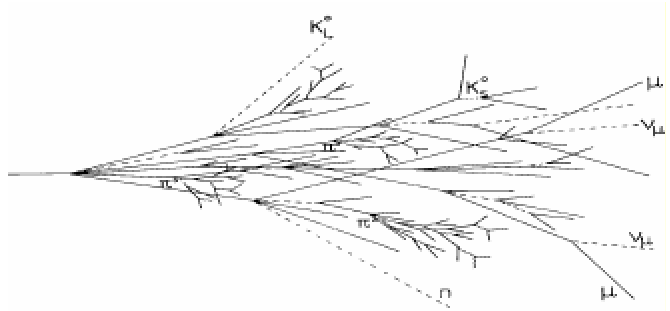
Hadron Calorimeters

Hadronic Showers

- Extra complication: ***The strong interaction*** with detector material
- Importance of calorimetric measurement
  - Charged hadrons: complementary to track measurement
  - Neutral hadrons: the only way to measure their energy

- In nuclear collisions numbers of secondary particles are produced
  - Partially undergo secondary, tertiary *nuclear reactions* ➔ formation of hadronic cascade
  - Electromagnetically decaying particles (π, η) initiate EM showers
  - Part of the energy is absorbed as nuclear binding energy or target recoil (*Invisible energy)*
- Similar to EM showers, but much more complex

  ➔ need simulation tools (MC)
- Different scale: hadronic interaction length



Hadronic Showers

Hadronic interaction:

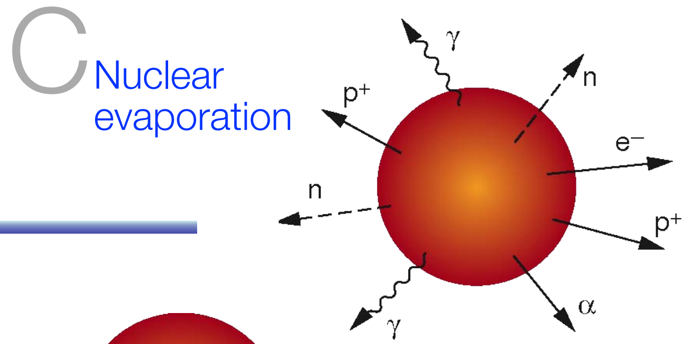
Elastic:

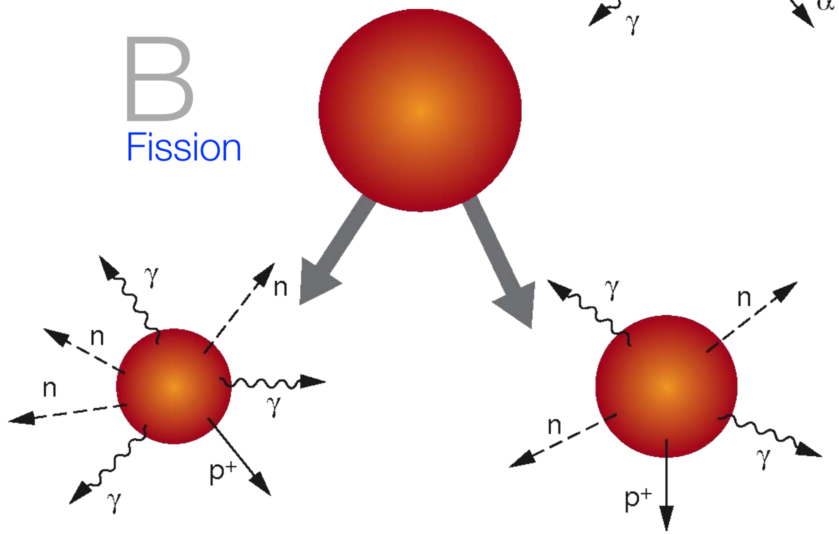
$$p + \mathrm{Nucleus} \rightarrow p + \mathrm{Nucleus}$$

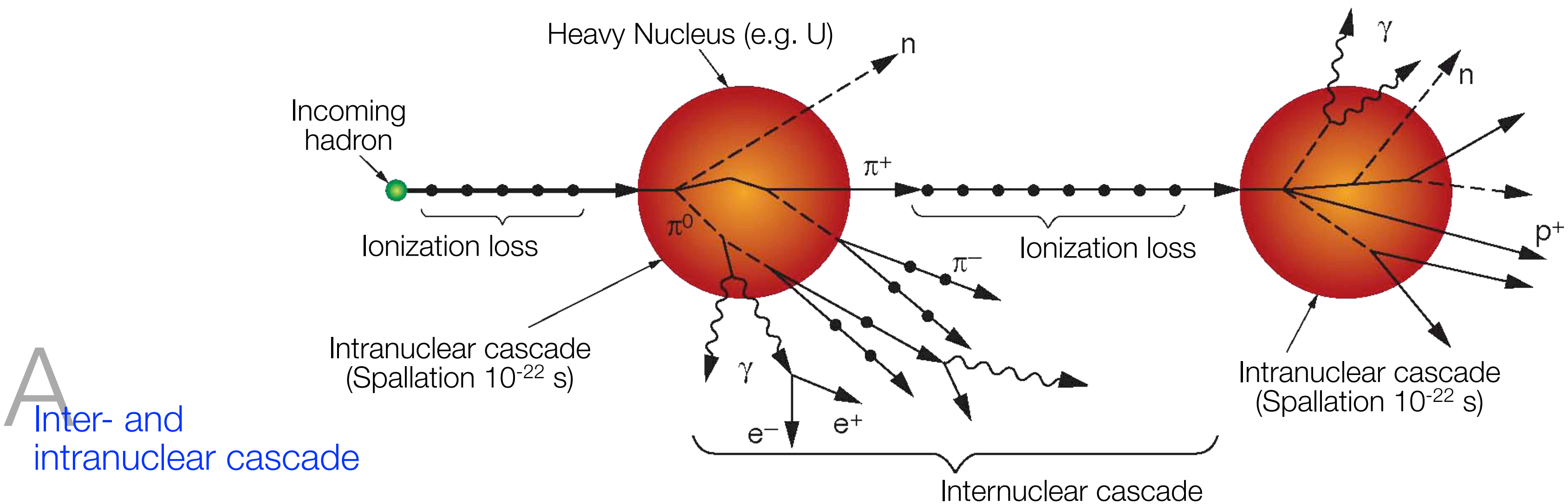
Inelastic:

