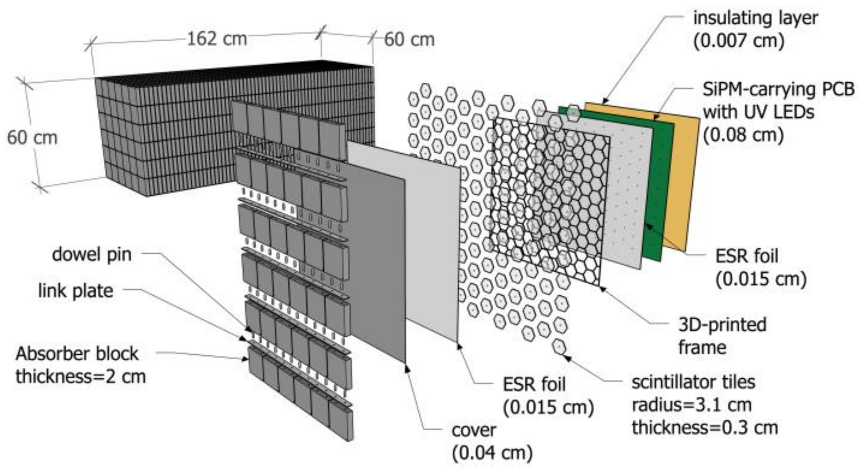
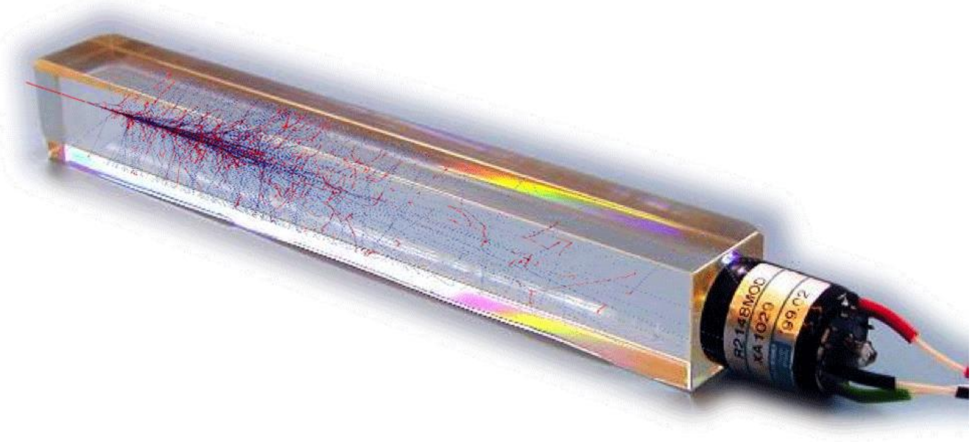
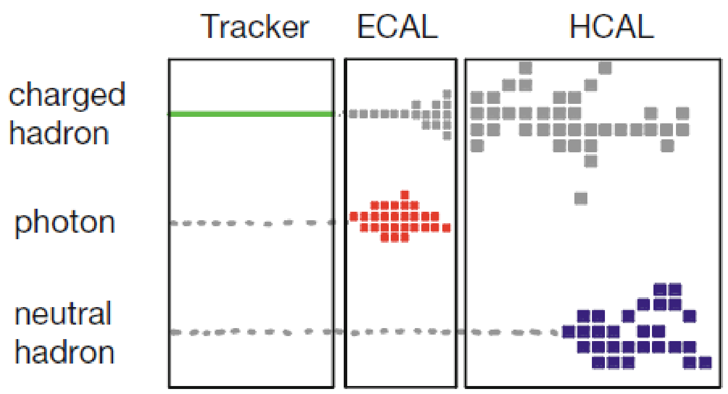




Calorimetry



Barak Schmookler

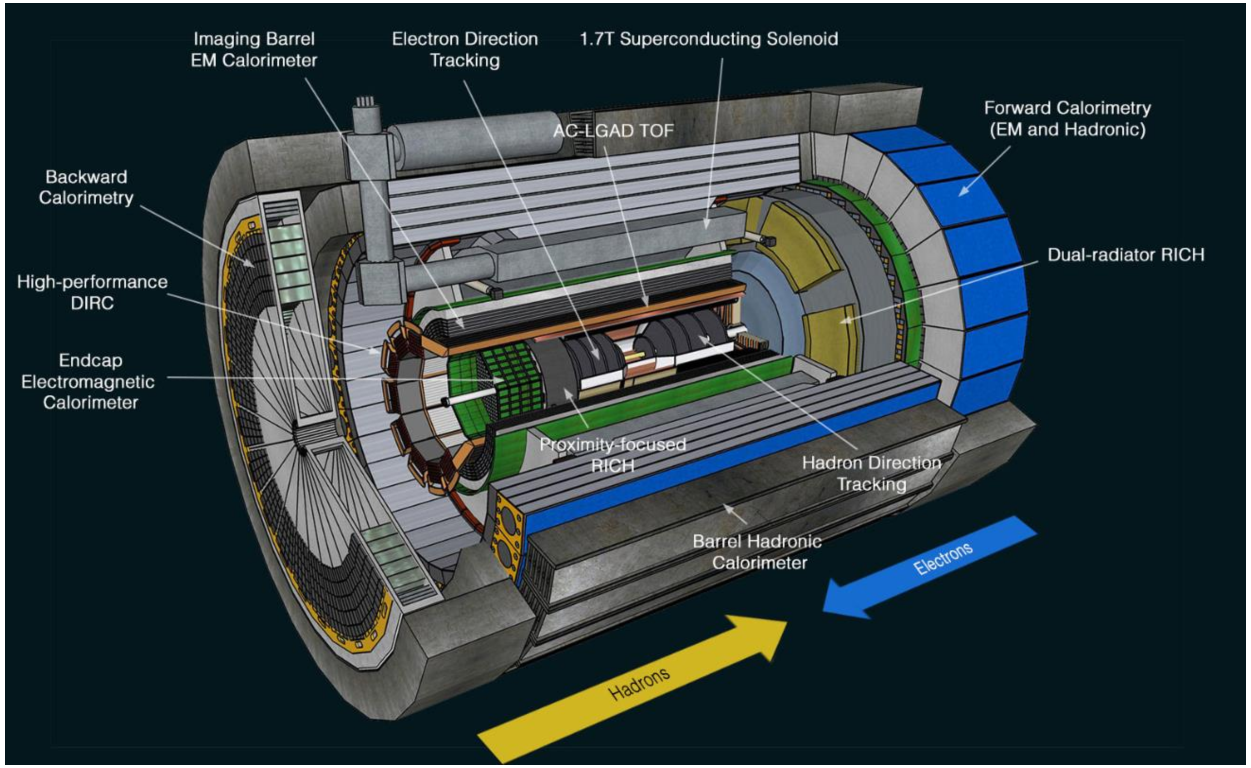
(University of Houston)

References

- Some presentations:
  - Desy lecture by E. Garutti
  - CMS lecture by G. Majumder
- Some papers:
  - Calorimetry for Particle Physics
  - Misconceptions about Calorimetry
  - On the limits of the hadronic energy resolution of calorimeters

Why calorimetry?

What do we want to measure and how can we do it?

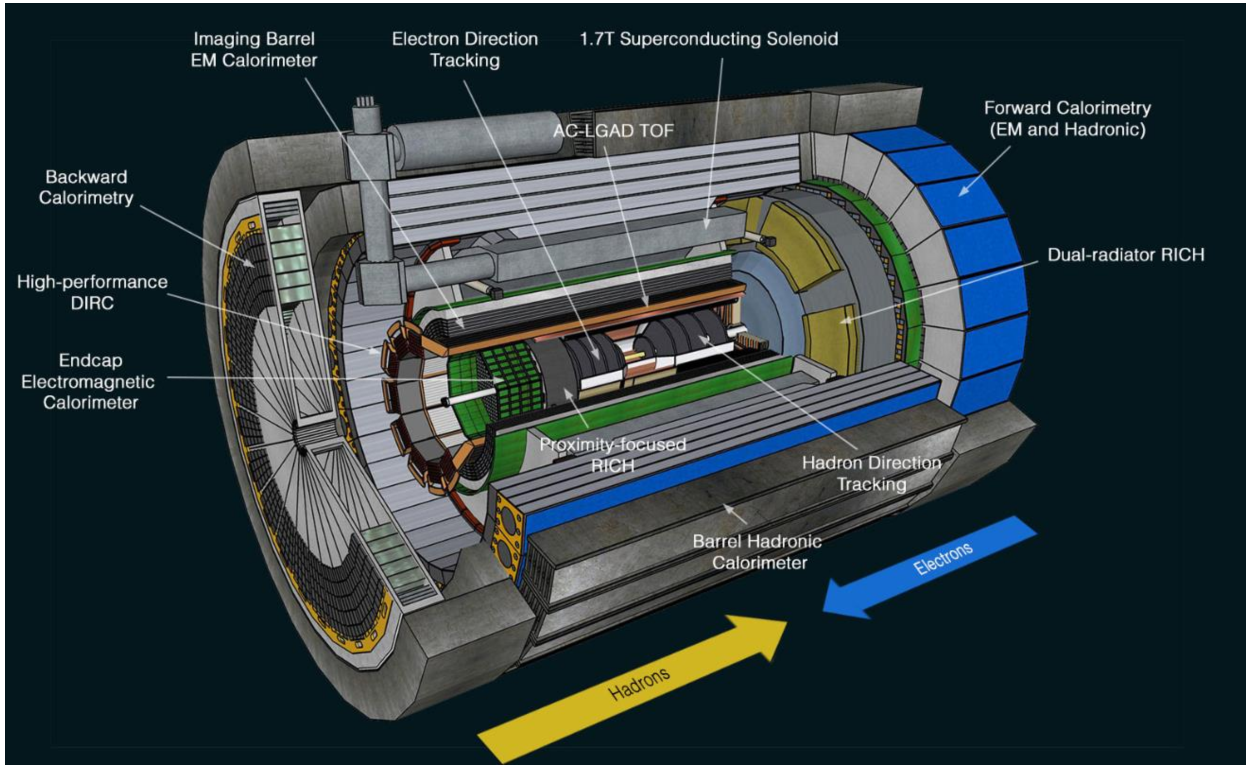


- What do we want to measure:
  - 4-momentum vectors (E, px, py, pz)
  - Particle type
  - Creation point

- For measuring the 4-momentum (and therefore particle mass), can we just do (*Calorimeter, Tracker*)?

Almost never…

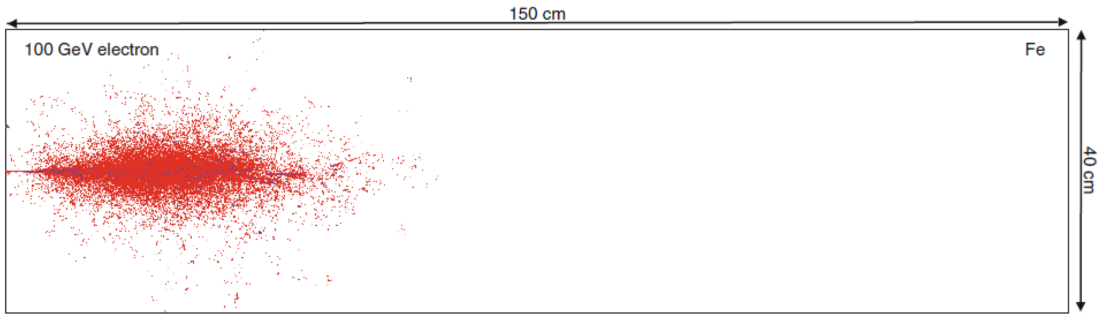
What do we want to measure and how can we do it?



- Since the masses of particles are well known, we can make precise measurements if we use one of these approaches:
    1. Calorimeter-based reconstruction: (PID, E $\hat{p}$)
    2. Tracker-based reconstruction: (PID, $\vec{p}$)
- In both approaches, we then use the relation $E^2 = m^2 + p^2$ to obtain our final 4-momentum.

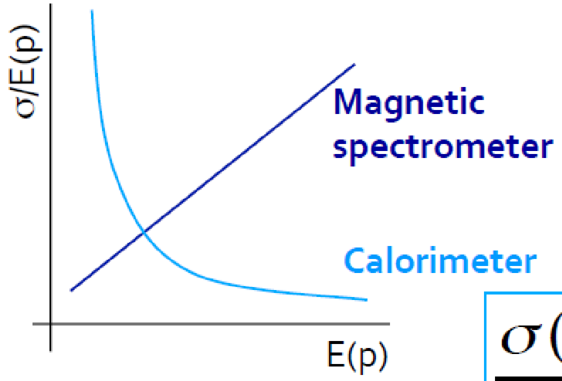
What are calorimeters?

- Calorimeters measure energy (as well as position). They make destructive measurements -- the particle is fully absorbed.
  - An exception is muons, which can pass through a large amount of material. This is an important means of identifying muons.
- The incoming particle initiates a shower, and all these secondary particles are absorbed: energy is converted into heat, hence the name *Calorimeter*. In nuclear/particle physics, we do not measure an increase in temperature, but rather ionization/excitation signals.



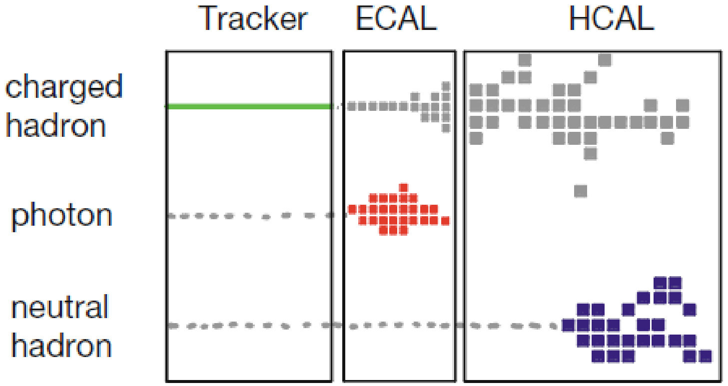
Why are calorimeters needed?

- Calorimeter performance (resolution) improves with increasing energy. This contrasts with tracking detectors where resolution worsens with increasing momentum/energy.
- For charged particles, calorimeters can be used in conjunction with tracking detectors for PID determination (E/p, shower shape). Calorimeters are the only way to detect neutral particles.
- Calorimeters can be arranged to have nearly 4π hermetic coverage – allowing for measurements of jets and missing energy.
- As we'll see, the longitudinal depth of a shower grows as the log of energy. A reasonably sized calorimeter can measure particles over a large energy range.
- The energy deposited in calorimeters can be read out in a short period of time. Calorimeters can be used for event triggering.



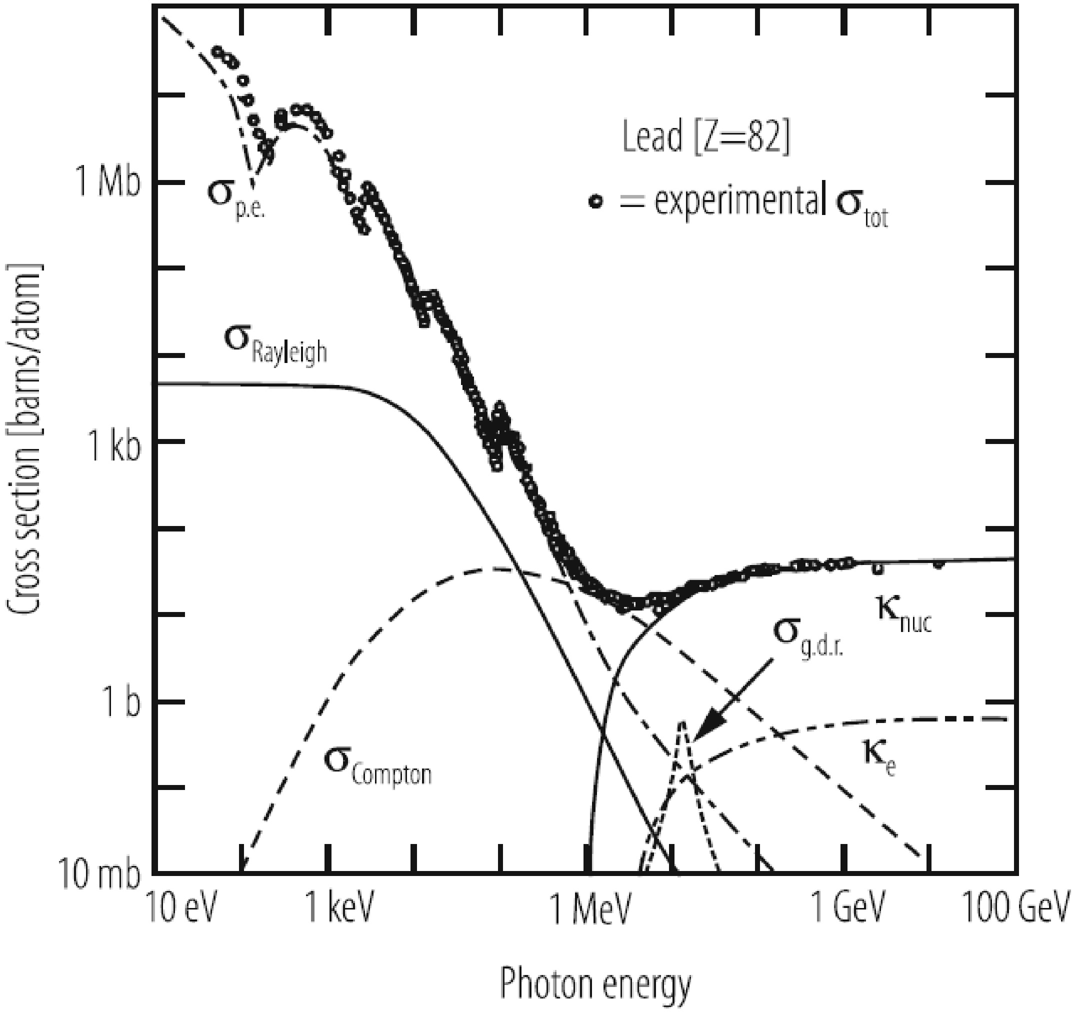
$$\boxed{\frac{\sigma(p)}{p} \approx ap}$$

$$\boxed{\frac{\sigma(E)}{E} \approx \frac{a}{\sqrt{E}}}$$



Electromagnetic Calorimeters (**EMCals**)

Interactions of **photons** and electrons/positrons with matter



$$\sigma(p.e.) \approx Z^5 \alpha^4 \left(\frac{m_e c^2}{E_\gamma}\right)^n$$

n=7/2 at $E\gamma \ll m_e c^2$
n→1 at $E\gamma \gg m_e c^2$

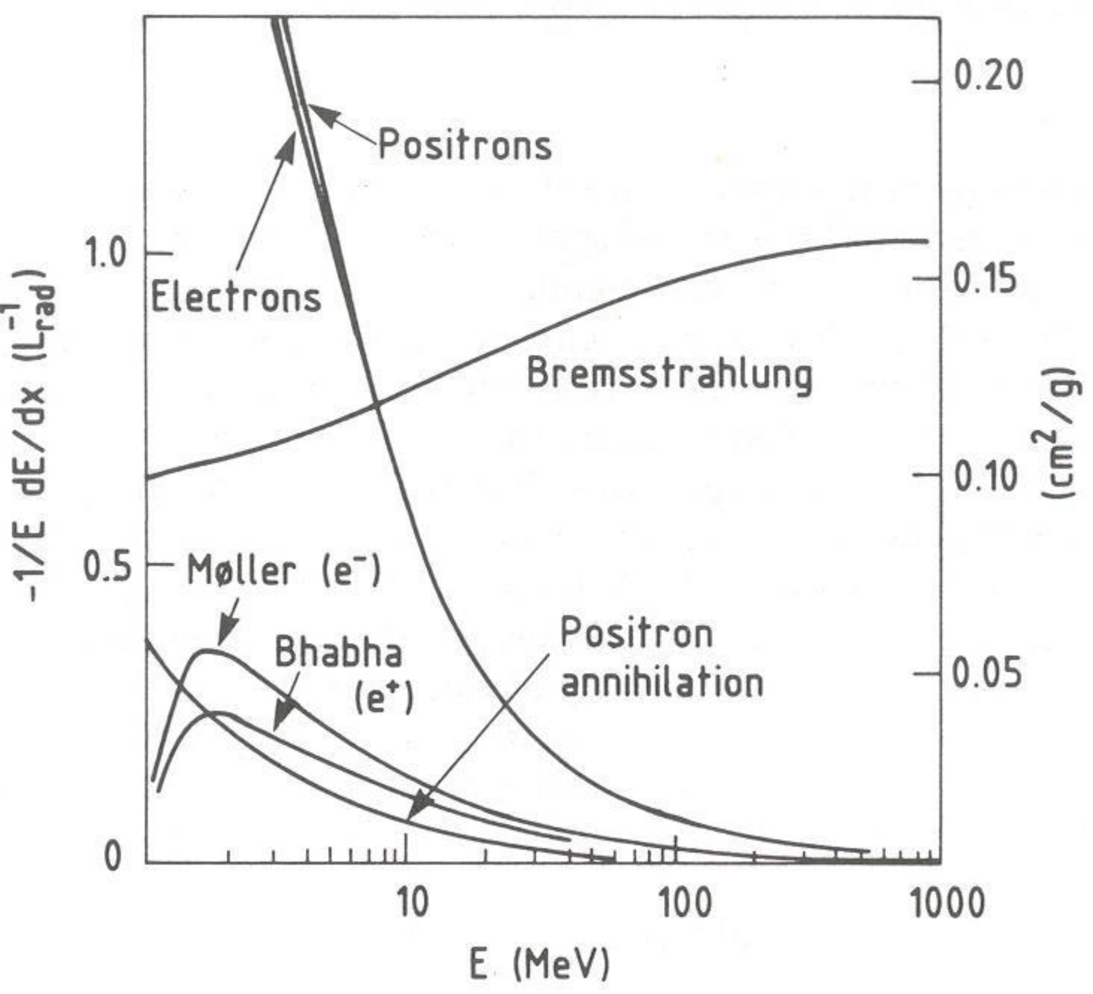
$$\sigma(comp) \approx Z \frac{\ln E_\gamma}{E_\gamma}$$

$$\sigma(pair) \propto Z^2 \propto \frac{1}{\lambda_{pair}} \approx \frac{7}{9}\frac{1}{X_0}$$

$$\boxed{X_0 = \frac{716.8(g)(cm)^{-2} A}{Z(Z+1)\ln\left(287/\sqrt{Z}\right)}}$$

- At energies > 100 MeV, the dominant interaction of photons in matter is pair production. 99% of pair production takes place in the nuclear EM field.
- The cross section approaches a constant for energies > 1 GeV. The radiation length (X_0) of the material sets the scale – mean-free path is proportional to X_0

Interactions of photons and **electrons/positrons** with matter



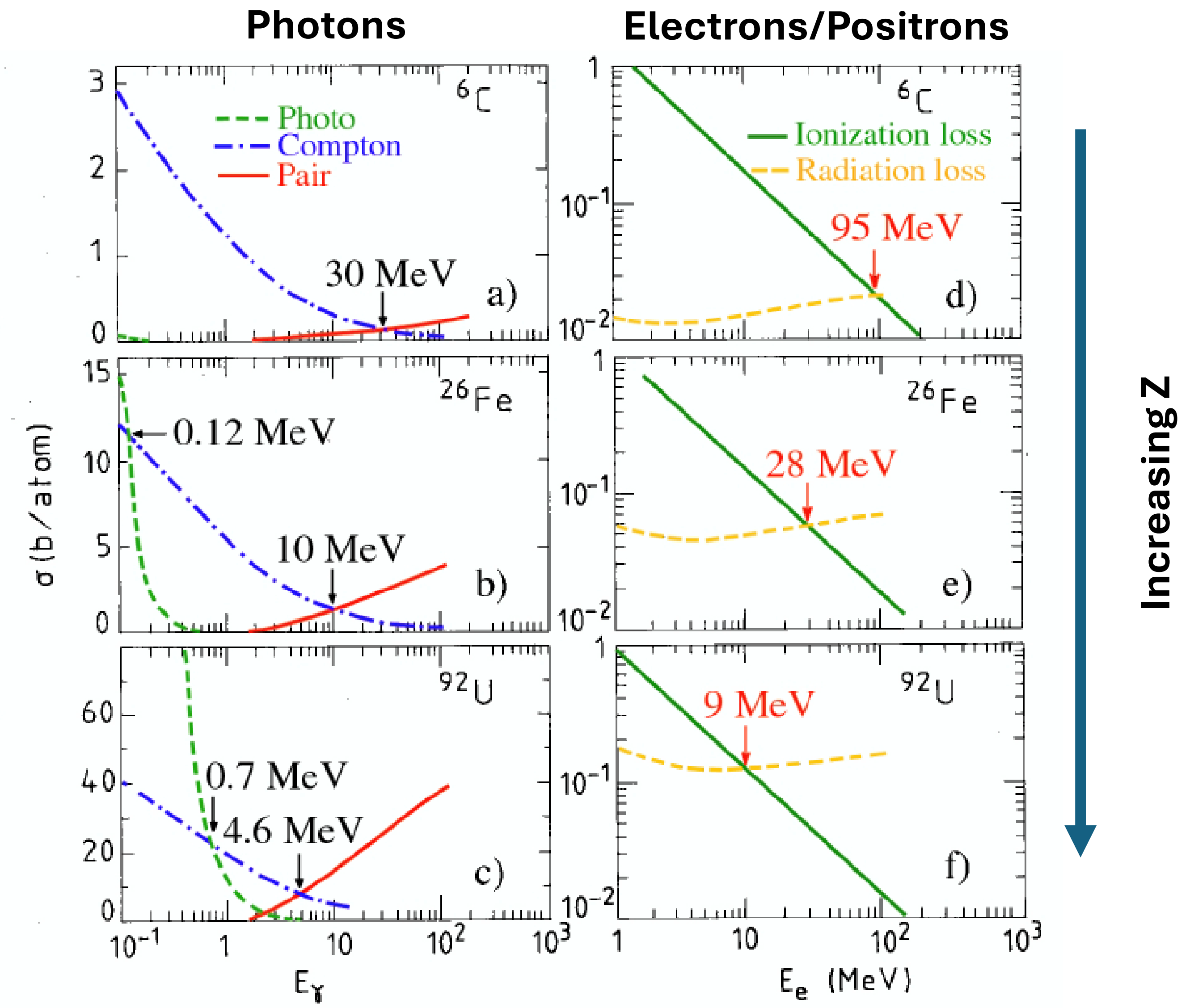
$$\frac{dE_i}{E_i} = dx\ n_a \sigma_{rad}, \quad \sigma_{rad} = 4\sigma_0[\ln(183 Z_2^{-1/3}) + 1/18]$$

$$\frac{1}{X_0} = 4\sigma_0 n_a \ln(183 Z_2^{-1/3}); \quad E = E_0 e^{-x/X_0}$$

$$\sigma_0 = \alpha Z^2 r_e^2, \qquad \frac{dE_\gamma}{dn} = \frac{1}{E_\gamma}$$

