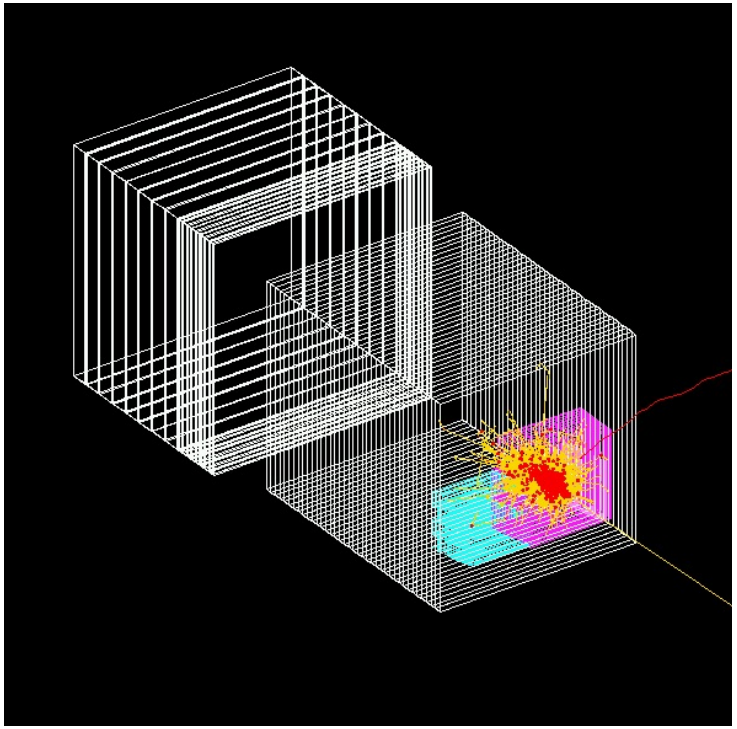
Chapter 2

Interactions of hadrons and hadronic showers

Comparison Electromagnetic shower – Hadronic shower

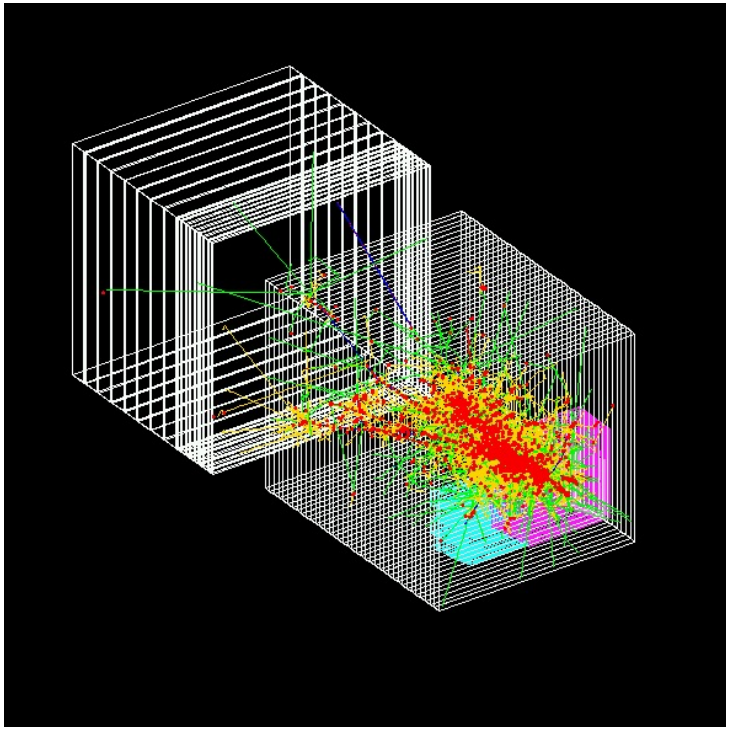
Elm. shower



Characterized by
Radiation Length: $X_0 \propto \frac{A}{Z^2}$

$$\frac{\lambda_{\text{int}}}{X_0} = \frac{A^{1/3}Z^2}{A} \propto A^{4/3} \Rightarrow R_M \propto \frac{21MeV}{\varepsilon_c} \bullet X_0$$

Hadronic shower



Characterized by
Interaction Length: $\lambda_{\text{int}} = \frac{A}{\sigma_{pN} A^{2/3} L\rho} \propto A^{1/3}$

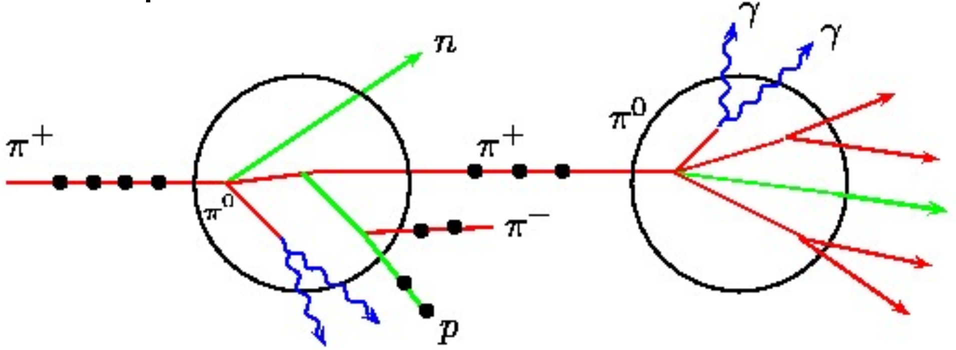
$\text{Size}_{\text{Hadronic Showers}} >> \text{Size}_{\text{elm. Showers}}$

Hadronic showers

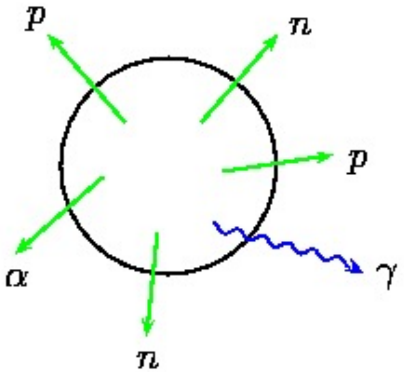
Hadronic Showers are dominated by strong interaction !

