Introduction to particle and radiation interactions with matter

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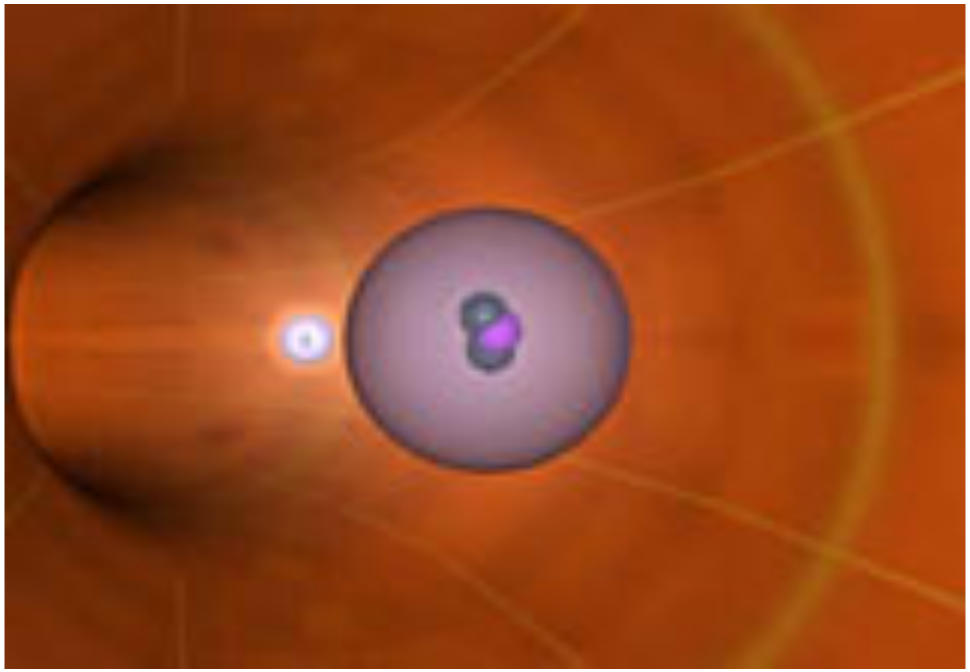
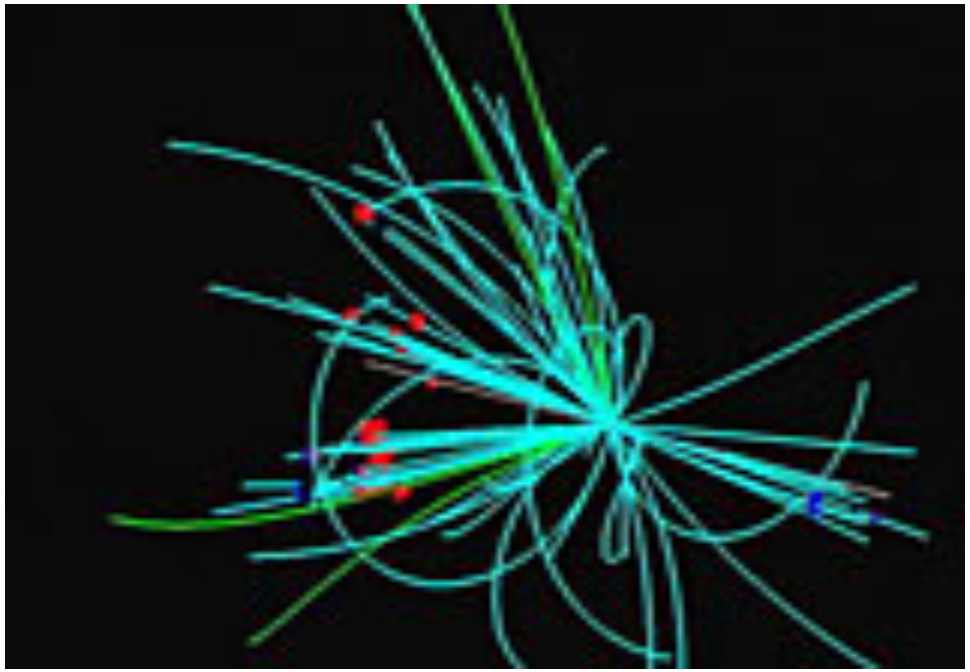


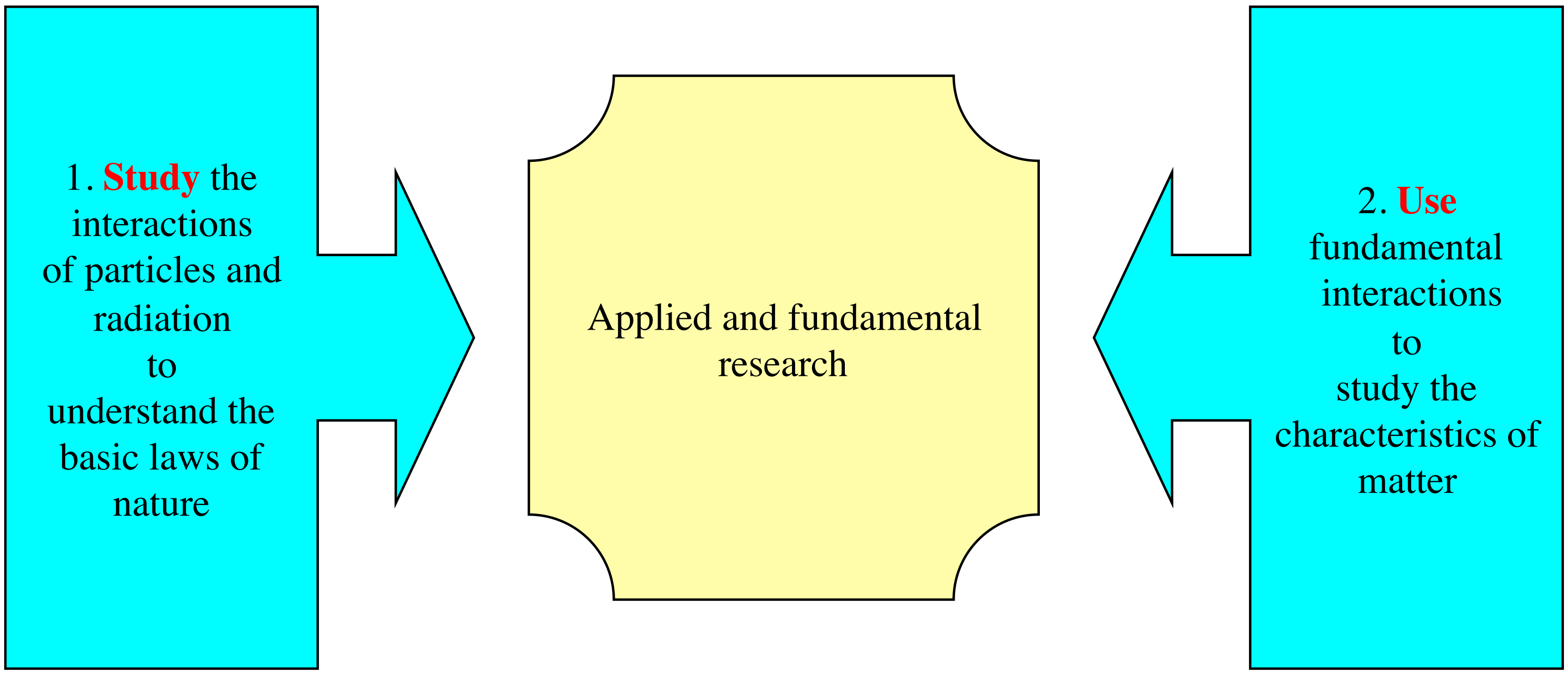


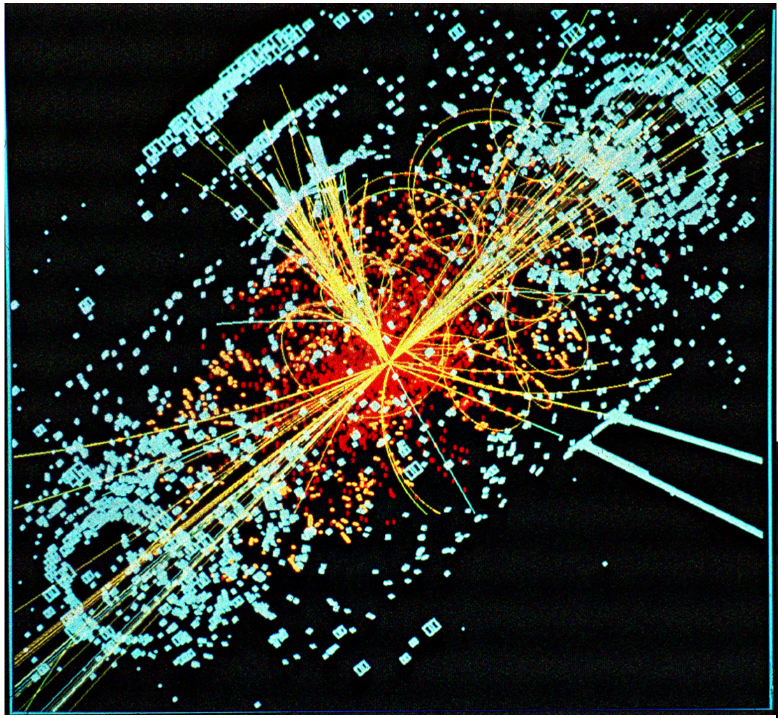
Plan:

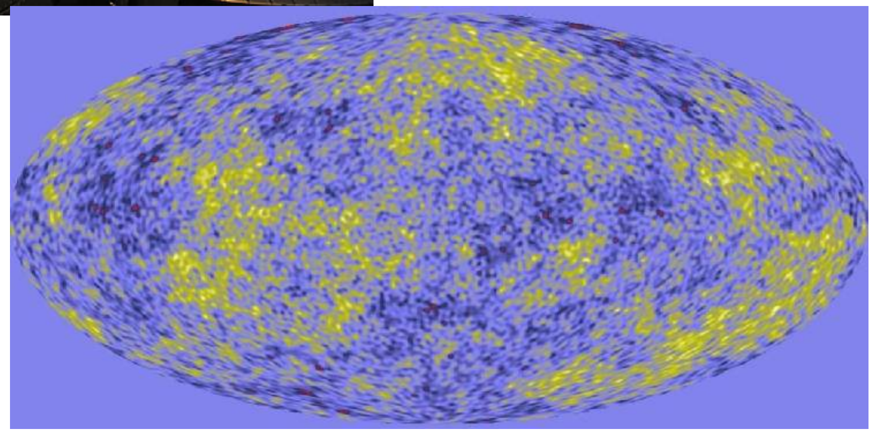
1. Introduction
2. Energy loss of charged particles in matter
3. Interactions of Photons
4. Some examples for light detection
5. Summary

1. Introduction

Two basic reasons why to detect particles or radiation:







Basic quantities:

$$\hbar c = 197,326960 \text{Mev fm}$$

Fine structure constant:

$$\alpha = \frac{e^2}{4\pi\epsilon_0}\frac{1}{\hbar c} = 1/137,03599976$$

Classical electron radius:

$$r_e = \frac{e^2}{4\pi\epsilon_0}\frac{1}{m_e c^2} = \alpha\frac{\hbar c}{m_e c^2} = 2,817940285 \times 10^{-15}\text{m}$$

Energy loss:

$$K = 4\pi N_A r_e^2 m_e c^2 = 4C m_e c^2 = 0,307\text{MeV.cm}^2.\text{g}^{-1}$$

More on orders of magnitude:

Basic units used in particle physics to describe detectors:

- **Photon absorption coefficient μ : $I = I_0 e^{-\mu x}$**
- **Radiation length X_0 : $E = E_0 e^{-x/X0}$**
- **Nuclear interaction length λ_I : $e^{-x/\lambda I}$**

Material	X_0 (g/cm^2) (cm)	λ_I (g/cm^2) (cm)
H	61.28 (866)	50.8 (715.5)
C	42.7 (18.8)	86.3 (38.1)
Scintillator	43.7 (42.4)	81.9 (79.3)
Fe	13.84 (1.76)	131.9 (16.7)
Xe	8.48 (2.87)	169. (29.1)
Pb	6.37 (0.56)	194. (17.1

Related cross sections:

Strong interaction : $\sigma \sim 10 \div 100$ mb
Electro-magnetic interaction: $\sigma \sim 10 \div 100$ nb
Weak interaction: $\sigma \sim 10 \div 100$ pb

(1 barn = 10^{-28} m^2)

Energy loss of particles (1):

Charged Particles:

Light particles: electrons & positrons

- Bremsstrahlung dominates @ E> 20 MeV
- Inelastic scattering with atoms (ionization)
- Elastic scattering with nucleons
- Cherenkov Radiation
- Nuclear reactions

Heavy particles: muons, protons, π, α

- Inelastic scattering with atoms (ionization): $\sigma \approx 10^{-17}$ - 10^{-16} cm^2
- Elastic scattering with nucleons
- Cherenkov Radiation
- Nuclear reactions
- Bremsstrahlung

Energy loss of particles (2): Neutral particles

photons

- Photoelectric Effect
- Compton Scattering
- Pair Production
- Nuclear reactions (small contribution)

neutrons

Slowing down (moderation) by:

- Elastic Scattering
- Inelastic Scattering

-> Nuclear Absorption
-> Nuclear Reactions (fission)

neutrinos

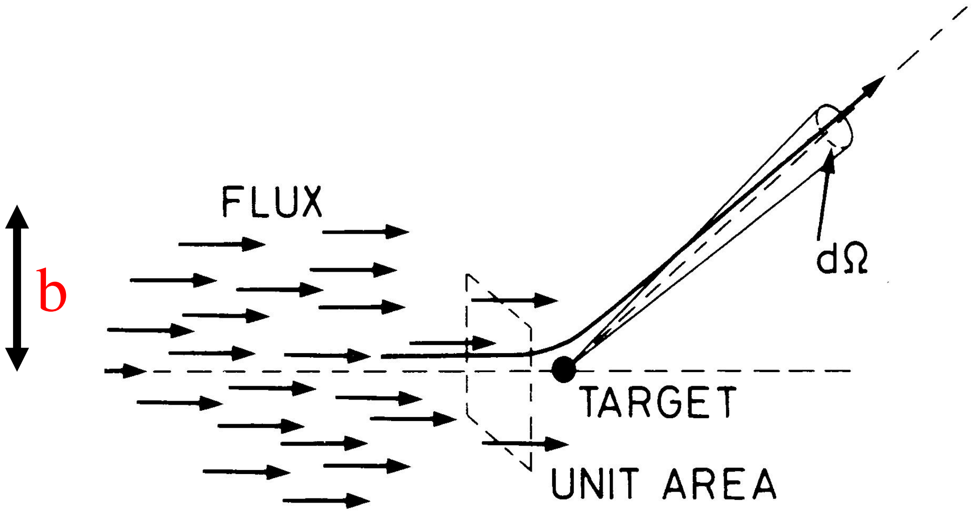
Electro-weak interaction:

$\nu_l + e^- \rightarrow e^- + \nu_l$

$\nu_l + N \rightarrow l + X$

2. Energy loss of charged particles in matter

Scattering and Cross Section



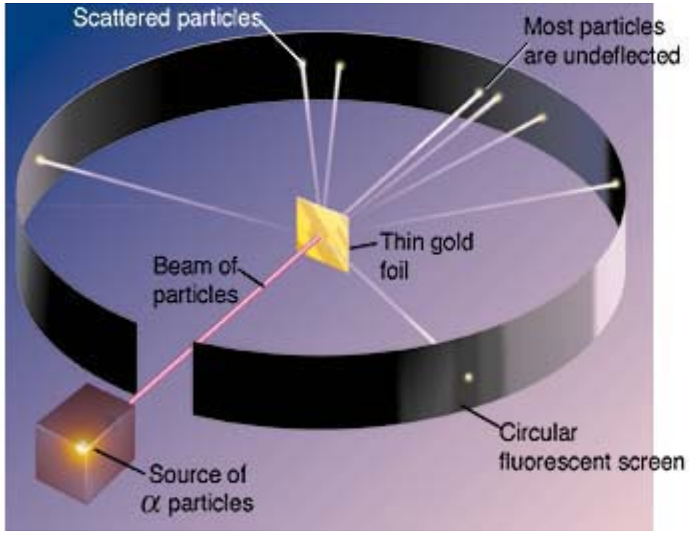
Average number of scattered particles into dΩ per unit time:

$$N_{scattered} = N_{incident} \text{ x } A_{target} \text{ x } N_{target} \text{ x } dx \text{ x } d\sigma/d\Omega$$

$N_{incident}$ = Flux of incident particles / unit area / unit time
A_{target} = Target area
N_{target} = Density of scattering centers
dx = Thickness of the material parallel to the beam
dσ/dΩ = Differential cross section

Lots of numbers from the experimental setup, the physics is in dσ/dΩ !

Example: Coulomb Scattering (Rutherford)



$$\frac{d\sigma}{d\Omega} = \frac{b}{\sin\theta}\left|\frac{db}{d\theta}\right|$$

b = impact parameter
θ = scattering angle

Relation between scattering angle, impact parameter and shortest approach:

$$\mathrm{tg}\left(\frac{\theta}{2}\right) = \frac{a_0}{2b},\ a_0 = \text{shortest distance of approach, b = impact parameter}$$

$$b = \frac{a_0}{2}\cot\left(\frac{\theta}{2}\right) \quad \text{and} \quad \frac{db}{d\theta} = \frac{a_0}{4} \times \frac{1}{\sin^2\left(\frac{\theta}{2}\right)}$$

$$\frac{d\sigma}{d\Omega} = \frac{b}{\sin\theta}\left|\frac{db}{d\theta}\right| = \boxed{\frac{a_0^2}{16\sin^4\left(\frac{\theta}{2}\right)}} \quad \text{with } a_0 = \frac{kZ_1Z_2e^2}{E},\ k = {}^{1}\!/_{4\pi\varepsilon_0},\ Z_1, Z_2 = \text{atomic numbers of beam and target}$$

Application:

We have a beam of protons with an energy of 22 MeV and an intensity of 200 nA on a thin gold foil target with a thickness e = 100 μg / cm^2.

Question: How many protons are detected in a detector with a surface S = 0.2 cm^2 at a distance, R = 10 cm and an angle θ = 10°?

$$N_{inc} = \frac{I}{q} = \frac{200 \times 10^{-9}\ \text{A}}{1.602 \times 10^{-19}\ \text{A s}} = 1.25 \times 10^{12}\ \text{particles/sec}$$

Number of detected particles $= \text{N}_{\text{det}} = N_{inc} \times N_{target} \times \Omega \times \sigma(\theta)$

$$N_{target} = \frac{N_{Avogardo} \times Thickness}{\text{atomic mass}} = \frac{6 \times 10^{23}(nucl/mol) \times 100 \times 10^{-6}(g/cm^2)}{197(g/mol)}$$

$$\Omega = \frac{S}{R^2} = \frac{0.2\ \text{cm}^2}{100\ \text{cm}^2}$$

$$\sigma(\theta) = \frac{a_0^2}{16\sin^4\left(\frac{\theta}{2}\right)} = \frac{1}{16\sin^4\left(\frac{\theta}{2}\right)} \times \left[\frac{kZ_1Z_2e^2}{E}\right]^2 \quad \text{using } \frac{\text{ke}^2}{\hbar\text{c}} = 1/137 \text{ and } \hbar\text{c} = 200 \text{ MeV fm}$$

$$\text{N}_{\text{det}} = 1.25 \times 10^{12}\ \text{particles/sec} \times \frac{6 \times 10^{23}(nucl/mol) \times 100 \times 10^{-6}(g/cm^2)}{197(g/mol)} \times \frac{0.2\ \text{cm}^2}{100\ \text{cm}^2} \times \left[\frac{\text{ke}^2}{\hbar\text{c}} \times \hbar\text{c} \times \frac{1 \times 79}{22\ \text{MeV}}\right]^2 \times \frac{1}{16\sin^4\left(\frac{\theta}{2}\right)}$$

$$N_{\text{det}} = 1.25 \times 10^{12}\frac{protons}{\text{sec}} \times \frac{3 \times 10^{17}}{cm^2} \times 2 \times 10^{-3}\left[\frac{1}{137} \times 200\ \times 10^{-13}\ \text{MeV cm}^2 \times \frac{1 \times 79}{22\ \text{MeV}}\right]^2 \times 10^3$$

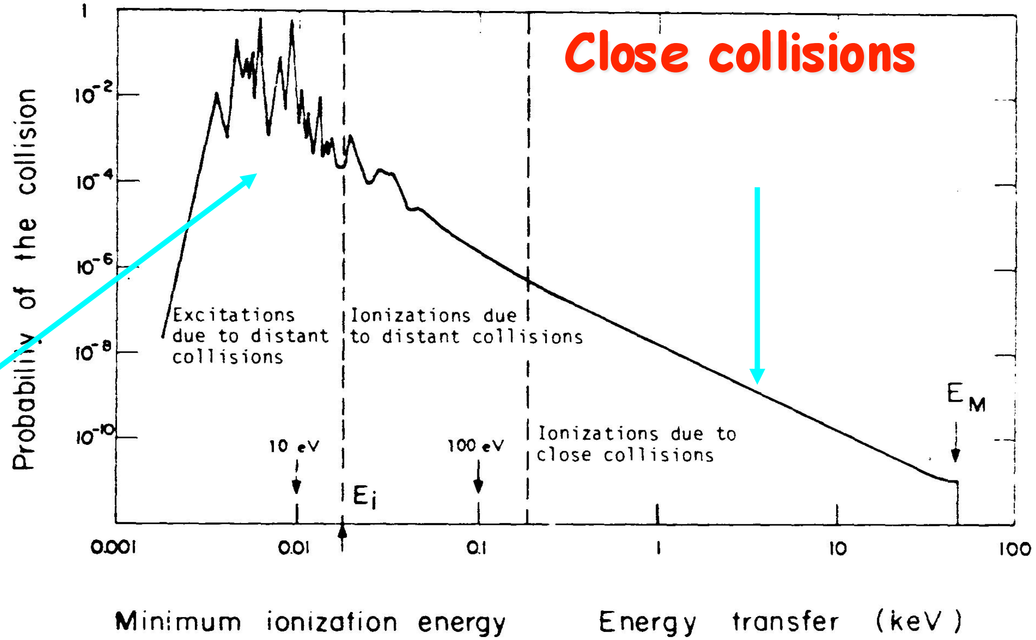
$$N_{\text{det}} = 2 \times 10^5 \text{protons/sec.}$$

Energy loss of heavy particles by ionization

A heavy particle, M, looses its energy in matter in a continues way by transferring it on electrons.

Dependent on the distance of the interaction, the energy loss is more or less important.

Distant collisions



Maximum energy transfer:

$$T_{max} = \frac{2\gamma^2 M^2 m_e v^2}{m_e^2 + M^2 + 2\gamma m_e M}$$

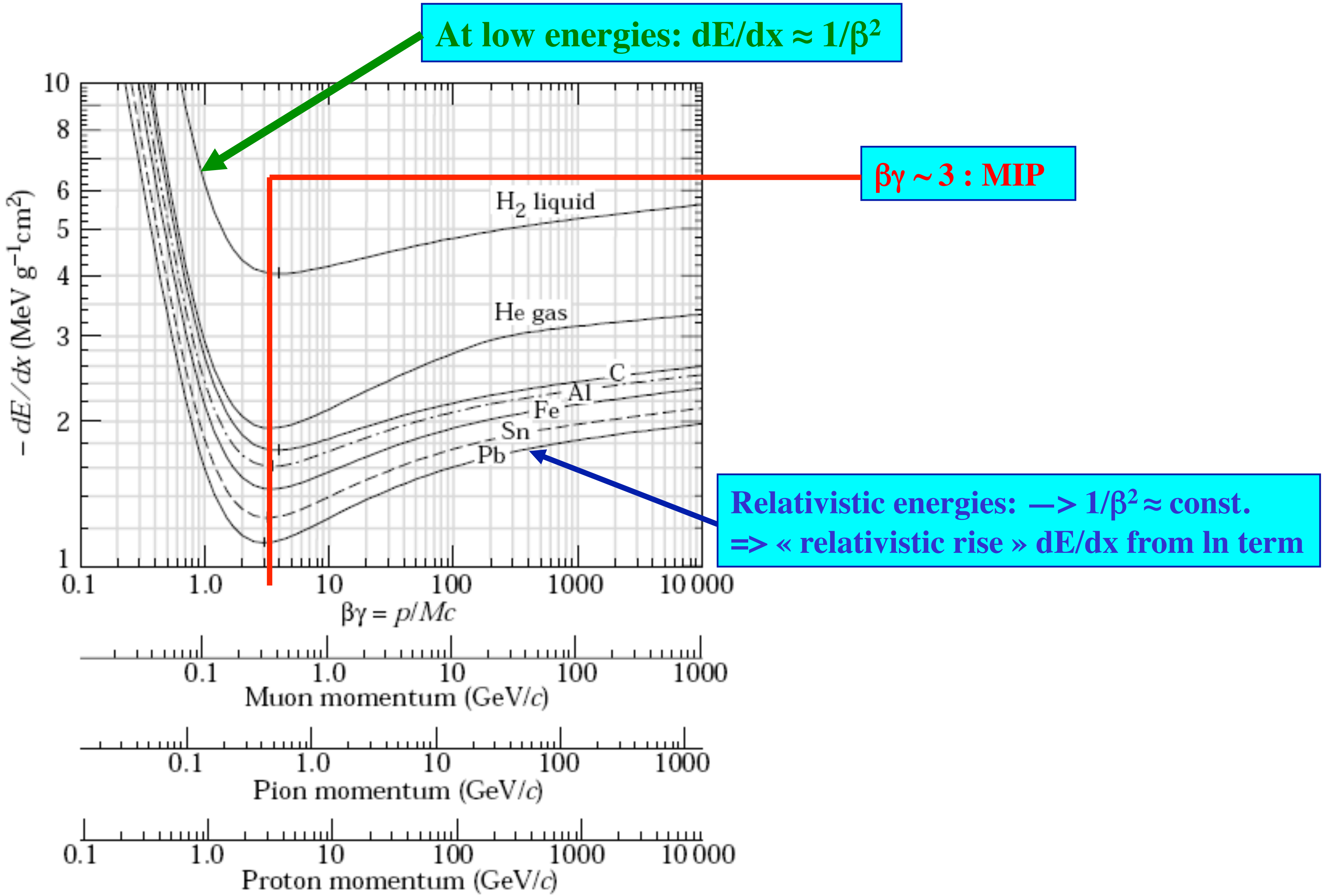
Mean rate of energy loss or stopping power:

Bethe-Bloch equation:

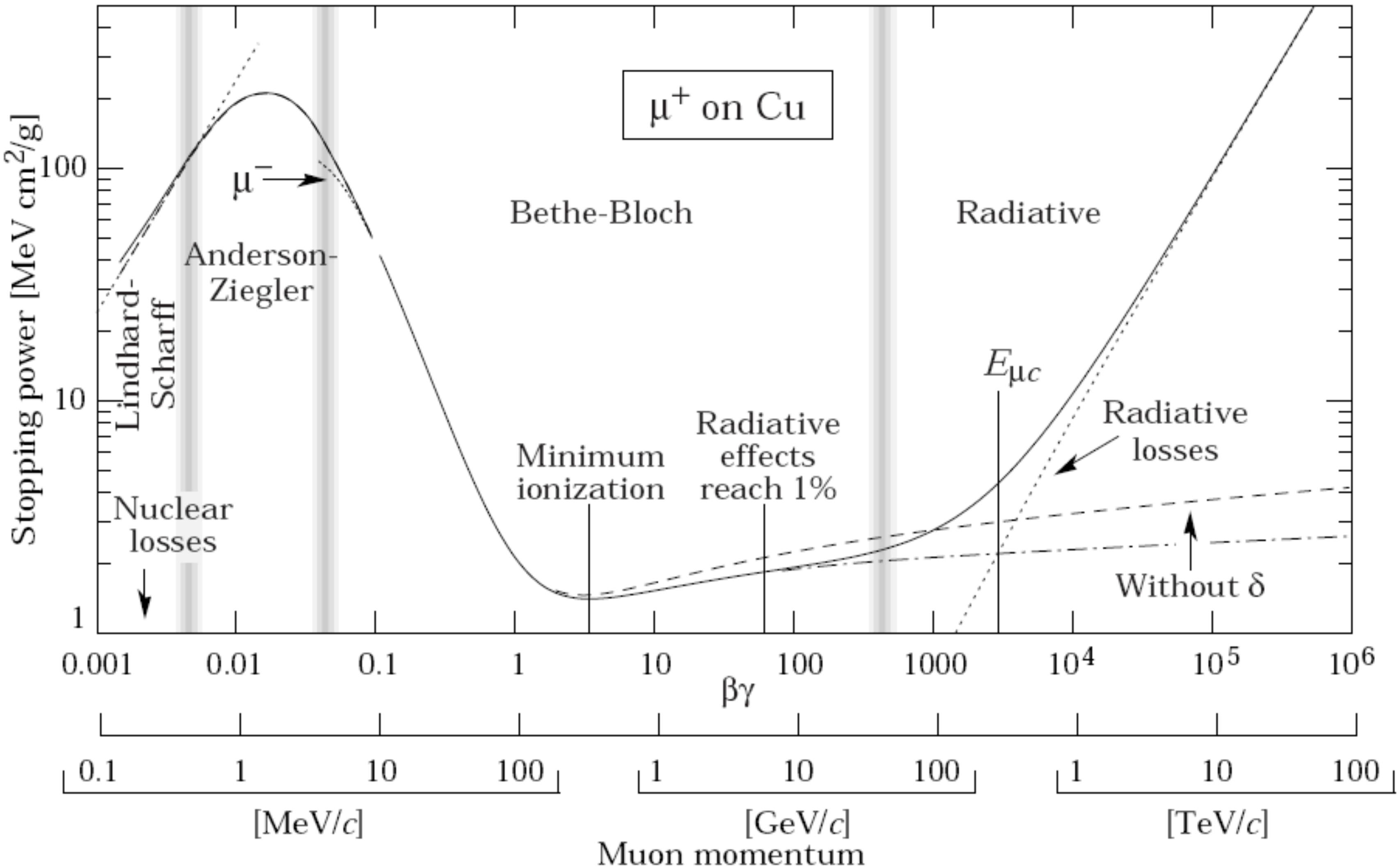
$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

Z	Atomic number of absorber	
A	Atomic mass of absorber	g mol^{-1}
K/A	$4\pi N_A r_e^2 m_e c^2/A$	0.307 075 MeV g^{-1} cm^2 for A = 1 g mol^{-1}
I	Mean excitation energy	eV (*Nota bene!*)
$\delta(\beta\gamma)$	Density effect correction to ionization energy loss	

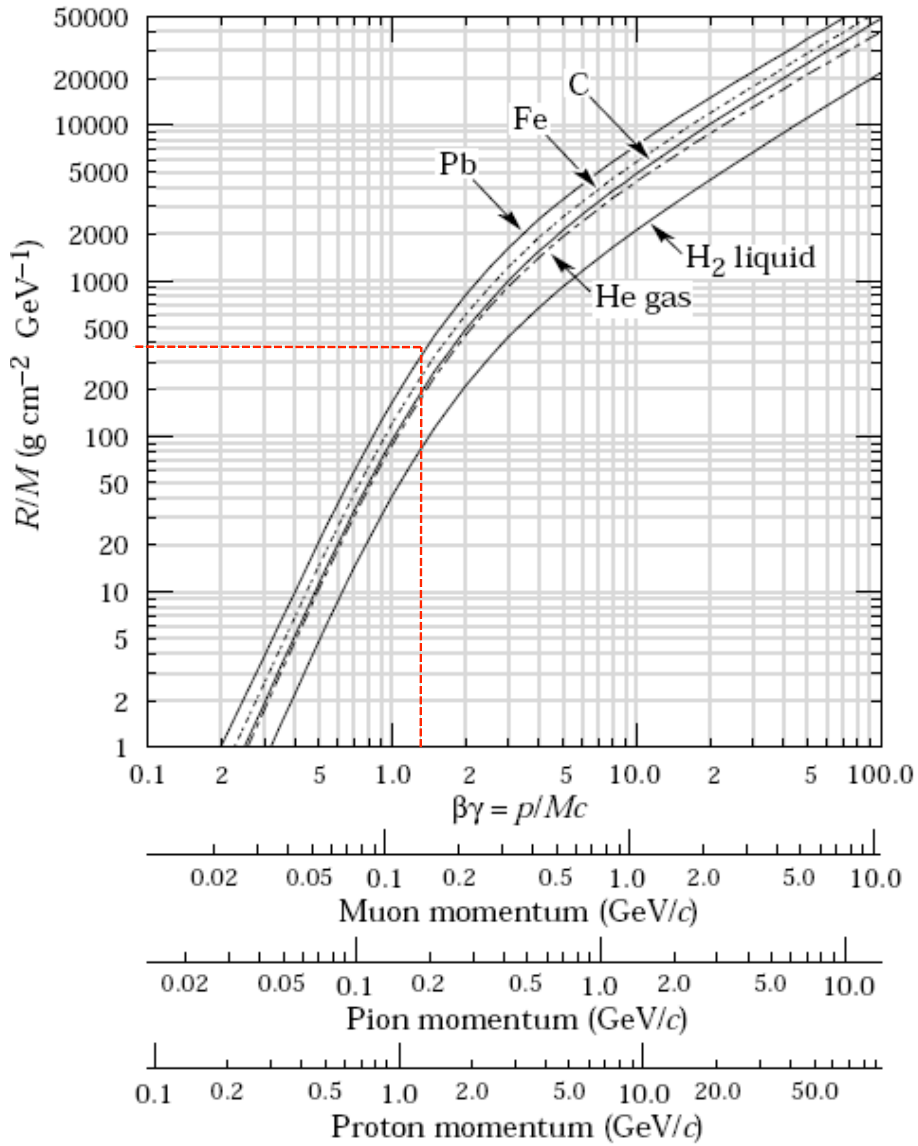
$$T_{\max} = \frac{2m_ec^2\,\beta^2\gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}$$



At low energies: dE/dx ≈ 1/β²
βγ ~ 3 : MIP
Relativistic energies: —> 1/β² ≈ const.
=> « relativistic rise » dE/dx from ln term
H2 liquid
He gas
C
Al
Fe
Sn
Pb
− dE/dx (MeV g⁻¹cm²)
βγ = p/Mc
Muon momentum (GeV/c)
Pion momentum (GeV/c)
Proton momentum (GeV/c)


μ+ on Cu
Stopping power [MeV cm2/g]
100
10
1
μ−
Bethe-Bloch
Radiative
Anderson-
Ziegler
Lindhard-
Scharff
Nuclear
losses
Minimum
ionization
Radiative
effects
reach 1%
Eμc
Radiative
losses
Without δ
0.001
0.01
0.1
1
10
100
1000
10^4
10^5
10^6
βγ
0.1
1
10
100
1
10
100
1
10
100
[MeV/c]
[GeV/c]
[TeV/c]
Muon momentum

Particle range:



Example : K^{+} with $p_k = 700\,MeV/c$

$m_k = 494\,MeV$

$$\beta\gamma = \frac{p_k}{m_k c} = \frac{700}{494} = 1{,}42$$

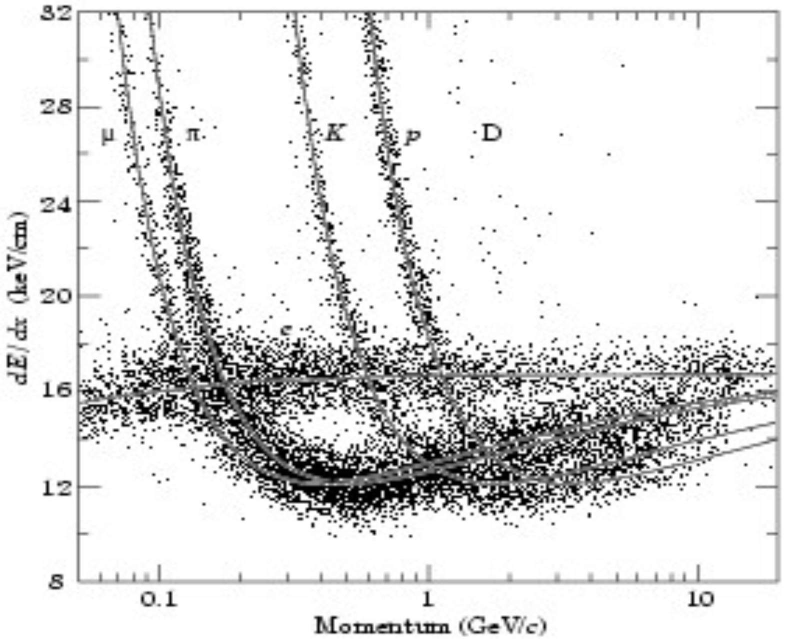
$For\,Pb : R/M = 396\,gcm^{-2}GeV^{-1}$

$\Rightarrow R = 396\,gcm^{-2}GeV^{-1} \times 0{,}494\,GeV = 196\,gcm^{-2}$

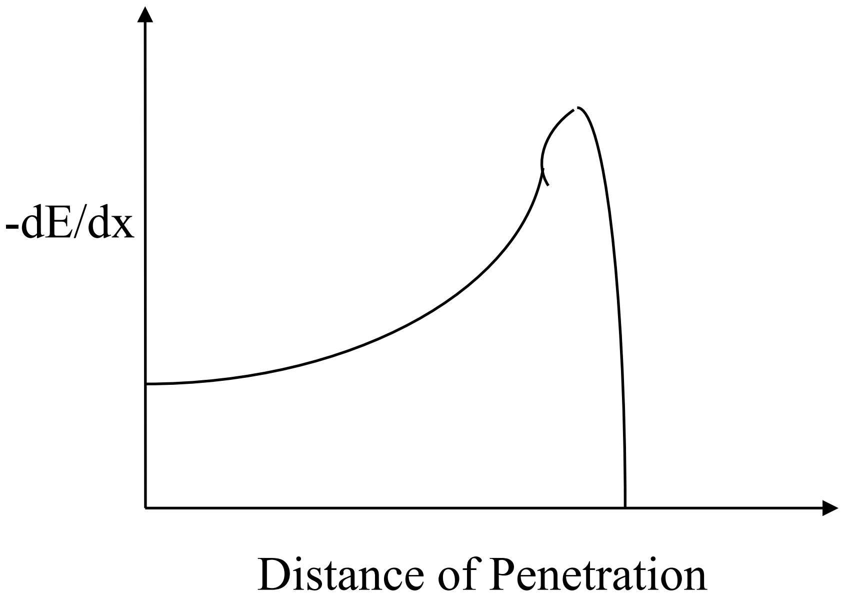
$\rho_{Pb} = 11{,}35\,gcm^{-3}$

$\Rightarrow R = 196\,gcm^{-2} \div 11{,}35\,gcm^{-3} = \underline{\underline{17\,cm}}$

Bragg curve:

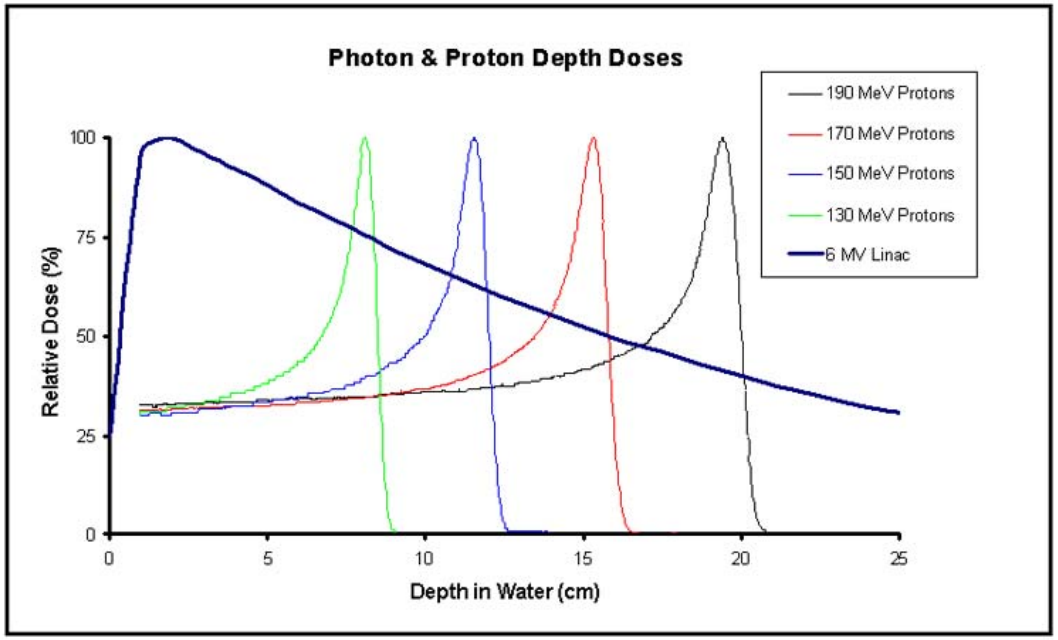


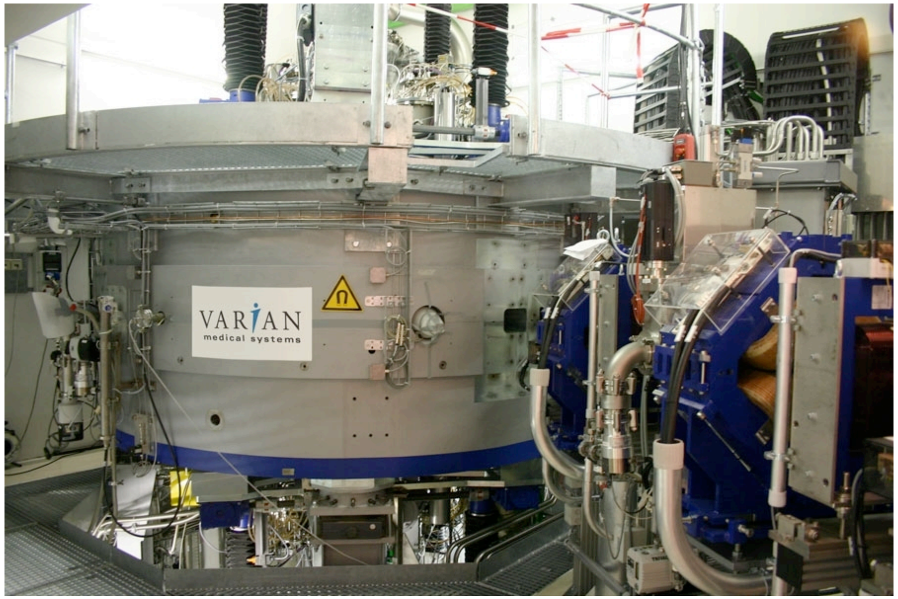
32
28
24
20
16
12
8
dE/dx (keV/cm)
μ
π
K
p
D
e
0.1
1
10
Momentum (GeV/c)



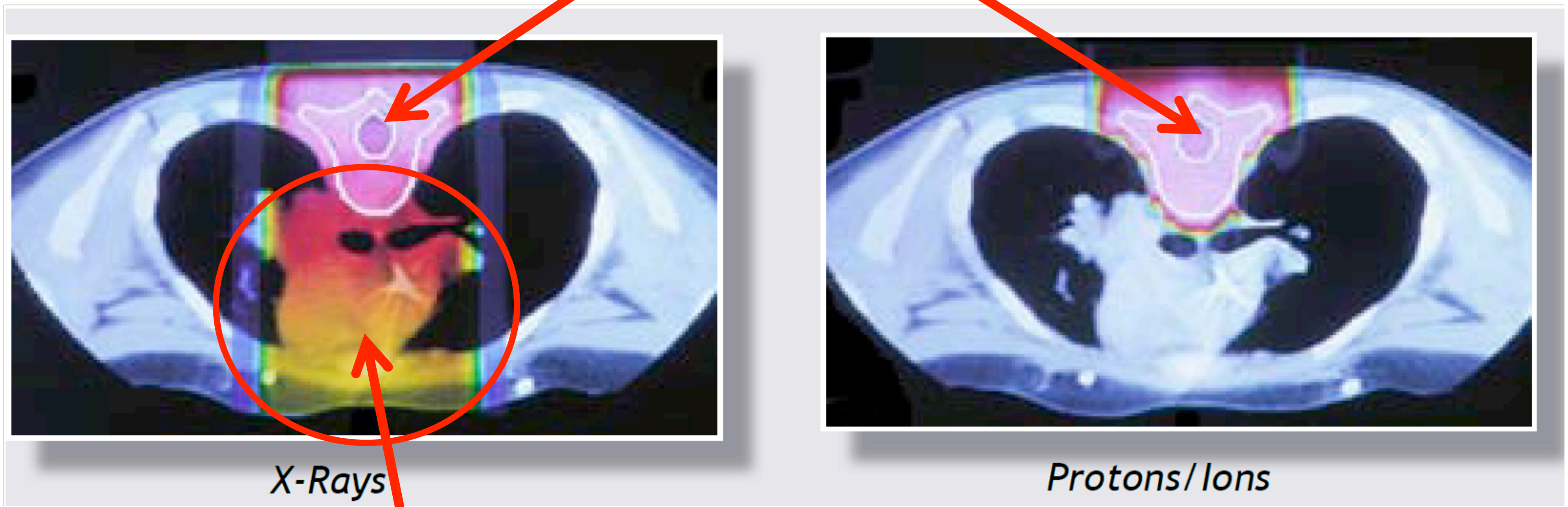
-dE/dx
Distance of Penetration

Thérapie avec les protons





Cancer



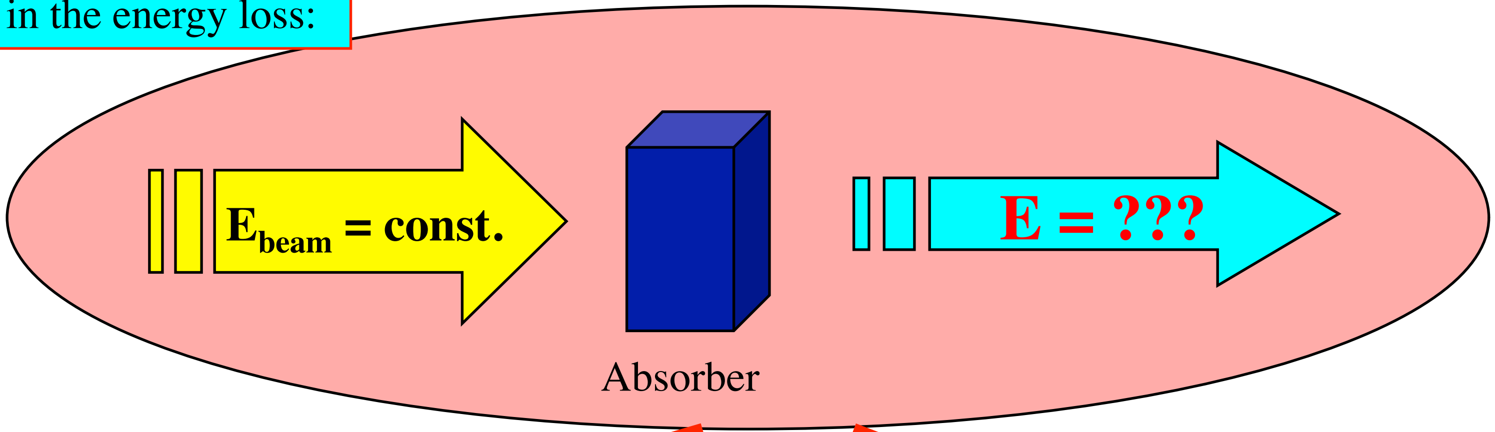
Tissu inutilement irradié

Avantages des protons:

•Lourdes → moins de dispersion → mieux focalisés
•dE/dx → peak de Bragg →depôt d'énergie concentré

Pour photons X et γ: **$I= I_0 e^{-\mu x}$**

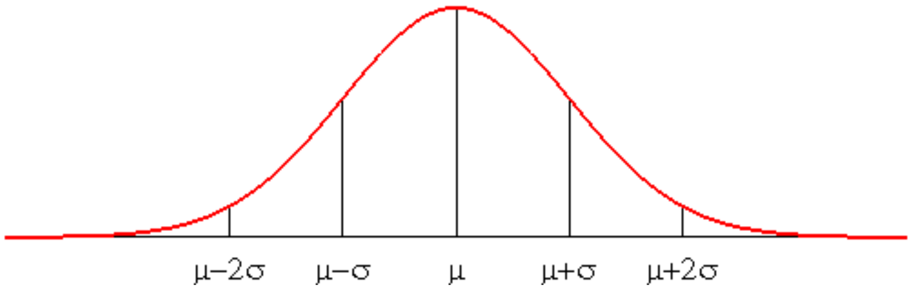
Fluctuations in the energy loss:



Thick Absorber:

Large number of collisions

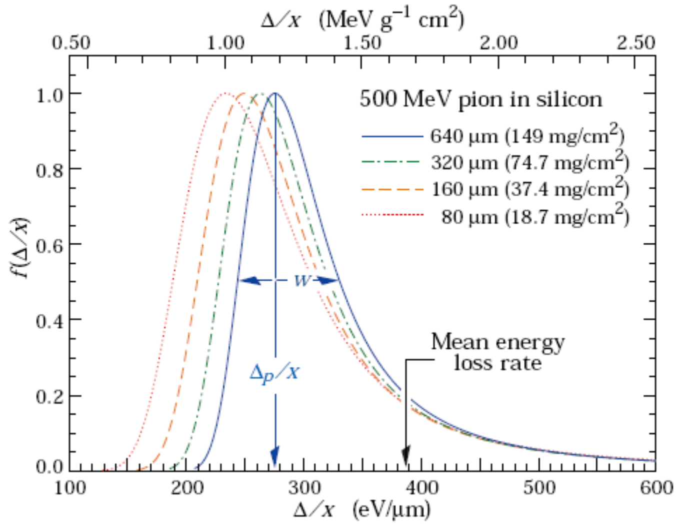
Gauss



Thin Absorber:

Small number of collisions

Landau Distribution



Electrons

Energy loss of Electrons and Positrons

$$\left(\frac{dE}{dx}\right)_{tot} = \left(\frac{dE}{dx}\right)_{rad} + \left(\frac{dE}{dx}\right)_{coll}$$

1. Energy loss by ionization like heavy particles:

Dominant at energies < 20 MeV

Bethe-Bloch Equation for electrons:

$$\left(\frac{dE}{dx}\right) = 0{,}307\left(\frac{MeV}{g/cm^2}\right)\frac{Z}{A}\rho\frac{1}{\beta^2}\left(\ln\frac{2T(T+2m_e)}{I\times m_e} - \beta^2\right)$$

T = Kinetic energy of the electron
I = Ionization potential

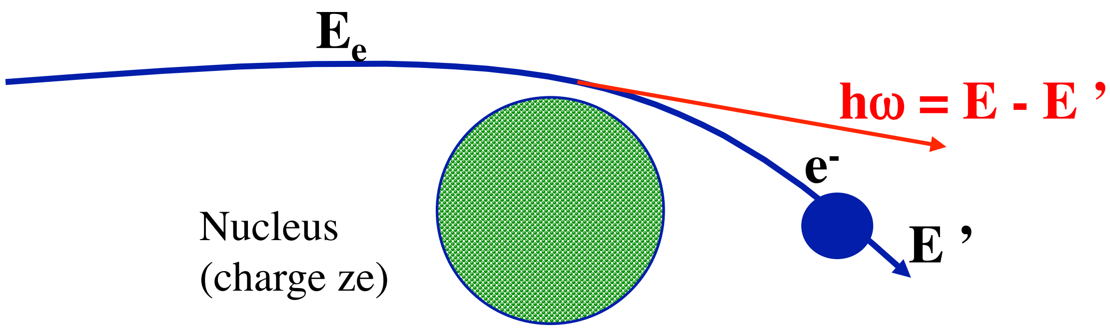
Two modifications needed in the equation

- Small mass —> larger deviation of the trajectory
- Diffusion of two identical particles (Pauli)

Energy loss of Electrons and Positrons

2. Energy loss by radiation (Bremsstrahlung): For E > 20 MeV

Classical interpretation::
Radiation from the acceleration of an electron or positron in the field of the nucleus.



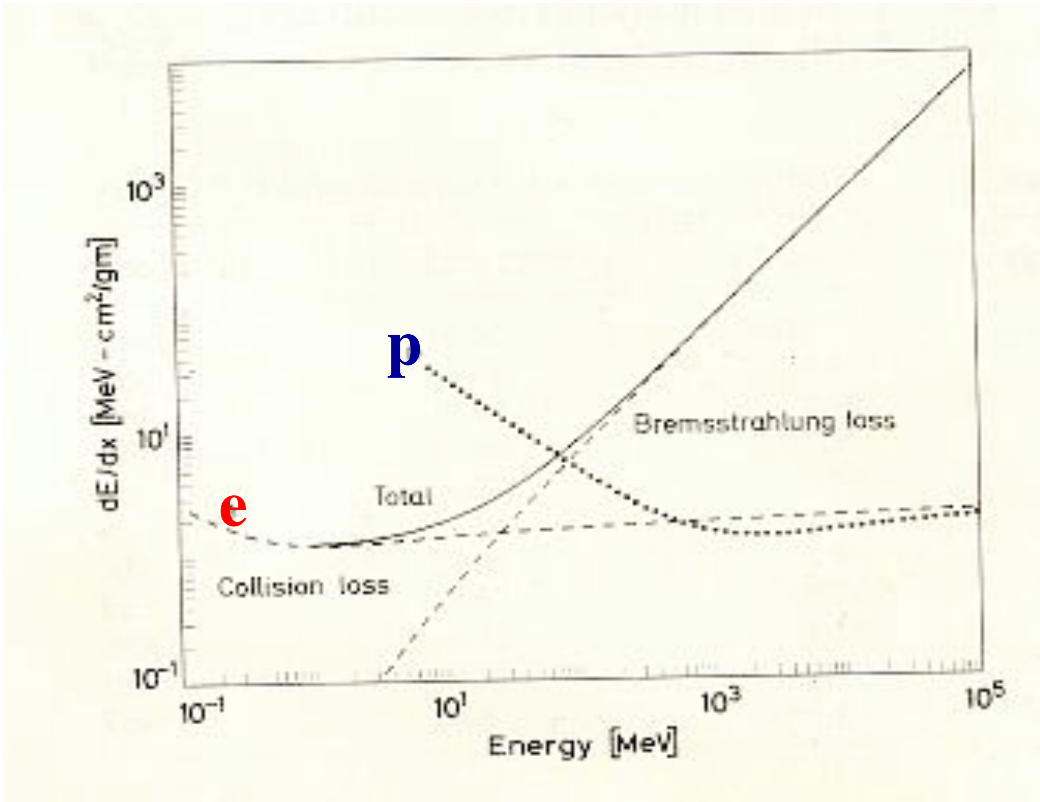
$$\frac{d\sigma}{dk} \cong 5\alpha z^2 Z^2 \left(\frac{m_e c^2}{Mc^2\beta}\right)^2 \frac{r_e^2}{k} \ln\left(\frac{Mc^2\beta^2\gamma^2}{k}\right)$$

With k = Energy of the radiation (photons)

Energy loss of Electrons and Positrons

$$\frac{d\sigma}{dk} \propto \frac{1}{M_{\text{incomming particle}}}$$

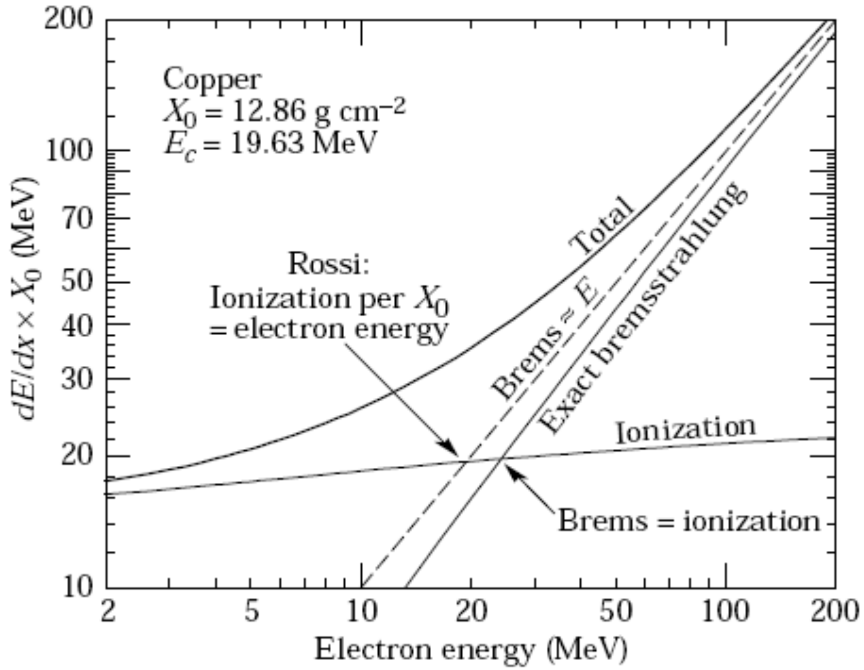
- For a muon (M = 106 MeV) σ_{brems} is **40000** times smaller than for an electron!
- For a proton σ_{brems} is roughly **4 million** times smaller!!!