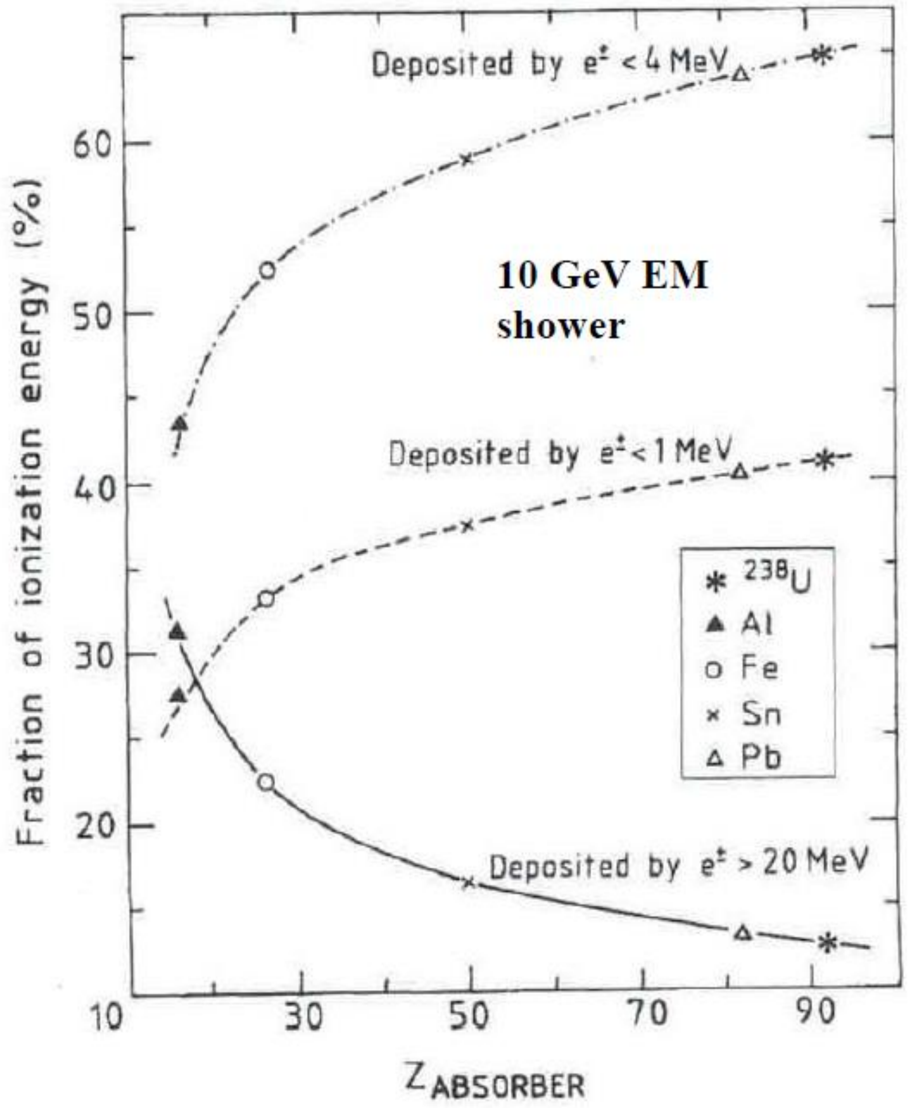
- At energies above 100 MeV, electrons and positrons lose energy mainly through bremsstrahlung
- The cross section approaches a constant for energies > 1 GeV. X_0 again sets the scale. Electrons/positrons will lose about 63% of their energy after 1 X_0

Material dependence of interactions



The calorimeter signal only comes from the ionization energy losses of electrons and positrons, not directly from the photons

Dominating energy regions



Even though calorimeters are intended to measure **GeV-TeV** energy deposits, their performance is determined by what happens at the **MeV-keV-eV** level

Simple analytic shower model

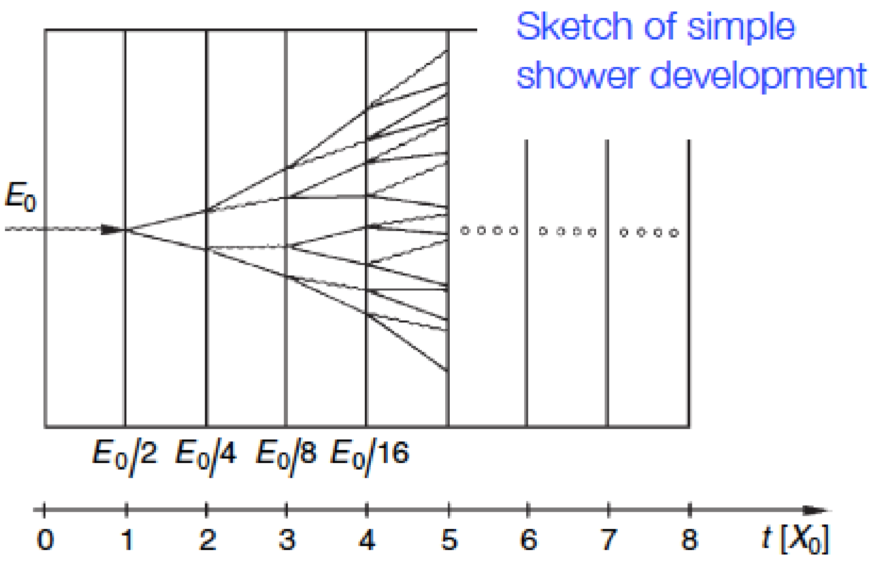
The critical energy, E_c, the energy where ionization losses and radiation losses are equal.

For developing a simple shower model, we will assume the following:

1. $E > E_c$: no energy loss by ionization/excitation
2. $E < E_c$: energy loss only via ionization/excitation

Then, we get the following shower development:

- 2^t particles after t [X0]
- Each particle has energy $E/2^t$
- Particle stops if $E <$ critical energy (E_c)
- Number of particles in shower $N = E / E_c$
- Maximum number of particles at $t_{\max} \propto \ln(E_0/E_c)$



Simple analytic shower model

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

$$L \sim \ln(\frac{E_0}{E_c})$$

Longitudinal shower distribution increases only logarithmically with the primary energy of the incident particle, i.e. (EM) calorimeters can be compact

Some numbers: $E_c \approx 10$ MeV, $E_0 = 1$ GeV → $t_{max} = \ln 100 \approx 4.5$; $N_{max} = 100$
$E_0 = 100$ GeV → $t_{max} = \ln 10000 \approx 9.2$; $N_{max} = 10000$

	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

Longitudinal profile of EM shower

Longitudinal profile

Parametrization:
[Longo 1975]

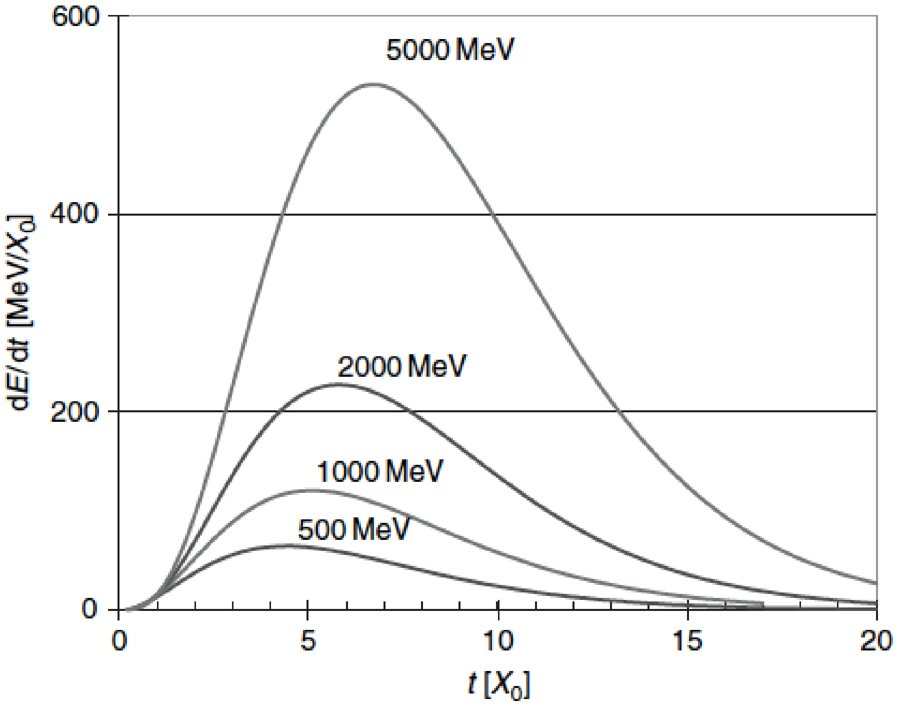
$$\frac{dE}{dt} = E_0 \, t^{\alpha} e^{-\beta t}$$

α,β : free parameters

t^{α} : at small depth number of secondaries increases ...

$e^{-\beta t}$: at larger depth absorption dominates ...

Numbers for E = 2 GeV (approximate):
$\alpha = 2$, $\beta = 0.5$, $t_{max} = \alpha/\beta$



Longitudinal profile of EM shower

Longitudinal profile

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[Longo 1975]

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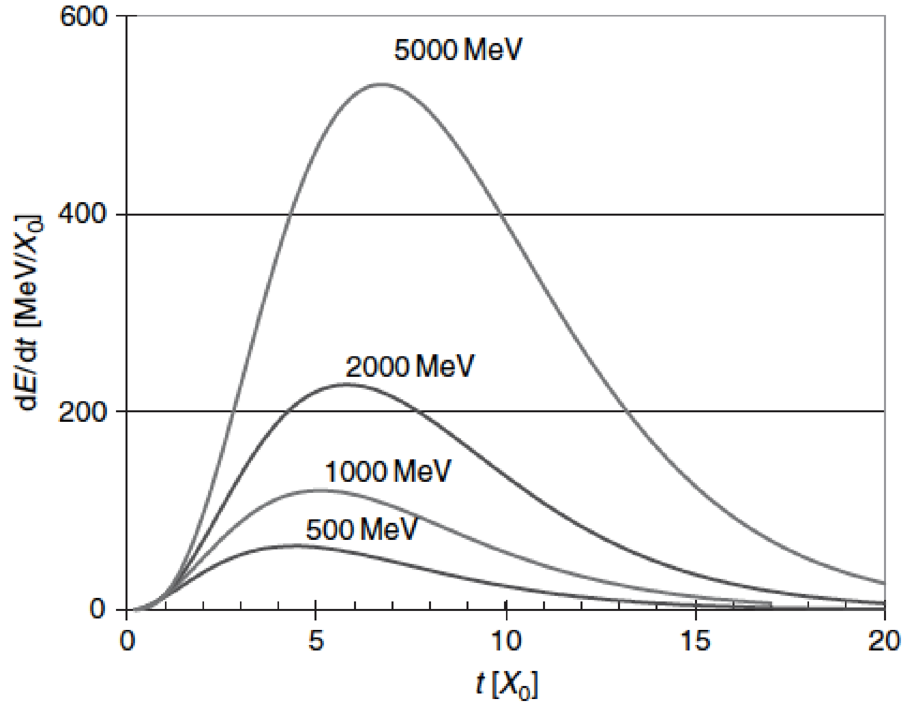
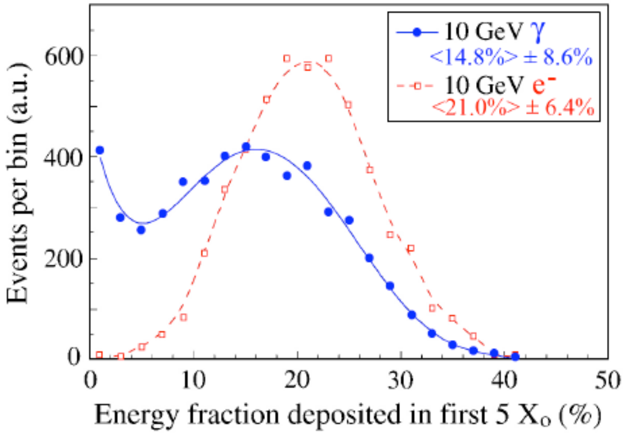


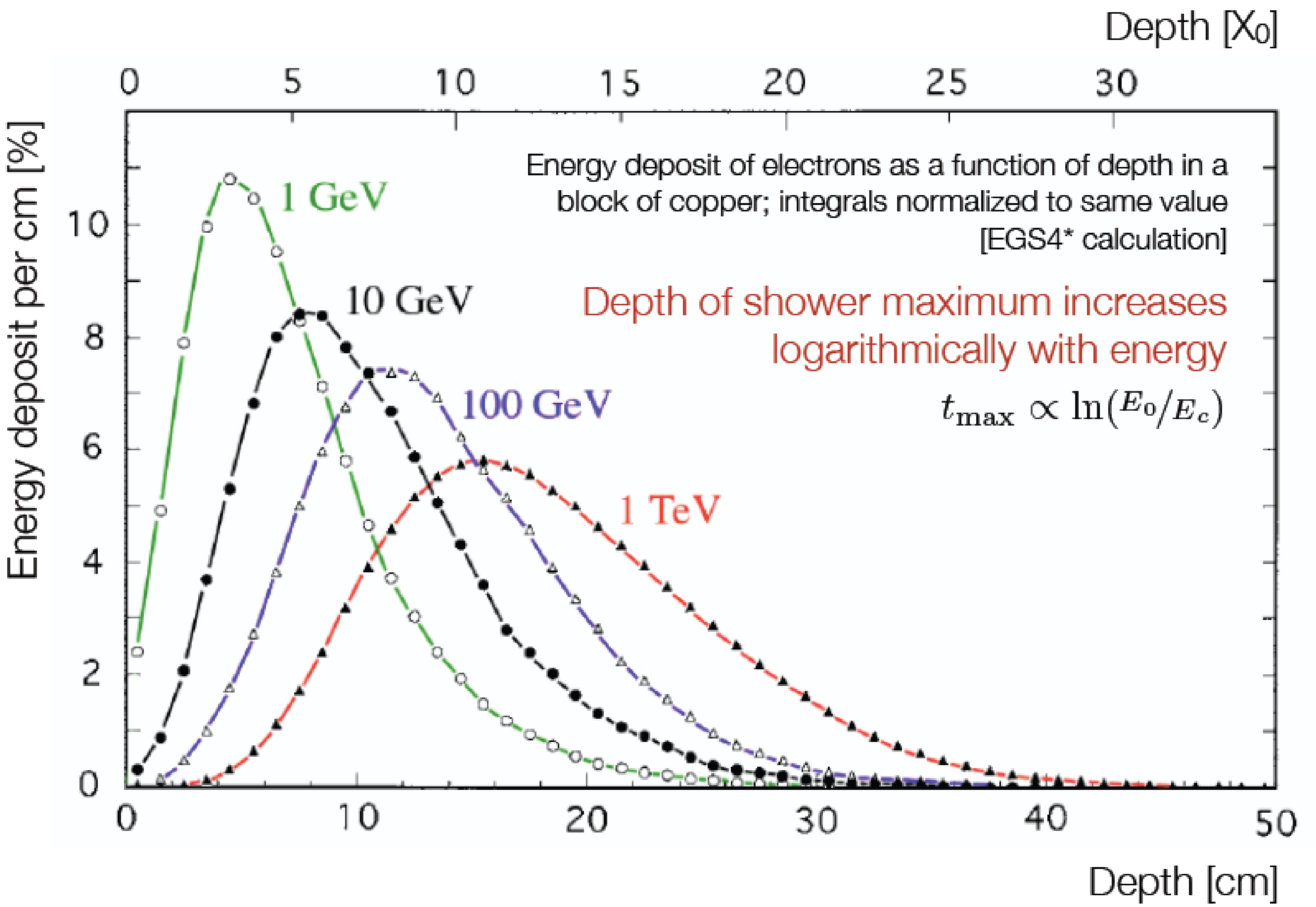


Important differences between showers induced by electrons/positrons vs. photons:

$$t_{max} = \frac{\alpha - 1}{\beta} = \ln\left(\frac{E_0}{E_c}\right) + C_{e\gamma}$$

with:
$C_{e\gamma} = -0.5$ [γ-induced]
$C_{e\gamma} = -1.0$ [e-induced]

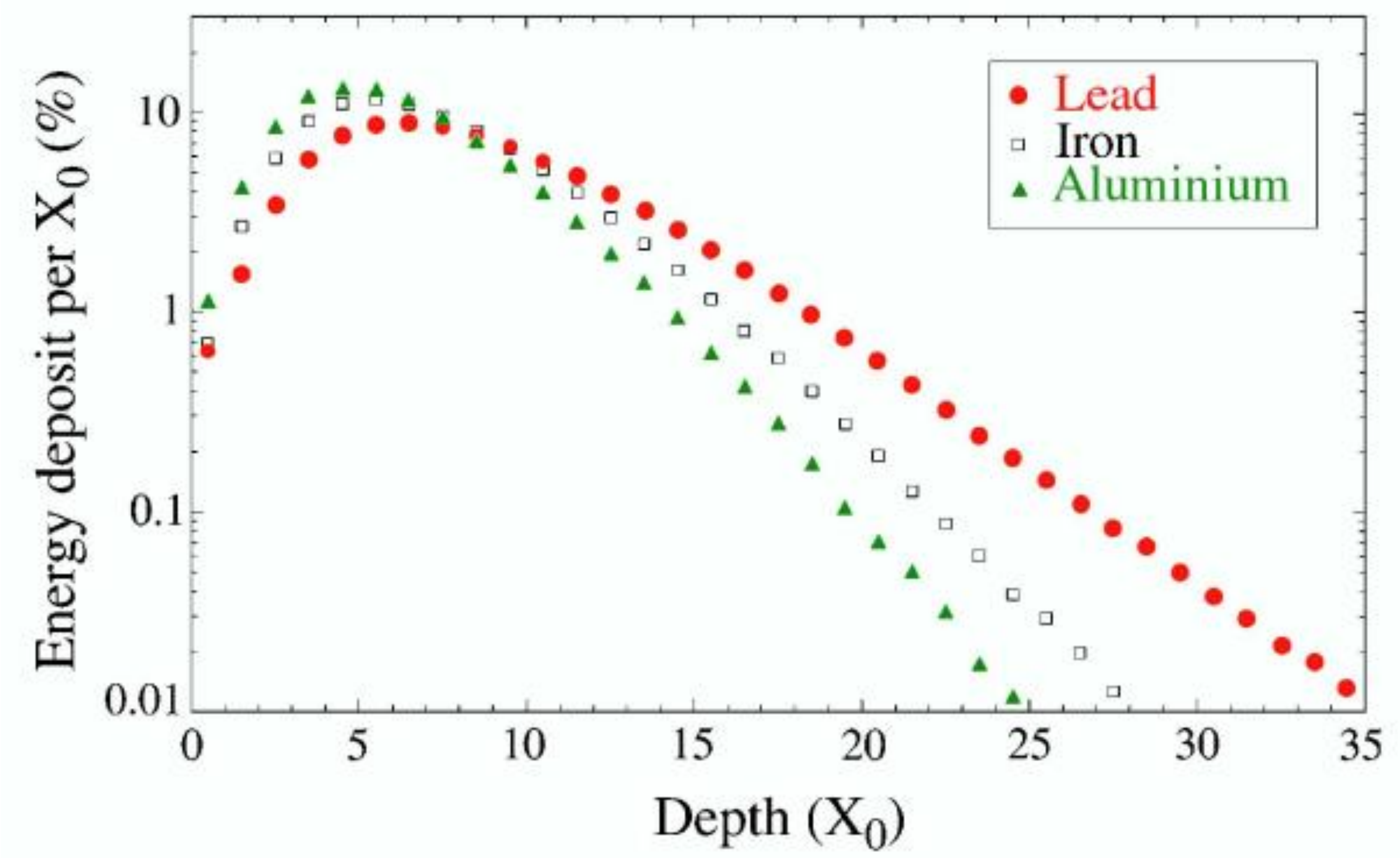
Longitudinal profile of EM shower



Longitudinal profile of EM shower

Shower decay: After the shower maximum, the shower decays slowly through ionization and Compton scattering. The decay is not proportional to X_0.

