Calorimetry in particle physics experiments

Unit n.2
The physics of calorimetry

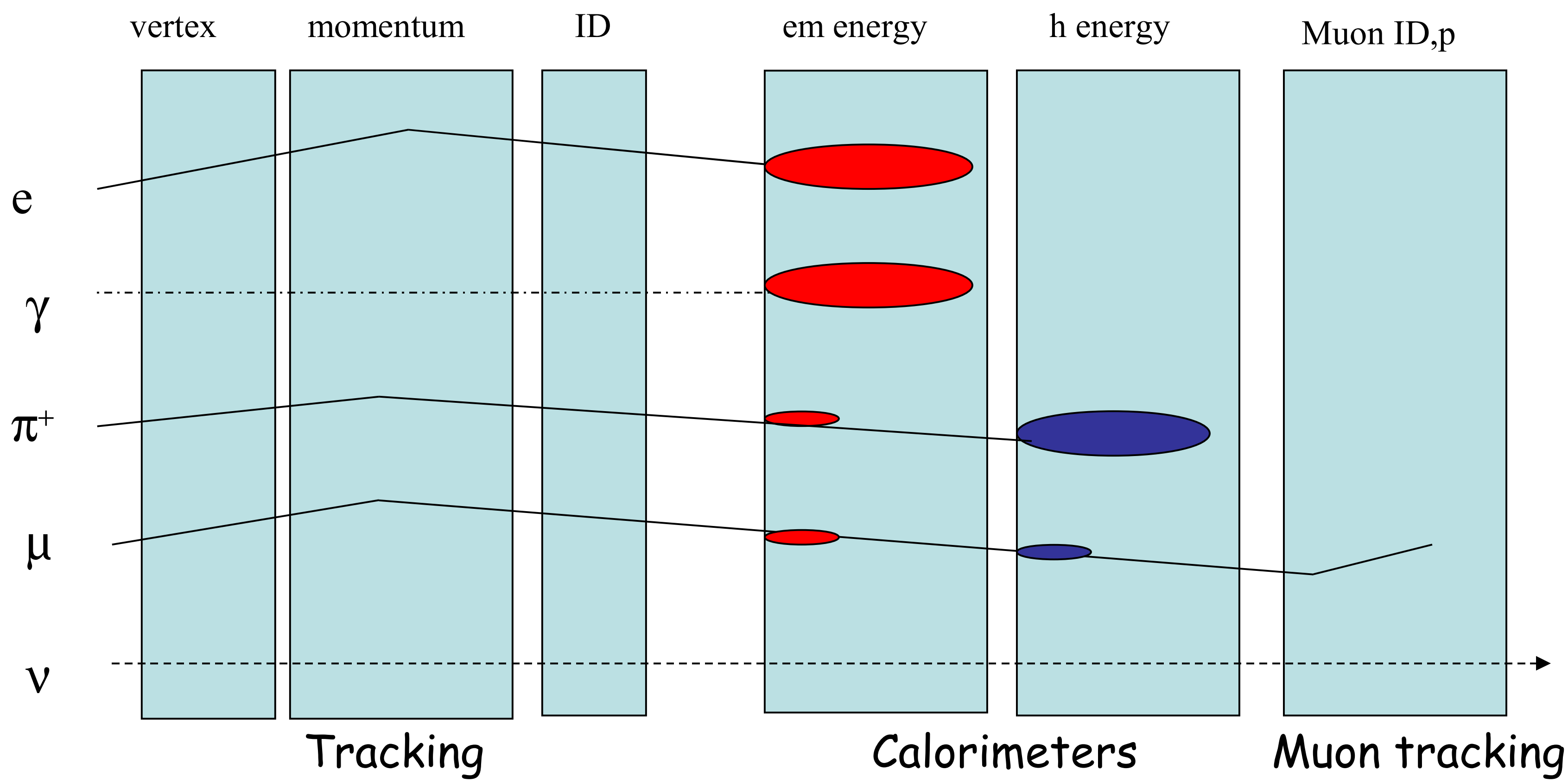
Lecture Overview

- Calorimeters vs Time
- Basics of calorimetry:
  - **Interactions of particles with matter (electromagnetic)**
  - **Definition of radiation length and critical energy**
  - **Development of electromagnetic showers**
  - **Interactions of particle with matter (nuclear)**
  - **Development of hadronic showers**

The Life of a Particle throu a Detector

NB: Calorimetry is a destructive method (**exceptions: muons, neutrinos), SO**

place your calorimeter in the right place!



Calorimeters Evolution

Random (biased) selection (mostly CERN based)

- Calorimeter for cosmic rays
- ISR
- UA2 ($Sp\bar{p}S$)
- L3 (LEP)
- CDF (TEVATRON)
- NA48 (SPS)
- CMS/ATLAS (LHC)

Calorimeters for cosmic rays

1954 N.L.Grigorov: idea of sampling calorimeters using ionization chambers (proportional counters) / iron absorber, to measure cosmic ray particles with energies $E > 10^{14}$ eV

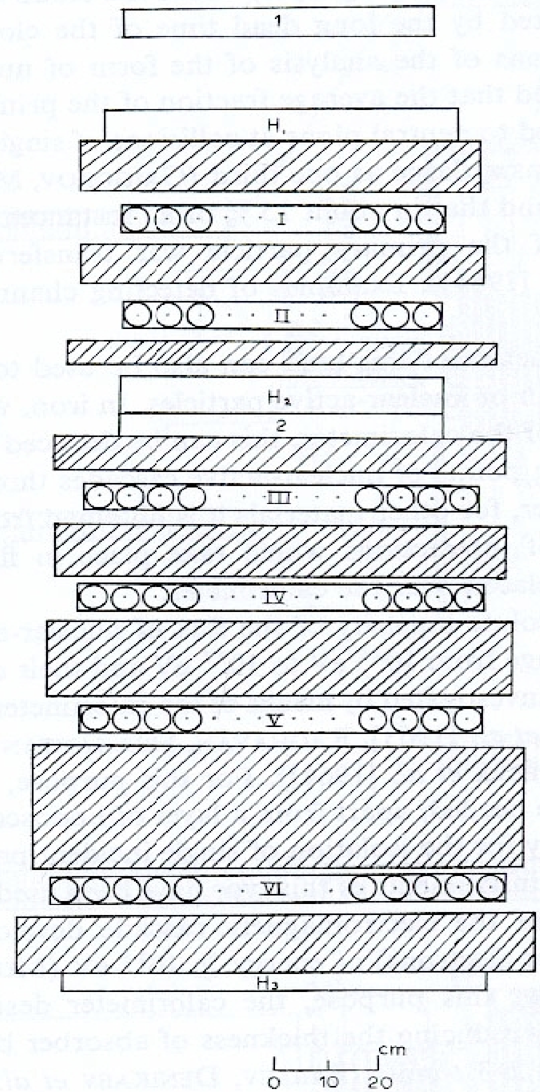


Fig. 14. Schematic diagram of the first ionization calorimeter (GRIGOROV, MURZIN and RAPOPORT [1958]). The shaded areas represent absorber. Layers 1 and 2 are the rows of counters forming the controlling telescope. Layers H_1, H_2, H_3 are hodoscoped counters, while layers I, . . ., VI are the detectors (ionization chambers) of the calorimeter.

EM calorimeter for ISR

√s = 63 GeV

1977 : Sampling calorimeter with Liquid Argon ionization chambers as active medium (80 K), absorber lead-copper
Energy measured using ionization charge

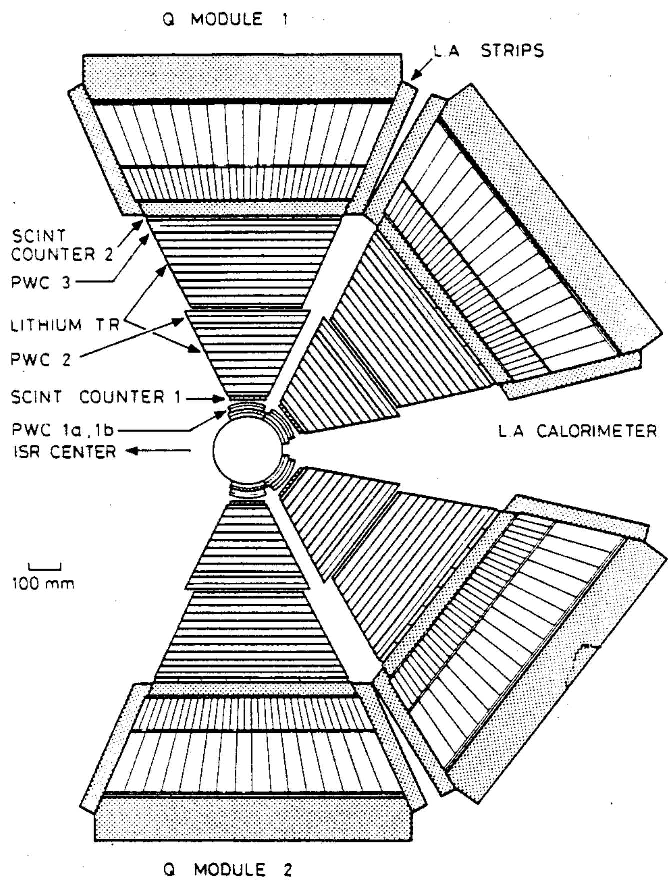
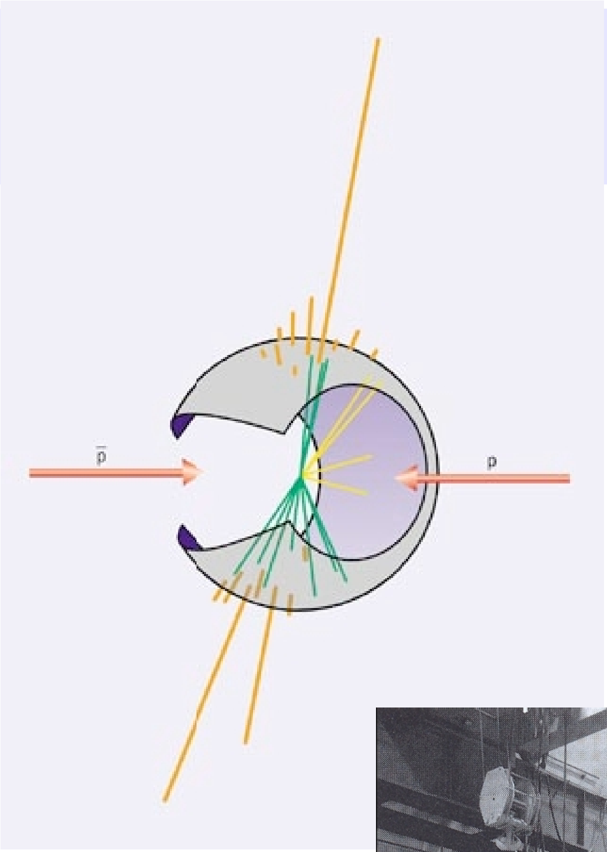


Fig. 1

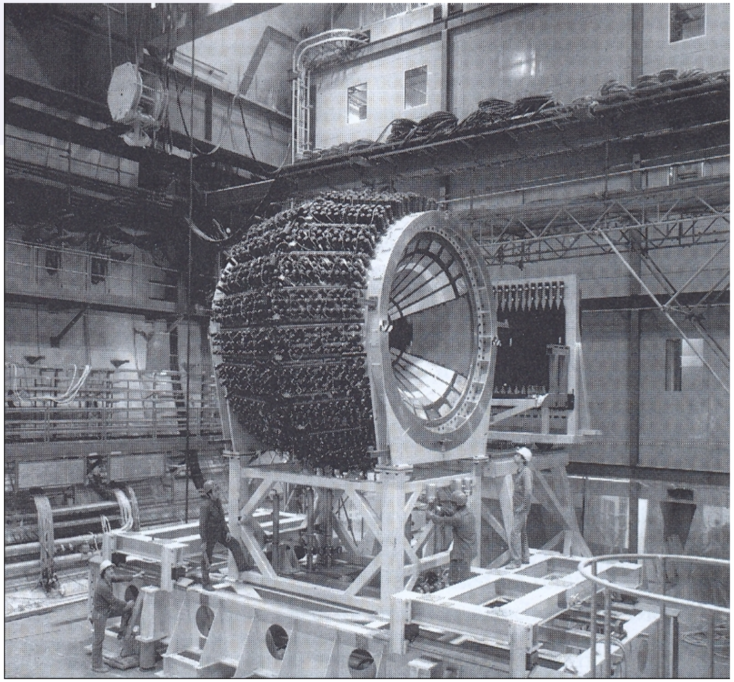
For electron pairs detection produced in pp collision @ ISR

UA2 @ S$p\bar{p}$S CERN

$\sqrt{s}$ = 630 GeV



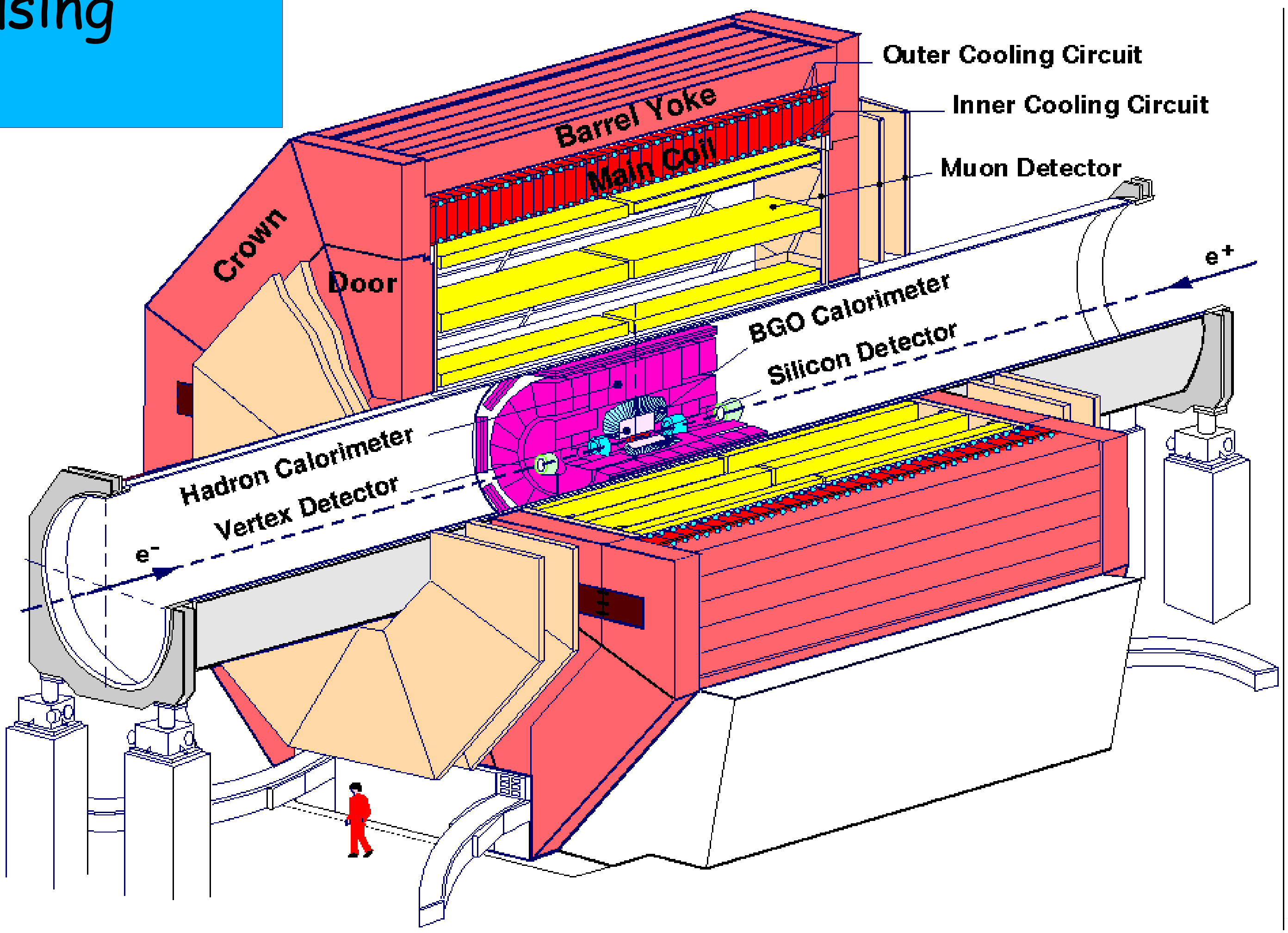
~1983 : sampling Lead-Scintillator sandwich (EM)
Fe-Scintillator sandwich (Hadron)