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

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





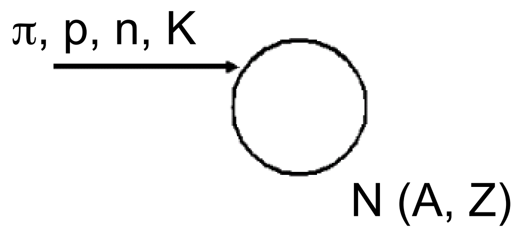


Hadronic Interactions

1st stage: the hard collision

- before first interaction:
  • pions travel 25-50% longer than protons (~2/3 smaller in size)
  • a pion loses ~100-300 MeV by ionization (Z dependent)

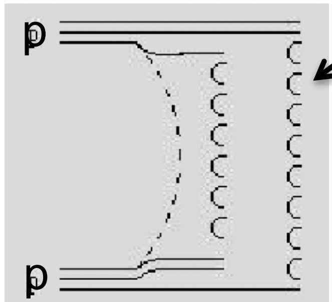
Particle nucleus collision according to cross-sections



– particle multiplication

(one example: string model)

average energy needed to produce a pion 0.7 (1.3) GeV in Cu (Pb)



q-qbar pairs

Nucleon is split in quark di-quark
Strings are formed
String hadronisation (adding qqbar pair)
fragmentation of damaged nucleus

– Multiplicity scales with E and particle type

– ~ 1/3 $\pi^0 \rightarrow \gamma\gamma$ produced in charge exchange processes:

$\pi^+ p \rightarrow \pi^0 n$ / $\pi^- n \rightarrow \pi^0 p$

– Leading particle effect: depends on incident hadron type

e.g fewer π^0 from protons, barion number conservation

Hadronic Interactions

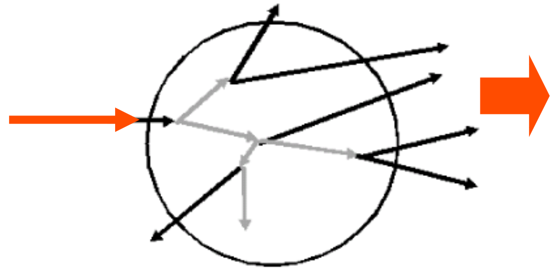
2nd stage: spallation

– Intra-nuclear cascade

Fast hadron traversing the nucleus frees protons and neutrons in number proportional to their numerical presence in the nucleus.

Some of these n and p can escape the nucleus

For $^{208}_{82}Pb$ ~1.5 more cascade n than p



dominating momentum component along incoming particle direction

– The nucleons involved in the cascade transfer energy to the nucleus which is left in an excited state

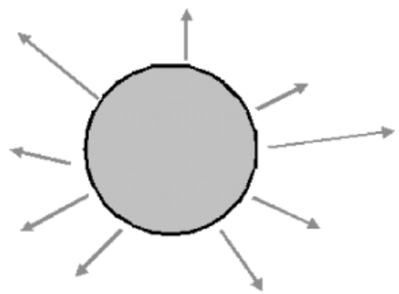
3d stage: Nuclear de-excitation

– Evaporation of soft (~10 MeV) nucleons and α

– + fission for some materials

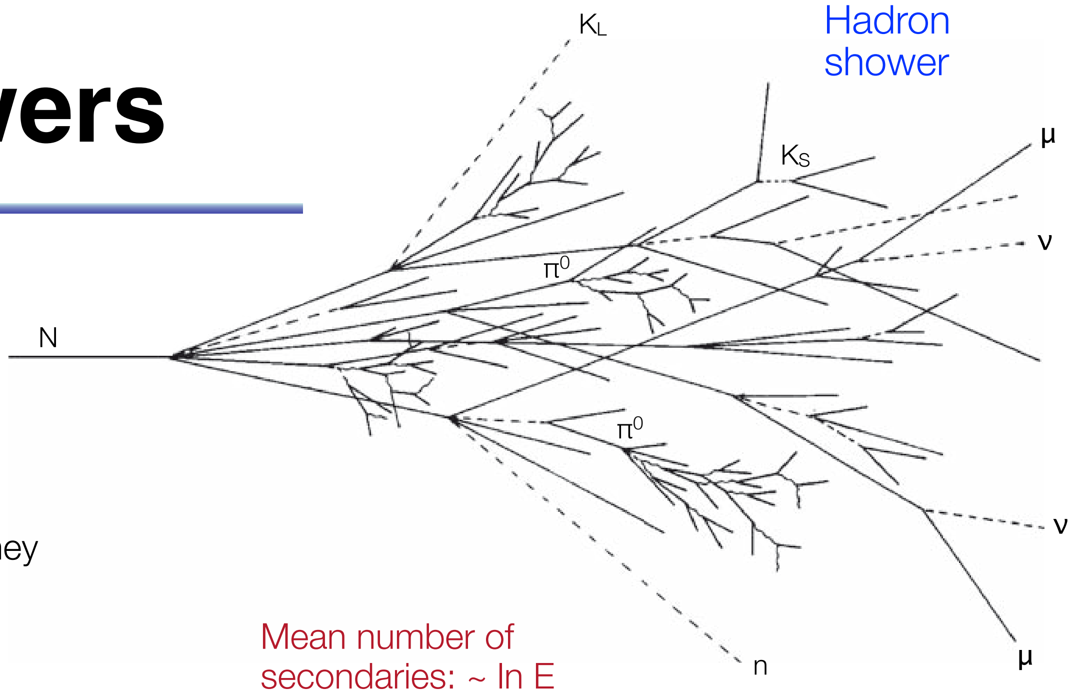
The number of nucleons released depends on the binding E (7.9 MeV in Pb, 8.8 MeV in Fe)

Mainly neutrons released by evaporation ➔ protons are trapped by the Coulomb barrier (12 MeV in Pb, only 5 MeV in Fe)



isotropic process

Hadronic Showers



Shower development:

1. p + Nucleus ➛ Pions + N* + ...
2. Secondary particles ...

   undergo further inelastic collisions until they fall below pion production threshold
3. Sequential decays ...

   π_0 ➛ $\gamma\gamma$: yields electromagnetic shower
   Fission fragments ➛ β-decay, γ-decay
   Neutron capture ➛ fission
   Spallation ...

Mean number of secondaries: ~ ln E

Typical transverse momentum: p_t ~ 350 MeV/c

Substantial electromagnetic fraction

$f_{em} \sim \ln E$

[variations significant]

Cascade energy distribution:
[Example: 5 GeV proton in lead-scintillator calorimeter]

Ionization energy of charged particles (p,π,μ)	1980 MeV [40%]
Electromagnetic shower (π^0,η^0,e)	760 MeV [15%]
Neutrons	520 MeV [10%]
Photons from nuclear de-excitation	310 MeV [6%]
Non-detectable energy (nuclear binding, neutrinos)	1430 MeV [29%]
	5000 MeV

Hadronic vs Electromagnetic Showers

Hadronic vs. electromagnetic interaction length:

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

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

[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 ...