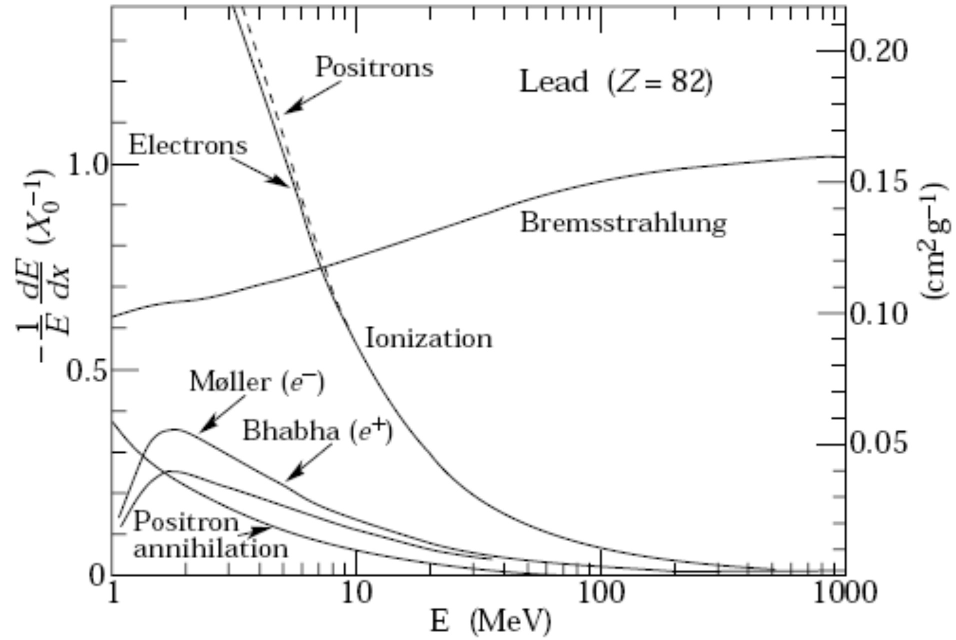


In first order, Energy loss by Bremsstrahlung is only relevant for electrons

Energy loss of Electrons and Positrons

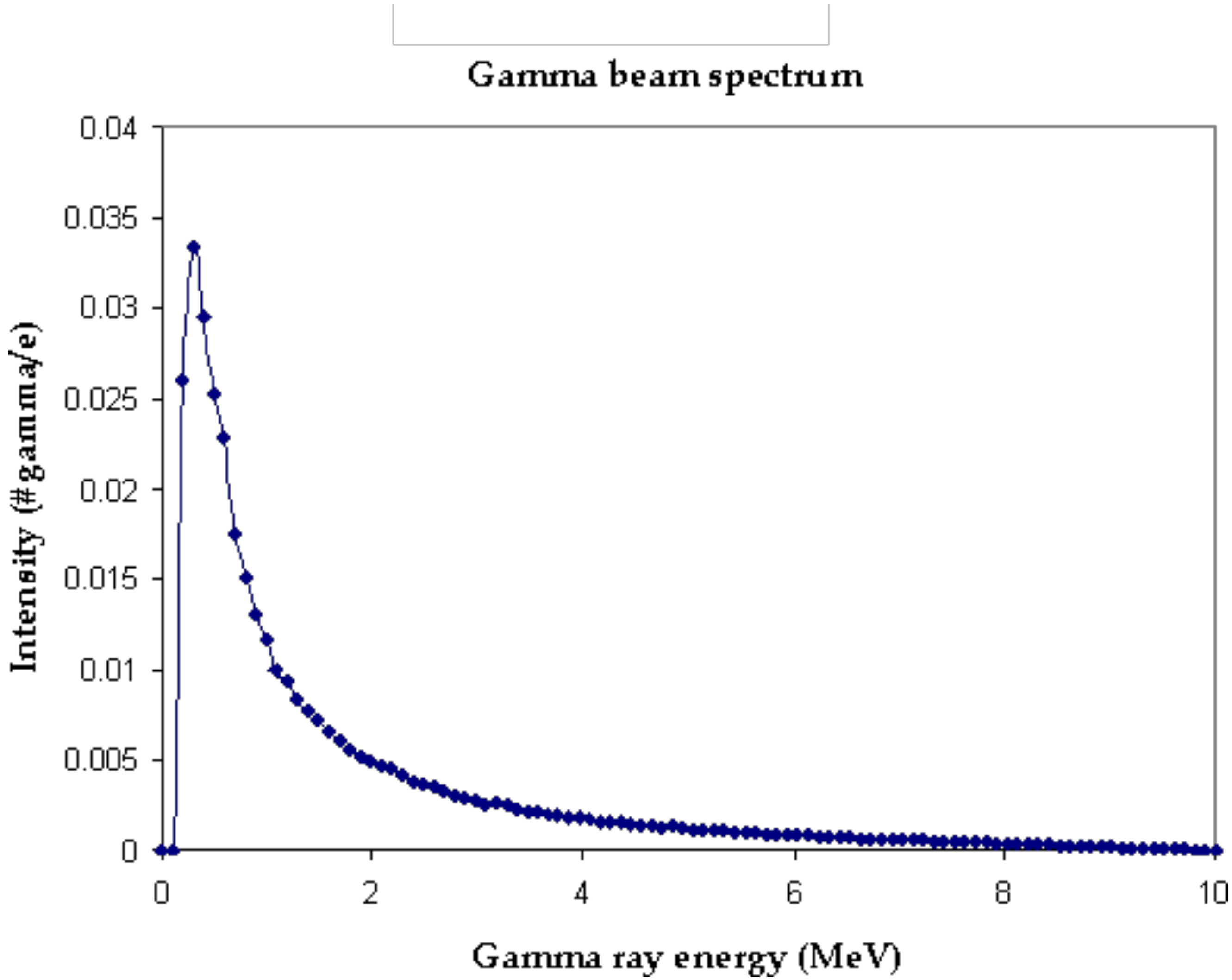
Definition of radiation length: X_0 = Average distance traveled by an electron before loosing 1/e of its energy by Bremsstrahlung.





Dahl's formula: $$X_0 = \frac{716.4\,g\,cm^{-2}\,A}{Z(Z+1)\ln(287/\sqrt{Z})}$$

- Electron energy: 10 MeV
-Target: 1 mm Ta (or 3 cm graphite)
- Average γ-ray energy: 1.7 MeV



Critical Energy:

Definition:

$$E = E_c \quad \text{for} \quad \left(\frac{\mathrm{dE}}{\mathrm{dx}}\right)_{rad} = \left(\frac{\mathrm{dE}}{\mathrm{dx}}\right)_{coll}$$

Above E_c radiation loss will dominate over collision losses

Liquids & solids

$$\epsilon_c = \frac{610\mathrm{MeV}}{Z + 1,24}$$

Gases

$$\epsilon_c = \frac{710\mathrm{MeV}}{Z + 0,92}$$

Range of Electrons

Multiple scattering in matter:

The range is very different from the dE/dx by Bethe-Bloch

Differences from 20% to 400%

More fluctuations in dE/dx than for heavy particles:

1. Energy transfer in each collision is bigger
2. Bremsstrahlung

Some empirical formulas to calculate the range of electrons::

Sternheimer relation:

$\mathbf{R_e(T) = (0.486\ g\ cm^{-2})\ T^n}$

with $n = 1.265 - 0.954 \ln(T)$

T en MeV

Example: Electron with T = 100 KeV in a TPC
With He at 77 K and 5 bars:
$R(T) = (0.486\ g\ cm^{-2} / 3{,}124 \times 10^{-3}\ g\ cm^{-3})\ T^{(1{,}265 - 0{,}0954 \ln(0{,}1))}$
R(0,1MeV) = 5 cm

Range of Electrons

$$R(T) = A \times E\left(1 - \frac{B}{1+CT}\right)$$

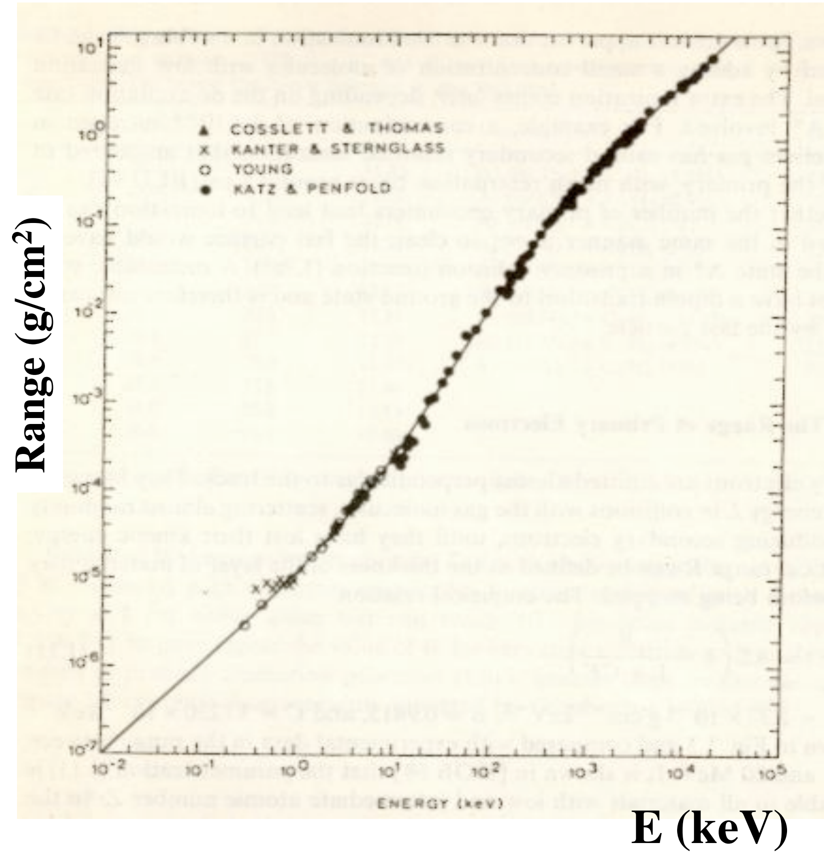
(Valid for small and medium Z)

Avec: $A = 5.37 \times 10^{-4}$ g cm^{-2} KeV^{-1}

$B = 0.9815$

$C = 3.1230 \times 10^{-3}$ KeV^{-1}

300 eV < T < 20 MeV



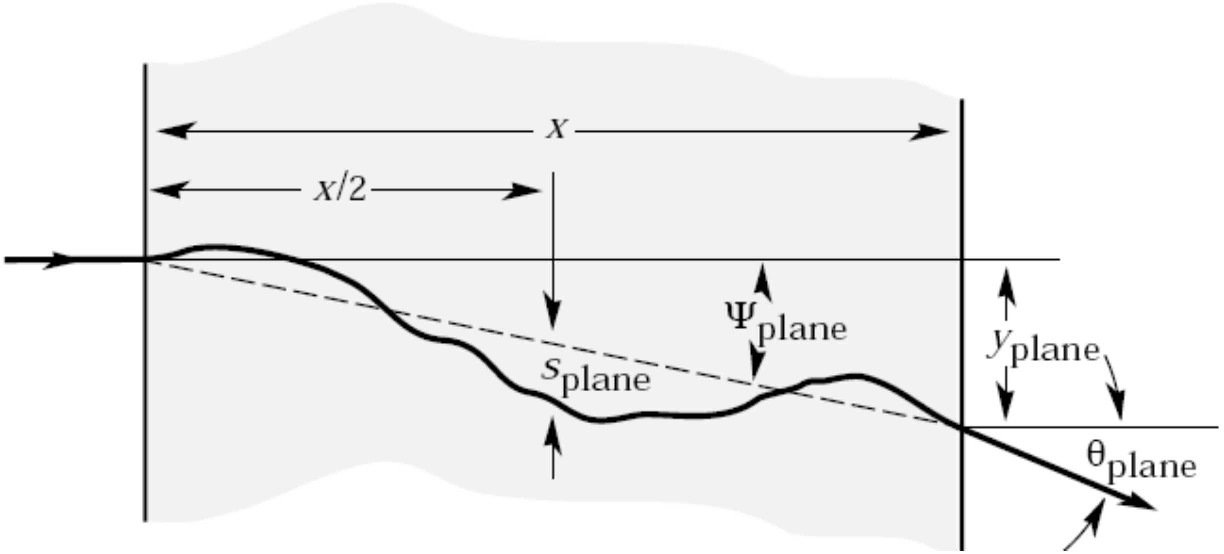
Blum, Rolandi: Particle Detection with Drift Chambers
Springer Verlag, 1993

Multiple scattering through small angles

- Charged particles traversing a medium are deflected by many small angle scatters.
- Scattering is mostly due to Coulomb scattering from nuclei. (for hadrons strong interaction also contributes)
- Angular distribution described by Molière theory and is in first approximation Gaussian.
- For large angles = Rutherford scattering (larger tails than the Gaussian distribution).

Gaussian approximation:

$$\theta_0 = \theta_{plane}^{rms} = \frac{1}{\sqrt{2}}\theta_{space}^{rms}$$



$$\theta_0 = \frac{13.6\text{MeV}}{\beta c \times p} z \sqrt{x/X_0}\left(1 + 0.038 \ln\{x/X_0\}\right)$$

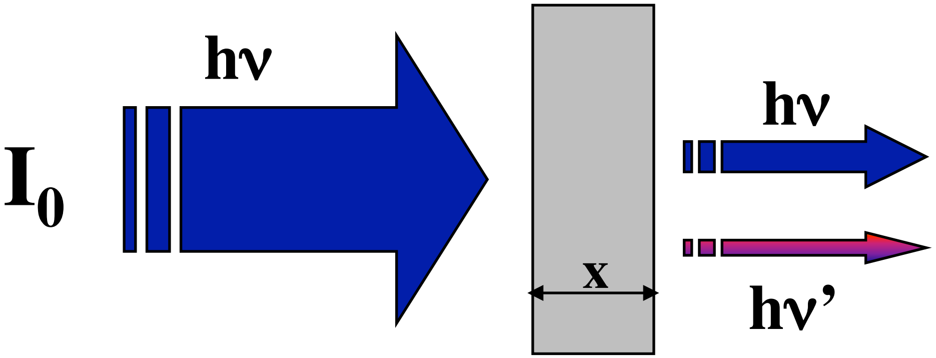
p, βc, z are momentum, velocity and charge of the incoming particle

3. Interactions of Photons

Interactions of Photons

Electric charge = 0 → **No Coulomb scattering with electrons of matter**

- Deeper penetration in matter (smaller cross section)
- A beam of photons traversing a slab of matter is attenuated in **intensity**, NOT in energy!
- Beam photons which passed through did NOT undergo an interaction.
- If they had an interaction, they change energy.



$$I(x) = I_0 \exp(-\mu x)$$

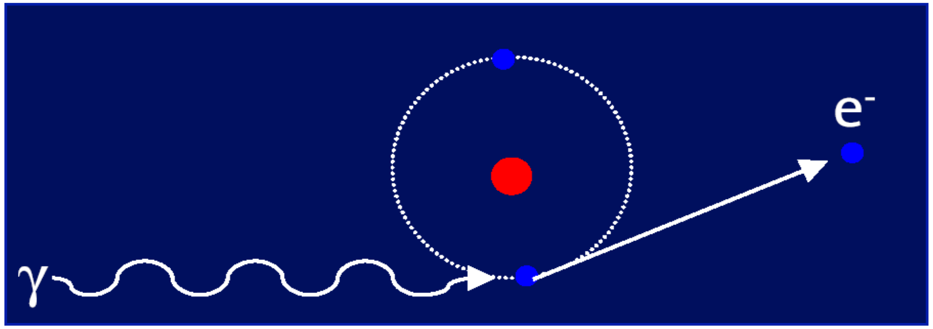
With:
I_0 = Intensity of the beam
μ = photon absorption coefficient
x = path length

Interactions of Photons

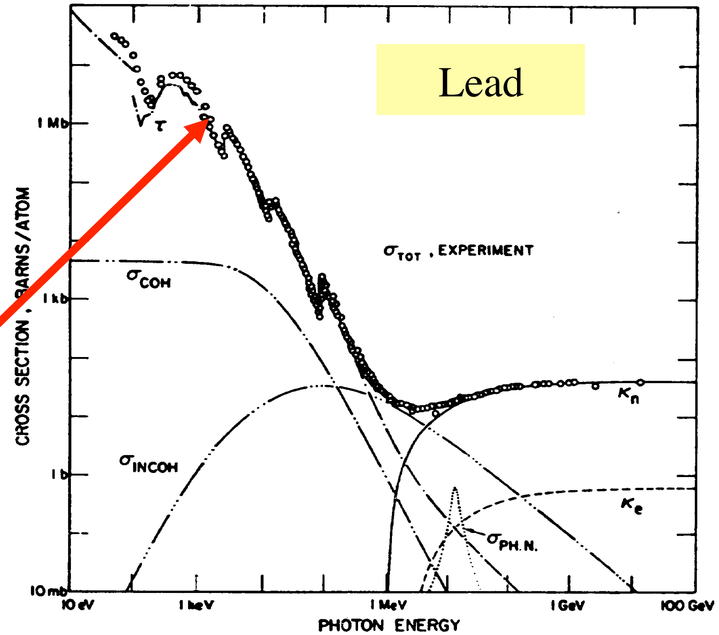
Three dominant Interactions:

1. Photoelectric effect: **absorption of the photon, ejection of the electron**

$$E_{(electron)} = h\nu - E_{binding}$$



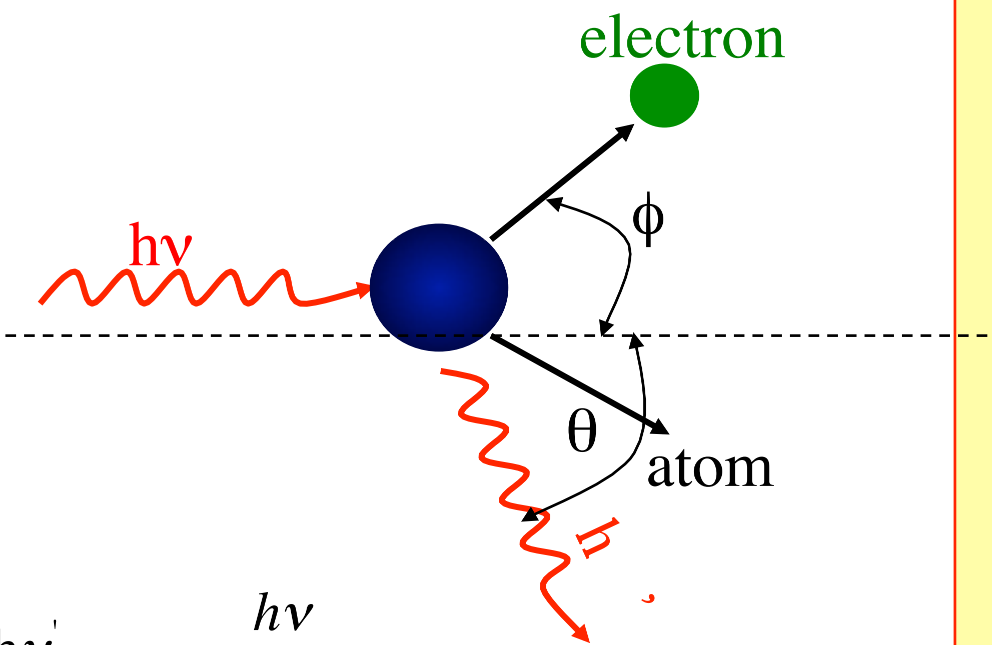
$$\sigma_{ph} = 4\sqrt{2}\alpha^4 Z^5 \left(\frac{8\pi r_e^2}{3}\right) \left(\frac{m_e c^2}{h\nu}\right)^{\frac{7}{2}}$$



Einstein: Prix Nobel 1921 pour l'explication de l'effet photoélectrique

Interactions of Photons

2. Compton Scattering: **elastic scattering on a free electron**

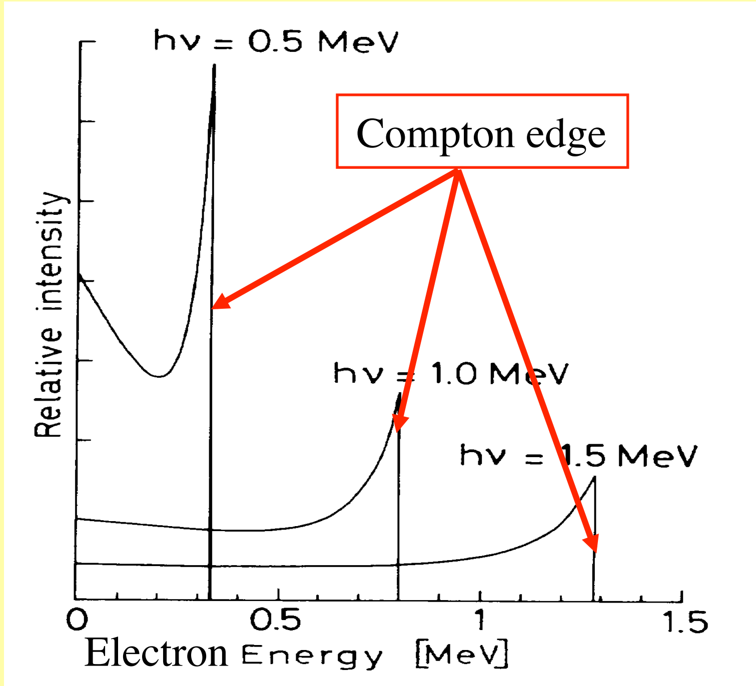


$$h\nu' = \frac{h\nu}{1+\gamma(1-\cos\theta)}$$

$$T = h\nu - h\nu' = h\nu\frac{\gamma(1-\cos\theta)}{1+\gamma(1-\cos\theta)}$$

$$\cot\varphi = (1+\gamma)\tan\frac{\theta}{2}, \gamma = h\nu/m_e c^2$$

Energy distribution of Compton recoil electrons:



$$T_{max} = E_{\gamma,in}\frac{2\gamma}{1+2\gamma}$$

Compton scattering:

Angular distribution of the scattered photon

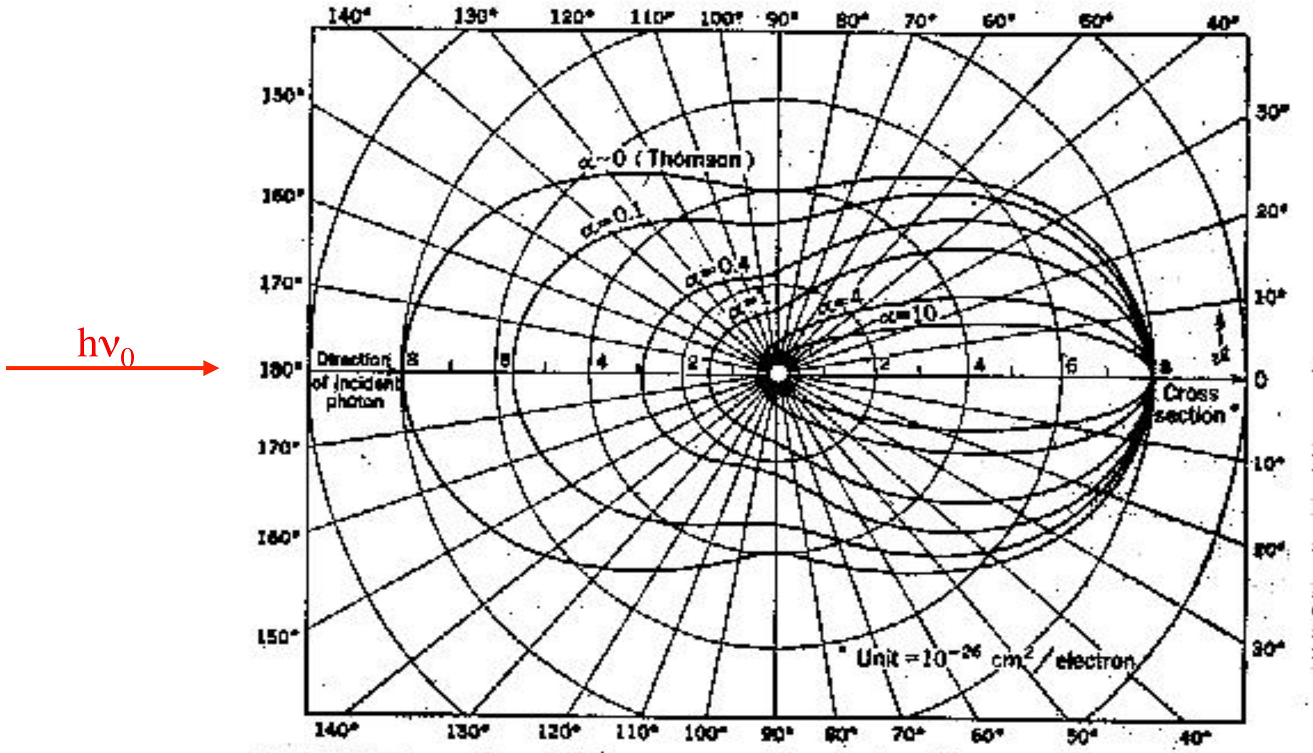


Fig. 2.8 The *number* of photons scattered into unit solid angle, $d({}_e\sigma)/d\Omega$, at a mean scattering angle ϑ, Eq. (2.8). [*From Davisson and Evans* (D12).]