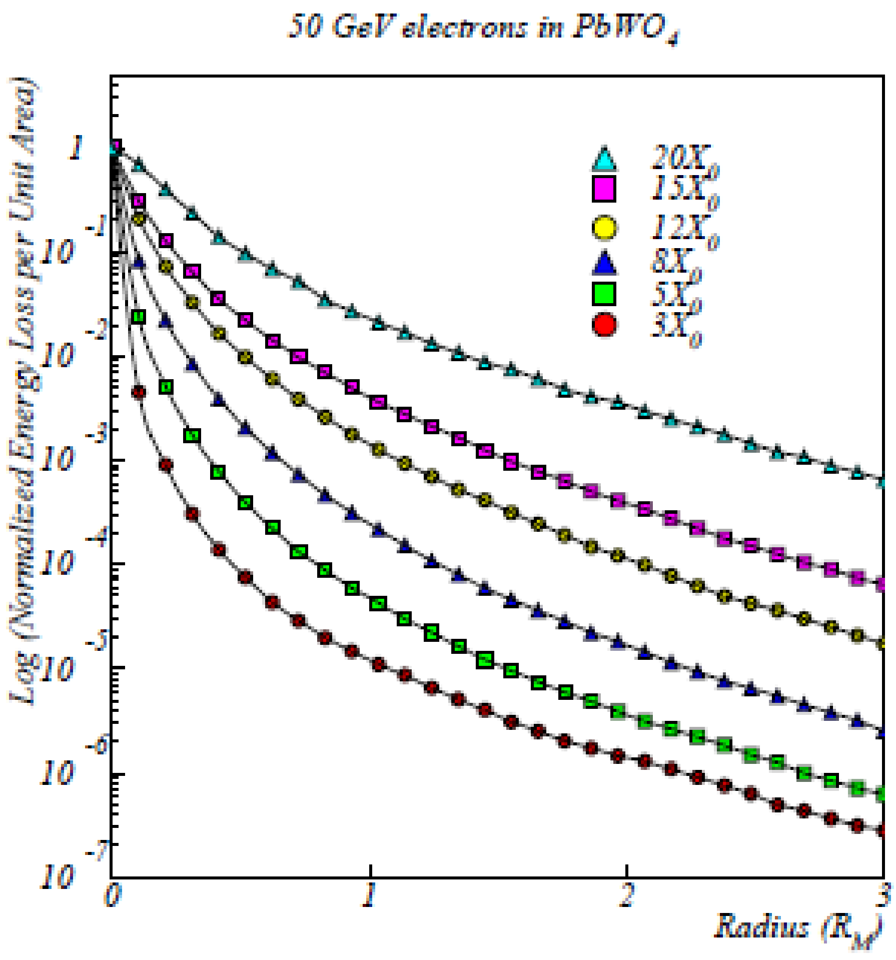
Showers are not just a collection of Minimum-Ionizing particles (MIPs)



Lateral profile of EM shower

- Transverse shower size is governed by
  1. Typical angle of bremsstrahlung emission at high energies
  2. Multiple scattering at low energies
  3. Propagation of photon
- Main contribution is from low-energy electron scattering:

$$\langle\theta\rangle = \frac{21.2\ \mathrm{MeV}}{E_e}\sqrt{\frac{x}{X_0}}$$ [β = 1, c = 1, z = 1]



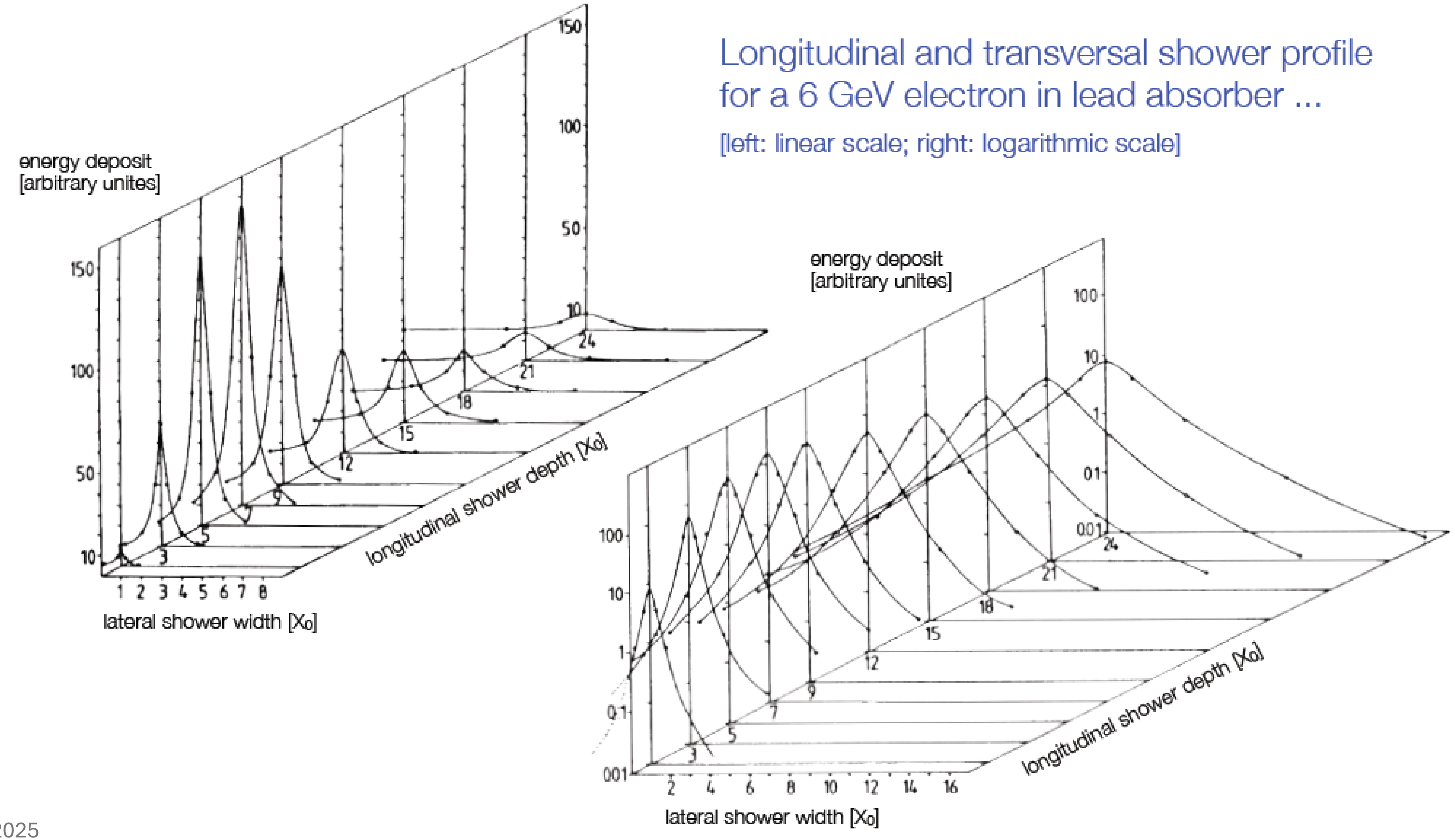
Moliere radius:

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

3D shower development

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

[left: linear scale; right: logarithmic scale]



Useful equations for quick calculations

Radiation length:

$$X_0 = \frac{180A}{Z^2} \frac{\mathrm{g}}{\mathrm{cm}^2}$$

Critical energy:
[Attention: Definition of Rossi used]

$$E_c = \frac{550\ \mathrm{MeV}}{Z}$$

Shower maximum:

$$t_{\max} = \ln\frac{E}{E_c} - \begin{cases} 1.0 & e^- \text{ induced shower} \\ 0.5 & \gamma \text{ induced shower} \end{cases}$$

Longitudinal
energy containment:

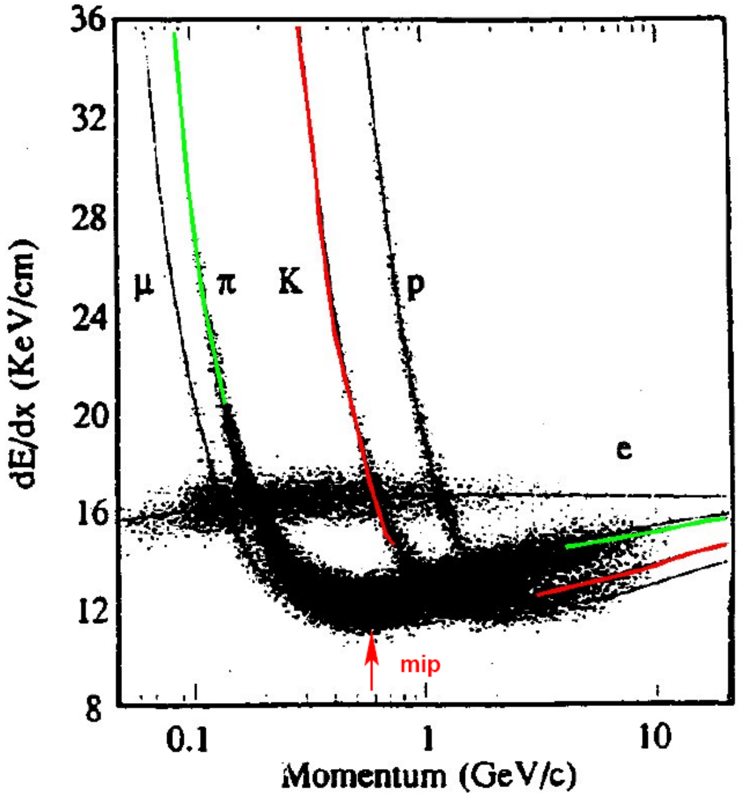
$$L(95\%) = t_{\max} + 0.08Z + 9.6\ [X_0]$$

Transverse
Energy containment:

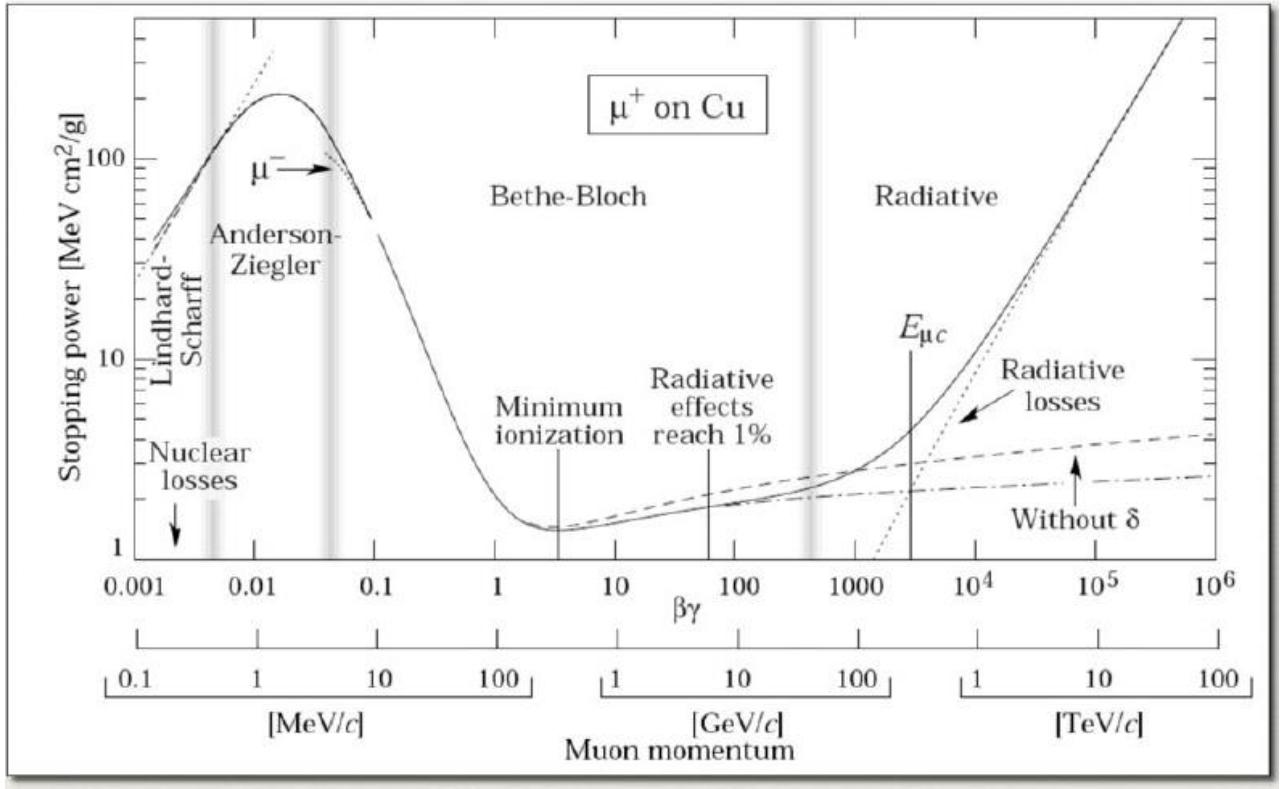
$$R(90\%) = R_M$$

$$R(95\%) = 2R_M$$

What about muons?



$$E_c^{\mu} = E_c^{e}\left(\frac{m_\mu}{m_e}\right)^2 \approx 4\cdot 10^4 E_c^{e}$$



Muons are not quite MIPs

For Pb (Z = 82):

$E_c(e^-) = 6$ MeV

$E_c(\mu) = 250$ GeV

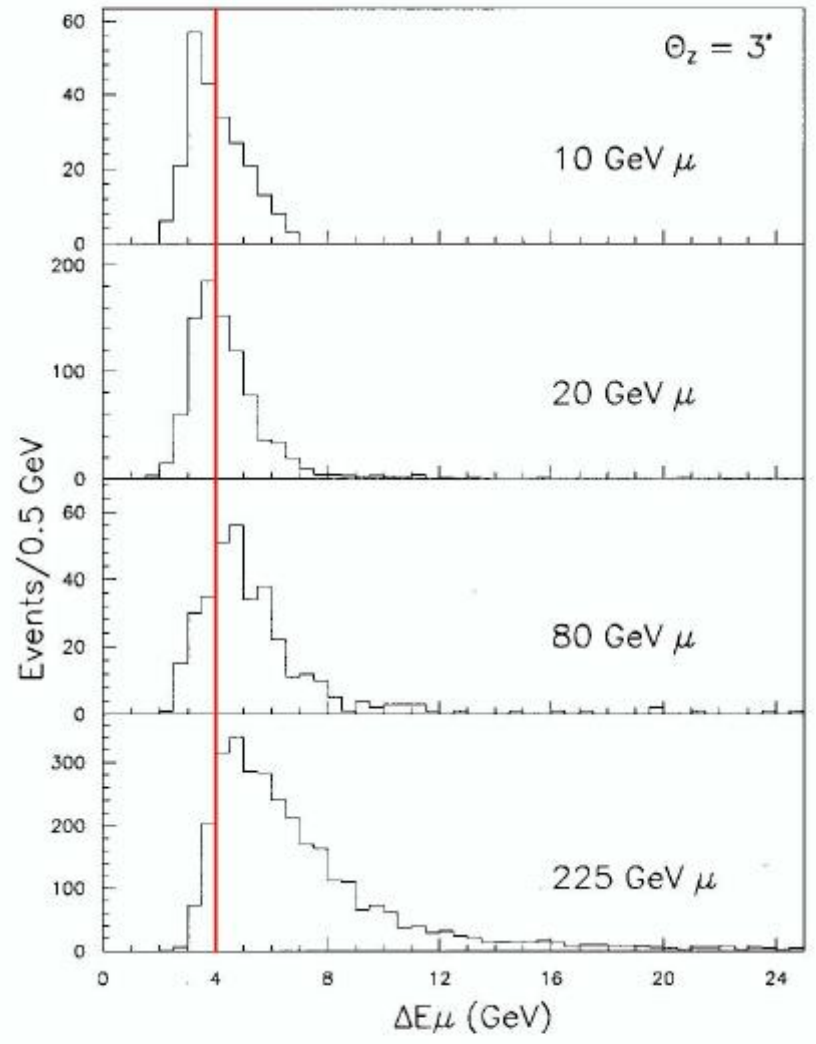
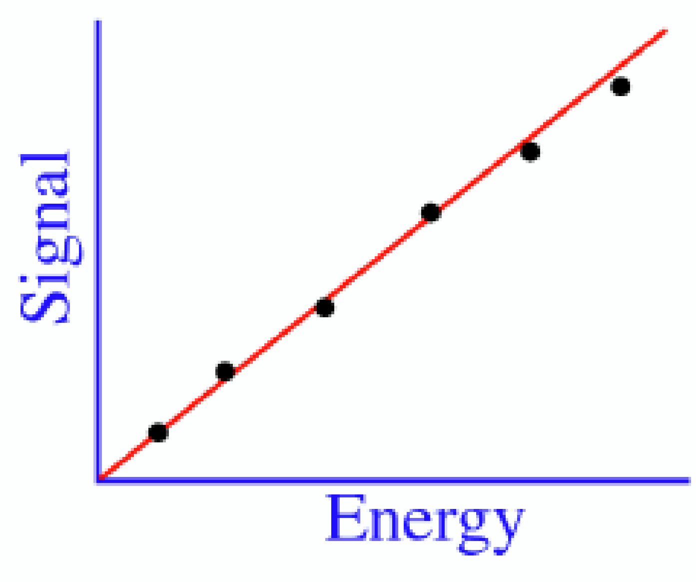
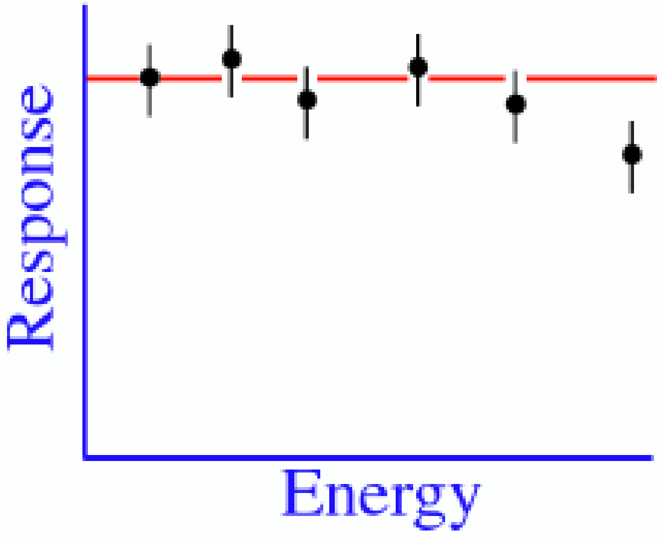


FIG. 2.19. Signal distributions for muons of 10, 20, 80 and 225 GeV traversing the $9.5\lambda_{\mathrm{int}}$ deep SPACAL detector at $\theta_z = 3^\circ$. From [Aco 92c].

What is important for the measurement of showers? **Linearity**

Define **response** as the average signal (in photoelectron, picoCoulombs, etc.) per unit deposited energy.





A linear calorimeter has a constant response.

- In general, EMCals are linear.
- HCals are usually non-linear due to something called non-compensation (we'll discuss this later).

Sources of non-linearity for ECals:

- Instrumental effects (e.g. saturation of PMTs)
- Response varies with something that varies with energy
- Leakage (increases with energy)

What is important for the measurement of showers? **Fluctuations**

Different effects have different energy dependence

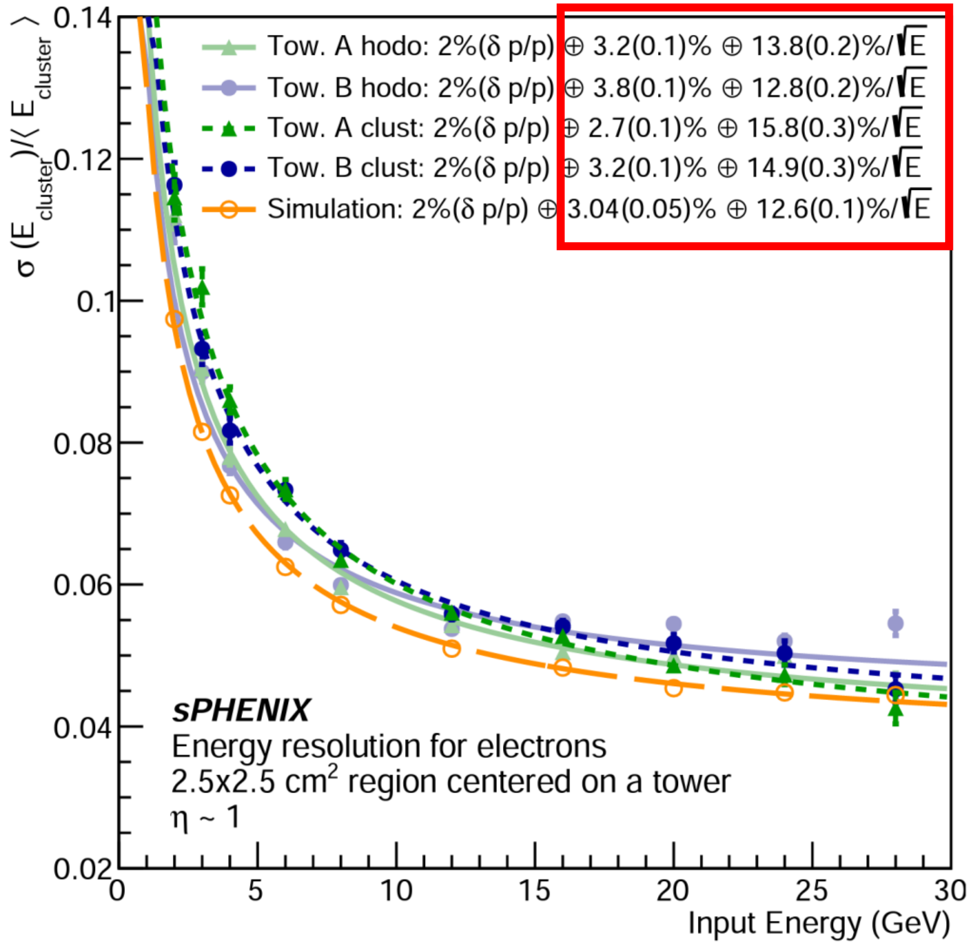
- quantum, sampling fluctuations $\sigma/E \sim E^{-1/2}$
- shower leakage $\sigma/E \sim E^{-1/4}$
- electronic noise $\sigma/E \sim E^{-1}$
- structural non-uniformities $\sigma/E = \text{constant}$

$$\frac{\partial E}{E} = \sqrt{{c_1}^2 + \left(\frac{c_2}{\sqrt{E}}\right)^2 + \left(\frac{c_3}{E}\right)^2} = c_1 \oplus \frac{c_2}{\sqrt{E}} \oplus \frac{c_3}{E}$$

a: stochastic term
- intrinsic statistical shower fluctuations
- sampling fluctuations
- signal quantum fluctuations (e.g. photo-electron statistics)

b: constant term
- inhomogeneities (hardware or calibration)
- imperfections in calorimeter construction (dimensional variations, etc.)
- non-linearity of readout electronics
- fluctuations in longitudinal energy containment (leakage can also be ~ $E^{-1/4}$)
- fluctuations in energy lost in dead material before or within the calorimeter

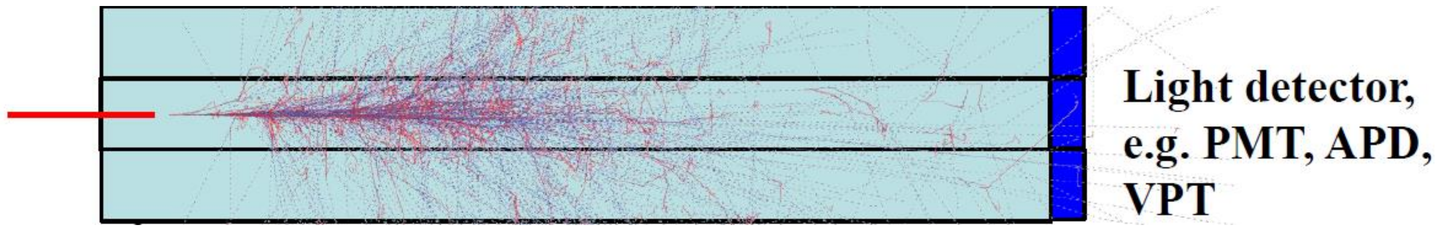
c: noise term
- readout electronic noise
- Radio-activity, pile-up fluctuations



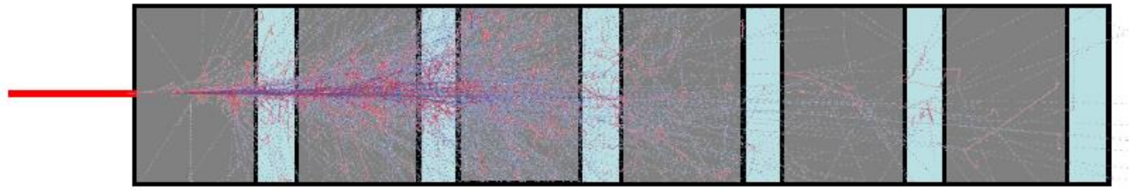
Calorimeter types

<u>There are two general types of calorimeters</u>

Homogeneous calorimeters: A single medium serves as both absorber and detector. Examples: liquified Xe or Kr, dense crystal scintillators (BGO, PbWO4…), lead-loaded glass.



Sampling calorimeters: Layers of passive absorber (such as Pb, or Cu) alternate with active detector layers such as Si, scintillator or liquid argon



Homogeneous calorimeters

One block of material serves as absorber and active medium at the same time

- Example: $PbWO_4$ scintillating crystals with high density and high Z used at CMS. Optimized for $H \rightarrow \gamma\gamma$ measurements.

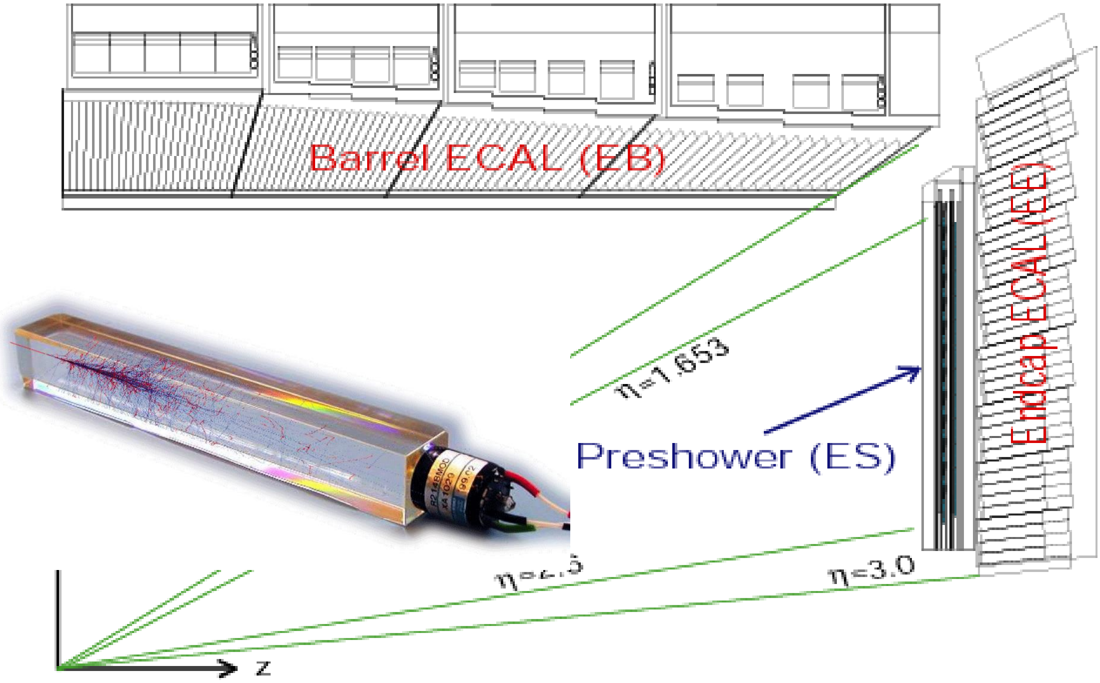
Advantages

- See all charged particles in the shower: best statistical precision
- Same response from everywhere: good linearity

Disadvantages

- Cost and limited segmentation

Other examples: Semiconductor crystals (e.g, Ge) used for MeV gamma spectroscopy. Semiconductor crystals cannot be used at high-energy colliders. Why?