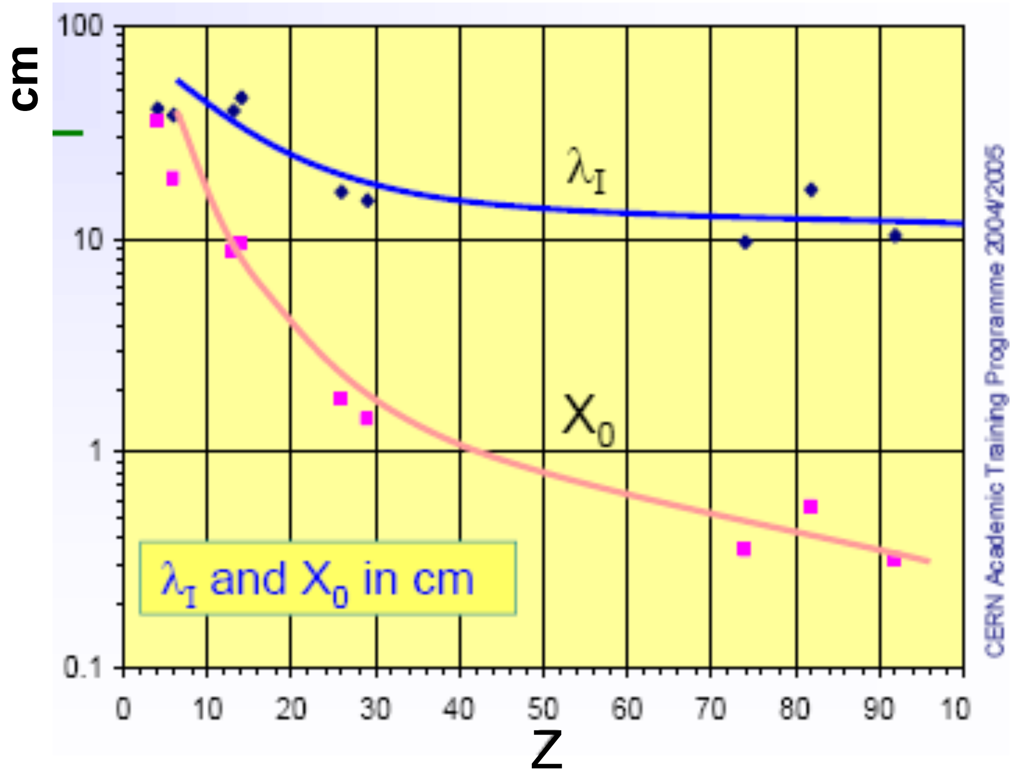
Some numerical values for materials typical used in hadron calorimeters

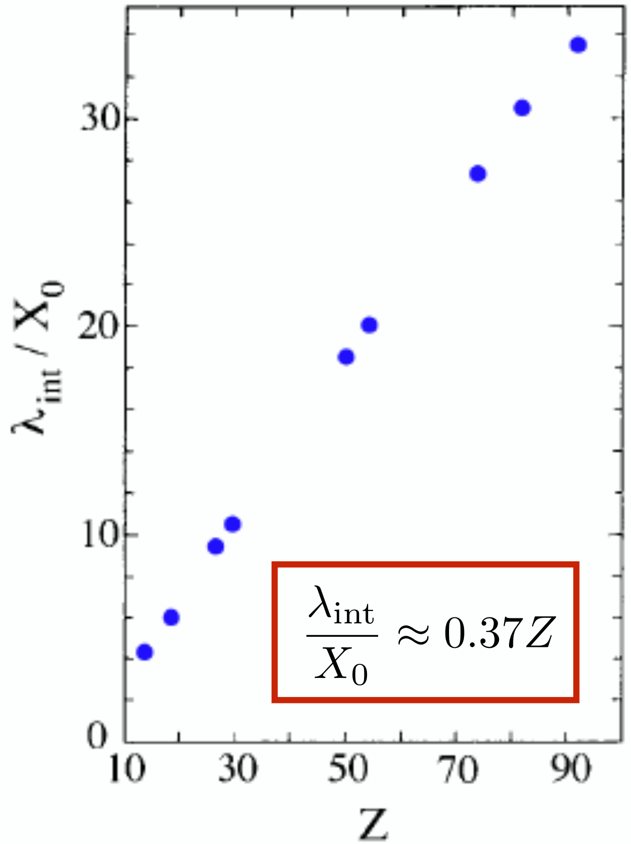
	λ_{int} [cm]	X_0 [cm]
Szint.	79.4	42.2
LAr	83.7	14.0
Fe	16.8	1.76
Pb	17.1	0.56
U	10.5	0.32
C	38.1	18.8

Material Dependence

$\boxed{\lambda_{int}\ (\mathrm{g\ cm^{-2}}) \propto A^{1/3}}$

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





Longitudinal Shower Development

Longitudinal shower development:

Strong peak near λ_{int} ...
followed by exponential decrease ....

Shower depth:

