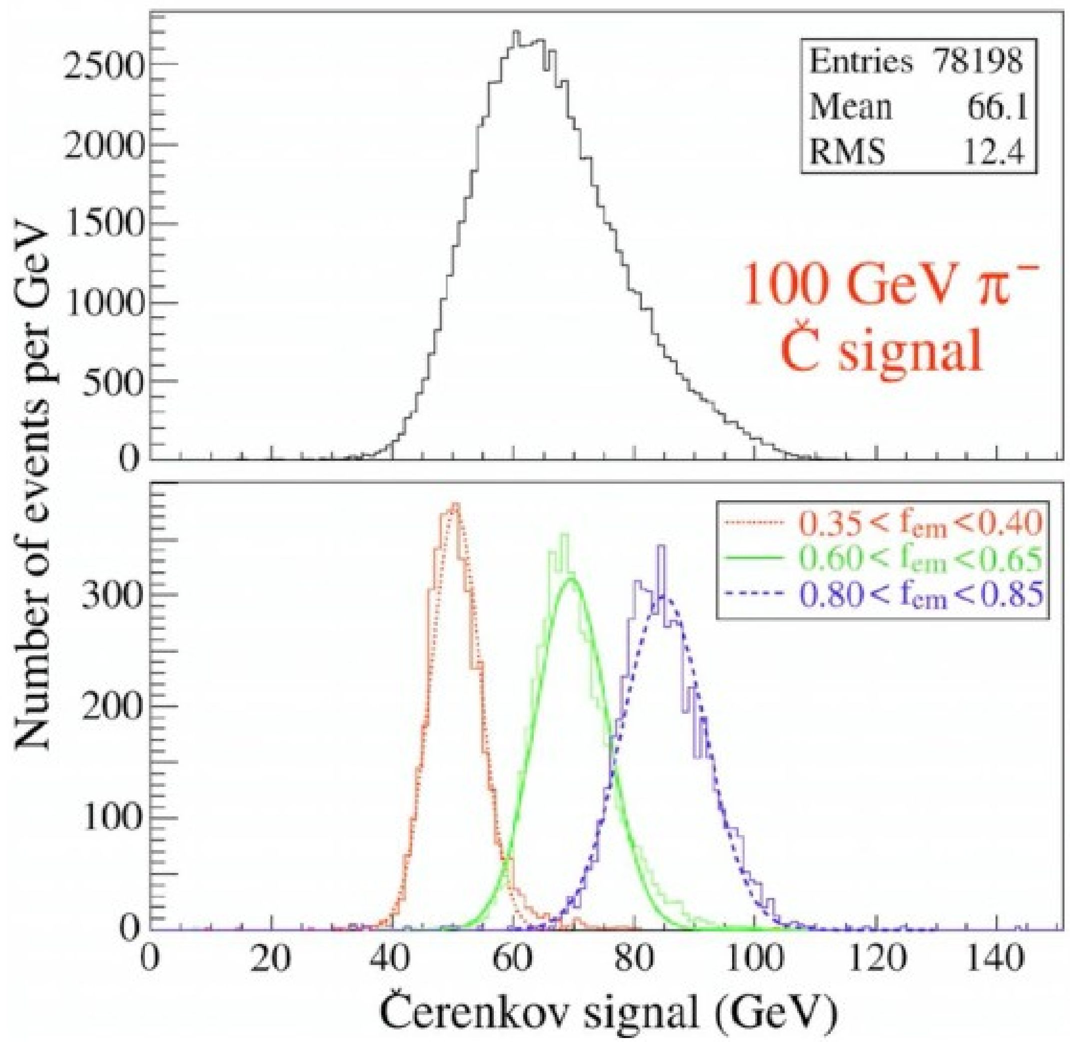


f_{em} fluctuations



$$f = \frac{c - s(C/S)}{(C/S)(1-s) - (1-c)}$$

DREAM: Effect of event selection based on f_{em}



From:
NIM A537 (2005) 537

invisible energy

- In nuclear reactions energy is lost (binding energy) to free protons and neutrons
- can't provide any measurable signal (*invisible energy*)
- accounts on average for ~ 30-40% of non-em shower energy

large event-by-event fluctuations limit resolution

Correlation between invisible energy and kinetic energy carried by released nucleons