L3 @ LEP CERN

1988: Homogeneous crystal (BGO) em calorimeter

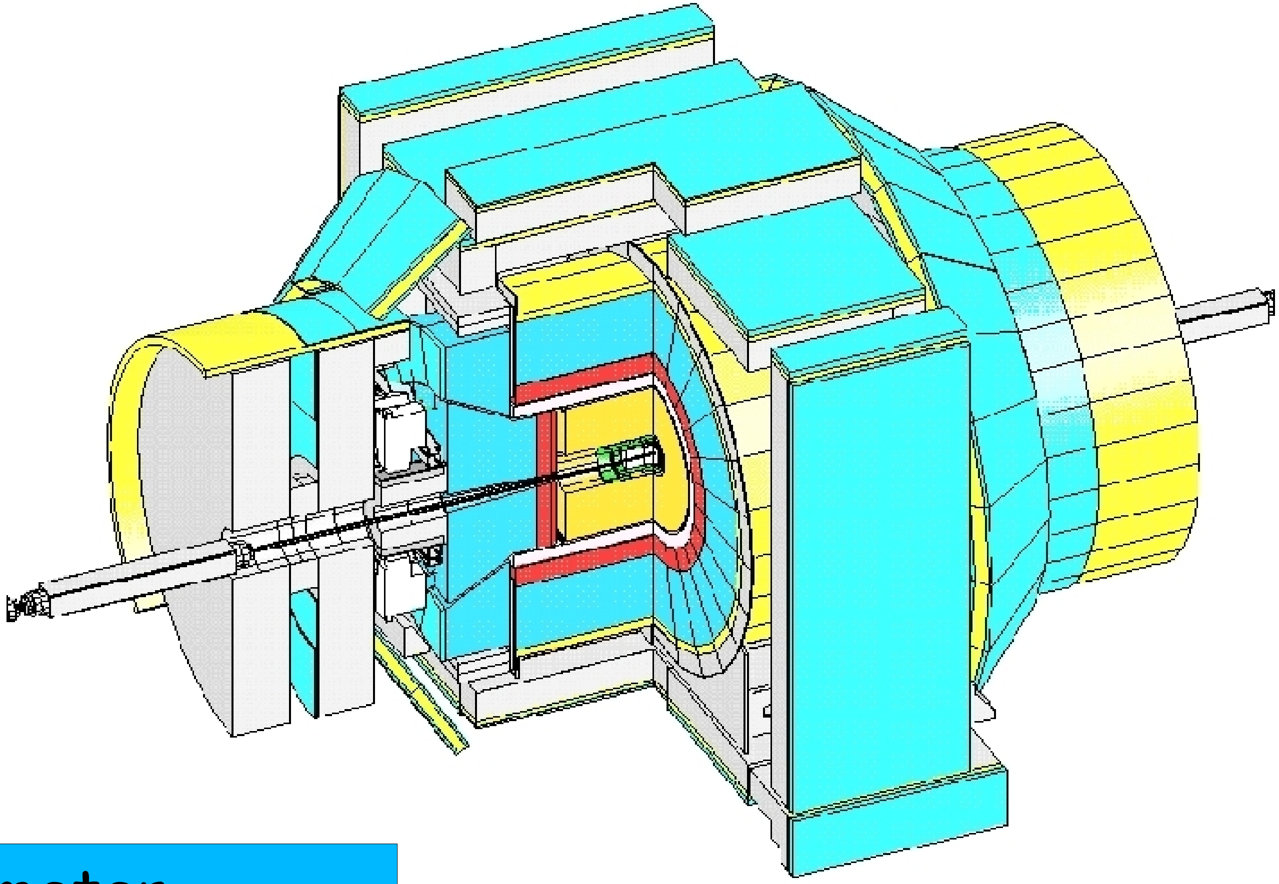
Energy measured using scintillation light



CDF @ TEVATRON FERMILAB

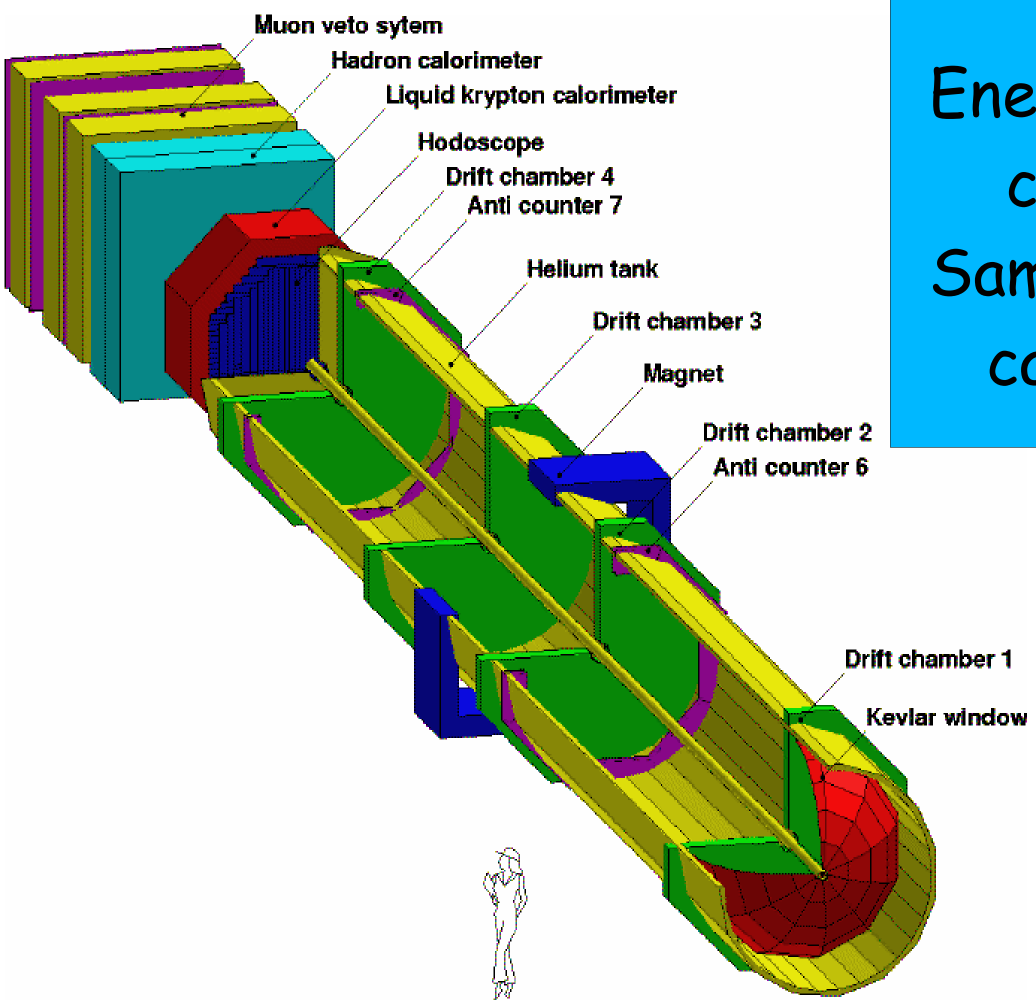
$p\bar{p}$ @ $\sqrt{s}$ = 1.8 TeV

		Central	Plug
EM	thickness	$19\,X_0$, 1λ	$21\,X_0$, 1λ
	sample(Pb)	$0.6\,X_0$	$0.8\,X_0$
	sample(scint.)	5 mm	4.5 mm
	resolution	$\frac{13.5\%}{\sqrt{E}} \oplus 2\%$	$\frac{14.5\%}{\sqrt{E}} \oplus 1\%$
HAD	thickness	$4.5\,\lambda$	$7\,\lambda$
	sample(Fe)	25-50 mm	50 mm
	sample(scint.)	10 mm	6 mm
	resolution	$\frac{50\%}{\sqrt{E}} \oplus 3\%$	$\frac{70\%}{\sqrt{E}} \oplus 4\%$



1987: sampling calorimeter
Pb/Fe + plastic scintillator
Energy measured with scint. light

NA48 @ SPS CERN



1997: Quasi homogeneous Liquid Krypton calorimeter (EM)

Energy measured with ionization charge

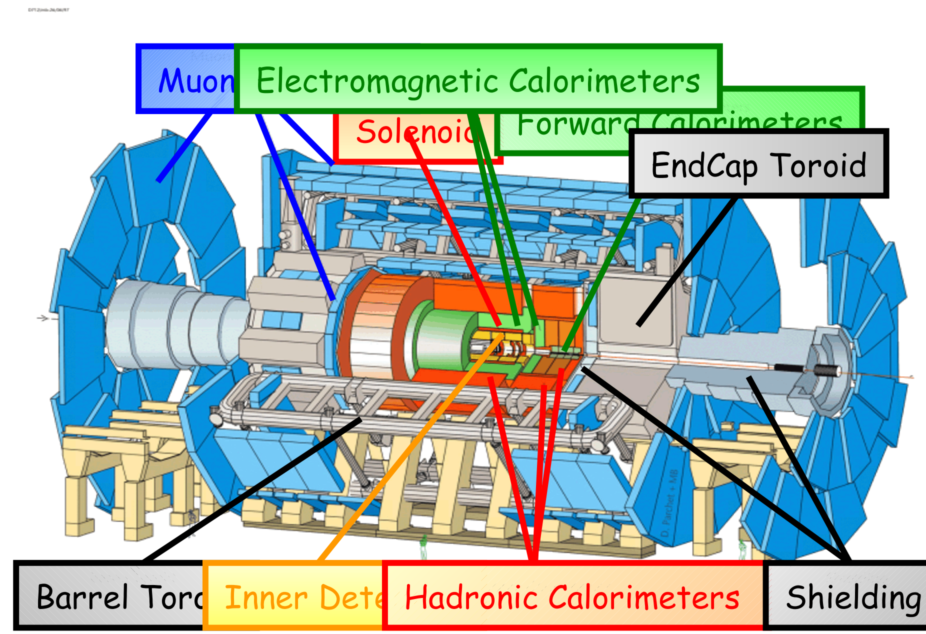
Sampling Iron-Lead Glass calorimeter (Hadron)

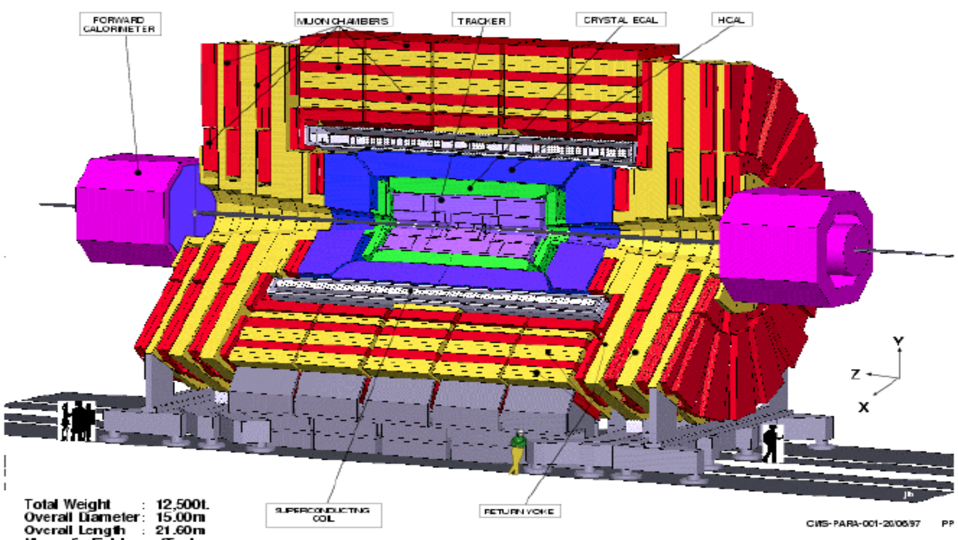
fix target-neutral K beam

CMS/ATLAS @ LHC CERN

Liquid Argon/Pb (EM) and Cu (Hadron) sampling calorimeter

Energy measured using ionization in the liquid argon





Homogeneous PbWO4 crystals (EM) and Brass (Hadron) sampling calorimeter

Energy measured using scintillation light

Trend in Energy Resolution

EM calorimeters

EXP	ENERGY RESOLUTION	range
cosmic	?	
ISR	0.10/ sqrt(E)	0.7-4 GeV
UA2	0.14/sqrt(E)	1-70 GeV
L3	1% for E> few GeV	3-100 GeV
CDF	2% @ 50 GeV	2-60 GeV
NA48	0.03/sqrt(E) +0.04	3-100 GeV
CMS	0.03/sqrt(E) +0.04	15-180 GeV
ATLAS	0.10/ sqrt(E)	15-180 GeV

Physics Processes to measure E

Basic mechanisms used in calorimetry in particle physics to measure energy

- **Ionization charge**
- **Scintillation light**
- **Čerenkov light**

Discoveries thanks to calorimeters

Just to mention fews:

- Neutral currents in GARGAMELLE
- Quark and gluon jets (SPEAR, UA2, UA1 and PETRA)
- W, Z bosons (UA1, UA2)
- Top quark (CDF, D0)
- Neutrino oscillations (SUPER-KAMIOKANDE, SNO)

Lecture Overview

- Calorimeters vs Time
- Basics of calorimetry:
  - **Interactions of particles with matter (electromagnetic)**
  - **Definition of radiation length and critical energy**
  - **Development of electromagnetic showers**
  - **Interactions of particle with matter (nuclear)**
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Particles-Matter Interaction (EM)

Electromagnetic (EM) processes:

- Main photon interactions with matter:
  - **Photoelectric effect**
  - **Compton scattering**
  - **Pair Production**
- Main electron interactions with matter:
  - **Ionization**
  - **Bremsstrahlung**
  - **Čerenkov radiation**
  - **Multiple Scattering**

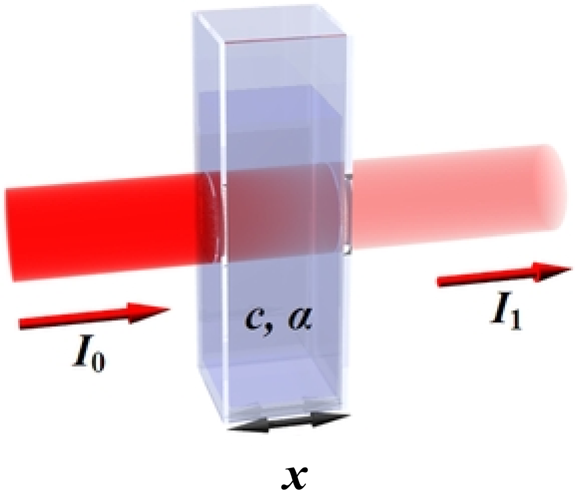
Photon Interactions

Photons are either absorbed (photoelectric effect, pair production) or scattered at large angle (Compton effect)

Photon beam attenuated in matter

(Beer-Lambert's law):

$$I_1(X) = I_0 e^{-\mu x} = I_0 e^{-\mu/\rho X}$$



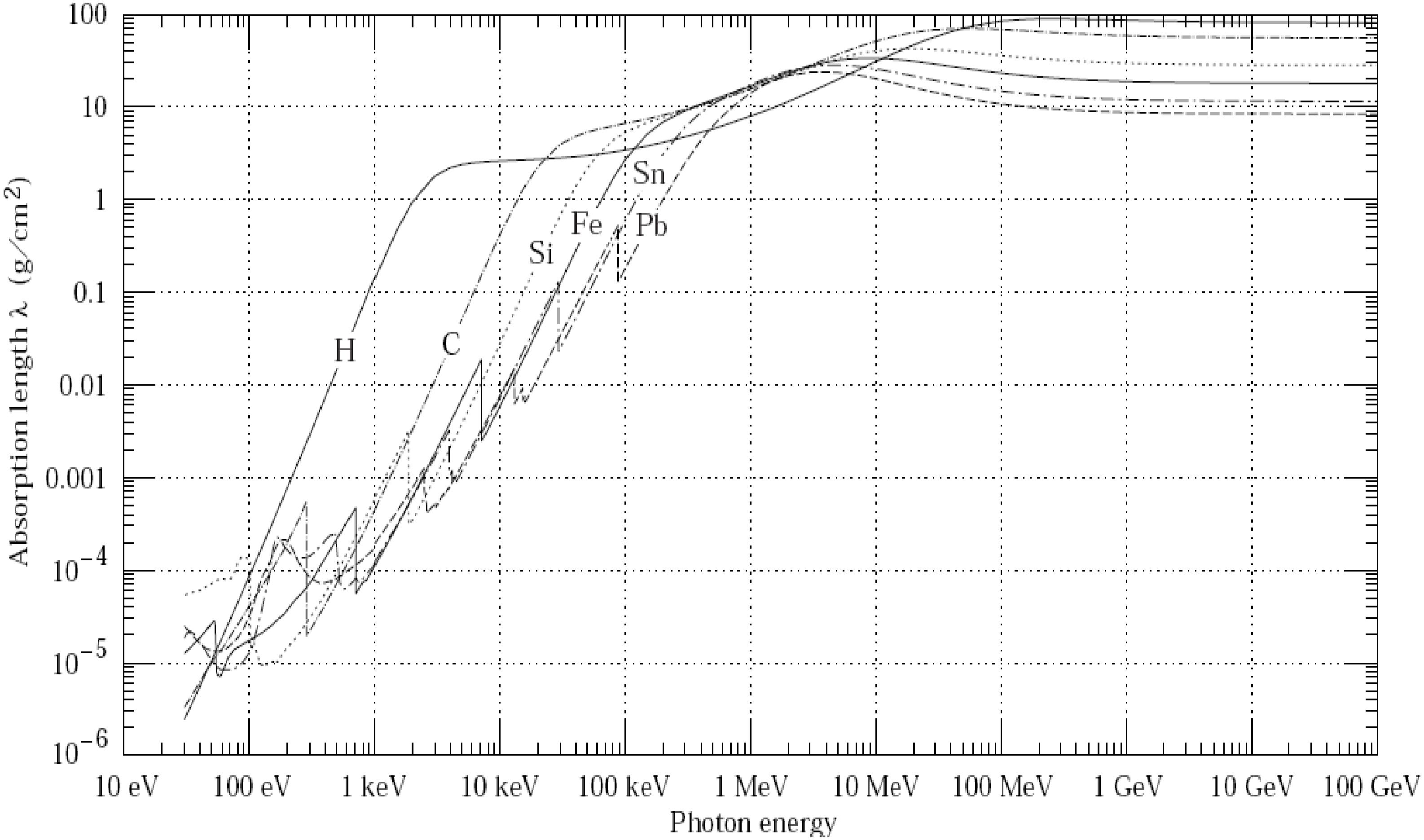
X = ρ x = mass thickness [g/cm²]

α = μ/ρ = mass absorption coefficient.