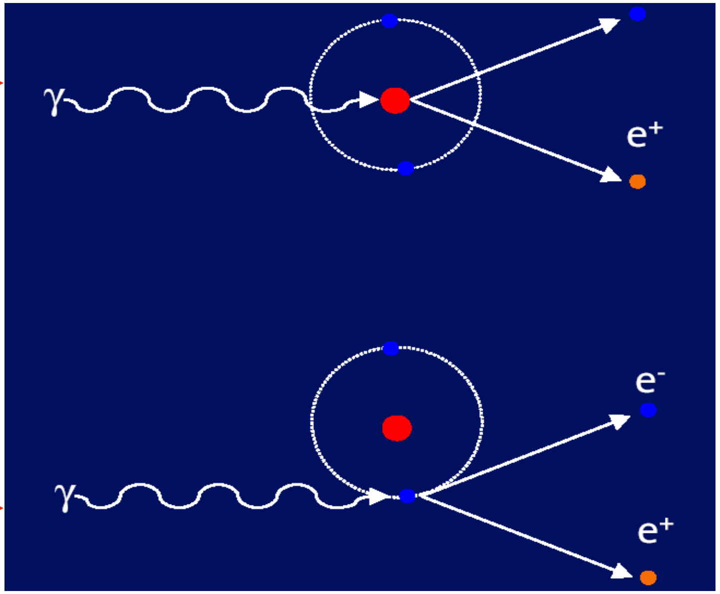
$\alpha = h\nu_0 / m_0c^2$, $m_0c^2 = 0{,}511$ MeV

α large → Photons scattered in forward direction

3. Pair Production: absorption of the photon and creation of a pair electron - positron

Creation in the field of the nucleus

Creation in the field of the electron



$$E_{threshold} = 2m_ec^2 = 1{,}022 \text{ MeV}$$

At high energies ($E_\gamma >> 137 m_e c^2 Z^{-1/3}$) the pair production cross section is almost constant

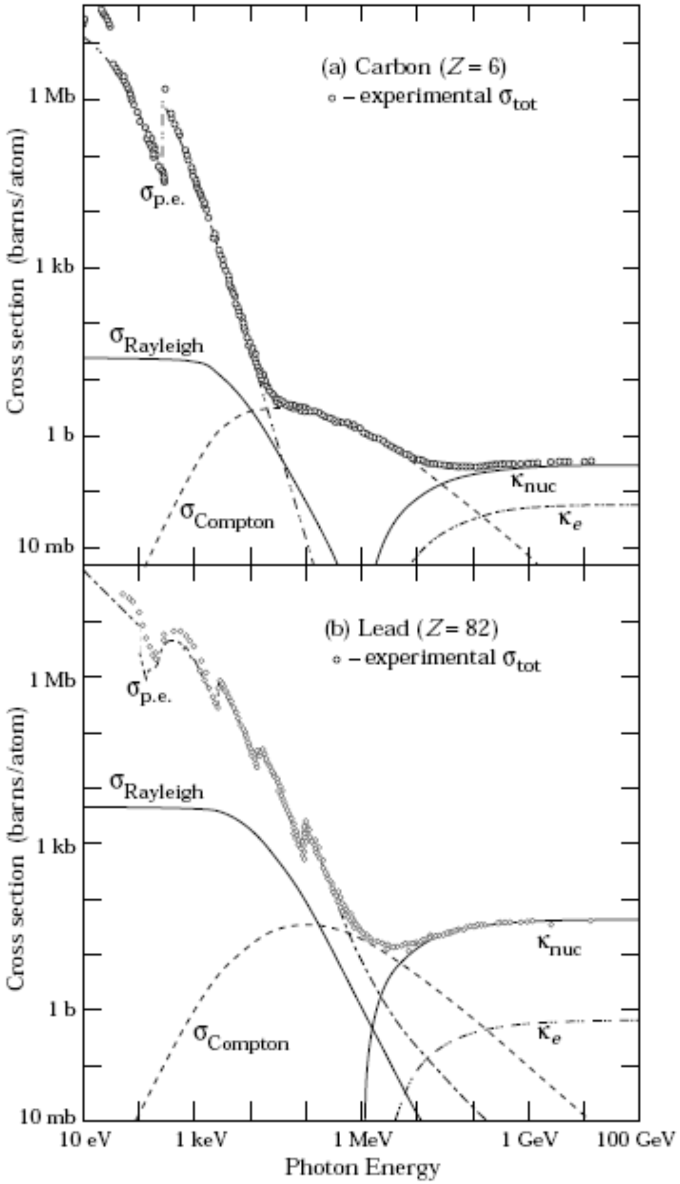
$$\sigma_{paire} = 4Z^2\alpha r_e^2[7/9\{\ln(183Z^{-1/3}) - f(Z)\} - 1/54]$$

f(z) = correction à l 'approximation de Born pour L 'interaction coulombienne d 'électron dans le champ électrique du noyau

$$\sigma = \frac{7}{9}\left(\frac{A}{X_0 N_A}\right)$$

For E > 1 GeV and high Z

Cross Sections for Photon Interactions:



$\sigma_{p.e.}$ = effet photo-électrique atomique
(absorption du photon, émission d 'un électron)

$\sigma_{coherent}$ = diffusion cohérente
(diffusion Rayleigh - ni ionisation, ni excitation d 'atome tout les électrons d 'atome en contribution les photons ne perdent pas d 'énergie)

$\sigma_{incoherent}$ = diffusion incohérente
(diffusion Compton sur un électron)

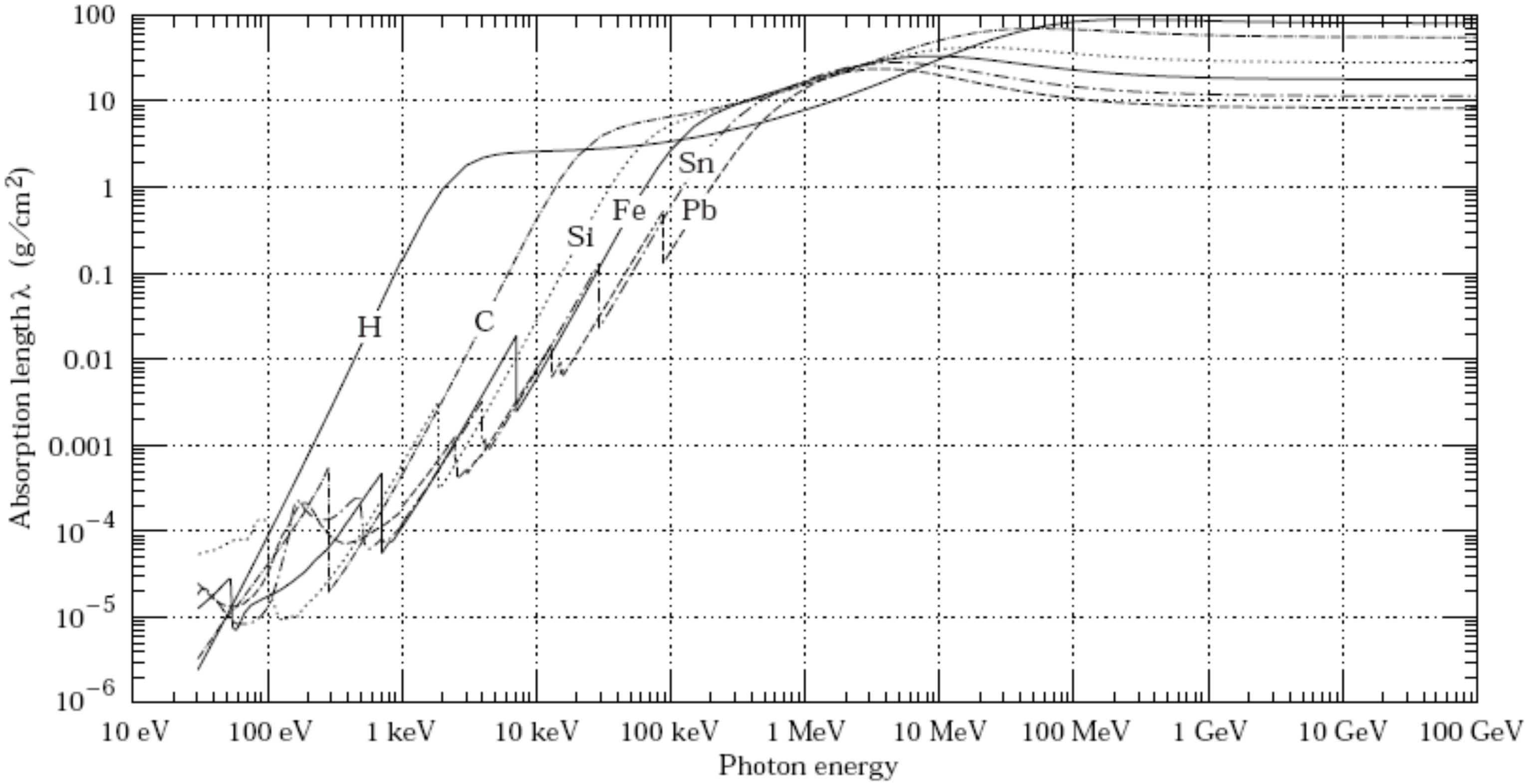
σ_{nuc} = absorption nucléaire

κ_n = production paire dans champ nucléaire

κ_e = production paire dans champ électronique

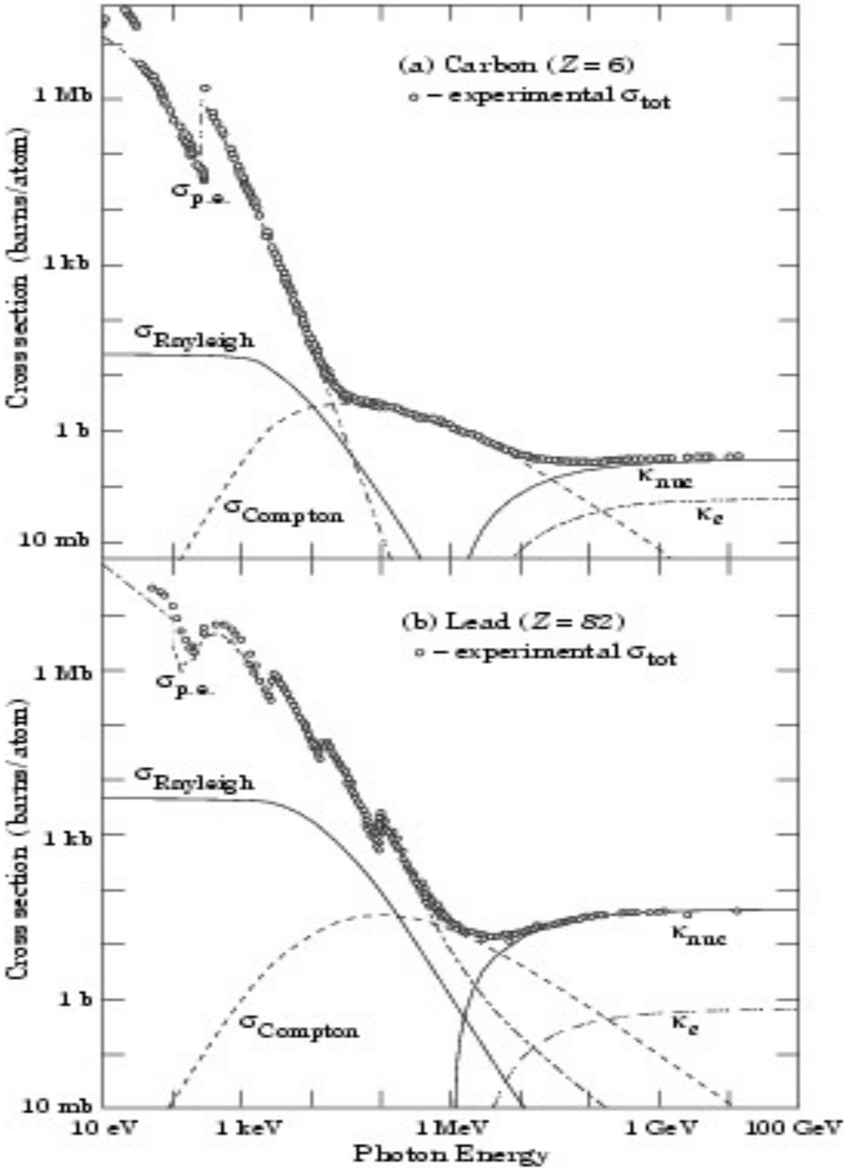
Interactions of Photons

Photon mass attenuation length (mean free flight path)



$$\lambda = \frac{1}{\mu/\rho} \quad \text{where } \mu/\rho \text{ is the mass attenuation coefficient, } \rho = \text{density}$$

Comparaison entre les différents processus d'interaction des photons



$$\sigma_{pe} \approx Z^5$$

$$\sigma_{compton} \approx Z$$

$$\sigma_{pair} \approx Z^2$$

Pour Z petit comme dans C, la diffusion Compton s'exerce entre 10 KeV et 10 MeV

Pour Z grand comme dans Pb, la diffusion Compton est négligeable

Electromagnetic Cascades:

High Energy Photon or Electron

Pair production and Bremsstrahlung

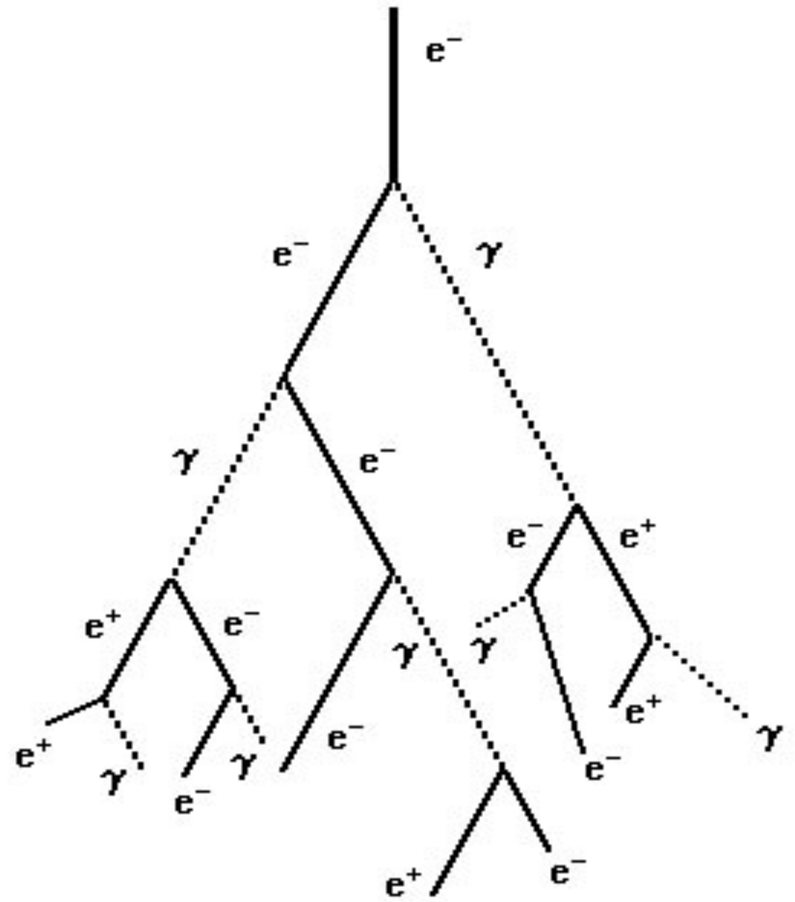
Generation of many electrons and photons of lower energy

Pair production and Bremsstrahlung

Generation of many electrons and photons of lower energy

$E = E_{critique}$

Cascade stops → dE/dx by ionization



Electromagnetic Cascades:

Some simple approximation:

1/ Longitudinal developement:

An interaction occurs after each radiation length, after t radiation lengths we have a total of
$N = 2^t$ particles
Each particle has an average energy of $E(t) = E_0 / 2$
Maximum penetration length of the cascade:
$E(t_{max}) = E_0 / 2^{tmax} = E_c$

$$t_{max} = \frac{\ln\left(\frac{E_0}{E_c}\right)}{\ln 2} \text{ and the maximum number of particles produced is } N_{max} \cong \frac{E_0}{E_c}$$

2/ Transversal dimensions:

$$\text{Molière radius}: R_M = X_0 \frac{E_s}{E_c} \quad \text{with } E_s = \sqrt{4\pi/\alpha} \times m_e c^2 = 21 \text{ MeV (scale energy)}$$

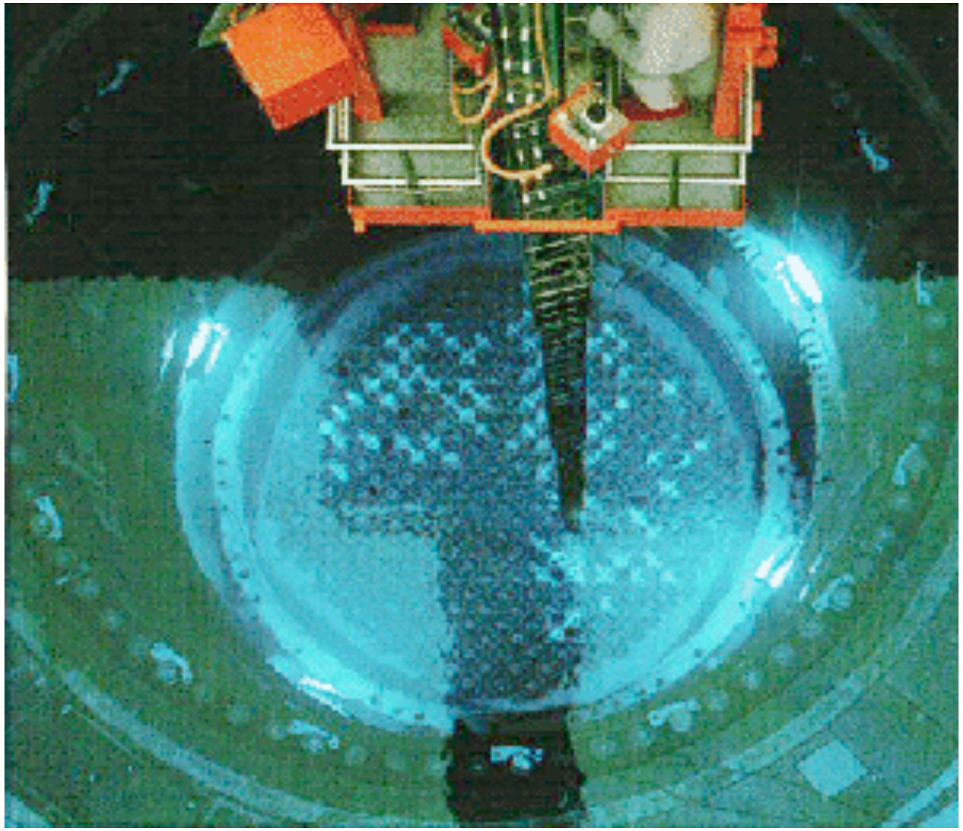
90% of the particles stay inside a cylinder with R_M around the shower axis.

Cherenkov Radiation

Radiation Cherenkov

Pavel Alekseyevich Cherenkov

1904-1990
Physics Institute of USSR Academy of Sciences, Moscow
Prix Nobel 1958



(Cœur d 'un réacteur nucléaire)

Cherenkov Radiation

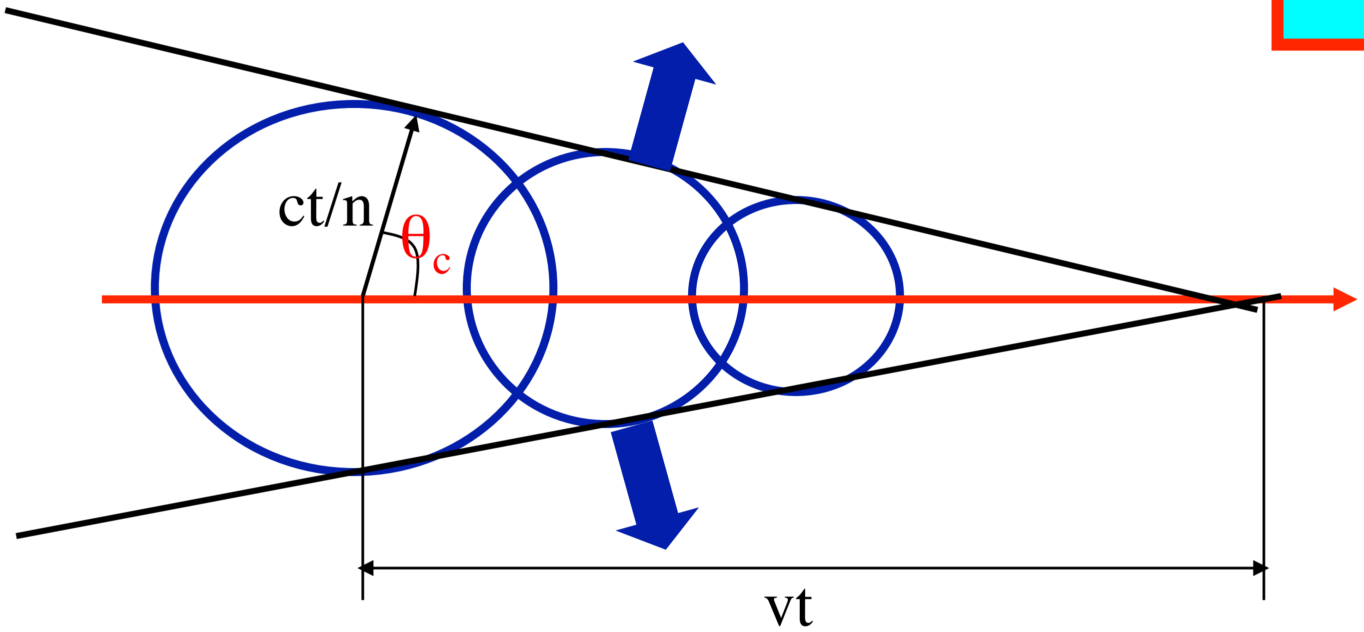
A particle goes faster than the speed of light in the material

Emission of Cherenkov radiation

ßc = v = c/n, n = index of refraction of the medium

Condition: $v_{part} > c/n$, v_{part}

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



Cherenkov Radiation

θ_c = Cherenkov angle
Radiation of « Cherenkov » photons with a continues spectrum
The photons are polarized

Firs theory by
Tamm et Frank
(Prix Nobel
with Cherenkov)

$$\left(-\frac{dE}{dx}\right)_{\text{Cherenkov}} = \frac{4\pi e^2}{c^2}\int \omega d\omega \left(1-\frac{1}{\beta^2 n^2}\right)$$

This is already included in the
dE/dx by Bethe & Bloch
(relativistic rise)

Energy loss by Cherenkov radiation: $-\left(\frac{dE}{dx}\right)_{\text{Cherencov}} \cong 10^{-3}\ \text{MeVcm}^2\text{g}^{-1}$

Energy loss by collision in H_2: $-\left(\frac{dE}{dx}\right)_{Coll} \cong 0{,}1\ \text{MeVcm}^2\text{g}^{-1}$

Energy loss by collision in a gas with large Z: $-\left(\frac{dE}{dx}\right)_{Coll} \cong 0{,}01\ \text{MeVcm}^2\text{g}^{-1}$

Cherenkov Radiation

Number of Cherenkov photons per path length of a particle of charge ze and per unit of photon energy:

$$\frac{\mathrm{d}^2 N}{dEdx} = \frac{\alpha^2 z^2}{r_e m_e c^2}\left(1 - \frac{1}{\beta^2 n^2(E)}\right)$$

$\approx 370 \sin^2\theta_c(E)\ \mathrm{eV}^{-1}\ \mathrm{cm}^{-1}$ (with z = 1)

For photons of 400 nm < λ < 700 nm ➡ **$N/L \approx 490 \sin^2\theta_c$**

Example: How to build a huge Water Cherenkov detector?

Question: Should one use a normal window or Silica for the PM?

$$\frac{dN}{dx} = 2\pi\, z^2\, \alpha\, \sin^2\theta \int_{\lambda_1}^{\lambda_2} \frac{d\lambda}{\lambda^2} \qquad \text{avec} \qquad 2\pi\, z^2\, \alpha = 4{,}584 \times 10^{-2}$$

Pour H_2O: n = 1.33

$\cos\theta = 1/\beta n$, avec $\beta = 1$: $\theta = 41.25°$

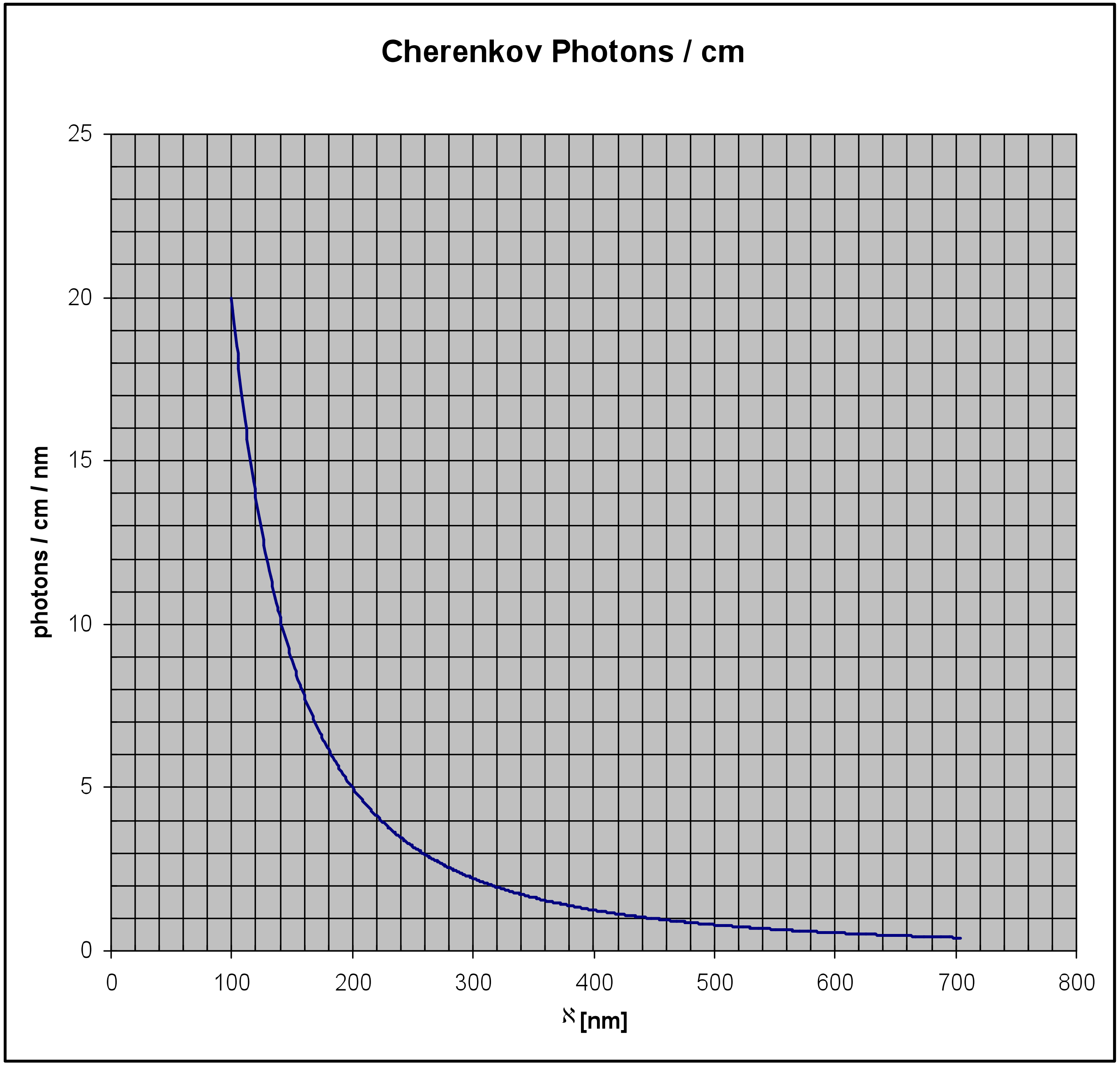
$\sin^2\theta = 0.437$

$$\frac{dN}{dx} = 2\pi\, z^2\, \alpha\, \sin^2\theta \int_{\lambda_1}^{\lambda_2} \frac{d\lambda}{\lambda^2} = 2 \times 10^{-2} \left[\frac{1}{\lambda_{min}} - \frac{1}{\lambda_{max}}\right] [\text{photons/nm}]$$

