European School of Instrumentation in Particle & Astroparticle Physics

European Scientific Institute

DETECTOR TECHNOLOGIES

Lecture 1: Principles of detection

- Generalities about detectors
- Interaction of particles with matter

Goal :

Observation and identification of final states
(whatever the processus)

A particle :

Mass
Electrical Charge
Moment
Energy
Lifetime
~~(spin, flavour, color….)~~

A Detector : does not give any measurement.
Gives an information coming after an **interaction** with the particle

Energy deposition

- **Limited** (the particle goes almost undisturbed)
  - Momentum
  - Electrical charge (if magnet)
    - → Trajectography
- **Total** (the particle stops)
  - Energy

Various processes

But first : some important notions
(supposed to be known ?)

Jean-Marie Brom (IPHC) – brom@in2p3.fr

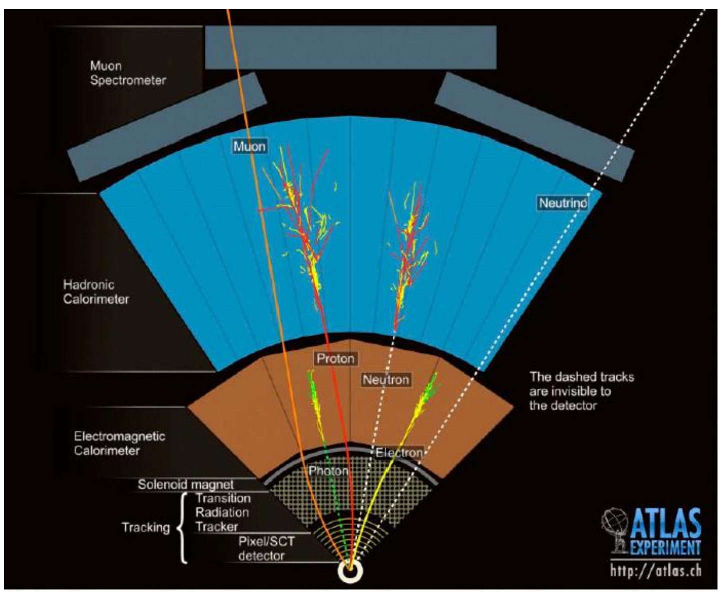
Types of detectors :

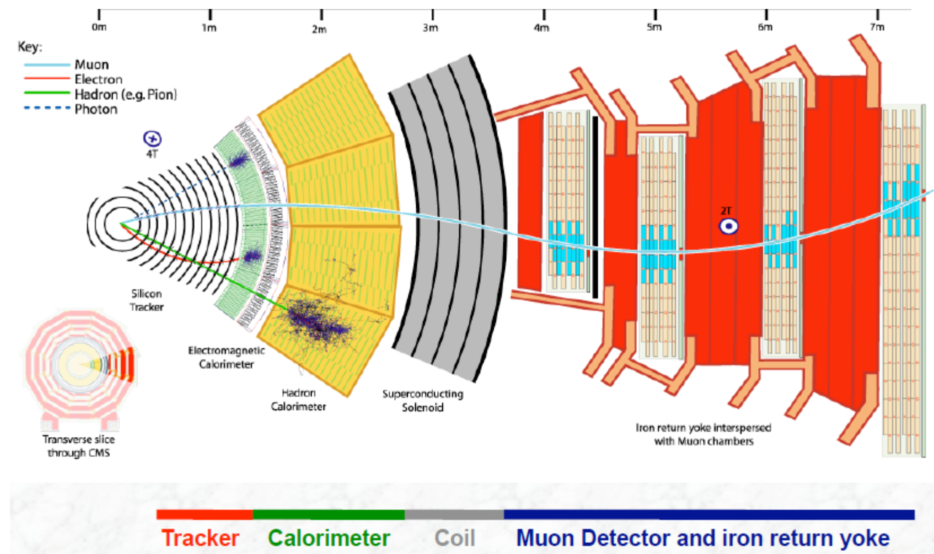
Trackers (position and momentum measurement)

Calorimeters (energy measurement)

Identifiers (identification of various types of particles)

Trigger counters





CROSS SECTION :

Probability of a phenomenon (interaction with the detector) to occur.

$$\frac{d\,\sigma}{d\Omega}(E,\Omega) = \frac{1}{F}\,\frac{dN_s}{d\Omega}$$

F = incident flux of particles
Ns = emitted number of particles
Ω = Solid angle

$$\sigma\,(E) = \int d\Omega\,\frac{d\sigma}{d\Omega}$$

MEAN FREE PATH :

Average distance travelled by a particle between 2 consecutive interactions in matter (detector) :

$$\lambda = \frac{1}{\sigma.n}$$

σ = total interaction cross section
n = number of interactive centers per unit volume

TIME OF FLIGHT :

For particles with a timelife of τo :

$$N(t) = No\, e^{-\frac{t}{\tau o}}$$

Of course, in the laboratory, for a particle with a speed v,

$$\tau = \gamma\, \tau o \qquad \gamma = \frac{1}{\sqrt{1 - \frac{v2}{c2}}}$$

and then,

DISTANCE OF FLIGHT :

Mean distance in the detector for a particle with a lifetime τ_o measured in the laboratory

$$L = v\, t = \beta\, c\, \tau = \beta\, \gamma\, c\, \tau_0 = \frac{p\, c\, \tau_o}{m}$$

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High energetic particle (particles at speed ≈ c
quasi-transparent detector

Particle	**c τ (cm)**
γ	∞ (stable)
e^+ / e^-	∞ (stable)
μ	$6.6\ 10^{4}$
neutrino	∞ (stable)
π^0	$2.5\ 10^{-6}$
π^+ / π^-	780
K^+ / K^-	371
K^0_s	2.7
K^0_l	1554
p	∞ (stable)
n	$2.7\ 10^{13}$

INTERACTION OF PARTICLE WITH MATTER :

Depends on the type of interactions

ELECTROMAGNETIC : $\lambda \approx \mu m$

ionization

pairs creation ($e^+ e^-$, electrons – holes…)

photon emission (Bremstrahlung, Cerenkov effect)

STRONG : $\lambda \approx cm$

hadronic showers of neutrons

(but the observed signal will be due to EM interaction)

WEAK : $\lambda \approx 10^{15}$ m (neutrinos)

GRAVITY : ??

Depends on the type of particle

CHARGED

NEUTRAL

And of course, **ENERGY**, **MEAN FREE PATH**, **LIFETIME**

In order to detect a particle, it must

- interact with the material of the detector
- transfer some energy in a recognizable way (signal to be processed)

4 CLASSES OF PARTICLES

Heavy ($m > m_e$) charged particles
Light ($m \approx m_e$) charged particles
Photons
Hadrons

3 POSSIBILITIES

Ionization (EM)
Radiation (EM)
Nuclear interaction (Strong)