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

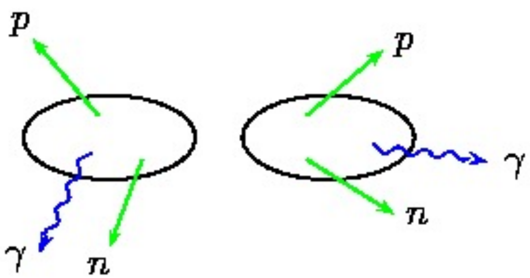
1st Step: Intranuclear Cascade



2nd Step: Highly excited nuclei Evaporation



Fission followed by Evaporation



Distribution of Energy
Example 5 GeV primary energy

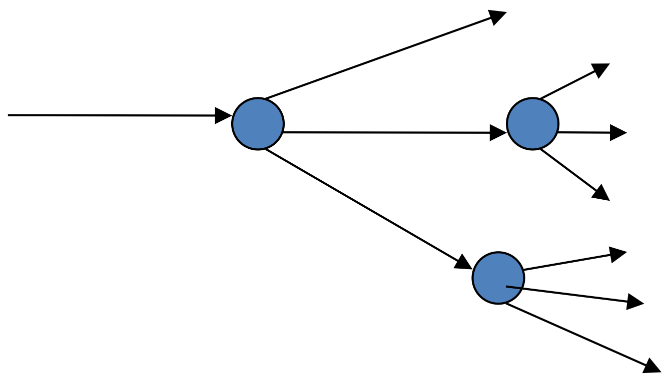
- Ionization Energy of charged particles	1980 MeV
- Electromagnetic Shower (by $\pi^0 \to \gamma\gamma$)	760 MeV
- Neutron Energy	520 MeV
- g by Excitation of Nuclei	310 MeV
- Not measurable E.g. Binding Energy	1430 MeV
	5000 MeV

Distribution and local deposition of energy varies strongly
Difficult to model hadronic showers
e.g. GEANT4 includes O(10) different Models

Further Reading:
R. Wigmans et al. NIM A252 (1986) 4
R. Wigmans NIM A259 (1987) 389

Detailed look into hadronic showers I

...the electromagnetic component



Simplified model - only π produced

π' s are isotriplett π' s are produced democratically in each nuclear interaction

$\pi^0 \to \gamma\gamma$ electromagnetic component f_{em}
f_{em} = 0.33 after 1st interaction
f_{em} = 0.33x2/3 + 1/3 = 0.55 after 2nd ia

After n generations of interactions

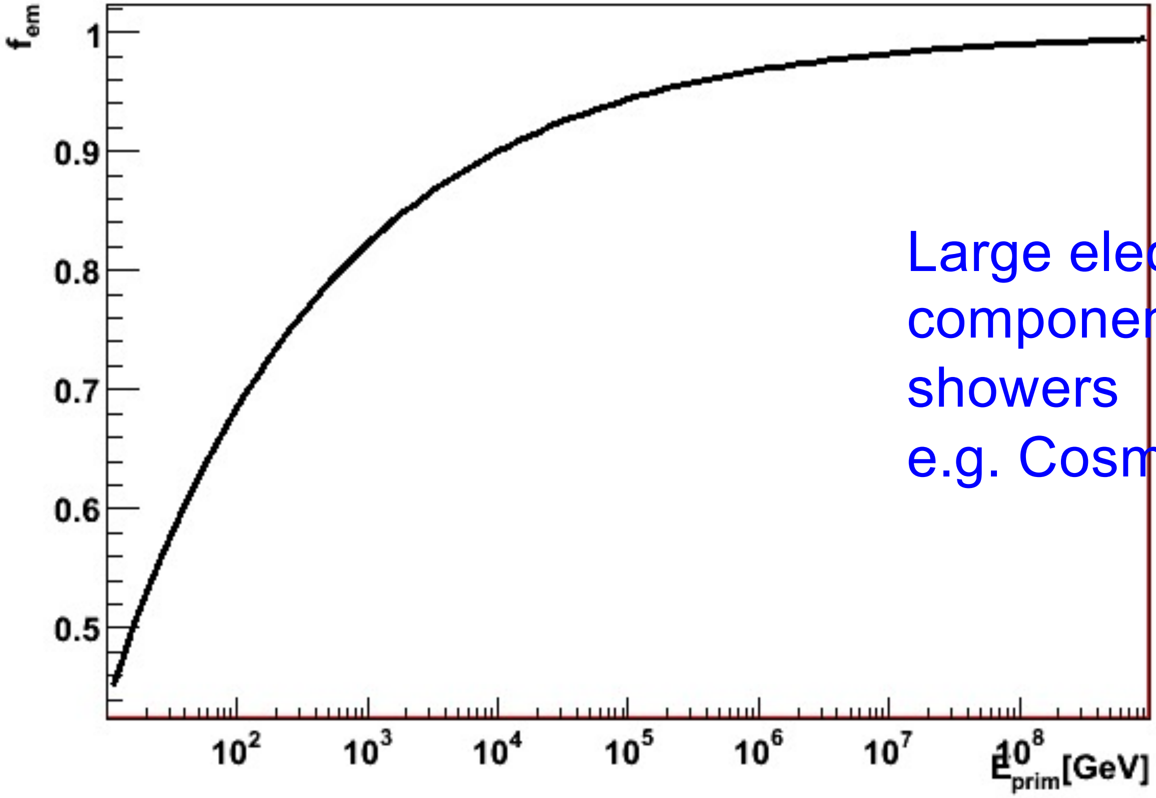
$$f_{\pi^0} = f_{em} = 1 - \left(1 - \frac{1}{3}\right)^b$$

