Particle Detectors

Lecture 9
31/04/17

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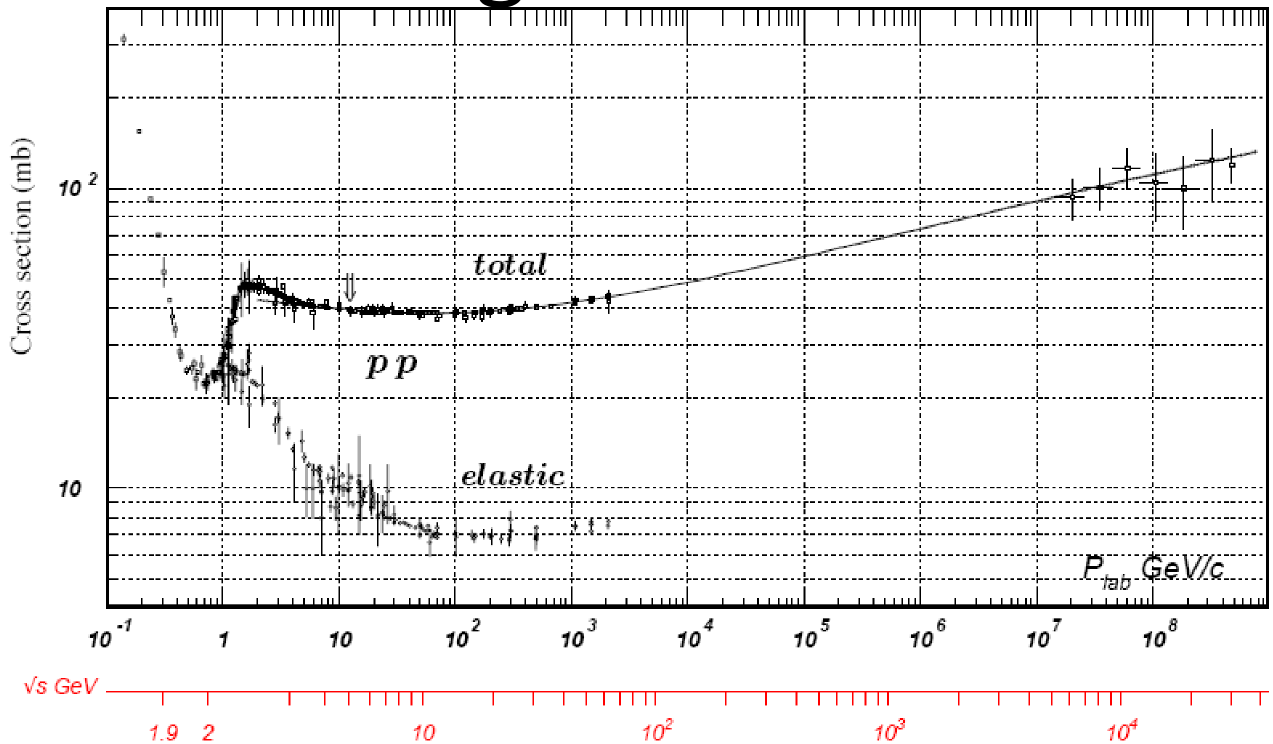
Emanuele Fiandrini

Strong Interactions

Apart from the electromagnetic interactions of charged particles strong interactions may also play a role for particle detection.
This is true for all the hadrons (particles sensitive to the strong nuclear force), charged and neutral.
Charged hadrons lose energy also by the elm processes.
Neutral hadrons DO NOT interact electromagnetically. So nuclear interactions are the only ones they can interact with materials

In this case, we are dealing mostly with inelastic processes, where secondary strongly interacting particles are produced in the collision, which in turn may produce new particles that undergo to nuclear and elm interactions, decay, emit radiation, producing new particles, …

Strong Interactions



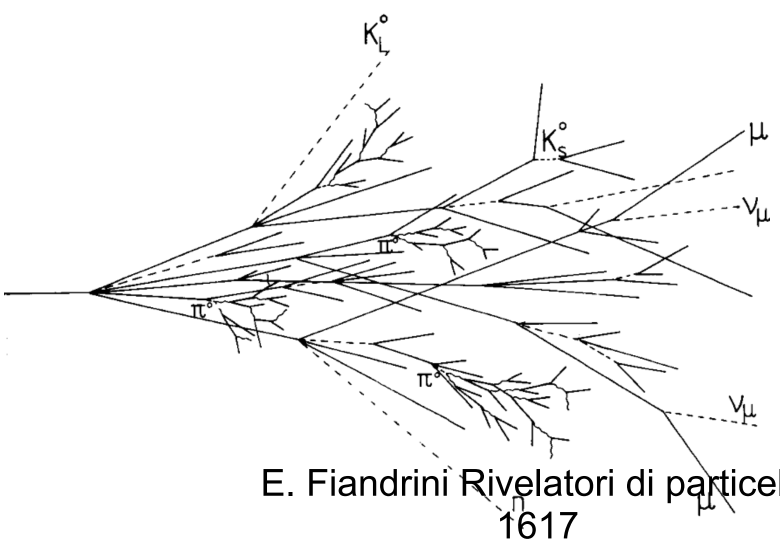
The total cross section for proton–proton scattering can be approximated by a constant value of 50 mb (1 mb = 10^{-27} cm^2) for energies ranging from 2 GeV to 100 TeV. Both the elastic and inelastic part of the cross section show a rather strong energy dependence at low energies, due to the formation of resonances (J/Ψ,Y,ρ D,...: The elastic part of the cross section → 0 at high energy and the inelastic part is dominant $\sigma_{tot} = \sigma_{el} + \sigma_{inel}$

Hadronic showers

When a strongly interacting particle above 5 GeV enters matter, both inelastic and elastic scattering between particles and nucleons occur.

Secondary hadrons → examples: π and K mesons, p and n.
Energy from primary goes to secondary, then tertiary, etc.

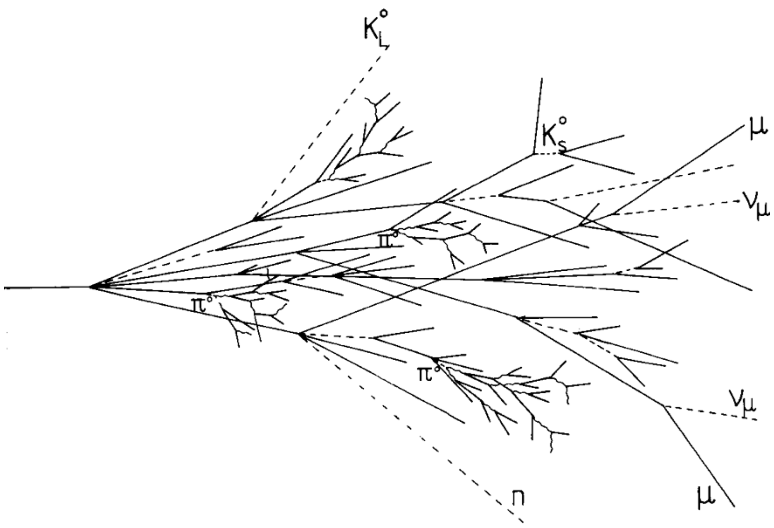
Cascade only ceases when hadron energies small enough to stop by ionization energy loss or nuclear absorption.



(Grupen)

hadronic showers

Many processes involved → much more complicated compared to elm showers.



(Grupen)

Longitudinal development is much longer than for elm showers.

While the lateral structure of electron showers is mainly determined by multiple scattering, in hadron cascades it is caused by large transverse momentum transfers in nuclear interactions, $cP_T \sim hc/R_n \sim 350$ MeV.