λ = α⁻¹ [g/cm²] = **photon** mass **attenuation length = mean free path**

Photon Interactions

attenuation length



Photon Interactions

Total Cross-section for photon absorption is related to attenuation length

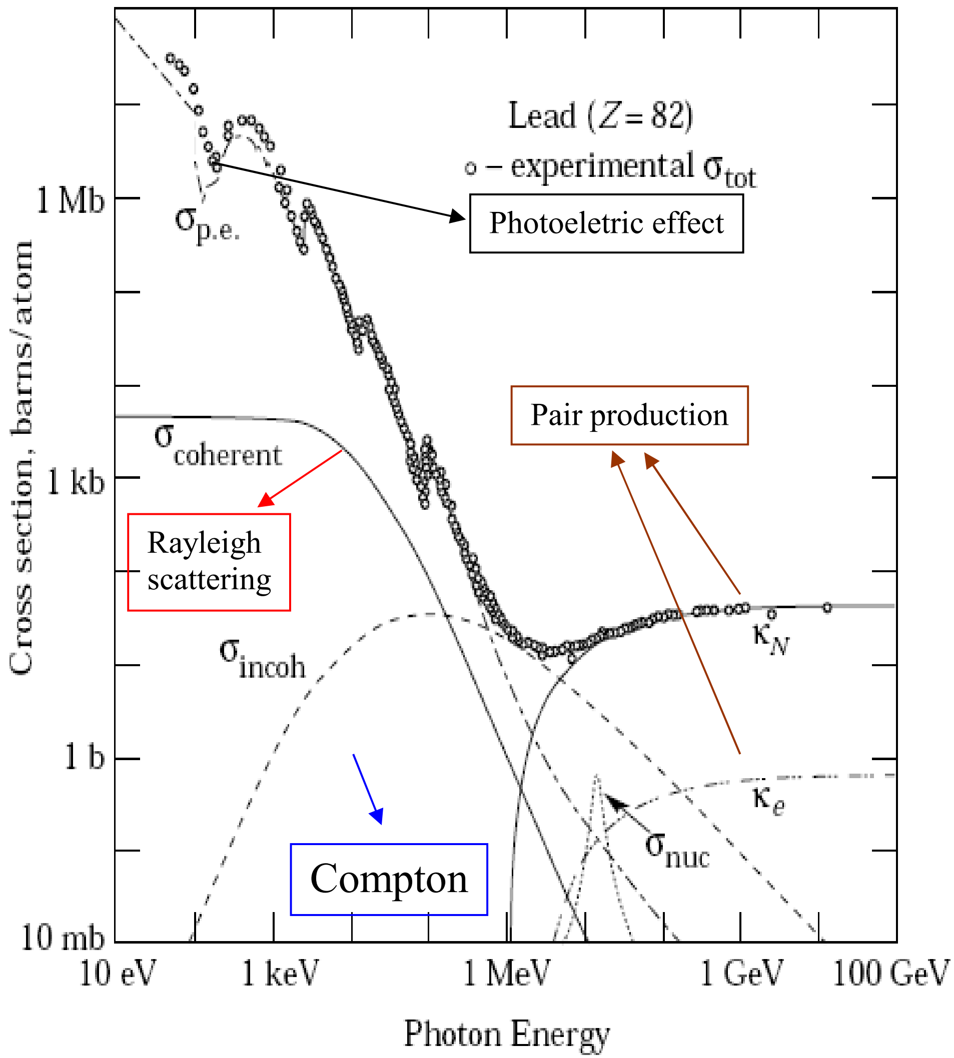
$$\lambda = A / N_A * 1/\sigma_{TOT}$$

A = Atomic mass of the material [g/mol]

$N_A = 6.022\,141\,99(47)\,10^{23}\ \mathrm{mol}^{-1}$ = Avogrado's number

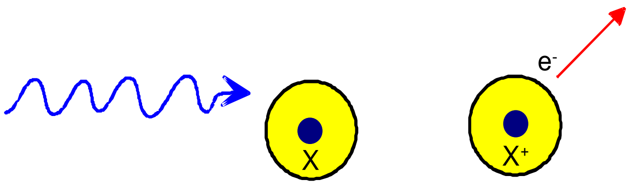
contributing processes:

photoelectric	ion. energy < E < 100 KeV
compton	E ~ 1 MeV
pair production	E >> 1 MeV



Photon Interactions

Photoelectric effect



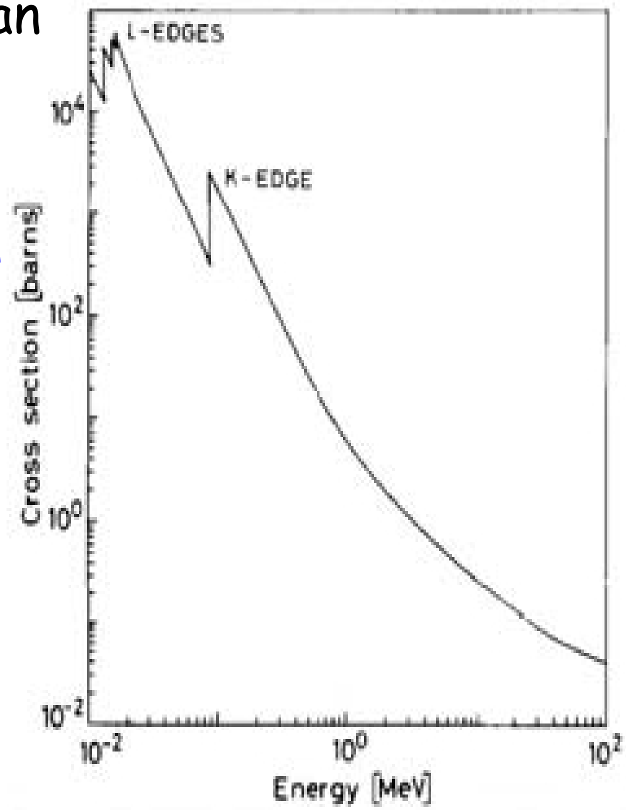
$$g + \text{atom}\,(X) \rightarrow \text{ion}\,(X^+) + e^-$$

→Can be considered as an interaction between a photon and an atom as a whole

→If a photon has energy $E_\gamma > E_b$ (= binding energy of an electron)

The photon energy is fully transferred to the electron

Electron is ejected with energy $T = E_\gamma - E_b$



→Discontinuities in the cross-section due to discrete energies E_b of atomic electrons (strong modulations at $E_\gamma = E_b$; L-edges, K-edges, etc)

Dominating process at low γ's energies (< *MeV*). Gives low energy electron

Photon Interactions

Photoelectric effect

Cross-section:

$$\epsilon = E_\gamma / mc^2$$ reduced photon energy

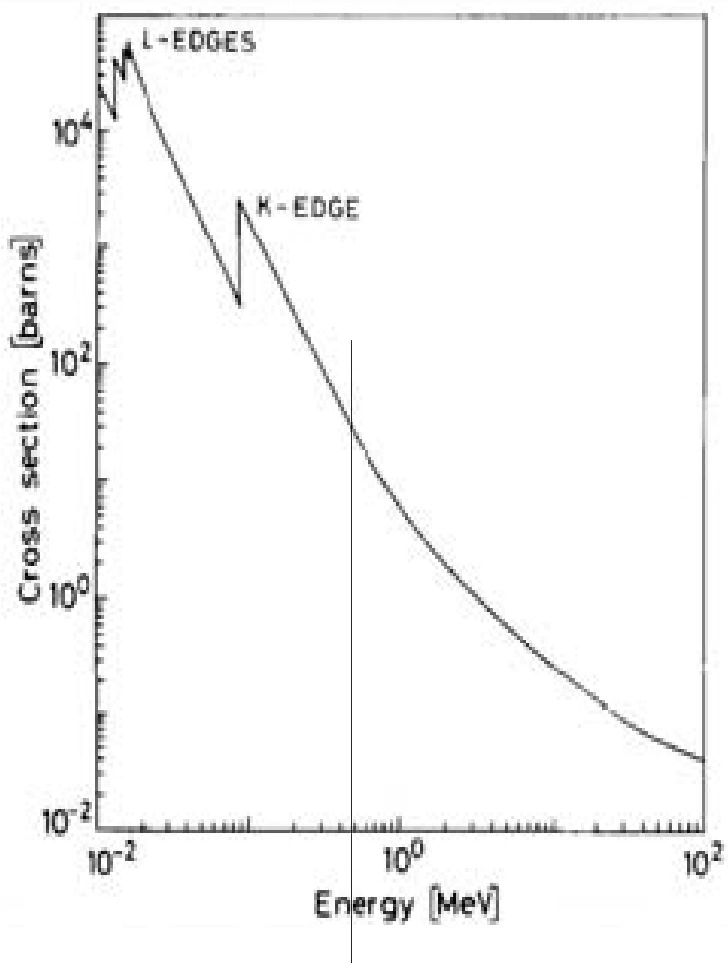
For $\varepsilon_K < \varepsilon < 1$ (ε_K is the K-absorption edge):

$$\sigma_{ph} = (32/\epsilon^7)^{1/2} \alpha^4 Z^5 \sigma_{Th}^e$$

For $\varepsilon >> 1$ ("high energy" photons):

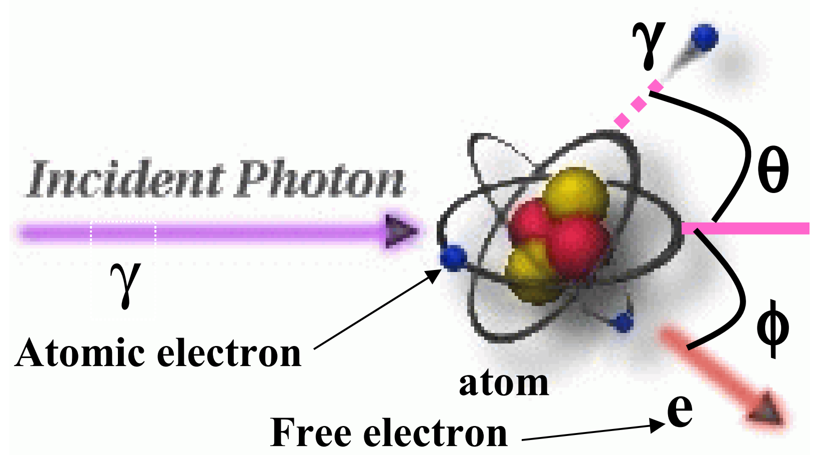
$$\sigma_{ph} = (1/\epsilon) 4\pi r_e^2 \alpha^4 Z^5$$

σ_{ph} goes with Z^5/ε



Photon Interactions

Compton scattering



A photon with energy E_{in} scatters off an (quasi-free) atomic electron

A fraction of E_{in} is transferred to the electron $g + \text{atom (X)} \rightarrow \text{ion } (X^{+}) + e^{-}$

The resulting photon emerges with $E_{out} < E_{in}$

The energy of the outgoing photon is:

$E_{out}/E_i = 1/(1+\epsilon(1-\cos\theta))$, where $\epsilon = E_\gamma/mc^2$

Photon Interactions

Compton scattering

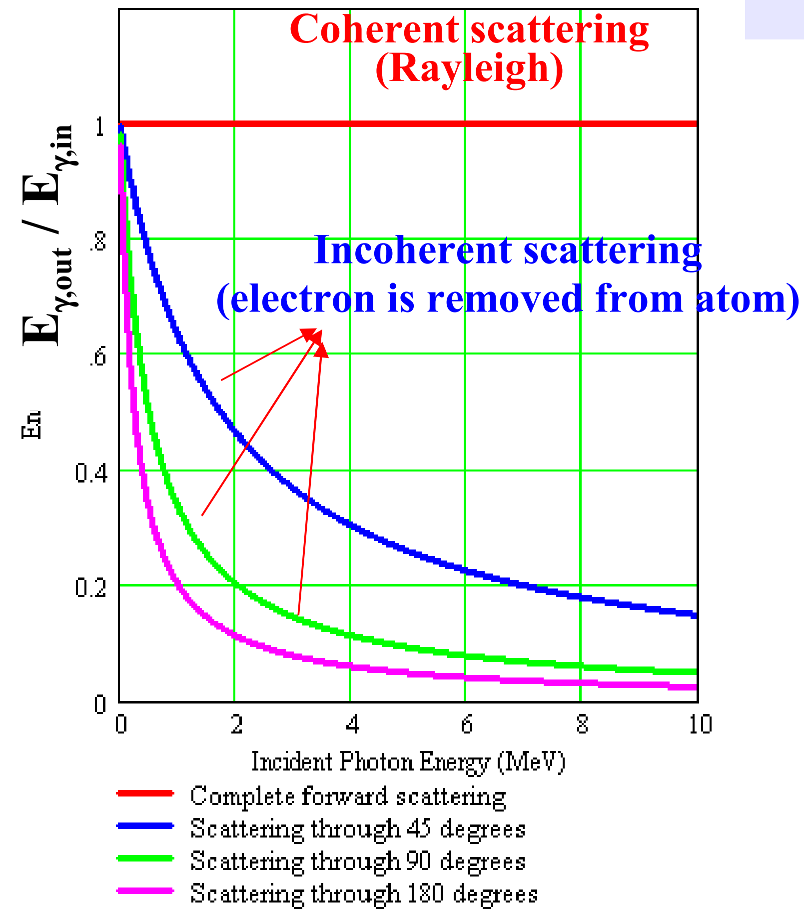
two extreme cases of energy loss:

→ $\theta \sim 0$: $E_{out} \sim E_{,in}$; $T_e \sim 0$

No energy transferred to the electron

→ Backscattered at $\theta = \pi$:

$$E_{out} = E_i / (1 + 2\epsilon) \rightarrow m_e c^2 / 2 \; for \; \epsilon \gg 1$$



Total cross-section per electron given by Klein-Nishina (QED) (1929)

$$\sigma_C^e = 2\pi r_e^2 \left\{ \left(\frac{1+\varepsilon}{\varepsilon^2} \right) \left[\frac{2(1+\varepsilon)}{1+2\varepsilon} - \frac{1}{\varepsilon} \ln(1+2\varepsilon) \right] + \frac{1}{2\varepsilon} \ln(1+2\varepsilon) - \frac{1+3\varepsilon}{(1+2\varepsilon)^2} \right\}$$

per atom

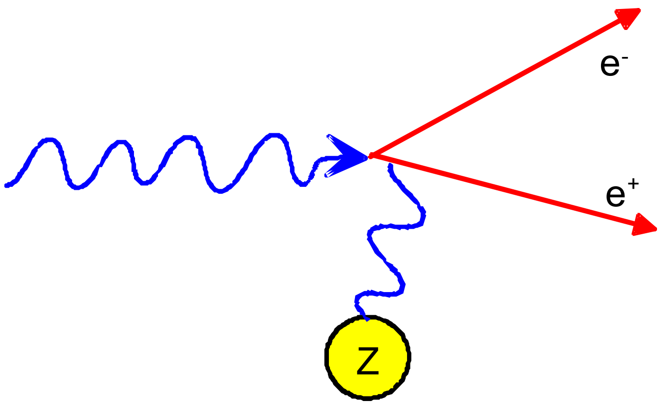
$$\sigma_c^{atomic} = Z \sigma_c^e$$

Photon Interactions

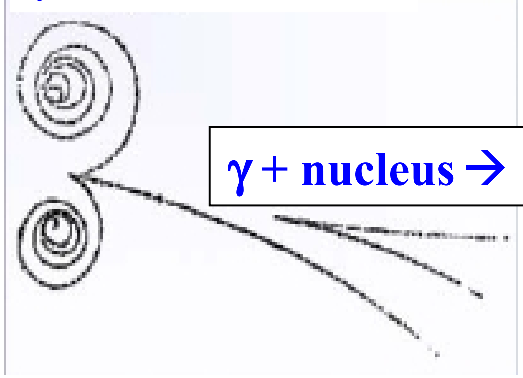
Pair Production

An electron-positron pair can be created when (and only when) a photon passes by the Coulomb field of a nucleus or atomic electron

this is needed for conservation of momentum.



