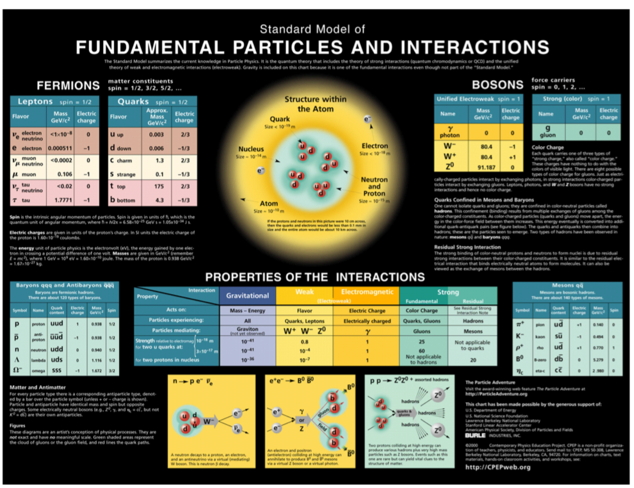
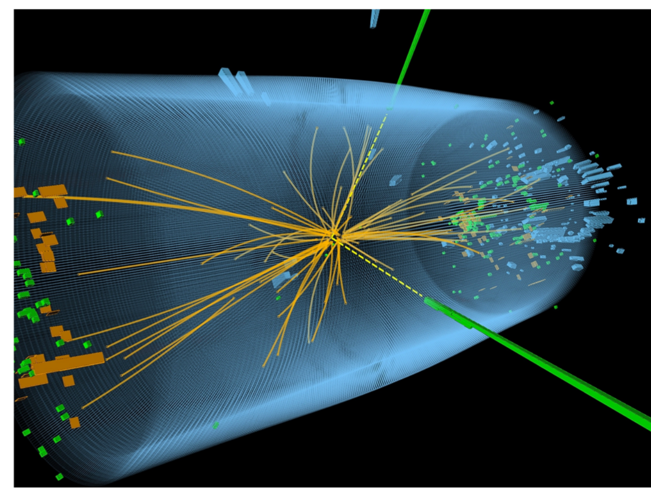
Introduction to particle and radiation interactions with matter





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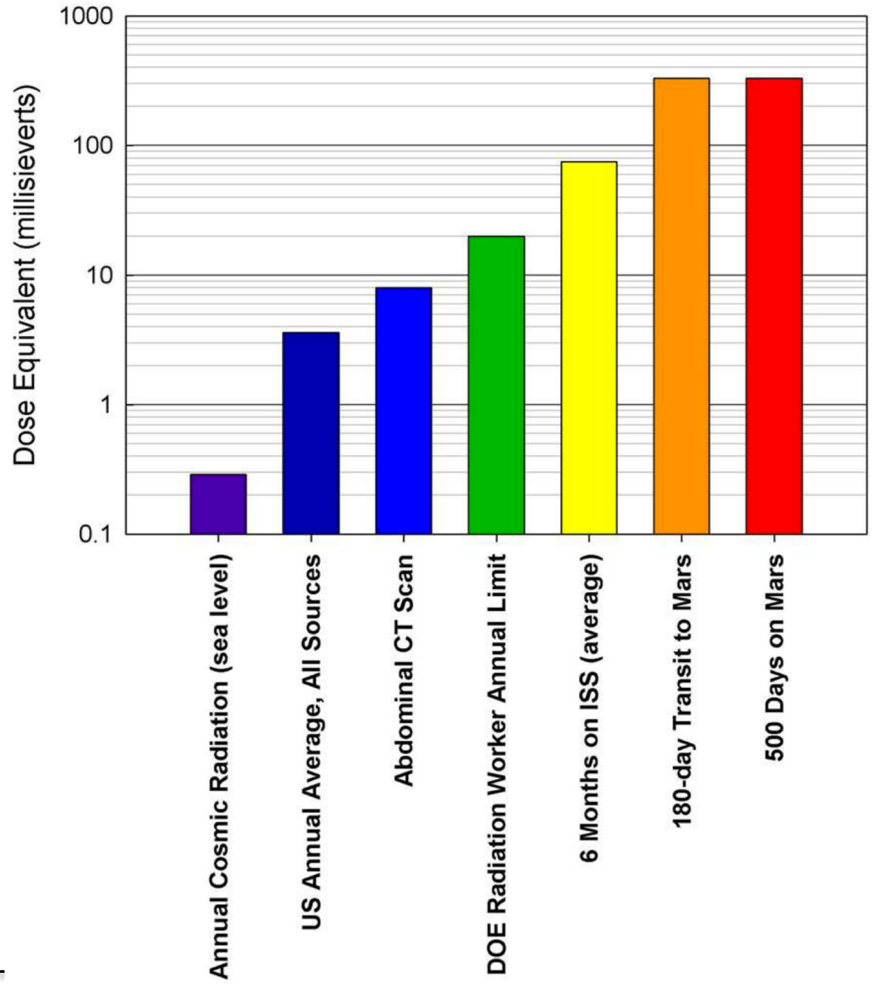
1. Introduction

Nuclear and Particle Physics is all around our life

- Primordial = before the creation of the earth
- Cosmogenic = continuously formed by cosmic rays
- Human produced = industry, medical, fires, arms, etc.



Units for Radiation:

Unité d'activité = becquerel (curie): 1 Bq = 1 désintégration / s (1/(3,7 x 10^{10}) Ci)