HEAVY ($m > m_e$) CHARGED PARTICLES : IONIZATION

Energy loss (energy transferred to the medium) by ionization in MeV g^{-1} cm^2

$$-\frac{dE}{dx} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

Bethe-Bloch, 1932

Where : $K = 4\pi N_A r_e^2 m_e = 0.3071$

A, Z : atomic mass and number relative to the medium

N_A : Avogadro's number

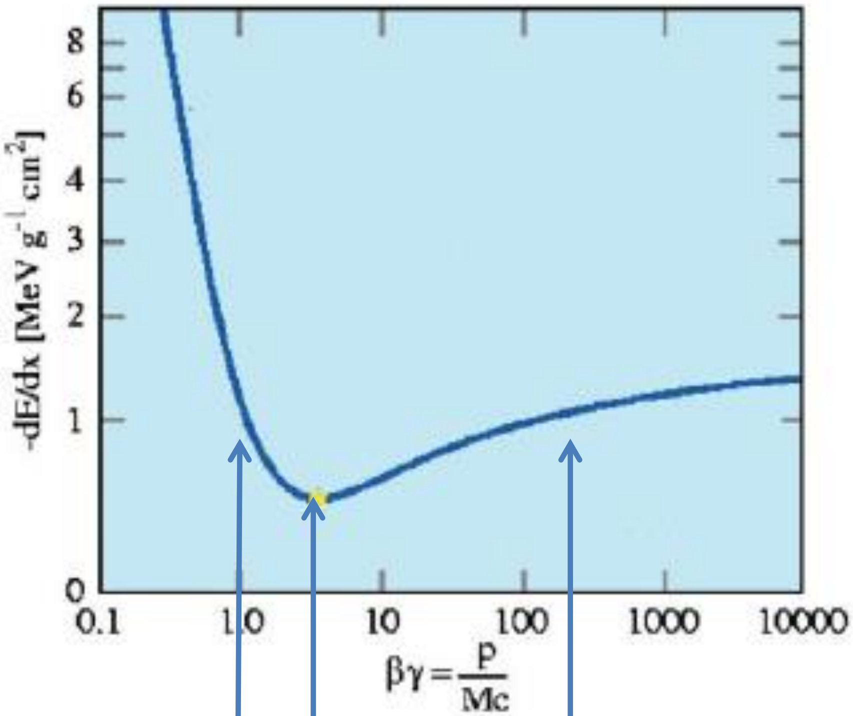
T_{max} : maximum possible energy transferred to an electron in the medium (see J. Collot's lecture)

z : charge of the incoming particle

β, γ : relatives to the particle

→ dE/dX in MeV.g^{-1}.cm^2
→ valid only for M>mμ
→ dE/dX depends on β,
→ dE/dX does not depend on M

HEAVY ($m > m_e$) CHARGED PARTICLES : IONIZATION



Non-relativistic

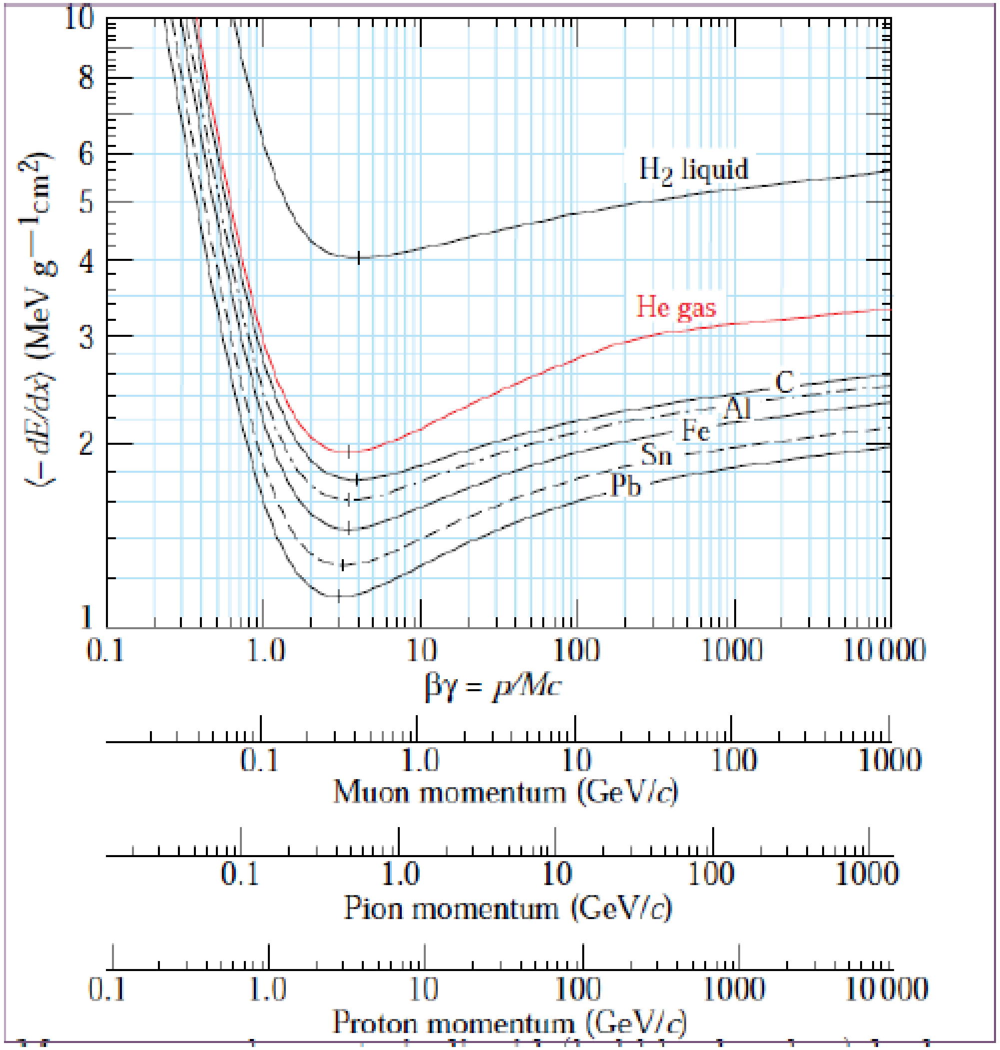
$\beta\gamma = p/m < 1$ → $-dE/dx \propto \beta^{-5/3}$

Relativistic increase

$\beta\gamma > 4$ → $-dE/dx \propto 2 \ln(\gamma)$

$\beta\gamma \approx 4$ → Minimum Ionizing Particle (MIP)

HEAVY ($m > m_e$) CHARGED PARTICLES : IONIZATION



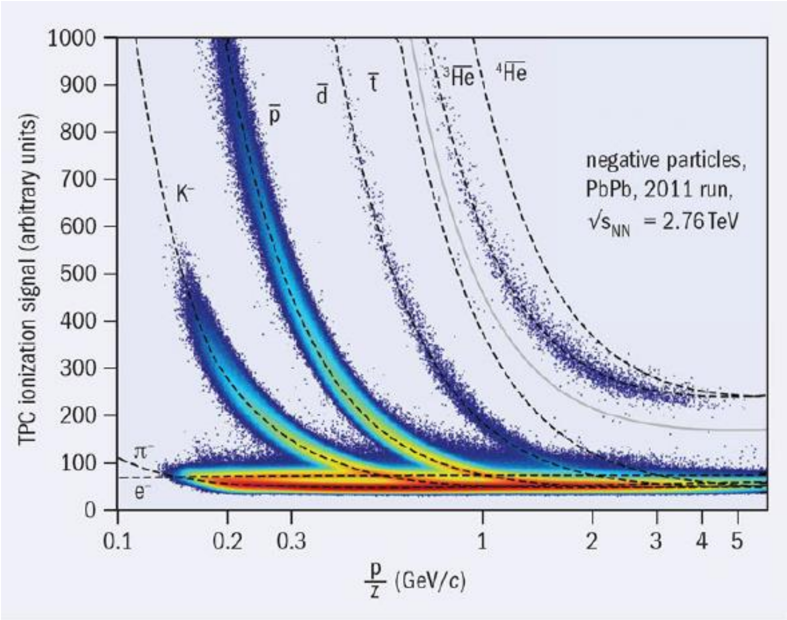
Relativistic rise :