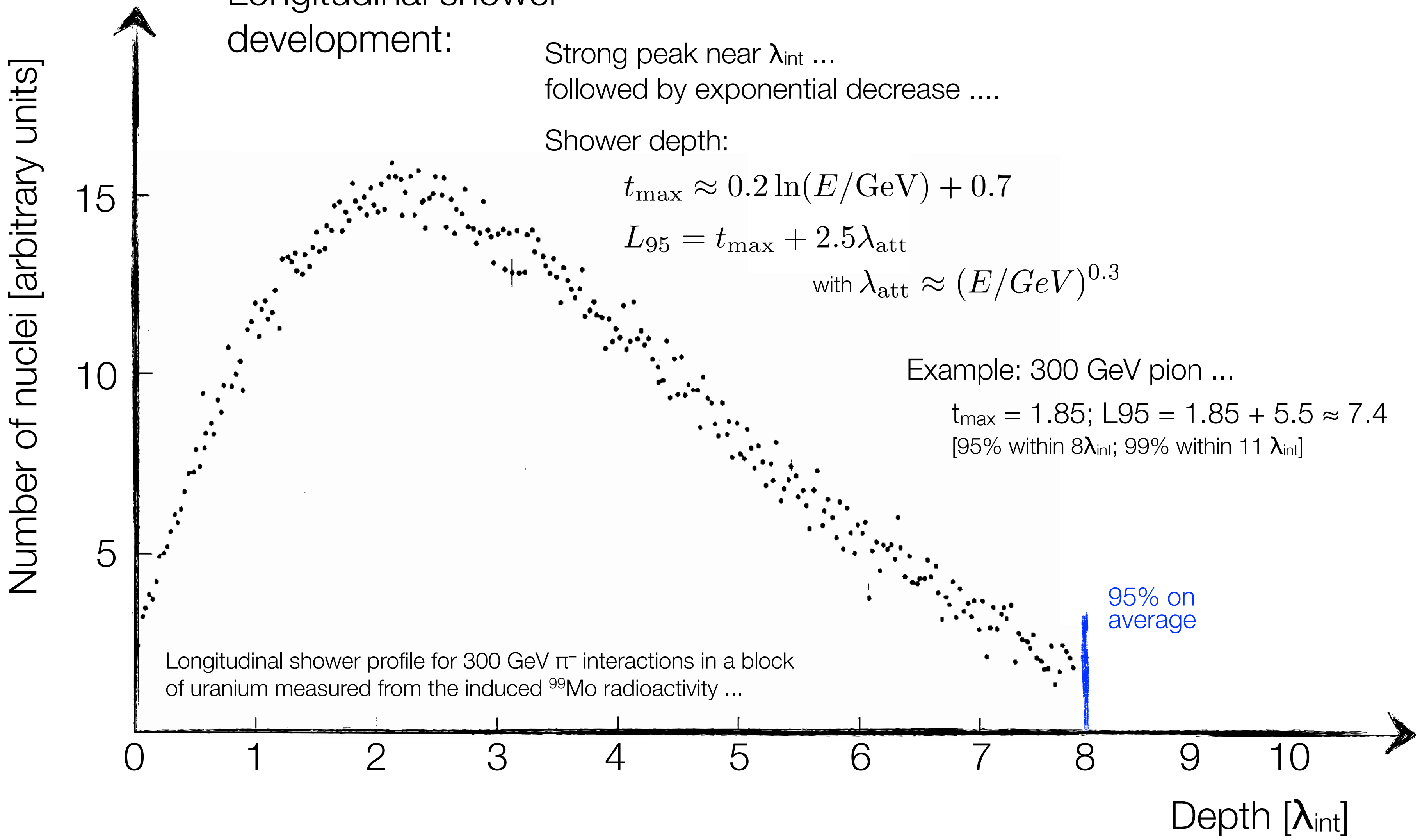
$$t_{max} \approx 0.2 \ln(E/\mathrm{GeV}) + 0.7$$

$$L_{95} = t_{max} + 2.5\lambda_{att}$$

with $\lambda_{att} \approx (E/GeV)^{0.3}$

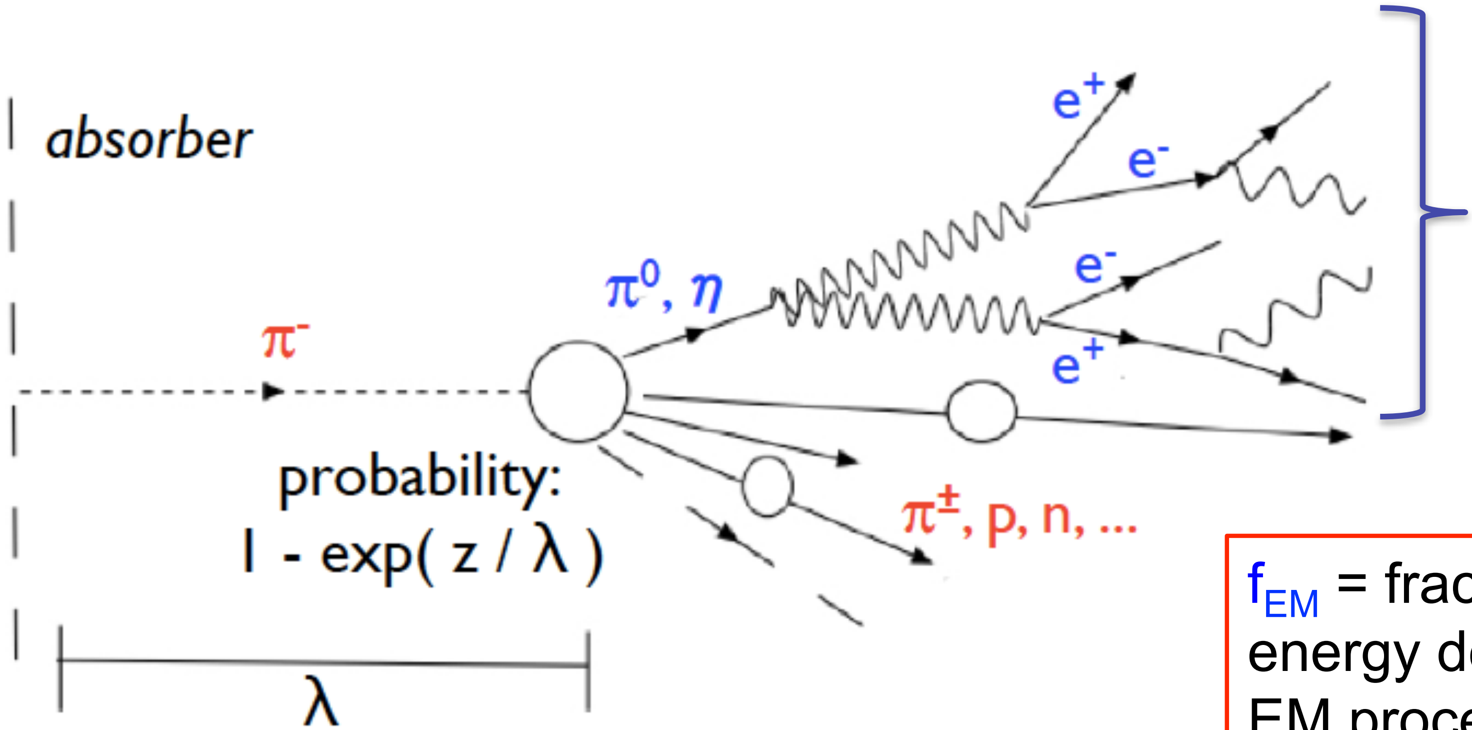
Example: 300 GeV pion ...

t_{max} = 1.85; L95 = 1.85 + 5.5 ≈ 7.4
[95% within 8λ_{int}; 99% within 11 λ_{int}]



Longitudinal shower profile for 300 GeV π^- interactions in a block of uranium measured from the induced ^{99}Mo radioactivity ...