$\gamma + e^- \rightarrow e^+ + e^- + e^-$



$\gamma + \text{nucleus} \rightarrow e^+ + e^- + \text{nucleus}$

Threshold energy for pair production

$E = 2mc^2$ near a nucleus

$E = 4mc^2$ near an electron (strongly suppressed)

Pair production is the dominant photon interaction process at high energies, hundred MeV or more.

Photon Interactions

Pair Production

Asymptotic value of cross-section, energy independent, is:

$$\sigma_{pair} \approx r_e^2 4\alpha Z^2 \left[\frac{7}{9}\ln\left(\frac{183}{Z^{1/3}}\right)\right] \approx \frac{7}{9}\frac{A}{N_A}\frac{1}{X_0}$$

$$X_0 = \frac{7}{9}\lambda$$

X_0 is called radiation length and corresponds to a layer thickness of material where pair creation has a probability ***$P = 1 - e^{-7/9} \approx 54\%$***

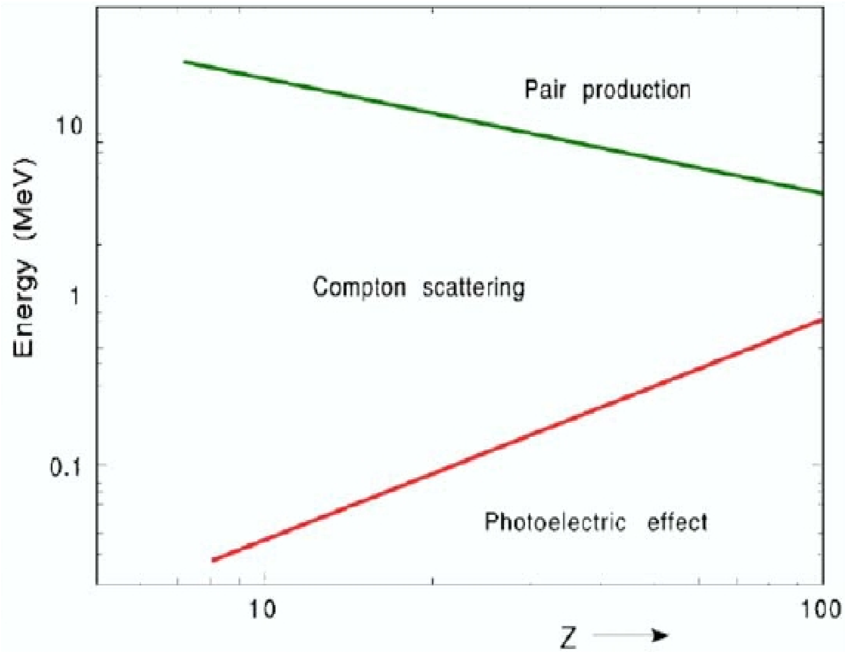
Along with Bremsstrahlung (more later), pair production is a very important process in the development of EM showers

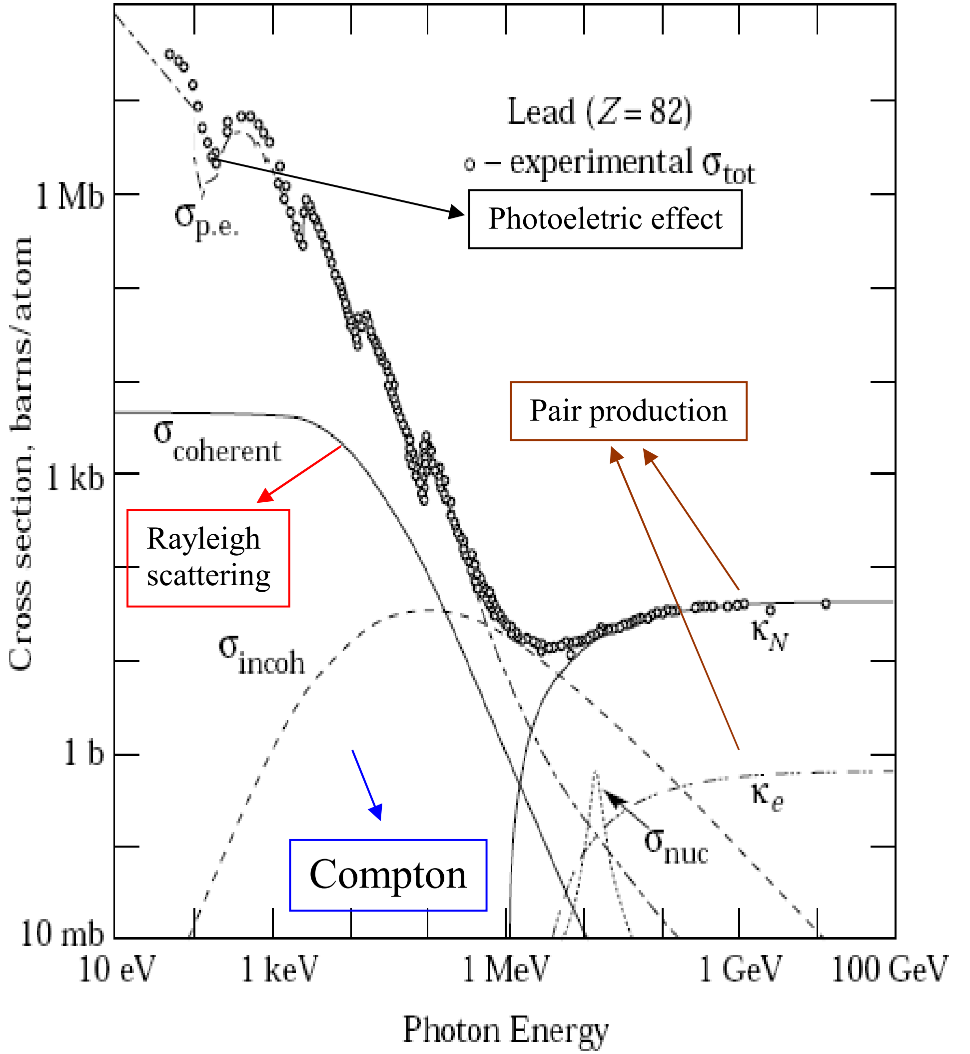
X_0 is a key parameter in the design of a calorimeter

Photon Interactions

SUMMARY PHOTONS

photoelectric ion. energy < E < 100 KeV
compton E ~ 1 MeV
pair production E >> 1 MeV





Charged-particle Interactions

Ionization-Excitation

For "**heavy" charged particles** ($M >> m_e$: p, K, π, μ), the average rate of energy loss (or stopping power) in an inelastic collision with an atomic electron is given by the Bethe-Bloch formula

$$-\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 \frac{Z}{A} \frac{z^2}{\beta^2} \left[\ln\left(\frac{2 m_e c^2 \beta^2 \gamma^2}{I} \right) - \beta^2 - \frac{\delta}{2} \right] \left[\frac{MeV}{g/cm^2} \right]$$

δ : density-effect correction

z : charge of the incident particle

$\beta = v/c$ of the incident particle

I : ionization constant, characteristic of the absorber

→ **approx precise @ few % up to energies of several hundred GeV**

→ **valid for particles with** $\beta >> \alpha Z$

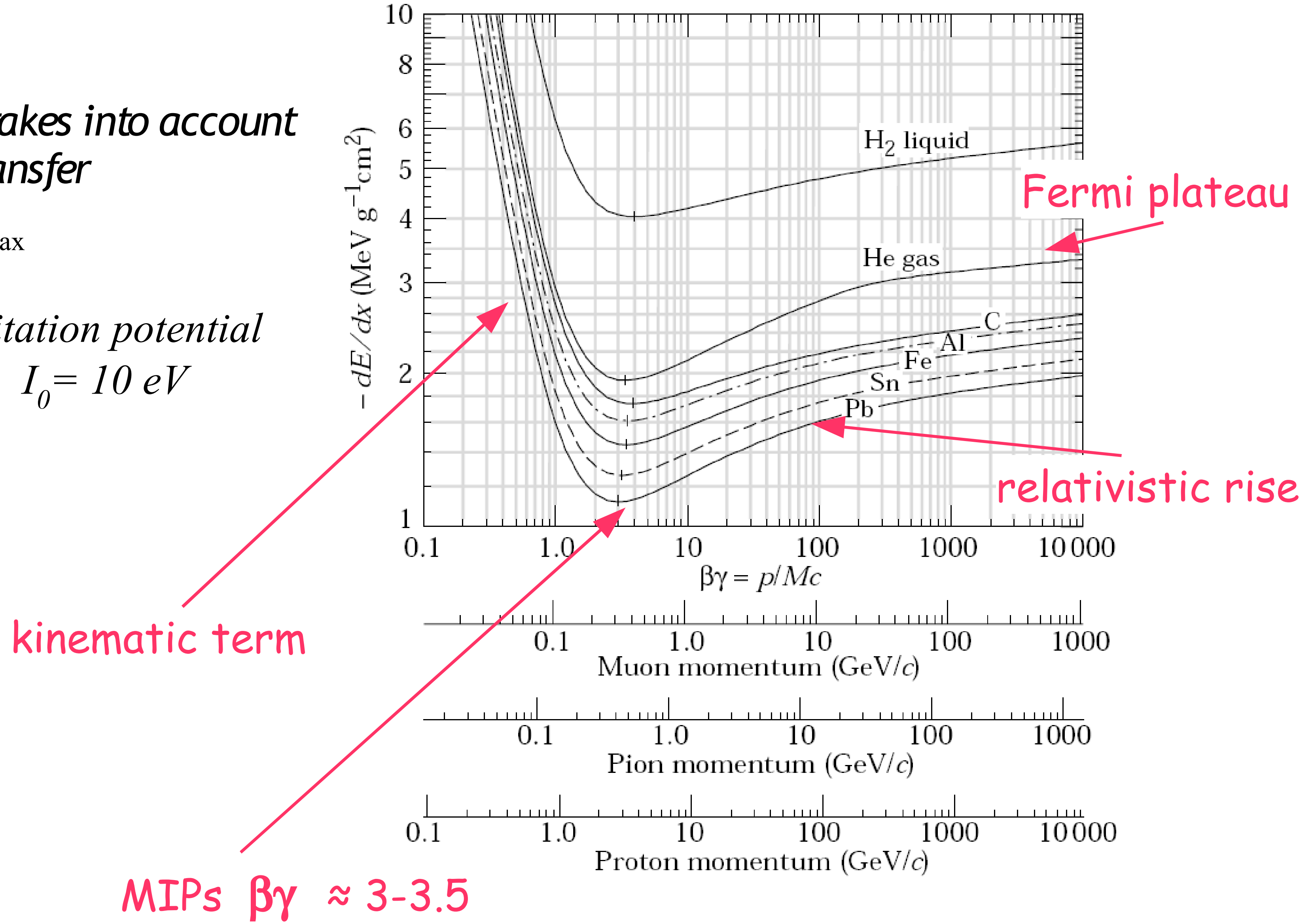
Charged-particle Interactions

this formula takes into account the energy transfer

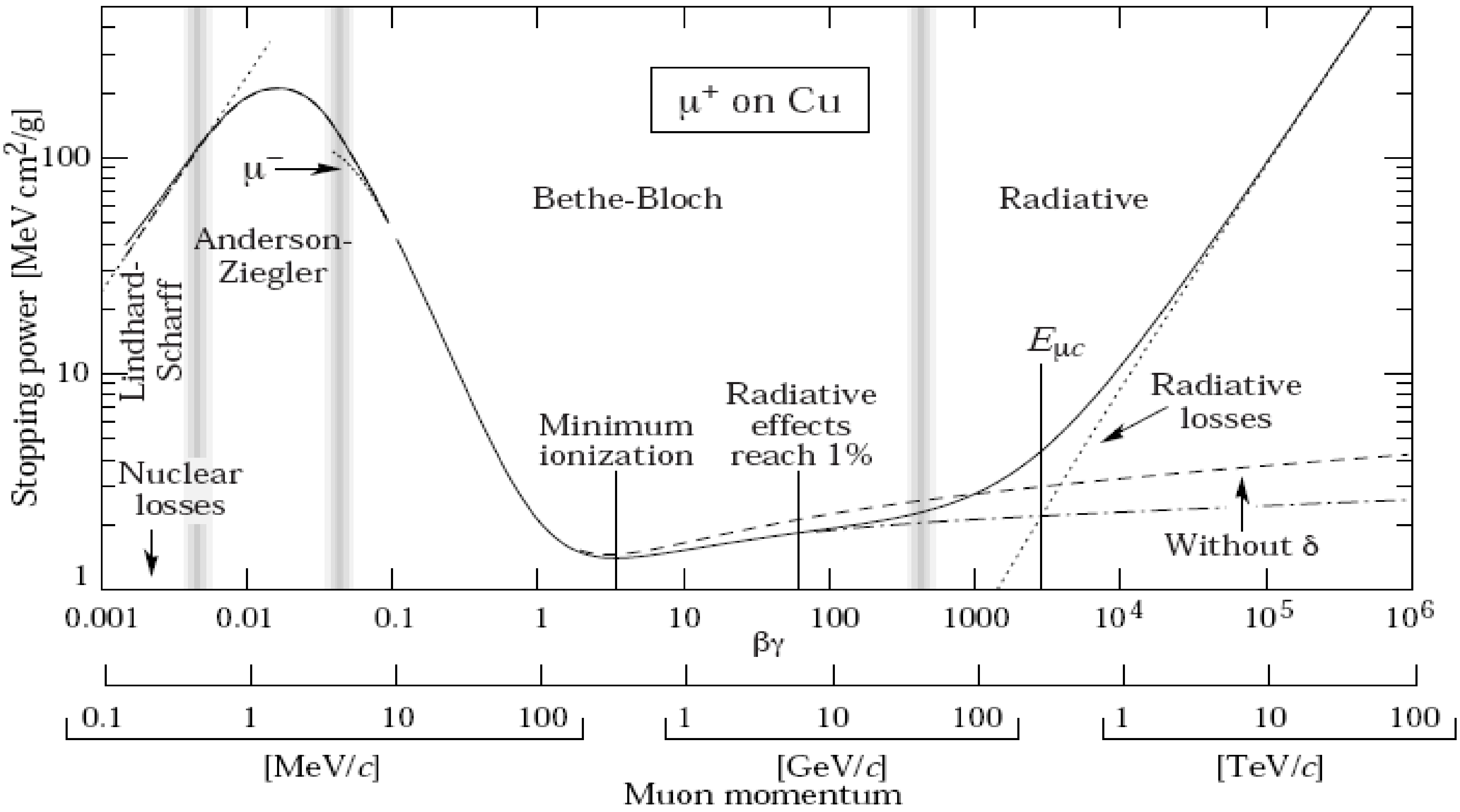
$I \leq dE \leq T_{max}$

I = mean excitation potential

$I \approx I_0 Z$ with $I_0 = 10$ eV



Charged-particle Interactions



Electron Interactions

Ionization

For electron and positron the average rate of energy loss is approximated by

$$-\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\ln\left(\frac{\gamma m_e c^2}{2I}\right) - \beta^2 - \frac{\delta^x}{2}\right] \left[\frac{MeV}{g/cm^2}\right]$$

≠ Bethe-Bloch

Small electron/positron mass ; Identical particles in the initial and final state ; Spin ½ particles in the initial and final states

Electron Interactions

Ionization

At high energy ($\beta \approx 1$), the energy loss for both "heavy" charged particles and electrons/positrons can be approximated by

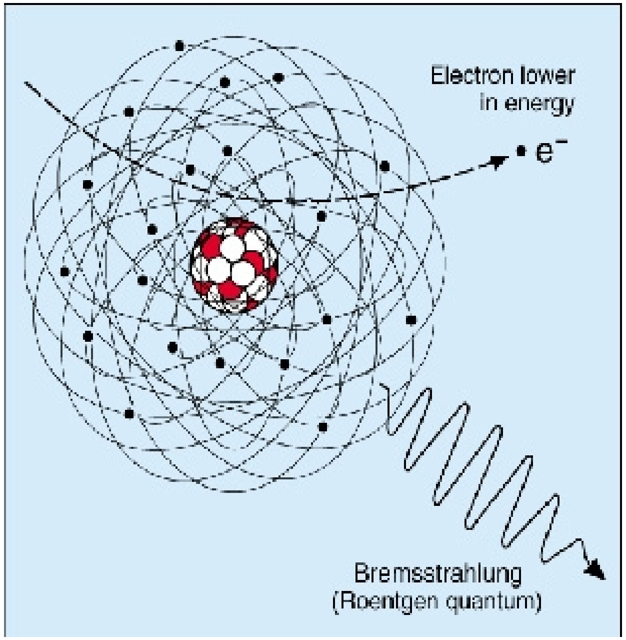
$$-\frac{dE}{dx} \propto \left[2\ln\left(\frac{2m_e c^2}{I}\right) + A\ln\gamma - B \right]$$

	A	B
electrons	3	1.95
heavy ch particles	4	2

B indicates that the rate of relativistic rise for electrons is slightly smaller than for "heavy" particles. This provides a criterion to distinguish charged particles of different masses.