- more distant collisions, increasing the transverse electric field with γ
- Typical for

gas : 1.5

liquid : 1.1

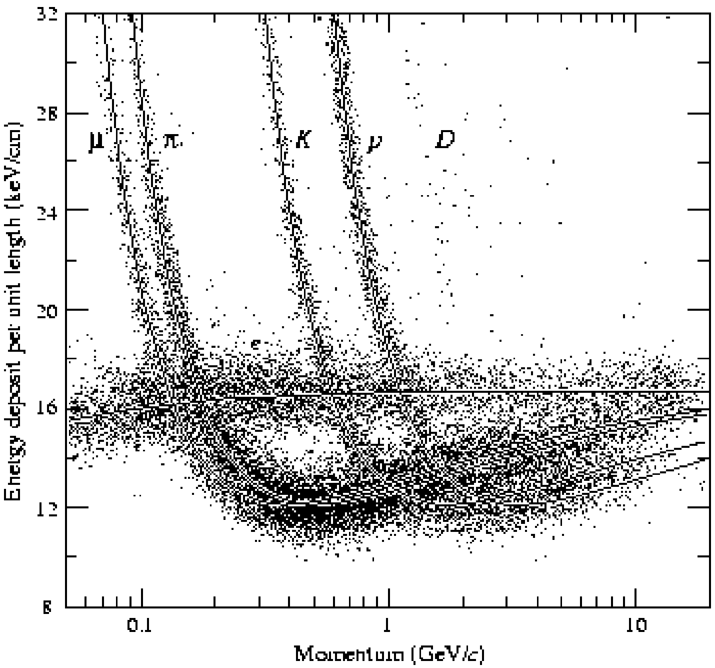
HEAVY (m > m_e) CHARGED PARTICLES : IONIZATION



Direct identification by energy loss

in Ne-CO2 90-10 %

(ALICE TPC)



Direct identification by energy loss

in Ar-CH_4 80-20 %

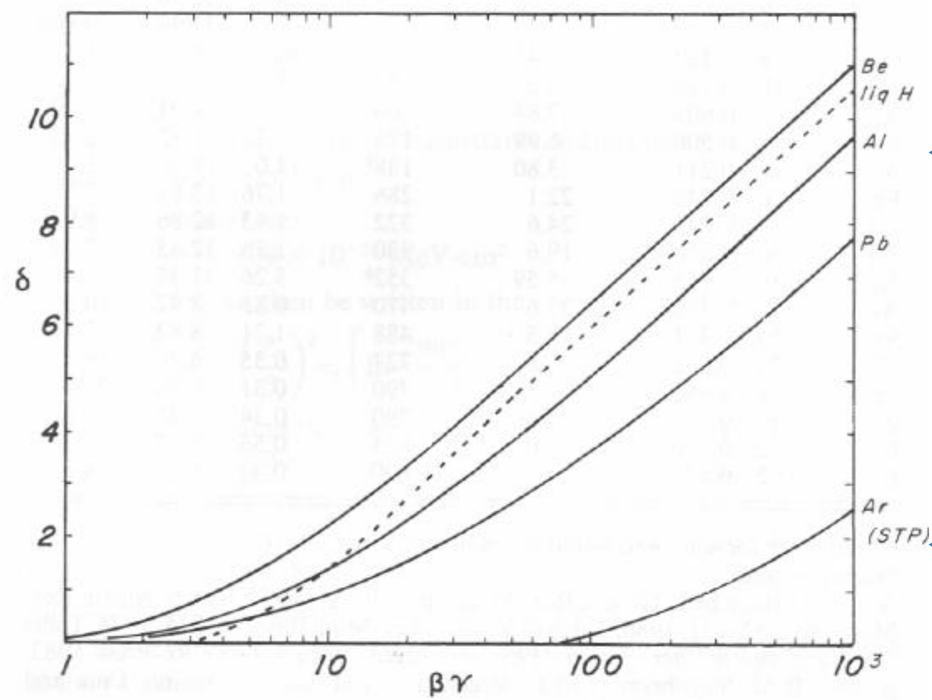
(DELPHI

HEAVY (m > m_e) CHARGED PARTICLES : IONIZATION

Corrections to the Bethe-Bloch formula :

Density effect : the density of the medium will have a screening effect on the relativistic rise (important for solids and liquids)

Figure 2.5 Density effect correction parameter δ for several materials. (The parameter was calculated using the formulas and coefficients given in R.M. Sternheimer, M.J. Berger, and S.M. Seltzer, Atomic Data and Nuclear Data Tables 30: 261, 1984.)



Solids
Liquids

Gaz

LIGTH (m≈me) CHARGED PARTICLES : IONIZATION

Corresponds to an energy loss by charged particle : Bethe-Bloch

But : small mass : electrons may be deflected

interaction electron – electron : collisions between identical particles

Bethe-Bloch :

$$-\left(\frac{dE}{dx}\right) = \left(\frac{4\pi N_A \alpha^2 (\hbar c)^2}{m_e}\right) z^2 \frac{\rho Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln\left(\frac{2(\beta\gamma)^2 m_e \varepsilon_{max}}{I^2}\right) - \beta^2 - \frac{\delta}{2}\right]$$

↓

Bethe-Bloch
For electrons

$$-\left(\frac{dE}{dx}\right)_{ION} = \left(\frac{2\pi N_A \alpha^2 (\hbar c)^2}{m_e}\right) \frac{\rho Z}{A} \frac{1}{\beta^2} \left[\ln \frac{(\beta\gamma)^2 m_e T}{2I^2} - \ln 2\left(\frac{2}{\gamma} - \frac{1}{\gamma^2}\right) + \frac{1}{\gamma^2}\right]$$

CHARGED PARTICLES : RADIATION (Bremsstrahlung)

For any charged particle :

When accelerated (or deccelerated), in the nucleus electrical field, any charged particle emits photons

§ 6. *Energy Loss of Fast Electrons by Radiation.*

For very high energies (case 2) the integration gives

$$-\left(\frac{dE_0}{dx}\right)_{rad} = N \frac{Z^2 r_0^2}{137} E_0 \left(4 \log 183 Z^{-\frac{1}{3}} + \frac{2}{9}\right) \qquad (\text{for } E_0 \gg 137 mc^2 Z^{-\frac{1}{3}}),$$

From :Bethe, H.A., Heitler, W., 1934. On the stopping of fast particles and on the creation of positive electrons

$$-\frac{dE^{rad}}{dx}\left(\frac{MeV}{g/cm^2}\right) = \frac{0.3071}{A(g)} \frac{\alpha}{\pi} Z^2 z^2 \left(\frac{m_e}{m}\right)^2 \frac{E}{m_e} \ln\left(\frac{183}{Z^{1/3}}\right)$$

Z : médium

z, m, E : particle

$\left(\frac{m_e}{m}\right)^2$ = 1 for e^+, e^-

= 1.3 10^{-5} for μ

= 2.3 10^{-5} for π

= 2.7 10^{-7} for p

Up to 100 GeV, on can neglect the Bremssttrahlung if particle ≠ e^+ or e^-

CHARGED PARTICLES : RADIATION (Bremsstrahlung)

For electrons,

$$-\frac{dE^{rad}}{dx}\left(\frac{MeV}{g/cm^2}\right)=\frac{0.3071}{A(g)}\frac{\alpha}{\pi}Z^2z^2\left(\frac{m_e}{m}\right)^2\frac{E}{m_e}\ln\left(\frac{183}{Z^{1/3}}\right)$$

Can be rewritten as

$$-\frac{dE^{rad}}{dx}(e^-)=\frac{E}{X_0}$$

$$X_0(g/cm^2)=\frac{716.4\ A(g)}{Z(Z+1)\ln\left(\frac{287}{Z^{1/2}}\right)}$$

Xo : radiation length (characteristic of the medium)

Medium	**Xo (g cm^{-2})**
Hydrogen	63.1
Helium	94.3
Carbon	42.7
Aluminium	24.0
Iron	13.8

CONSEQUENCE : CRITICAL ENERGY

The energy loss has 2 components :

- ionization (for heavy and energetic particles, it is ≈ constant
- radiation (for heavy particles, it is almost negligible) proportional to E

$$\frac{dE}{dx} = \left(\frac{dE}{dx}\right)_{\text{ion}} + \left(\frac{dE}{dx}\right)_{\text{rad}}$$