Electromagnetic Fraction



π_0 production is a one way street: all energy deposited via EM processes

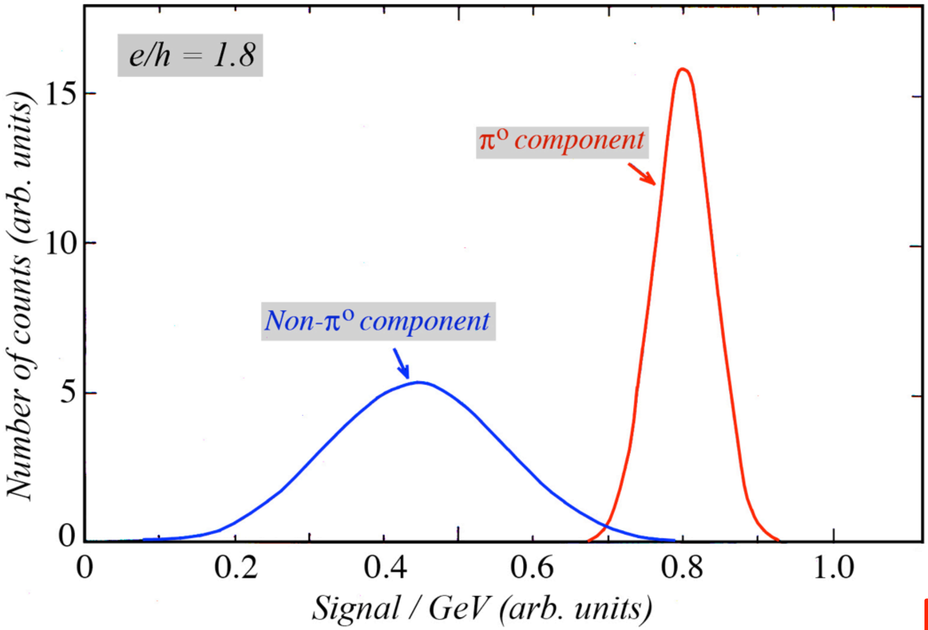
f_{EM} = fraction of hadron energy deposited via EM processes

Electromagnetic → ionization, excitation (e±)
→ photo effect, scattering (γ)

Hadronic → ionization (π±, p)
→ invisible energy (binding, recoil)

Electromagnetic Fraction

The origin of the non-compensation problems



Charge conversion of $\pi^{+/-}$ produces electromagnetic component of hadronic shower (π^0)

e = response to the EM shower component

h = response to the non-EM component

Response to a pion initiated shower:

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

Comparing pion and electron showers:

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

Calorimeters can be:

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

e/h and e/π

e/h: not directly measurable ➔ give the degree of non-compensation

e/π: ratio of response between electron-induced and pion-induced shower

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

e/h is energy independent

e/π depends on E via $f_{em}(E)$ ➔ non-linearity

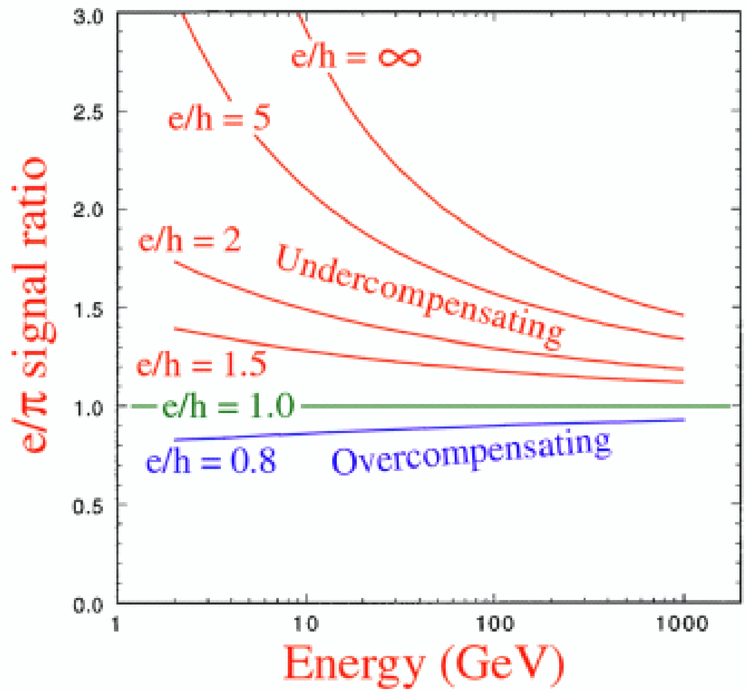
$f_{em}(E)$ approximately follows a power law:

$$\boxed{f_{\rm em} \approx 1 - \left(1 - \frac{1}{3}\right)^n \approx 1 - \left(\frac{E}{E_0}\right)^{k-1}}$$

Approaches to achieve compensation:

e/h → 1 right choice of materials or

f_{em} → 1 (high energy limit)



Hadronic Response

- Energy deposition mechanisms relevant for the absorption of the non-EM shower energy:
- Ionization by charged pions f_{rel} (Relativistic shower component).
- spallation protons f_p (non-relativistic shower component).
- Kinetic energy carried by evaporation neutrons f_n
- The 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 expressed 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 mip:

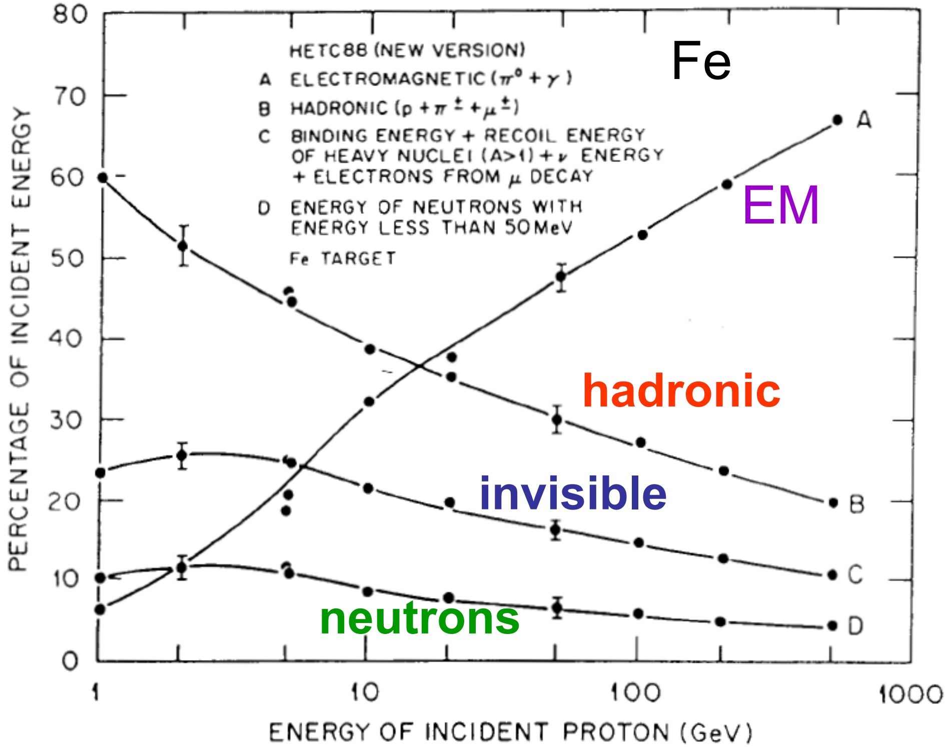
$$\boxed{\frac{e}{h} = \frac{e/mip}{f_{rel} \cdot rel/mip + f_p \cdot p/mip + f_n \cdot n/mip}}$$

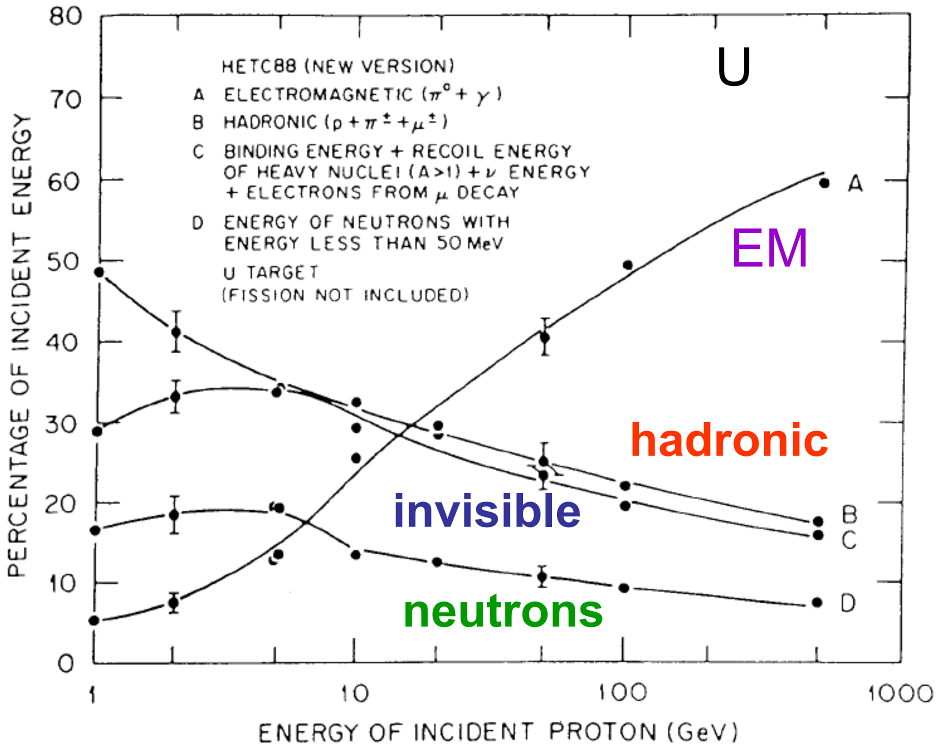
The e/h value can be determined once we know the calorimeter response to the three components of the non-em shower

Hadronic Shower Energy Fractions

$$E_p = \underline{f_{em}}\, e + (1 - f_{em})\, h$$

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





Fluctuations

- Same types of fluctuations as in EM showers, plus:
- 1) Fluctuations in visible energy
  (ultimate limit of hadronic energy resolution)
- 2) Fluctuations in the EM shower fraction, f_{em}
  – Dominating effect in most hadron calorimeters (e/h >1)
  – Fluctuations are asymmetric in pion showers (one-way street)
  – Differences between p, π induced showers
  No leading π^0 in proton showers (barion # conservation)

$$E_p = \underline{f_{em}} e + (1 - f_{em}) h$$

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

Sampling Fluctuations

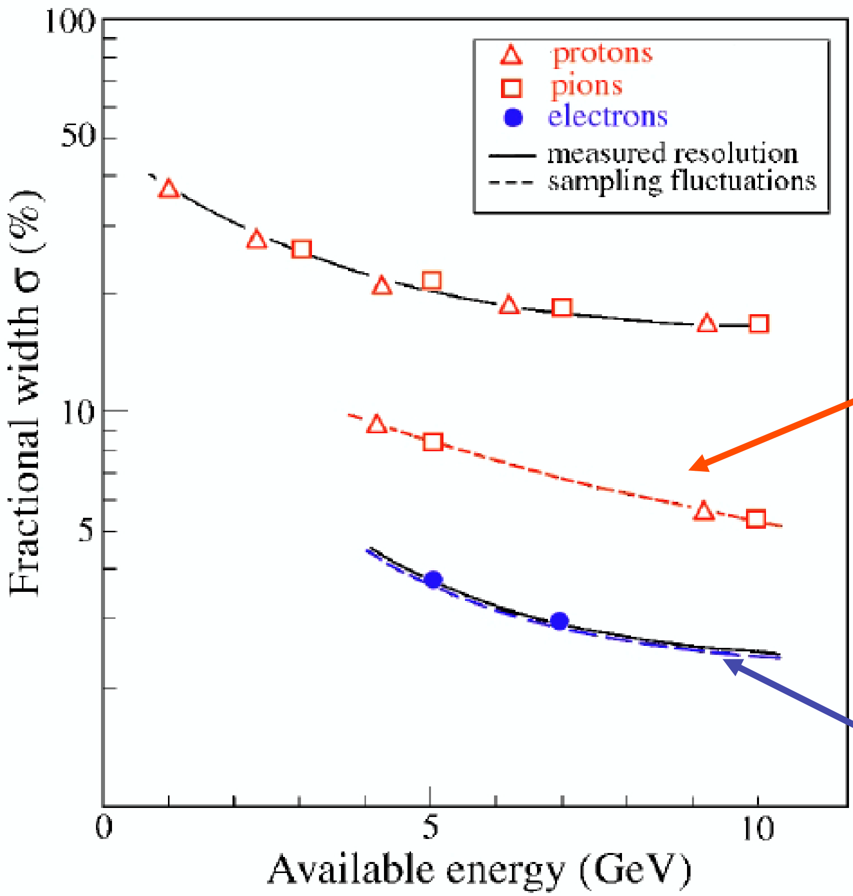


FIG. 4.15. The energy resolution and the contribution from sampling fluctuations to this resolution measured for electrons and hadrons, in a calorimeter consisting of 1.5 mm thick iron plates separated by 2 mm gaps filled with liquid argon. From [Fab 77].

sampling fluctuations only minor contribution to hadronic resolution in non-compensating calorimeter

EM resolution dominated by sampling fluctuations

A Typical Calorimetric System

Typical Calorimeter: two components ...