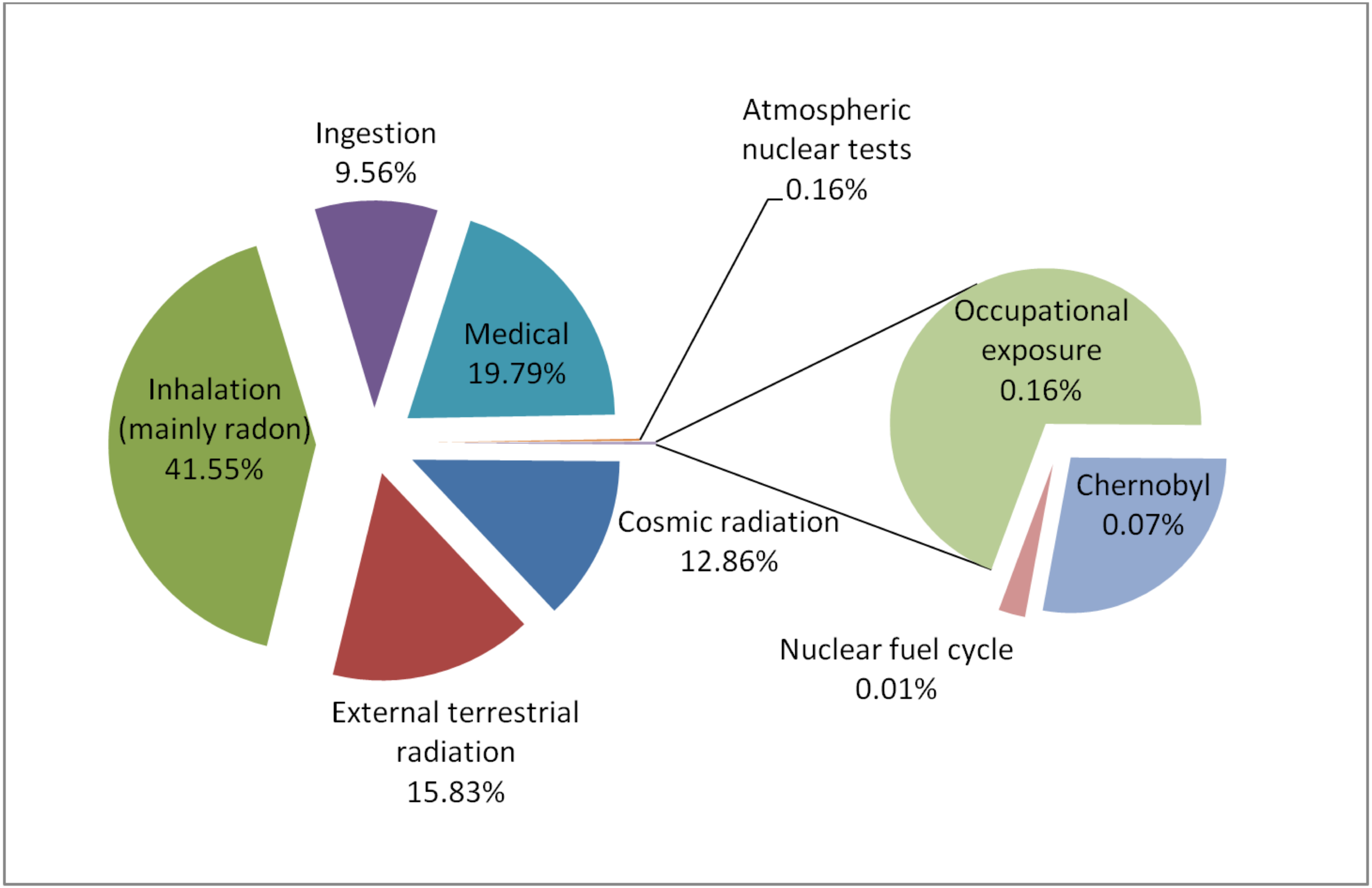
Unité de la dose absorbée = gray: 1 Gy = 1 joule kg^{-1} = 6,24 x 10^{12} MeV kg^{-1} d'énergie déposée

rem or Sv represent the stochastic biological effects of ionizing radiation, primarily radiation-induced cancer

1 Sv = 100 rem

Unité de dose équivalente = sievert
L'équivalent de dose HT (Sv) dans un organe =
dose absorbée x ω_R (« dangerosité de la radiation »)

Radiation	ω_R
X-rays, γ-rays, all energies	1
Electrons and muons, all energies	1
Neutrons < 10 keV	5
Neutrons 10 – 100 keV	10
Neutrons >100 keV-2 MeV	20
Neutrons 2 – 20 MeV	10
Neutrons > 20 MeV	5
Protons > 2 MeV	5
Alphas, fission fragments, heavy nuclei	20


Ingestion
9.56%
Atmospheric
nuclear tests
0.16%
Medical
19.79%
Inhalation
(mainly radon)
41.55%
Occupational
exposure
0.16%
Chernobyl
0.07%
Cosmic radiation
12.86%
Nuclear fuel cycle
0.01%
External terrestrial
radiation
15.83%

We are radioactive !

On average a human of 70 kg has 17 mg of Potassium 40

This results in 4,4 kBq of activity

This is 4400 disintegrations per second !

$$\beta^- : {}^{40}_{19}K \rightarrow {}^{40}_{20}Ca + e^- + \bar{\nu}_e$$

$$EC : {}^{40}_{19}K + e^- \rightarrow {}^{40}_{18}Ar^* + \nu_e \rightarrow {}^{40}_{18}Ar^* + \nu_e \rightarrow {}^{40}_{18}Ar + \gamma + \nu_e$$

$$\beta^+ : {}^{40}_{19}K \rightarrow {}^{40}_{18}Ca + e^+ + \nu_e$$

And when you eat a healthy carrot you get 0,1 kBq / kg !

Radiation naturel: 1,0 à 13 mSv /année

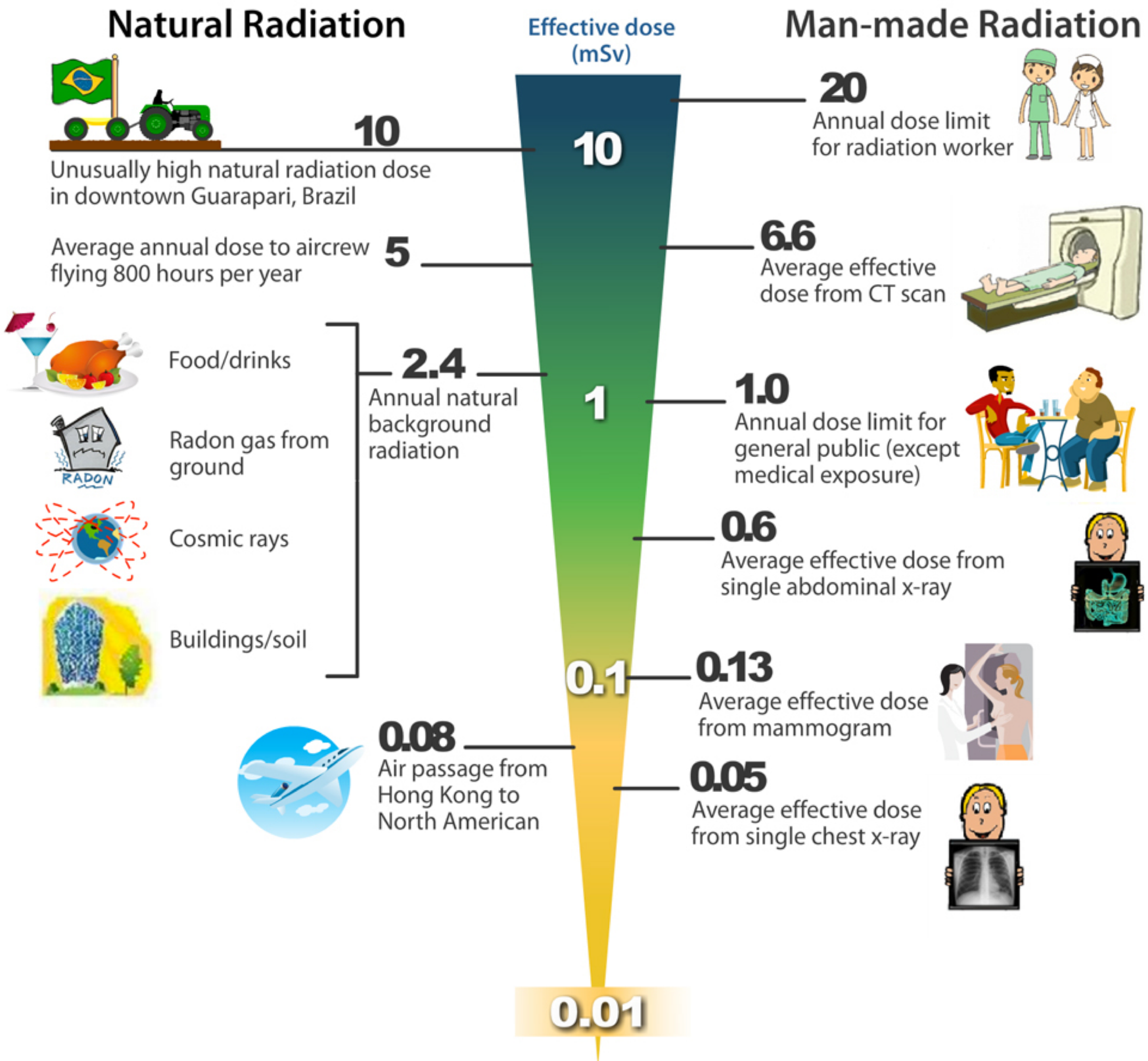
Radiation dû au rayonnes cosmiques: 0,1 µSv/h (niveau de la mer) à qq µSv/h (avions)