Interazioni nucleari (forti)

In analogia alla lunghezza di interazione elettromagnetica possiamo definire una lunghezza di assorbimento –per reazioni anelastiche-

$$\lambda_a = A/(N_a \sigma_{inel})$$

Ed una lunghezza di interazione totale che comprende anche quelle elastiche $\lambda_I = A/(N_a \sigma_{total})$ NB: e' tutto espresso in g/cm^2

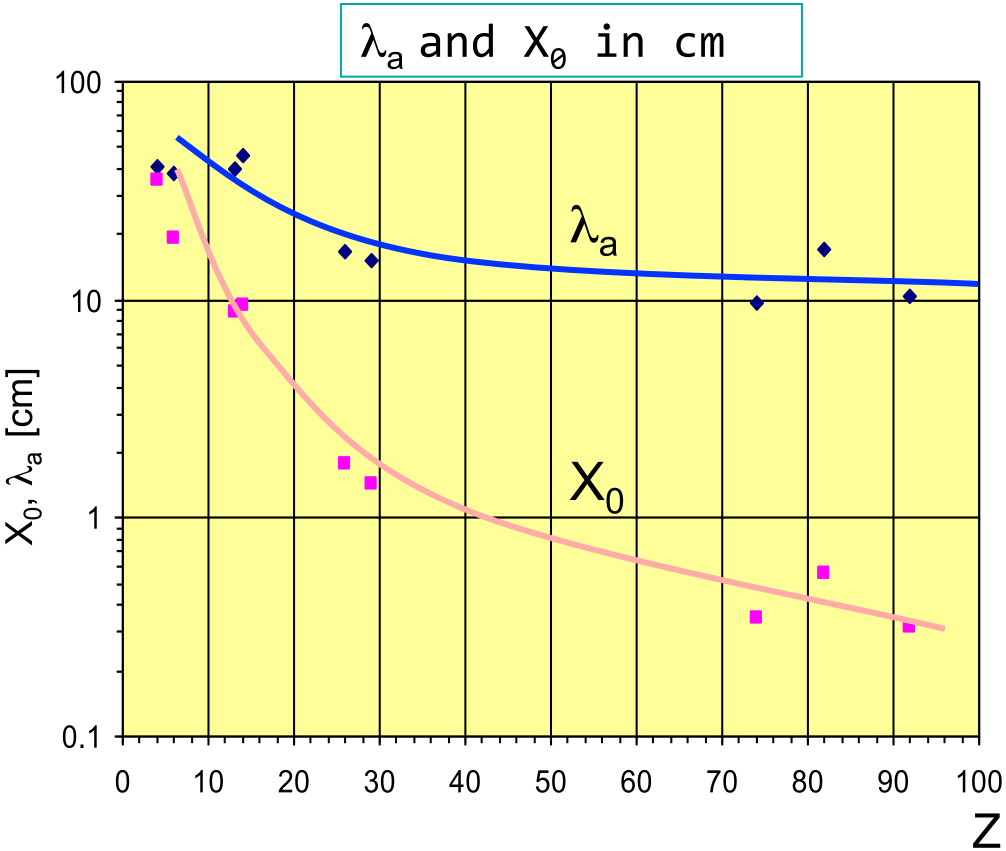
Ad alte energie (>qualche GeV) la sezione d'urto anelastica dipende poco dall'energia e dal tipo di particella incidente (p, π, K….) e domina il processo. Po' essere parametrizzata come

$\sigma_{inel} \approx \sigma_0 A^{2/3}$ con $\sigma_0 \approx 35$ mb sez. d'urto pp

Quindi $\lambda_a = (A^{1/3}/N_A)\sigma_0$

Interazioni nucleari (forti)

Per Z>6 $\lambda_a > X_0$



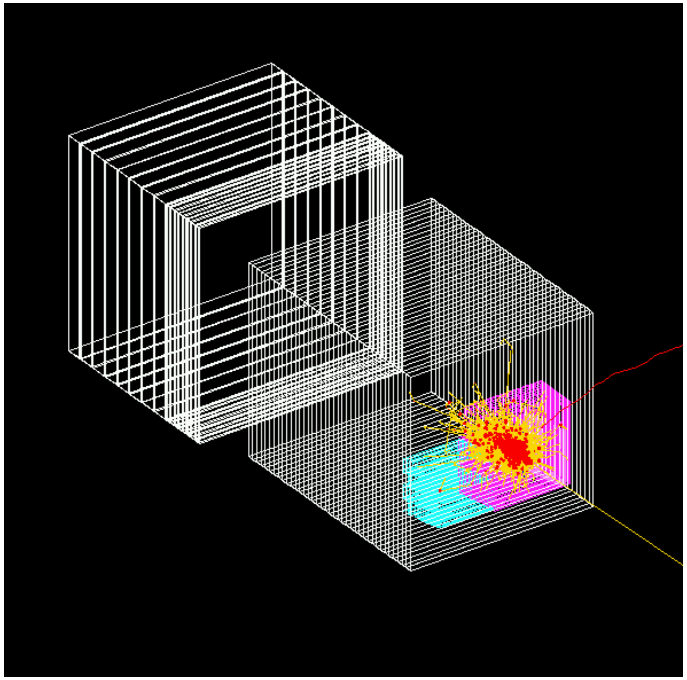
Le due grandezze sono quelle che fissano le dimensioni longitudinali degli sciami: quelli adronici sono piu' "lunghi" di quelli elettromagnetici

Interazioni nucleari (forti)

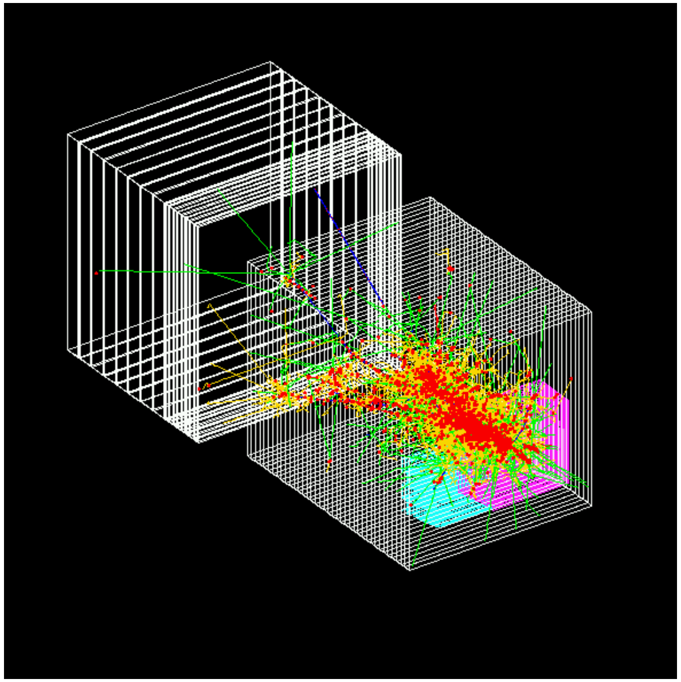
Material	Z	A	ρ [g/cm^3]	X_0 [g/cm^2]	λ_a [g/cm^2]
Hydrogen (gas)	1	1.01	0.0899 (g/l)	63	50.8
Helium (gas)	2	4.00	0.1786 (g/l)	94	65.1
Beryllium	4	9.01	1.848	65.19	75.2
Carbon	6	12.01	2.265	43	86.3
Nitrogen (gas)	7	14.01	1.25 (g/l)	38	87.8
Oxygen (gas)	8	16.00	1.428 (g/l)	34	91.0
Aluminium	13	26.98	2.7	24	106.4
Silicon	14	28.09	2.33	22	106.0
Iron	26	55.85	7.87	13.9	131.9
Copper	29	63.55	8.96	12.9	134.9
Tungsten	74	183.85	19.3	6.8	185.0
Lead	82	207.19	11.35	6.4	194.0
Uranium	92	238.03	18.95	6.0	199.0