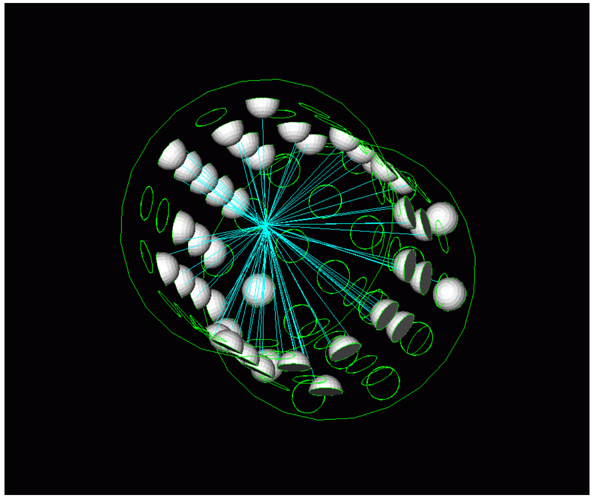
$$\frac{dN}{dx} = 2 \times 10^{5} \left[\frac{1}{\lambda_{min}} - \frac{1}{\lambda_{max}}\right] [\text{photons/cm}] \quad (\lambda \text{ en nm})$$

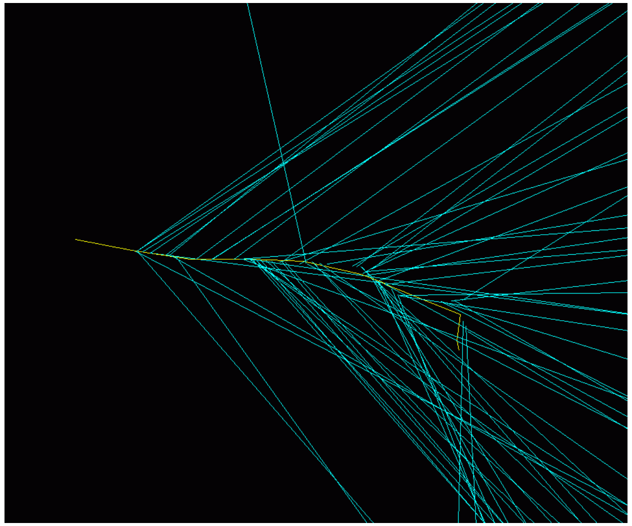
Pour 180 nm – 550 nm: dN / dx = 747 photons / cm

Pour 380 nm – 550 nm: dN / dx = 303 photons / cm


Cherenkov Photons / cm
photons / cm / nm
25
20
15
10
5
0
0
100
200
300
400
500
600
700
800
ℵ [nm]

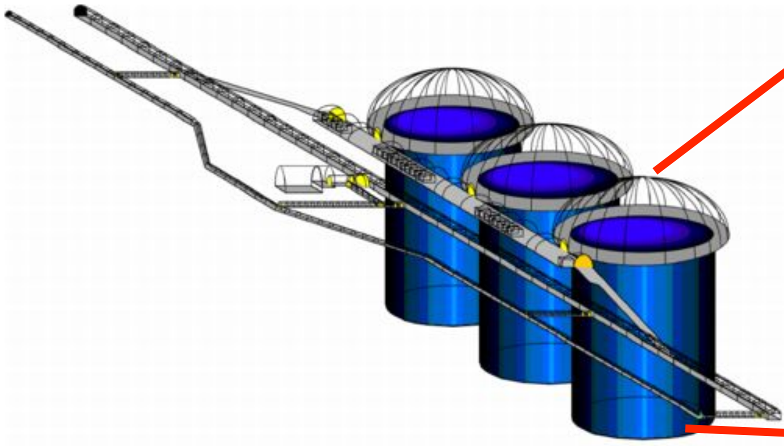
Prototype 10t

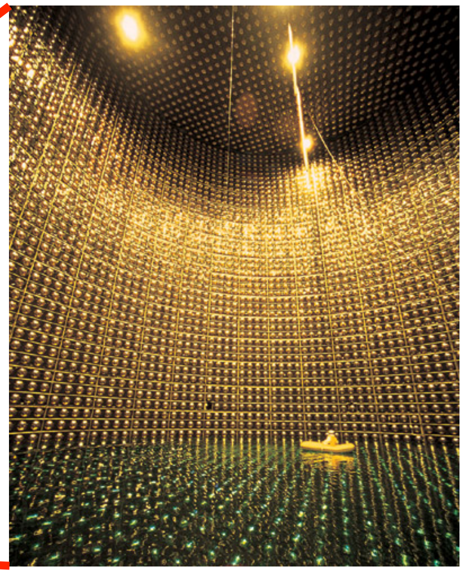




Simulation: électron dans l'eau avec émission des photons Cherenkov

Projet « Memphys » 1 Mt





Cherenkov Detectors

3 types:

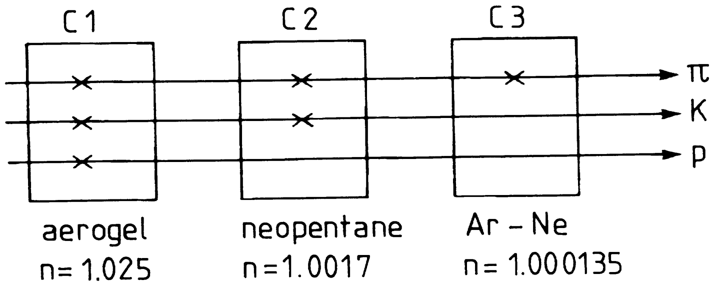
- **Threshold counter** (Yes / No)
- **Differential counter** (uses the Cherenkov angle)
- **Ring imaging counter** (uses the image of the Cherenkov ring)

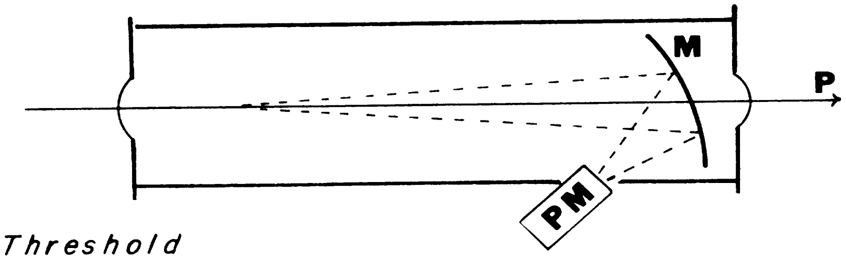
1. Threshold counter: Particle ID over threshold:

$$\beta_t = \frac{1}{n}$$

Example for He:

electrons	63 MeV/c
kaons	61 GeV/c
pions	17 GeV/c
protons	115GeV/c





Threshold

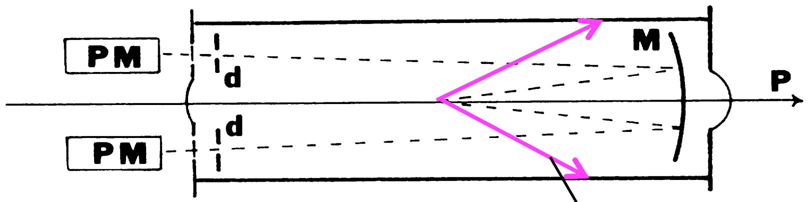
Cherenkov Detectors

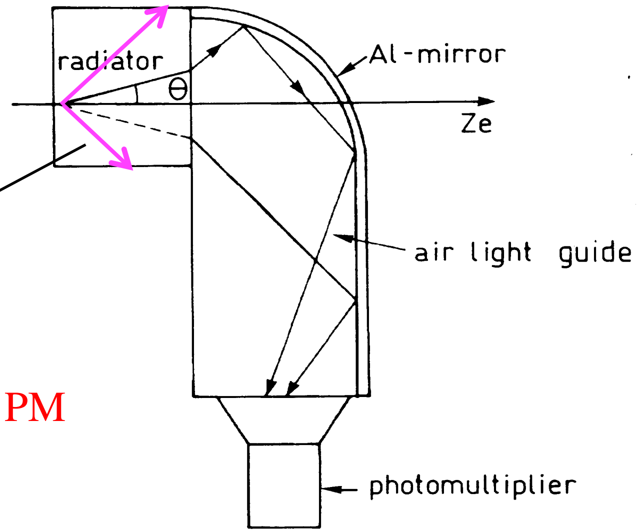
2. Différentiel counters: Emission of Cherenkov light at a defined angle:

For a given momentum, cosθ is fonction of the mass

$$\cos\theta = \frac{1}{n\beta} = \frac{1}{n(p/E)} = \frac{\sqrt{m^2 + p^2}}{np}$$

Used as beam monitor: e.g. contamination of π and k.

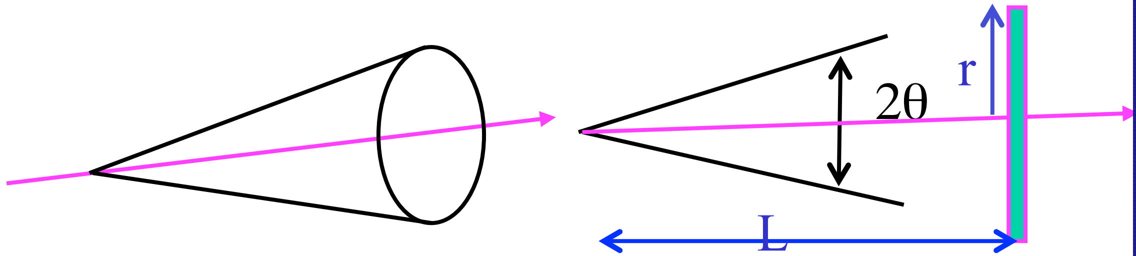


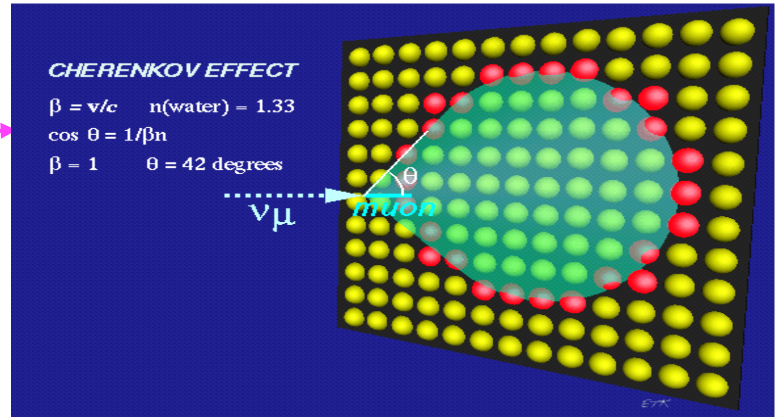


Only the light of a certain angle goes to the PM

Cherenkov Detectors

3. Ring imaging counter (RICH):





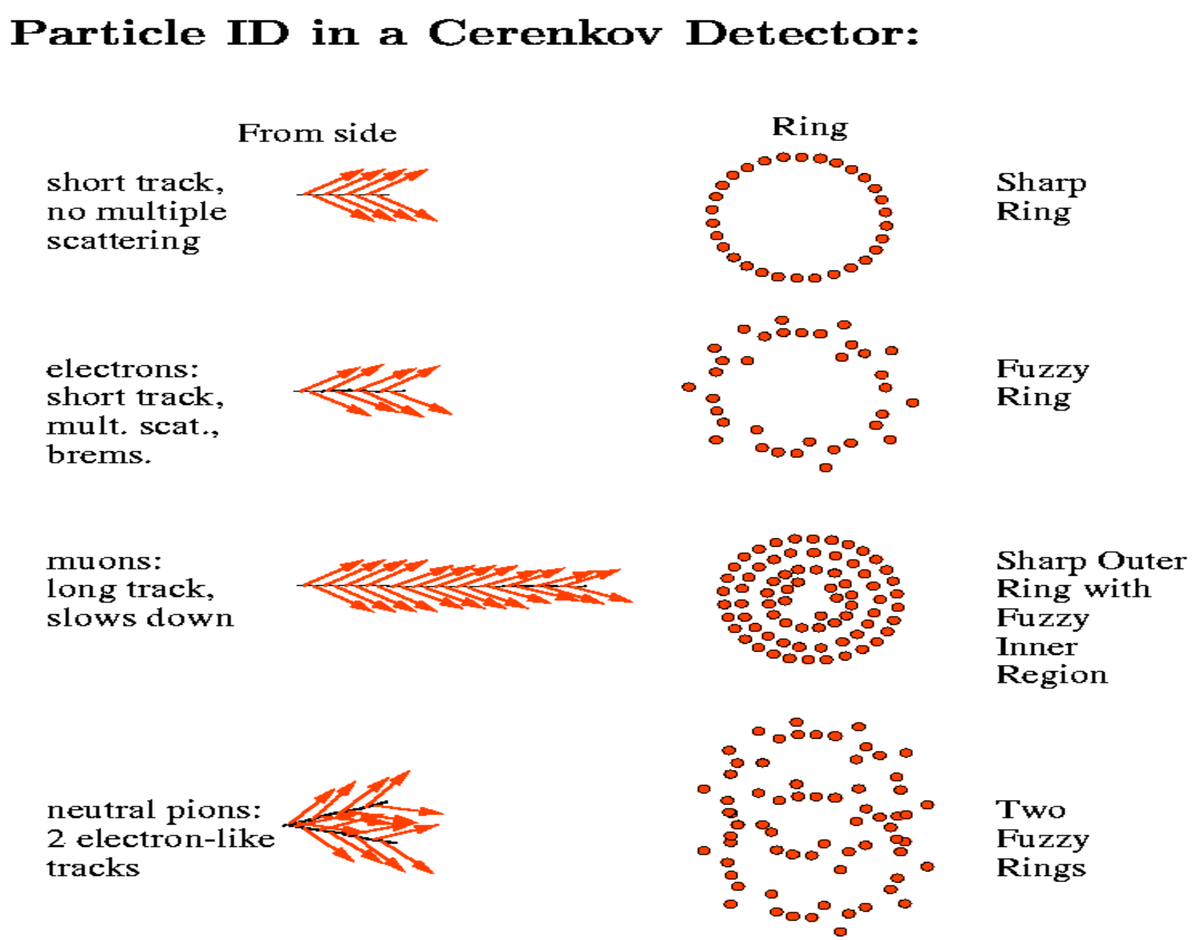
$r = L \times \tan\theta$

Incoming particle with p = 1GeV/c, L = 1 m, in LiF (n = 1.392):

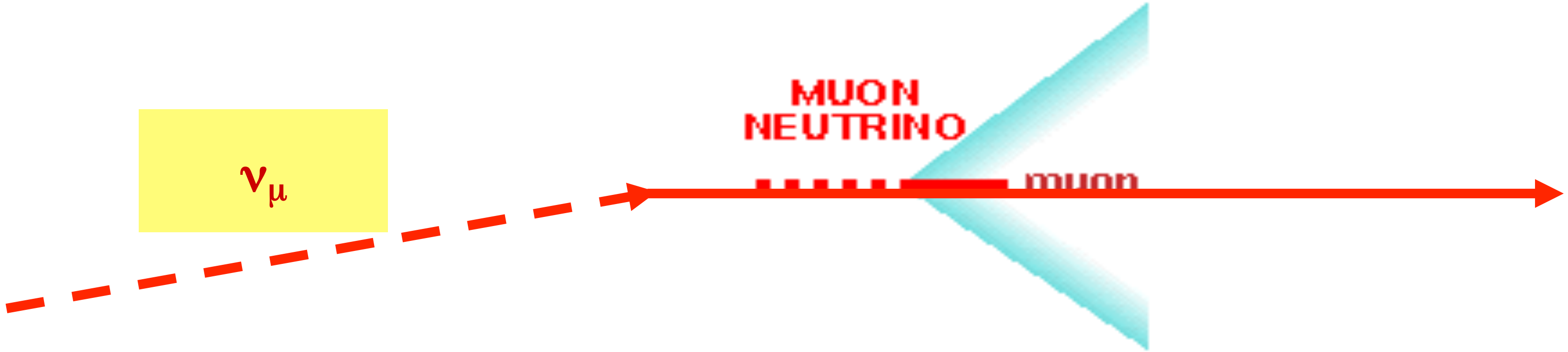
	θ(deg)	r(m)
π	43.5	0.95
K	36.7	0.75
P	9.95	0.18

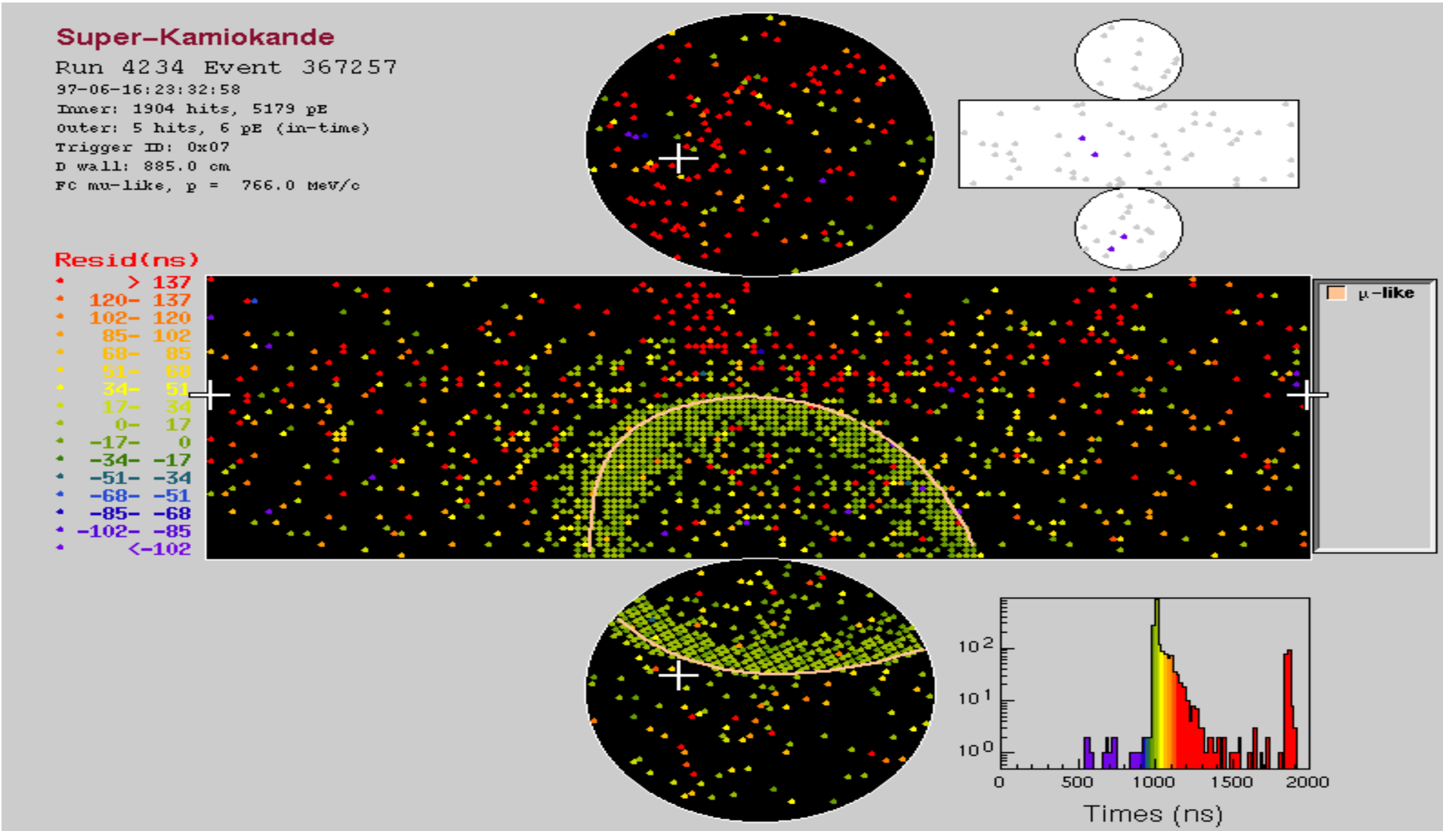
Very good π/K/p seperation

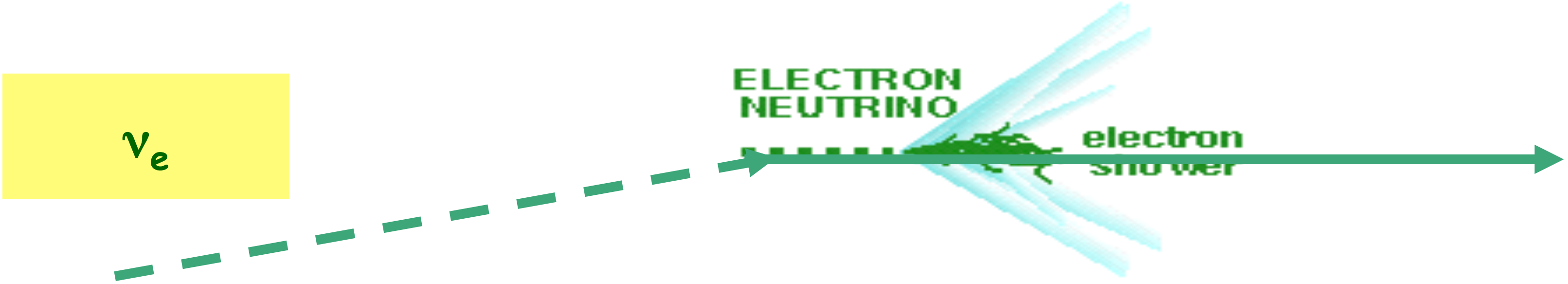
→ **Particle ID**

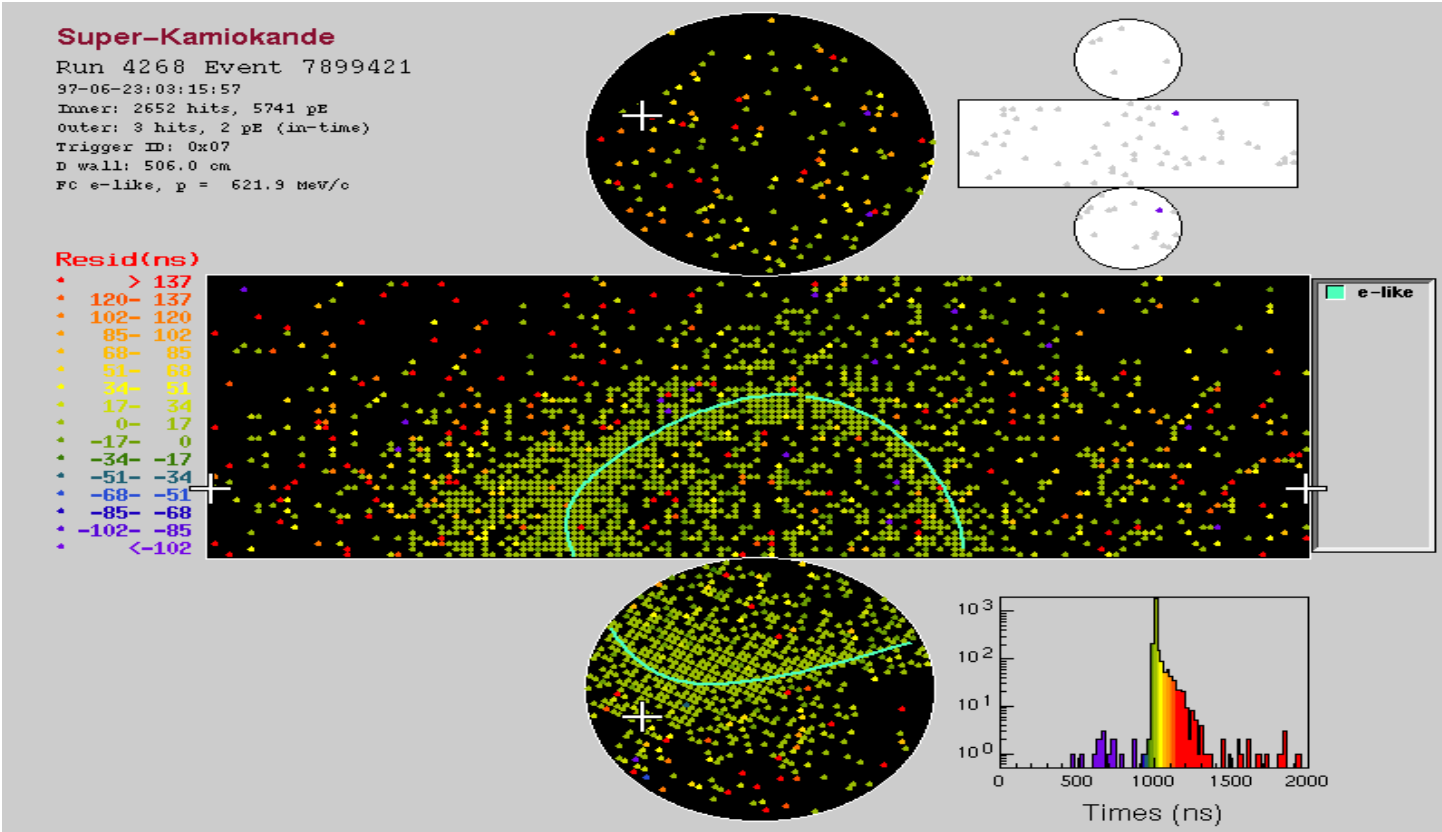


From SK and Miniboone)


νμ
MUON
NEUTRINO
muon


Super-Kamiokande
Run 4234 Event 367257
97-06-16:23:32:58
Inner: 1904 hits, 5179 pE
Outer: 5 hits, 6 pE (in-time)
Trigger ID: 0x07
D wall: 885.0 cm
FC mu-like, p = 766.0 MeV/c
Resid(ns)
> 137
120- 137
102- 120
85- 102
68- 85
51- 68
34- 51
17- 34
0- 17
-17- 0
-34- -17
-51- -34
-68- -51
-85- -68
-102- -85
<-102
μ-like
10^2
10^1
10^0
0
500
1000
1500
2000
Times (ns)


ν_e
ELECTRON
NEUTRINO
electron
shower


Super–Kamiokande
Run 4268 Event 7899421
97-06-23:03:15:57
Inner: 2652 hits, 5741 pE
Outer: 3 hits, 2 pE (in-time)
Trigger ID: 0x07
D wall: 506.0 cm
FC e-like, p = 621.9 MeV/c
Resid(ns)
> 137
120- 137
102- 120
85- 102
68- 85
51- 68
34- 51
17- 34
0- 17
-17- 0
-34- -17
-51- -34
-68- -51
-85- -68
-102- -85
<-102
e-like
Times (ns)

Radiation Cherenkov: exemple SuperKamiokande = RICH à l 'eau

Mesure des neutrinos solaires et atmosphériques:

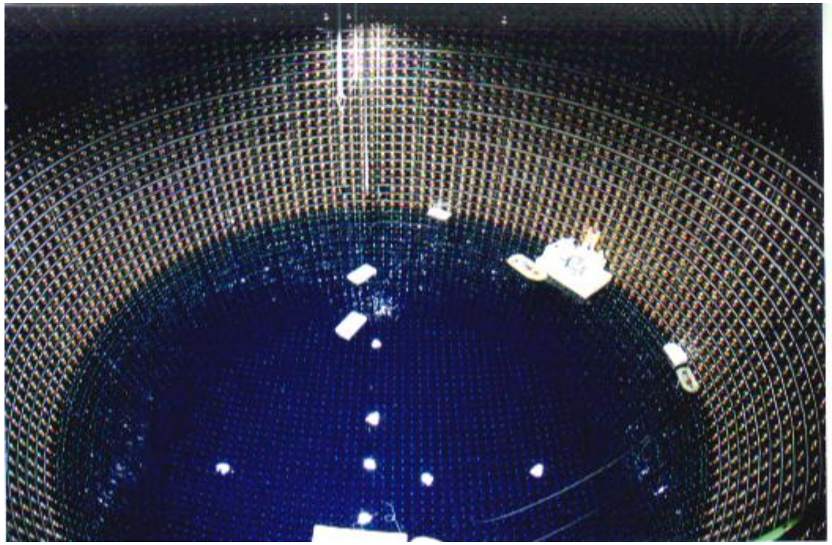
Neutrinos solaires: $\nu_e + e^- \longrightarrow e^- + \nu_e$