Electron Interactions

Bremsstrahlung (braking radiation)



Fast charged particles radiate a real photon while being decelerated in the Coulomb field of a nucleus:

$$\frac{d\sigma}{dE} \propto \frac{Z^2}{m_i^2} \frac{\ln E}{E}$$

for electrons and positrons this loss plays an important role

$$\left(\frac{d\sigma}{dE}\right)_e \Big/ \left(\frac{d\sigma}{dE}\right)_\mu = \left(m_\mu / m_e\right)^2 \approx 37 \times 10^3$$

Electron Interactions

Bremsstrahlung

The rate of energy loss for $E >> m_e c^2/\alpha Z^{1/3}$ is given by:

$$-\frac{dE}{dx} \approx r_e^2 4\alpha Z^2 \frac{N_A}{A}\left(\ln\frac{183}{Z^{1/3}}\right)E$$

It can be written as

$$\frac{dE}{dx} = -\frac{E}{X_0} \Rightarrow E(x) = E_0 e^{-\frac{x}{X_0}} \quad \Longrightarrow \quad X_0 = \frac{A}{N_A}\frac{1}{r_e^2 4\alpha Z^2 \ln\left(183/Z^{1/3}\right)}$$

The radiation length X_0 is the layer thickness that reduces the electron energy by a factor e (~63%). In literature, X_0 defined for incident e-.

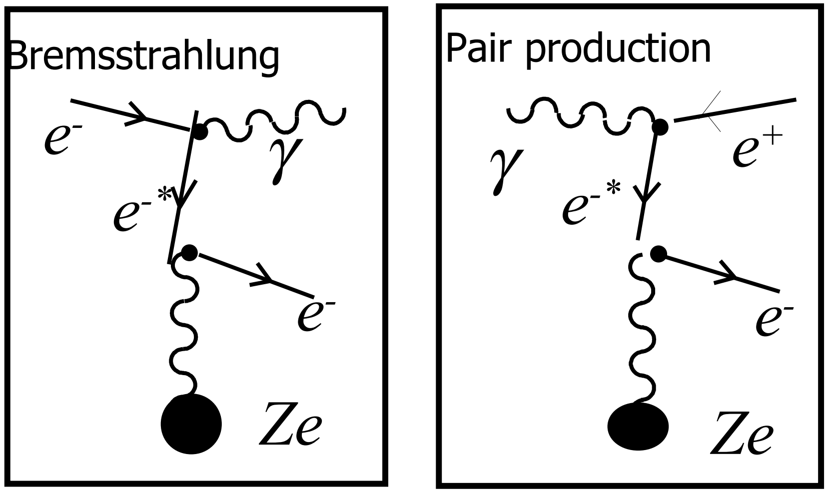
Electron Interactions

Bremsstrahlung and Pair production

The mean free path for photons (pair production) is very similar to X_0 , electrons radiation length

$$\lambda_{pair} = \frac{9}{7} X_0$$

pair production and Bremsstrahlung have very similar Feynman diagrams

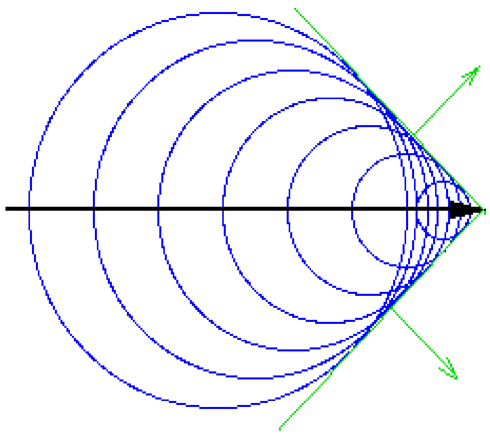


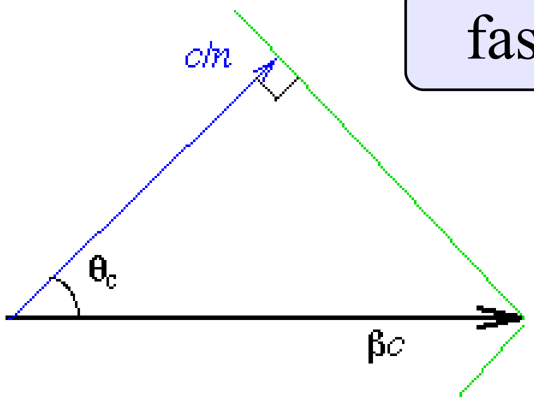
Basis of Shower development ⇨ electron-positron pair will each subsequently radiate a photon by Bremsstrahlung, which will produce a electron-positron pair and so on...

Electron Interactions

Cerenkov radiation

Fast moving particles traversing a medium (refr. index ***n***) with $v > c/n$ emit real photons (medium atoms are polarized -> electric dipoles)





fast

$$\cos\theta_c = \frac{1}{\beta n}$$

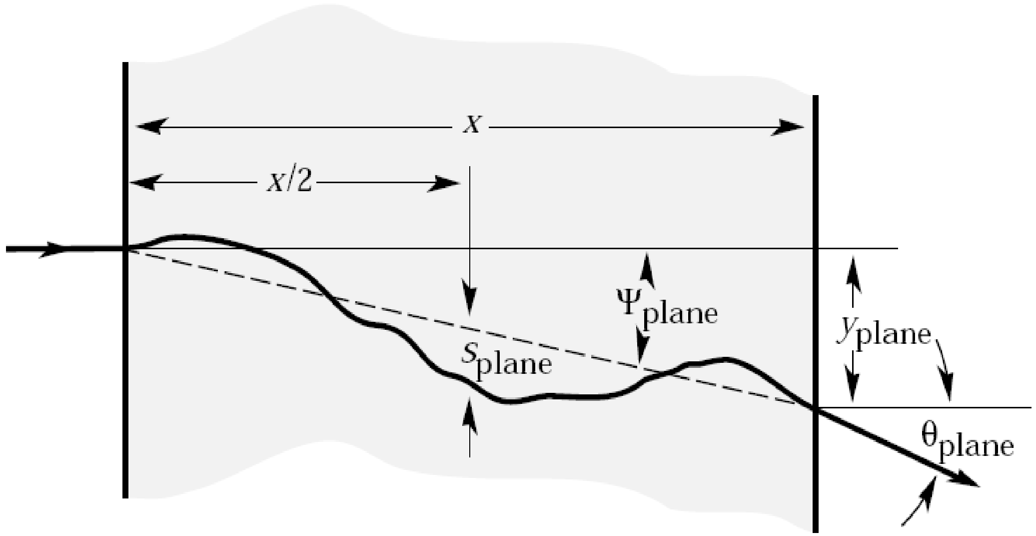
Photons only in optical region (n > 1 and medium is transparent)
small contribution: < 1% of ionization loss for Z > 7, 5% for light gas

Electron Interactions

Multiple Scattering

- Multiple elastic interactions charged particle-medium
- Average scattering angle is roughly Gaussian for small deflection angles

$$\theta_0 = \theta_{plane}^{RMS} = \frac{1}{\sqrt{2}}\theta_{space}^{RMS} \propto \frac{1}{p}\sqrt{\frac{x}{X_0}}$$



X_0 is the radiation length

This contributes to the transverse size of an electromagnetic shower

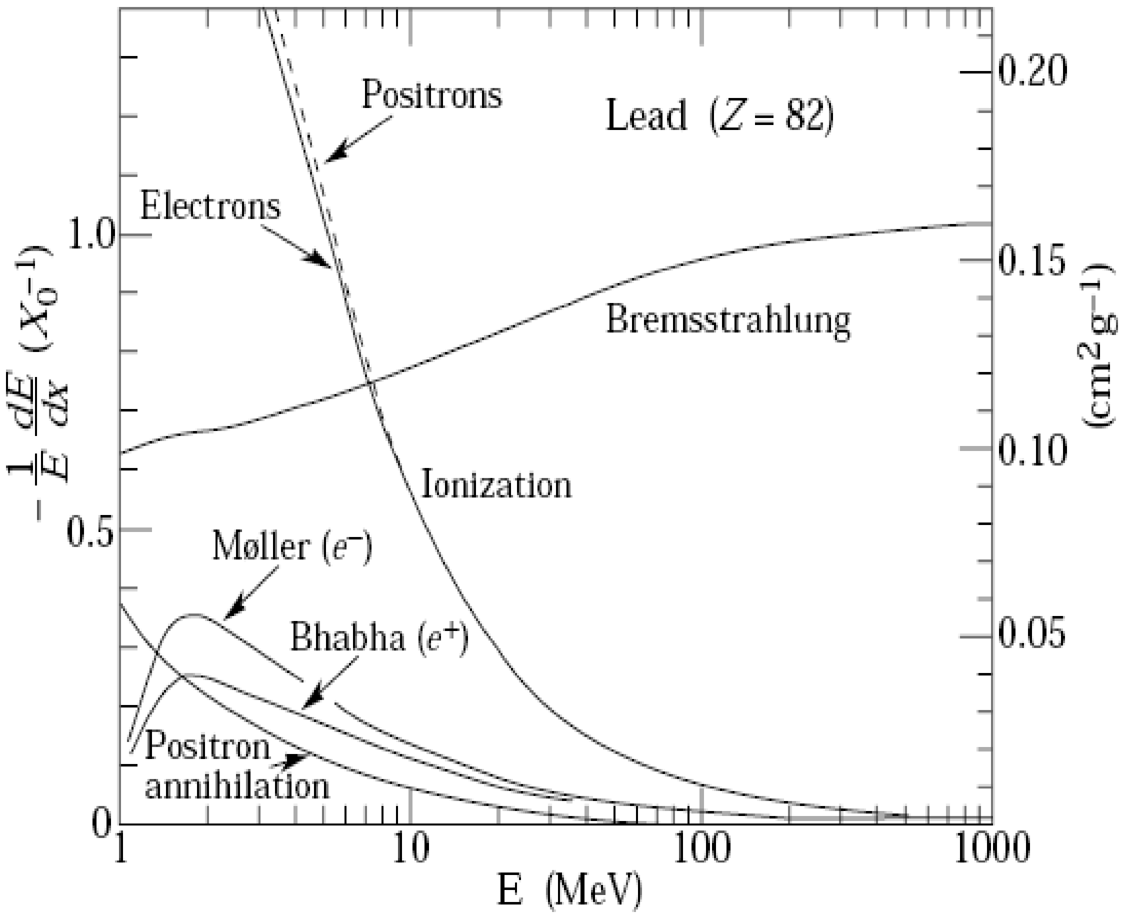
Electron Interactions

SUMMARY ELECTRONS

ionization E < 10 MeV

bremsstrahlung E > 10 MeV

Relative energy loss as a function of electron energy



Electron Interactions

Another important quantity in calorimetry is the so called **critical energy**. It is the energy at which the loss due to radiation equals that due to ionization

$$E_c \approx \frac{dE}{dx}(E_c)\Big|_{Brem} = \frac{dE}{dx}(E_c)\Big|_{ion}$$

Alternate definition (Rossi):

$$\frac{dE}{dx}_{ion} = \frac{E}{X_0}$$

Approx formula using Rossi def. per solid and gas

$$E_c \approx \frac{610(710)\,MeV}{Z + 1.24(0.92)}$$

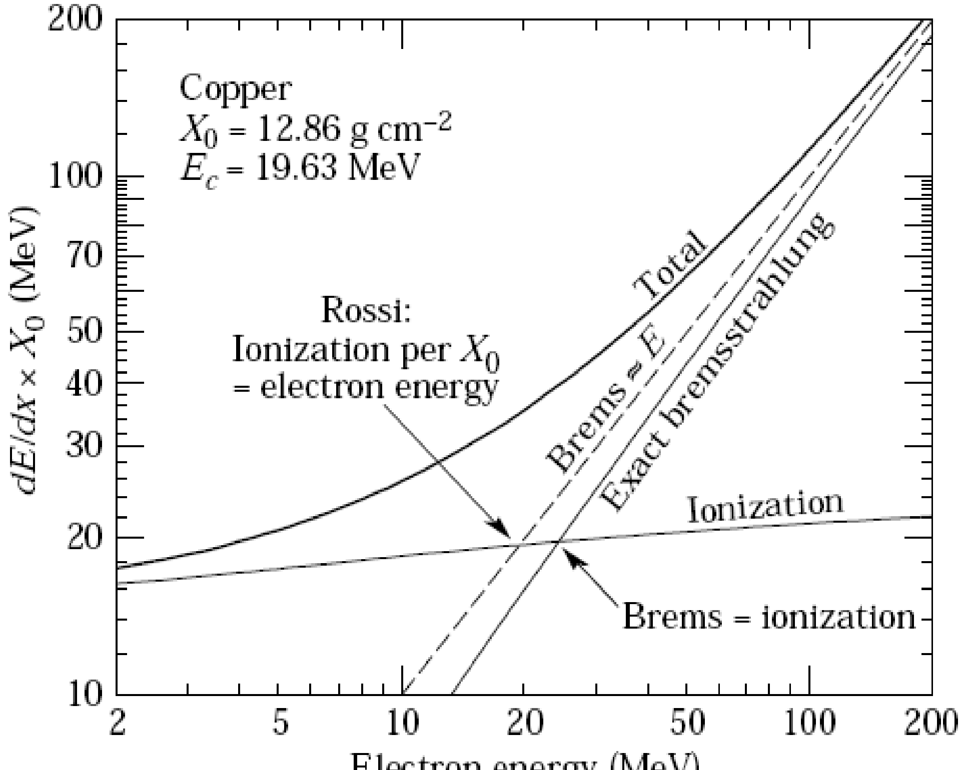


Figure 27.12: Two definitions of the critical energy E_c.