Comparison Elm Shower - Hadronic Shower

elm. Shower



hadronic Shower



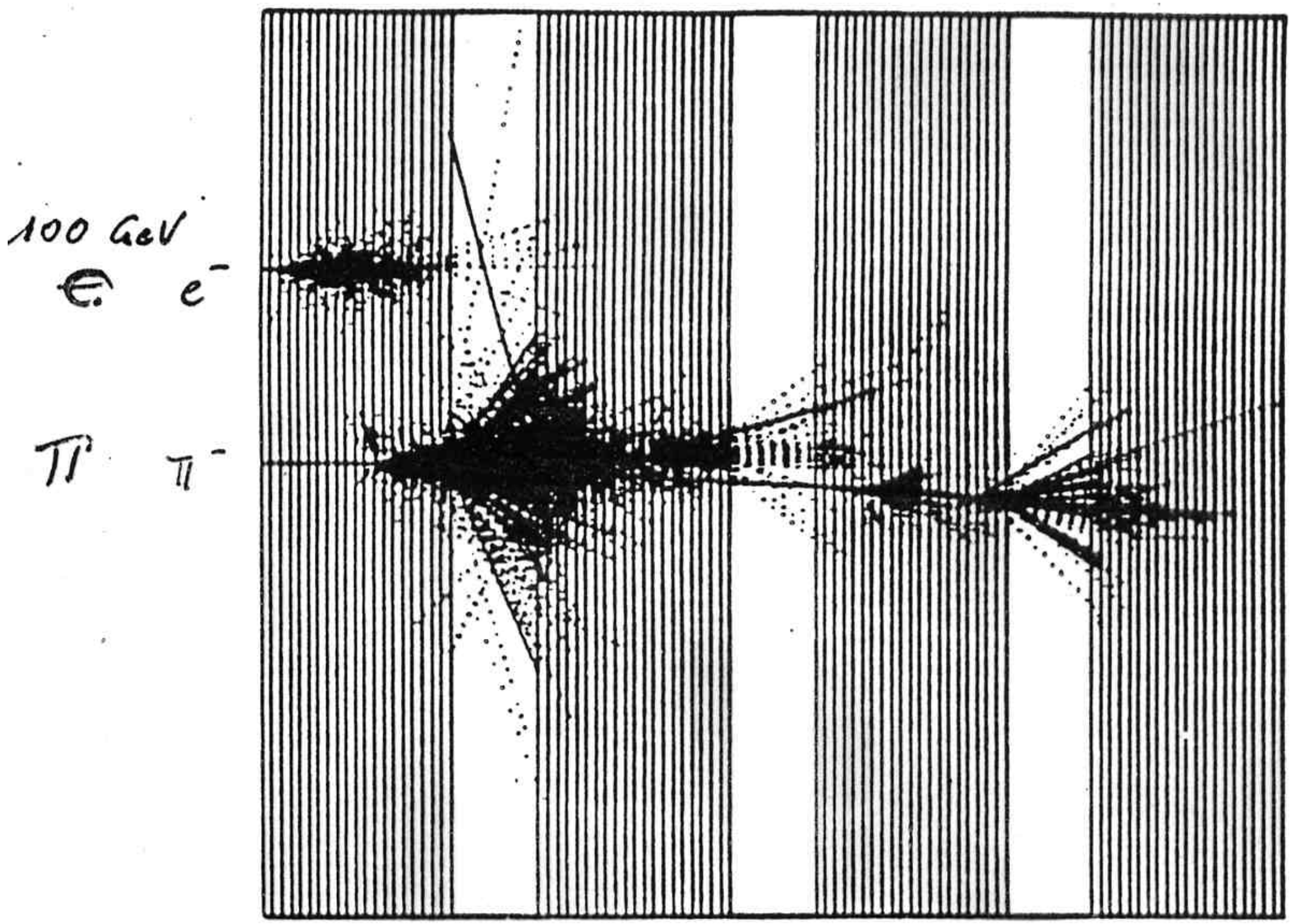
Characterized by Radiation Length: $X_0 \propto \frac{A}{Z^2}$

Characterized by Interaction Length: $\lambda_{int} \propto A^{1/3}$

$$\frac{\lambda_{int}}{X_0} = \frac{A^{1/3} Z^2}{A} \propto \frac{Z^2}{A^{2/3}} = \left(\frac{Z}{A}\right)^{2/3} Z^{4/3} \Rightarrow$$

$Size_{HadrShowers}$ >> $Size_{elm.\ Showers}$
Since Z/A is of the order of 0.5-1

Comparison of Hadronic & Electromagnetic Showers



Hadronic Showers

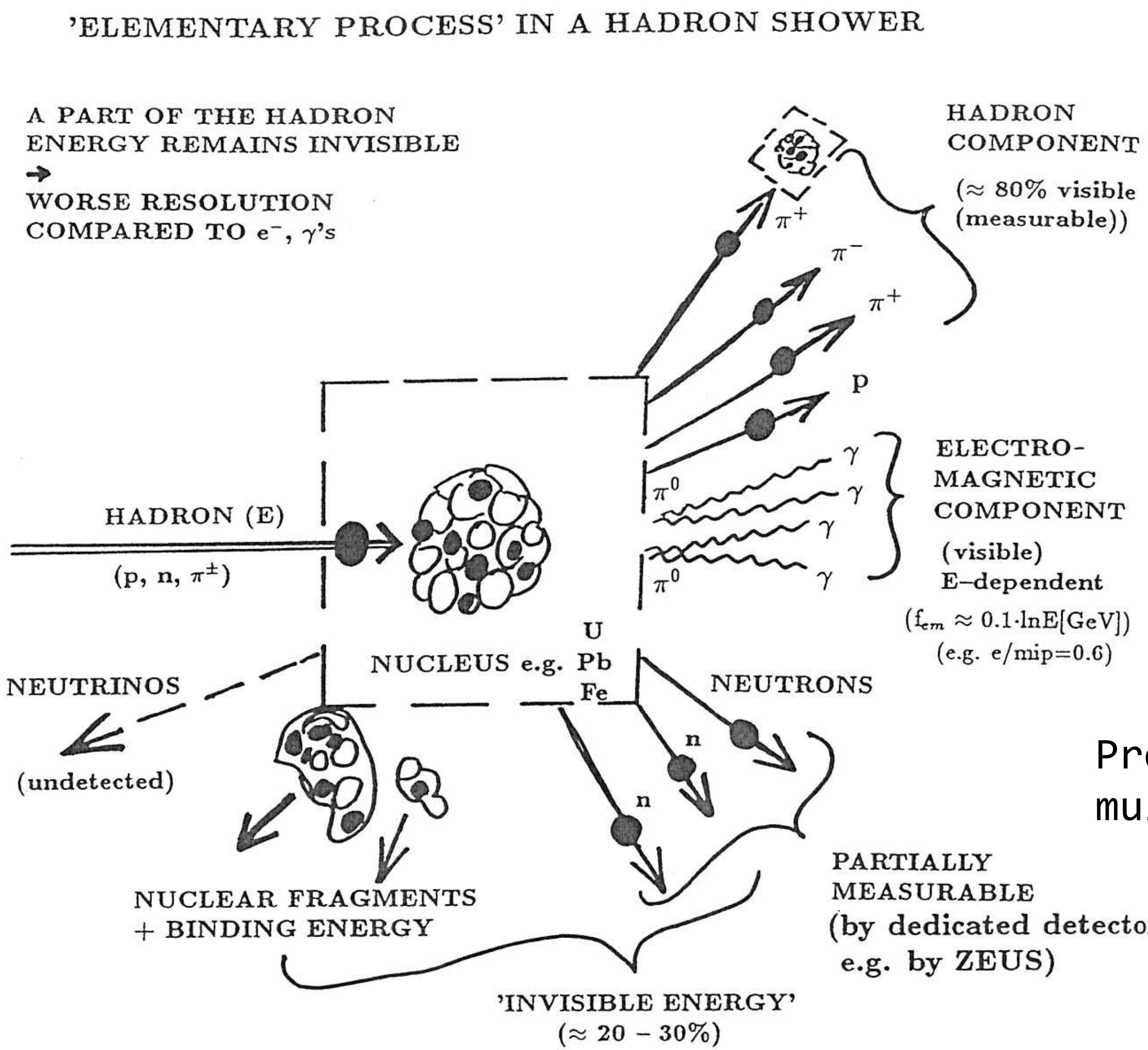


Fig. 3.6 'Elementary physical process' in a hadron shower.

La produzione di particelle e' determinata da processi nucleari anelastici.

Produced particle multiplicity ∝ ln*(E)*

$p_t \approx 0.35$ GeV/c

Interazioni nucleari (forti)

Nello sviluppo dello sciame sono presenti due componenti:

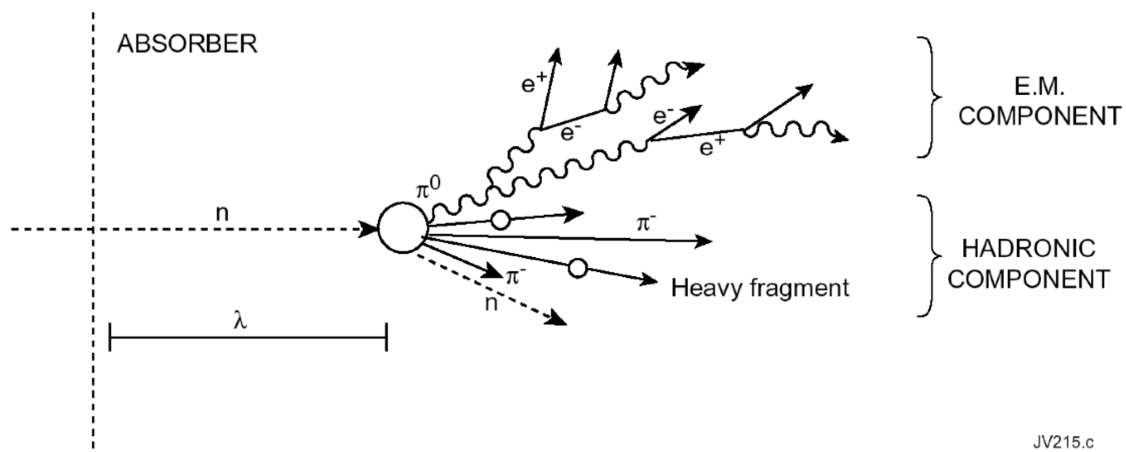
Adronica + **Componente e.m.**

↓

charged pions, protons, kaons ….
Breaking up of nuclei
(binding energy),
neutrons, neutrinos, soft γ's
muons …. → invisible energy