Effets pathogènes: Dose mortelle: 50% dans 30 jours sans traitement med = 2,5 à 4,5 Gy

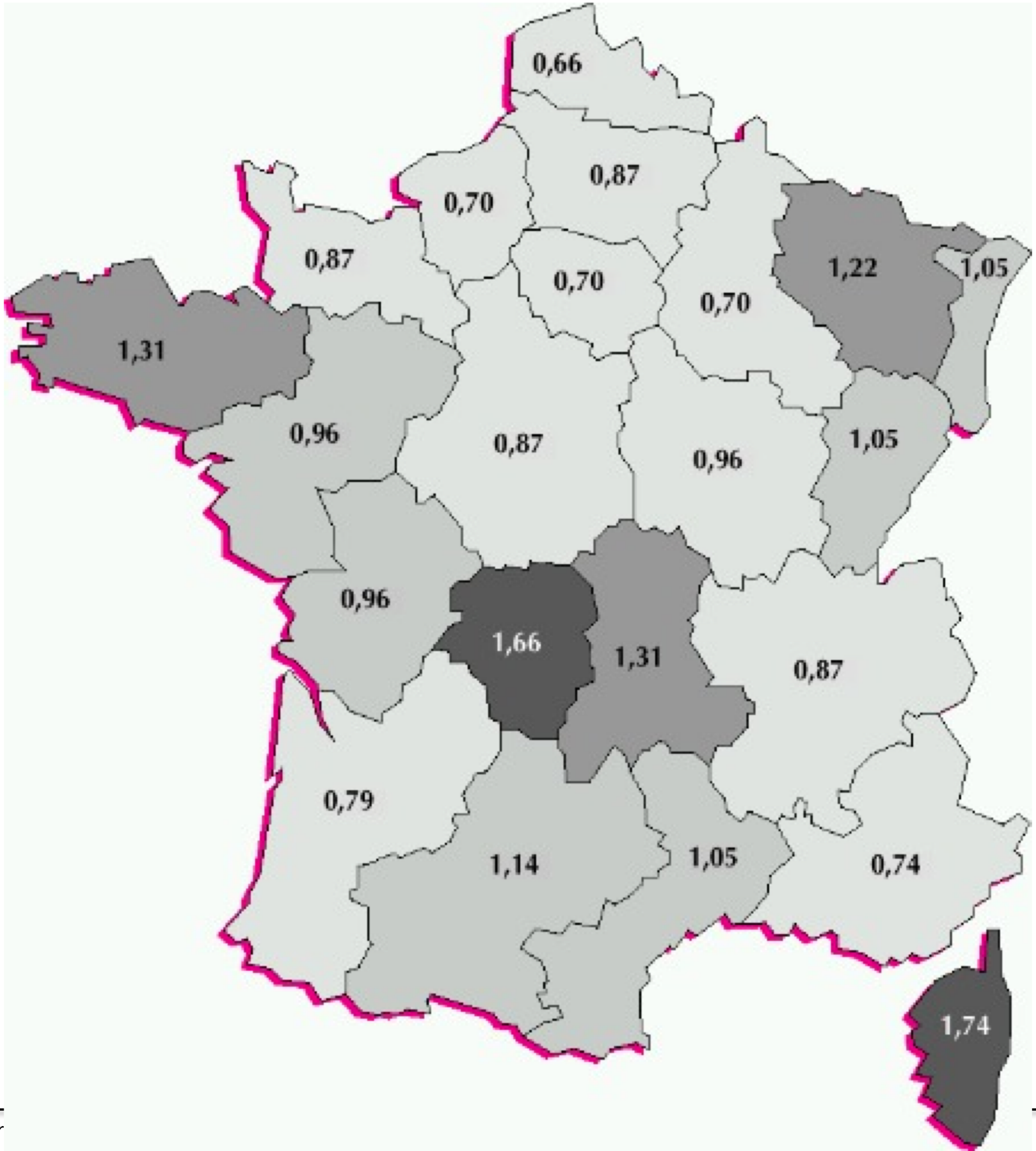
Cancer: manifestation d'un cancer = 5% par Sv

Limite recommandé pour personnel dans installations nucléaires: 20 mSv yr^{-1}

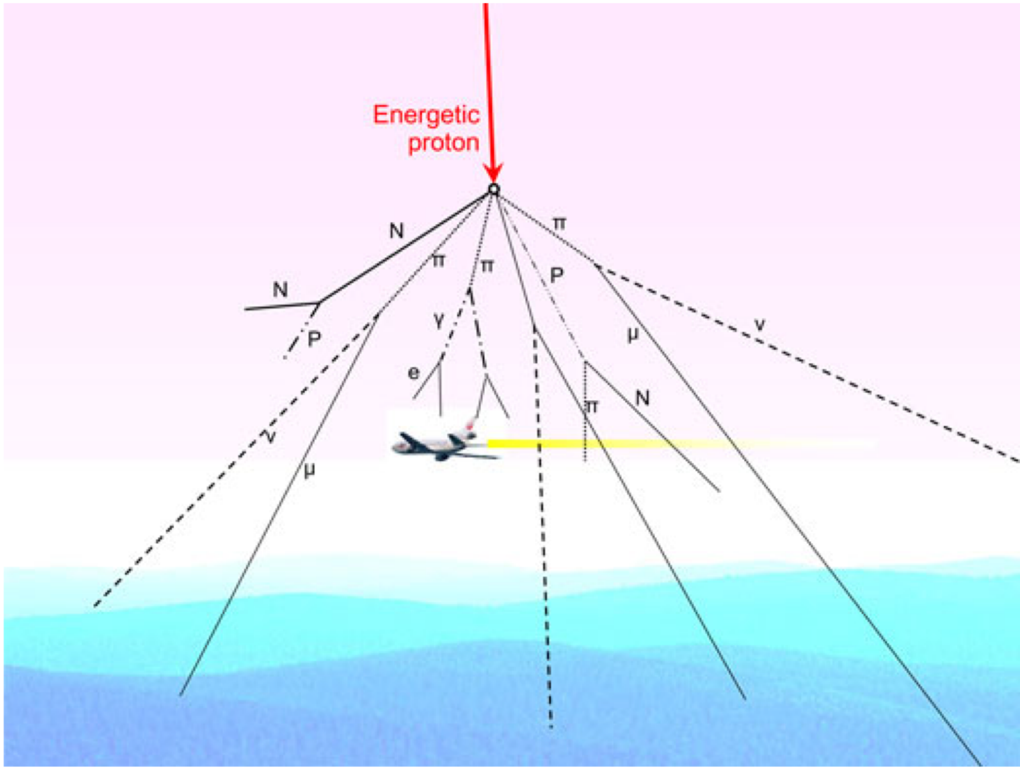
Radiation in Daily Life



Radioactivité naturelle d'origine tellurique (provenant de la terre) en mSv/an:

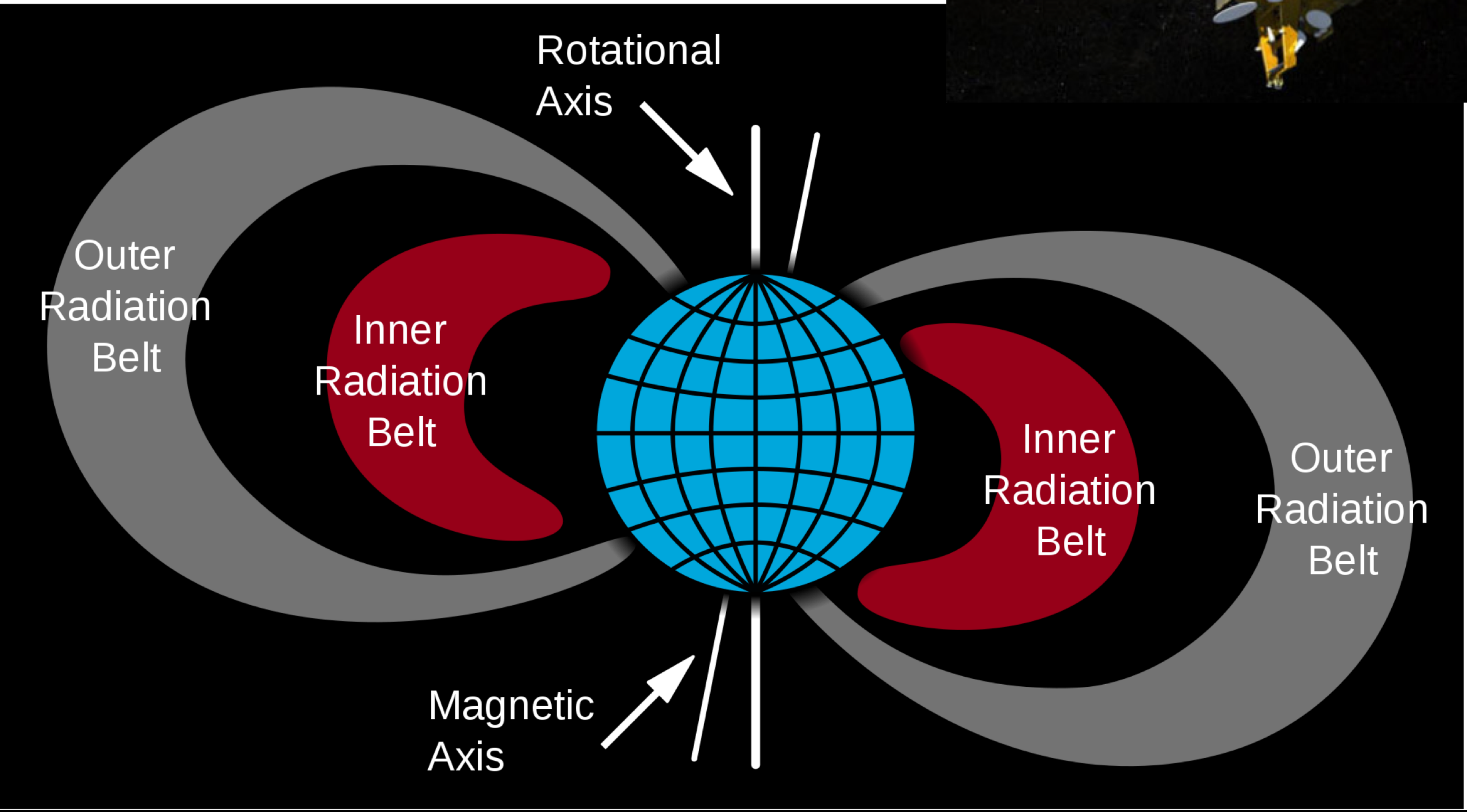


Exposure in flight:



- The lowest dose rate measured was 3 μSv h^{-1} during a Paris-Buenos Aires flight.
- The highest rates were 6.6 μSv h^{-1} during a Paris to Tokyo flight and 9.7 μSv h^{-1} on the Concorde in 1996–1997.
- The corresponding annual effective dose, based on 700 hours of flight for subsonic aircraft and 300 hours for the Concorde, can be estimated at between 2 mSv for the least exposed routes and 5 mSv for the more exposed routes.

High level electronics in Satellites is affected

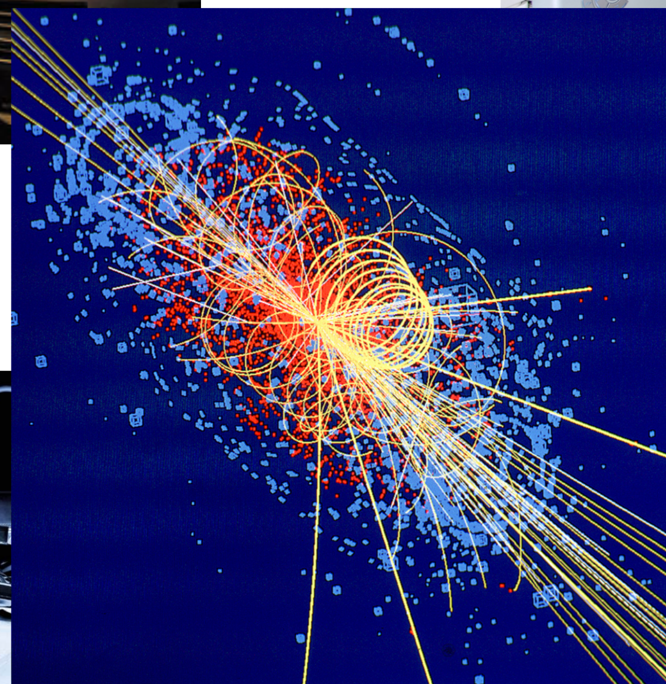


Two basic reasons why to detect particles or radiation:

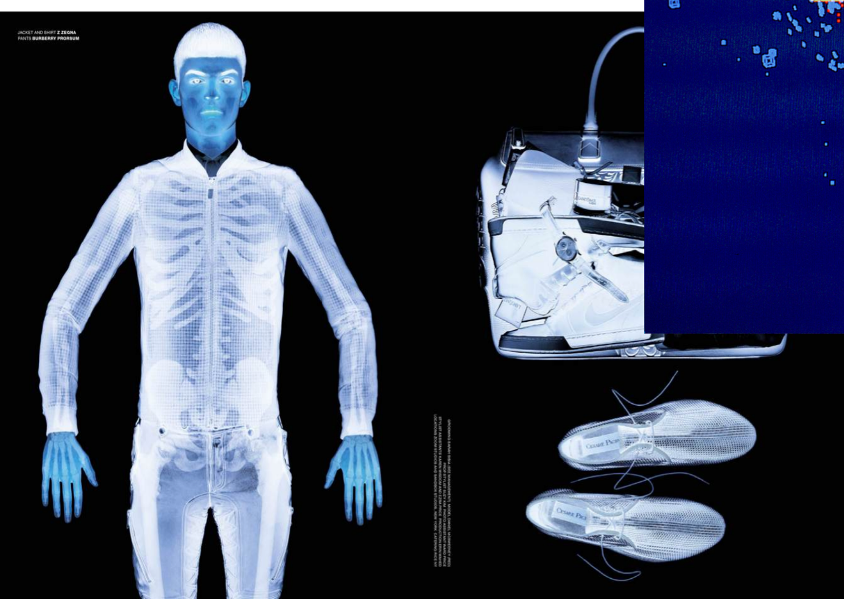
1. **Study** the interactions of particles and radiation to understand the basic laws of nature