Electromagnetic Component increases with increasing energy of primary particle

f_{em} as function of energy

Reality: $f_{em} = 1 - \langle m \rangle^{n(k-1)}$

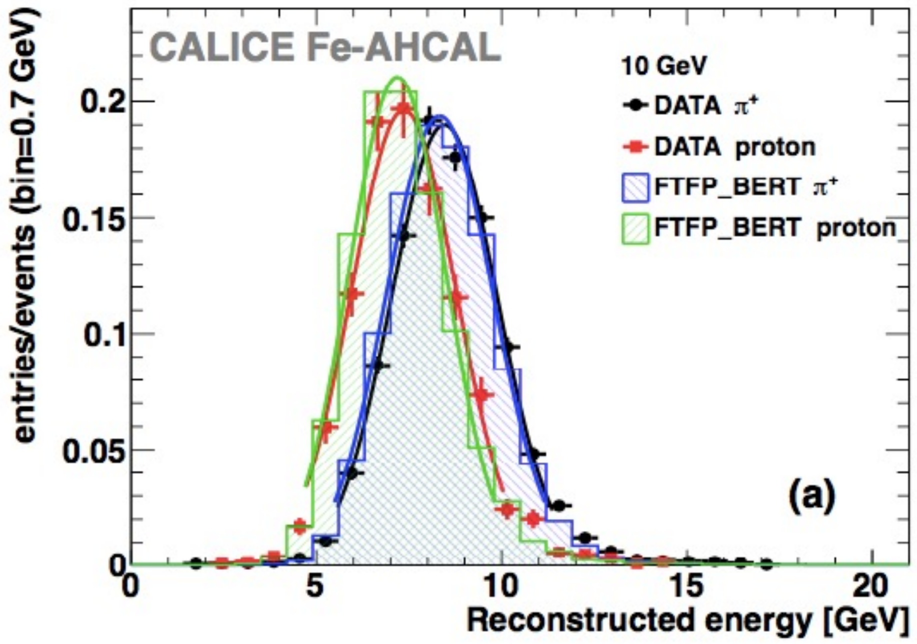
<m> Average multiplicity per interaction
n Number of Generations
k Slope Parameter

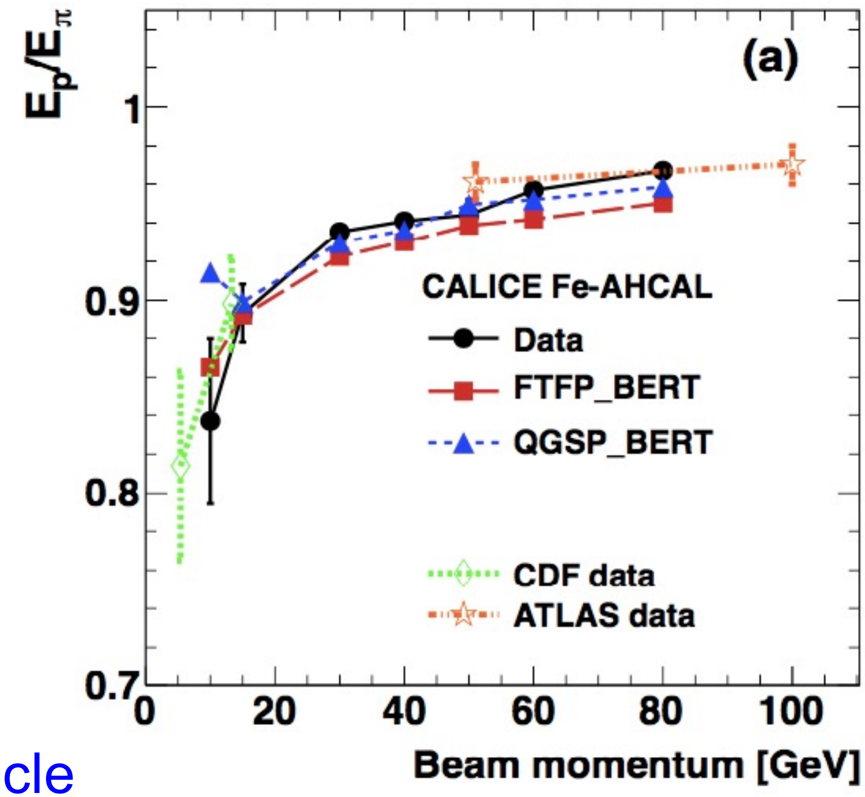


Large electromagnetic component in high energetic showers
e.g. Cosmic Air Showers

Attention - Production of π^0 ist statistical process
At small energies: Small multiplicity
Large statistical fluctuations in production of π 'species'
$\Rightarrow$Large fluctuations of electromagnetic component of shower

Differences Protons - Pions





Smaller signal if proton is primary particle

Proton is Baryon

Baryonnumber conservation favors production of baryons in cascade and suppresses meson i.e. π^0 production

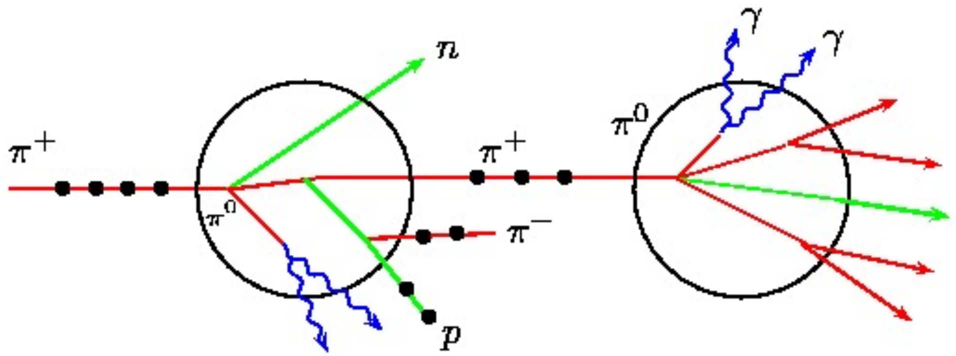
Different Detector response to different particles

Difficult to calibrate calorimeters w.r.t hadronic responce

Hadronic showers – The nuclear sector

Spallation reaction → Internuclear cascade
→ Evaporation by excited nucleon

1) Internuclear cascade



Nucleus as
Mini Calorimeter

- Interaction of incoming hadron with quasi free nucleons
- Strucked high energetic nucleons can escape the nucleon