↓

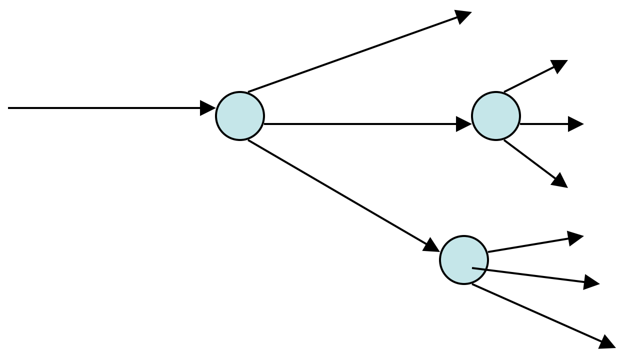
neutral pions → 2γ →
electromagnetic cascade, e-, e+



Larghe fluttuazioni dell'energia → risoluzione in energia limitata

Hadronic Shower

-the electromagnetic component



Simplified model - only π produced

π's are isotriplet 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 b generations of interactions

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

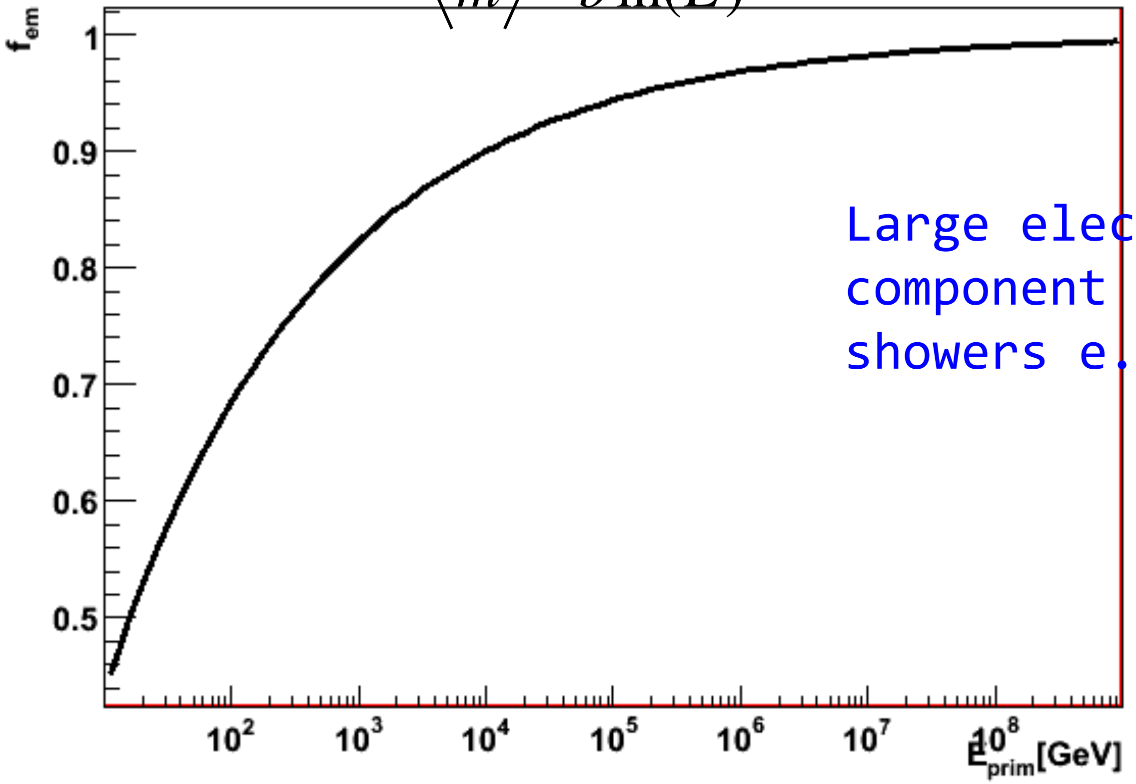
Electromagnetic Component increases with increasing energy of primary particle $f_{em} \approx 0.1 \ln E[\mathrm{GeV}]$

f_{em} as a function of the energy

Reality: $$f_{em} = 1 - \langle m \rangle^{a}$$

$$\langle m \rangle = b \ln(E)$$

<m> Average multiplicity per interaction
a Slope Parameter



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

Attention - Production of π^0 is a statistical process

At small energies: Small multiplicity

Large statistical fluctuations in production of π 'species'

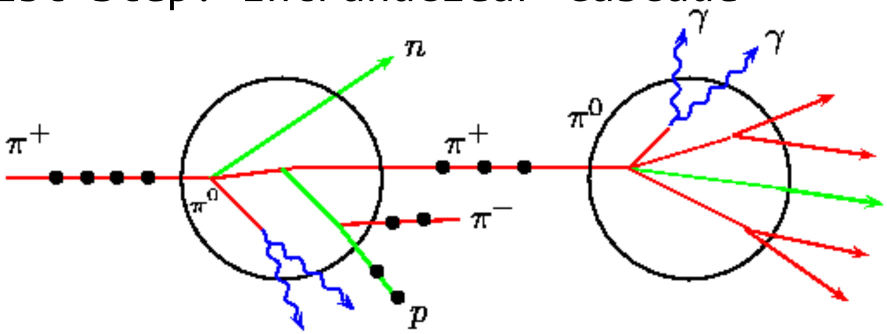
⇒Large fluctuations of electromagnetic component of shower

Hadronic Showers

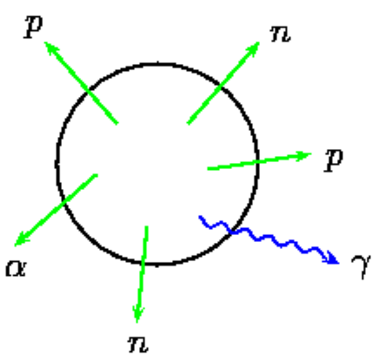
Hadronic Showers are dominated by strong interaction!

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

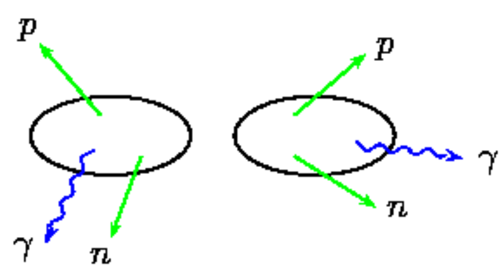
1st Step: Intranuclear Cascade



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 $\pi^0 \rightarrow \gamma\gamma$)	760 MeV
- Neutron Energy	520 MeV
- γ 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. Wigman et al. NIM A252 (1986) 4
R. Wigman NIM A259 (1987) 389

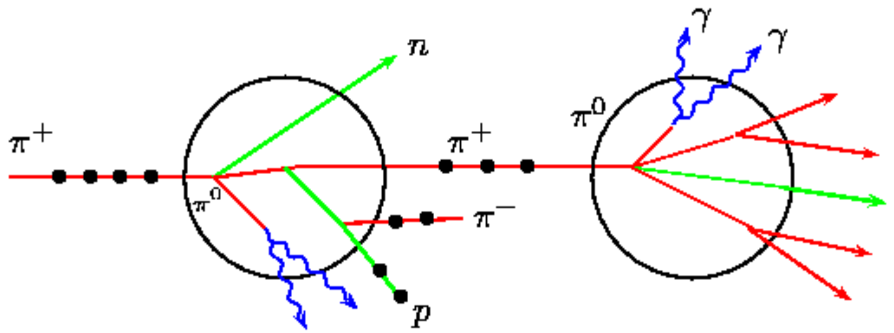
Hadronic Showers - The Nuclear Sector

Internuclear Cascade

Spallation Reaction

Evaporation by excited nucleon

1) Internuclear Cascade



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

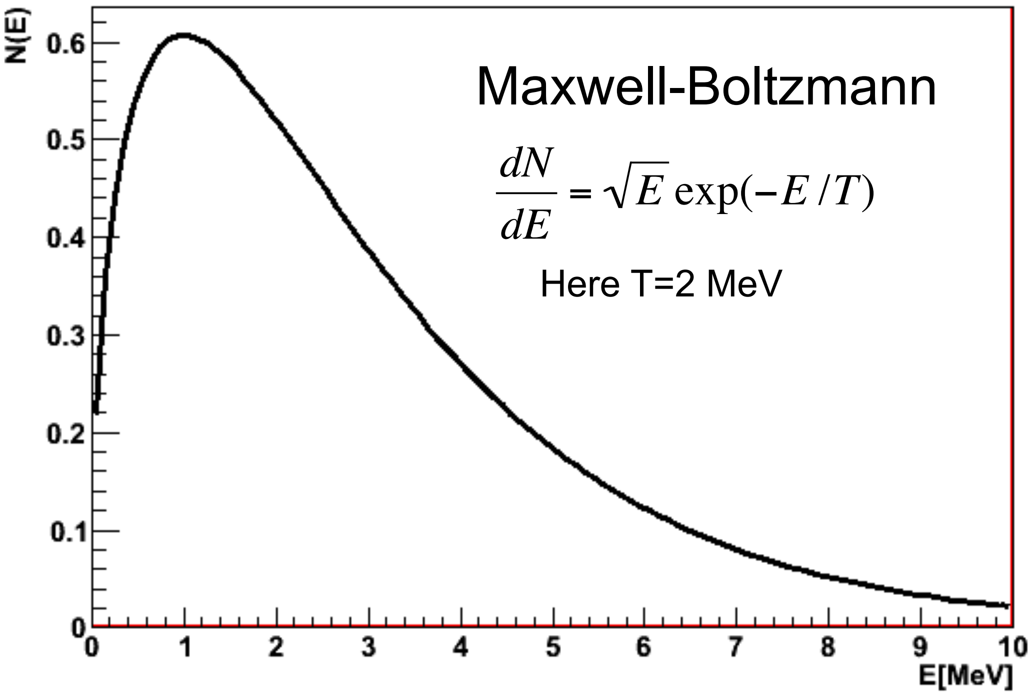
Nucleon with less energy remain bound in Nucleus