The critical energy (Ec) is defined as the energy at which the two mechanisms are equal

$$E_c = \frac{610 \;\; MeV}{Z + 1.24}$$

For liquids and solids

$$E_c = \frac{710 \;\; MeV}{Z + 0.92}$$

For gas

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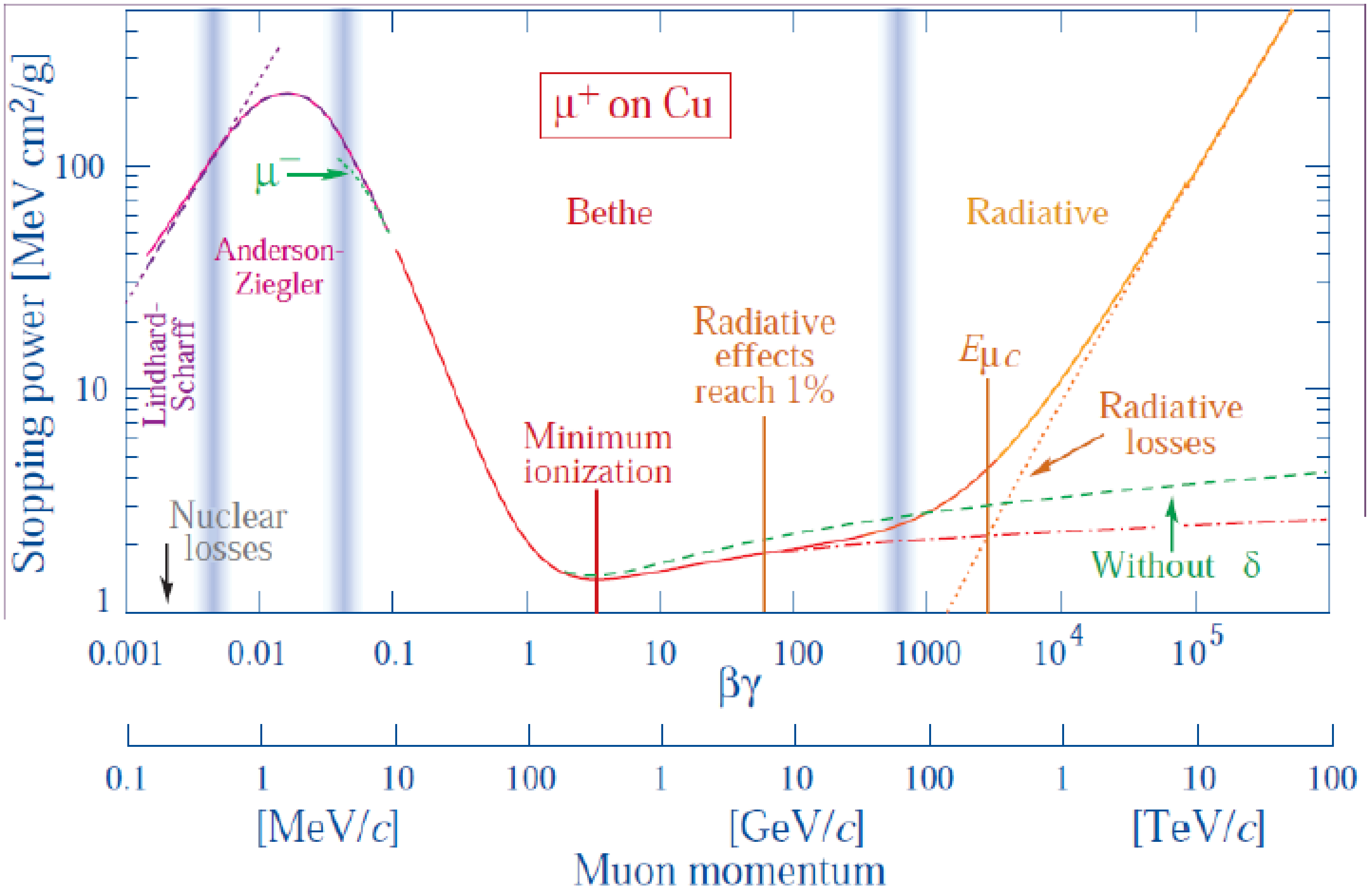
medium	*Z*	*A*	X_0 (g/cm^2)	X_0 (cm)	E_c (MeV)
hydrogen	1	1.01	63	700000	350
helium	2	4	94	530000	250
lithium	3	6.94	83	156	180
carbon	6	12.01	43	18.8	90
nitrogen	7	14.01	38	30500	85
oxygen	8	16	34	24000	75
aluminium	13	26.98	24	8.9	40
silicon	14	28.09	22	9.4	39
iron	26	55.85	13.9	1.76	20.7
copper	29	63.55	12.9	1.43	18.8
silver	47	109.9	9.3	0.89	11.9
tungsten	74	183.9	6.8	0.35	8
lead	82	207.2	6.4	0.56	7.4
air	7.3	14.4	37	30000	84
silica (SiO_2)	11.2	21.7	27	12	57
water	7.5	14.2	36	36	83

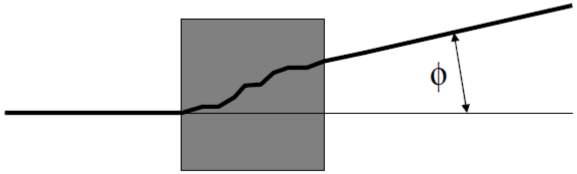
Note : table for electrons only (the most sensitive)
for other particles, it would scale to the square of the particle mass

INTERACTION OF CHARGED PARTICLES



CHARGED PARTICLES (Hadrons) : Coulomb scattering and interactions

Hadrons are interacting mainly with the nucleus by (strong interaction)
- collisions (coulomb))
- interaction (strong force)



$$\phi_{\rm rms} = \langle\phi^2\rangle^{1/2} = \frac{zE_s}{pv}\sqrt{\frac{t}{X_0}}$$

X

Phenomenon governed by the interaction lengths λ_T (collisions) and λ_i (interactions)