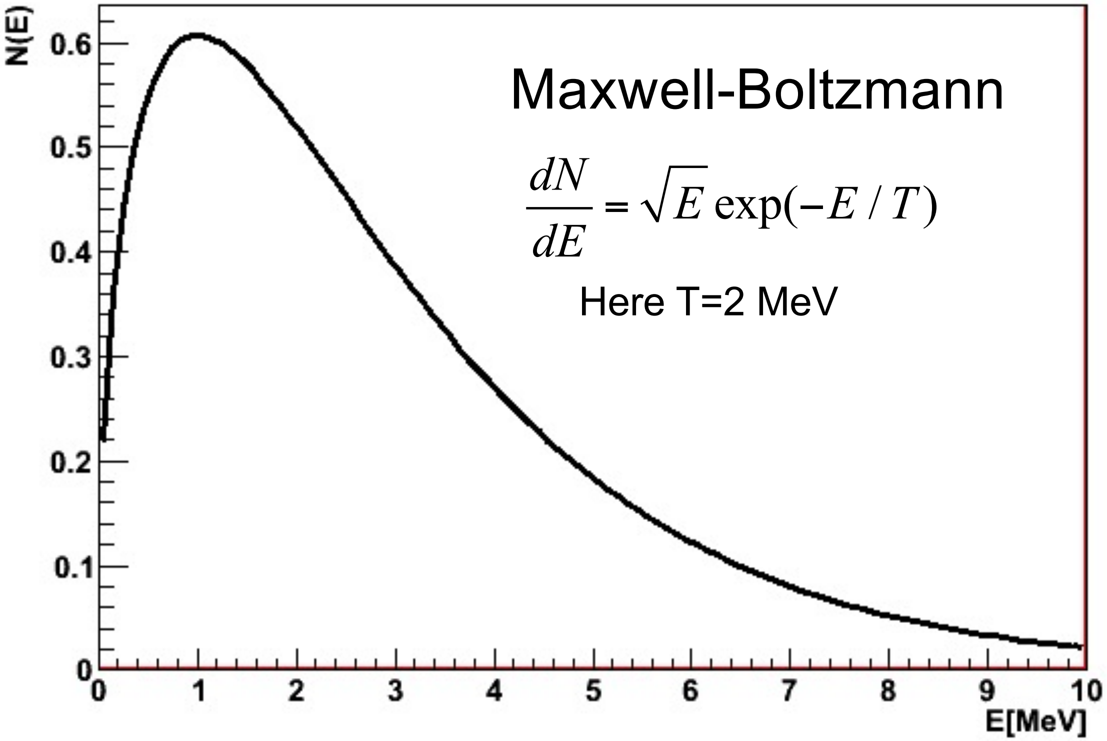
=> Fast Shower Component

- Nucleon with less energy remain bound in nucleus
- Nucleus is left in excited state

Dexcitation by Radiation of nucleons - Evaporation

Evaporation neutrons

Nearly all evaporated nucleons are soft neutrons
Dexcitation happens ~ns after nuclear interaction
Soft or slow component of hadronic shower



Kinetic energy: Evaporated neutrons have on average 1/3 of nuclear binding energy