Nucleus is left in excited state

Dexcitation by Radiation of nucleons – Evaporation and/or nuclear fission

Evaporation Neutrons

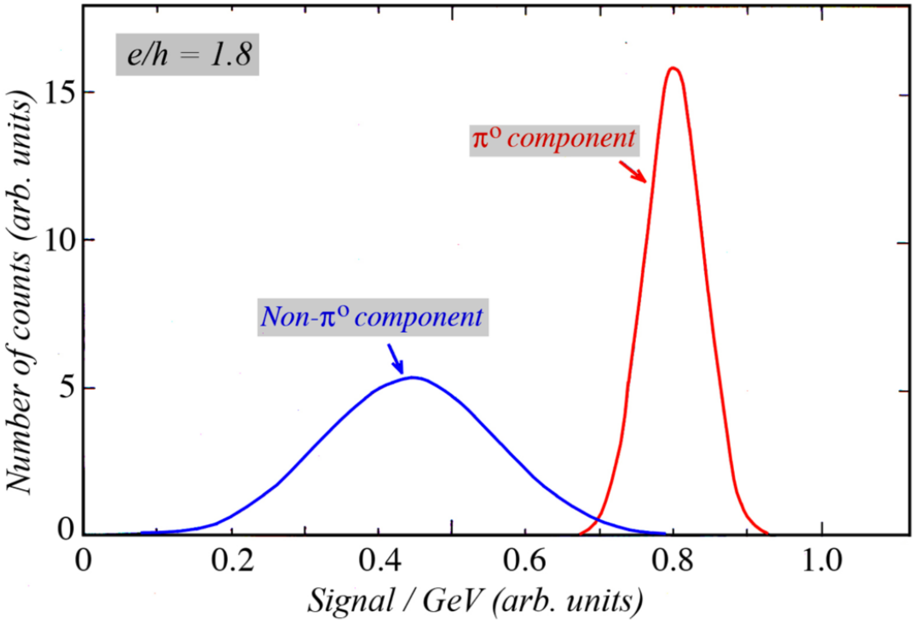
Nearly all evaporated nucleons are soft neutrons
De-excitation happens ~ns after nuclear interaction
Soft or Slow component of hadronic shower



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

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:

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

Comparing pion and electron showers:

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

Calorimeters can be:

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

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

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

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

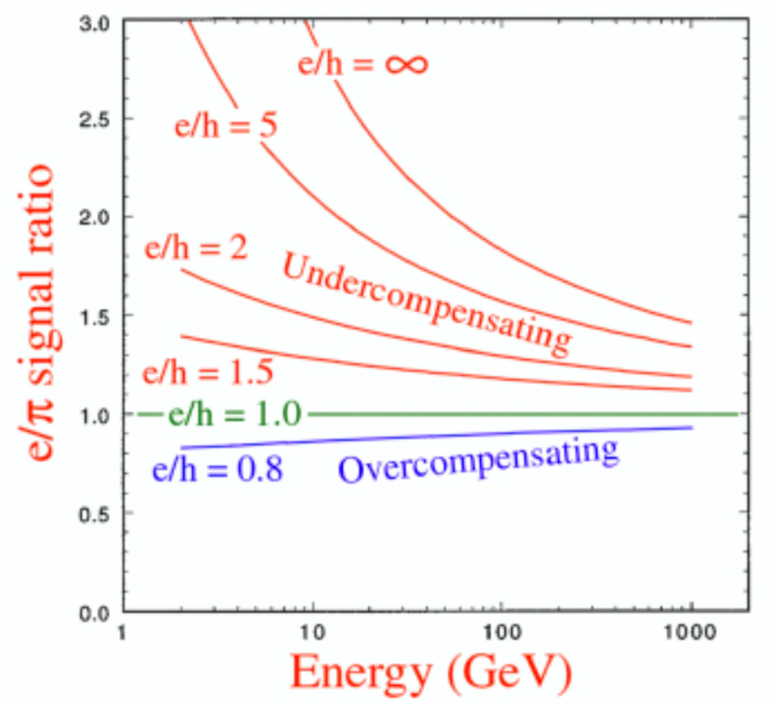
e/h is energy independent

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

Approaches to achieve compensation:

e/h → 1 right choice of materials or

f_{em} → 1 (high energy limit)



Compensating Calorimeters

Improvements in energy resolution can be achieved if showers induced by electrons and hadrons of same energy produce same visible energy (detector response).

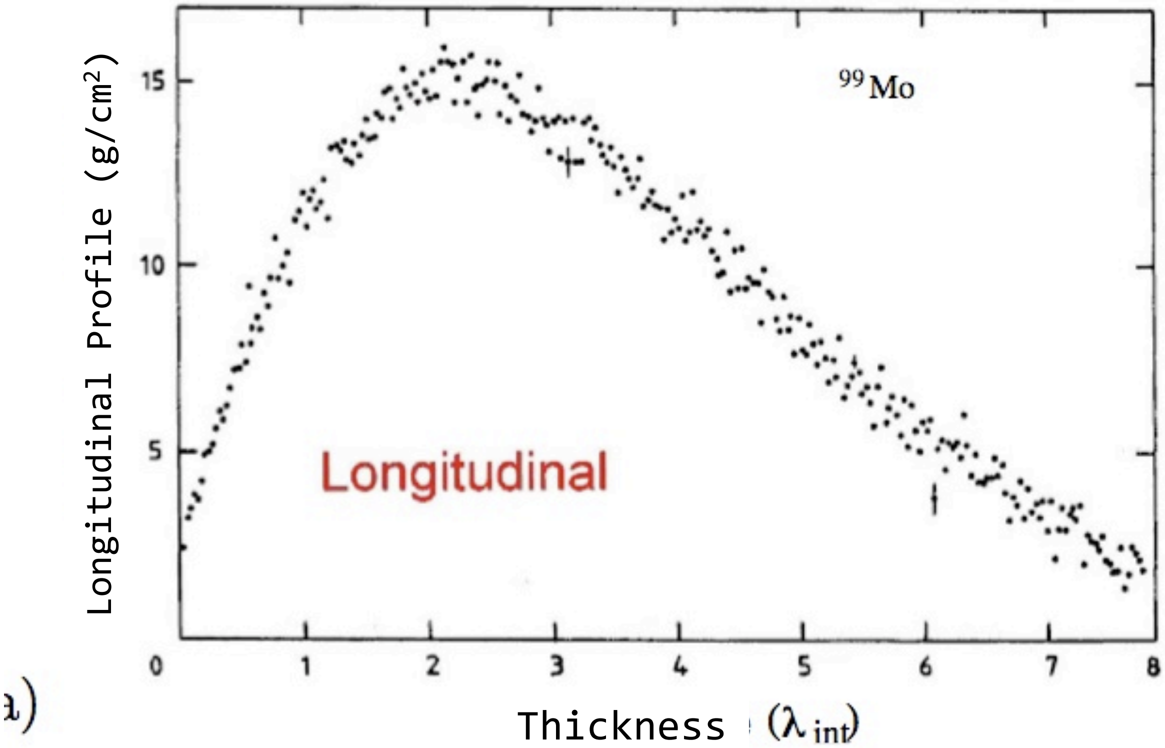
Requires the losses to be "compensated" in some way.

Two methods:

1) Energy lost by nuclear reactions made up for by fission of ^{238}U, liberating n and soft γ–rays. Can get response close to equal: proton-rich detector em shower decreases, had shower increases due to more nuclear reactions.
2) If have lots of H2, compensation achieved with high absorber material: in inelastic collision of hadrons w/ absorber nuclei, neutrons are produced → recoil protons, larger signal.