$$\lambda_T = \frac{A}{N_A \sigma_T} \text{g cm}^{-2}$$

$$\lambda_I = \frac{A}{N_A \sigma_{inelastic}} \text{g cm}^{-2}$$

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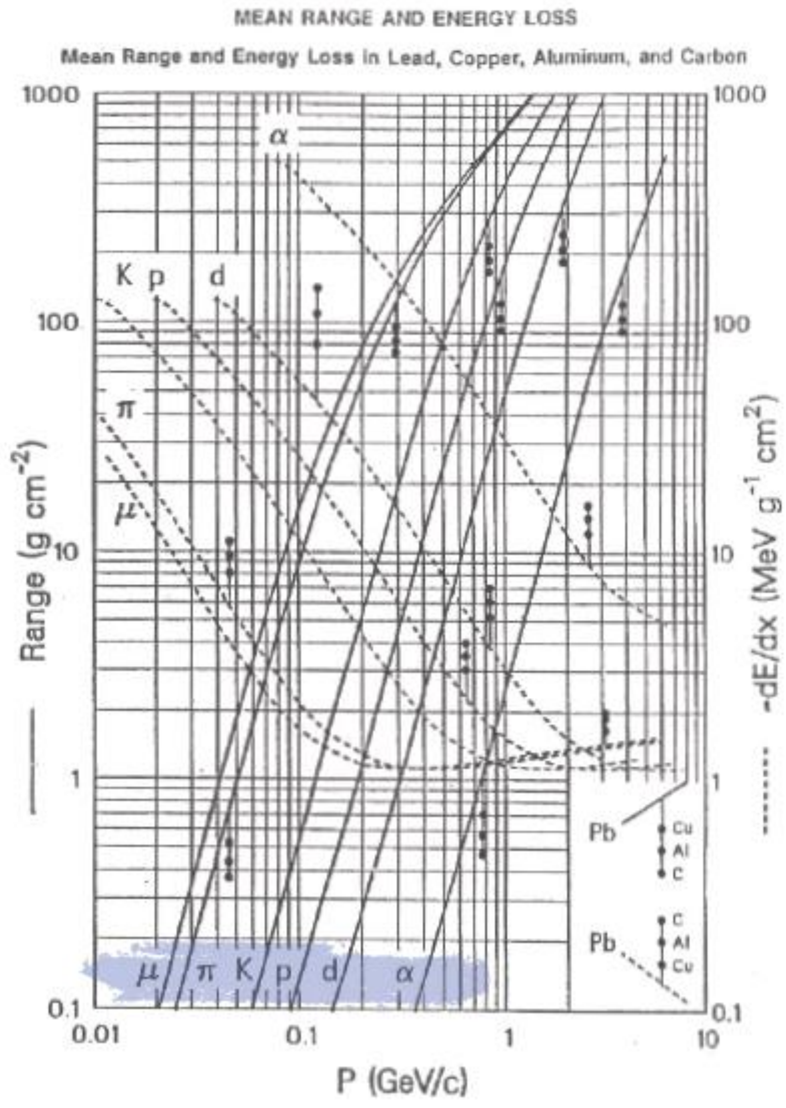
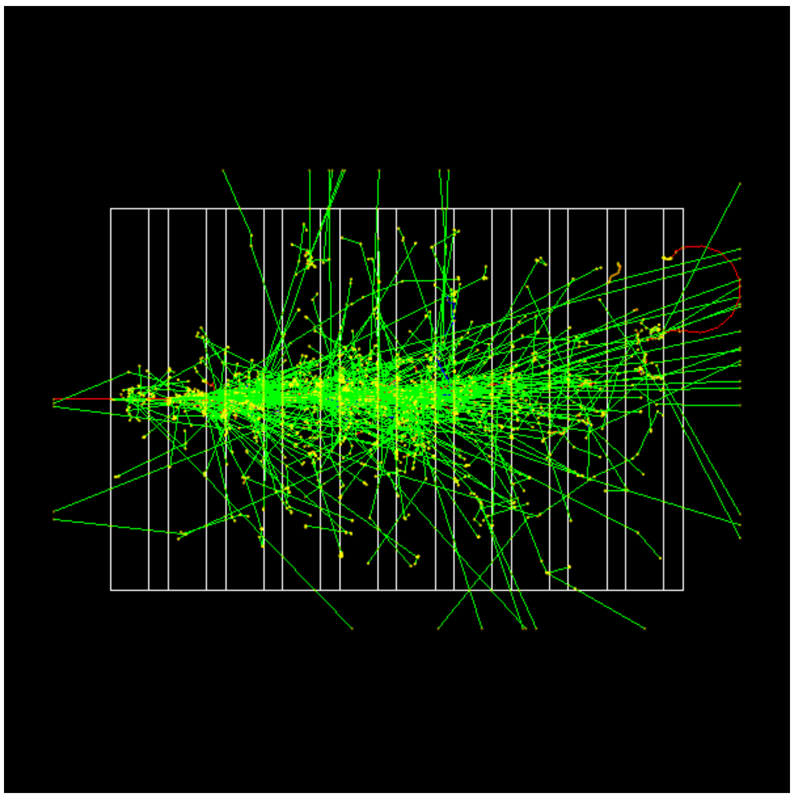
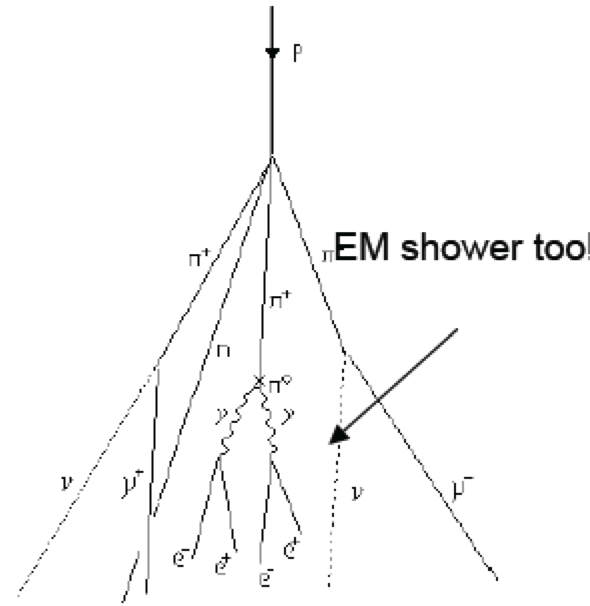
Range : measured of the stopping power
for various material
for different energies (momentum)

$$R(T_0) = \int_0^{T_0} \frac{dT}{\frac{dE}{dx}(T)}$$



Hadronic shower : λ instead of X_o

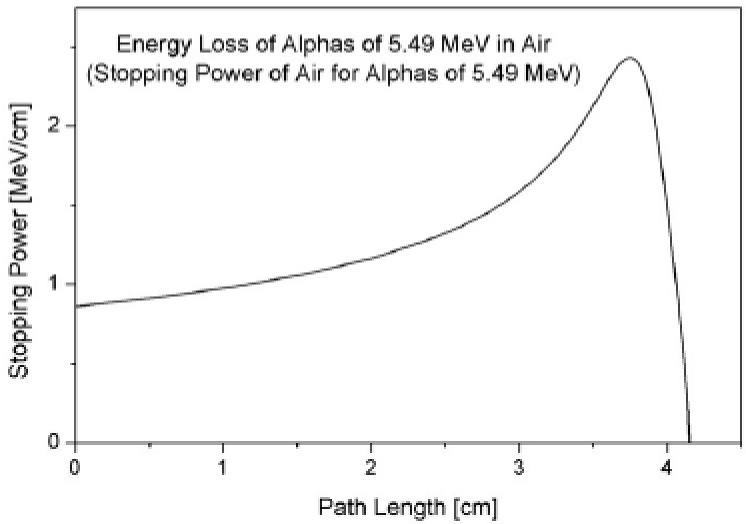




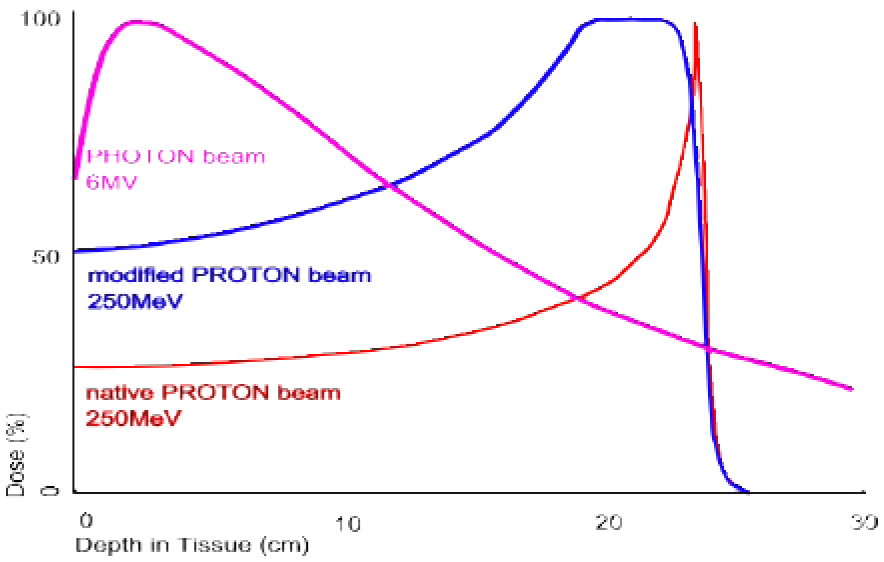
CONSEQUENCE : RANGE IN MATTER

In a medium a particle will loose its energy by any means (ionization radiation, scattering) until it stops in the medium

Of course, it depens on the MASS and ENERGY of the incoming particle
Of course, it depens on the DENSITY and the THICKNESS of the medium

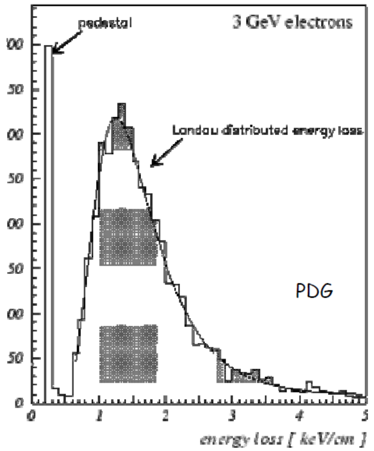


Almost negligible for High Energy Physics



ENERGY LOSS DISTRIBUTION

The Bethe-Bloch formula describes the **average** energy loss of charged particles.
But there can be large fluctuations which have an effect on larger energy losses
The fluctuation around the mean is decribed by an asymetric distribution