Evaporation nucleons: soft spectrum, mostly neutrons (2-3 MeV)

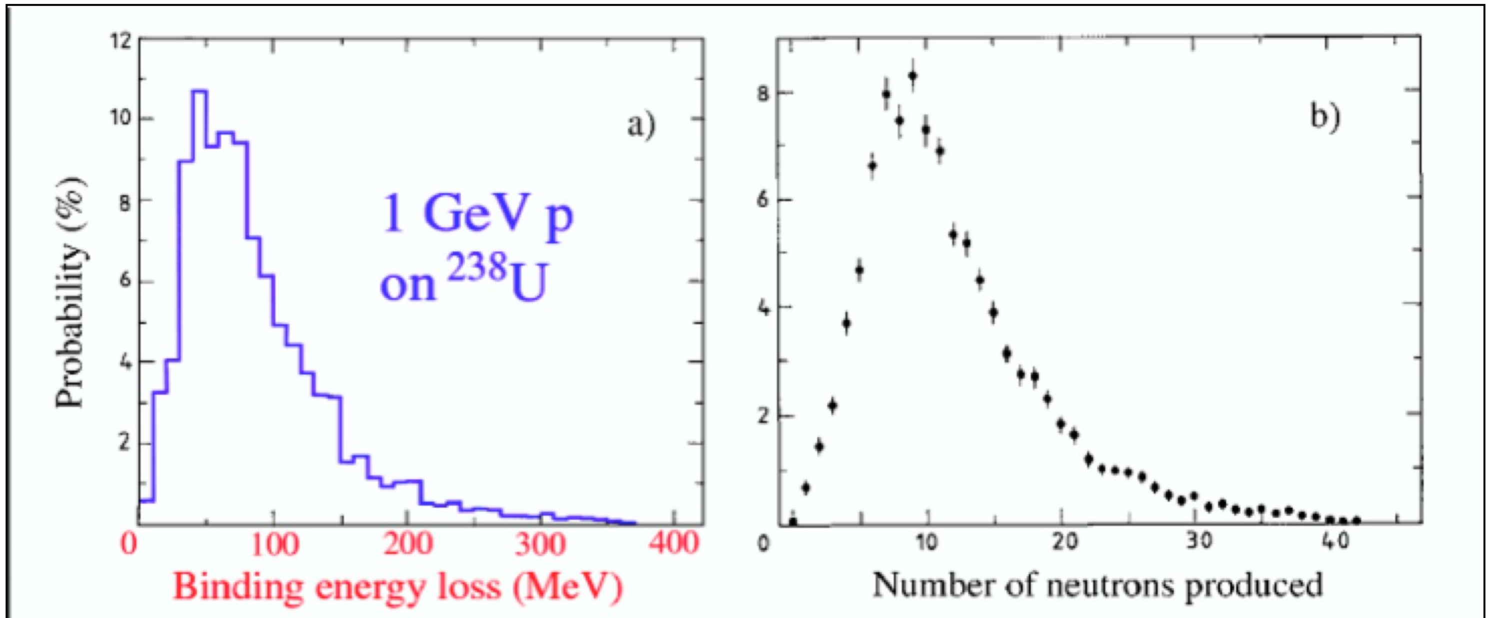
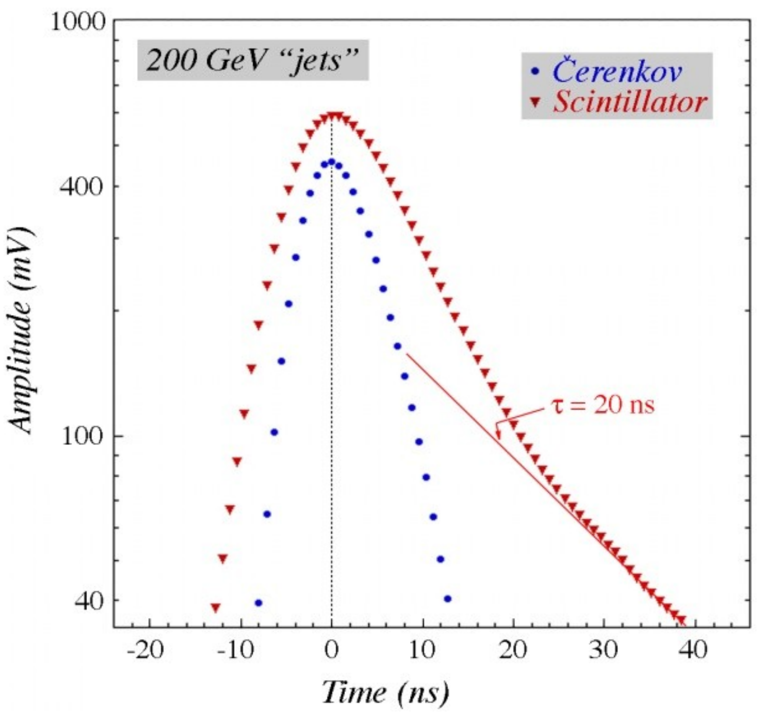