Longitudinal Shower Profiles

Signals from radioactive nuclei after 1 week exposure
Of U stack to ~100 Billion 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

Semi-empirical model of hadron shower development

$$\frac{dE}{dS} = E_{INC}\left\{\frac{Cx^{(\alpha_E - 1)}e^{-x}}{\Gamma(\alpha_E)}\right\} + E_{INC}(1-C)\left\{\frac{y^{(\alpha_H - 1)}e^{-y}}{\Gamma(\alpha_H)}\right\}$$

electromagnetic part

hadronic part

$$x \equiv \beta_E \frac{(S - S_0)}{\chi_0}$$

radiation length

$$y \equiv \beta_H \frac{(S - S_0)}{\lambda}$$

interaction length

$$\alpha_H = \alpha_E = 0.62 + 0.32 \ln E$$

$$\beta_H = 0.91 - 0.02 \ln E$$

$$\beta_E = 0.22$$

$$C = 0.46$$

$S_0 \neq 0$ - significant amount of material in front of calorimeter (magnet coil etc.)

The processes are complex and a simple calculation is not possible.
Monte Carlo based simulations yield emperical relation for the longitudinal and transverse shower development

More Rules of Thumb for the Hobbyist

- Shower maximum

$$t_{\max}(\lambda) \sim 0.2 \ln E(GeV) + 0.7$$

- 95% Longitudinal containment

$$L_{95\%}(\lambda) \sim t_{\max} + 2.5\lambda_{ATT}$$

$$\lambda_{ATT} \approx \lambda \left[E(GeV)\right]^{0.13}$$

- 95% Lateral containment

$$R_{95\%} \sim 1\lambda$$

- Mixtures in sampling calorimeters

active + passive material

$$\frac{1}{\chi_{eff}} = \sum_i \frac{f_i}{\chi_0^i}$$

$$f_{act} = \frac{m_{act}}{m_{act} + m_{pass}}$$

$$\frac{\varepsilon_{eff}^{crit}}{\chi_{eff}} = \sum_i f_i \frac{\varepsilon_i^{crit}}{\chi_0^i}$$

$$\frac{E_{vis}}{E_{inc}} = f_{act} \frac{\varepsilon_{act}^{crit} / \chi_0^{act}}{\varepsilon_{eff}^{crit} / \chi_{eff}}$$

Interazioni nucleari (forti)

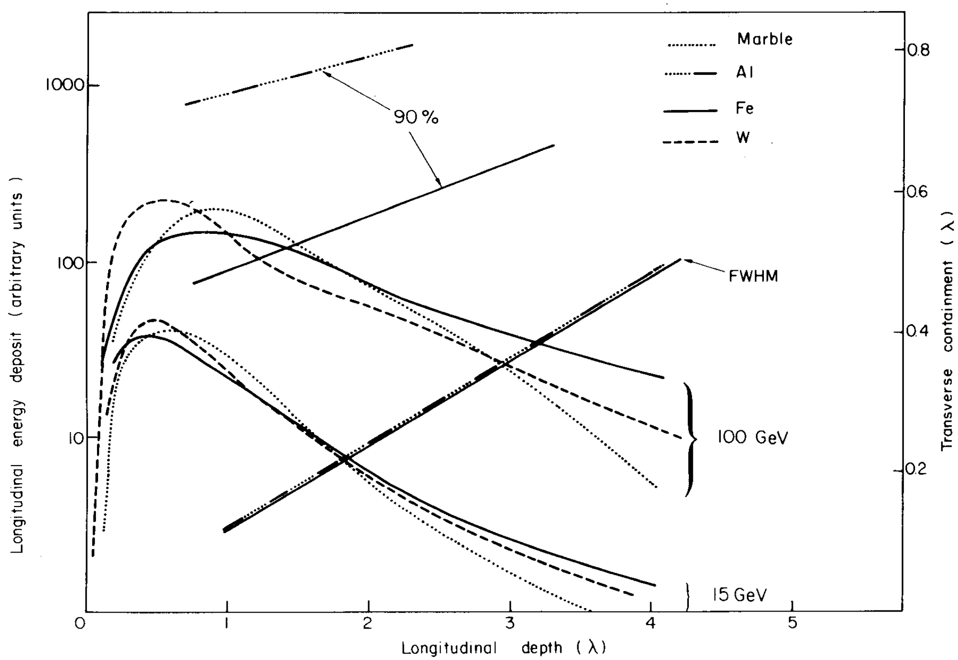
- Sviluppo longitudinale dello sciame

$$t_{\max}(\lambda_I) \approx 0.2 \ln E[GeV] + 0.7$$

$$t_{95\%}(cm) \approx a \ln E + b$$

Ferro: a = 9.4, b=39
λ_a =16.7 cm

E =100 GeV
→ $t_{95\%} \approx 80$ cm



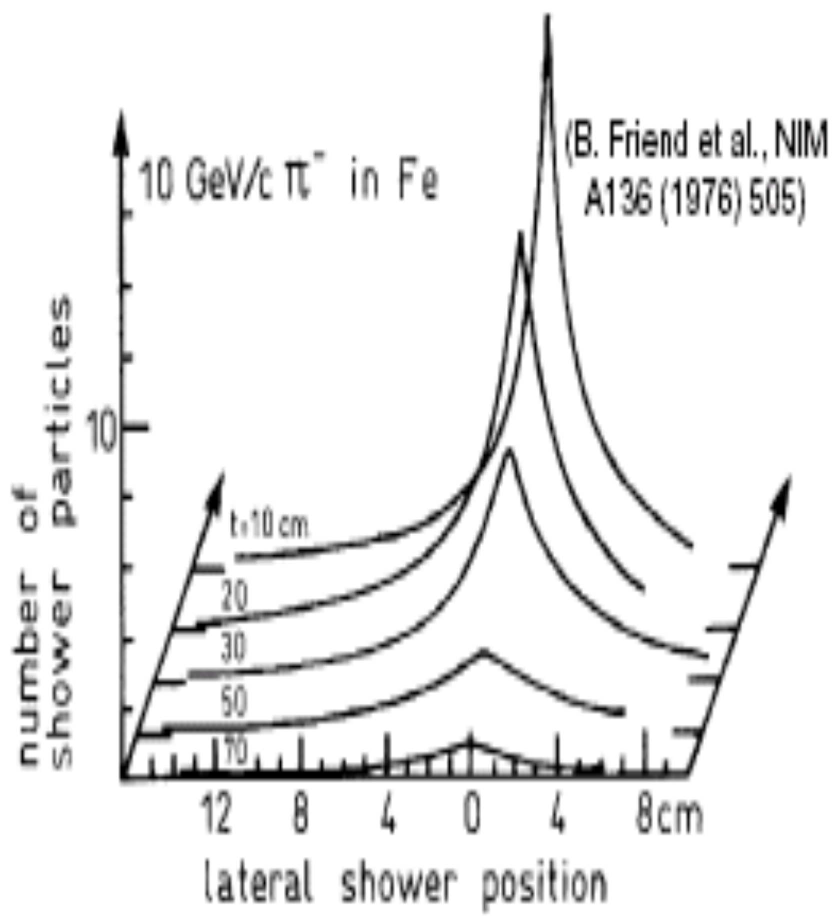
(C. Fabjan, T. Ludlam, CERN-EP/82-37)

Interazioni nucleari (forti)