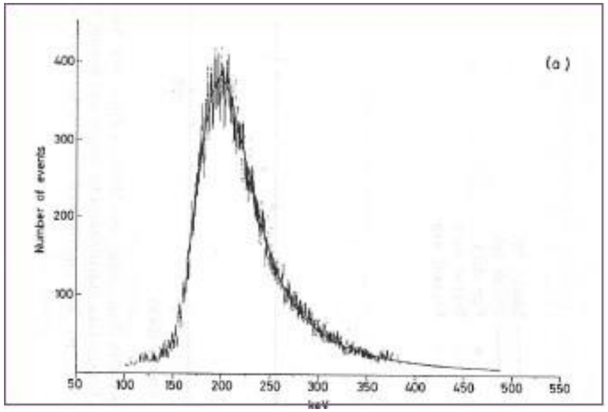


Landau distribution :

$$\Omega(\lambda) = \frac{1}{\sqrt{2\pi}} \exp\left\{-\frac{1}{2}(\lambda + e^{-\lambda})\right\}$$

In fact, for thin absorbers, the reality is more a convolution of a Landau and a Gaussian distribution…

Energy deposited by 736 MeV/c proton in Silicon
(Xo = 9.4 cm , Ec = 39 MeV for electrons)



INTERACTION OF PHOTONS

Photons are interacting with matter through 3 types of processes:

- Photoelectric emission $\longrightarrow$ Absorption

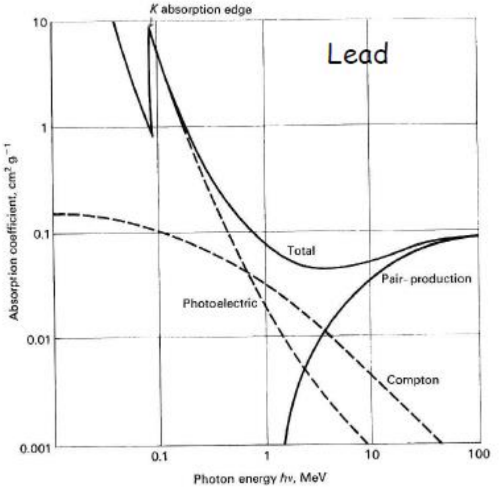
  $\sigma \sim 1 / E^3$

- Compton scattering $\longrightarrow$ Deflection

  $\sigma \sim 1 / E$

- Pair production $\longrightarrow$ Absorption

  $\sigma \sim$ constant (above threshold)



Note : Main effect : electron production.
Attenuation

$$I(x) = Io\ e^{-\mu x}$$

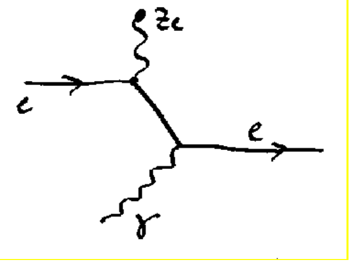
µ : realtive to the medium and the absorption cross section

$$\sigma_{ABS} = \sigma_{phot} + \sigma_{Compton} + \sigma_{pairs}$$

INTERACTION OF PHOTONS : PHOTOELECTRIC EMISSION

A. Einstein, 1905

$\gamma + A \longrightarrow A^+ + e^-$

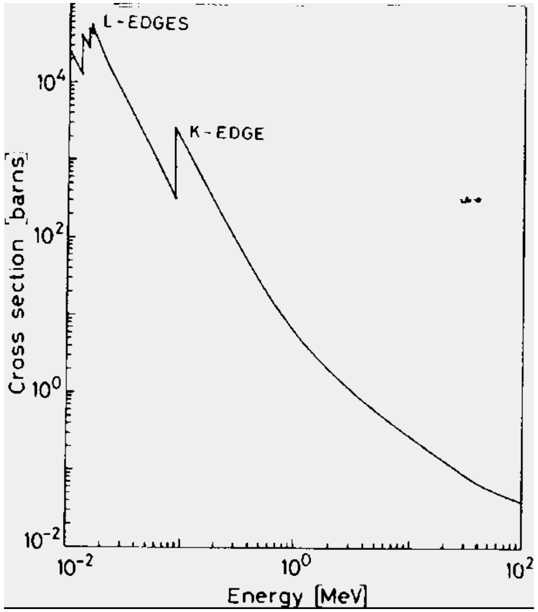


Again : Energy transfert to an electron :

$$E_e = E_\gamma - E_{binding}$$

For $E_\gamma > E_{binding}$ $\sigma_{phot} \sim Z^5 / E_\gamma^{7/2}$

For $E_\gamma >> E_{binding}$ $\sigma_{phot} \sim Z^5 / E_\gamma$



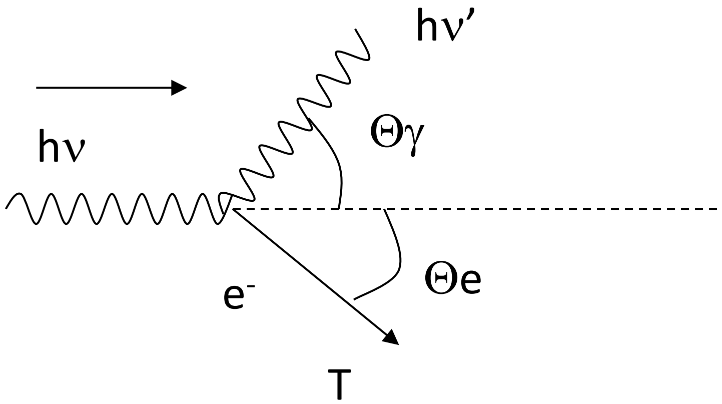
Dominant process for $E_\gamma < 100$ keV

INTERACTION OF PHOTONS : COMPTON SCATTERING

$$\frac{E_\gamma'}{E_\gamma} = \frac{1}{1+\epsilon(1-\cos\theta_\gamma)} \quad with \;\; \epsilon = \frac{E_\gamma}{m_e}$$

$$cotg\,\theta_e = (1+\epsilon)\; tg\left(\frac{\theta_\gamma}{2}\right)$$

Θ_e can not be > /2



Cross section : calculated using QED :
Klein – Nishima formula

$$\frac{d\sigma_c^e}{d\Omega} = \frac{r_e^2}{2} \frac{1+\cos^2\theta_\gamma}{(1+\epsilon(1-\cos\theta_\gamma))^2} \left(1+\frac{\epsilon^2(1-\cos\theta_\gamma)^2}{(1+\cos^2\theta_\gamma)(1+\epsilon(1-\cos\theta_\gamma))}\right) \;\; (\,per\ electron\,)$$

Intergating over Ω :

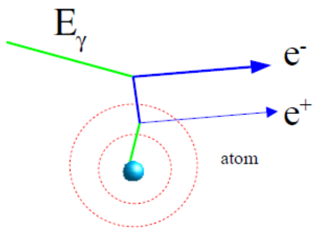
$$\sigma_{Compton} = 2\pi r_e^2 \left(\left(\frac{1+\epsilon}{\epsilon^2}\right) \left\{ \frac{2(1+\epsilon)}{1+2\epsilon} - \frac{1}{\epsilon}\ln(1+2\epsilon) \right\} + \frac{1}{2\epsilon}\ln(1+2\epsilon) - \frac{1+3\epsilon}{(1+2\epsilon)^2} \right) \;\; (\,per\ electron\,)$$