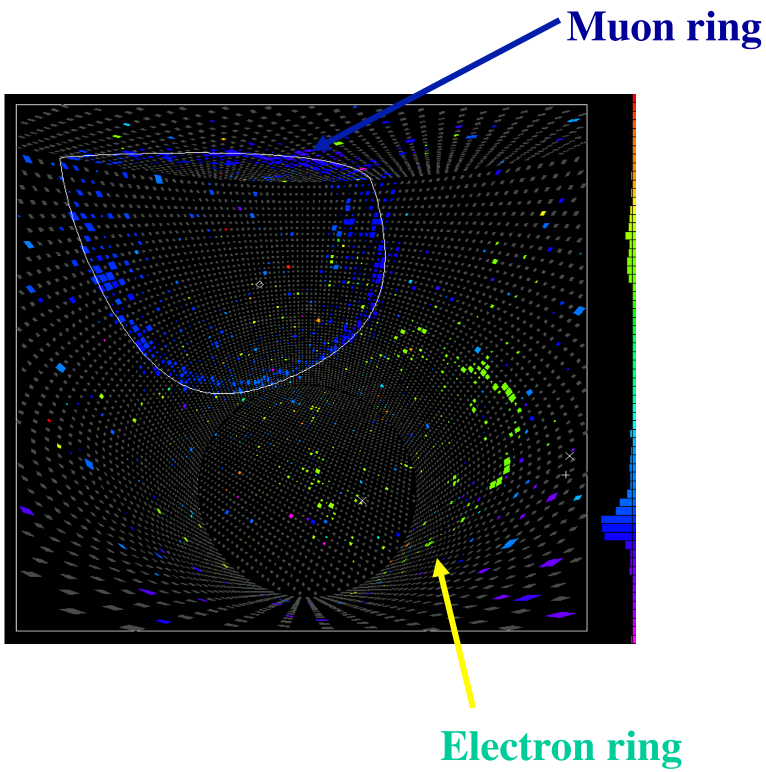
Neutrinos atmosphériques: $\nu_l + N \longrightarrow l + X$

Exemple: 481 MeV muon neutrino —> 394 MeV muon —> 52 MeV électron

Pour l'eau: n=1.33

Pour β=1 particule $\cos\theta = 1/1.33$, $\theta = 41°$



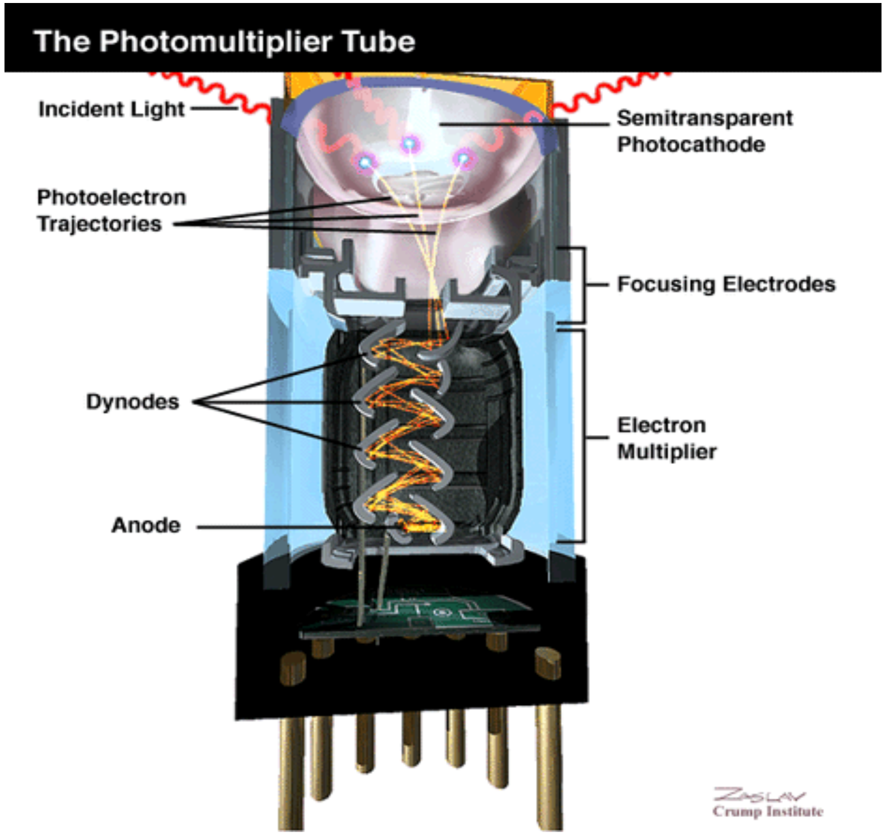


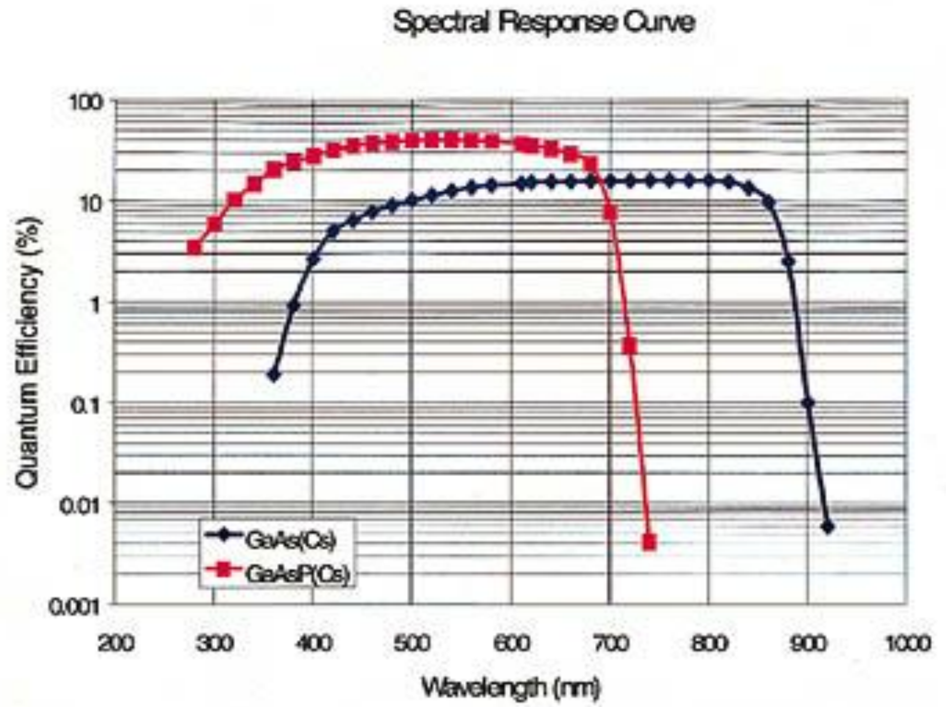
50 ktons d 'eau

11146 photomultiplicateurs

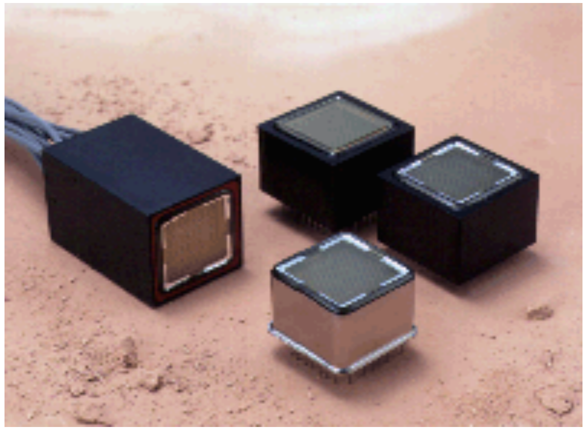
2. Some examples for light detection

Basic device: The Photomultiplier

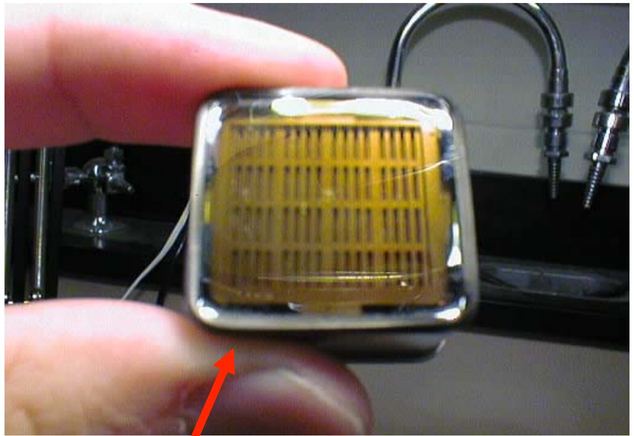




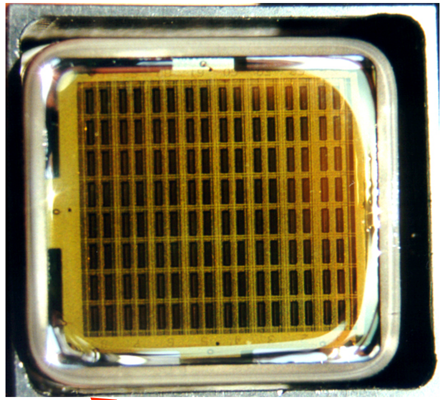
Multi-Anode Photomultiplier Tubes (MAPMT)



HV ≈ 900 V



M16



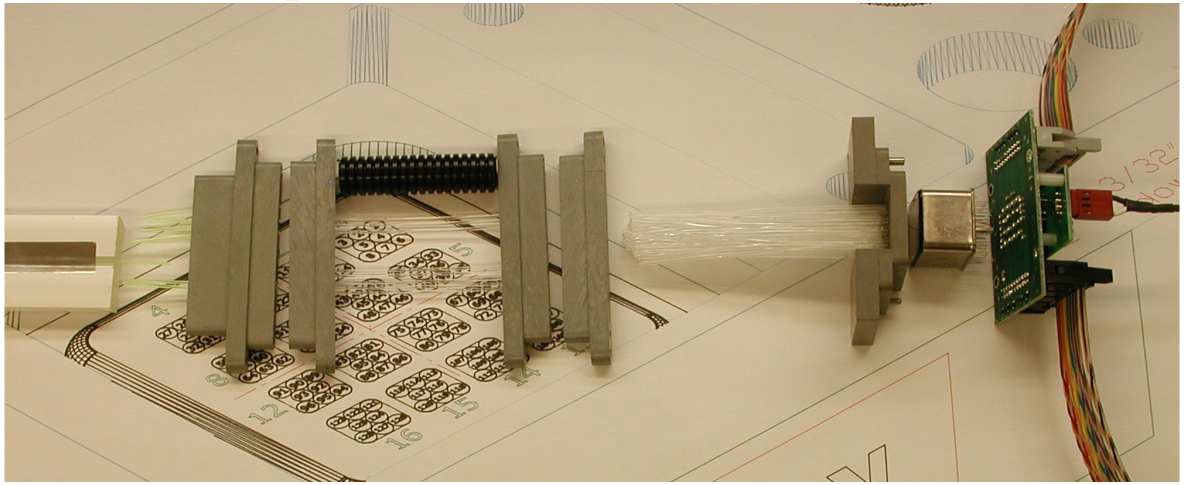
M64

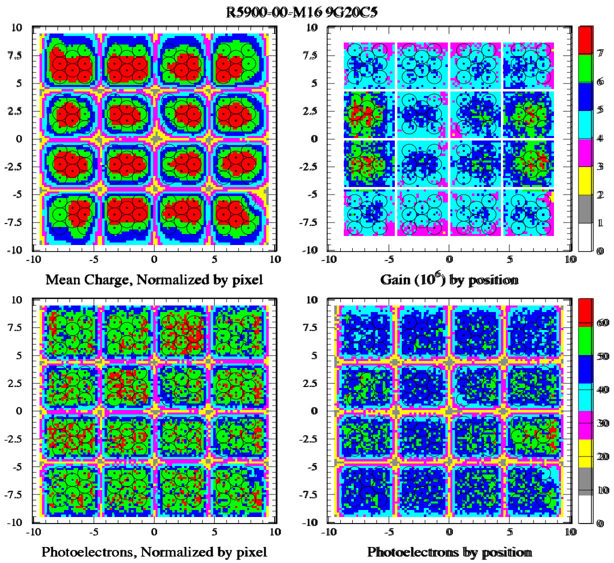
Type No.	R5900U	R5900U-00-M4	H6568 (R5900-00-M16)	H7546 (R5900-00-M64)	R8520-C12	R5900U-00-L16	H7260 (R7259)
Anode format							
Number of anodes	1	4	16	64	6(X)+6(Y)	16	32
Number of dynode stages	10	10	12	12	11	10	10

Multi-anode photomultiplicateurs (MAPMT)

Example: Test Hamamatsu M16 for the MINOS experiment:

1,2 mm WLS fibres and LED blue



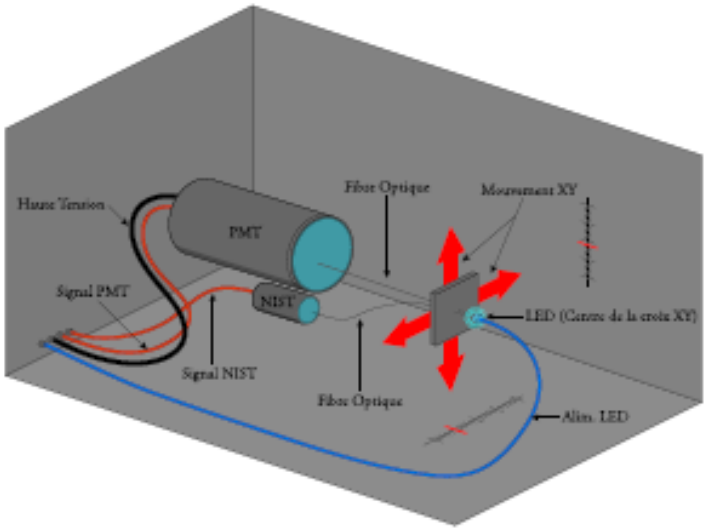


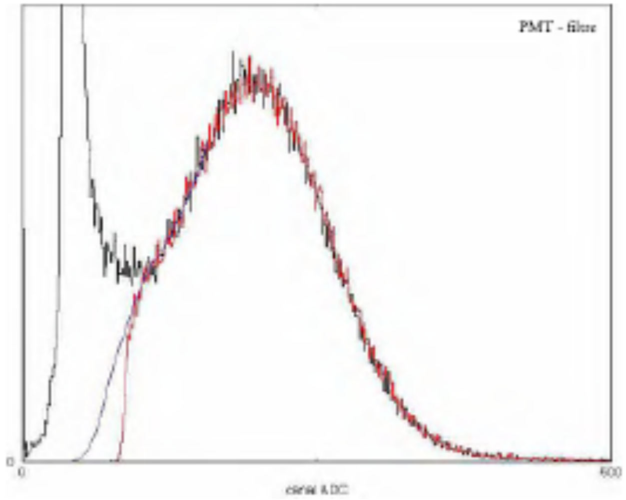
Attention to variation pixel to pixel but also inside one pixel

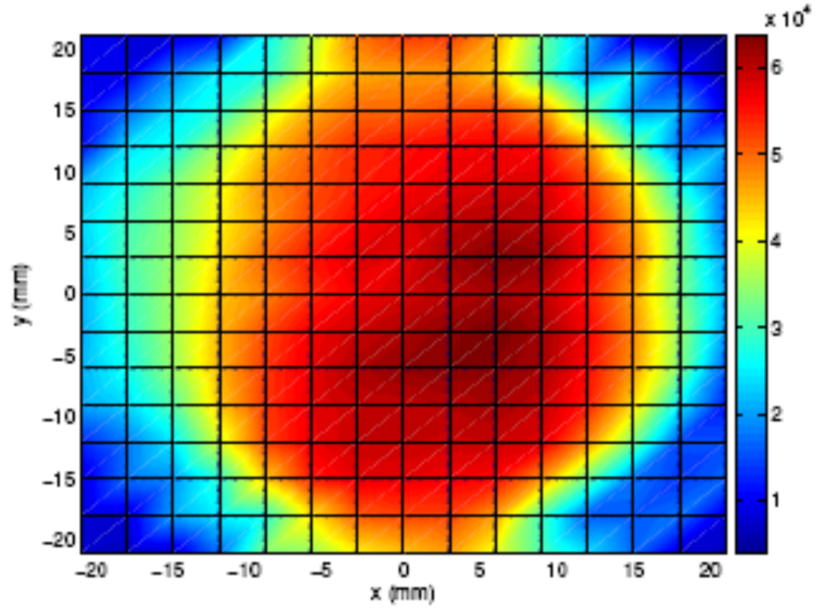
Variations up to 20%

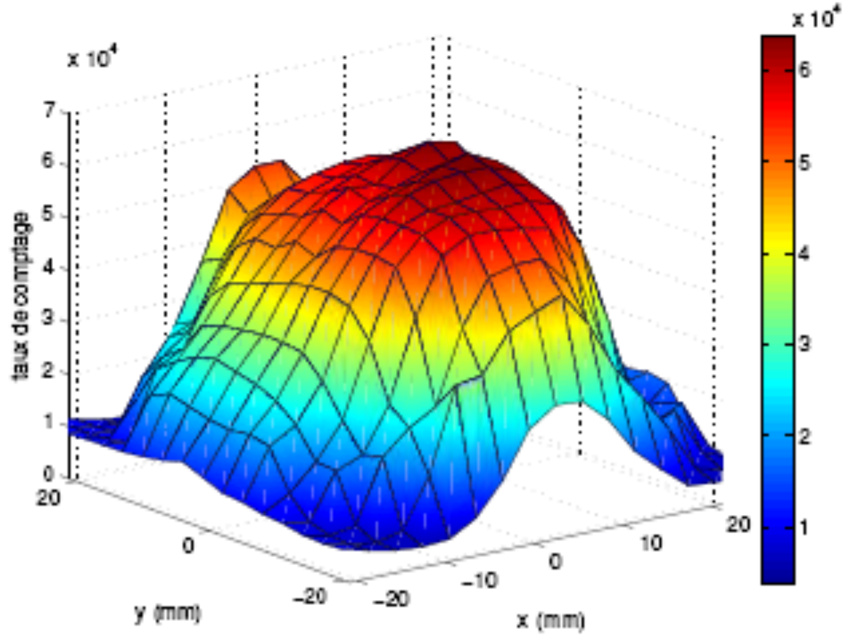
Spectre de photo-électron unique

These de Gwenaëlle Lefeuvre, APC, P7, 2006









Detection of particles and radiation by conversion of dE/dx into light

Typical setup: PM + Scintillator

Light output:

- Inorganic scintillators like NaI : 4×10^4 / MeV
  - Other crystals 1% to 20% of a NaI

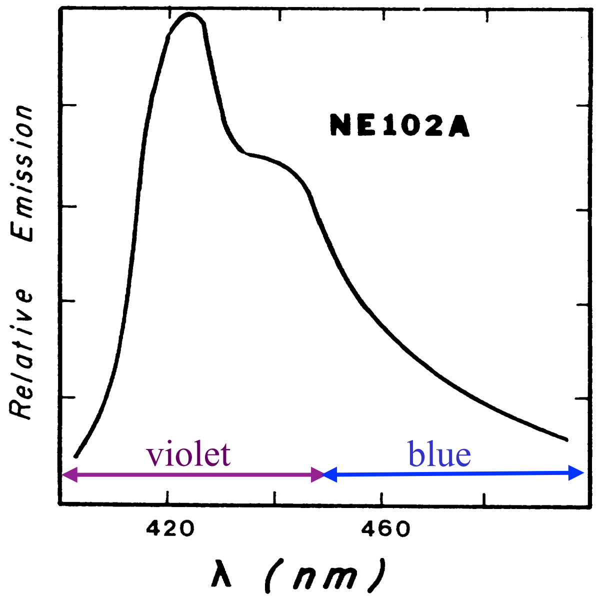
- Organic scintillators produce: O 10^4 /MeV (1 /100 eV)

Plastic Scintillators

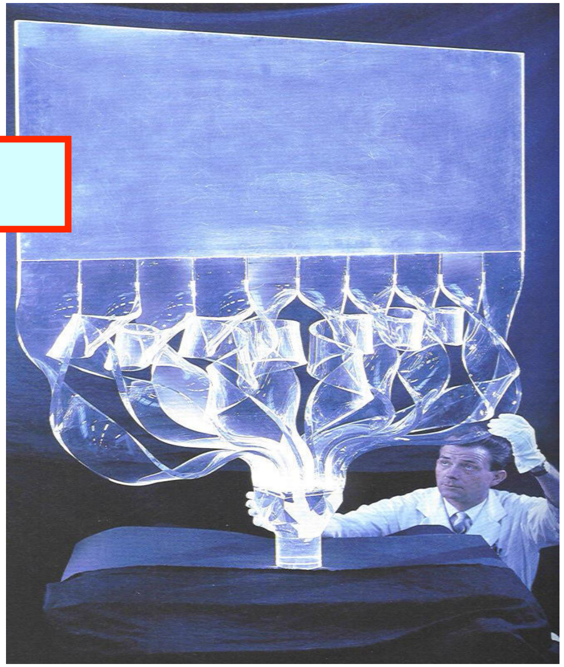
Type	Light[a] output	λ_{max}[b] (nm)	Attenuation[c] length (cm)	Risetime (ns)	Decay[d] time (ns)	Pulse FWHM (ns)
NE 102A	58–70	423	250	0.9	2.2–2.5	2.7–3.2
NE 104	68	406	120	0.6–0.7	1.7–2.0	2.2–2.5
NE 104B	59	406	120	1	3.0	3
NE 110	60	434	400	1.0	2.9–3.3	4.2
NE 111	40–55	375	8	0.13–0.4	1.3–1.7	1.2–1.6
NE 114	42–50	434	350–400	~1.0	4.0	5.3
Pilot B	60–68	408	125	0.7	1.6–1.9	2.4–2.7
Pilot F	64	425	300	0.9	2.1	3.0–3.3
Pilot U	58–67	391	100–140	0.5	1.4–1.5	1.2–1.9
BC 404	68	408	—	0.7	1.8	2.2
BC 408	64	425	—	0.9	2.1	~2.5
BC 420	64	391	—	0.5	1.5	1.3
ND 100	60	434	400	—	3.3	3.3
ND 120	65	423	250	—	2.4	2.7
ND 160	68	408	125	—	1.8	2.7

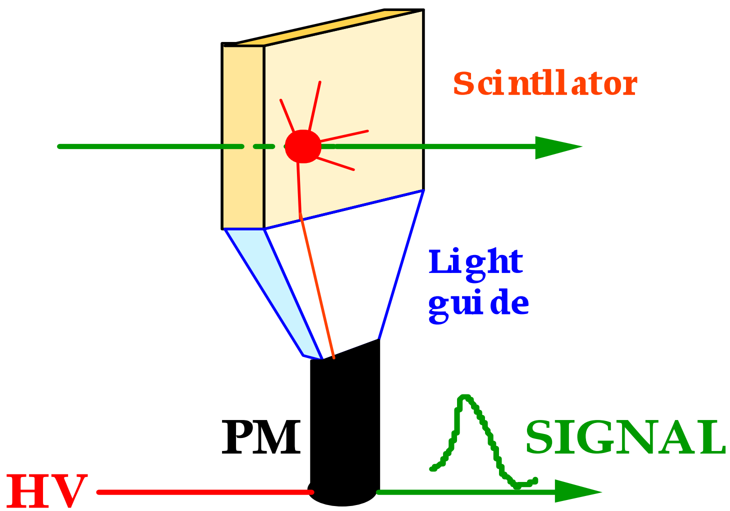
[a] Percentage of anthracene.
[b] Wavelength of maximum emission.
[c] 1/e length.
[d] Main component.

Typical emission spectrum



100 eV/photon





Inorganic Scientillators :

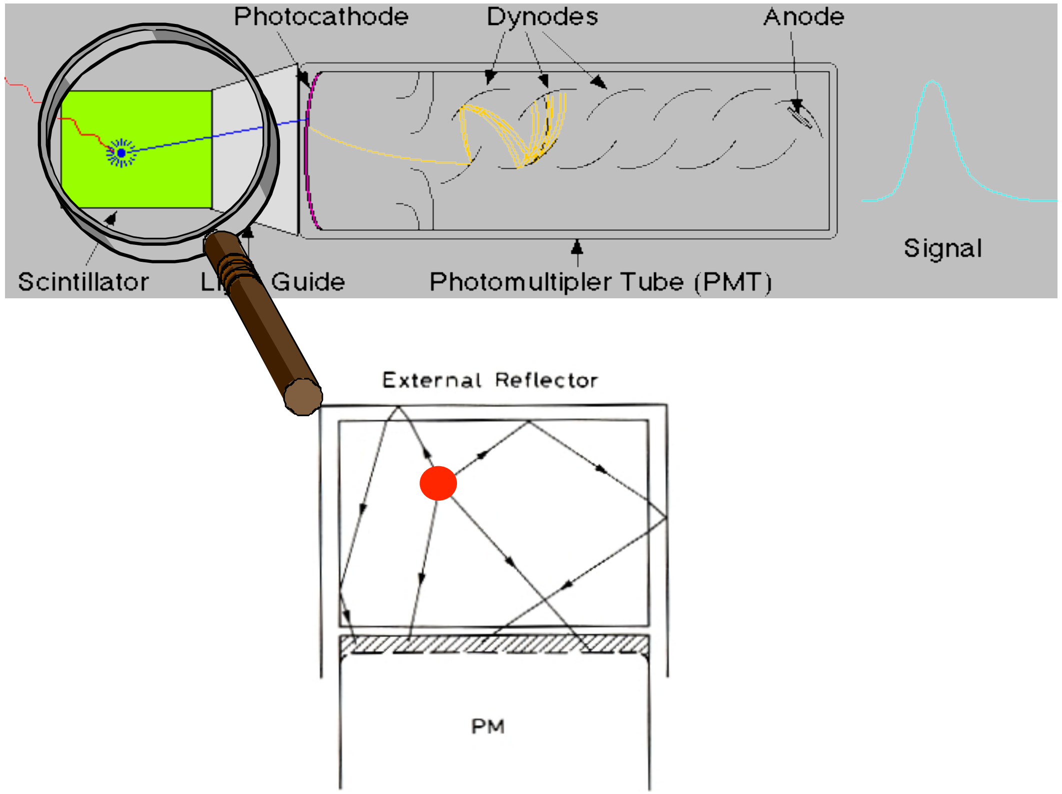
Table 25.2: Properties of several inorganic crystal scintillators.