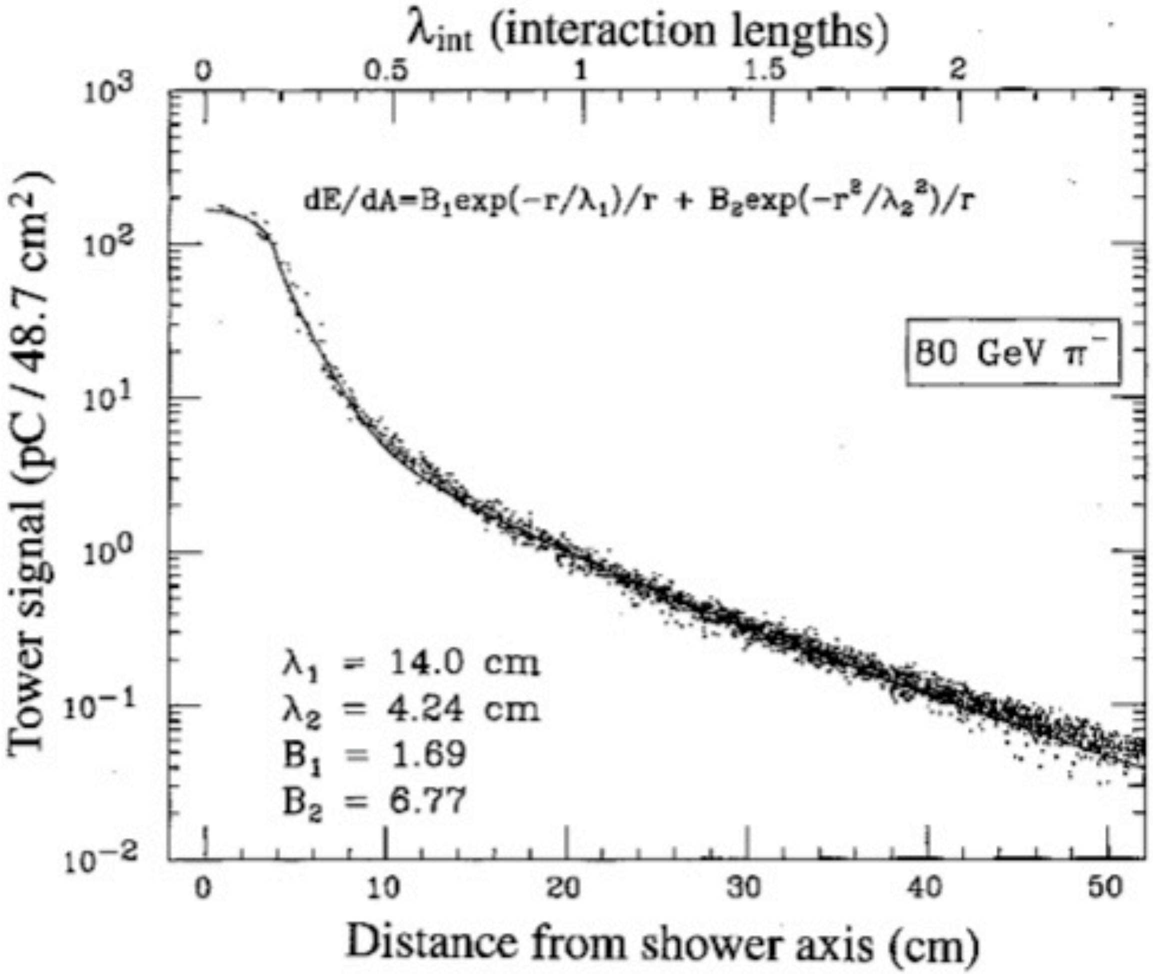
Trasversalmente lo sciame consiste in un nocciolo + un alone.

Il 95% e' contenuto in un cilindro di raggio λ_I.

Gli sciami adronici sono molto più lunghi e più larghi di quelli elettromagnetici