$\sigma_{Compton}\ \alpha\ Z / E_\gamma$

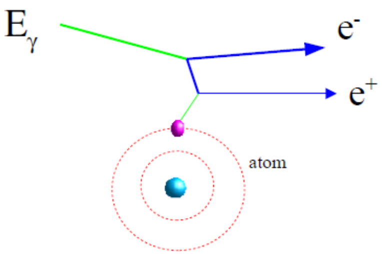
INTERACTION OF PHOTONS : PAIRS PRODUCTION

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

Needs a nucleus
or another electron…



$E_\gamma \geqslant 2m_e$



$E_\gamma \geqslant 4m_e$

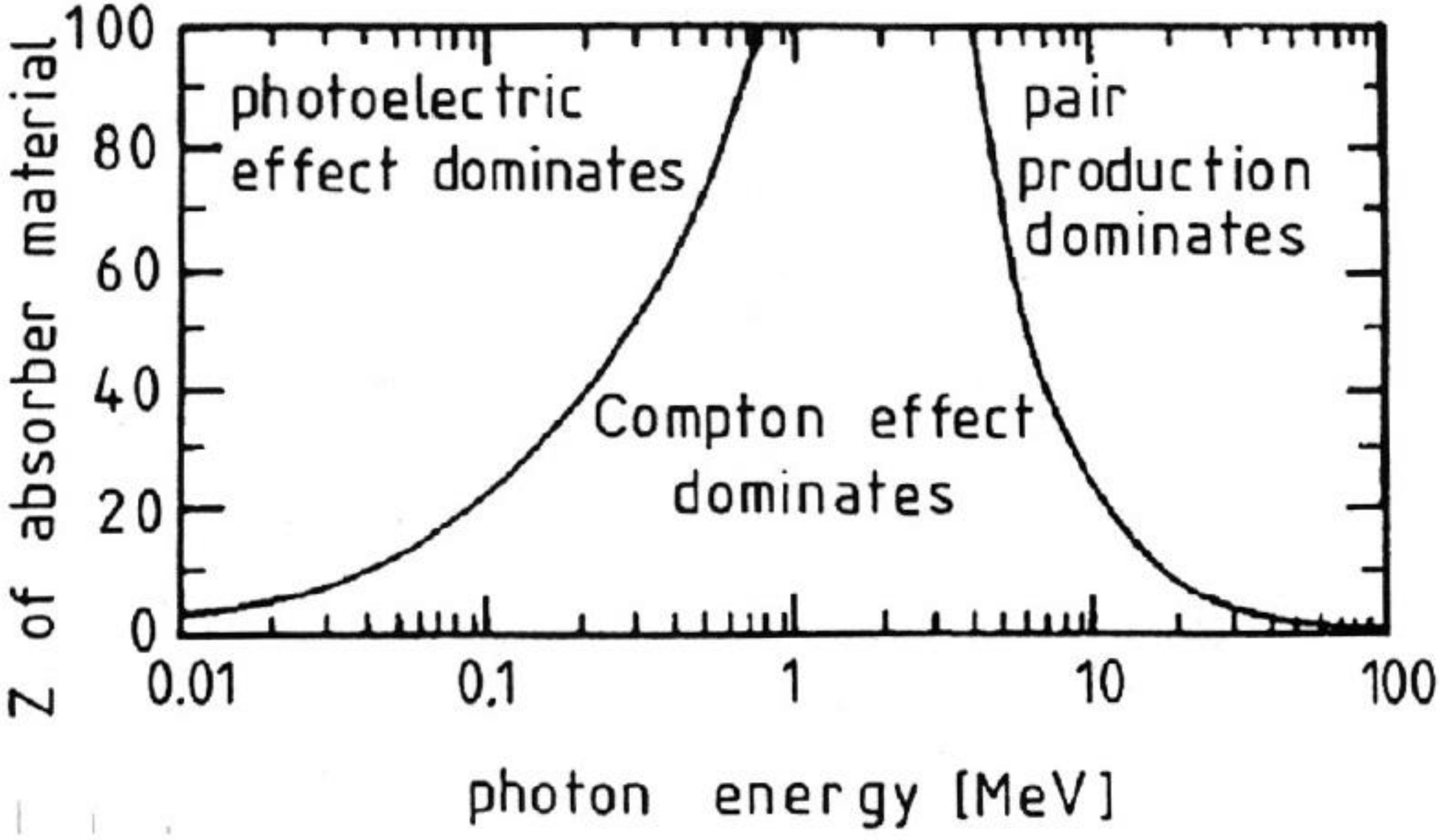
Threshold :

$E_\gamma \geq 2m_e + 2\frac{m_e^2}{m_{nucleus}}$ And because m $_{nucleus}$ >> m $_e$ $\boxed{E_\gamma \geq 2m_e \approx 1{,}022 MeV}$

Cross section : $\sigma_{pair} = Z^2 \ln\left(\frac{E_\gamma}{m_e c^2}\right)$

For higher energies (> 10 MeV) : $\sigma_{pair} = \frac{7}{9} 4\alpha . r_e . Z^2 \ln \frac{183}{Z^{1/3}}$

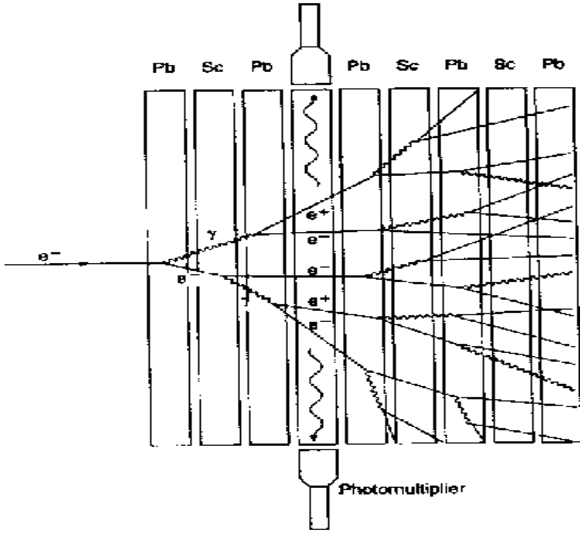
Note : If enough energy, the positron will annihilate with another electron, producing another photon, which will annihilate in a pair …
⟶ Electromagnetic shower

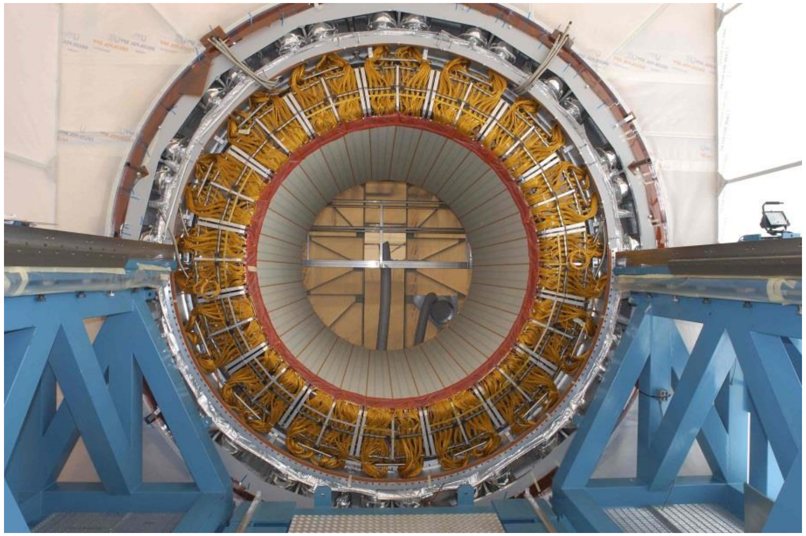

photoelectric
effect dominates
Compton effect
dominates
pair
production
dominates
Z of absorber material
100
80
60
40
20
0
0.01
0.1
1
10
100
photon energy [MeV]