	NaI(Tl)	BGO	BaF_2	CsI(Tl)	CsI(pure)	$PbWO_4$	CeF_3
Density ($g\ cm^{-3}$):	3.67	7.13	4.89	4.53	4.53	8.28	6.16
Radiation length (cm):	2.59	1.12	2.05	1.85	1.85	0.89	1.68
Molière radius (cm):	4.5	2.4	3.4	3.8	3.8	2.2	2.6
dE/dx (MeV/cm) (per mip):	4.8	9.2	6.6	5.6	5.6	13.0	7.9
Nucl. int. length (cm):	41.4	22.0	29.9	36.5	36.5	22.4	25.9
Decay time (ns):	250	300	0.7^f 620^s	1000	$10, 36^f$ $\sim 1000^s$	5–15	10–30
Peak emission λ (nm):	410	480	220^f 310^s	565	305^f $\sim 480^s$	440–500	310–340
Refractive index:	1.85	2.20	1.56	1.80	1.80	2.16	1.68
Relative light output:*	1.00	0.15	0.05^f 0.20^s	0.40	0.10^f 0.02^s	0.01	0.10
Hygroscopic:	very	no	slightly	somewhat	somewhat	no	no

* For standard photomultiplier tube with a bialkali photocathode. See Ref. 21 for photodiode results.

f = fast component, s = slow component

(Example NaI) : 25 eV / photon



Résolution attendue avec un NaI:

La statistique d 'ionisation et d 'excitation est de type **Poissonnienne**

$$N_{\text{Ionisation}} = \frac{E}{w}$$

Avec une variance $\sigma^2 = N_{Ionisation}$ ($N_{\text{ionisation}}$ = nombre moyen d 'ionisation)

$$R = 2.35 \frac{\sqrt{N_{\text{Ionisation}}}}{N_{\text{Ionisation}}} = 2.35\sqrt{\frac{w}{E}} = 2.35\sqrt{\frac{1}{N}}$$

$N_{\text{ionisation}}$ = 1photon / 25 eV

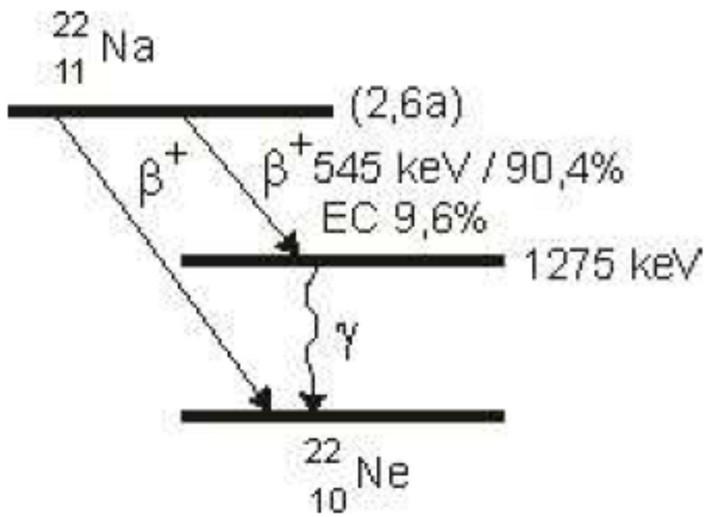
1 γ de 511 keV génère 2 x 10^4 photons

Efficacité de collection = 50 %
Efficacté quantique de la photocathode = 20 %

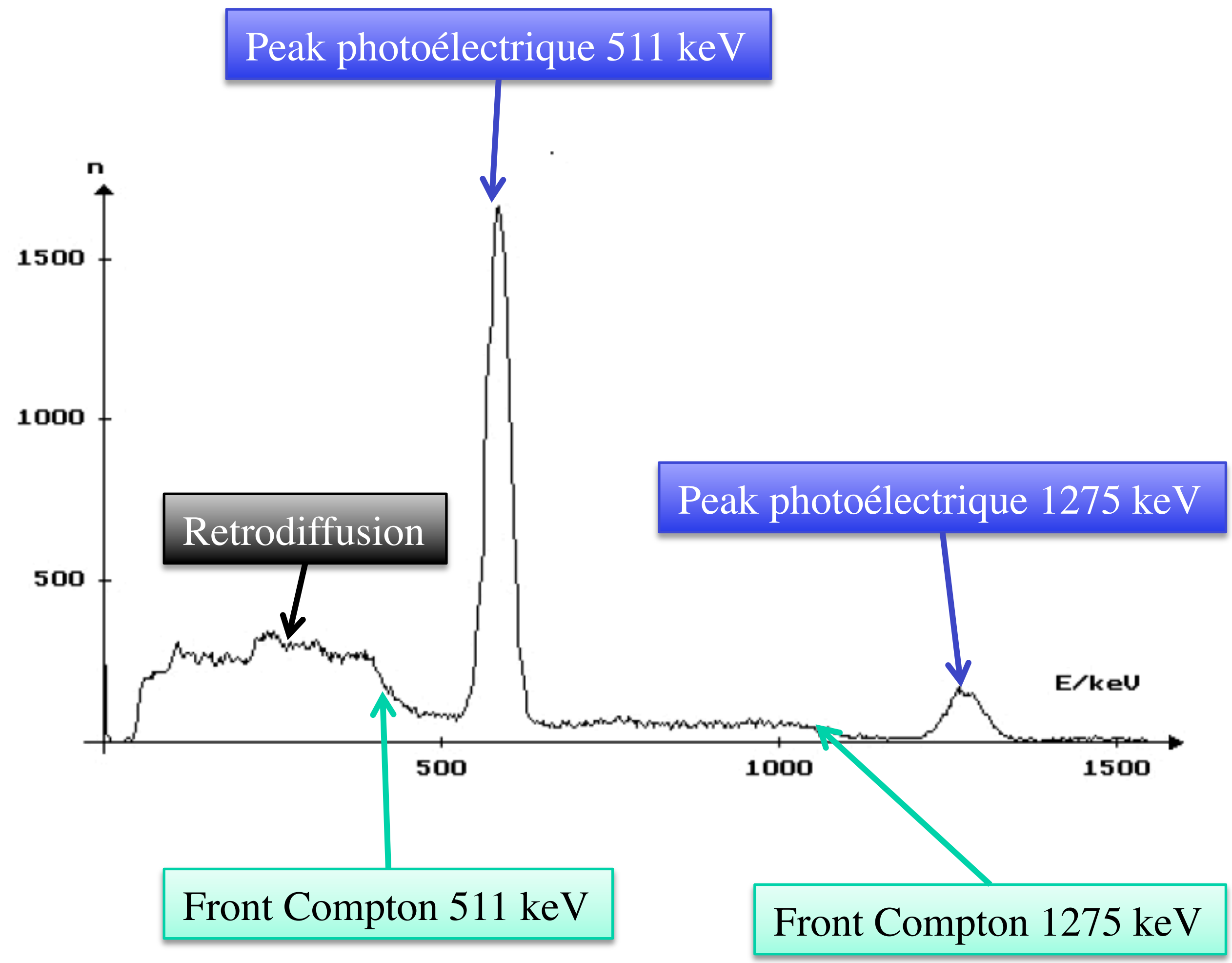
Nombre d'électrons dans le PM = 2 x 10^4 x 0,5 x 0,2 = 2000 photoélectrons

R = 2.35 x sqrt(1/2000) = 5,2 %

^{22} Na:



22
11
Na
(2,6a)
β+
β+ 545 keV / 90,4%
EC 9,6%
1275 keV
γ
22
10
Ne



Peak photoélectrique 511 keV
n
1500
1000
500
Retrodiffusion
Peak photoélectrique 1275 keV
E/keV
500
1000
1500
Front Compton 511 keV
Front Compton 1275 keV

Exemple: PM couplé à un scintillateur plastique:

Quelques paramètres typiques d 'un scintillateur plastique:

Perte d 'énergie	2MeV/cm
Efficacité de scintillation	1 photon/100 eV
Efficacité de collection (nombre de photons arrivés au PM)	0,1
Efficacité quantique du PM	0,25

Quel signal électrique peut-on attendre avec un scintillateur de 1 cm?

Une particule chargée traversant le scintillateur perd 2 MeV, donc crée 2×10^4 photons

$2 \times 10^4 \times 0{,}1 = 2 \times 10^3$ photons arrivent au PM qui les transforme en $2 \times 10^3 \times 0{,}25 =$ 500 électrons

Avec un gain de 10^6: $500 \times 10^6 = 5 \times 10^8$ électrons $= 8 \times 10^{-11}$ C

Si la charge est collectée en 50 ns —> $I = dq/dt = 8 \times 10^{-11}\ \mathrm{C} / 5 \times 10^{-8}\ \mathrm{s} = 1{,}6 \times 10^{-3}$ A

Ce courrant traverse une résistance de 50 Ω —> $V = IR = (50\ \Omega)(1.6 \times 10^{-3}\mathrm{A}) =$ **80mV**

Visible avec un oscilloscope!

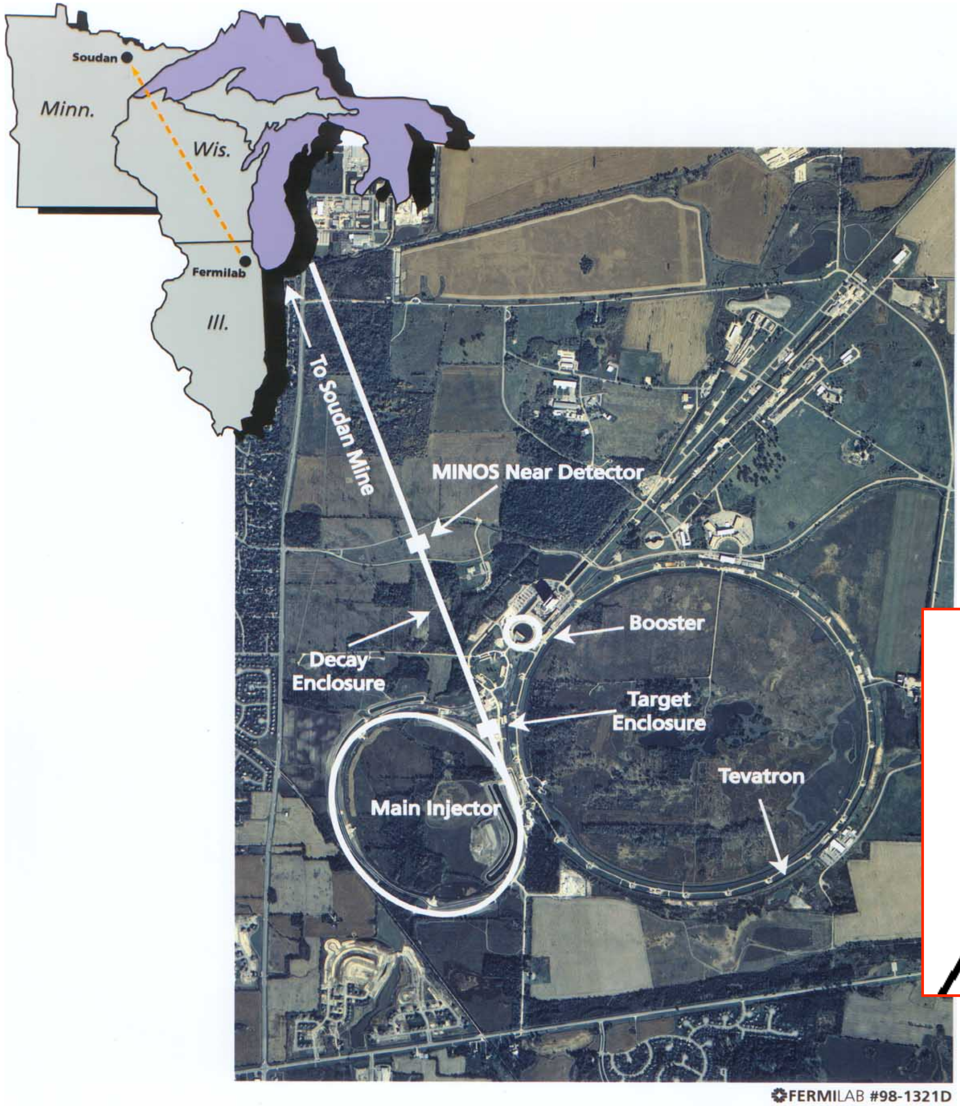
Quelle est l 'efficacité de ce compteur? = Quelle est la probabilité d 'avoir 0 photoélectrons?

Statistique = Poisson:

$$P(r) = \frac{\mu^r e^{-\mu}}{r!} \rightarrow P(O) = \frac{500^0 e^{-500}}{0!} \cong O$$

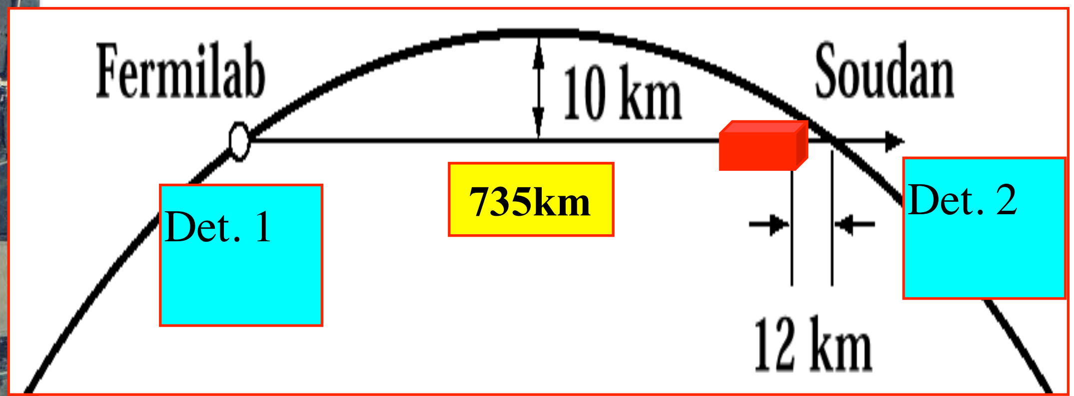
Donc l 'efficacité est de 100%

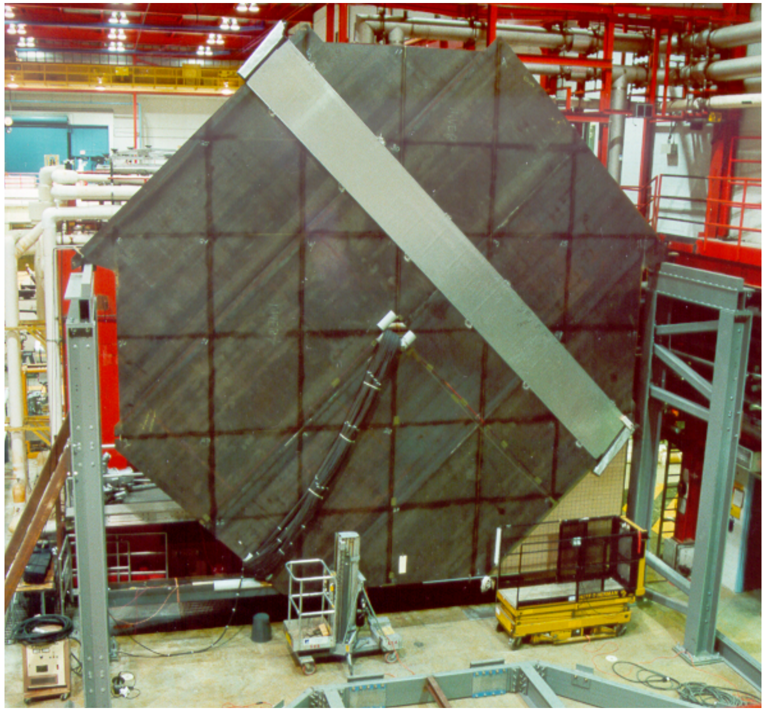
Exemple 1: détecteur MINOS - oscillations du neutrino

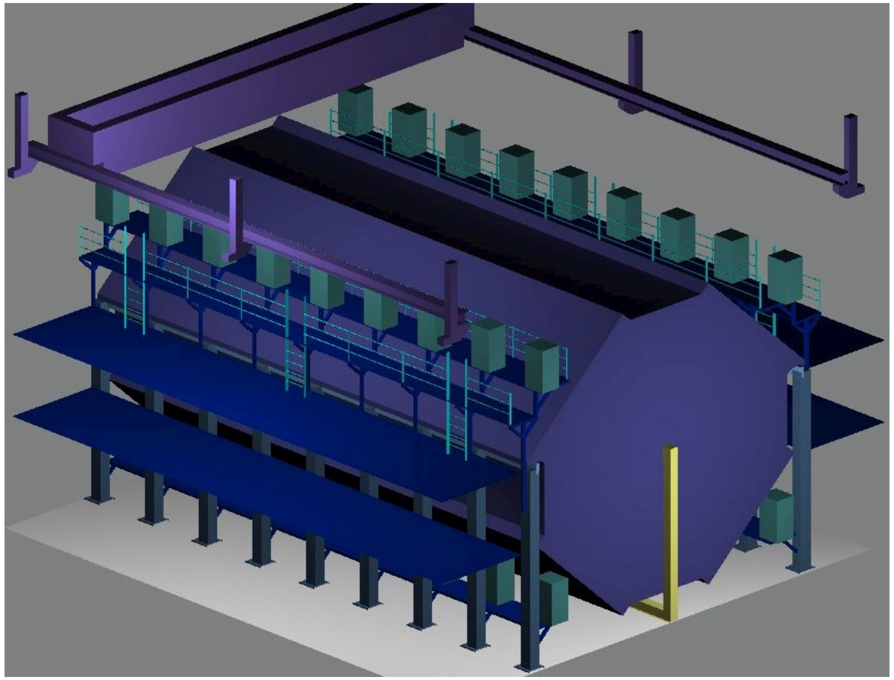


MINOS:Composé de :

- **Un faisceau de neutrino (3 faisceaux!)**
- **Un détecteur proche (980 t @ 1 km)**
- **Un détecteur lointain (5,4 kt @ 730 km)**







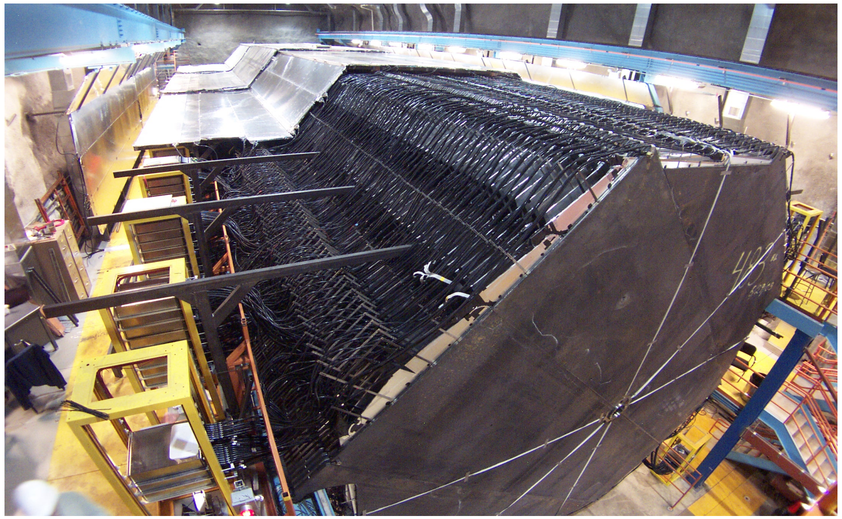
Constitué de :

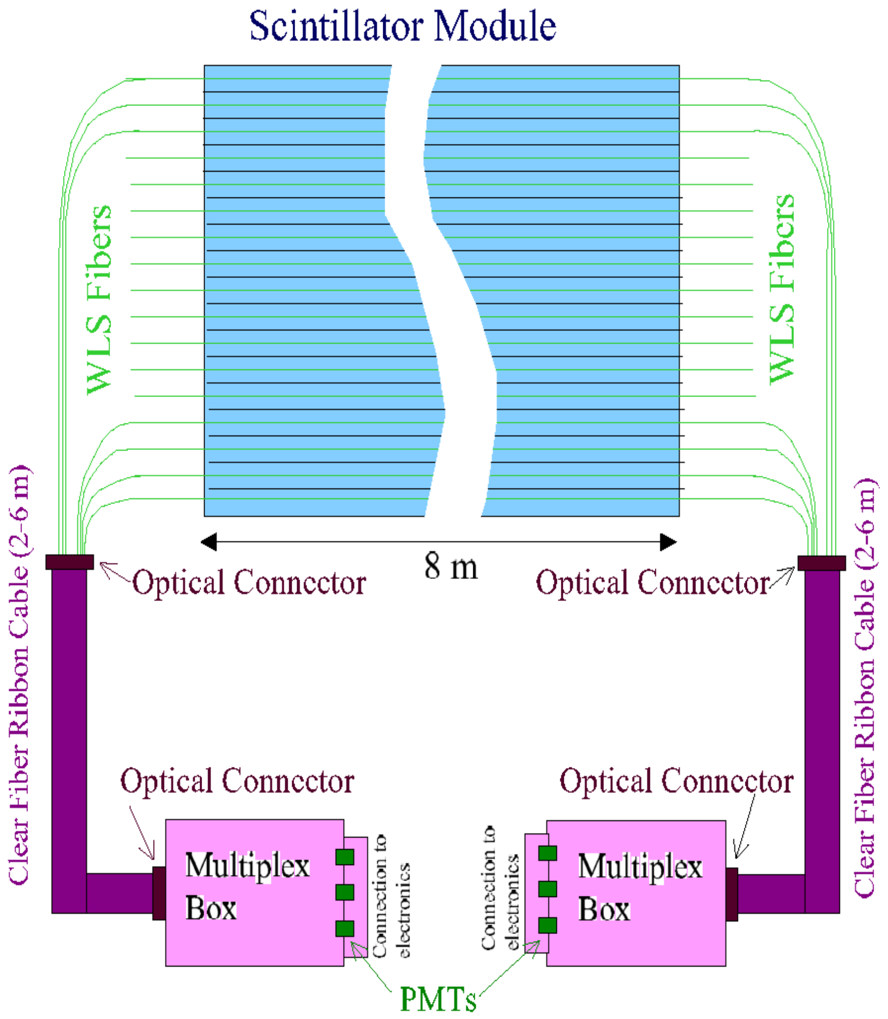
485 plaques d'acier octogonales (5,14 kt)

484 plaques de scintillateur octogonales (0,26 kt)

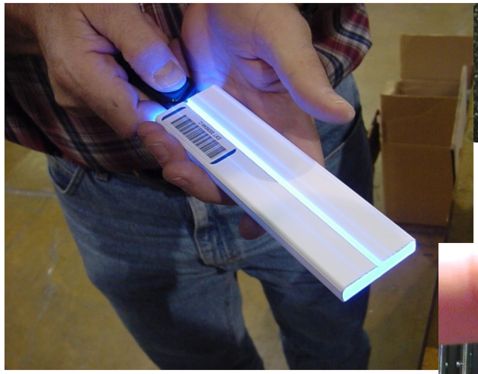
- 92,928 strips (4.1 x 1.0 cm), 1452 M16s
- 722 km de fibre (WLS fiber)
- 794 km fibre (clear fiber)

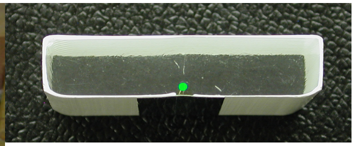
Un champ magnétique de 1,5 Tesla!

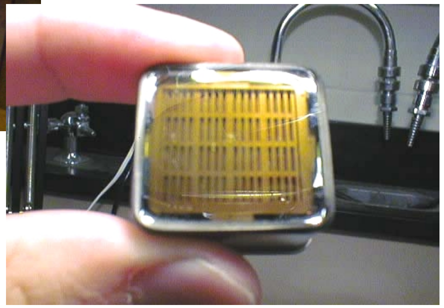




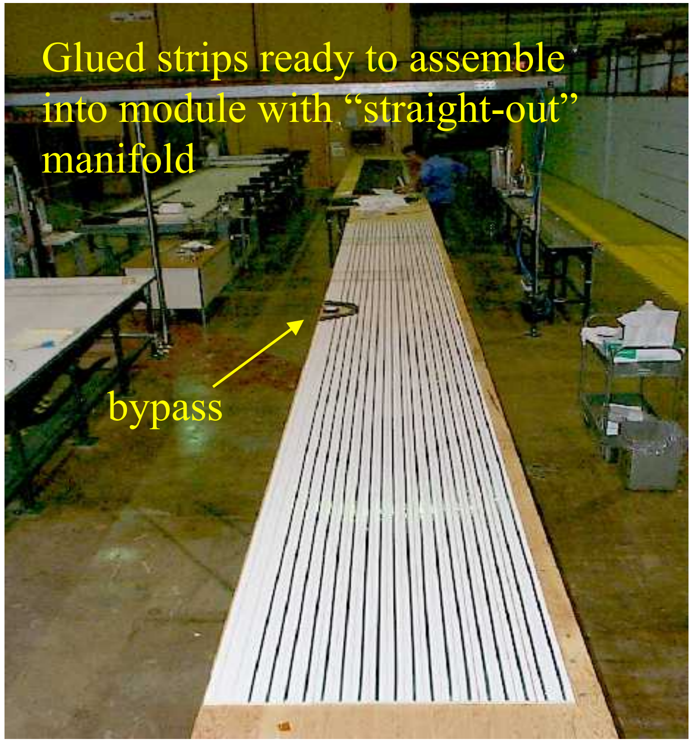
Scintillator Module
WLS Fibers
WLS Fibers
8 m
Optical Connector
Optical Connector
Clear Fiber Ribbon Cable (2-6 m)
Clear Fiber Ribbon Cable (2-6 m)
Optical Connector
Optical Connector
Multiplex Box
Multiplex Box
Connection to electronics
Connection to electronics
PMTs