FIG. 4.43. The nuclear binding energy lost in spallation reactions induced by 1 GeV protons on ^{238}U nuclei (a), and the number of neutrons produced in such reactions (b). From [Wig 87].

invisible energy correlations

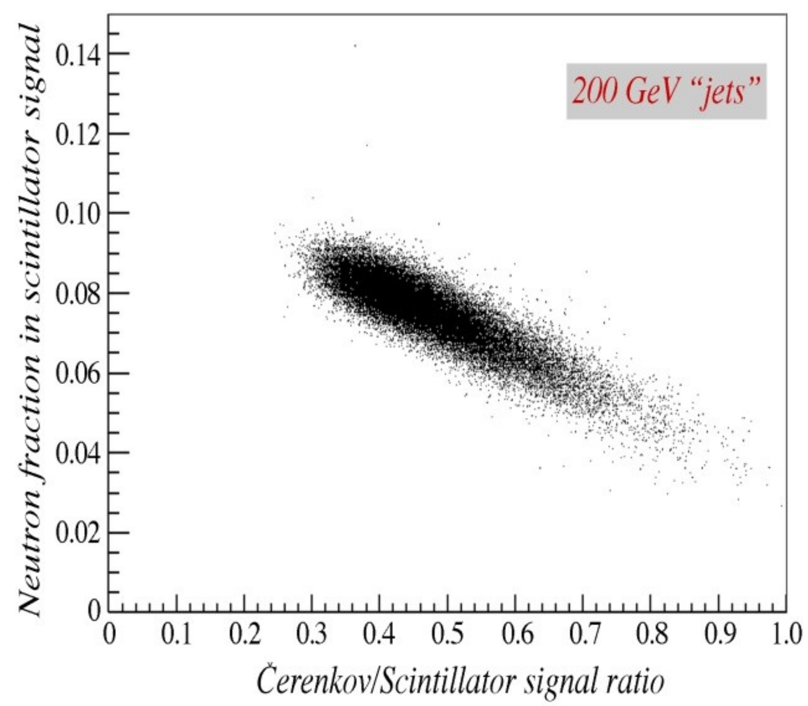
Measurement of the kinetic energy of neutrons - correlated to nuclear binding energy loss (invisible energy) - from signal time structure (DREAM)