Number of neutrons produced in nuclear cascades are large

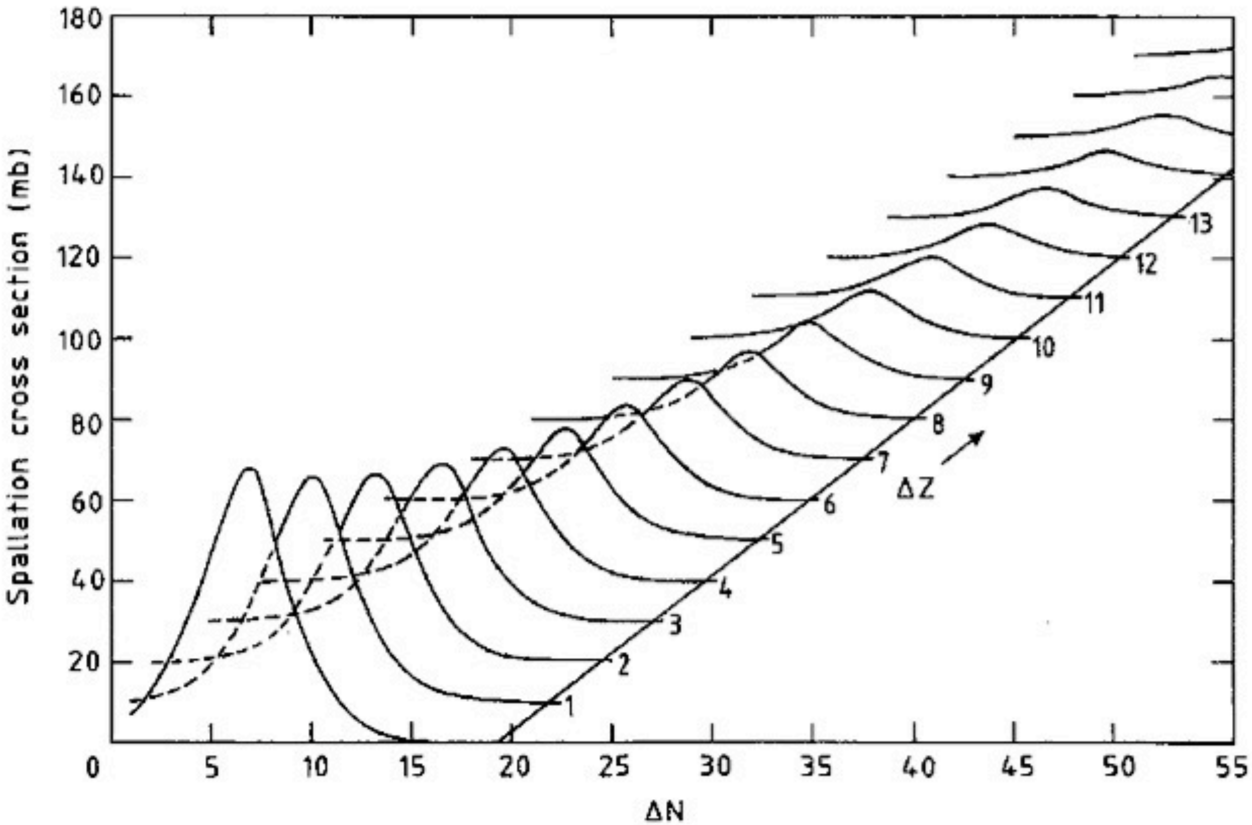
Some numbers: 20 Neutrons/GeV in Pb

60 Neutrons/GeV in ^{238}U, slow or thermalized neutrons induce nuclear fission by neutron capture

Analysis of spallation nucleons I

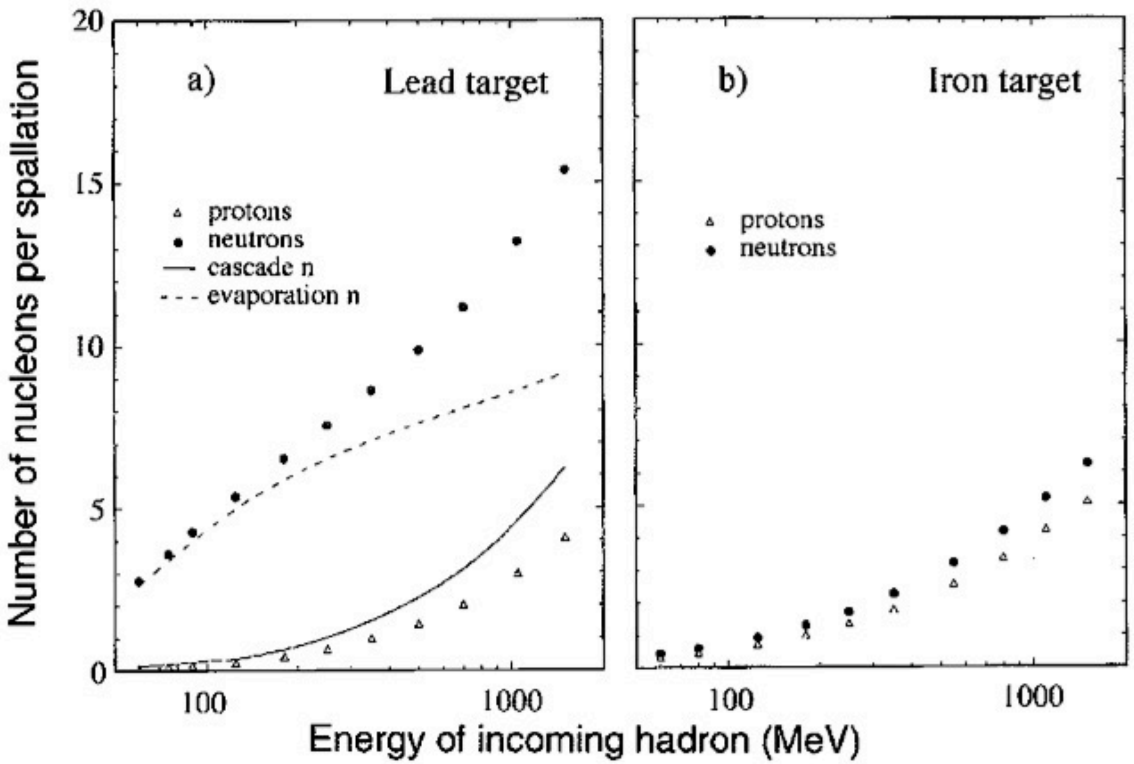
Empirical formular by Rudstam for spallation cross section

$$\sigma(Z_f, A_f) \sim \exp\left[-P(A_T - A_f) \times \exp\left[-R\left|Z_f - SA_f + TA_f^2\right|^{3/2}\right]\right]$$



Even the largest Partial cross section contributes only 2% to total spallation cross section

Analysis of spallation nucleons II



Striking difference in Pb

Protons cannot pass

Coulomb barrier ~12 MeV

Fe has lower Coulomb barrier

$\Rightarrow (n/p)_{Pb} >> (n/p)_{Fe}$

Binding energy of Pb < Binding energy of Fe

Protons loose energy between interactions due to ionization

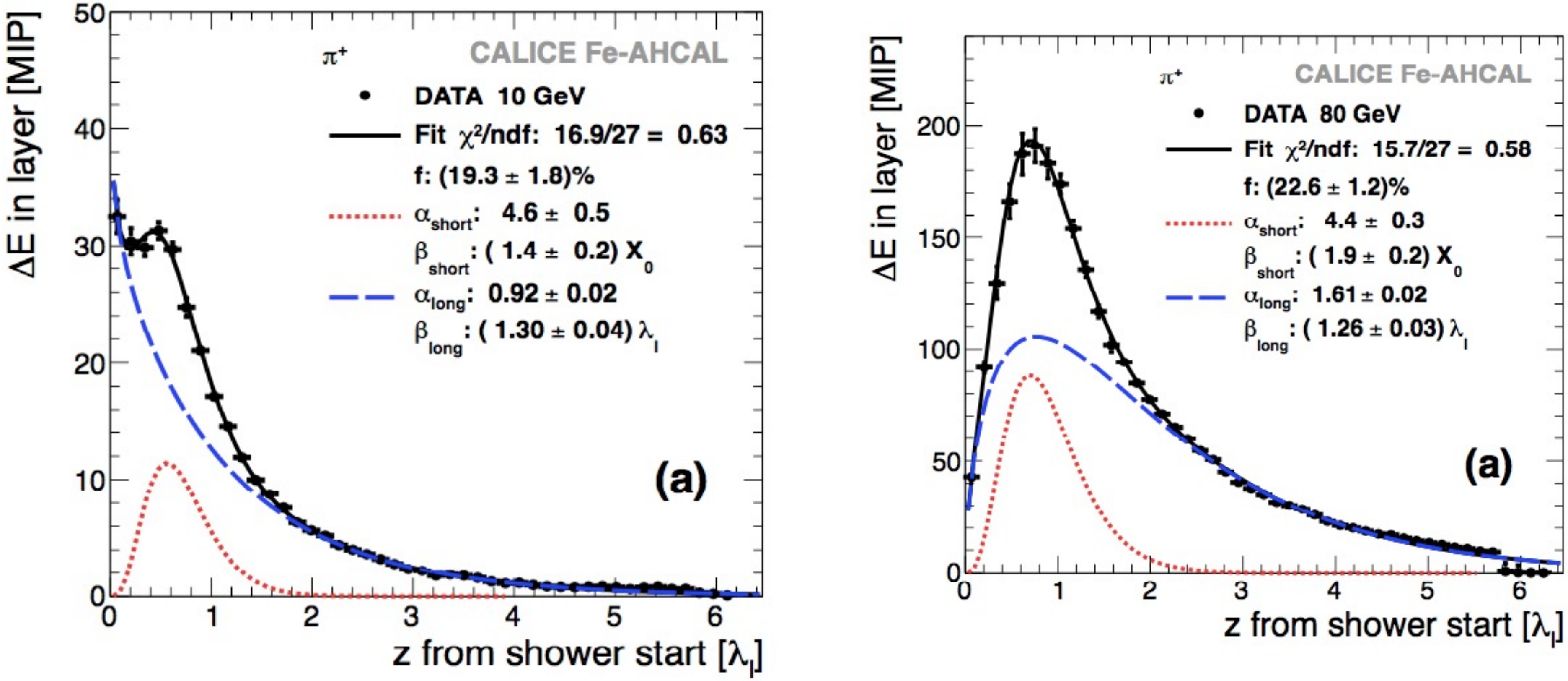
Smaller contribution to nuclear reactions