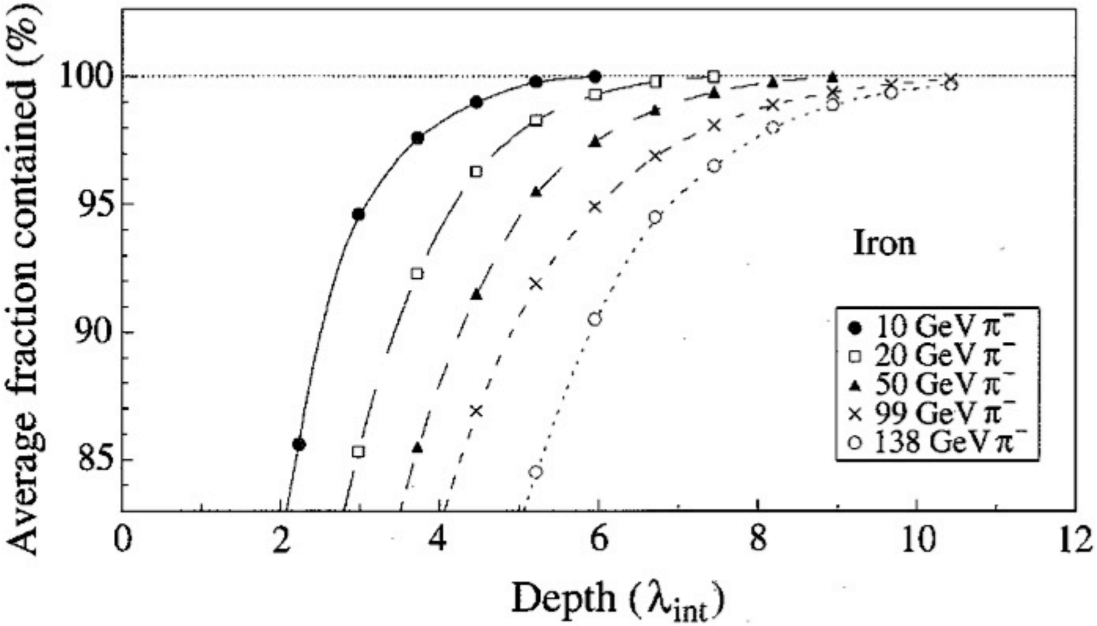


Transversal Shower Profile



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

Shower Containment

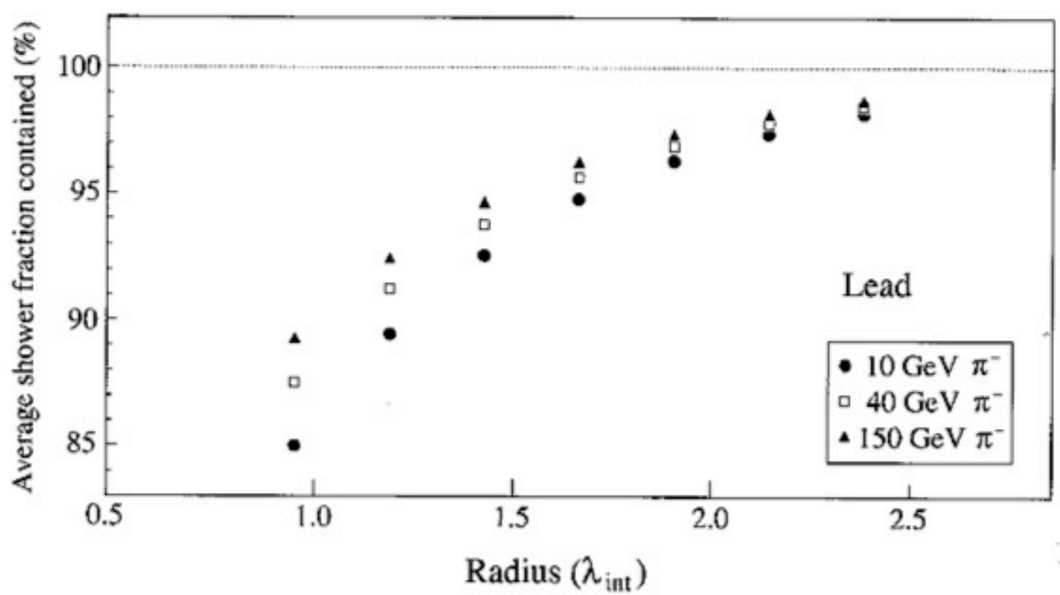


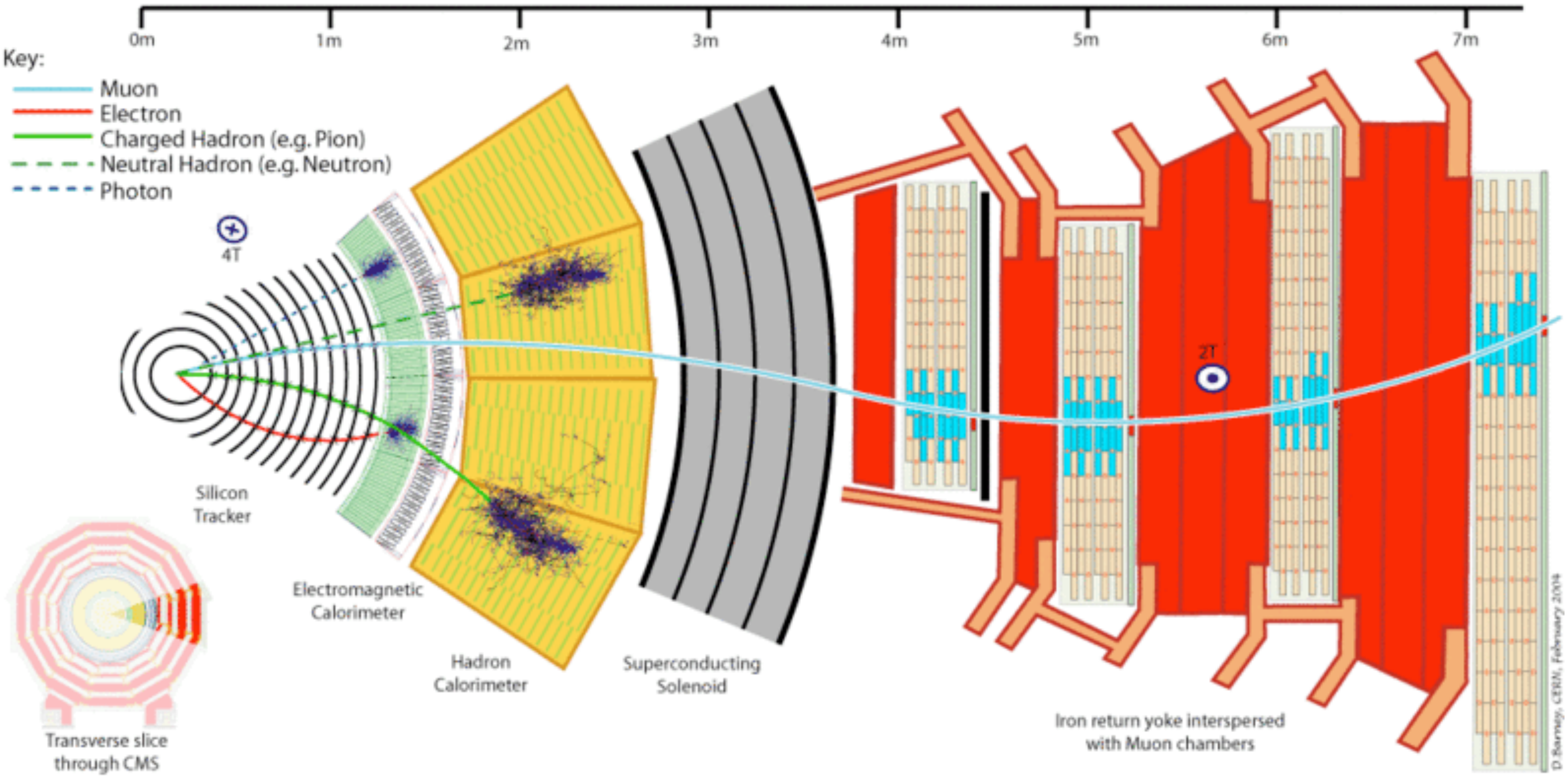
Longitudinal Containment

Shower absorbed after 9-10 λ_{int}

Lateral Containment

Shower absorbed after 3 λ_{int}

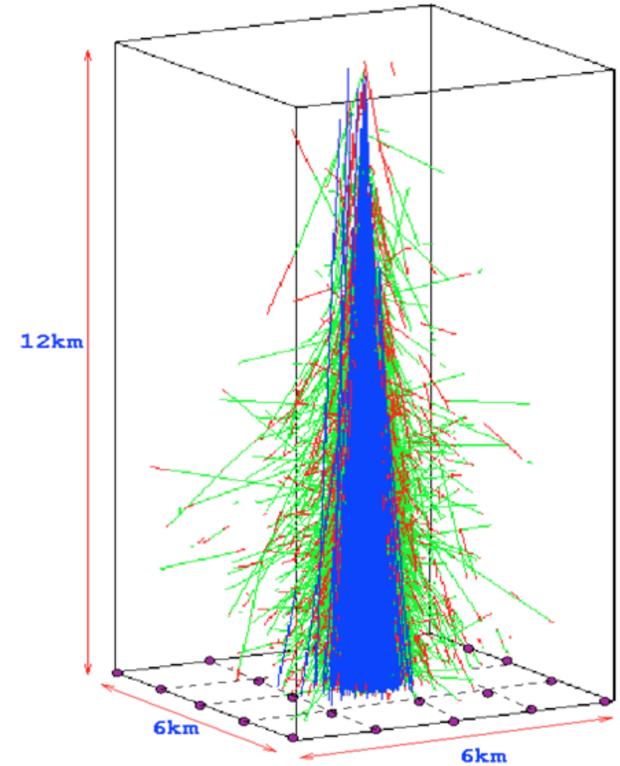




Le dimensioni del calorimetro adronico di CMS sono molto maggiori di quelle del calorimetro elettromagnetico

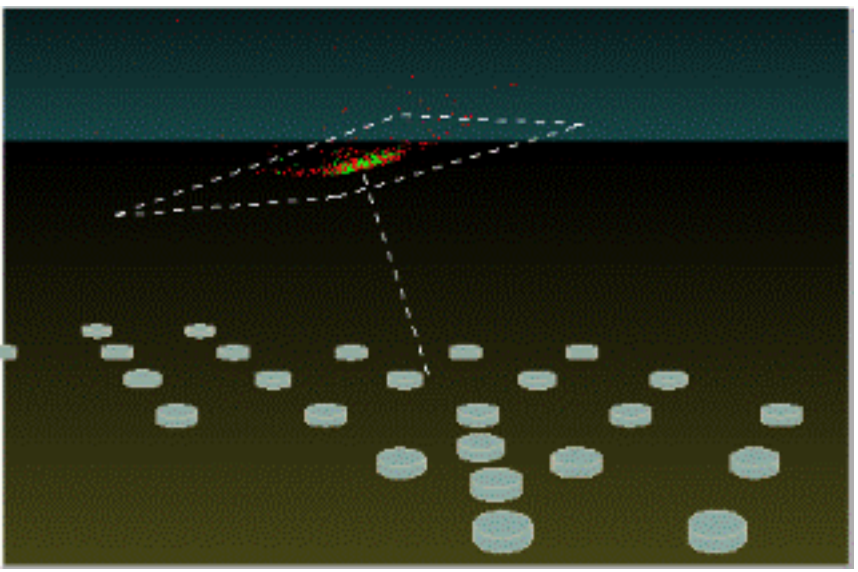
CMS Hadron Calorimeter

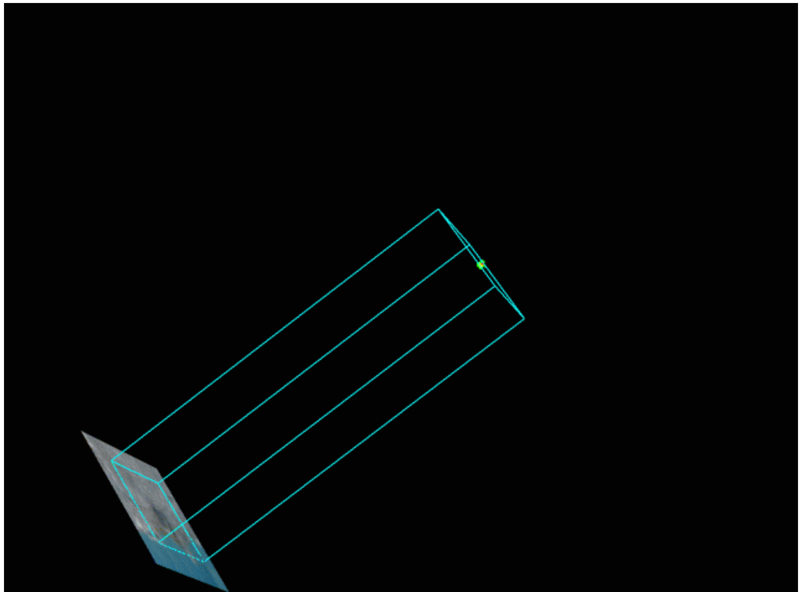
I raggi cosmici di altissima energia (10^{19} eV) vengono rivelati a terra usando l'atmosfera come convertitore: i raggi cosmici danno luogo a uno sciame adronico, in cui le particelle emettono luce cherenkov.
Un array di rivelatori a terra la rivela.
Necessarie grandissime superfici



Nucleo di Fe che colpisce la sommita' dell'atmosfera

Esperimento AUGER (Argentina)
2000 km^2





Conclusioni

Abbiamo accennato a tutti i processi e.m. o forti che avvengono quando una particella carica (o no) attraversa la materia (escludendo il neutrino), tutti processi utili per costruire i rivelatori.

Da un punto di vista puramente strumentale possiamo suddividere i processi in non distruttivi e distruttivi:

- **Distruttivi:**
  - produzione di sciami elettromagnetici e adronici. Questi processi sono utili per misurare l'energia della particella ($e^{\pm}$, γ → calorimetri elettromagnetici); (adroni e μ → calorimetri adronici). È ovvio che la parte distruttiva dell'apparato sperimentale deve stare alla fine del rivelatore
  - Assorbimento di fotoni (fotoelettrico, compton, prod di coppie)
- **Non distruttivi:**
  - o Perdita di energia per collisione (Bethe-Block) (misuro il b o il g della particella carica).
  - o Effetto Čerenkov (misuro il b della particella carica).
  - o Radiazione di transizione (misuro il g della particella carica).

Tutti e tre i processi non distruttivi possono essere usati per identificare la particella, ed il primo (perdita di energia per collisione) è più spesso usato per misurare la posizione della particella carica