Signal time structure

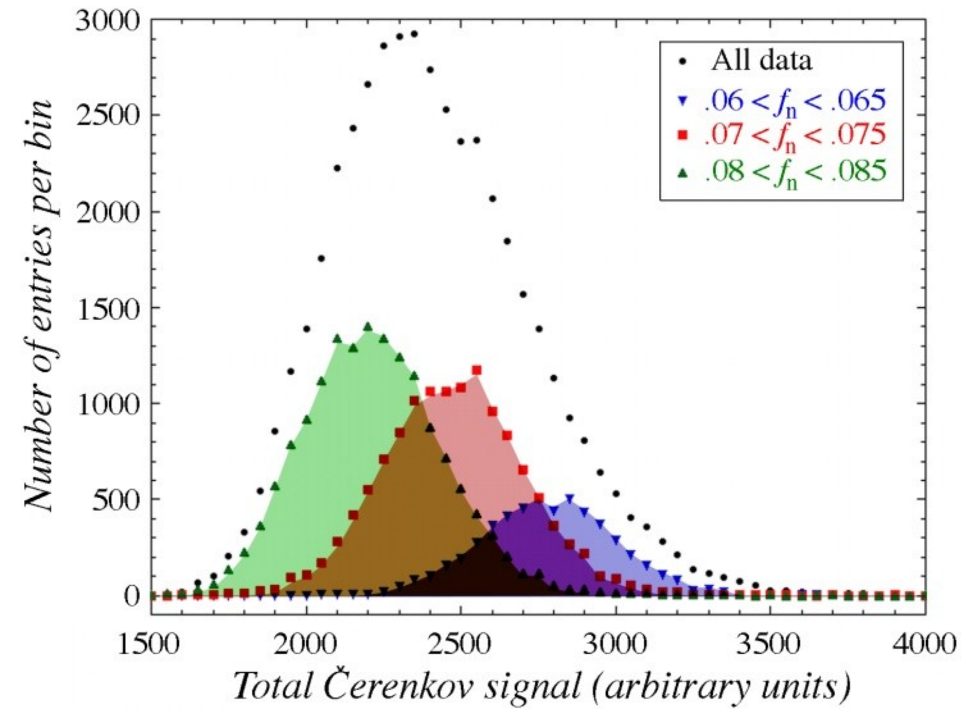


no tail in em showers

f_n anti-correlated to f_{em}



Probing the tot. signal distribution with f_n



detector response

Response:

detected signal per unit energy deposit

e.g. number of scintillating (or Cherenkov) p.e. / deposited GeV

Hadronic showers:

em component → response e

hadronic component → response h

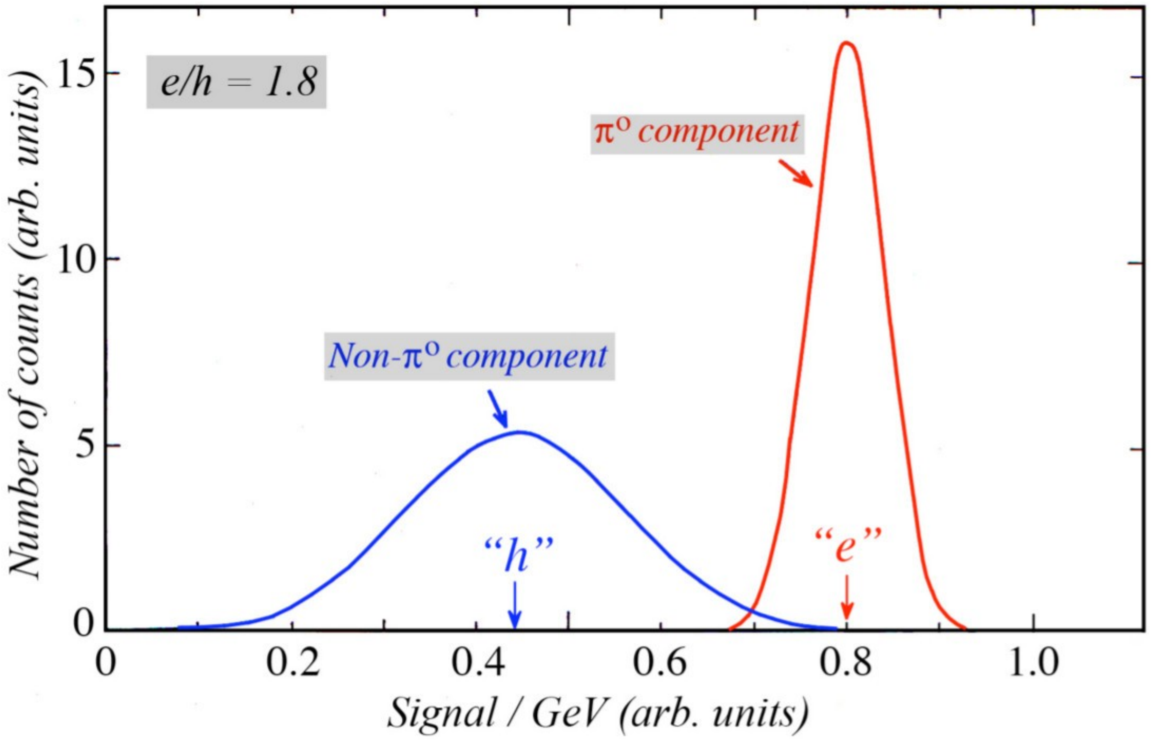
what about the relative ratio e/h ?