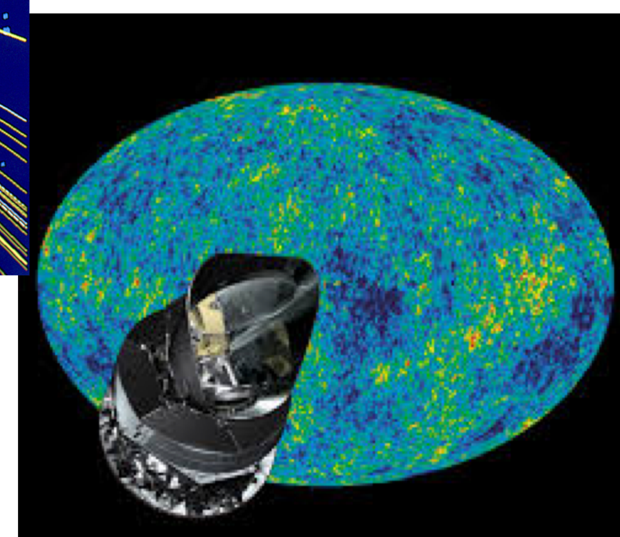
Applied and fundamental research

2. **Use** fundamental interactions to study the characteristics of matter



Affects all of our life!





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:

$\nu_l + e^- \rightarrow e^- + \nu_l$
$\nu_l + N \rightarrow l + X$

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:

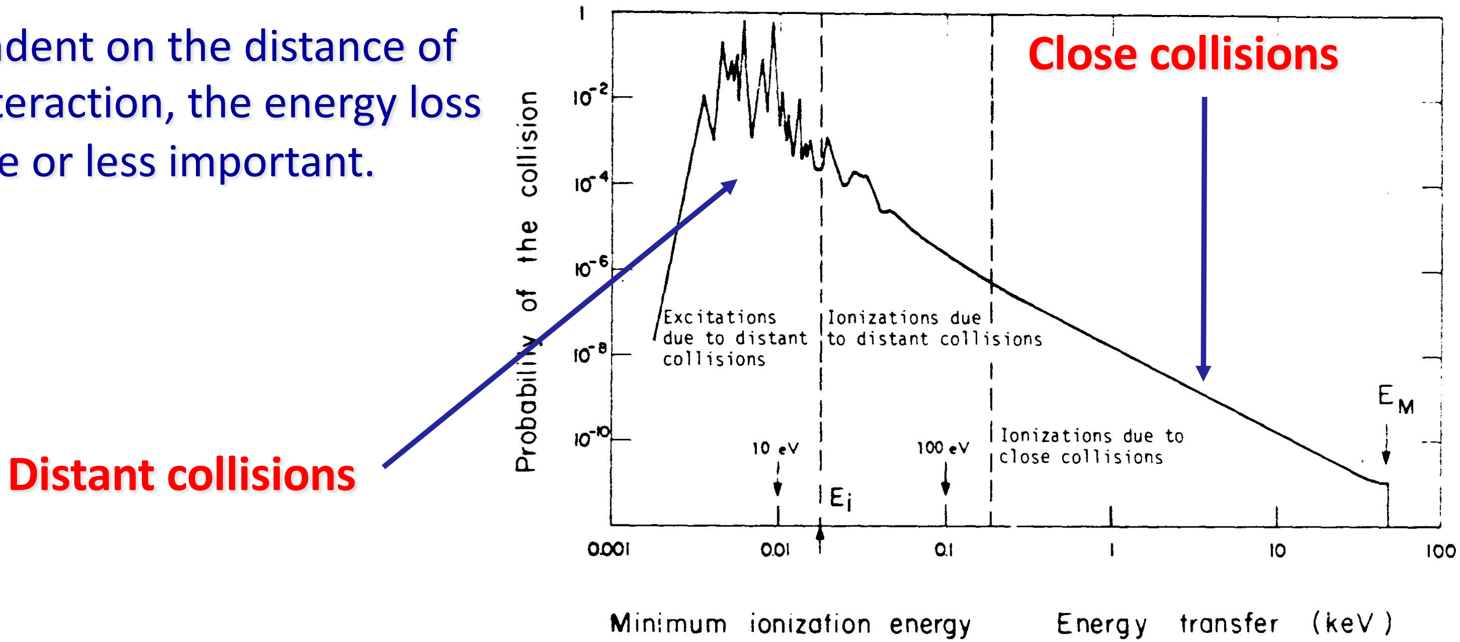
Strong interaction : $\sigma \sim 10 \div 100$ mb
Electro-magnetic interaction: $\sigma \sim 10 \div 100$ nb
Weak interaction: $\sigma \sim 10 \div 100$ pb

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

Energy loss of 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.



Maximum energy transfer:

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

Interaction of charged particles

Charged particle X, with $Mc^2 >> m_e c^2$
Dominant: Coulomb interaction between the particle X and the atom A

Two electromagnetic processes:

1) Elastic scattering from nuclei:

$$\text{Atom} + X \longrightarrow \text{Atom}^* + X \qquad \text{excitation}$$

$$\text{Atom}^* \longrightarrow \text{Atom} + \gamma \qquad \text{de-excitation}$$