Lecture Overview

- What is a calorimeter?
- Calorimeters vs Time
- Basics of calorimetry:
  - Interactions of particles with matter (electromagnetic)
  - Definition of radiation length and critical energy
  - **Development of electromagnetic showers**
  - Interactions of particle with matter (nuclear)
  - Development of hadronic showers

Development of electromagnetic shower

Two energy regimes:

1. "High" Energy (> ~10 MeV):

   electrons lose energy mostly via Bremsstrahlung

   photons via pair production

Photons from Bremsstrahlung can create an electron-positron pair which can radiate new photons via Bremsstrahlung (until E> Ec)

2. Low Energy

   electrons lose energy mostly throu collisions with atoms/molecules (ionization and excitation)

   photons via Compton scattering and photoelectric effect

Electrons E > 1 GeV give rise to a cascade (shower) of particles. Number of particles increases until the energy of the elctron component falls below Ec

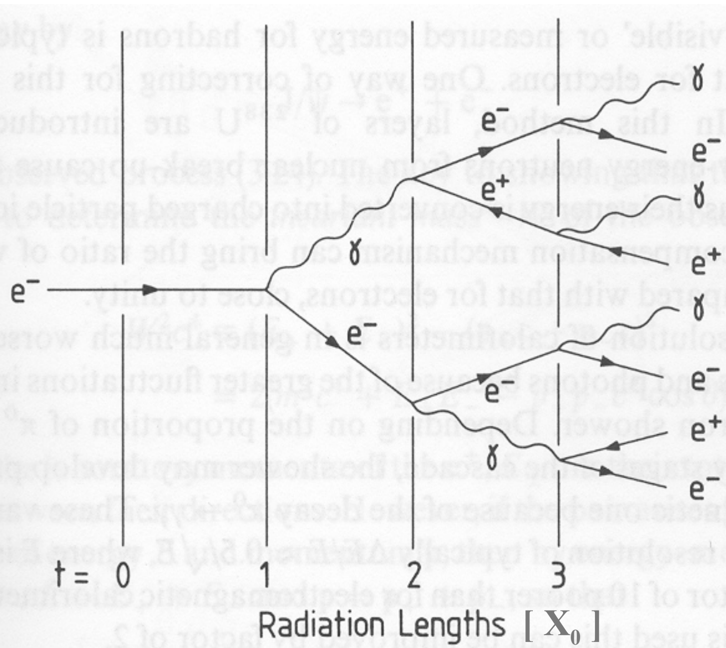
Development of electromagnetic shower

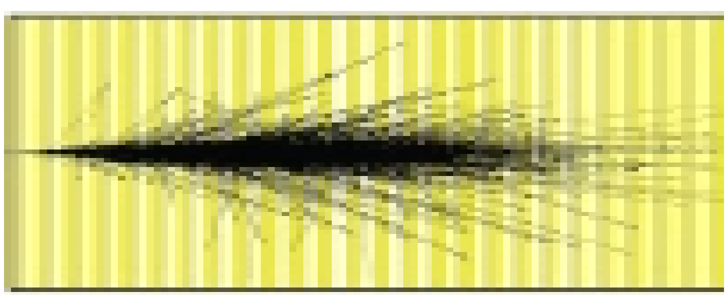
main shower characteristics

Simple Shower Model assumptions:

- $\lambda_{pair} \approx X_0$
- Electrons and positrons behave identically
- Neglect energy loss by ionization or excitation for $E > E_c$
- Each electron with $E > E_c$ gives up half of its energy to bremsstrahlung photon after $1X_0$
- Each photon with $E > E_c$ undergoes pair creation after $1X_0$ with each created particle receiving half of the photon energy
- Shower development stops at $E = E_c$
- Electrons with $E < E_c$ do not radiate; remaining energy lost by collisions

Development of electromagnetic shower





Simple Shower Model

After $1X_0$: 1 e- and 1 γ , each with $E_0/2$

After $2X_0$: 2 e-, 1 e+ and 1 γ , each with $E_0/4$

After tX_0 :

$$N(t) = 2^t$$

$$E(t) = E_0 2^{-t}$$

Maximum number of particles reached at E = Ec

$$N_{max} = E_0 / E_c \qquad t_{max} = \frac{\ln(E_0/E_c)}{\ln 2}$$

Total Number of Particles

$$N_{all} = \sum_{t=0}^{t_{max}} 2^t = 2 \times 2^{t_{max}} - 1 \approx 2 \times 2^{t_{max}} = 2\frac{E_0}{E_c} \quad \propto E_0$$

Development of electromagnetic shower

Simple Shower Model

Total number of charge particles (e^+ and e^- ~ 2/3 and γ ~ 1/3)

$$N_{e^+e^-} = \frac{2}{3} \times 2\frac{E_0}{E_c} = \frac{4}{3}\frac{E_0}{E_c}$$

Total charged track length (g/cm^2) $\propto X_0 E_0/E_c$

Measured energy proportional to E_0

95% of Shower contained in: $t_{95} \approx t_{max} + 0.08Z + 9.6$ X_0 units

For calorimeters thickness 25X_0 , back leakage is below 1% for E~ 300 GeV

Development of electromagnetic shower

Longitudinal profile

Simulation of the energy deposit in copper as a function of the shower depth for incident electrons at 4 different energies showing the logarithmic dependence of t_{max} with E.

EGS4* (electron-gamma shower simulation)

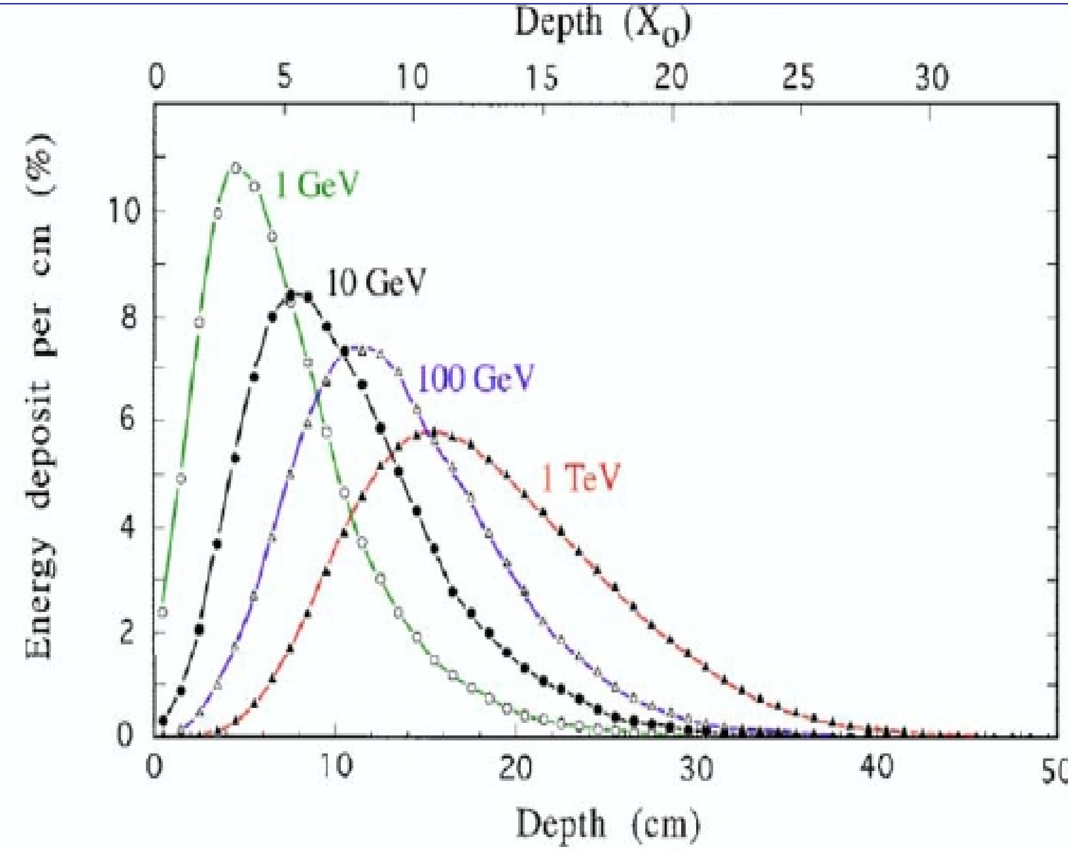


FIG. 2.9. The energy deposit as a function of depth, for 1, 10, 100 and 1000 GeV electron showers developing in a block of copper. In order to compare the energy deposit profiles, the integrals of these curves have been normalized to the same value. The vertical scale gives the energy deposit per cm of copper, as a percentage of the energy of the showering particle. Results of EGS4 calculations.

Development of electromagnetic shower

The simple model can explain well the main characteristics.
What is not taken into account by the simple model:

- Discontinuity at t_{max} : shower stops: no energy dependence of the cross-section
- Lateral spread: electrons undergo multiple Coulomb scattering
- Difference between showers induced by γ and electrons
  - $\lambda_{pair} = (9/7)\ X_0$
- Fluctuations: Number of electrons/positrons produced not governed by Poisson statistics.

Development of electromagnetic shower

Lateral Shower profile

Lateral spread due to electron/positron undergoing multiple Coulomb scattering

Electrons are increasingly affected by multiple scattering as they become slower.

Measurement of transverse size, integrated over the full shower depth, is given by the **Molière radius ρ_M**

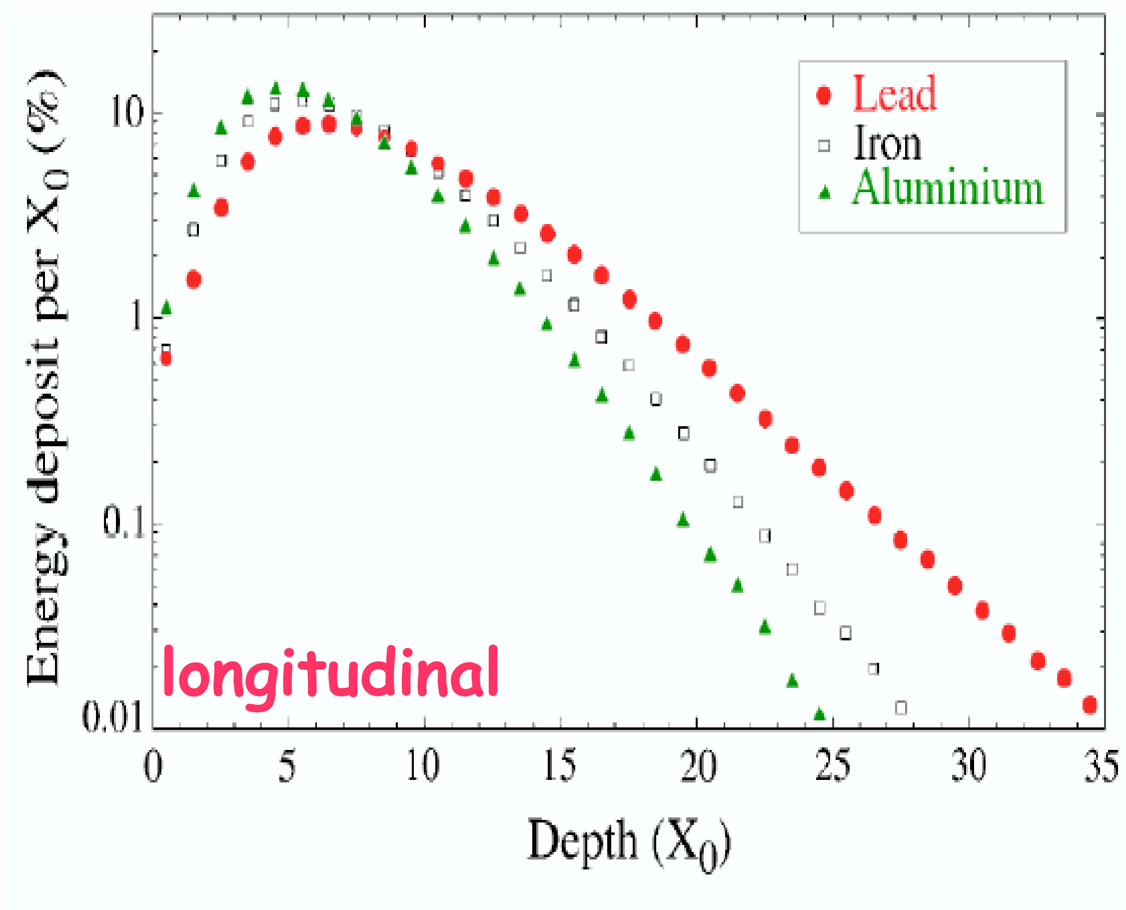
$$\rho_M = X_0 \frac{E_s}{E_c} \left[g/cm^2 \right] \quad , \; E_s \approx 21\,\mathrm{MeV}$$

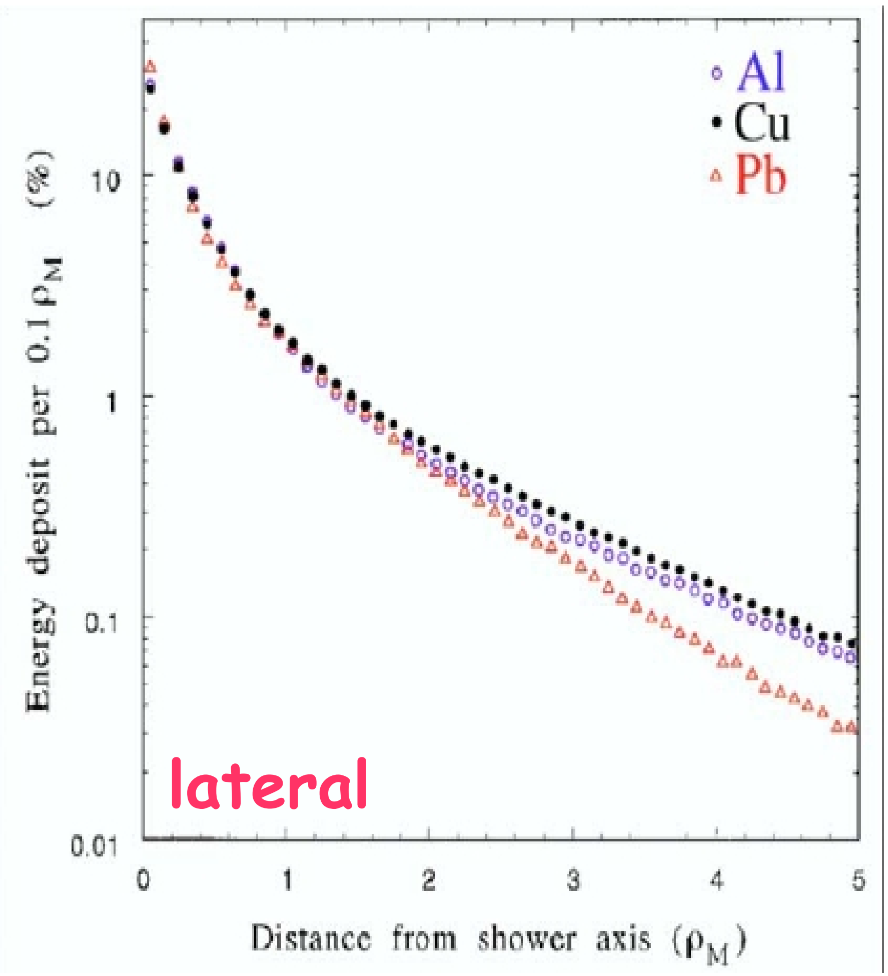
About 90% of the shower is contained in a cylinder of radius < $1\rho_M$

95% of the shower is contained laterally in a cylinder with radius $2\rho_M$

Development of electromagnetic shower

Shower profile



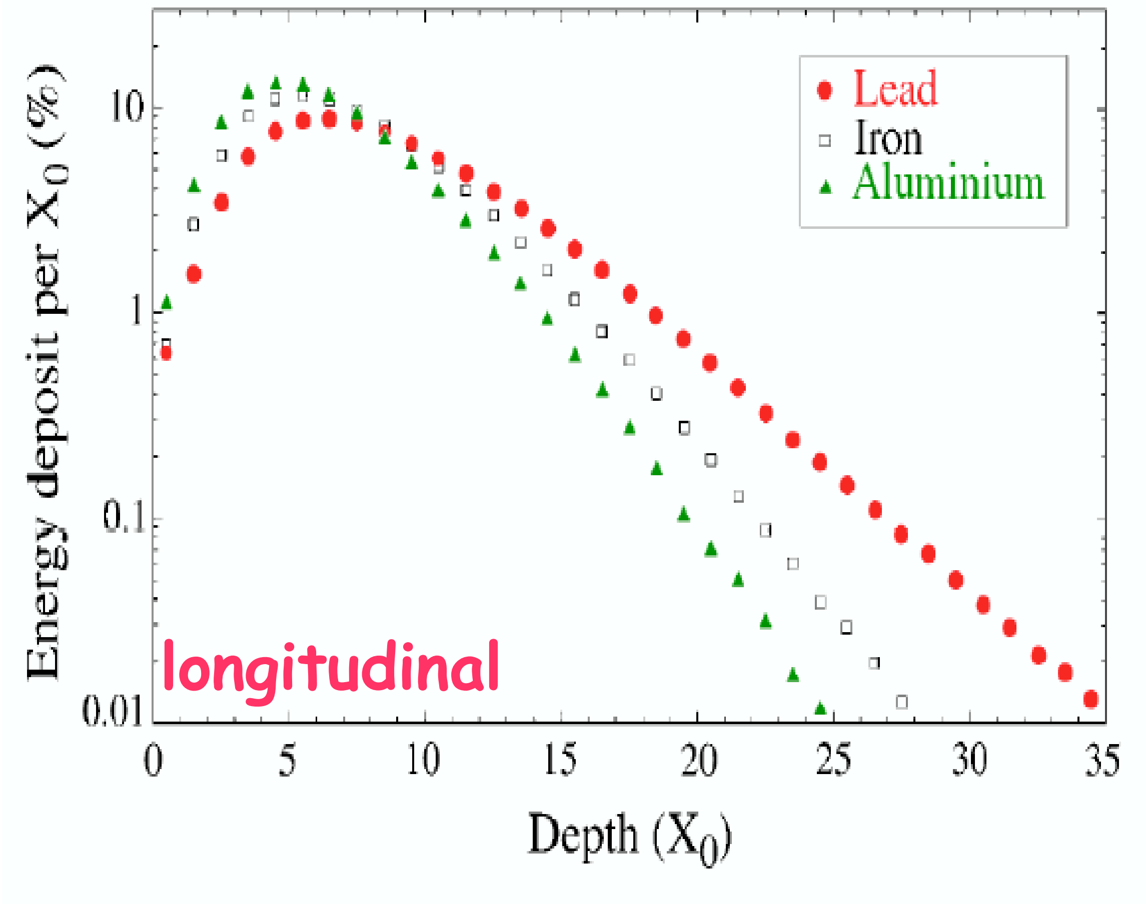


ρ_M less dependent on Z than X_0:

$$X_0 \propto A/Z^2, \quad E_c \propto 1/Z \Rightarrow \quad \rho_M \propto A/Z$$