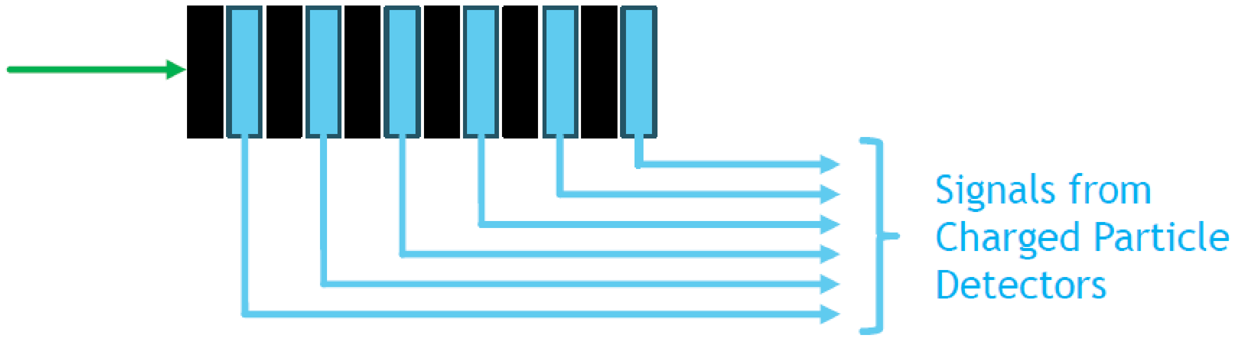


Sampling calorimeters

Sampling calorimeters use both passive (absorber) and active material.

- High density absorber…
- …Interleaved with active readout devices
- Most used: sandwich structures. But also, embedded scintillating fibers

Sampling fraction: ratio of energy deposited into active material to total energy deposited.



Advantages

- Cost
- Transverse and longitudinal segmentation

Disadvantages

- Only part of shower seen, less precise

Examples

- ATLAS EMCal
- All HCals

Sampling calorimeters

Sampling calorimeters use both passive (absorber) and active material.

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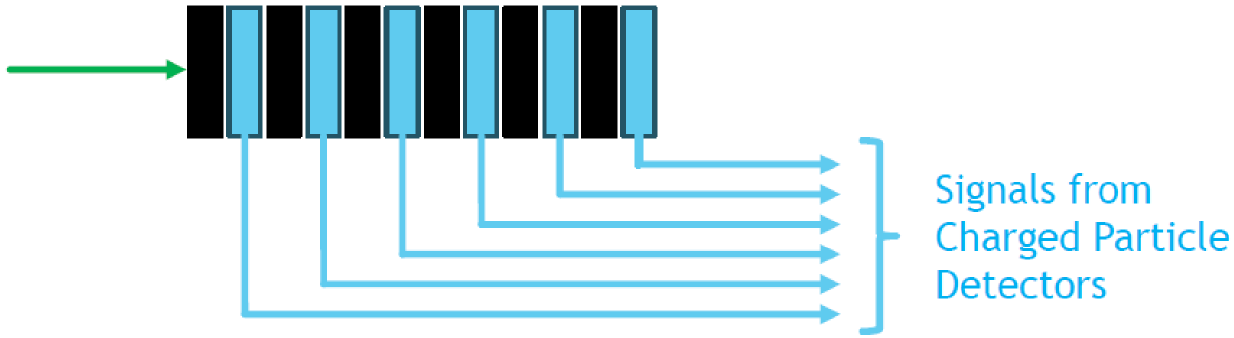


Sampling fraction: ratio of energy deposited into active material to total energy deposited.

Sandwich structures: Shashlik calorimeters
Embedded fibers: SPACAL (Spaghetti calorimeters)

Shashlik

Advantages

- Cost
- Transverse and longitudinal segmentation

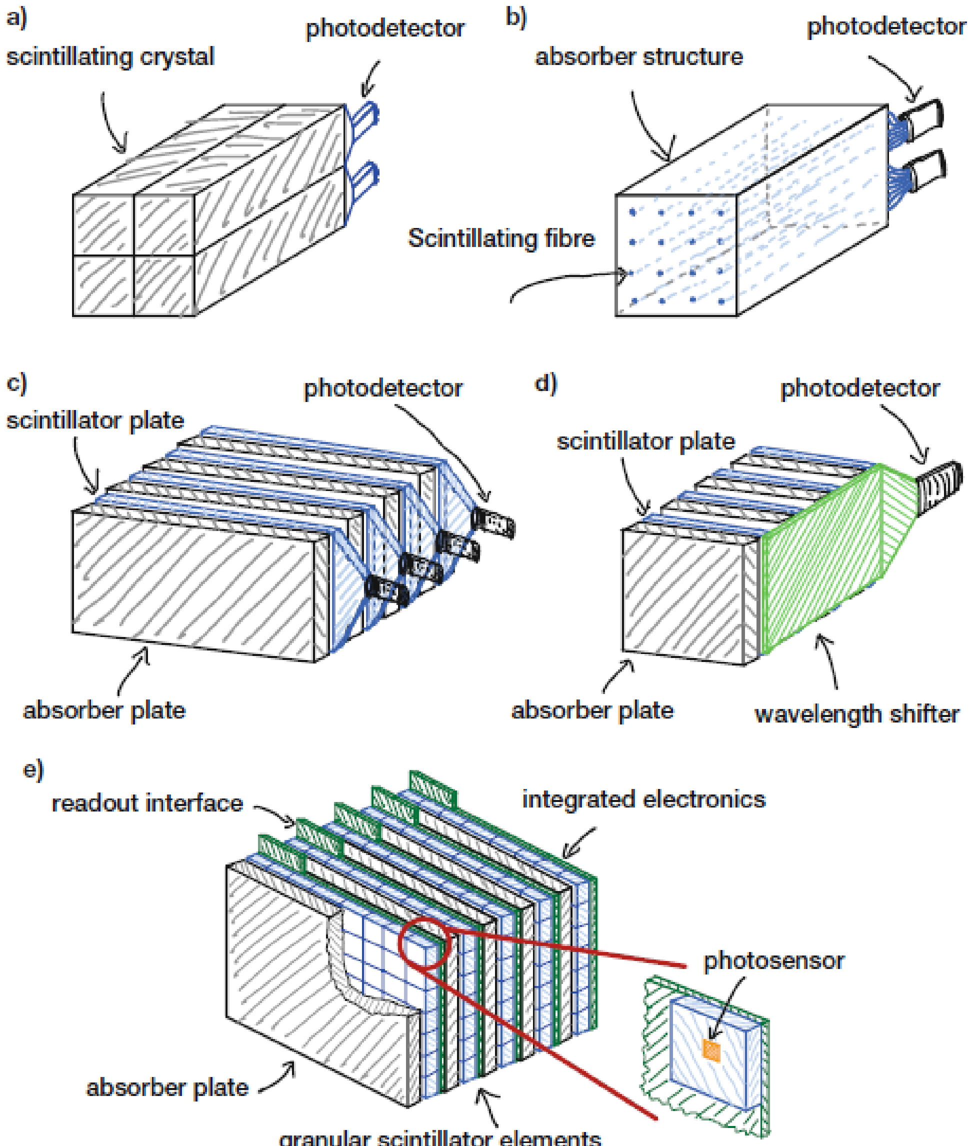
Disadvantages

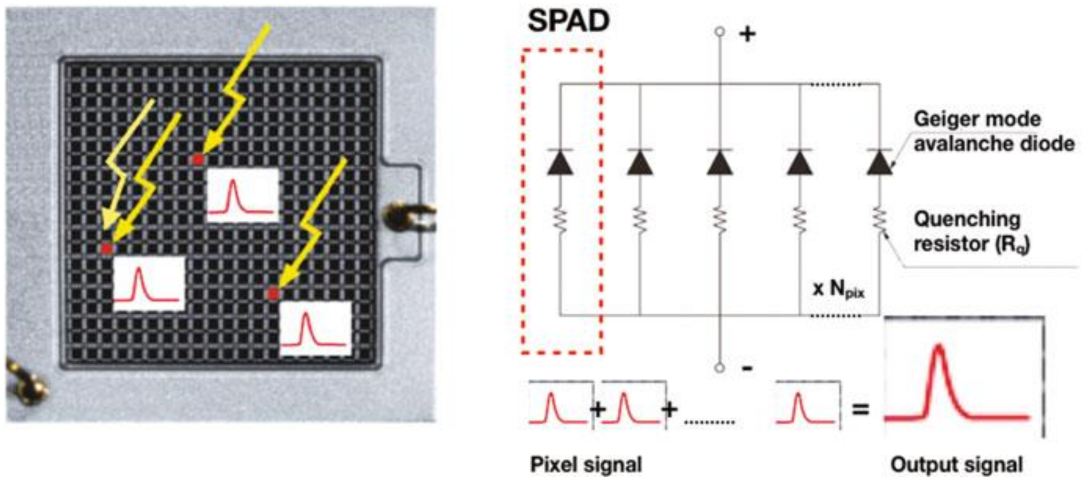
- Only part of shower seen, less precise

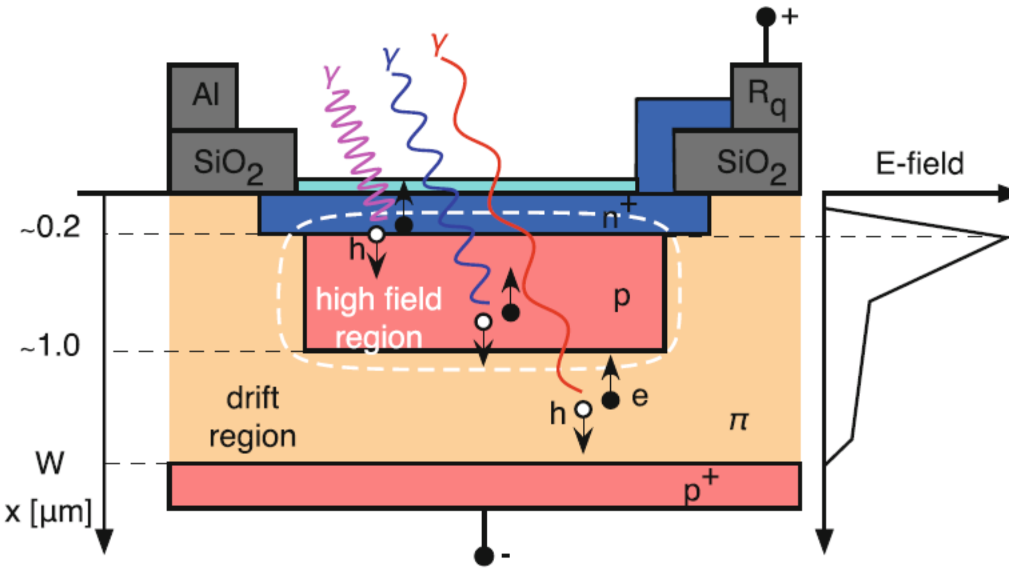
Examples

- ATLAS EMCal
- All HCals

How to read out calorimeter signals?







What determines calorimeter resolution?

Homogeneous

- The signal is the sum of all E deposited by charged particles with $E > E_{threshold}$
- If W is the energy required to produce a signal quantum, the average number of quanta produced is

$$< n > = \frac{E_0}{W}$$

- Resolution is based on number of signal quantum produced. Not quite Poisson statistics – need to use Fano factor.
- Resolutions can be on the order of

$$1\text{-}3\% / \sqrt{E\ [GeV]}$$

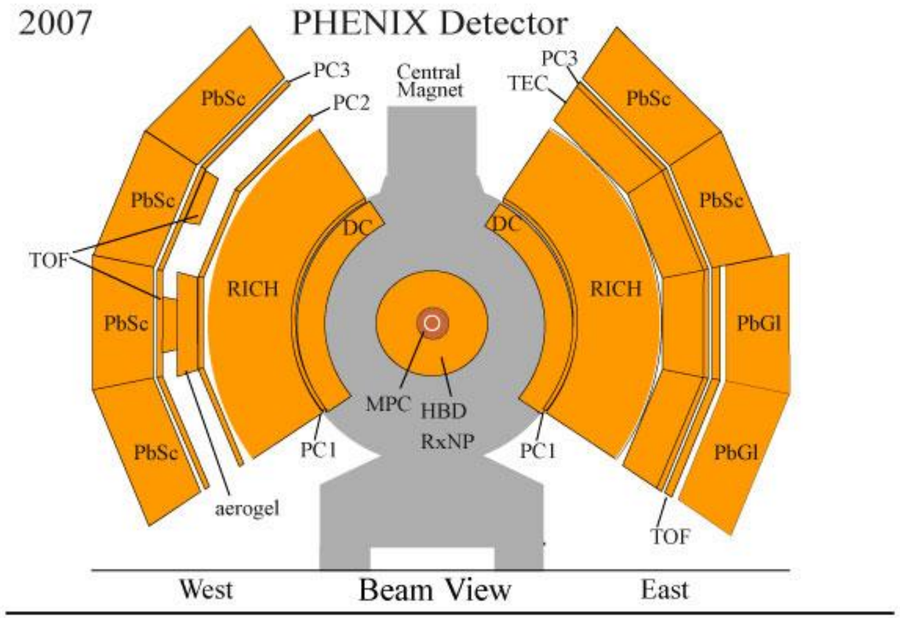
Silicon detectors	:	W ≈ 3.6 eV
Gas detectors	:	W ≈ 30 eV
Plastic scintillator	:	W ≈ 100 eV

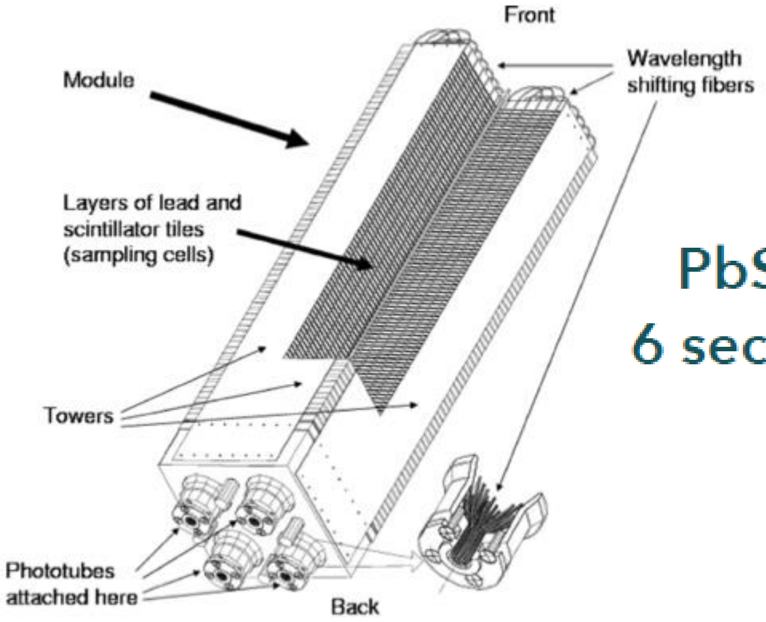
Sampling

- Number of charged particles contributing to the signal increases linearly with incoming particle's energy
- The resolution is given by sampling fluctuations – fluctuations in the number of charged particles contributing to the signal – convoluted with fluctuations in the amount of energy deposited by individual shower particles in the active calorimeter layers
  - Resolution depends on sampling fraction – determined by the ratio of the active and passive elements
  - And the sampling frequency – determined by the number of sampling elements
- Over 100 samplings would be needed to approach the energy resolution of homogeneous calorimeter. So, typical resolution is about

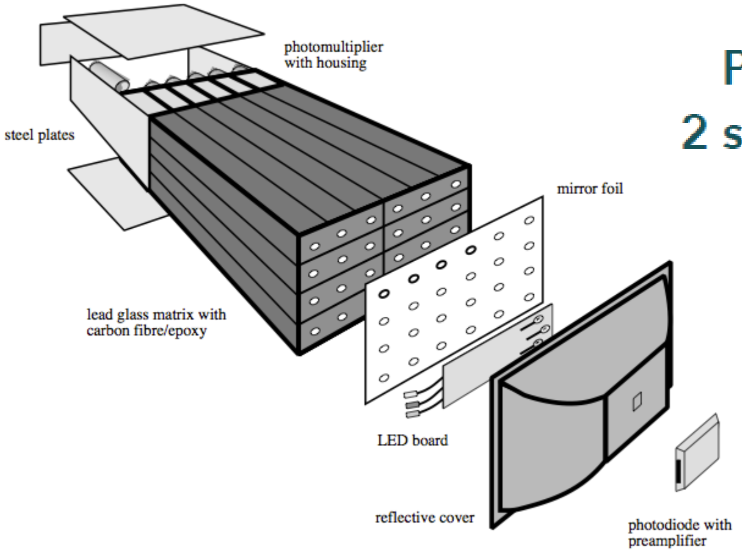
$$10\% / \sqrt{E\ [GeV]}$$

EMCal examples: PHENIX detector





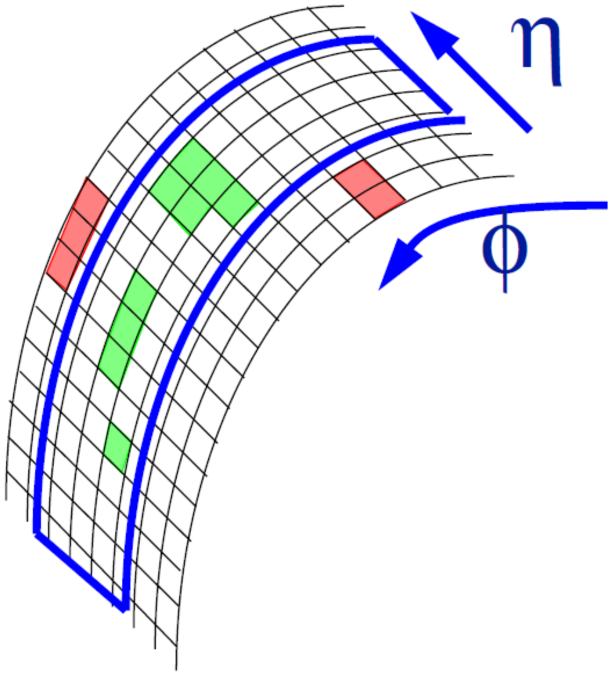
PbSc
6 sectors

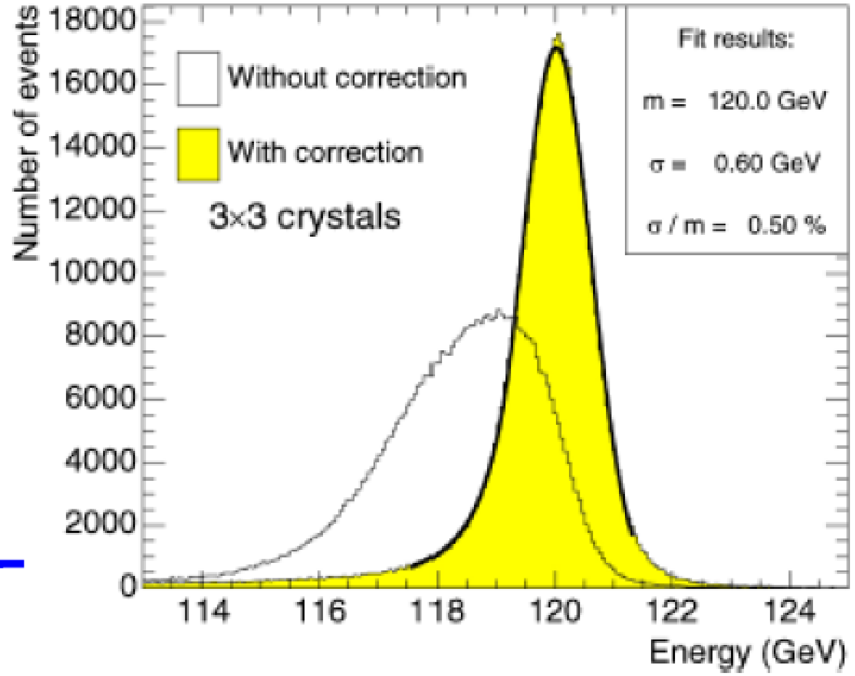


PbGl
2 sectors

	PbSc	PbGl
type	66 – Scintillator+Lead	Cherenkov
radiation length (X_0) [mm]	21	29
Moliere radius [mm]	30	37
cross section of a channel [mm^2]	52.5 × 52.5	40 × 40
depth [mm (X_0)]	375 (18)	400 (14)
$\Delta\eta$ of a channel	0.011	0.008
$\Delta\phi$ of a channel	0.011	0.008
number of channels in a super-module	144 (12 × 12)	24 (4 × 6)
number of super-modules in a sector	18 (3 × 6)	192 (12 × 16)
number of total sectors	6	2
number of total channels	15552	9216

EMCal examples: CMS PbWO4 crystals

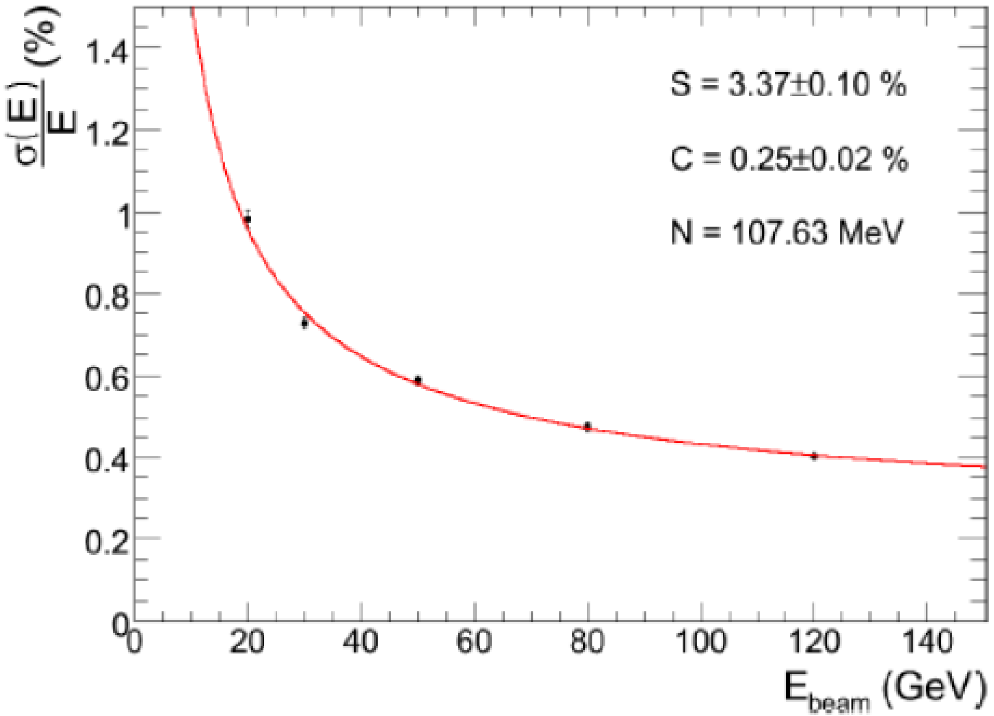




Correction for radial loss

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{3.37\%}{\sqrt{E}}\right)^2 + \left(\frac{0.107}{E}\right)^2 + (0.25\%)^2$$

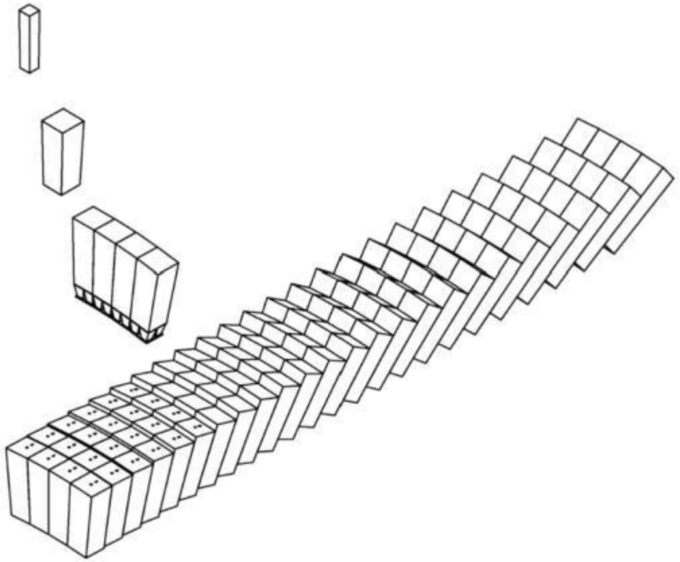
stoch. noise const.