2) Inelastic collisions with the electrons of the atoms

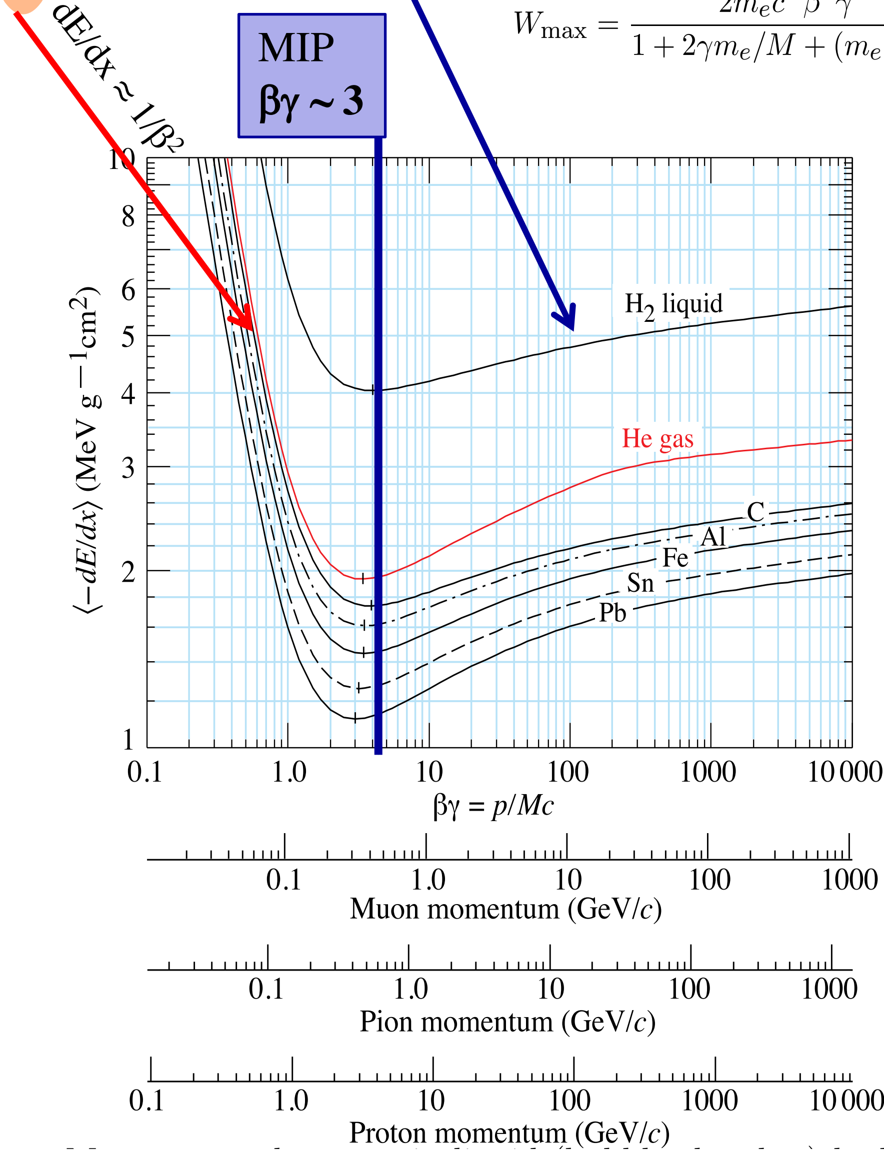
$$\text{Atom} + X \longrightarrow \text{Atom}^+ + e^- + X \qquad \text{ionization}$$

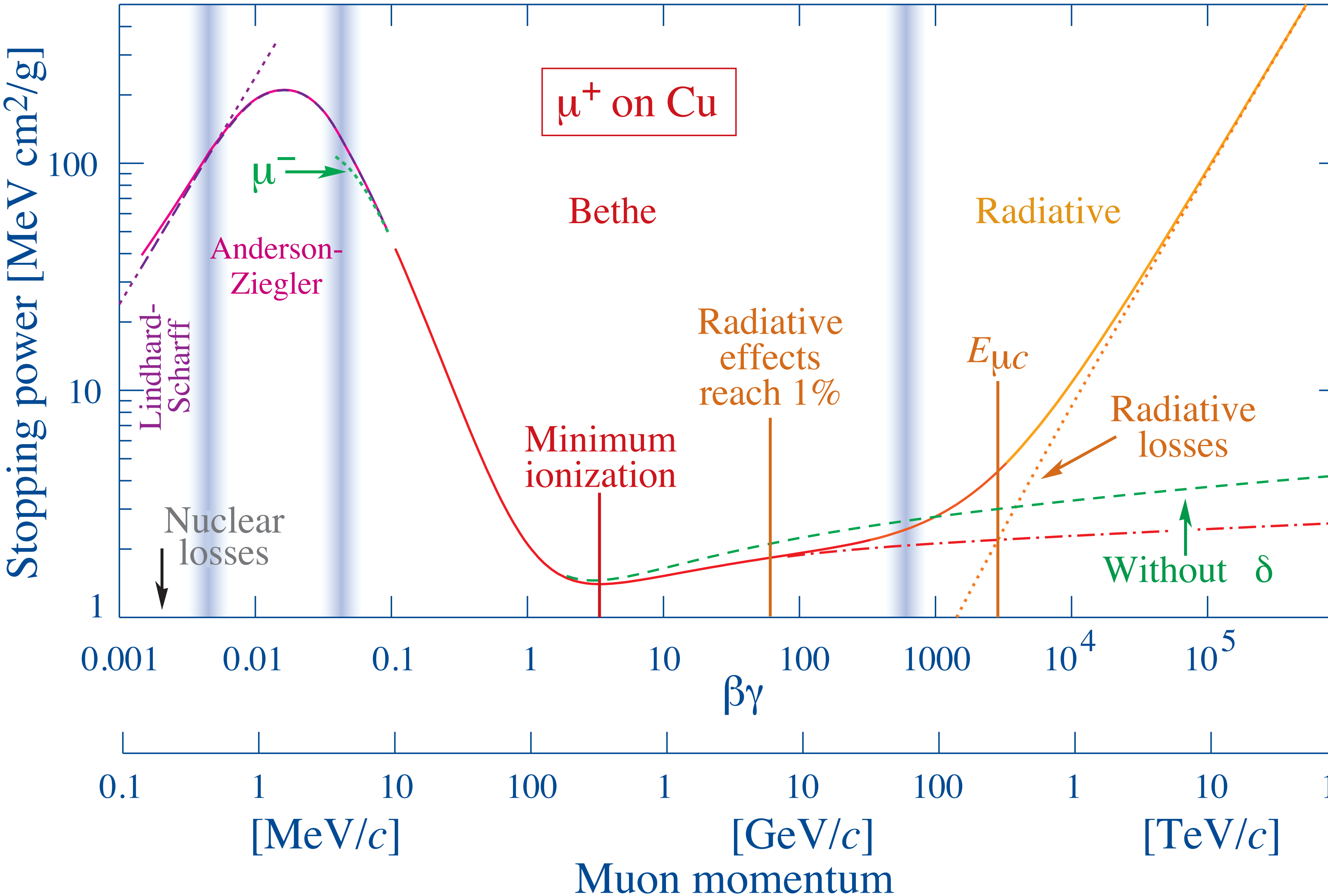
Mean Energy Loss: (Bethe-Bloch)