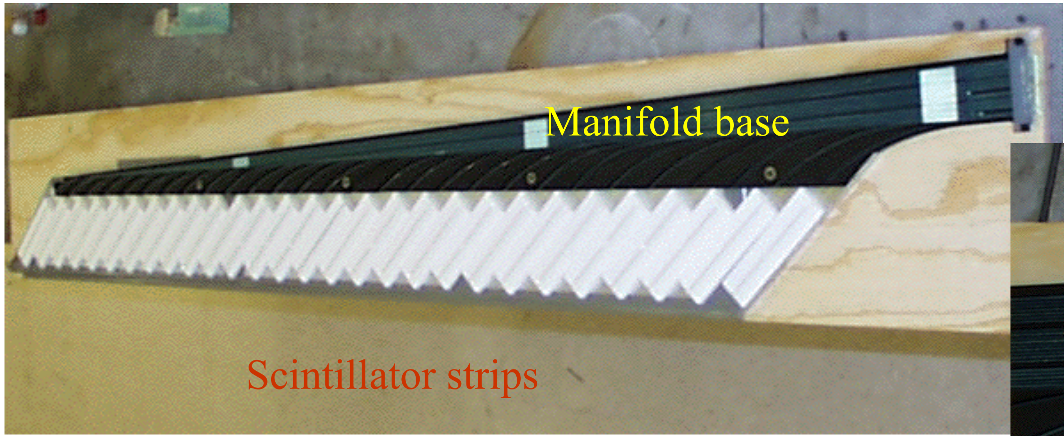


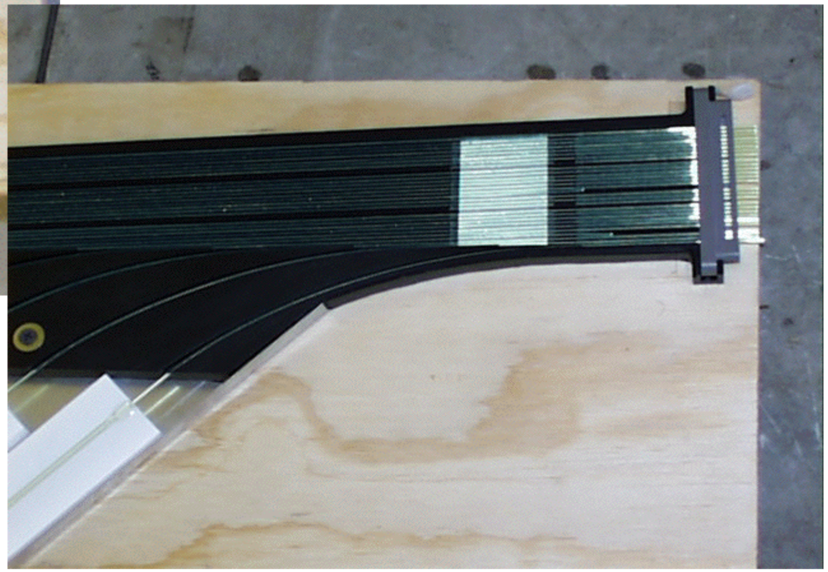


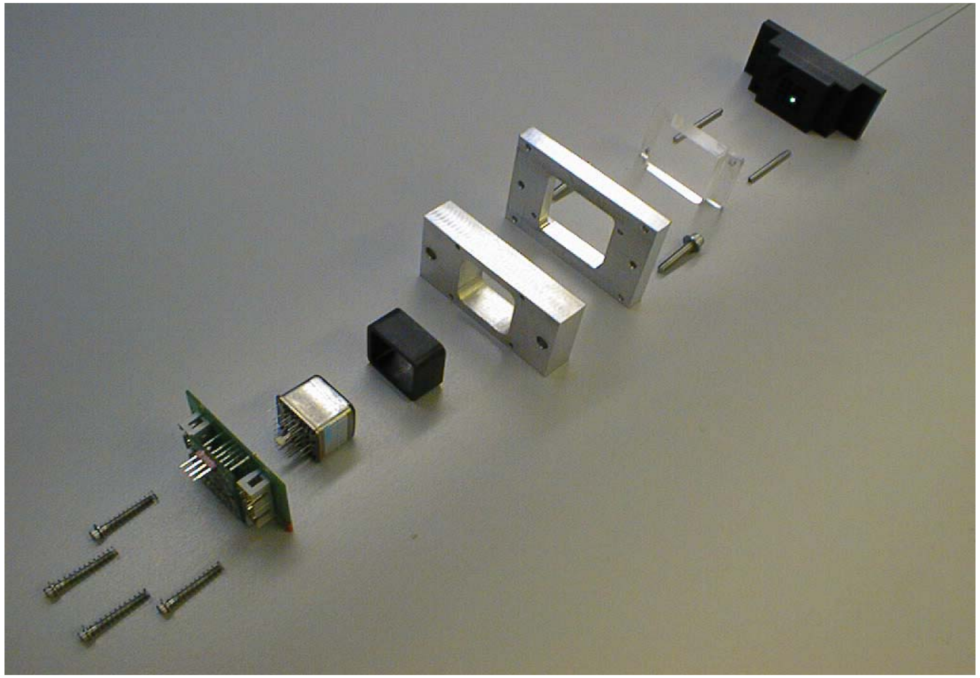


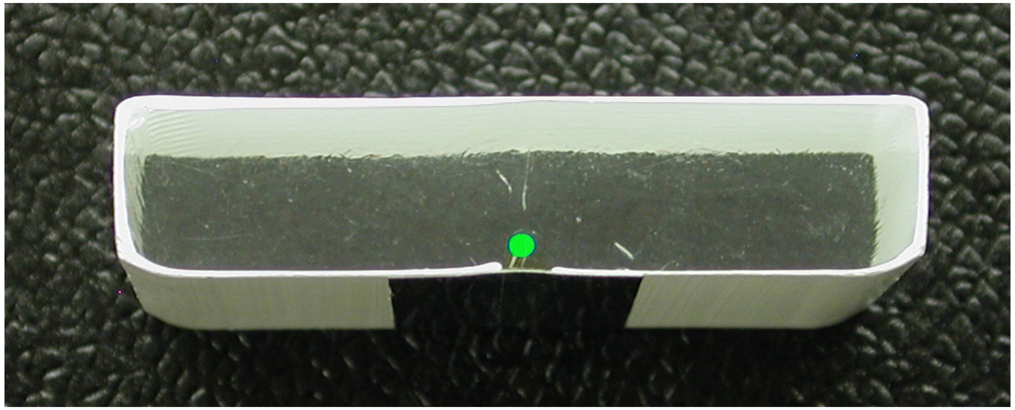

Light Case
Manifold base with fiber grooves
Variable width seal
Light injection cover
Formed Al cover
Optical connector

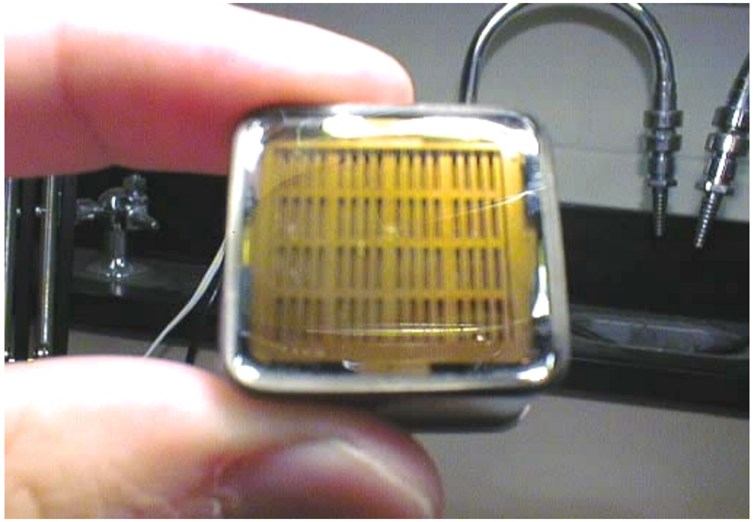

Glued strips ready to assemble into module with "straight-out" manifold
bypass

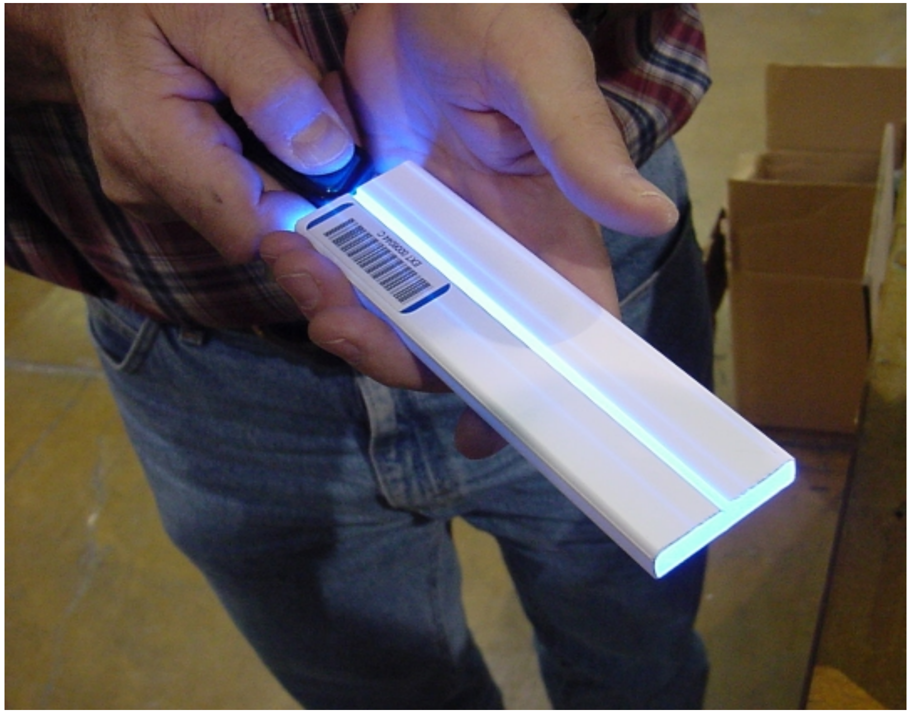

Manifold base
Scintillator strips



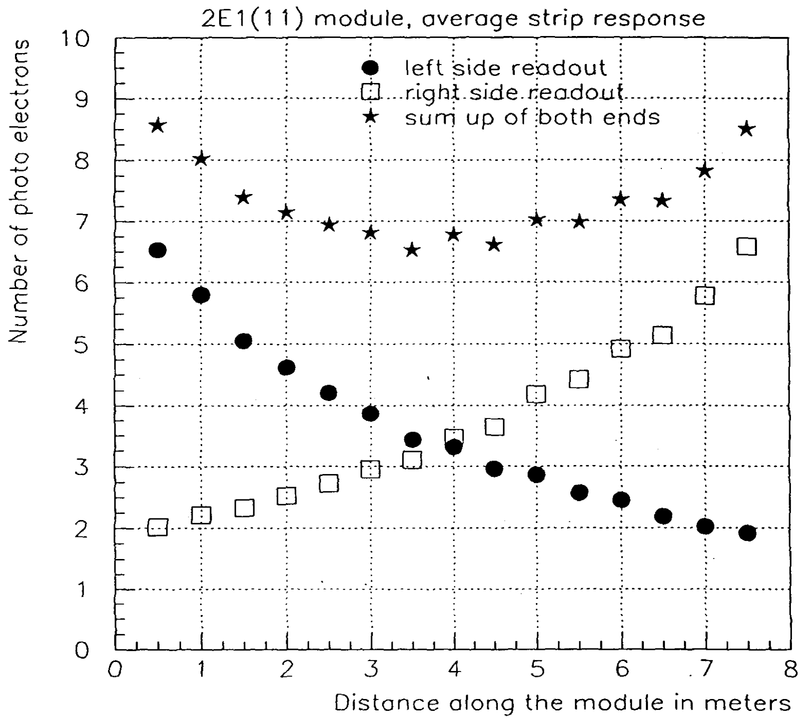




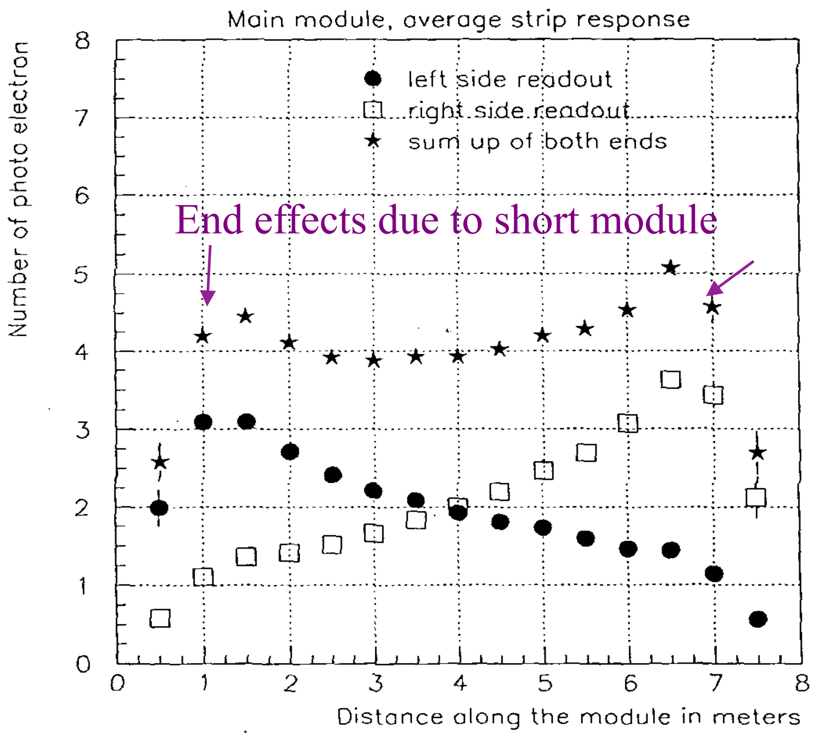




Résultats de test: nombre des photo-électrons par particule d 'ionisation minimale



Meilleur module



Mauvaise module

Exemple 2: Application en médecine

Les principes de la tomographie à émission de positrons (TEP)

Source: M-L Gallin-Martel, ISN, IN2P3

Etape 1 : Production du traceur

- Isotopes standards émetteurs β^+ ⇒

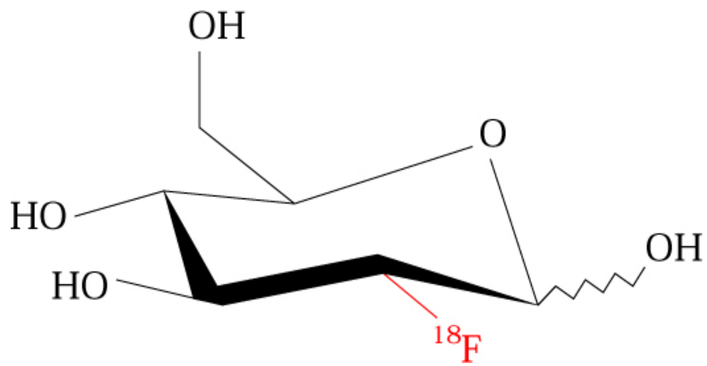
	^{18}F	^{15}O	^{11}C	^{13}N
T :	114 min.	2 min.	20 min.	10 min.

Etape 2 : Synthèse du radio traceur

Marquage d 'un composé biologique

EX : Fluorodésoxyglucose marqué ^{18}F ⇒ FDG
90 % des radio pharmaceutiques utilisés en TEP

Radio Synthèse : Introduction du ^{18}F sur une liaison carbone



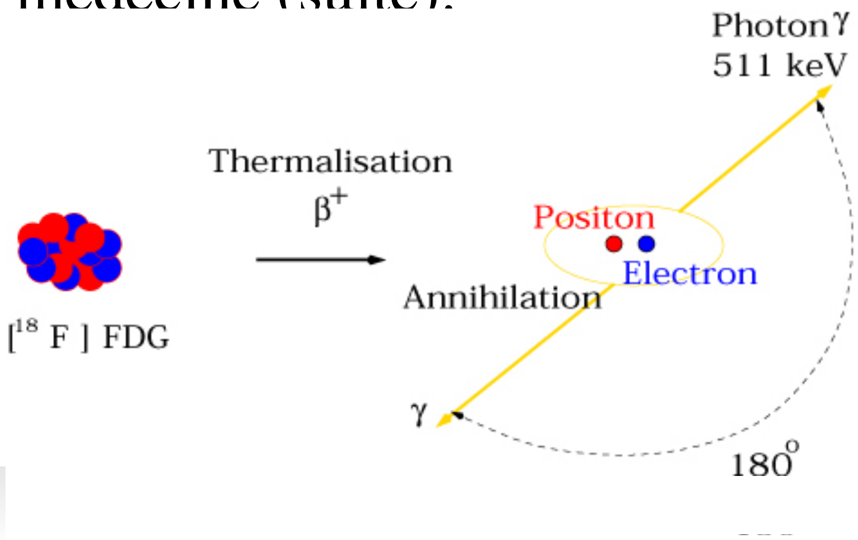
Exemple: Application en médecine (suite):

Etape 3 : Processus physiques

1♦ Désintégration β^+ du traceur

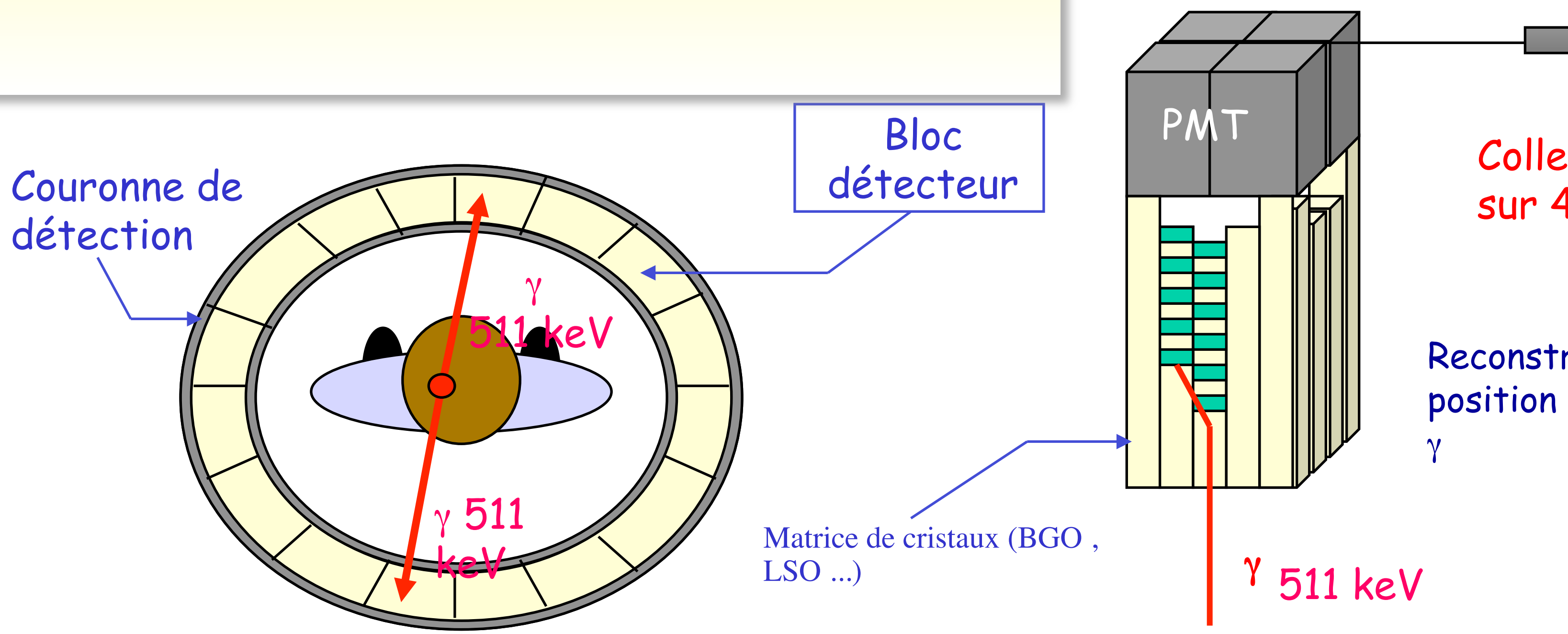
2♦ Thermalisation du β^+ dans les tissus

3♦ Annihilation : $e^+e^- \rightarrow \gamma\ \gamma$



Etape 4 : Détection et acquisition du signal

♦ Détection des γ en coïncidence ♦ Collimation électronique



5. Conclusions

1. **The basics of interactions of particles and radiation with matter are reviewed.**

2. **One should get the order of magnitude of the expected signal from a « back of the envelope calculation.**

3. **For this conference examples on light detection are chosen.**

4. **Many application in LEP, HEP, medical imaging, environmental surveillance and many more.**

Thank you for your attention,

And

Put the lights on!!!!

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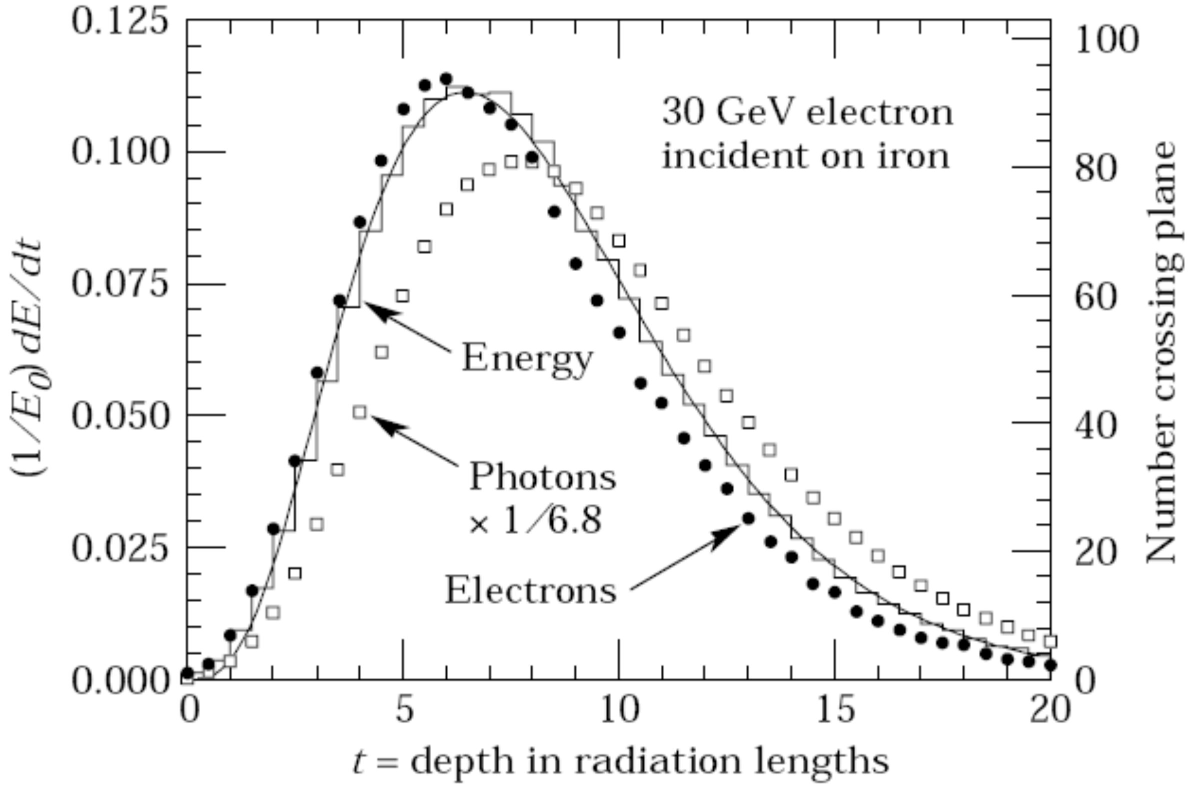
http://pdg.lbl.gov/


30 GeV electron
incident on iron
Energy
Photons
× 1/6.8
Electrons
(1/E0) dE/dt
Number crossing plane
t = depth in radiation lengths
0.000
0.025
0.050
0.075
0.100
0.125
0
20
40
60
80
100
0
5
10
15
20

Bremsstrahlung ↔ Cherenkov radiation

Origin: Acceleration of a particle in the field of the nucleus

$$Intensity \propto \frac{z^2 Z^2}{M}$$

$$\theta \propto \frac{m_0 c^2}{E_0}$$

Origin: Polarization of the material after passage of the particle

Intensity is independent of the particle mass

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

Compton scattering:

1929: Klein-Nishima formula:

$$\frac{d\sigma}{d\Omega} = \frac{r_e^2}{2[1+\gamma(1-\cos\theta]^2}\left(1+\cos^2\theta + \frac{\gamma^2(1-\cos\theta)^2}{1+\gamma(1-\cos\theta)}\right)$$

with $\gamma = h\nu / m_e c^2$

★ High energy limit ($\gamma >>1$) all photons are foreward scattered ($\theta = 0$)

★ **Thomson scattering** (classical limit of scattering of photons by free electrons) – Klein –Nishime reduces to

$$\sigma = \frac{8\pi}{3} r_e^2 \quad \text{Thomson cross section}$$

Rayleigh scattering = scattering of photons by atoms as a whole (all electrons contribute) = coherent scattering

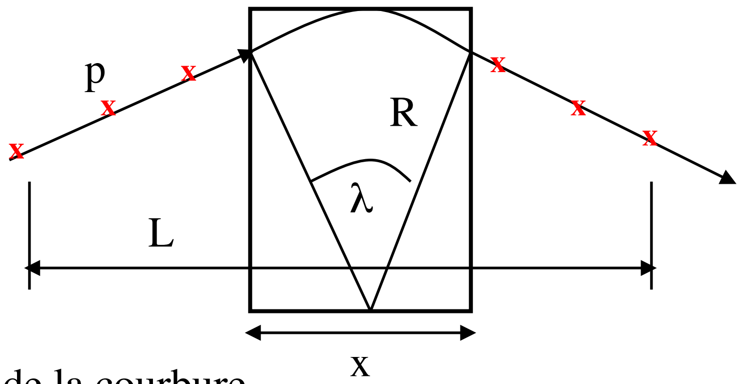
Some examples for X_0 and E_c

Material	X_0 g/cm^2	X_0 cm	E_C MeV
Air	37	287m	84
Water	37	37	65
Al	24	9.1	49
Fe	14	1.8	24
Cu	13	1.5	22
Pb	6.5	0.58	7.8

Measurement of particle momentum in a magnetic field:

P cosλ = 0.3 z B R

(R [m], rayon de courbure et
B [Tesla], champ magnétique)



La distribution des mesures de la courbure **k = 1/R** est ≈ gaussienne

$$(\ \ k)^2 \quad (\ \ k_{res})^2 \quad (\ \ k_{ms})^2$$

δk = erreur de la courbure
δk_{res} = erreur de la résolution
δk_{ms} = erreur de la diffusion multiple

Mesure le long de la trace de N>10 points avec une erreur σ(x) par point :

$$k_{res} \quad \frac{(x)}{L^2}\sqrt{\frac{720}{N \quad 4}}$$

L = projection de la longueur
σ(x) = erreur de la mesure de chaque point de la trace

La résolution en impulsion sera affectée par la diffusion multiple

$$k_{ms} \quad \frac{(0.016)(GeV/c)z}{Lp \quad \cos^2}\sqrt{\frac{L}{X_0}}$$

Et aussi:

$$k_{ms} \quad 8s^{rms}_{plane} / L^2$$

Résolution pour l 'impulsion

$$\left|\frac{p}{p}\right| \quad \frac{p}{0.3B} \quad k$$

Mesure de l 'impulsion en champ magnétique

Exemple: expérience CHORUS (CERN)

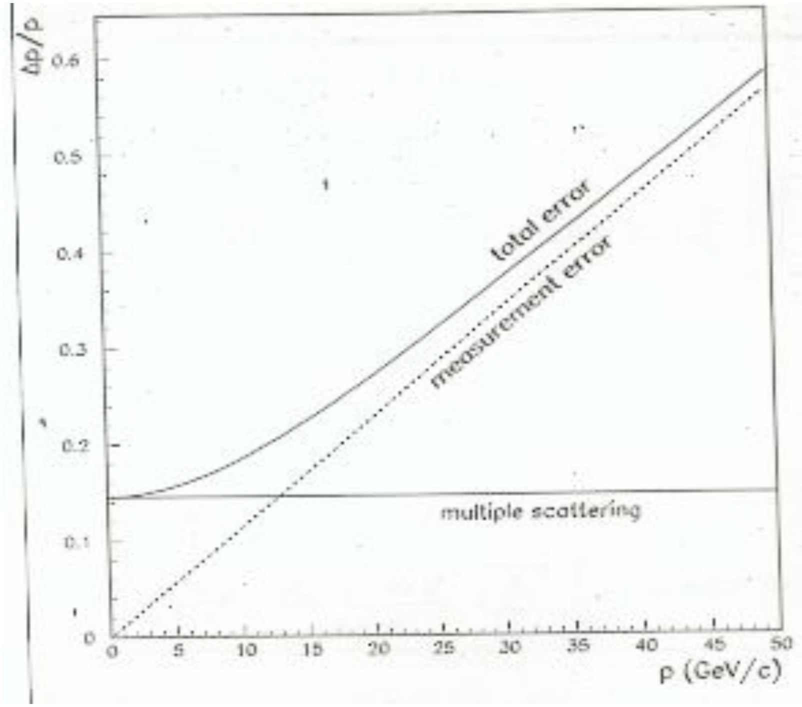
$\sigma(x)$ = 1 mm = 10^{-3} m, L = 1,3 m, x = 0,5 m, B = 1,65 T, 4 points de mesure

$$k_{res} \quad \frac{(x)}{L^2}\sqrt{\frac{720}{N \quad 4}} \quad \frac{10^{-3}}{1.69}\sqrt{\frac{720}{8}} \quad 5.61 \quad 10^{-2}$$

$$\left|\frac{p}{p}\right|_{res} \quad k_{res} \quad \frac{p}{0.3 \quad 1.65} \quad 1.13 \quad 10^{-2} \quad p$$

$$k_{ms} \quad \frac{1}{L^2} 8 \frac{1}{4\sqrt{3}} x \quad _0 \quad \frac{1}{p} \quad \frac{1.154}{1.69} \quad 0.5 \quad 0.2112 \quad \frac{1}{p} \quad 0.0721 \quad \frac{1}{p}$$

$$\left|\frac{p}{p}\right|_{ms} \quad k_{ms} \frac{p}{0.3 \quad 165} \quad 0.1456$$



Erreur totale:

$$\left|\frac{p}{p}\right| \quad \sqrt{\left|\frac{p}{p}\right|_{res}^2 \quad \left|\frac{p}{p}\right|_{ms}^2} \quad \sqrt{1.277 \quad 10^{-4} p^2 \quad 0.0212}$$