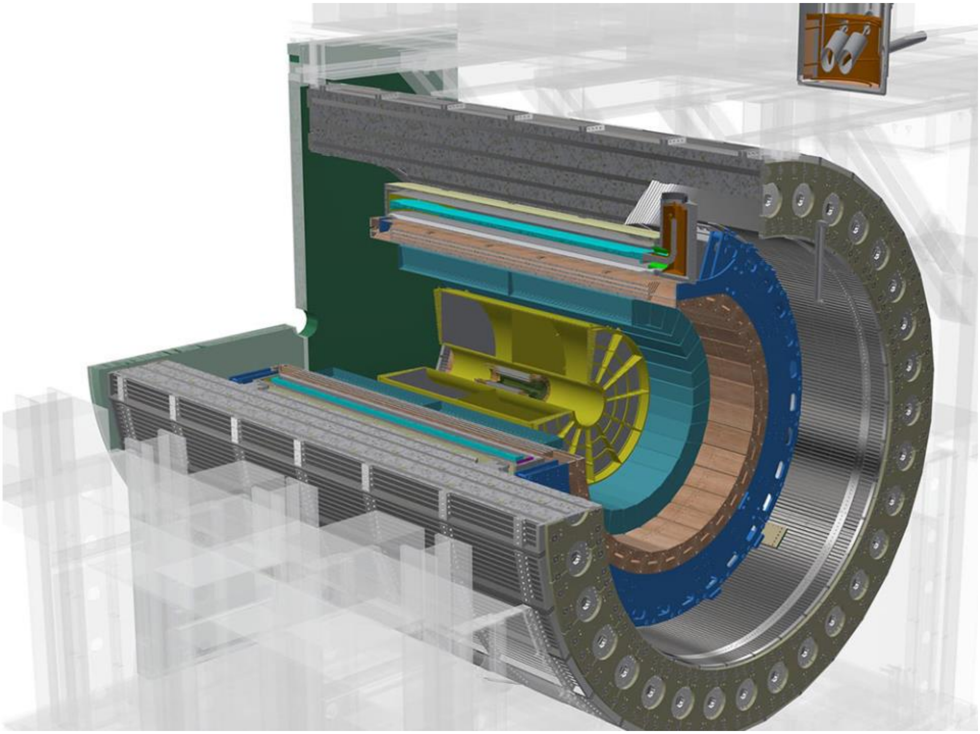


The sampling term is 3 times smaller than ATLAS; other terms are similar

EMCal examples: sPHENIX SciFi

- Scintillating fibers with close spacing direct light out the back without wavelength shifters
- The surrounding material is W powder mixed with a minimal amount of epoxy that has been "injection-molded" around a tight array of scintillating fibers



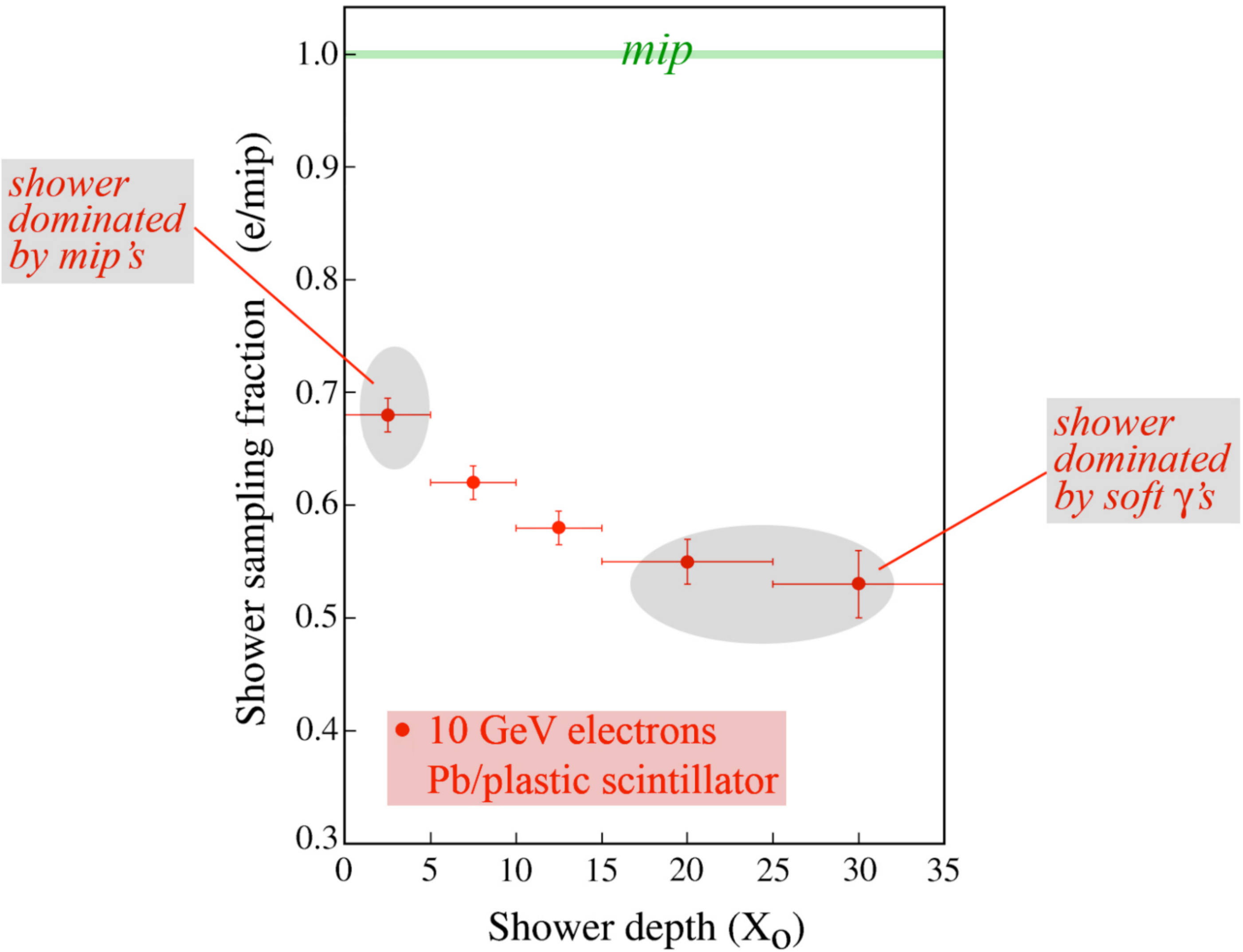


Summary table: Examples of EM calorimeters

Technology (Experiment)	Depth	Energy resolution	Date	
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/\mathrm{E}^{1/4}$	1983	Homogeneous
$\mathrm{Bi_4Ge_3O_{12}}$ (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	
$\mathrm{PbWO_4}$ (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	Sampling
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	

E in GeV

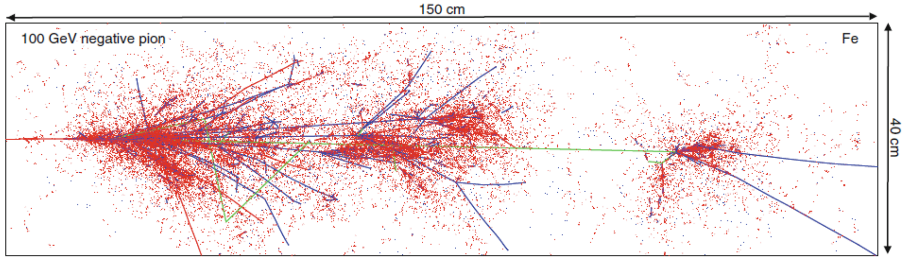
One important consideration: EM showers are not a collection of MIPs



- The sampling fraction for a high-energy electron, for example, is smaller than that for a MIP particle. The sampling fraction also changes with shower depth.
- This is a challenge for the intercalibration of different sections of longitudinally-segmented calorimeters
- In calorimeters consisting of high-Z absorber material (e.g., lead) and low-Z active material (plastic, liquid argon), the sampling fraction may vary by as much as 25 - 30% over the volume in which the absorption takes place.

Hadronic Calorimeters (**HCal**s)

Hadronic showers



- For hadronic particles, the extra complication is the Strong Interaction with detector material
- A hadron that undergoes a nuclear reaction will create a number of secondary particles. These particles will
  1. Undergo additional nuclear interactions (formation of hadronic cascade)
  2. Neutral pions and eta mesons will electromagnetically decay -- leading to EM showers
  3. Part of the initial energy is used to break nuclear binding -- this is *Invisible energy* that cannot contribute to the signal
- The governing length scale is the hadronic interaction length

Hadronic showers

Hadronic interaction:

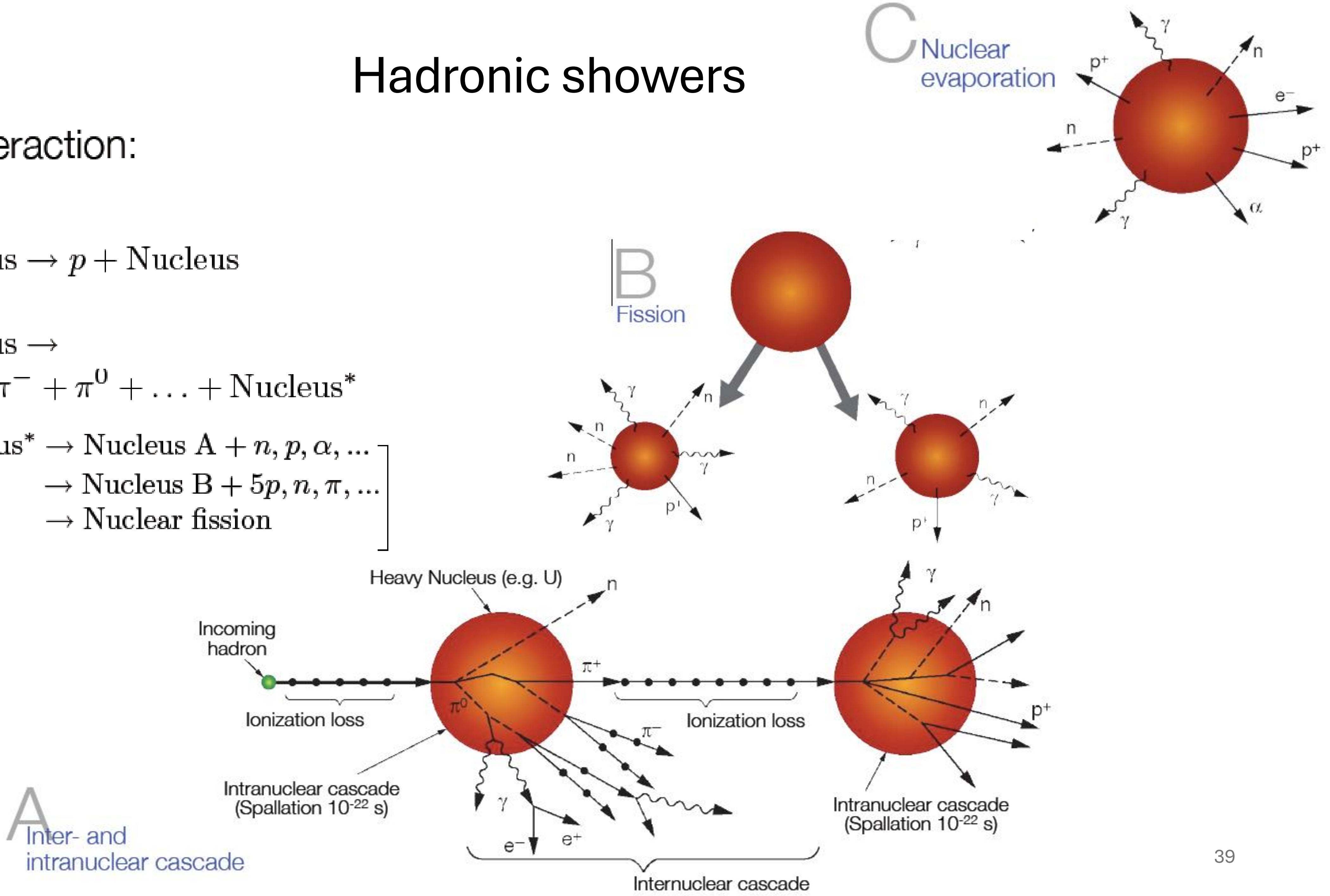
Elastic:

$$p + \mathrm{Nucleus} \rightarrow p + \mathrm{Nucleus}$$

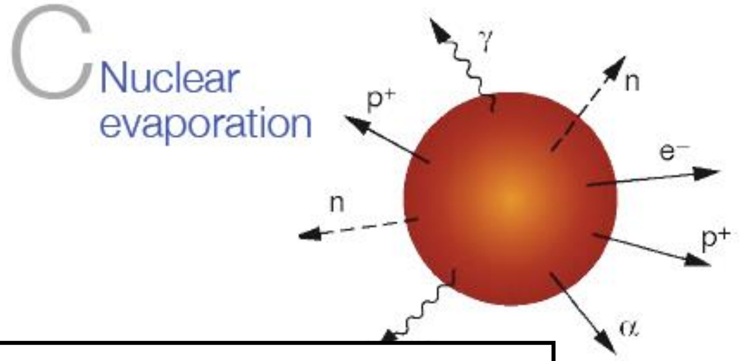
Inelastic:

$$p + \mathrm{Nucleus} \rightarrow$$
$$\pi^+ + \pi^- + \pi^0 + \ldots + \mathrm{Nucleus}^*$$

$$\left[\begin{array}{ll} \mathrm{Nucleus}^* & \rightarrow \mathrm{Nucleus\ A} + n, p, \alpha, \ldots \\ & \rightarrow \mathrm{Nucleus\ B} + 5p, n, \pi, \ldots \\ & \rightarrow \mathrm{Nuclear\ fission} \end{array}\right]$$



Hadronic showers



Hadronic interaction:

Elastic:

$$p + \text{Nucleus} \rightarrow p + \text{Nucleus}$$

Inelastic:

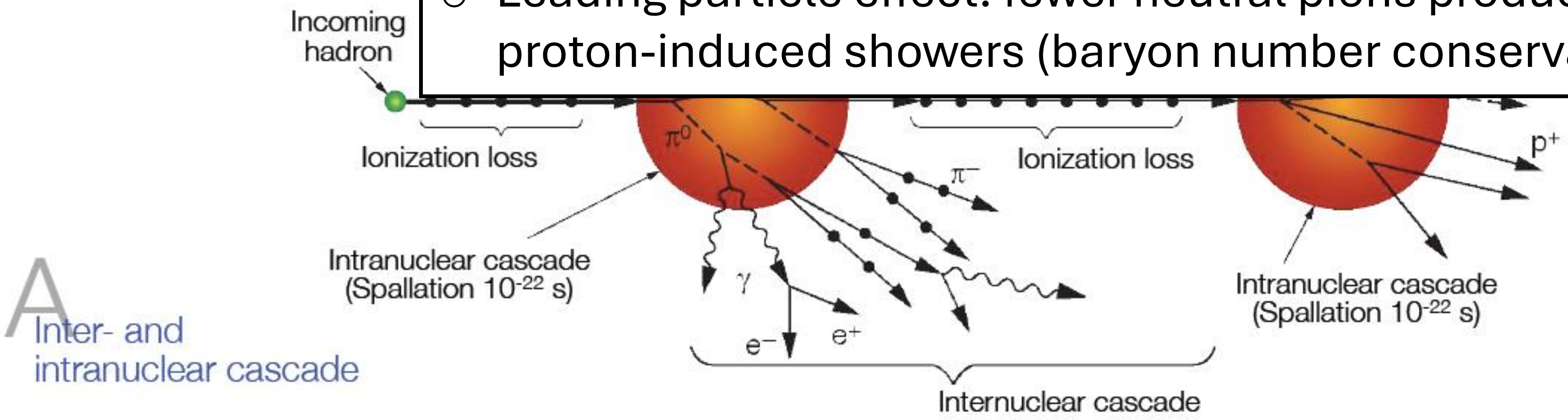
$$p + \text{Nucleus} \rightarrow$$

$$\pi^+ + \pi^- + \pi^0 + \ldots + \text{Nuc}$$

$$\left[\begin{array}{l} \text{Nucleus}^* \rightarrow \text{Nucleus A} + n, \\ \quad\quad\quad\;\; \rightarrow \text{Nucleus B} + 5p, \\ \quad\quad\quad\;\; \rightarrow \text{Nuclear fission} \end{array}\right.$$

<u>Some general features of hadronic showers</u>

- Particle multiplicity scales with energy and particle type
- For incident charged pions, a third of shower particles are neutral pions (charge exchange process). If this charge-exchange process occurs in first nuclear reaction, most of the energy will be deposited through EM showers
- Leading particle effect: fewer neutral pions produced in proton-induced showers (baryon number conservation)



Hadronic interactions

Hadronic interaction:

Cross Section:

at high energies
also diffractive contribution

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

For substantial energies
σ_{inel} dominates:

$\sigma_{\text{el}} \approx 10\text{ mb}$

$\sigma_{\text{inel}} \propto A^{2/3}$ [geometrical cross section]

$$\therefore\ \sigma_{\text{tot}} = \sigma_{\text{tot}}(pA) \approx \sigma_{\text{tot}}(pp) \cdot A^{2/3}$$

[σ_{tot} slightly grows with $\sqrt{s}$]

Hadronic interaction length:

$$\lambda_{\text{int}} = \frac{1}{\sigma_{\text{tot}} \cdot n} = \frac{A}{\sigma_{pp}\, A^{2/3} \cdot N_A \rho} \sim A^{1/3}$$

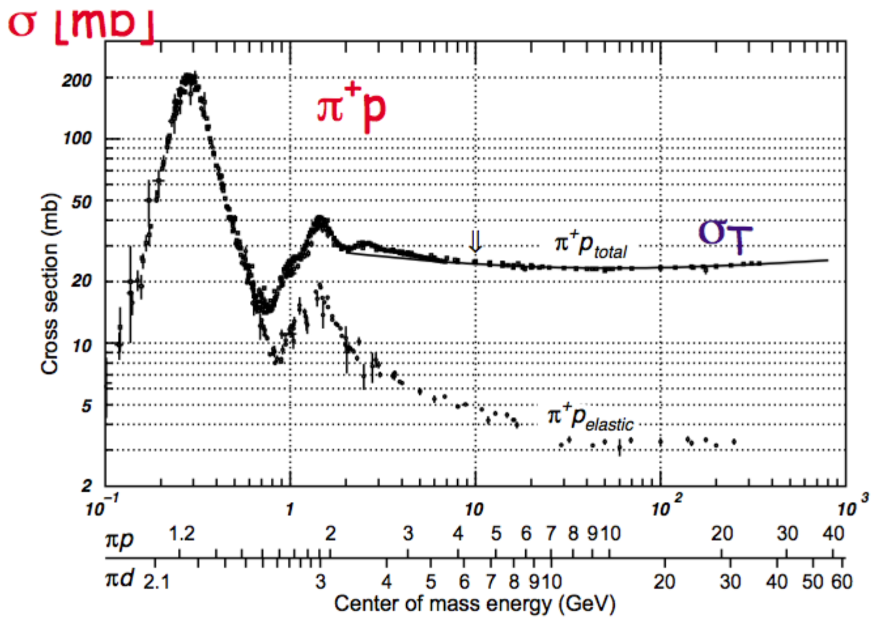
[for $\sqrt{s} \approx 1 - 100$ GeV]

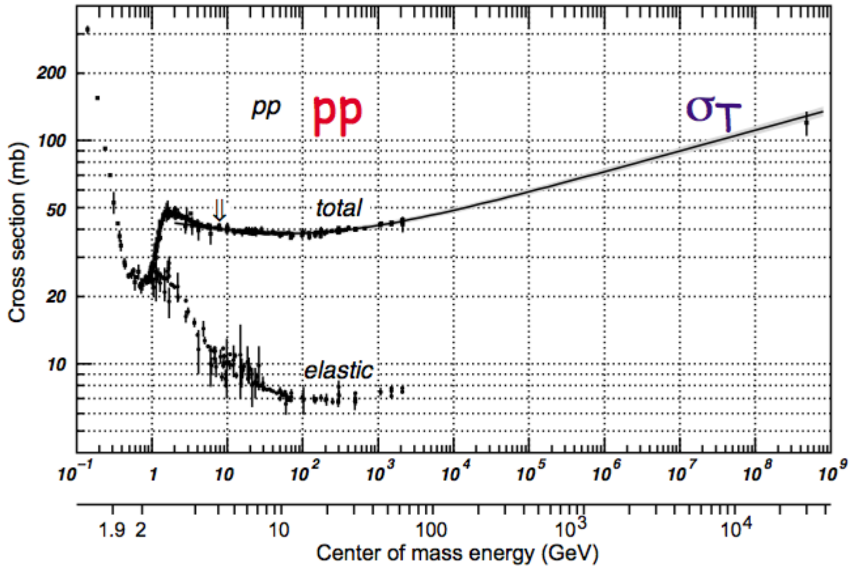
$$\approx 35\ \text{g/cm}^2 \cdot A^{1/3}$$

which yields:

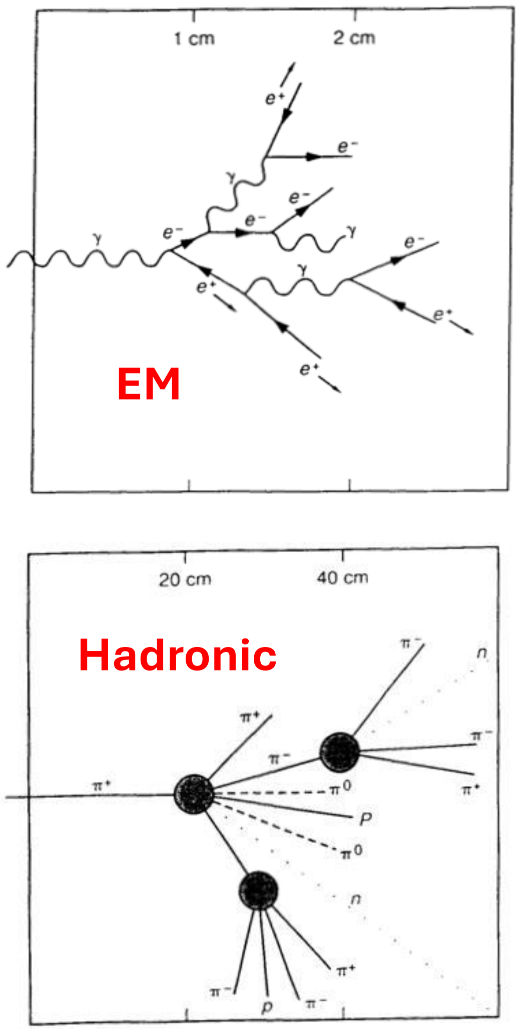
$$N(x) = N_0 \exp(-x/\lambda_{\text{int}})$$

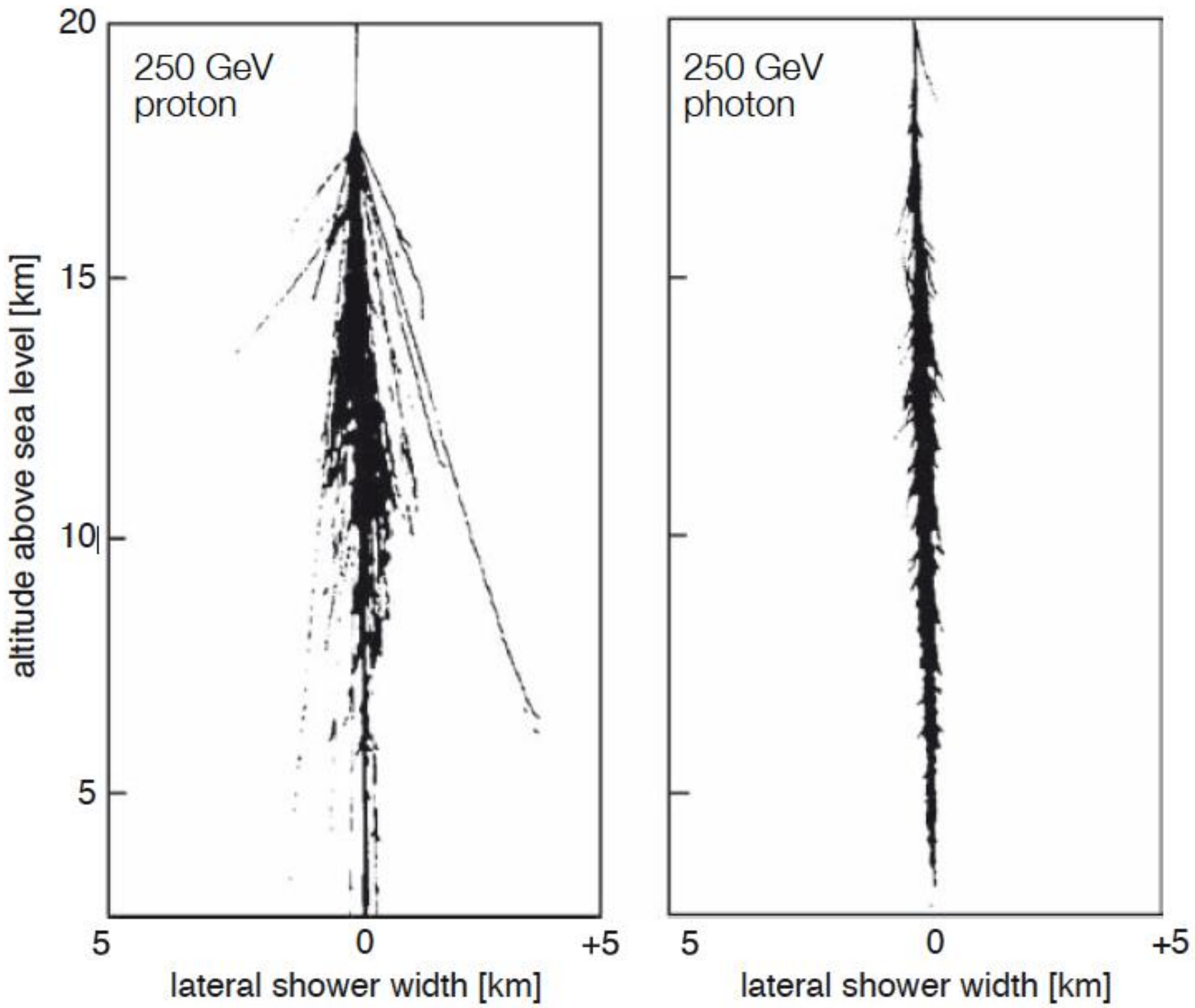
Interaction length characterizes both, longitudinal and transverse profile of hadronic showers ...