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

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

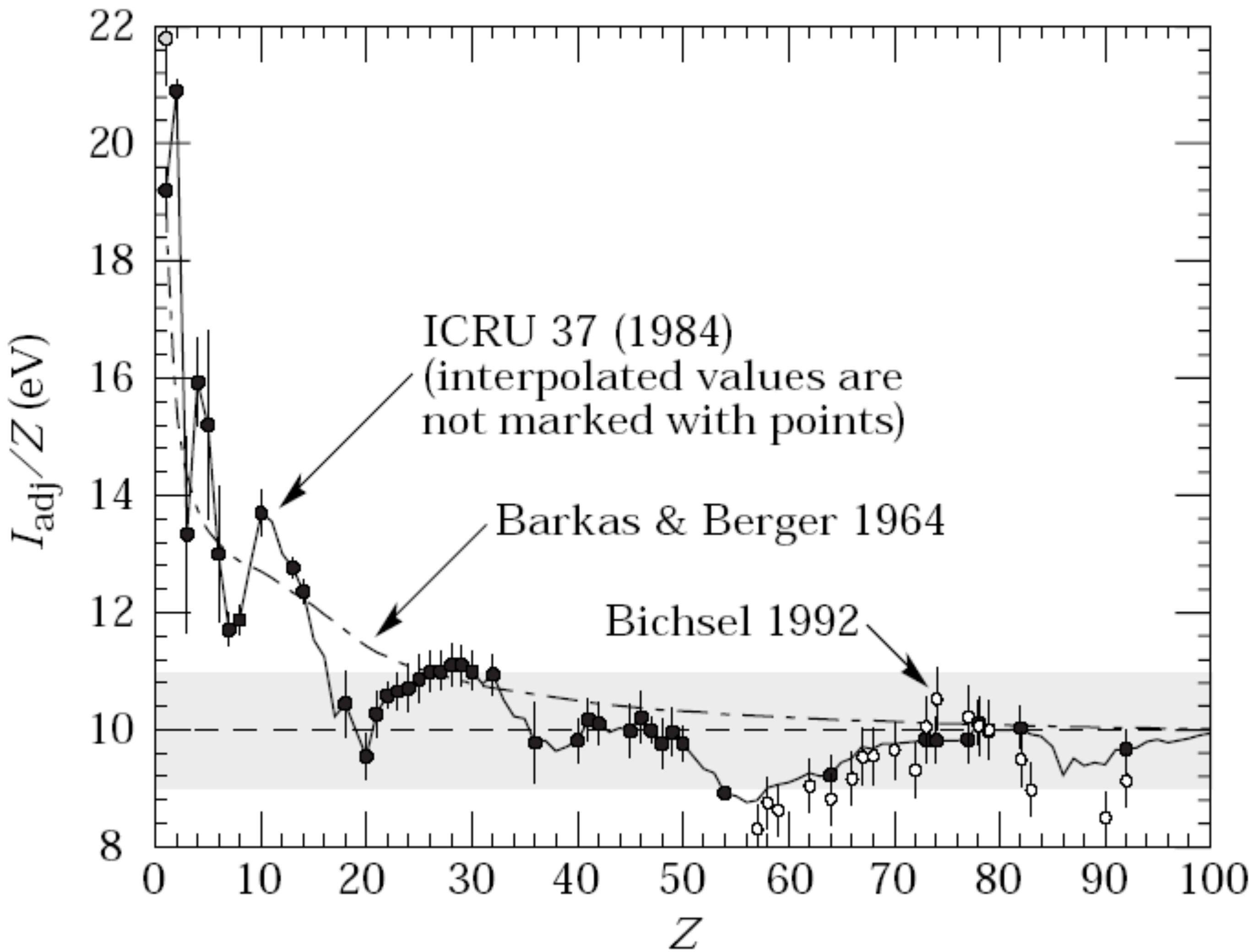
Symbol	Definition	Value or (usual) units
α	fine structure constant	
	$e^2/4\pi\epsilon_0\hbar c$	$1/137.035\,999\,074(44)$
M	incident particle mass	MeV/c^2
E	incident part. energy $\gamma M c^2$	MeV
T	kinetic energy, $(\gamma - 1)Mc^2$	MeV
W	energy transfer to an electron in a single collision	MeV
k	bremsstrahlung photon energy	MeV
$m_e c^2$	electron mass $\times\, c^2$	$0.510\,998\,928(11)$ MeV
r_e	classical electron radius	
	$e^2/4\pi\epsilon_0 m_e c^2$	$2.817\,940\,3267(27)$ fm
N_A	Avogadro's number	$6.022\,141\,29(27) \times 10^{23}$ mol^{-1}
z	charge number of incident particle	
Z	atomic number of absorber	
A	atomic mass of absorber	g mol^{-1}
K	$4\pi N_A r_e^2 m_e c^2$	$0.307\,075$ MeV mol^{-1} cm^2
I	mean excitation energy	eV (*Nota bene!*)
$\delta(\beta\gamma)$	density effect correction to ionization energy loss	
$\hbar\omega_p$	plasma energy	$\sqrt{\rho\,\langle Z/A \rangle} \times 28.816$ eV
	$\sqrt{4\pi N_e r_e^3}\; m_e c^2/\alpha$	$\hookrightarrow$ ρ in g cm^{-3}
N_e	electron density	(units of r_e)$^{-3}$
w_j	weight fraction of the jth element in a compound or mixture	
n_j	$\propto$ number of jth kind of atoms in a compound or mixture	
X_0	radiation length	g cm^{-2}
E_c	critical energy for electrons	MeV
$E_{\mu c}$	critical energy for muons	GeV
E_s	scale energy $\sqrt{4\pi/\alpha}\; m_e c^2$	21.2052 MeV
R_M	Molière radius	g cm^{-2}





Stopping power [MeV cm²/g]
μ⁺ on Cu
μ⁻
Bethe
Radiative
Anderson-
Ziegler
Lindhard-
Scharff
Radiative
effects
reach 1%
Eμc
Radiative
losses
Minimum
ionization
Nuclear
losses
Without δ
100
10
1
0.001
0.01
0.1
1
10
100
1000
10⁴
10⁵
βγ
0.1
1
10
100
1
10
100
1
10
[MeV/c]
[GeV/c]
[TeV/c]
Muon momentum

Average Ionisation Energy



Density Correction

As the particle energy increases, its electric field flattens and extends, so that the distant-collision contribution increases as $\ln\beta\gamma$.

However, real media become polarized, limiting the field extension and effectively truncating this part of the logarithmic rise.

The density effect correction is usually computed using Sternheimer's parameterization:

$$\delta(\beta\gamma) = \begin{cases} 2(\ln 10)x - \overline{C} & \text{if } x \geq x_1; \\ 2(\ln 10)x - \overline{C} + a(x_1 - x)^k & \text{if } x_0 \leq x < x_1; \\ 0 & \text{if } x < x_0 \text{ (nonconductors);} \\ \delta_0 10^{2(x-x_0)} & \text{if } x < x_0 \text{ (conductors)} \end{cases}$$

Here $x = \log_{10} \eta = \log_{10}(p/Mc)$

From PDG.

Energy loss by ionization dE/dx

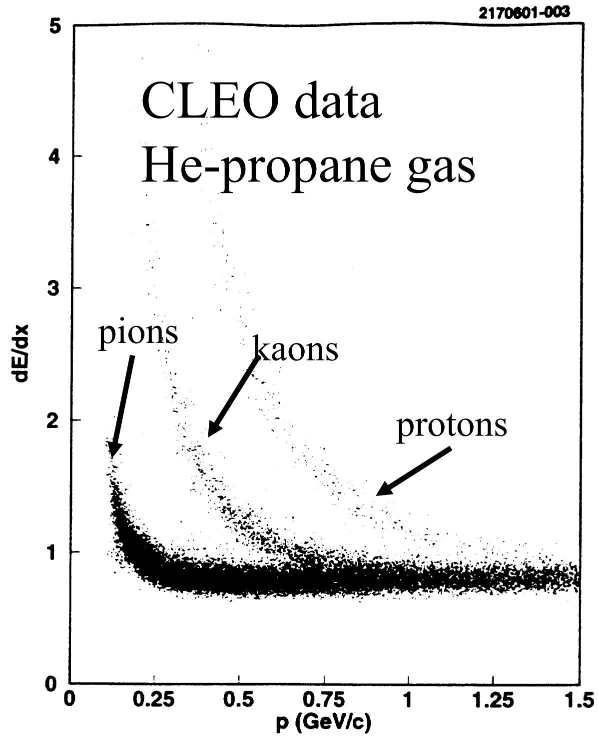
$$-\frac{dE}{dx} \propto \frac{1}{\beta^2}\left(\ln(\beta\gamma) - 2\beta^2 + c_1\right)$$