detector response to hadronic showers

e ≠ h

e.g. (right plot):

only 1/1.8 ≈ 56% of non-π^o energy accounted by signal



Note:

e/h ratio: detector characteristic

typically, ~2 for crystals, in range 1-1.8 for sampling calorimeters

Nevertheless:

1) e/π depends on energy (f_{em} *depends on E and shower "age"*)

2) f_{em} different for π, K, p → response depends of particle type

compensation

e/h = 1 → compensating calorimeter

1) increase h → boost hadron response
e.g. by adding hydrogen or by using Uranium, both acting as "neutron converters" → large integration volume and time

2) decrease e → decrease em sampling fraction (i.e. em performance) → tune active / passive material ratio

compensation pros & cons

- not a guarantee for high resolution
  - fluctuations in f_{em} are eliminated, but others may be very large
- has drawbacks
  - high-Z absorber required → small e/mip → non linearity @ low energy
  - low sampling fraction required → em resolution limited
  - relies on neutrons → integration over large volume and time
    SPACAL 30%/√E needed ~15 tonnes and ~50 ns
- high-res em and high-res hadron calorimetry mutually exclusive:
  - good jet energy resolution ⇒ compensation
    ⇒ small sampling fraction (~3%) ⇒ poor em resolution
  - good em resolution ⇒ high sampling fraction (100% crystals, 20% LAr)
    ⇒ large non compensation ⇒ poor jet resolution

real hadronic calorimeters

Experiment	Detector	Absorber material	*e/h*	Energy resolution (E in GeV)
UA1 C-Modul	Scintillator	Fe	≈ 1.4	$80\%/\sqrt{E}$
ZEUS	Scintillator	Pb	≈ 1.0	$34\%/\sqrt{E}$
WA78	Scintillator	U	0.8	$52\%/\sqrt{E} \oplus 2.6\%$*
D0	liquid Ar	U	1.11	$48\%/\sqrt{E} \oplus 5\%$*
H1	liquid Ar	Pb/Cu	≤ 1.025*	$45\%/\sqrt{E} \oplus 1.6\%$
CMS	Scintillator	Brass (70% Cu / 30% Zn)	$\neq 1$	$100\%/\sqrt{E} \oplus 5\%$
ATLAS (Barrel)	Scintillator	Fe	$\neq 1$	$50\%/\sqrt{E} \oplus 3\%$
ATLAS (Endcap)	liquid Ar	Brass	$\neq 1$	$60\%/\sqrt{E} \oplus 3\%$

* after software compensation

dual-readout calorimetry

What ?

Don't spoil em resolution to get e/h = 1 (i.e. keep e/h > 1) *BUT* measure f_{em} event-by-event

⟹ *correct energy measurements for f_{em} fluctuations*

How ?

Exploit the fact that (e/h) values for scintillation light (S) and Čerenkov light (Č) production processes are (very) different

Why ?

Charged hadrons contribute to S but very marginally to Č

working principles

$$S = E \cdot [\ f_{em} + (h/e)_S \cdot (1 - f_{em})\ ] = E \cdot [\ f_{em} + s \cdot (1 - f_{em})\ ]$$

$$C = E \cdot [\ f_{em} + (h/e)_C \cdot (1 - f_{em})\ ] = E \cdot [\ f_{em} + c \cdot (1 - f_{em})\ ]$$

$(h/e)_S = s$, $(h/e)_C = c$ → *detector-specific parameters*

Both f_{em} and E can be reconstructed:

$$f = \frac{c - s(C/S)}{(C/S)(1-s) - (1-c)}$$

$$E = (S - \chi C) / (1 - \chi)$$

where:

$$\chi = (1 - s) / (1 - c) = (E - S) / (E - C)$$

→ *χ can be evaluated from testbeam data* *to be continued …*