Electromagnetic (EM) +
Hadronic section (Had) ...

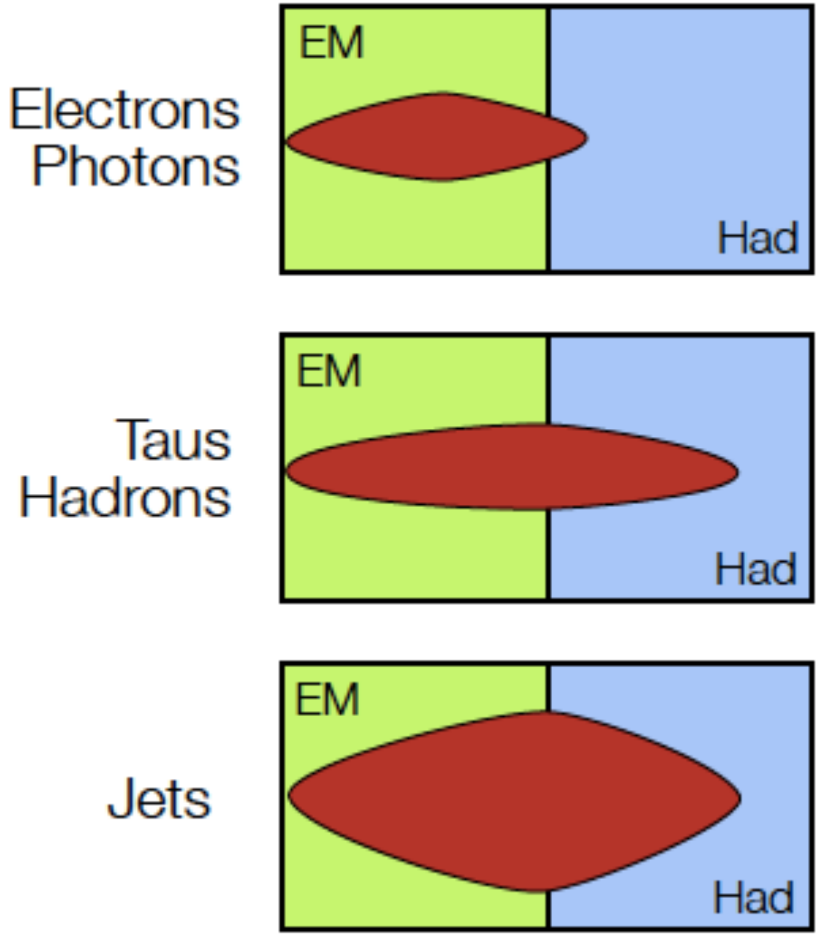
Different setups chosen for
optimal energy resolution ...

But:

Hadronic energy measured in
both parts of calorimeter ...

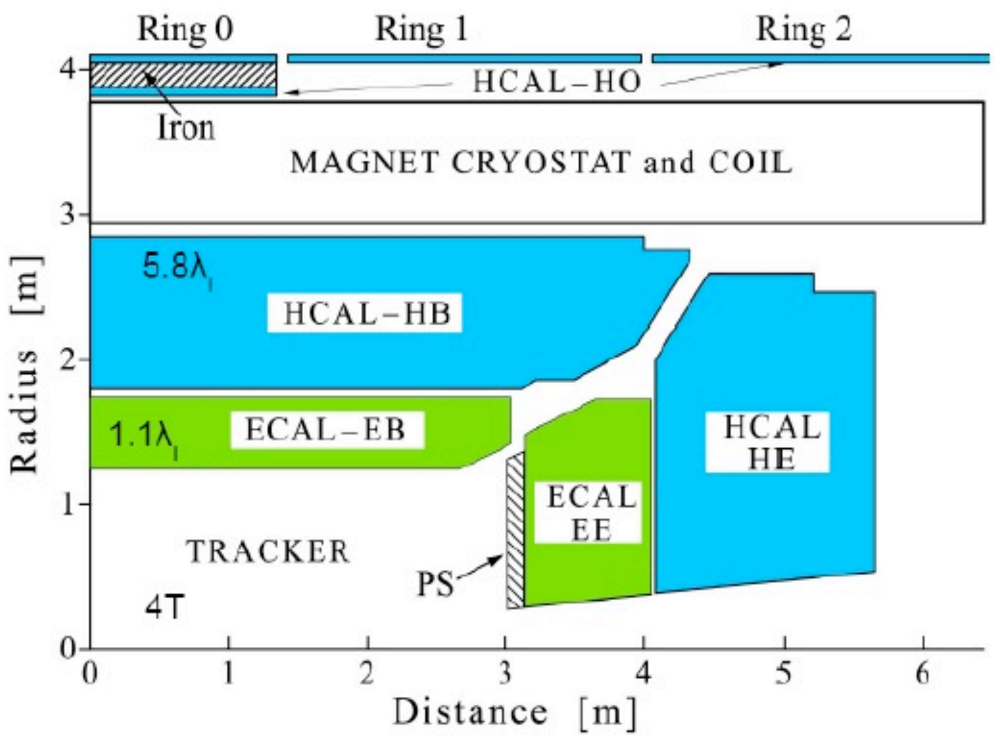
Needs careful consideration of
different response ...