on average more neutrons in Pb

$\Rightarrow$ More nucleons in 'Pb' cascades

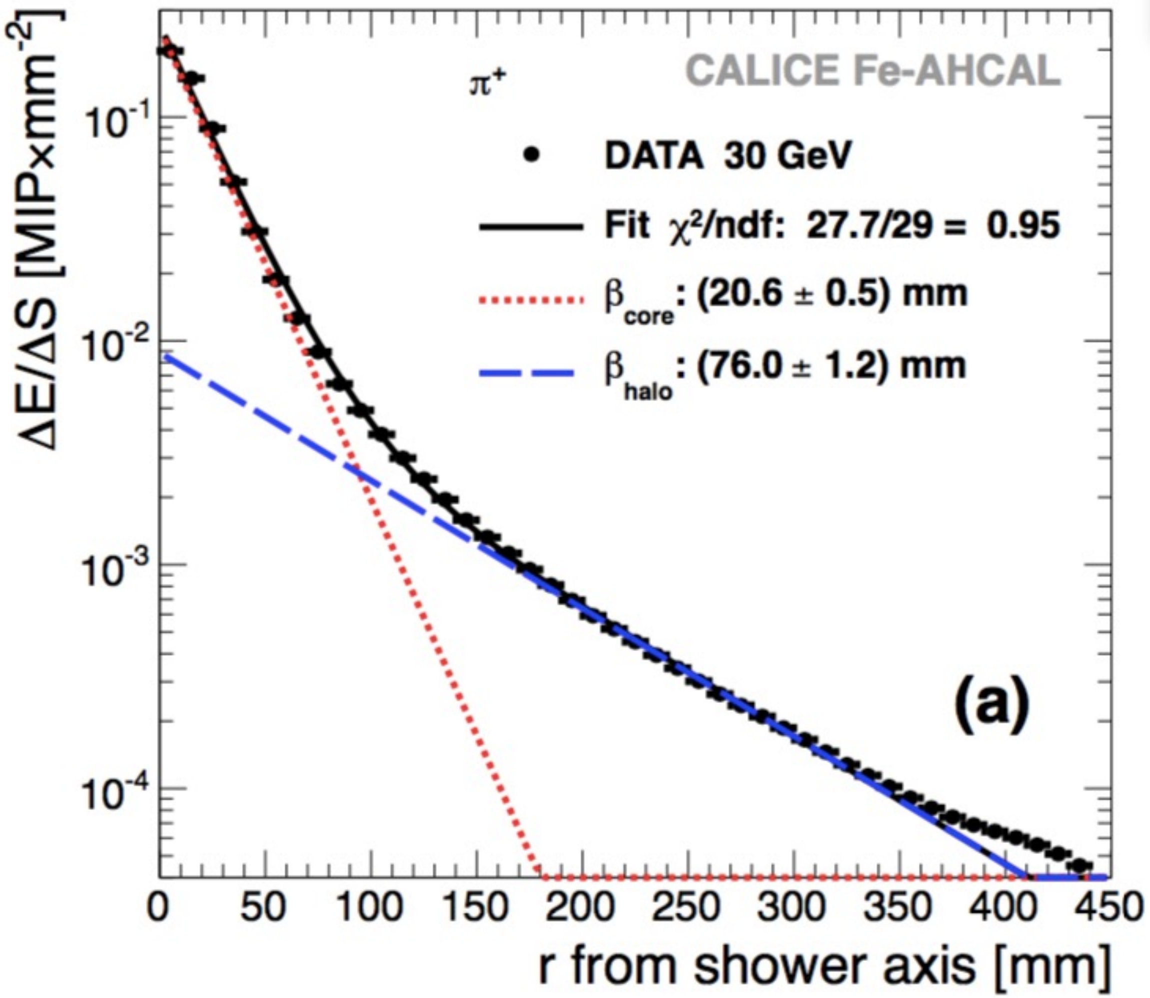
Longitudinal shower profiles

Detailed analysis of hadronic showers with modern granular calorimeters



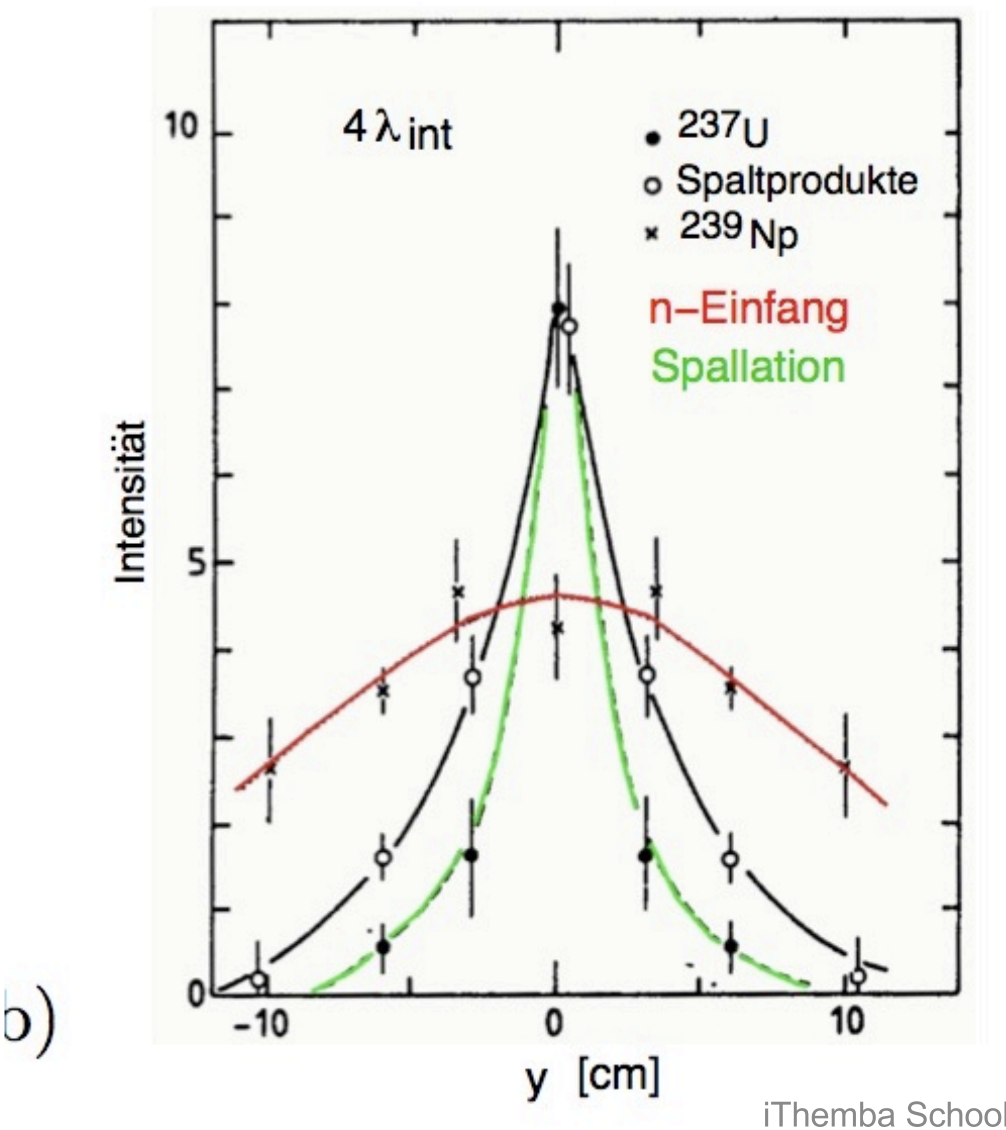
Shower extension much larger than for elm. Showers
Small energies: “Separation” of short and long shower component
High energies: Superposition of short and long shower component