Comparison of EM and Hadronic showers





Simulated air showers

Comparison of EM and Hadronic showers

Hadronic vs. electromagnetic interaction length:

$$\left. \begin{array}{l} X_0 \sim \dfrac{A}{Z^2} \\ \lambda_{\mathrm{int}} \sim A^{1/3} \end{array} \right] \rightarrow \frac{\lambda_{\mathrm{int}}}{X_0} \sim A^{4/3}$$

$$\lambda_{\mathrm{int}} \gg X_0$$

[λ_{int}/X_0 > 30 possible; see below]

Typical
Longitudinal size: 6 ... 9 λ_{int} [95% containment] [EM: 15-20 X_0]

Typical
Transverse size: one λ_{int} [95% containment] [EM: 2 R_M; compact]

Hadronic calorimeter need more depth than electromagnetic calorimeter ...

Some numerical values for materials typical used in hadron calorimeters

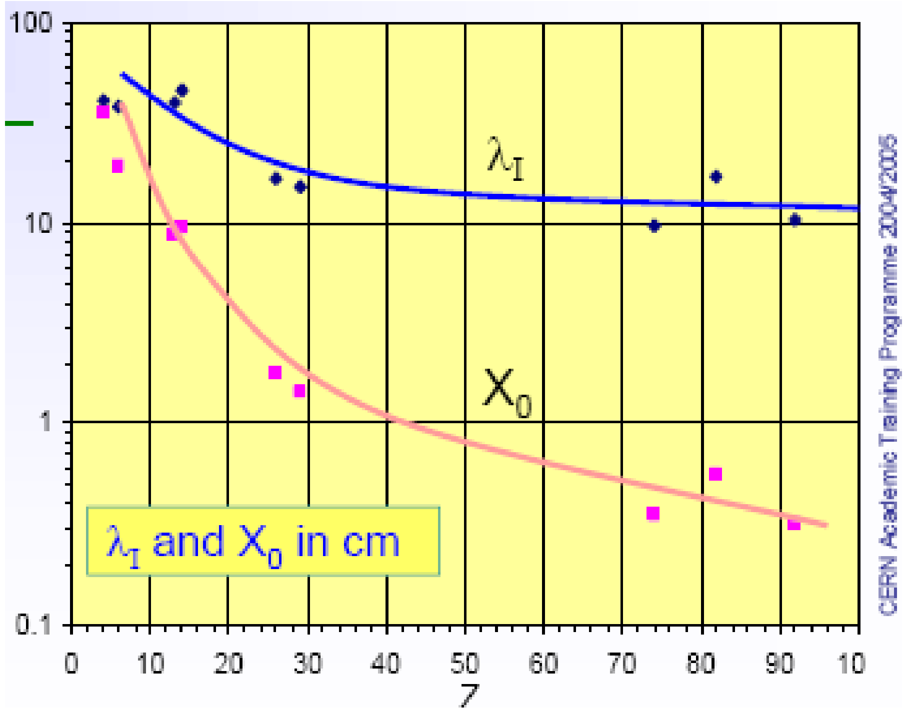
	λ_{int} [cm]	X_0 [cm]
Szint.	79.4	42.2
LAr	83.7	14.0
Fe	16.8	1.76
Pb	17.1	0.56
U	10.5	0.32
C	38.1	18.8

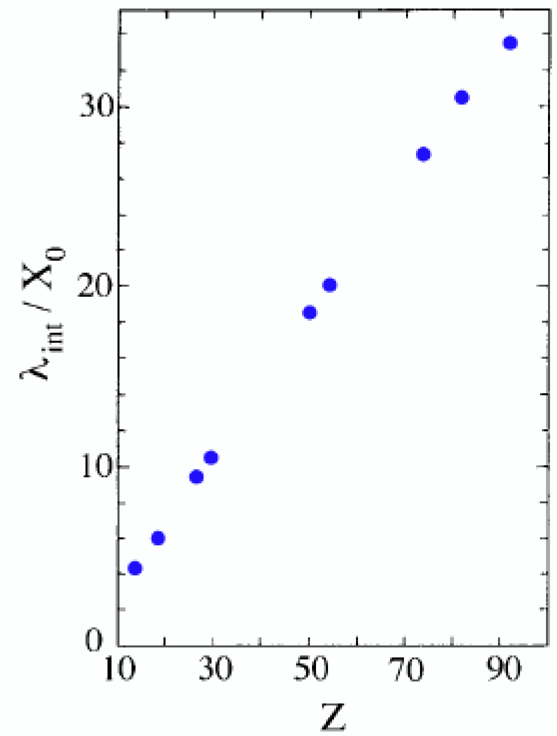
Material Dependence

λ_{int}: Mean-free path between hadronic collisions

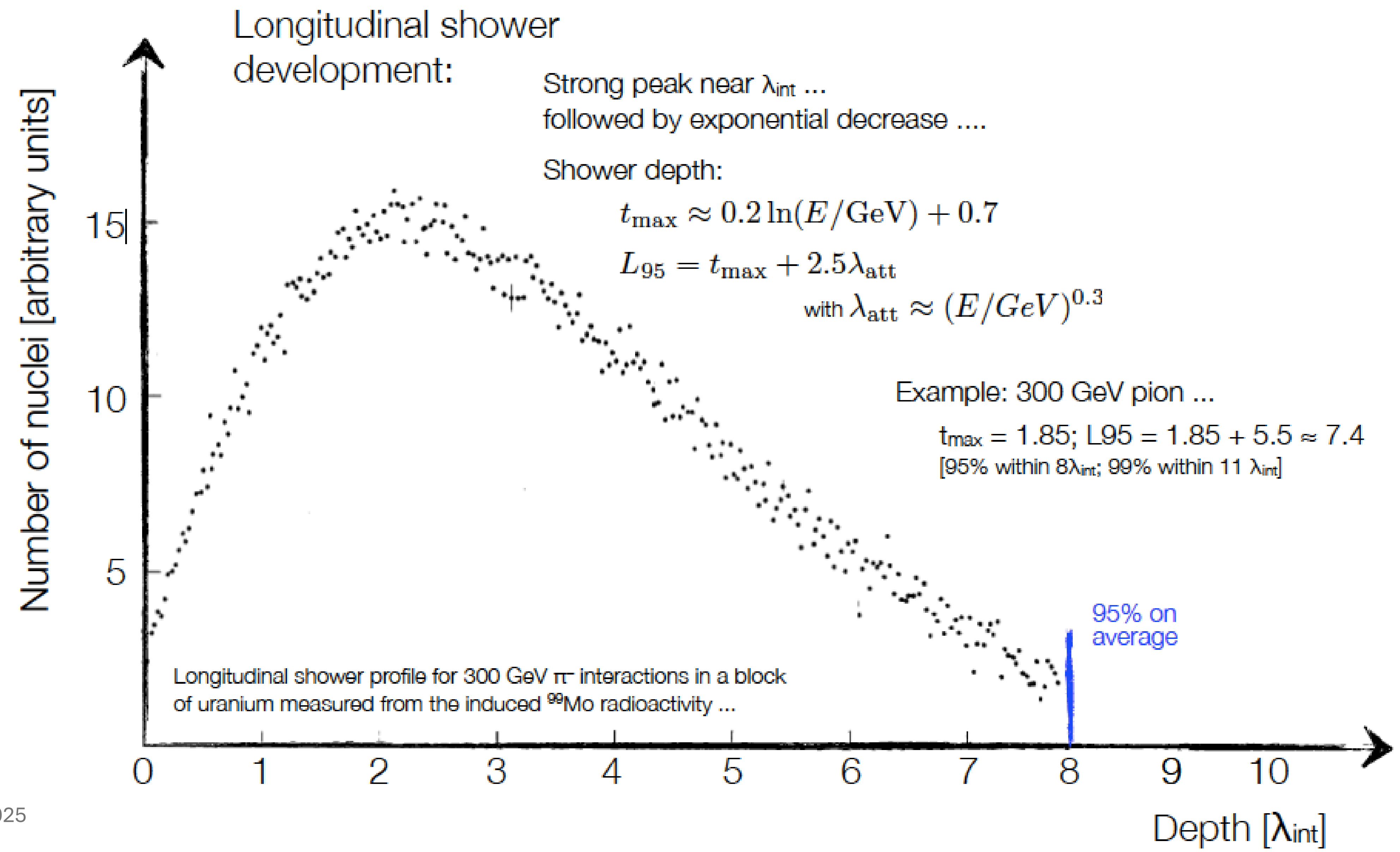
$$\lambda_{\text{int}} \sim A^{1/3} \quad [\text{g/cm}^2]$$

Hadron showers are much longer than EM ones – how much, depends on Z

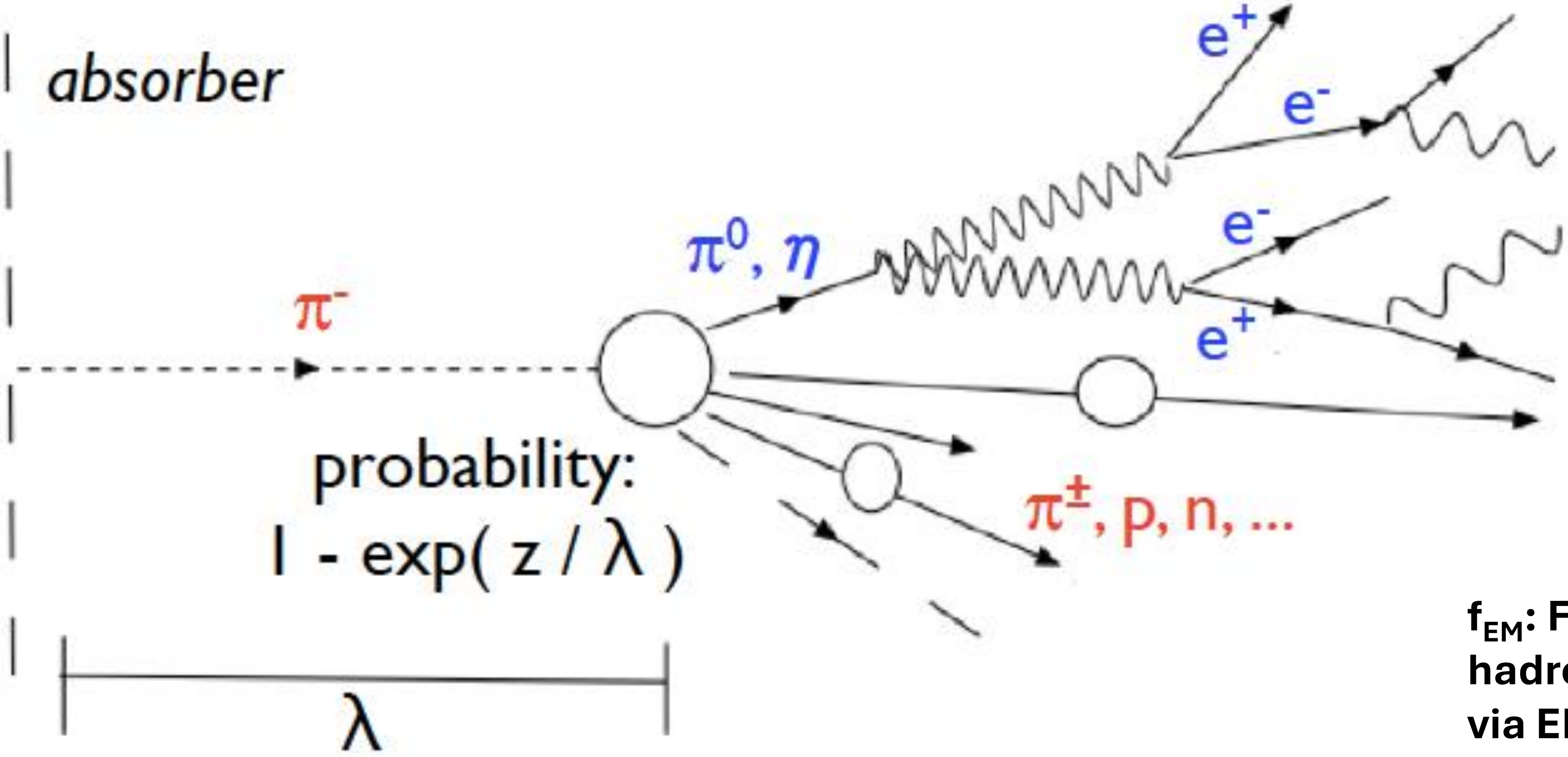




Longitudinal profile of Hadronic shower



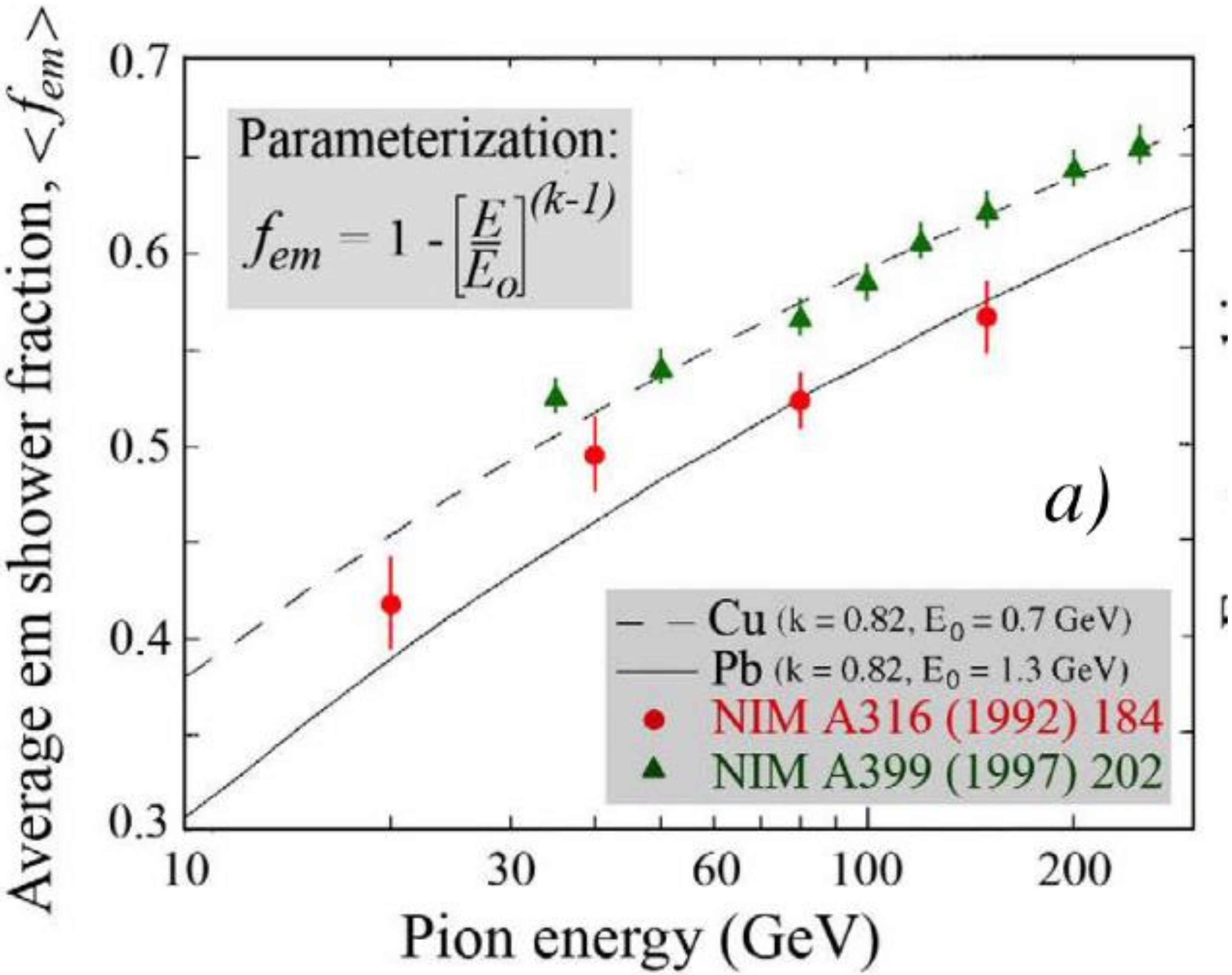
Hadronic showers contain a significant EM component



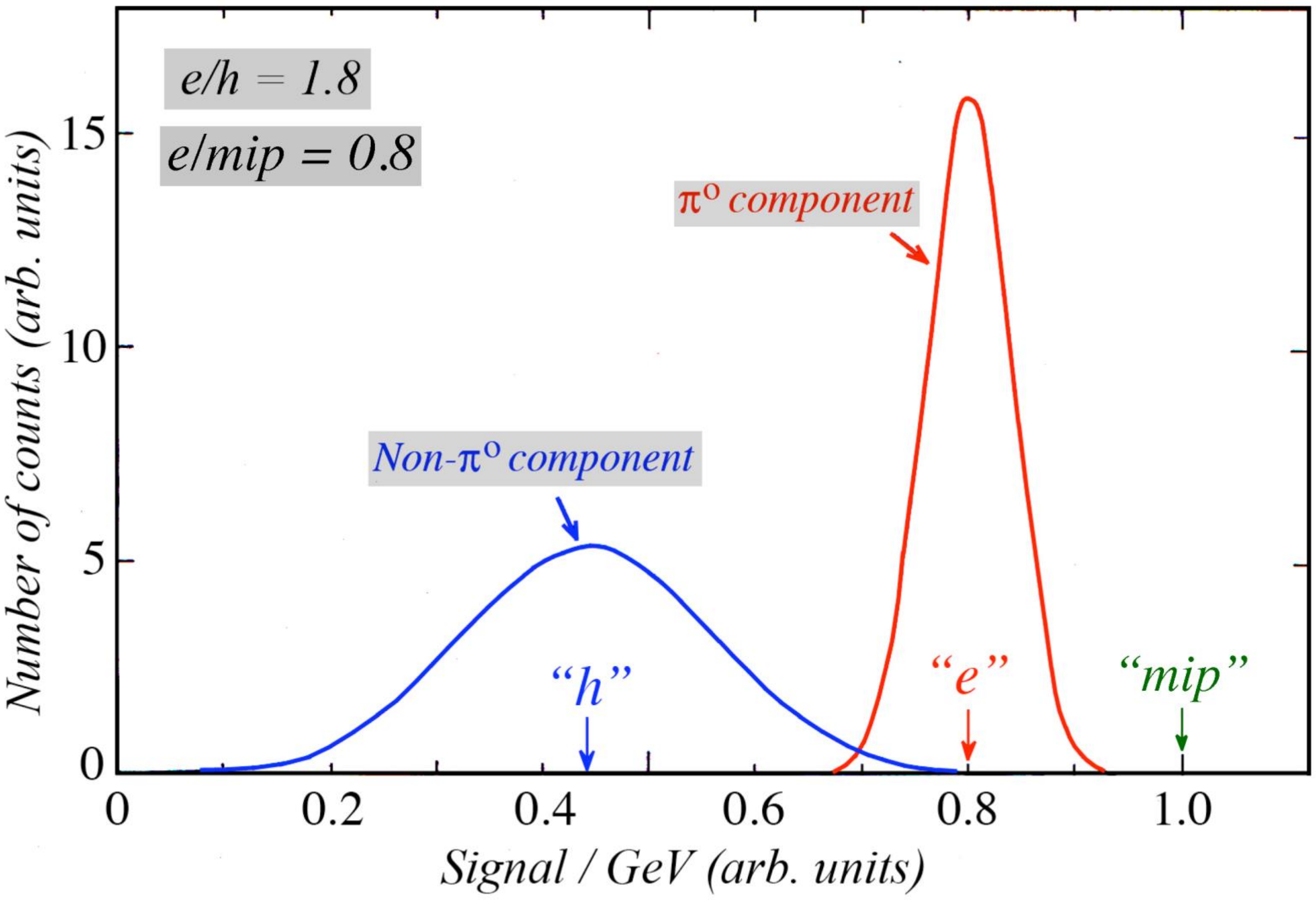
Once a neutral-pion is produced, all its energy gets deposited via EM processes

f_{EM}: Fraction of incident hadron's energy deposited via EM processes

Electromagnetic Fraction grows with energy



Response for EM and non-EM components



- The response of the calorimeter to the EM component is generally larger than the response to the non-EM component.
- The response to the non-EM component is lower due to the *Invisible energy*. It is also wider due to event-by-event fluctuations in the size of this *Invisible energy*.
- Both components are smaller than the MIP response, as we discussed earlier.

Total response for hadrons

Response for pion-initiated shower:

$$\pi = f_{EM}e + (1 - f_{EM})h$$

Ratio of electron to pion response:

$$\frac{e}{\pi} = \frac{e}{f_{EM}e + (1 - f_{EM})h} = \frac{e}{h}\frac{1}{1 + f_{EM}(\frac{e}{h} - 1)}$$

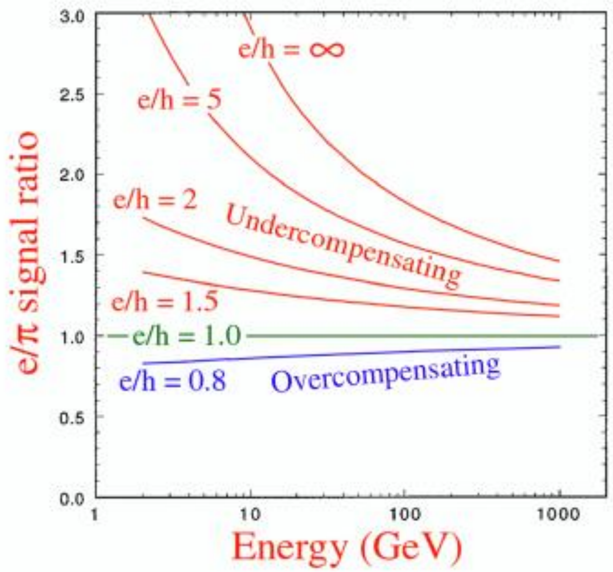
Since f_{EM} is energy dependent, while e/h is mostly energy-independent the response of a non-compensating calorimeter is non-linear.

e = response to EM component
h = response to non-EM component

e/h is not directly measurable, but gives the degree of non-compensation

Calorimeters can be:

- Overcompensating e/h < 1
- Undercompensating e/h > 1
- Compensating e/h = 1



Components of the non-EM response

Energy deposition mechanisms relevant for the absorption of the non-EM shower energy:

- Ionization by charged particles (mostly pions) f_{rel} (Relativistic shower component).
- Spallation protons f_p (non-relativistic shower component).
- Kinetic energy carried by evaporation neutrons f_n
- Energy used to release protons and neutrons from calorimeter nuclei, and the kinetic energy carried by recoil nuclei do not lead to a calorimeter signal. This is the invisible fraction f_{inv} of the non-em shower energy

The total hadron response can be written as:

$$h = f_{rel} \cdot rel + f_p \cdot p + f_n \cdot n + f_{inv} \cdot inv$$
$$f_{rel} + f_p + f_n + f_{inv} = 1$$

Components of the non-EM response

The total hadron response can be written as:

$$h = f_{rel} \cdot rel + f_p \cdot p + f_n \cdot n + f_{inv} \cdot inv$$
$$f_{rel} + f_p + f_n + f_{inv} = 1$$

Normalizing to the MIP response, we can write

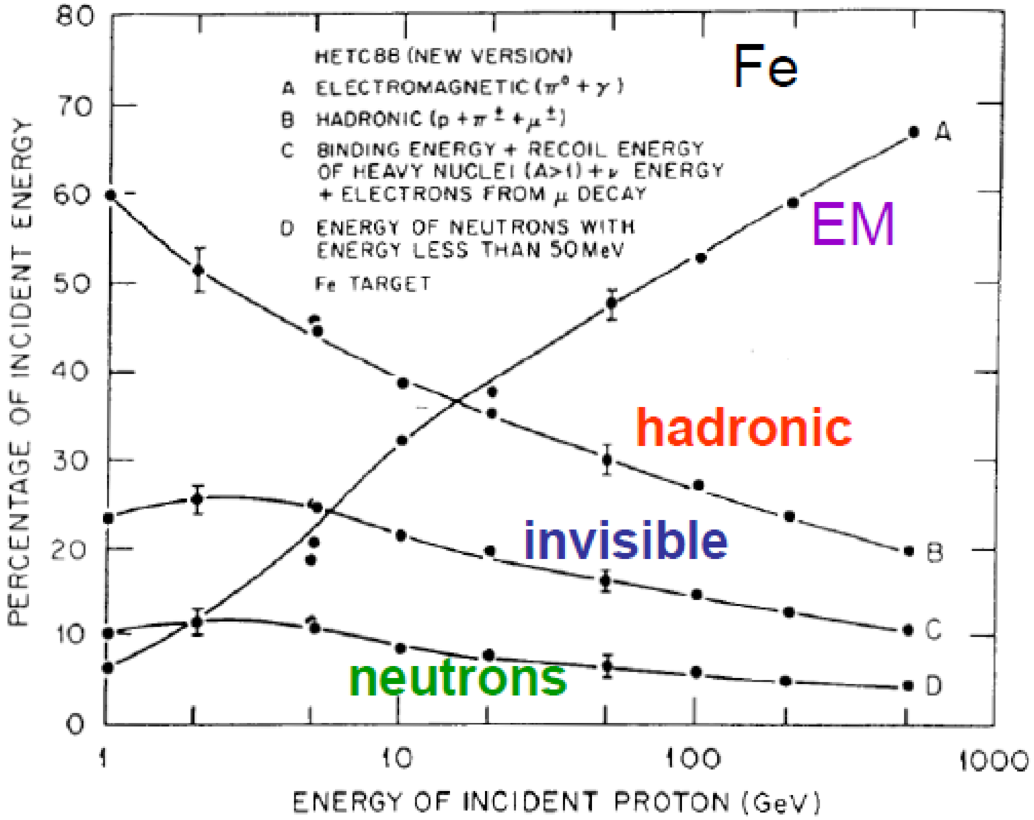
$$\frac{e}{h} = \frac{e/mip}{f_{rel} \cdot rel/mip + f_p \cdot p/mip + f_n \cdot n/mip}$$