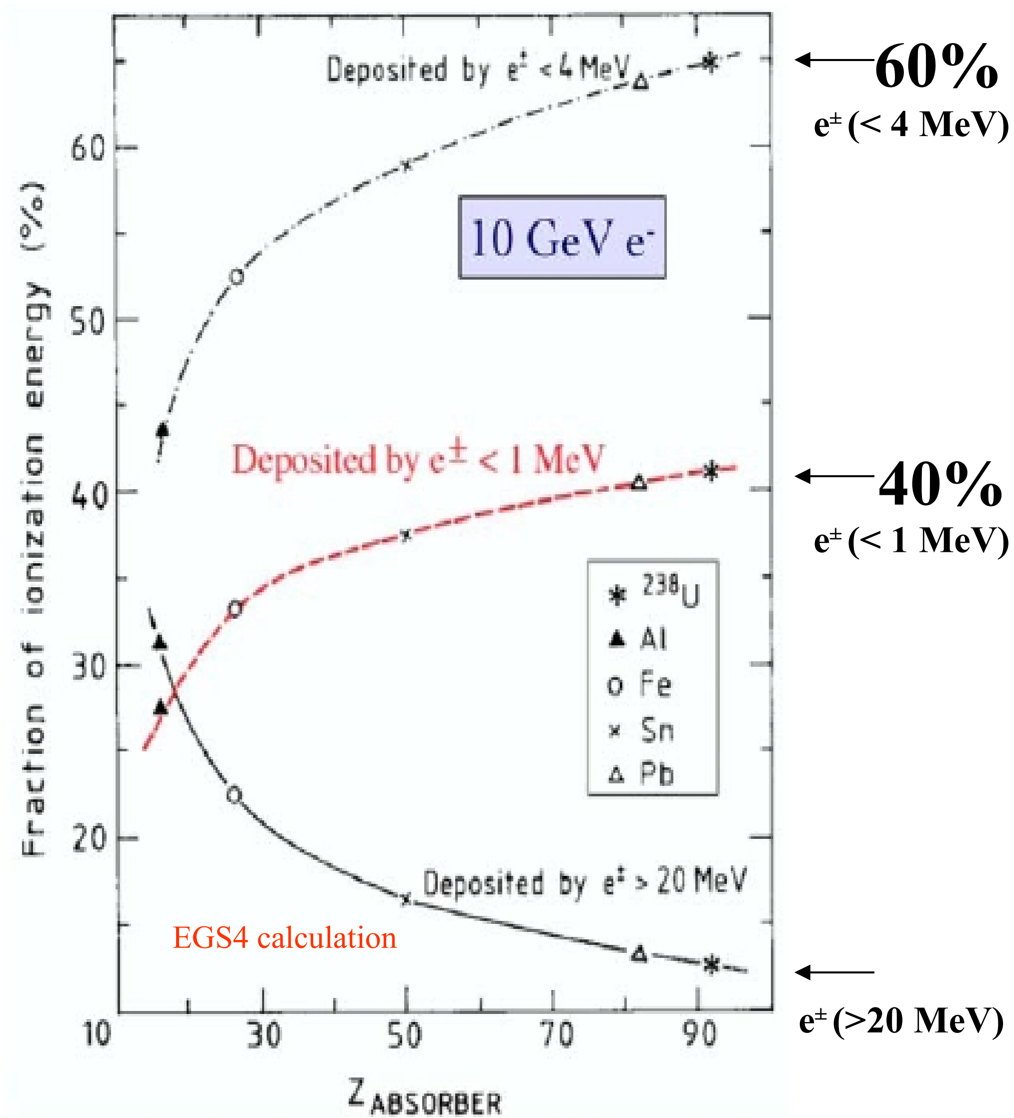
More on longitudinal shower profile

Shower profile



Even though the shower profile scale with X_0 , the scaling is not perfect. Reason: particle multiplication continues up to lower energies in high Z material and decreases more slowly

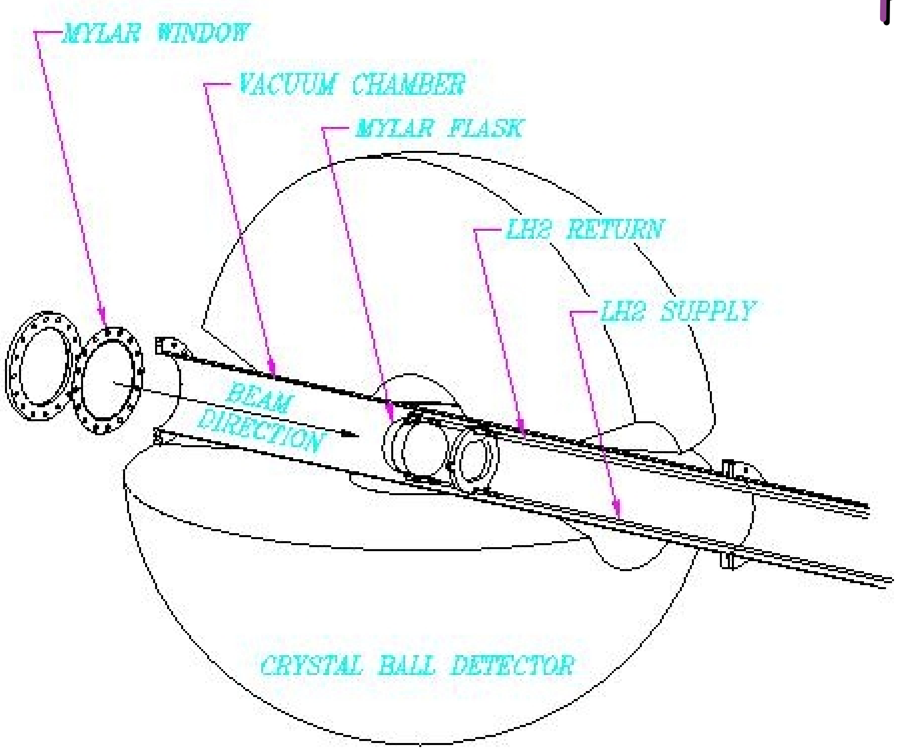
Development of electromagnetic shower



Finally, energy deposited in the active medium by low energy electrons/positrons...

intermezzo

Crystal Ball



Famous EM homogeneus calorimeter.

The Crystal Ball is a hermetic particle detector used initially @ SPEAR (e+ e- 3 GeV) SLAC -1979.

Designed to detect neutral particles; used to discover the η_c meson.

Its central section was a spark chamber surrounded by a nearly-complete sphere of 672 scintillating crystals (NaI(Tl)).

Sphere + endcaps = 98% of the solid angle coverage around the interaction point.

long life!

SLAC (J/psi) → DESY (B physics) → BNL (Barion spectroscopy) → Mainz (neutral meson production/polarization)

Crystal Ball

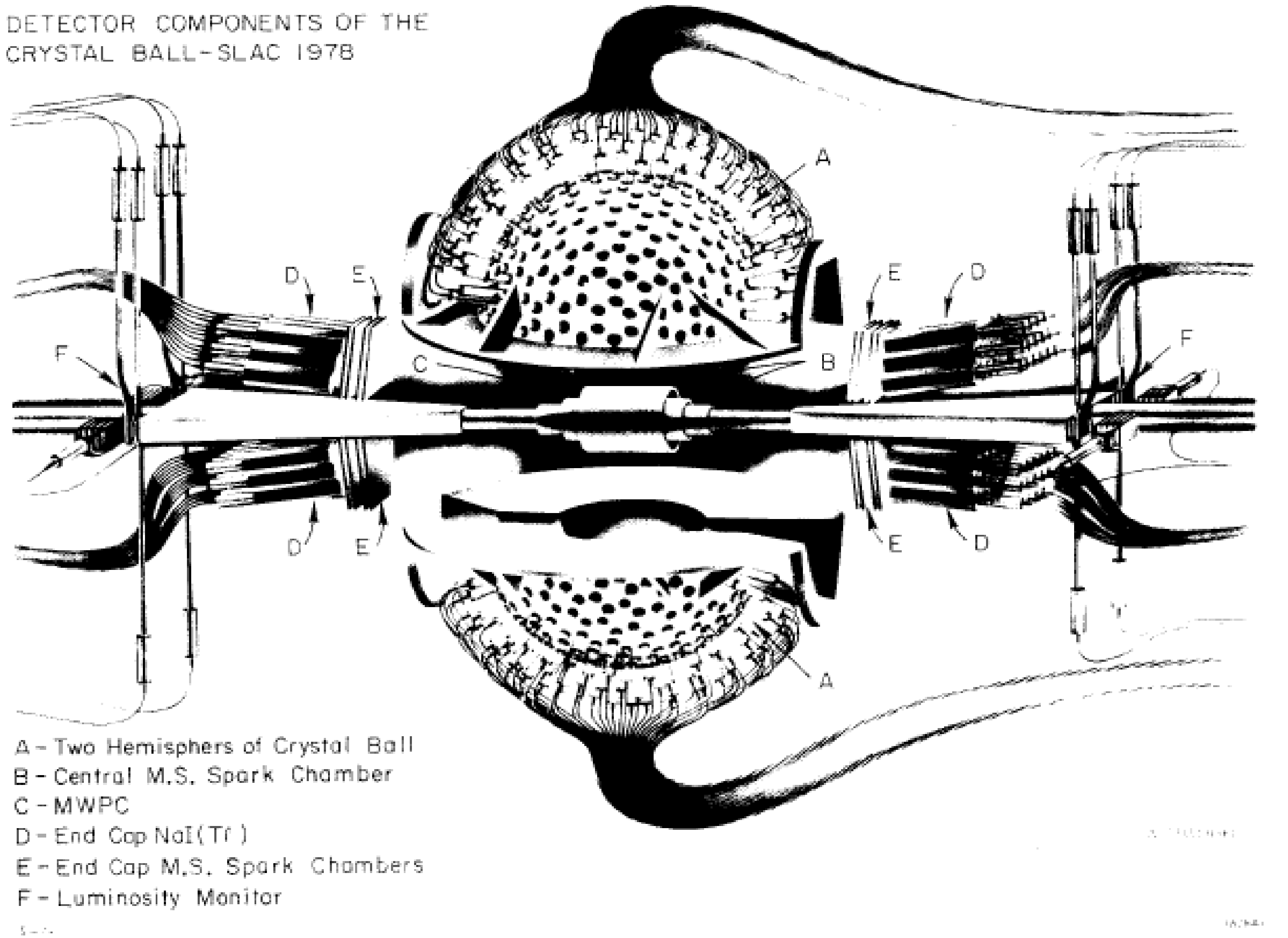
detector length $16X_0$

read by PMT

$\sigma(E)/E = 2.7\% / E^{1/4}$

** deviation from $E^{-\frac{1}{2}}$ law attributed to energy leakage or other instr. effects

Crystal Ball



Crystal Ball Function

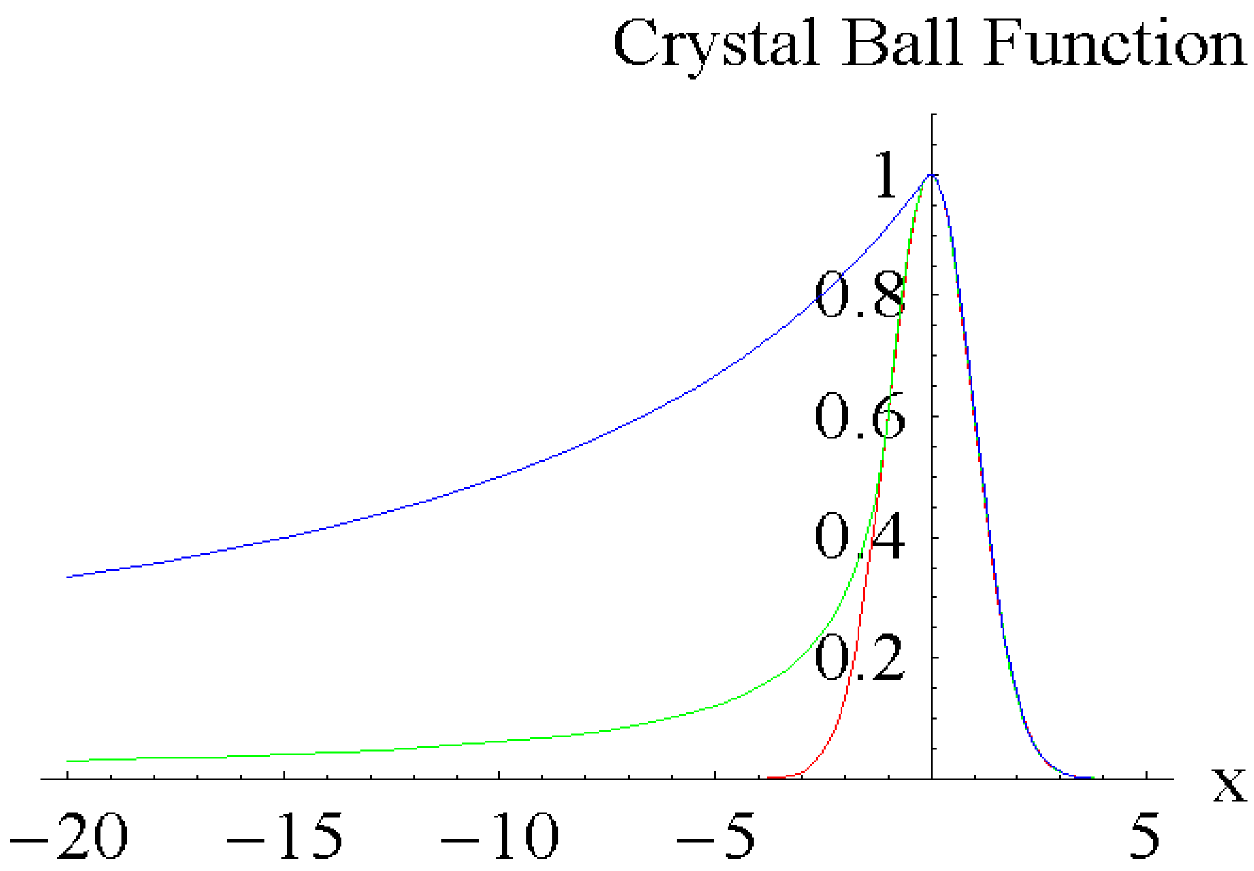
Probability Density Function named after Crystal Ball Collaboration.

$$f(x;\alpha,n,\bar{x},\sigma) = N \cdot \begin{cases} \exp(-\frac{(x-\bar{x})^2}{2\sigma^2}), & \text{for } \frac{x-\bar{x}}{\sigma} > -\alpha \\ A \cdot (B - \frac{x-\bar{x}}{\sigma})^{-n}, & \text{for } \frac{x-\bar{x}}{\sigma} \leqslant -\alpha \end{cases}$$

$$A = \left(\frac{n}{|\alpha|}\right)^n \cdot \exp\left(-\frac{|\alpha|^2}{2}\right) \qquad B = \frac{n}{|\alpha|} - |\alpha|$$

- Gaussian + power-law low-end tail
- Use to model lossy processes, like detector response function