Shape similar to electromagnetic showers

Transversal shower profile



- Narrow core due to electromagnetic component
- Exponentially decreasing halo from non-elm. component

Decomposition of transversal shower profile



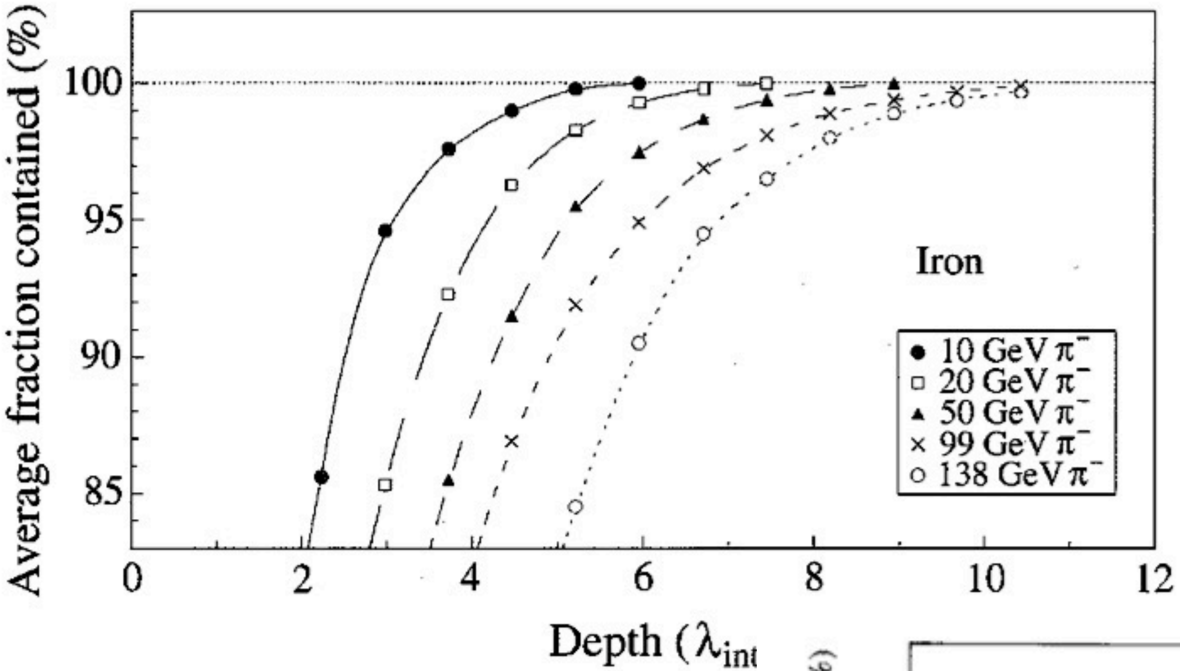
Profile deduced from radioactivity at 4 λ_{int}

^{237}U created by ^{238}U(γ,n)^{237}U
i.e. by fast compenent
close to the shower axis