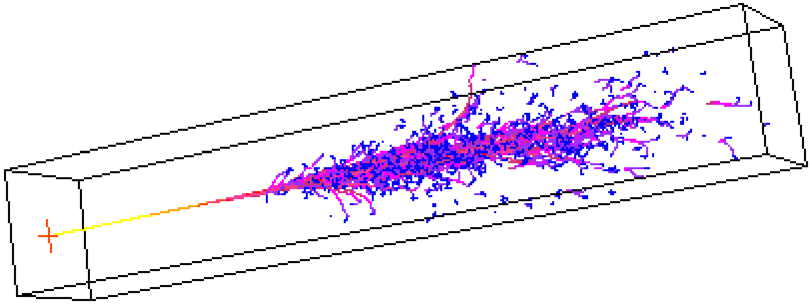
INTERACTION OF PHOTONS : PAIRS PRODUCTION

Note : If enough energy, the positron will annihilate with another electron, producing another photon, which will annihilate in a pair …

⟶ Electromagnetic shower





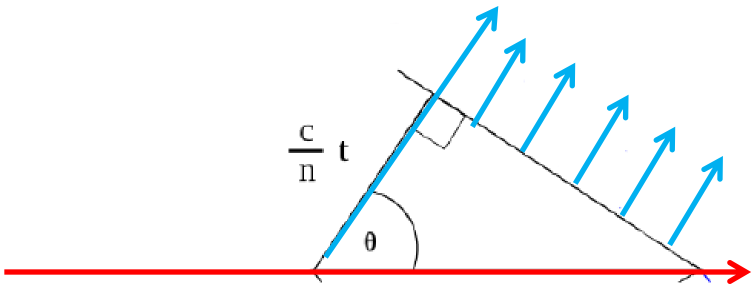


The ATLAS electromagnetioc calorimeter

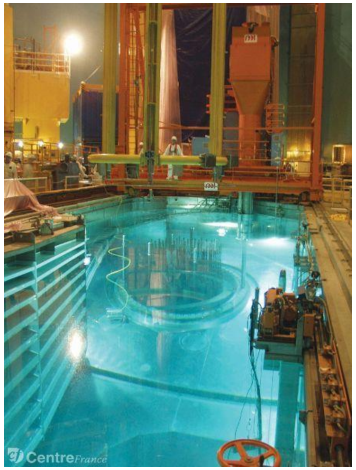
CERENKOV EMISSION

When a particle is moving faster than the velocity of ligth in a given medium

$\longrightarrow$ production of photons



$$\cos\theta = \frac{c/n\,t}{\beta c t} = \frac{1}{\beta n}$$



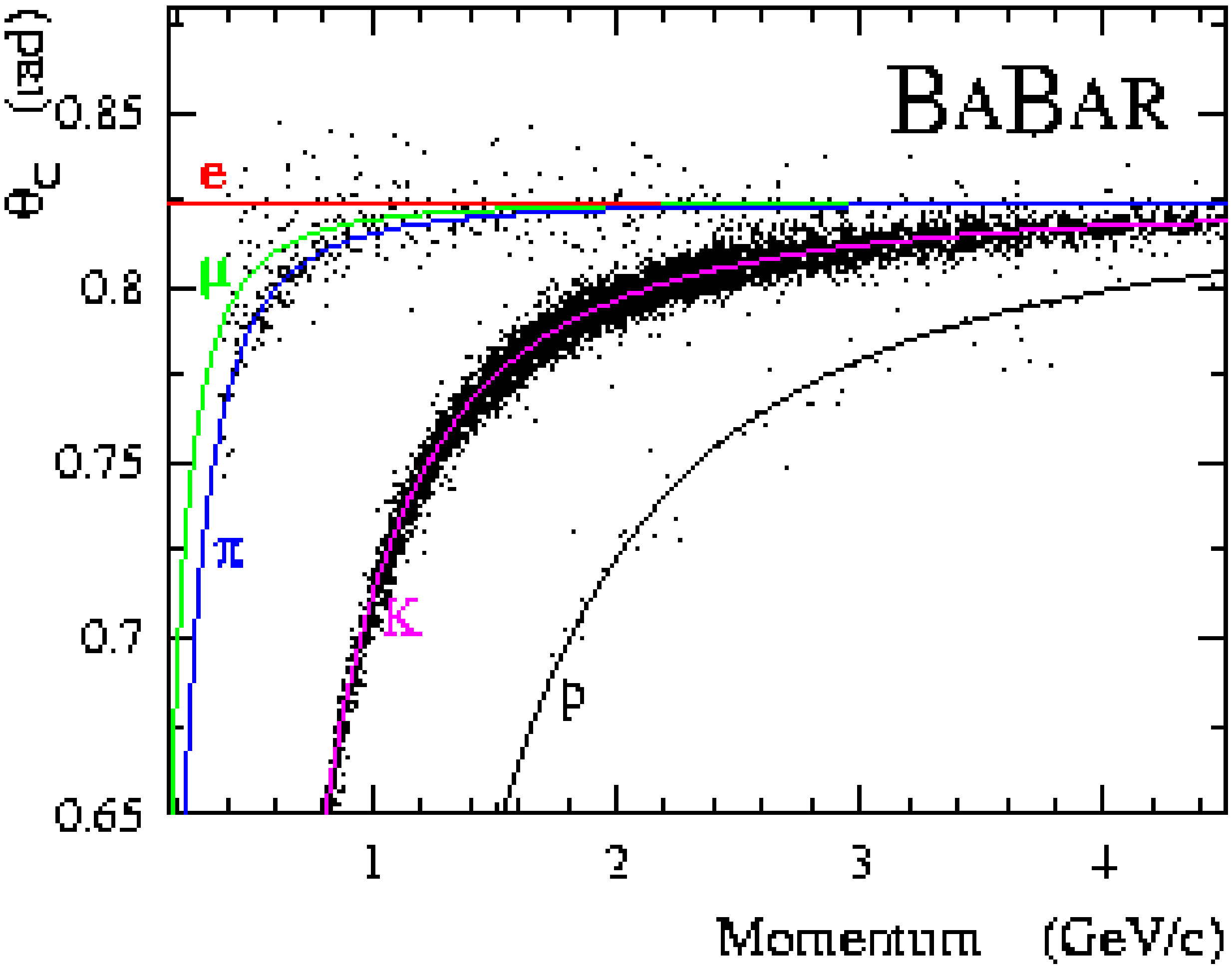
Treshold : $\beta > \frac{1}{n}$ (n is the refractive index of the medium)

Photon production is rather small : $\frac{dN}{dx\,d\lambda} = 2\pi\alpha\frac{1}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2}\right)$

Energy loss is very small (can be neglected):
10^{-3} MeV.cm^2.g^{-1} for solids
0.01 – 0.2 MeV.cm^2.g^{-1} for He, H2

$$\frac{d\lambda}{\lambda^2} = \left(-hc\frac{dE}{E^2}\right) / \left(\frac{(hc)^2}{E^2}\right) = K.dE$$

Typical : 0.35 µm < $\lambda_{cerenkov}$ < 0.55 µm



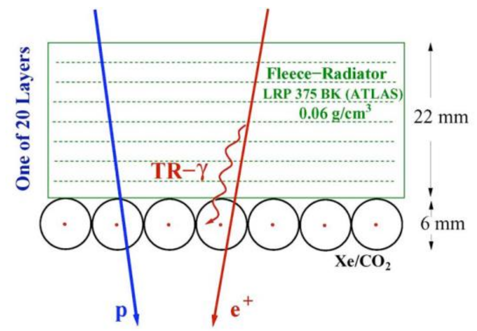
Identification of particles by measurement of Θ (Experience Babar)

TRANSITION RADIATION

Transition radiation is a photon emission (X) occuring when a charged particle passes through inhomogeneous media, such as a boundary between two different media with different dielectric properties

Emission at an angle $\cos\theta = \frac{1}{\gamma}$

Very low rate ~ 1/2 α (fine structure constant)



In the momentum range 1 – 10 GeV, only electrons produce transition radiation with a relatively low probablity (1%) per boundary crossing.
Thus, a TRD is mostly used for electron identification.