Crystal Ball Function



Examples of the Crystal Ball function $\bar{x}=0\,;\sigma=1\,;N=1$

α = 10, α = 1, α = 0.1

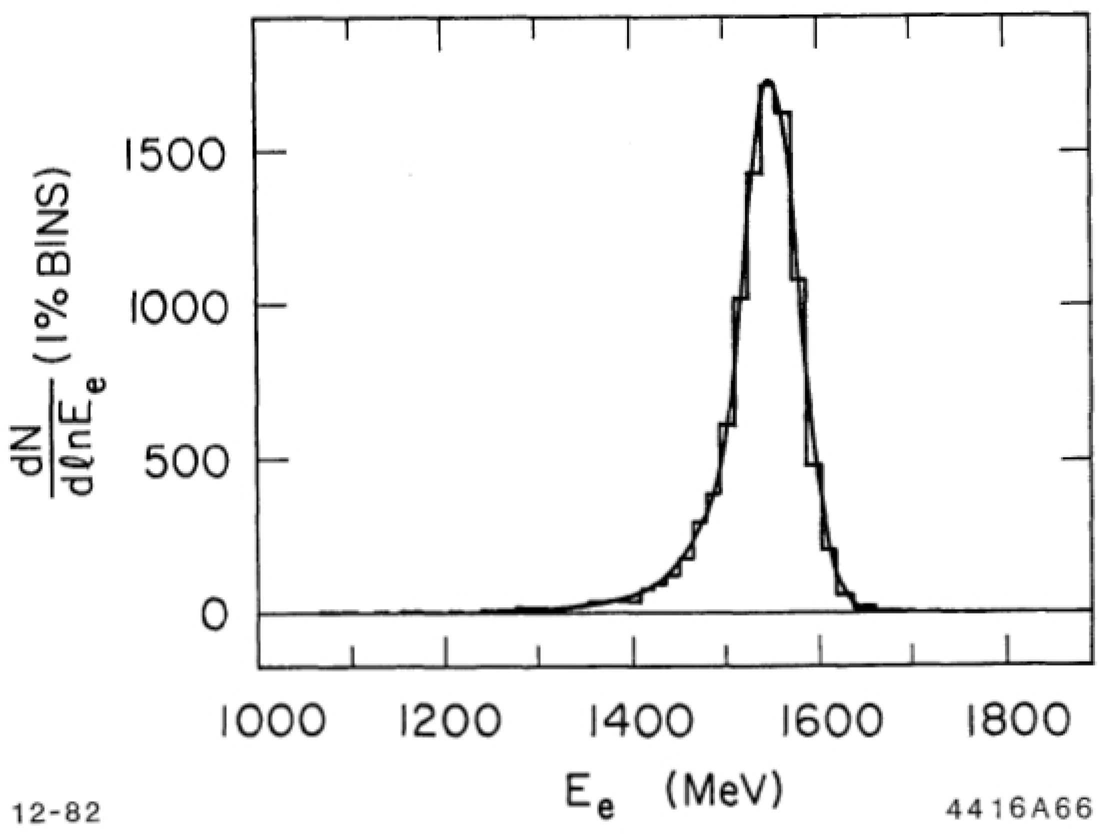
Crystal Ball Function

- Measured 1st time in the **Crystall Ball Experiment** with NaI(Tl) crystals
  - using monochromatic e+ e- from Bhabba reaction $e^+e^- \Rightarrow e^+ e^-$ at J/Psi resonance
  - from the direct decay J/Psi $\Rightarrow e^+e^-$

    (require electrons back to back)

Crystal Ball Function

Measured $e^+e^- \Rightarrow e^+e^-$
final state spectrum
(J.E. Gaiser Ph.D. thesis - '70s)



Lecture Overview

- What is a calorimeter?
- Calorimeters vs Time
- Basics of calorimetry:
  - Interactions of particles with matter (electromagnetic)
  - Definition of radiation length and critical energy
  - Development of electromagnetic showers
  - **Interactions of particle with matter (nuclear)**
  - **Development of hadronic showers**

Hadron-Matter Interactions

Complex process:

- hadron strikes a nucleus:
  - interaction between partons
  - excitation and breakup of the nucleus
    - nucleus fragmentation/ hadronization/ production of secondary particles

- **Charged hadrons: $\pi^{\pm}$, K,p, …**
- **Neutral hadrons: n, π^0, …**
- **Charged leptons: $\mu^{\pm}$, …**
- **Low energy γ**
- **etc…**

$$\sigma_{tot} = \sigma_{abs} + \sigma_{el}$$

σ_{abs} = absorption cross-section (inelastic interaction)

σ_{el} = elastic cross-section (hadron is preserved)

Hadron-Matter Interactions

Two classes of effects:

- production of energetic secondary hadrons, with mean free path λ_I (momenta ~ fair fraction of the primary hadron)
- significant part of the primary energy consumed in:
  - excitation
  - nuclear spallation (slow neutron)
    - low energy particles (MeV)...

For example, in lead (Pb):
Nuclear break-up (invisible) energy: 42%
Ionization energy: 43%
Slow neutrons (E_K ~ 1 MeV): 12%
Low energy λ's (E_γ ~ 1 MeV): 3%

An energy dependent fraction of incoming E goes in breaking nuclei, in low energy neutrons or undetectable neutrinos

invisible energy → large energy fluctuations → limited energy resolution

Hadron-Matter Interactions

Neutrons interaction is based only on strong (and weak) nuclear force. To detect neutrons, we have to create charged particles. Possible neutron conversion and elastic reactions

n + 6Li → α + 3H
n + 10B → α + 7Li   } per E< 20 MeV
n + 3He → p + 3H
n + p → n + p   per E< 1 GeV

In addition there are …

- neutron induced fission En ≈ Eth ≈ 1/40 eV
- inelastic reactions -> hadronic cascades En > 1 GeV

Slow neutrons can interact with H atoms in active material -recovered

No hope to detect neutrinos in a typical Hadron Calorimeter!

[$\sigma \sim 10^{-43}$ cm^2 , $\varepsilon \sim 10^{-16}$]

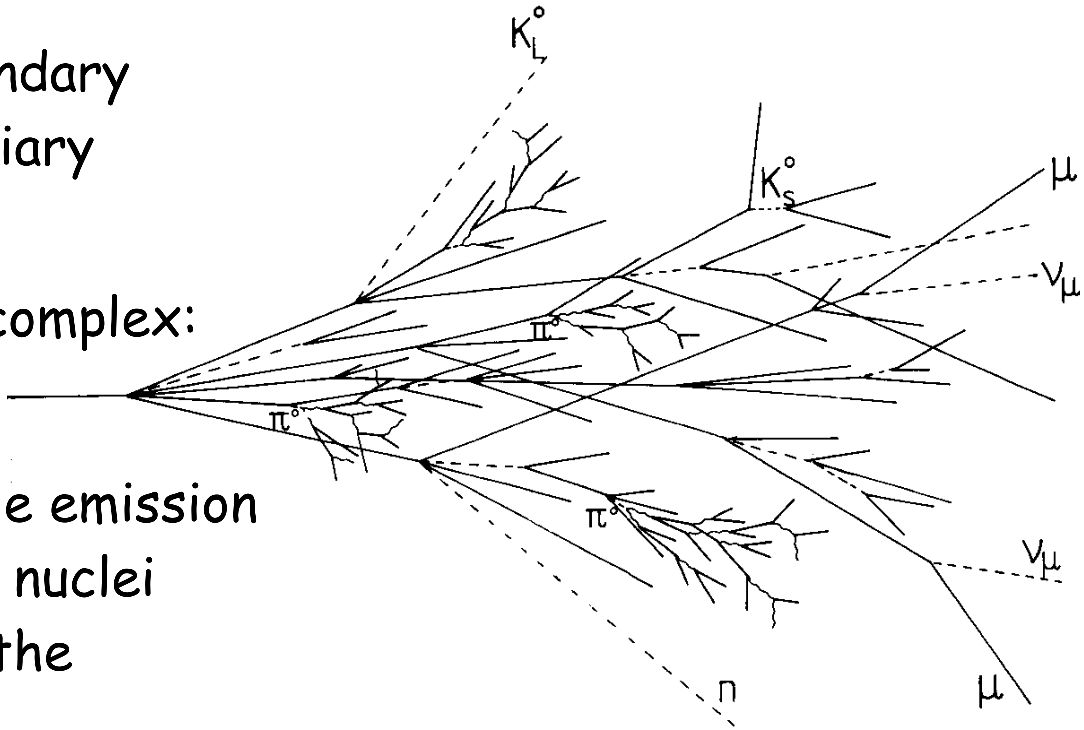
Development of hadronic showers

Hadronic shower

Process similar to EM shower: Secondary particles interact and produce tertiary particles … (and so forth)

Processes involved are much more complex:

- Many more particles produced
  - hadrons production and particle emission from nuclear decay of excited nuclei
- Multiplicity $\propto$ ln E (E = energy of the primary hadron)



The longitudinal development of the shower scales with the nuclear interaction length, λ_I :

$$\lambda_I = \frac{A}{N_A \sigma_{TOT}}$$

Secondary particles have large transverse momentum $\langle p_T \rangle > 0.35$ GeV/c

hadronic showers spread more laterally than EM showers.

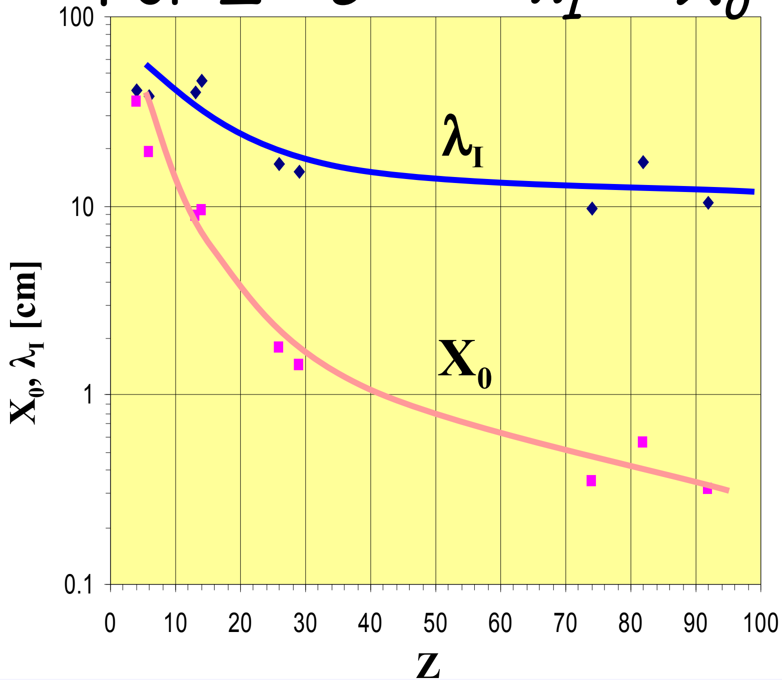
Development of hadronic showers

At **energies > 1 GeV**, cross-section depends little on energies and on the type of incident particle:

$\sigma_{abs} \approx \sigma_0 A^{0.7}$, $\sigma_0 \approx 35\,mb$ $\Rightarrow$ $\lambda_a \propto A^{1/4}$ absorption length

$\lambda_I \propto A^{1/3}$ $\lambda_I < \lambda_a$

For $Z > 6$ → $\lambda_I > X_0$



Material	Z	A	ρ [g/cm^3]	X_0 [g/cm^2]	λ_I [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

Development of hadronic showers

Shower profile

Initially the shower is narrow, and spreads laterally with the shower depth
Shower maximum depends logarithmically on energy E of the primary hadron:

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

$$t_{95}[cm] \approx a \ln E + b$$

Ex.: 100 GeV in iron (λ_i =16.7 cm)
a = 9.4 cm, b = 39 cm
→ ***tmax* = 1.6 λ_i = 27 cm**
→ ***t95%* = 4.9 λ_i = 80 cm**

Laterally, 95% of the shower contained in a cylinder of radius λ_I .

Development of hadronic showers

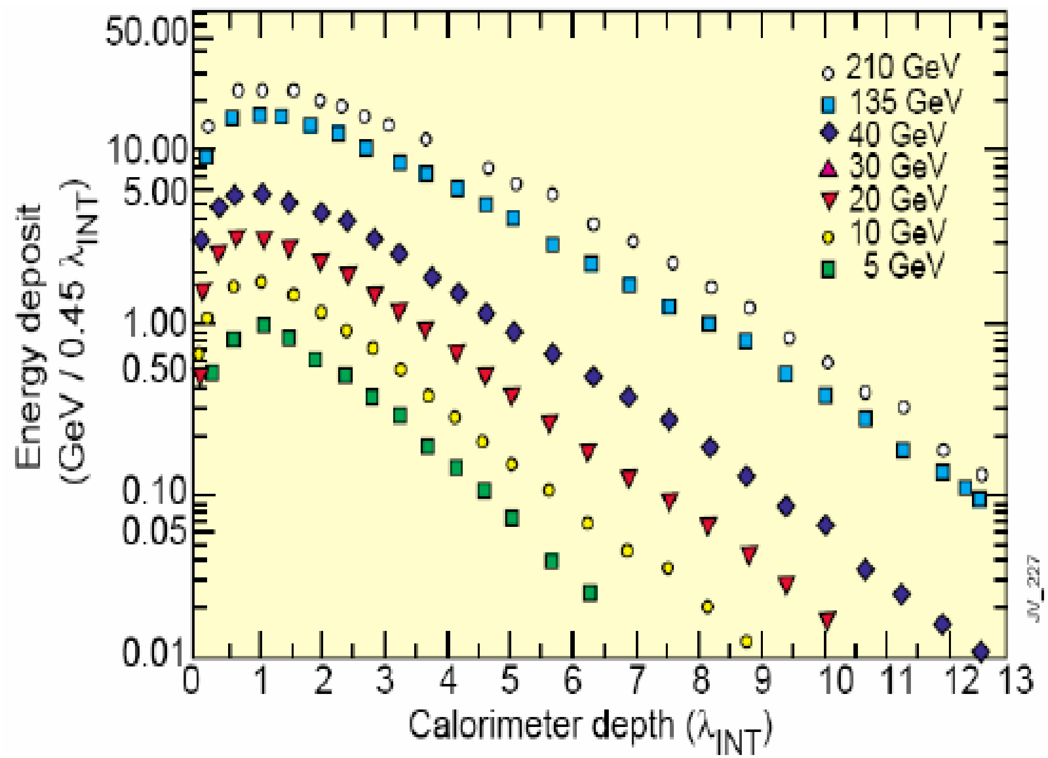
Longitudinal profile

Hadronic shower has a long longitudinal development. For 200 GeV, need > 10 λ_I to contain 99% of the energy

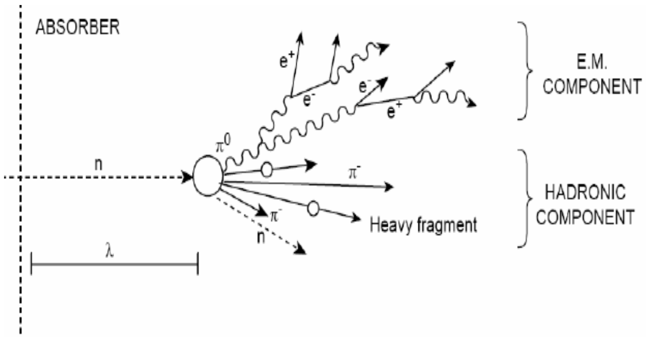
Hadronic showers much longer than EM shower

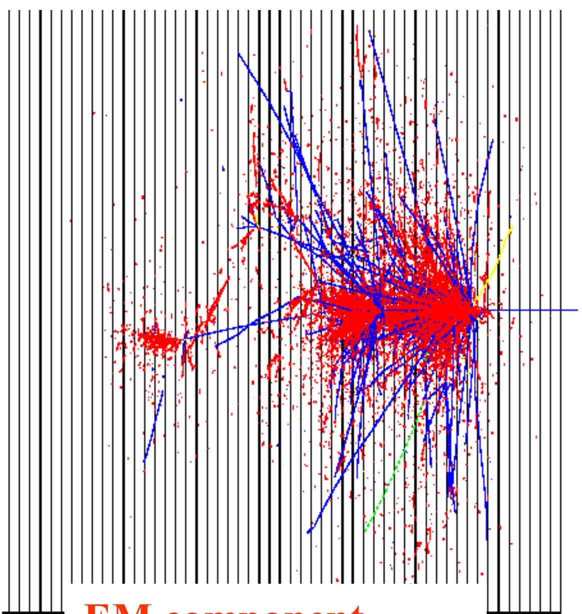
The maximum at low depth values is due to the EM component in the shower that develops more readily due to the X_0 dependence on Z compared to λ_I:

$$X_0 \propto \frac{A}{Z^2} << \lambda_I \propto A^{1/3}$$



Development of hadronic showers





EM component
Hadronic component

Energy measurement

- Shower develops until a E_{min}
- Energy deposition by ionization ($\pi^0 \rightarrow \gamma\gamma$ and charged hadrons) and low-energy hadronic activity (fission, neutron elastic scattering off proton, etc)

Two components:

- **Electromagnetic component**, due to π^0 1/3
- **Hadronic** 2/3

Detection efficiency in energy deposition of EM and hadronic components typically different!

response to em and hadronic particles:

e/h range ~ 1.1-1.35

Development of hadronic showers

Shower time evolution

Contrary to electromagnetic showers, which develop in sub-nanosecond time, the physics of hadronic showers is characterized by different time scales, the slowest of which (de-excitation of heavy nuclei) may reach a microsecond.