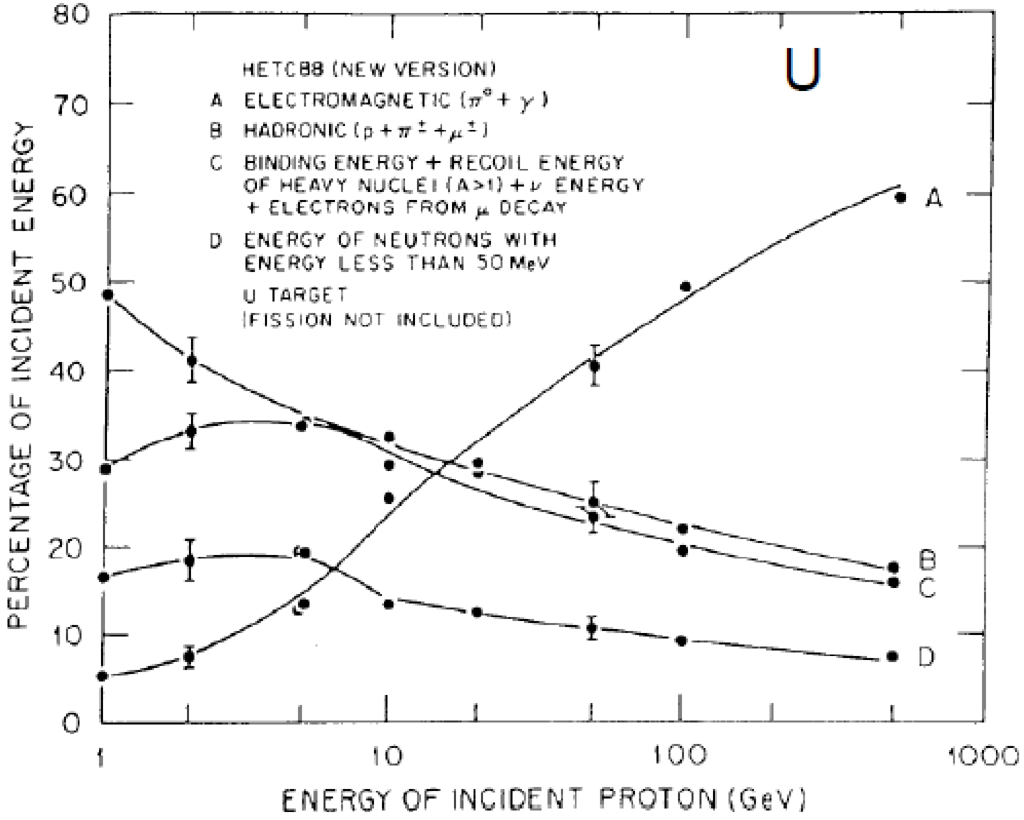
*On the plots, the fractions are shown as total energy fractions, rather than as fractions of non-em response

Energy fractions

$$\pi = \boxed{f_{EM}} e + (1 - f_{EM}) h$$

$$h = \boxed{f_{rel}} \cdot rel + \boxed{f_p} \cdot p + \boxed{f_n} \cdot n + \boxed{f_{inv}} \cdot inv$$





Compensation by tuning the neutron response – I

Compensation with hydrogenous active material

- Elastic scattering of soft neutrons on protons: high energy transfer to protons; high energy loss for scattered soft protons

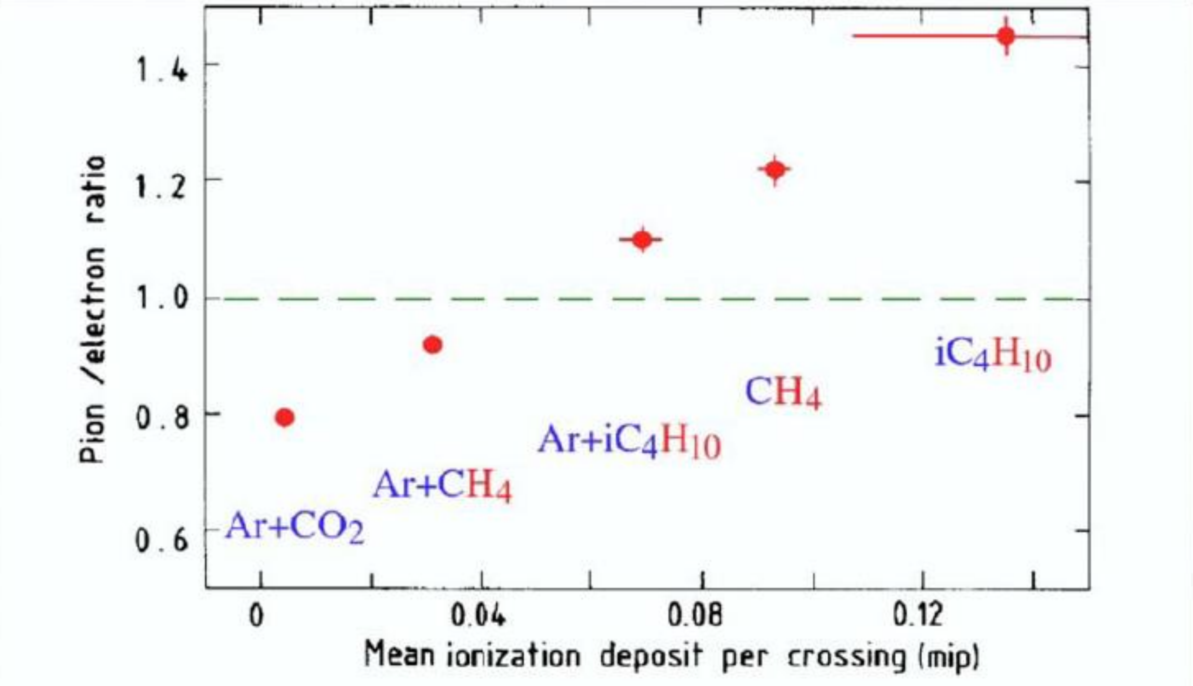
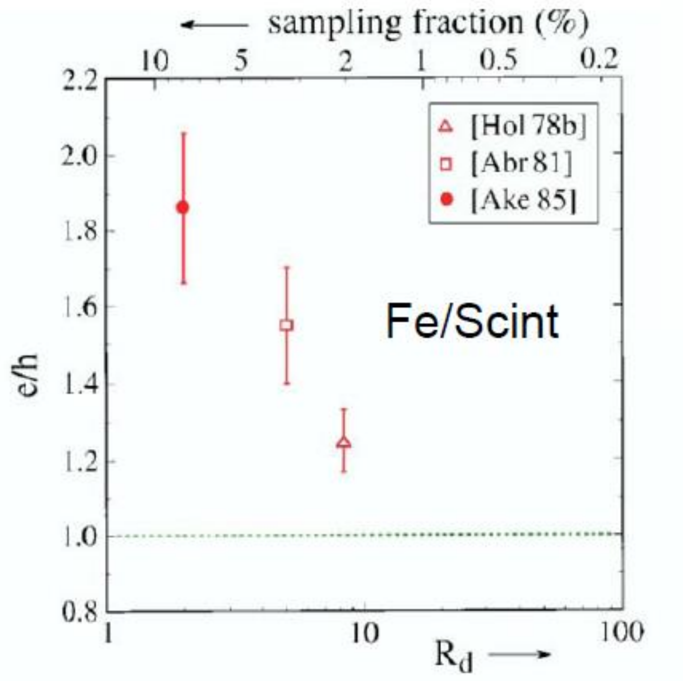


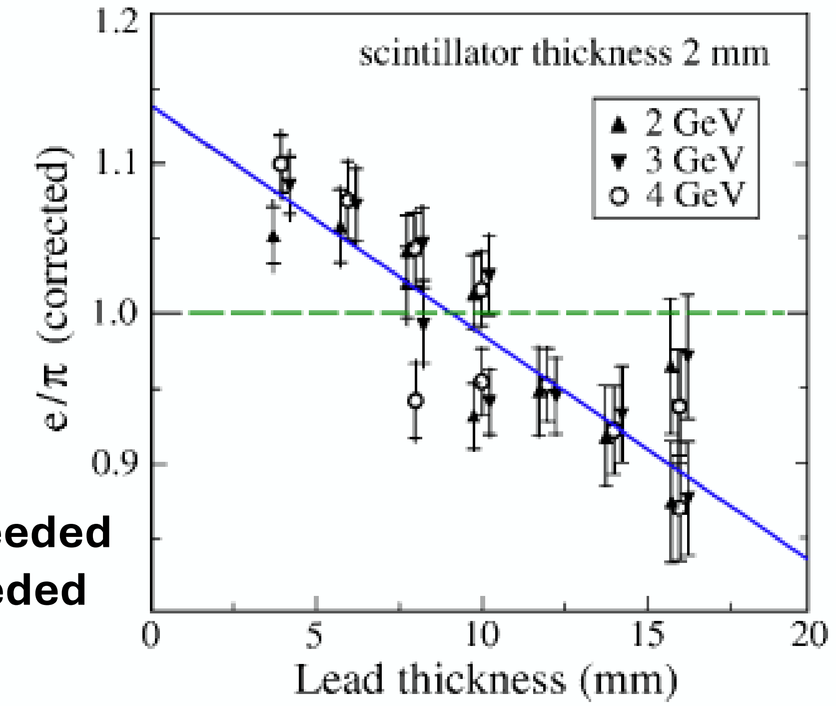
FIG. 3.32. The pion/electron signal ratio, averaged over the energy range 1 5 GeV, measured for different gas mixtures with the uranium/gas calorimeter of the L3 Collaboration. The horizontal scale gives the (calculated) average energy deposit in a chamber gap by slow neutrons [Gal 86].

Compensation by tuning the neutron response – II

- Compensation by adjusting the sampling frequency
- Reduce the EM response for high-Z absorbing materials.
  - The best performance for EM particles is incompatible with e/h = 1
- Works best with Pb and U
- Also possible for Fe in principle, but it requires too large absorber thickness
  - > 10:1 Fe/Sc ratio needed



4:1 Pb/Sc ratio needed
1:1 U/Sc ratio needed



Compensation by tuning the neutron response – III

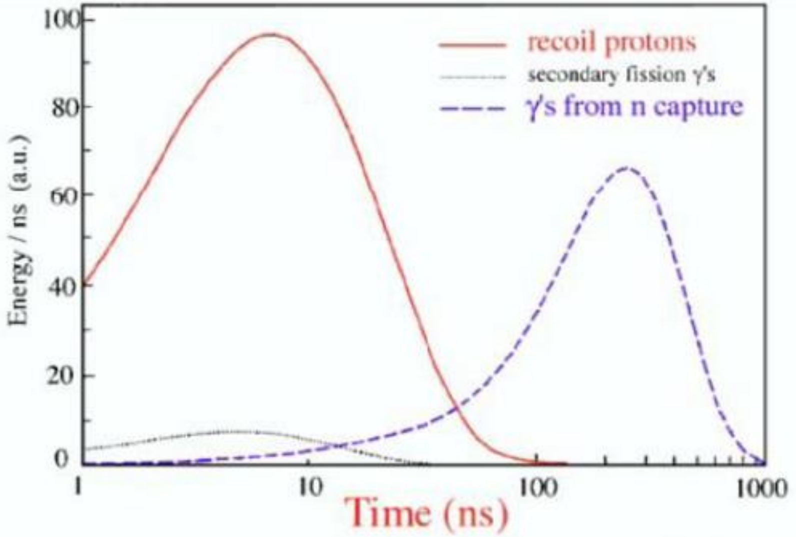


FIG. 3.22. Time structure of various contributions from neutron-induced processes to the hadronic signals of the ZEUS uranium/plastic-scintillator calorimeter [Bru 88].

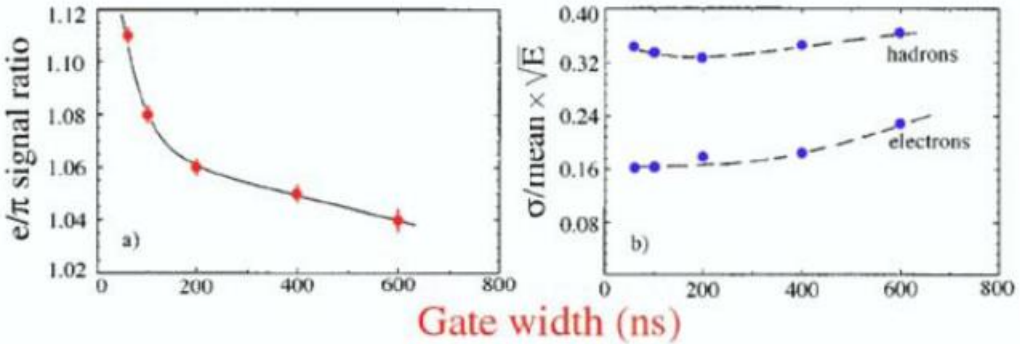


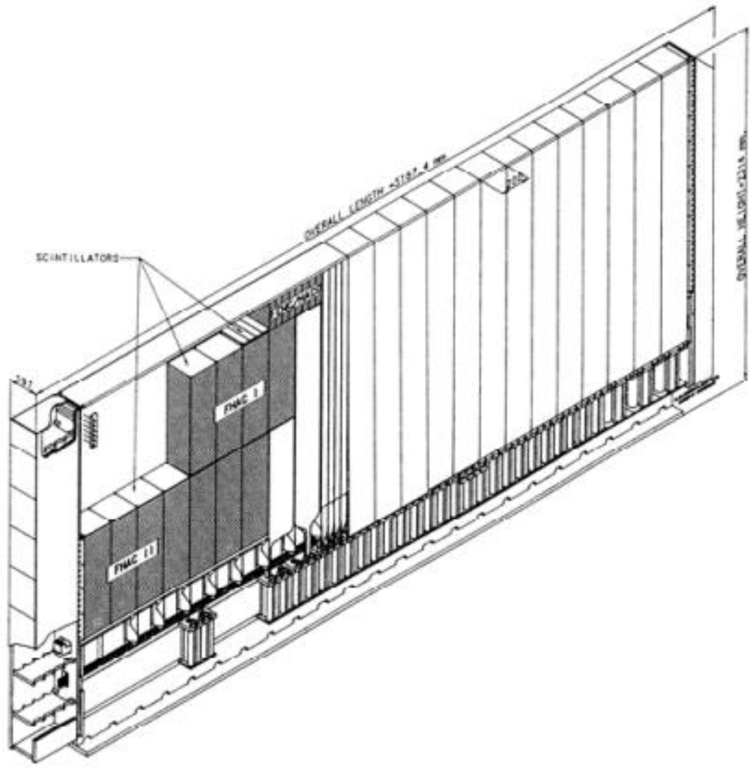
FIG. 3.23. The ratio of the average ZEUS calorimeter signals from 5 GeV/c electrons and pions (a) and the energy resolutions for detecting these particles (b), as a function of the charge integration time [Kru 92].

Large fraction of neutron energy captured and released after >100ns

Long integration time:

- collect more hadron E → closer to compensation
- integrate additional noise → worse resolution

ZEUS compensating calorimeter



View of a module of the ZEUS U-scintillator calorimeter. Wavelength-shifter readout is used to read cells of $5*20\ cm^2$ cross-section in the electromagnetic compartment and of $20*20\ cm^2$ in the two subsequent hadronic compartments

First compensating calorimeter used depleted Uranium as the absorber material:

- The ZEUS HCal had an energy resolution better than $35\% / \sqrt{E\ [GeV]}$. This is better than modern HCals at the LHC, for example.
- Initial idea was that the fission energy released in the absorption process would compensate for the invisible energy losses.
- ZEUS did achieve compensation – but fission had nothing to do with it. Uranium was neither necessary nor sufficient.
- The important things were the hydrogenous active material, the tuned sampling fraction (about 2%), and an integration time of over 30 ns.

- Even with the small sampling fraction (degraded EM/sampling resolution) and large integration time, the ZEUS HCal has the world record in hadronic energy resolution.
- The main driver for poor HCal is the *Invisible energy* produced in hadronic showers, which leads to non-compensation.

Sampling fluctuations in EM and Hadronic Showers

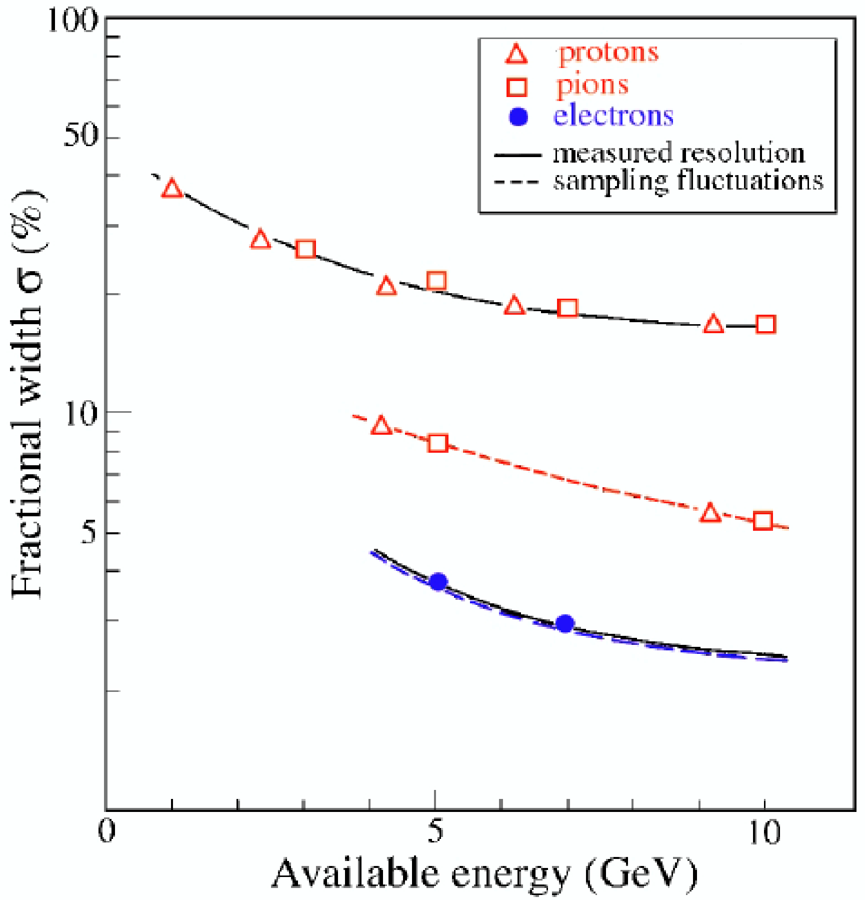


FIG. 4.15. The energy resolution and the contribution from sampling fluctuations to this resolution measured for electrons and hadrons, in a calorimeter consisting of 1.5 mm thick iron plates separated by 2 mm gaps filled with liquid argon. From [Fab 77].

Sampling fluctuations only contribute a small amount to the total resolution of Hadronic showers.

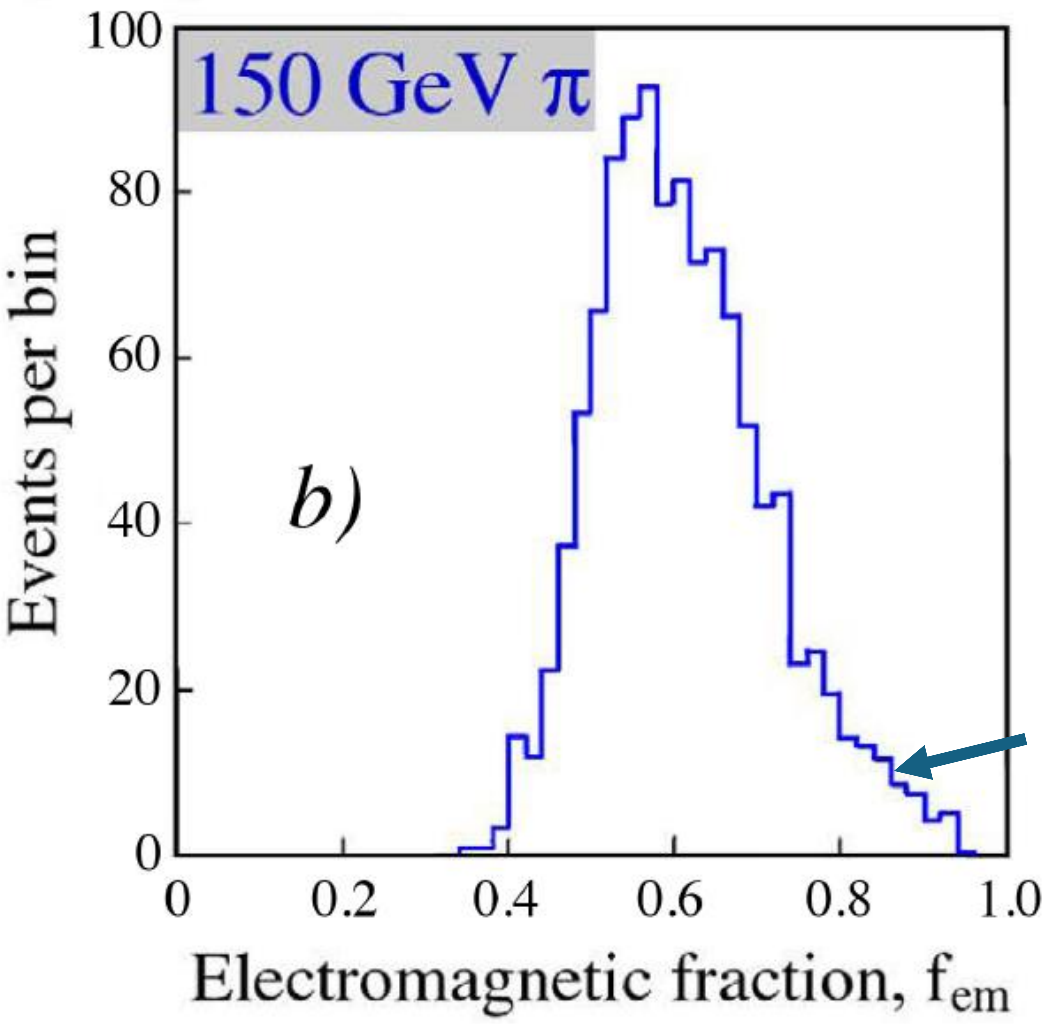
Sampling fluctuations dominate the resolution for EM showers.