Schematic of a
typical HEP calorimeter



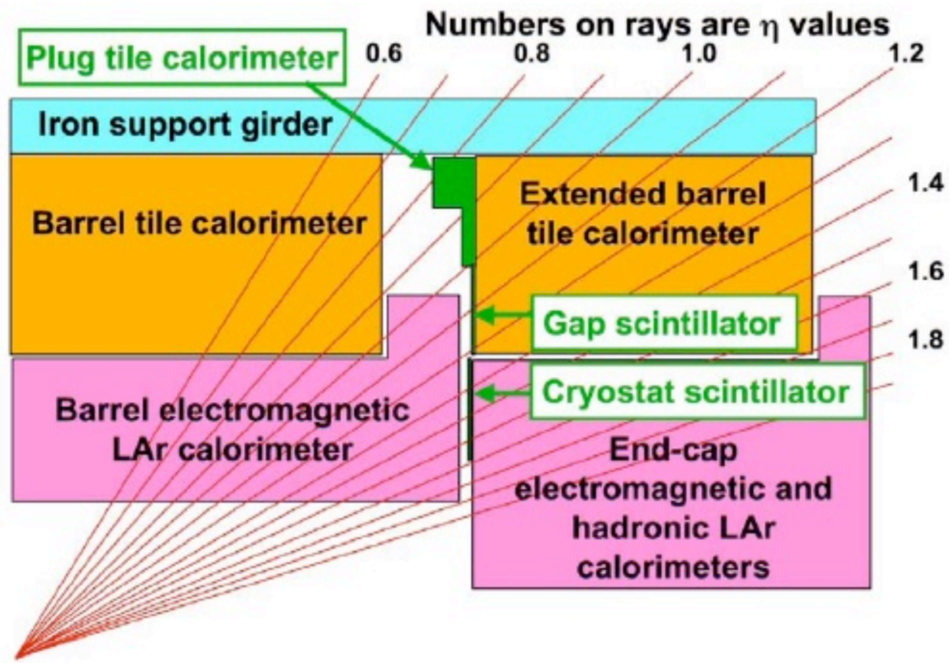
The CMS and ATLAS Calorimeters

CMS



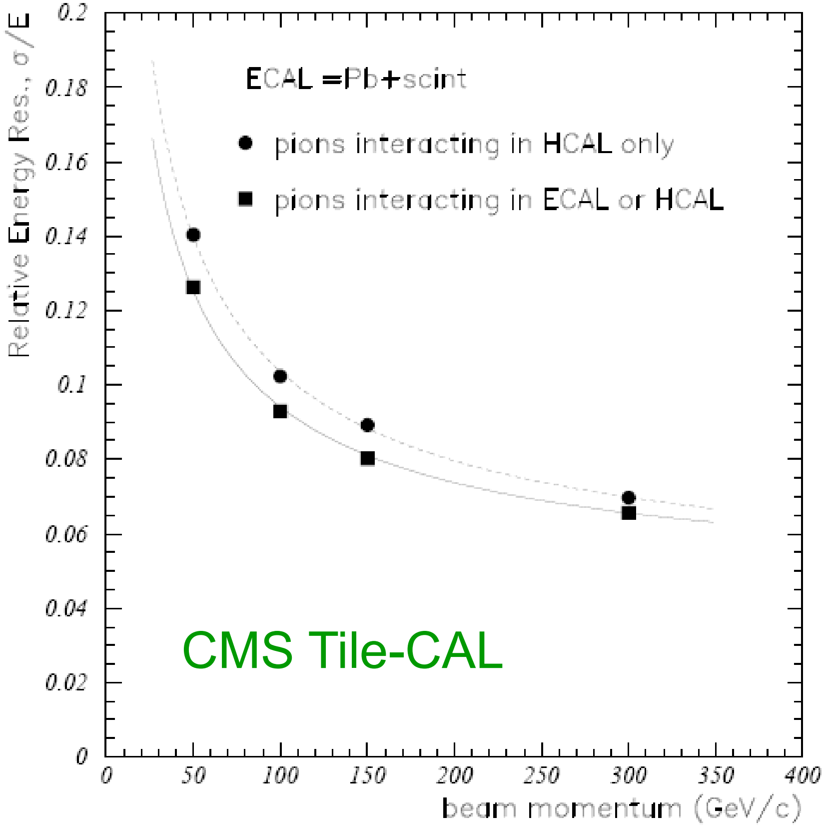
5 cm brass / 3.7 cm scint.
Embedded fibres, HPD readout

ATLAS



14 mm iron / 3 mm scint.
sci. fibres, read out by phototubes

The CMS and ATLAS Calorimeters



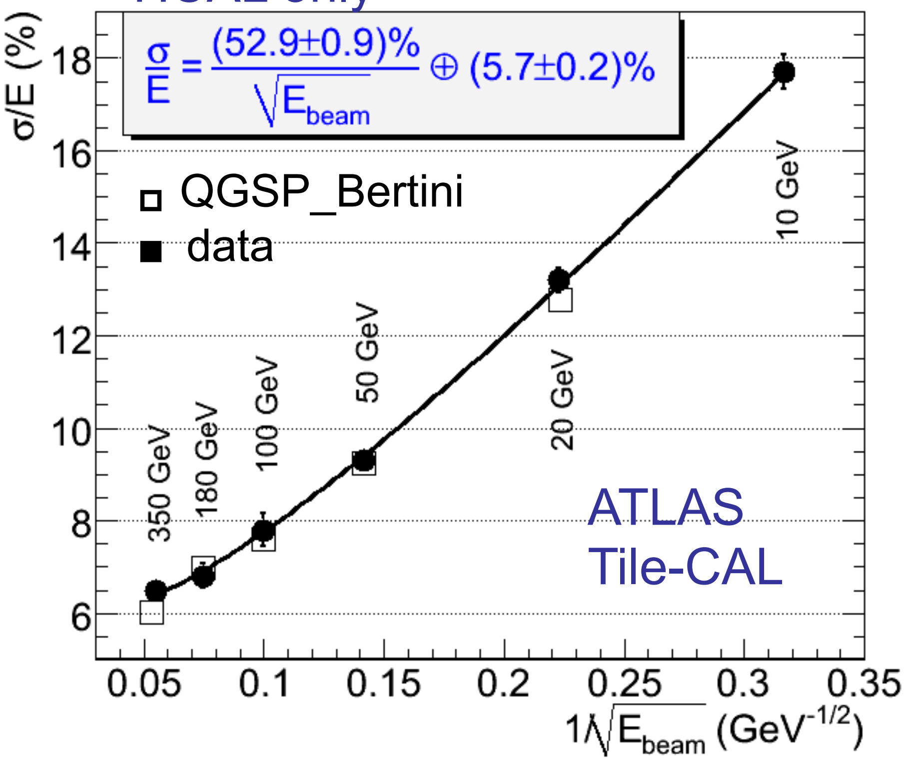
HCAL only

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

ECAL+HCAL

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

HCAL only



Improved resolution using full calorimetric system (ECAL+HCAL)

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