Fission products i.e. ^{99}Mo
created by MeV type
evaporation neutrons

^{239}Np created by ^{238}U after
capture of thermalized (evaporation)
neutrons

Shower containment

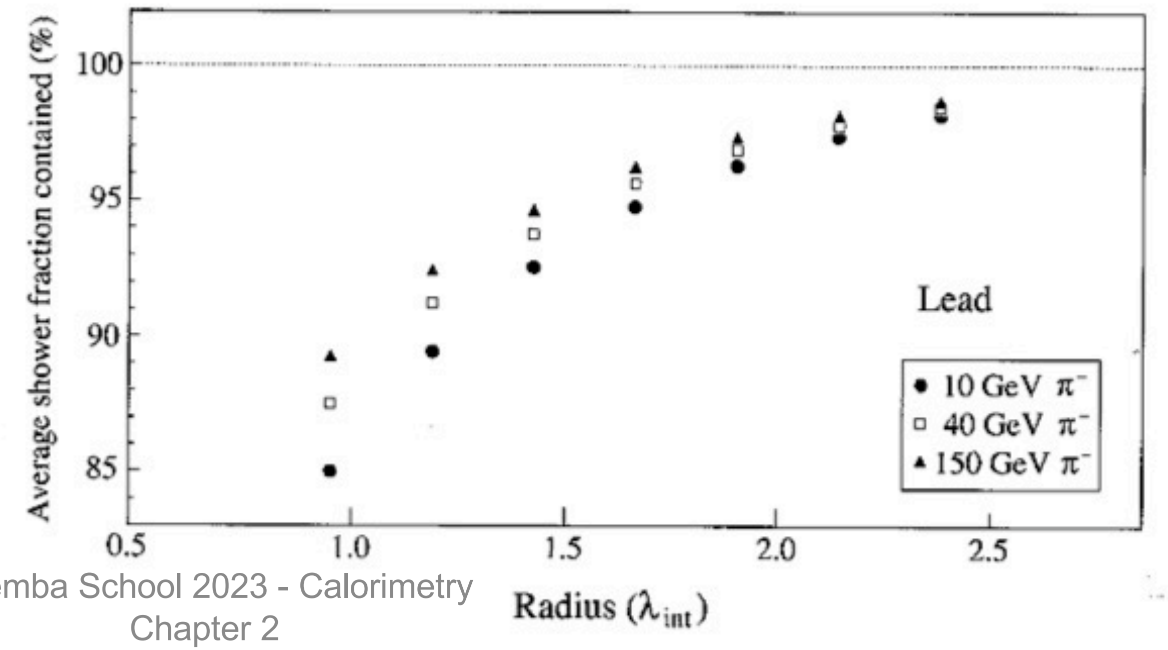


Longitudinal containment

Shower absorbed after 9-10 λ_{int}

Lateral containment

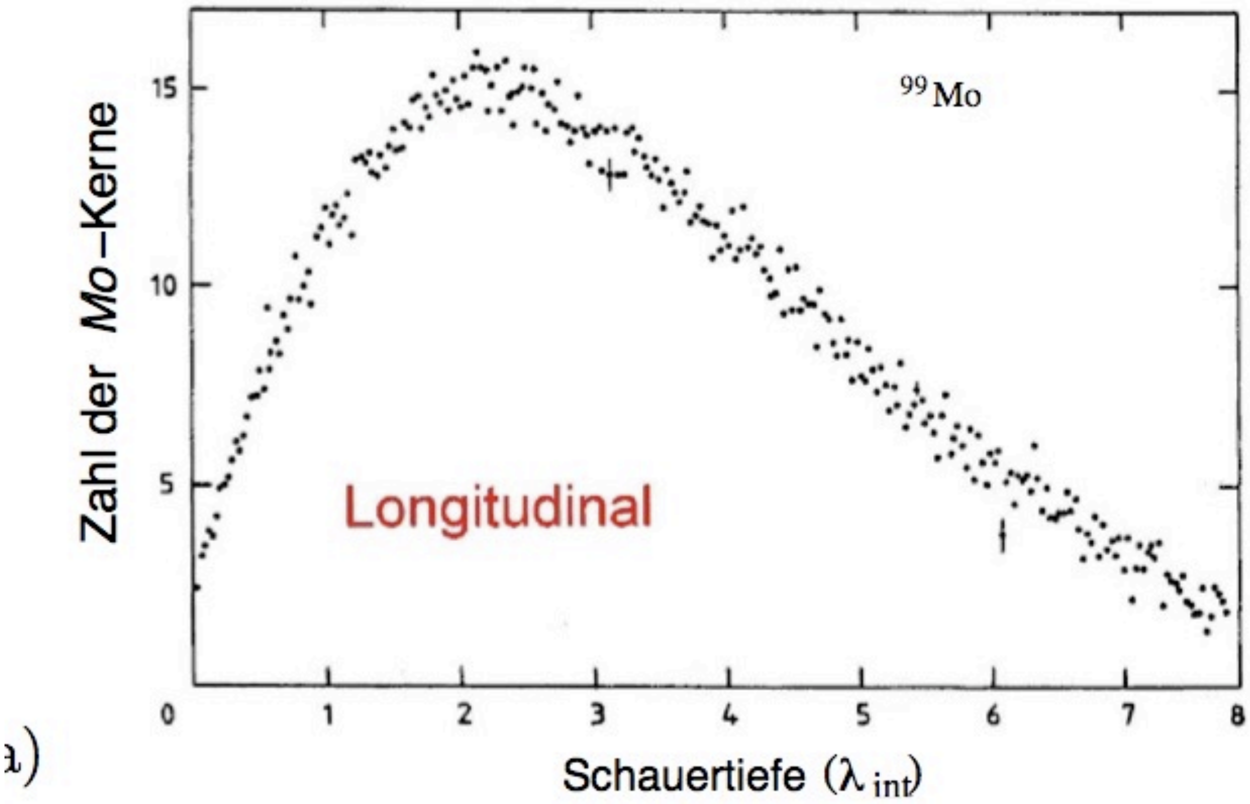
Shower absorbed after 3 λ_{int}



Backup

Longitudinal shower profiles

Signals from radioactive nuclei after 1 week exposure
Of U stack to ~100Billion π of 300 GeV
Longitudinal profile is ‘frozen’ in U Stack



Typical length
$6\ \lambda_{int}$ - $9\ \lambda_{int}$

Shape similar to electromagnetic showers
Shower extension much larger
Strong impact on design of calorimeters built for hadron
Measurements – Hadron calorimeters