Fluctuations in hadronic showers

Hadronic showers have the same type of fluctuations as EM showers, plus:

1. Fluctuations in the EM shower fraction, f_{EM}
   - Large event-by-event fluctuations: dominating effect in most HCals (e/h > 1)
   - Fluctuations are asymmetric (i.e. have a high-energy tail) for charge-pion induced showers
   - Leading-particle effect: difference between pion and proton showers
2. Fluctuations in the *Invisible energy* fraction
   - Large event-by-event fluctuations in high-Z absorber material
   - Represents ultimate limit of hadronic resolution

Fluctuations in EM Shower Fraction

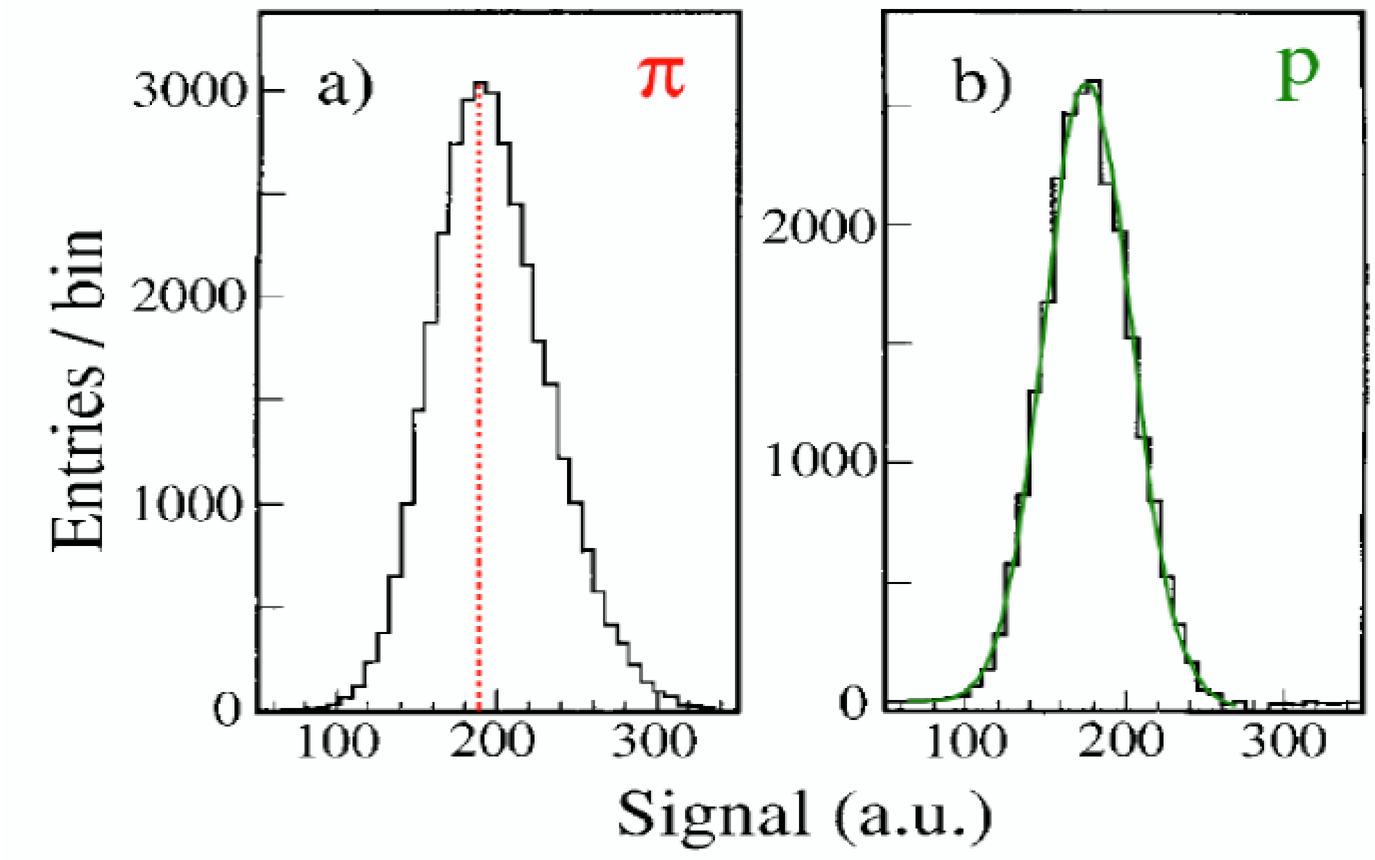


Pion showers: Due to the irreversibility of the production of neutral pions and because of the leading particle effect, there is an asymmetry in the probability that an anomalously large fraction of the energy goes into the EM shower component

Positive tail for non-compensating calorimeters

$$\pi = f_{EM}e + (1 - f_{EM})h$$

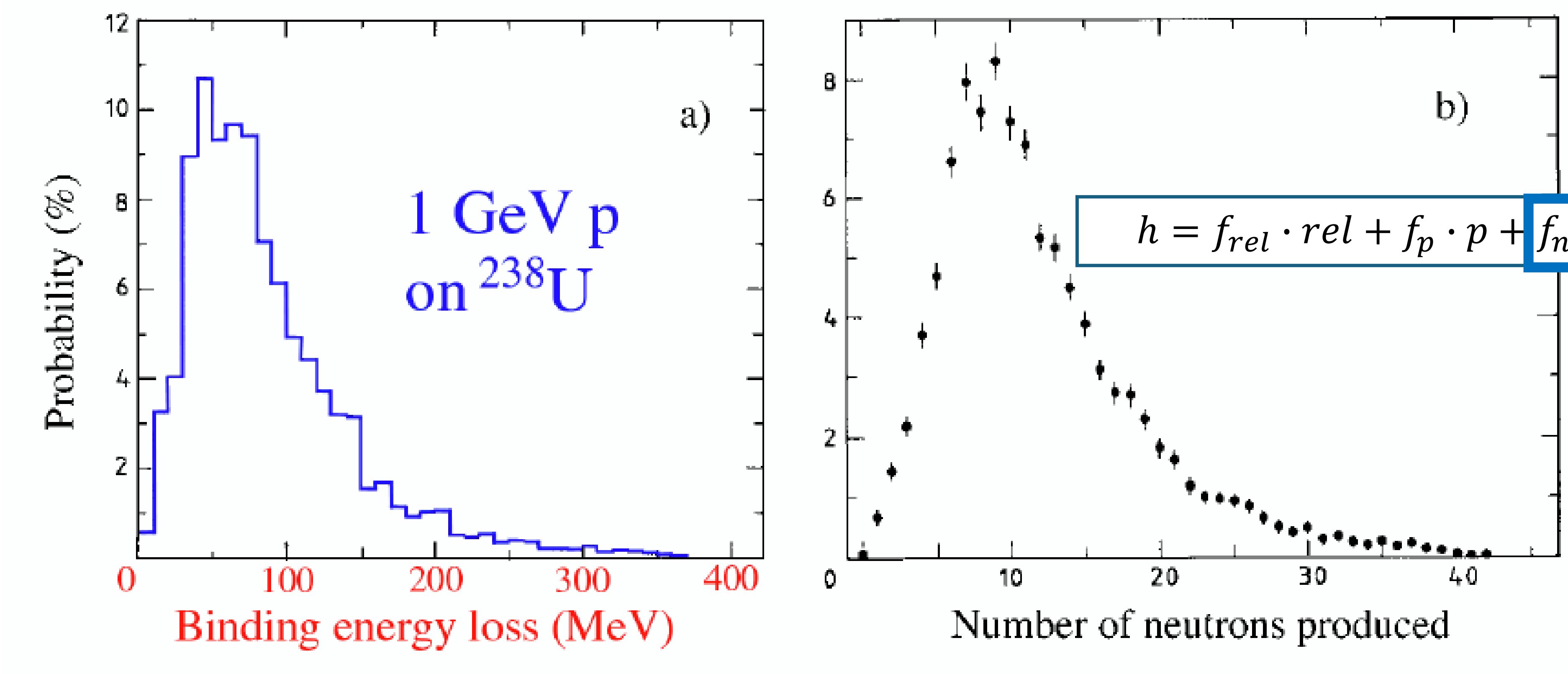
Differences in proton vs. pion induced showers



The average f_{EM} is smaller in proton-induced showers than in pion-induced ones

Proton-induced showers: baryon number conservation prohibits the production of leading neutral pions and thus reduces the EM component vs. pion-induced showers

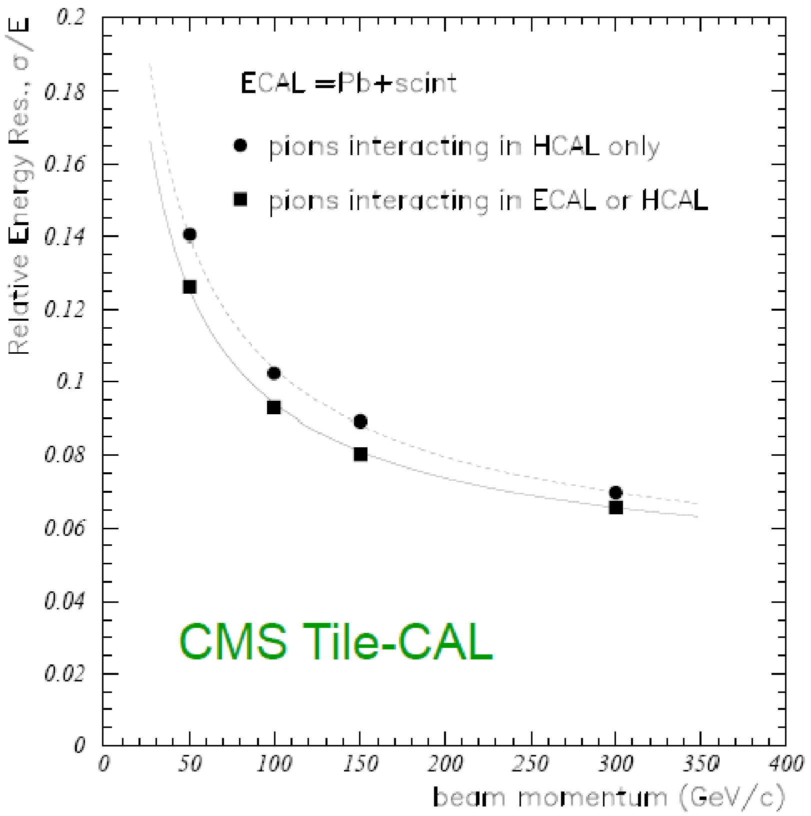
Fluctuations in (in)visible energy



$$h = f_{rel} \cdot rel + f_p \cdot p + \boxed{f_n}\, n + \boxed{f_{inv}} \cdot inv$$

- Significant fluctuations in high-Z absorber material
- **Strong correlation** between the distribution of the binding energy loss and the distribution of the number of neutrons produced in the spallation reactions.
- Efficient neutron detection gives a quantity that correlates with the invisible energy and thus reduces the impact of fluctuations.

Examples: (non-compensating) HCal performance at the LHC

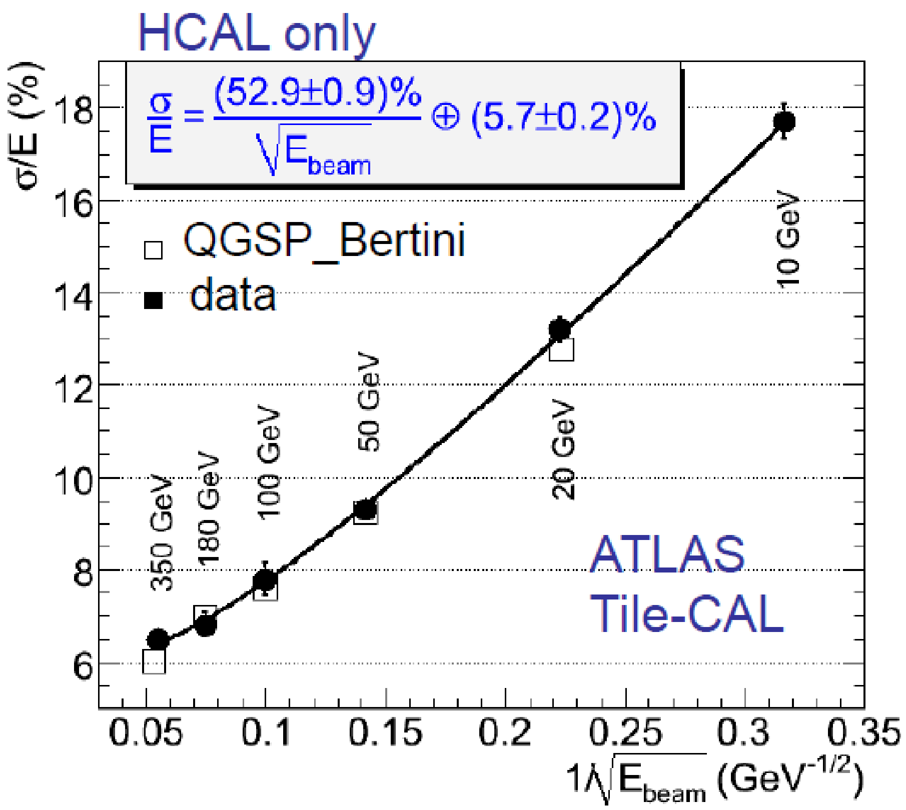


HCAL only

$\sigma/E = (93.8 \pm 0.9)\%/\sqrt{E} \oplus (4.4 \pm 0.1)\%$

ECAL+HCAL

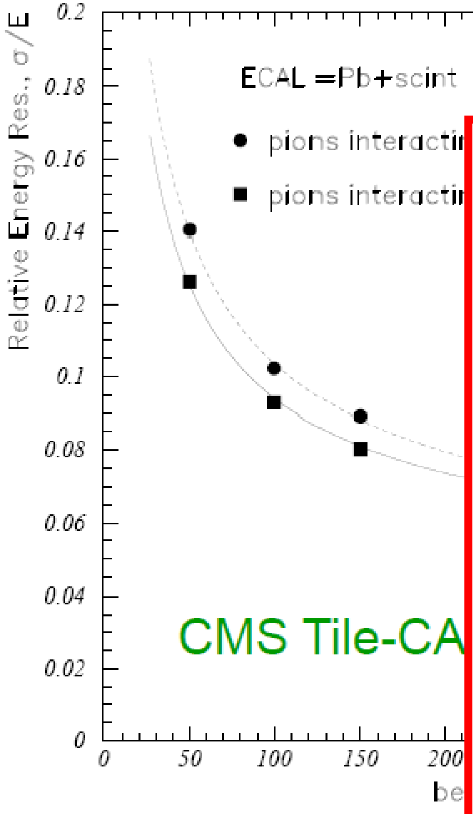
$\sigma/E = (82.6 \pm 0.6)\%/\sqrt{E} \oplus (4.5 \pm 0.1)\%$

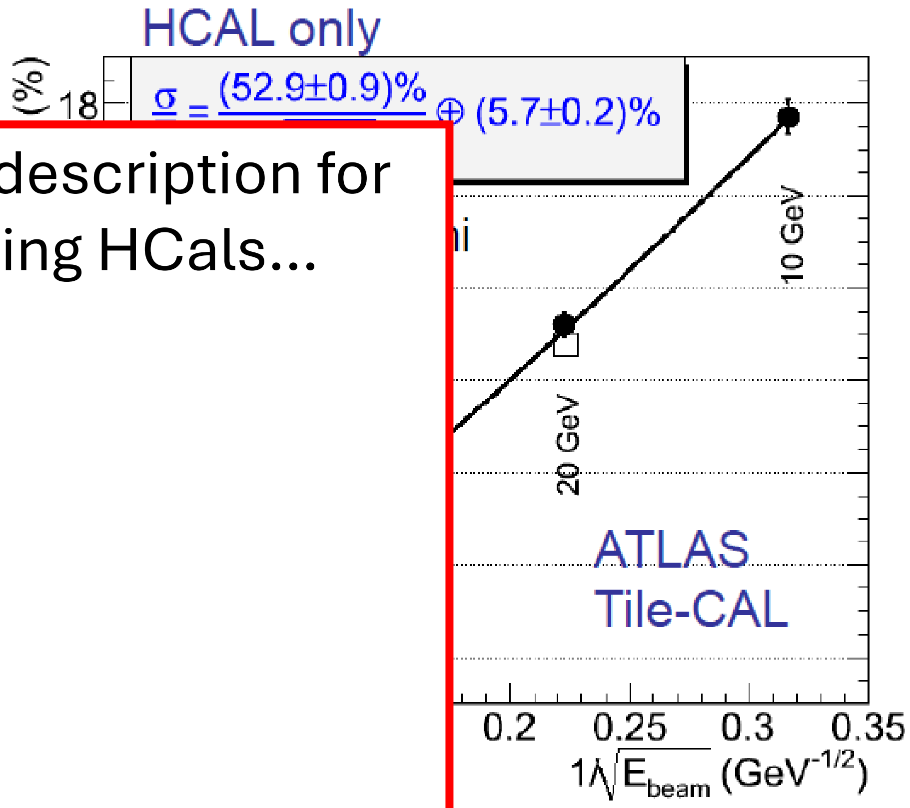


Improved resolution using full calorimetric system (ECAL+HCAL)

ATLAS LAr + Tile for pions: $\frac{\sigma(E)}{E} = \frac{42\,\%}{\sqrt{E}} \oplus 2\,\%$

Examples: (non-compensating) HCal performance at the LHC





Note that this is sometimes a better description for the full resolution of non-compensating HCals...

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} + b$$

Rather than...

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

HCAL only

$\sigma/E = (93.8 \pm 0.9)\%/\sqrt{E} \oplus (4.4 \pm 0.1)\%$

ECAL+HCAL

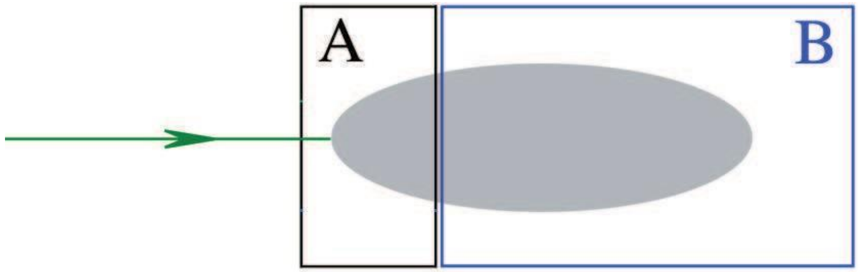
$\sigma/E = (82.6 \pm 0.6)\%/\sqrt{E} \oplus (4.5 \pm 0.1)\%$

Improved resolution using full calorimetric system (ECAL+HCAL)

ATLAS LAr + Tile for pions: $\frac{\sigma(E)}{E} = \frac{42\ \%}{\sqrt{E}} \oplus 2\ \%$

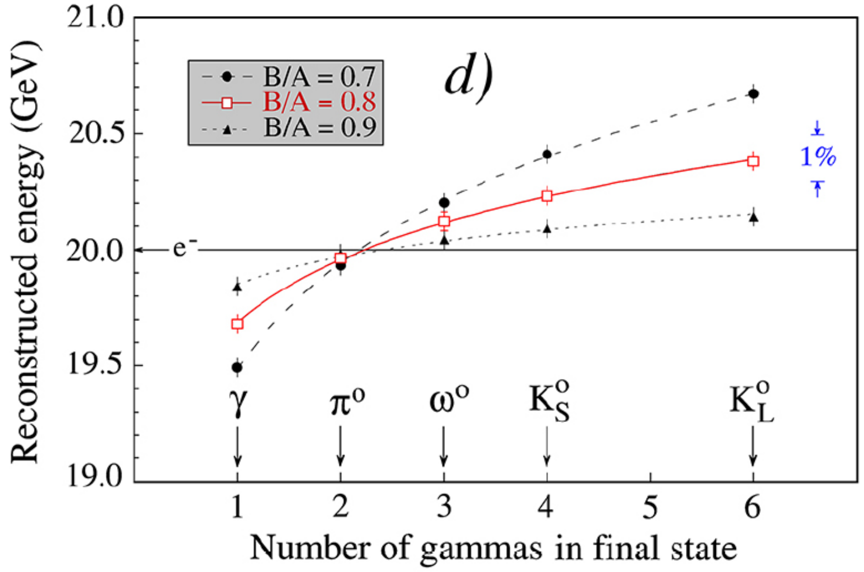
Realistic calorimeter systems: EMCal + HCal

- Challenges for calibration: Ratio of energy deposits is not same as ratio of observed signal
- There are several different calibration techniques, all of which have advantages/drawbacks.
- One is to try and minimize energy resolution for a particular type of particle, but this leads to some unwanted effects:
    - Calibration constant for one particular type of particle, or jet, leads to systematic mismeasurements of other type
    - Calibration constant for one particular energy leads to systematic mismeasurements in other energy ranges



Minimize $Q = \sum_{j=1}^{N} \left[E - A \sum_{i=1}^{n} S_{ij}^{A} - B \sum_{i=1}^{n} S_{ij}^{B} \right]^2$

→ *Determine A,B*



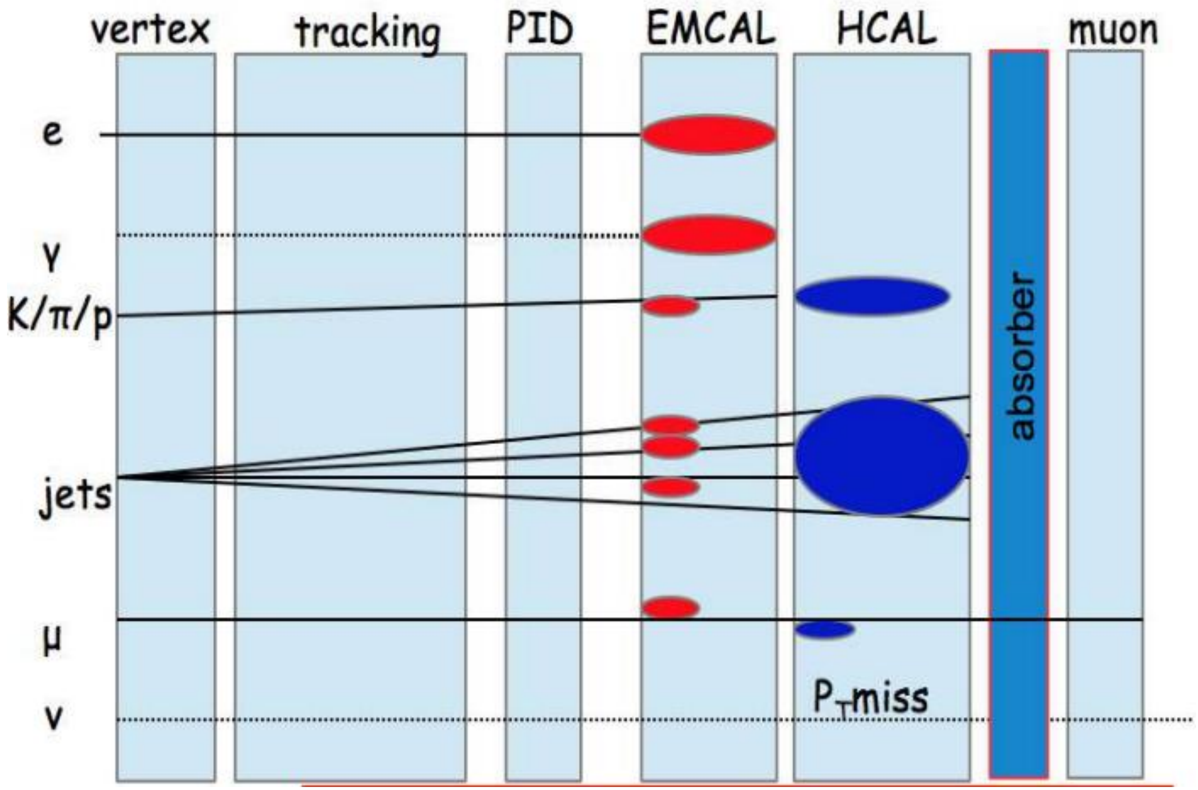
Modern and Future Calorimetry

Energy resolution: attack fluctuations

- ➢Hadronic calorimeters (if not compensating) give the largest contribution to, for example, jet energy resolution.
- ➢If you want to improve performance, reduce/eliminate the (effects of) fluctuations that dominate the performance.
- ➢Two approaches:
  1. Minimize influence of calorimeters through a holistic reconstruction approach -- this is sometimes called the Particle Flow approach (PFA)
  2. Directly measure hadronic shower components for each event, allowing direct access to the source of fluctuations. This is the Dual (Triple) Readout approach from the DREAM collaboration.

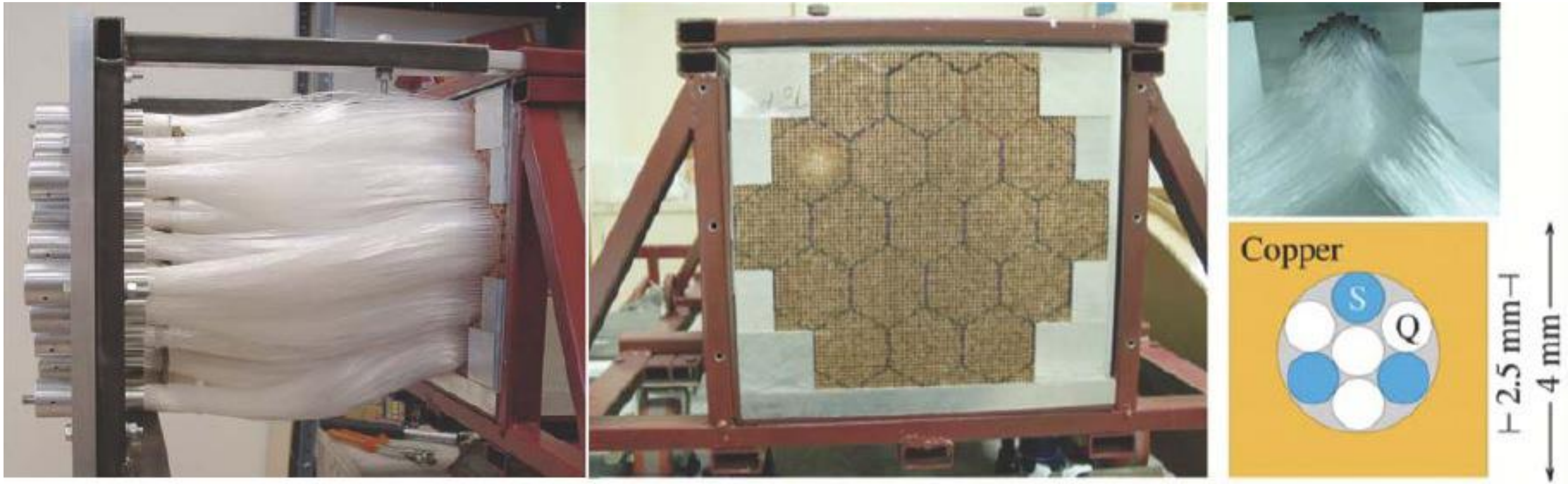
Particle Flow

- Basic idea is to reconstruct charged particles using tracking detectors when they have the best resolution. The tracks are matched to calorimeter clusters and their energy subtracted. Neutral particles are still measured by calorimeters.
- Highly granular calorimeters are needed, as well as sophisticated reconstruction software (software compensation)
- This approach is used in modern high-energy collider experiments



Dual Readout Calorimetry

- Measure EM fraction event-by-event with SPACAL calorimeter consisting of interleaved Quartz (Cherenkov) and Scintillating fibers
- Production of Cherenkov light only by relativistic particles
- The 'DREAM' is to measure jets as accurately as electrons: 15% / $\sqrt{E\ [GeV]}$
- Triple readout approach will also measure neutron component with hydrogenous material



Summary

- ➢Calorimeters are used widely in nuclear and particle physics
- ➢There are a wide variety of calorimeter types to serve specific situations
- ➢The interaction of particles in calorimeters is based on simple physics principles, but, as we have seen, the response of calorimeters can be quite complex
- ➢The future of calorimetry is based on 1) integrating calorimeter response with that of other detectors; and 2) reducing the effects of hadronic shower fluctuations