p = 0.1 GeV/c

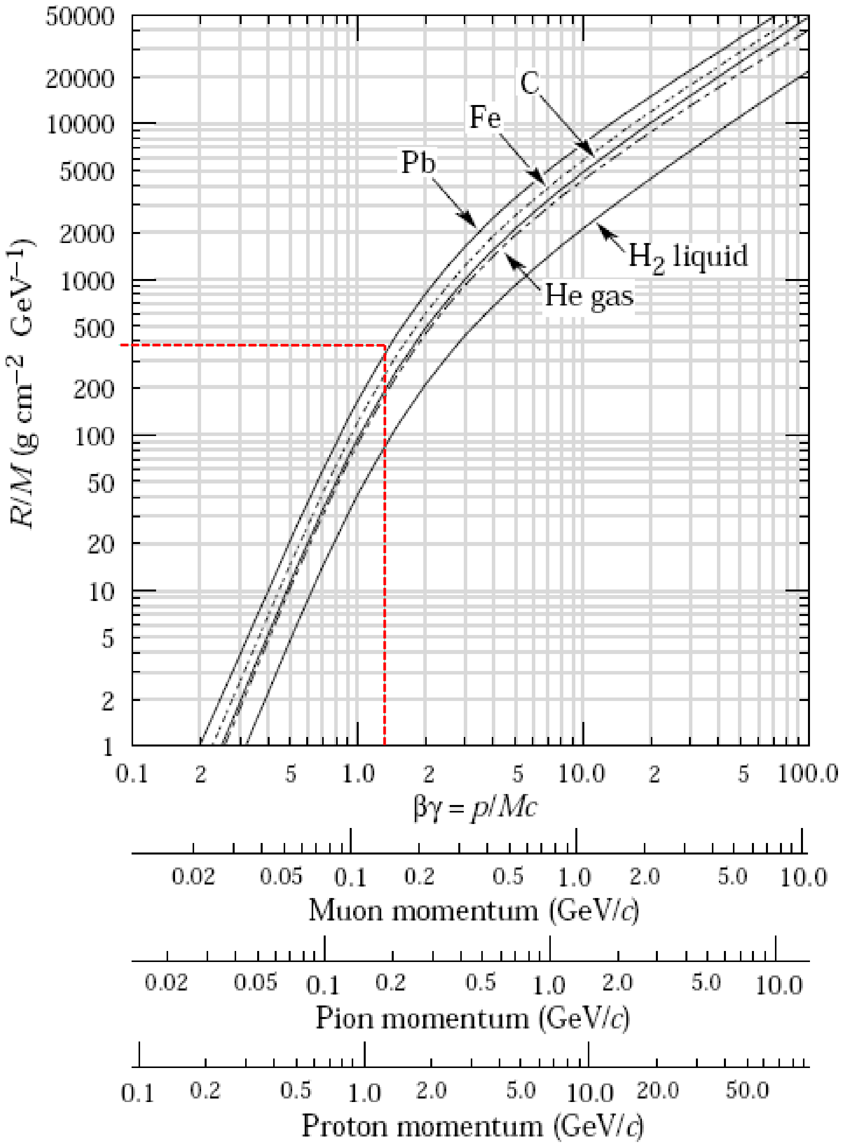
	π	K	p
β	0.58	0.20	0.11
$1/\beta^2$	2.96	25.4	89.0
ln(βγ)	-0.34	-1.60	-2.24

p = 1.0 GeV/c

	π	K	p
β	0.99	0.90	0.73
$1/\beta^2$	1.02	1.24	1.88
ln(βγ)	1.97	0.71	0.06



Particle range:



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

$$m_k = 494\,MeV$$

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

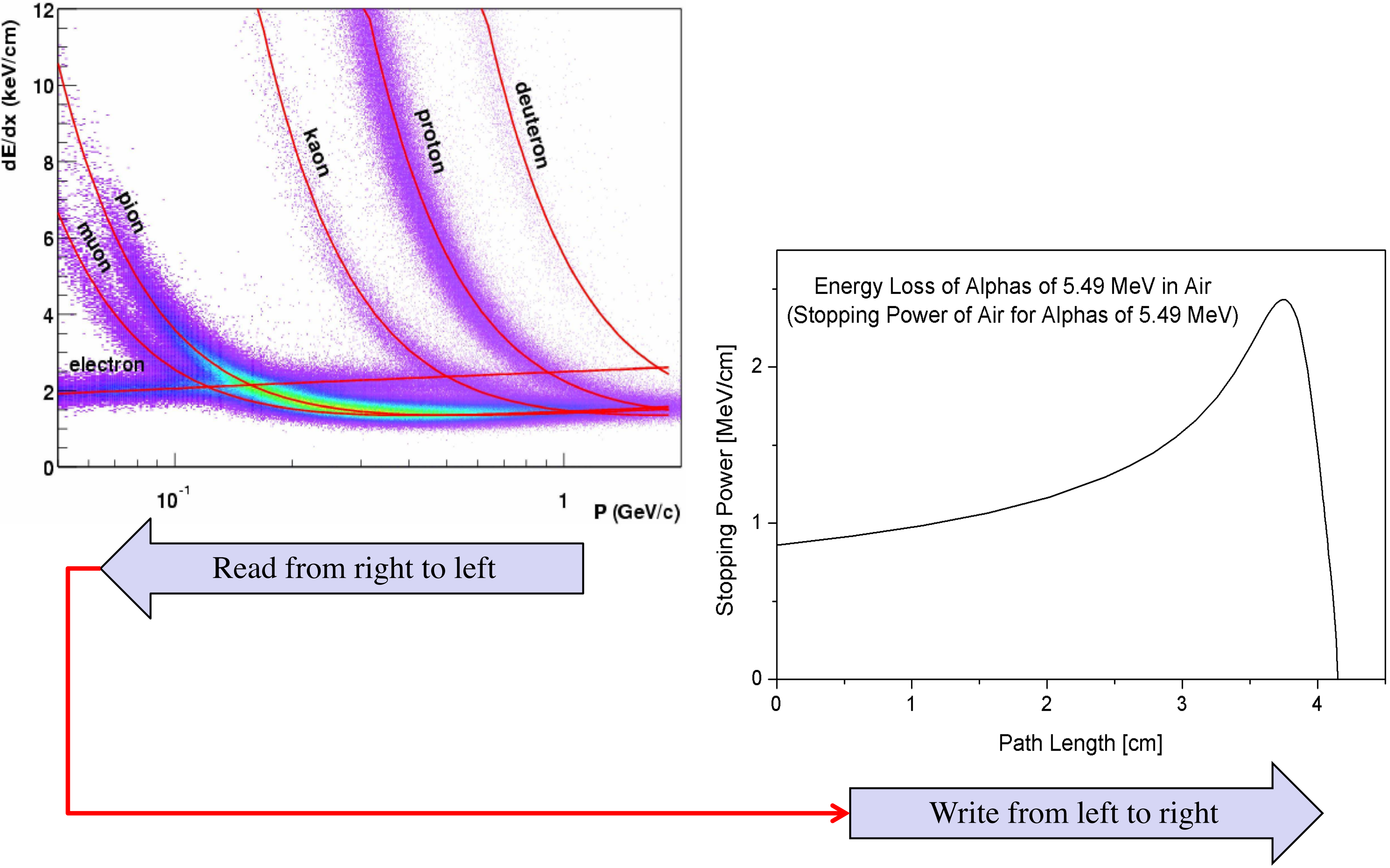
$$For Pb: R/M = 396 gcm^{-2} GeV^{-1}$$

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

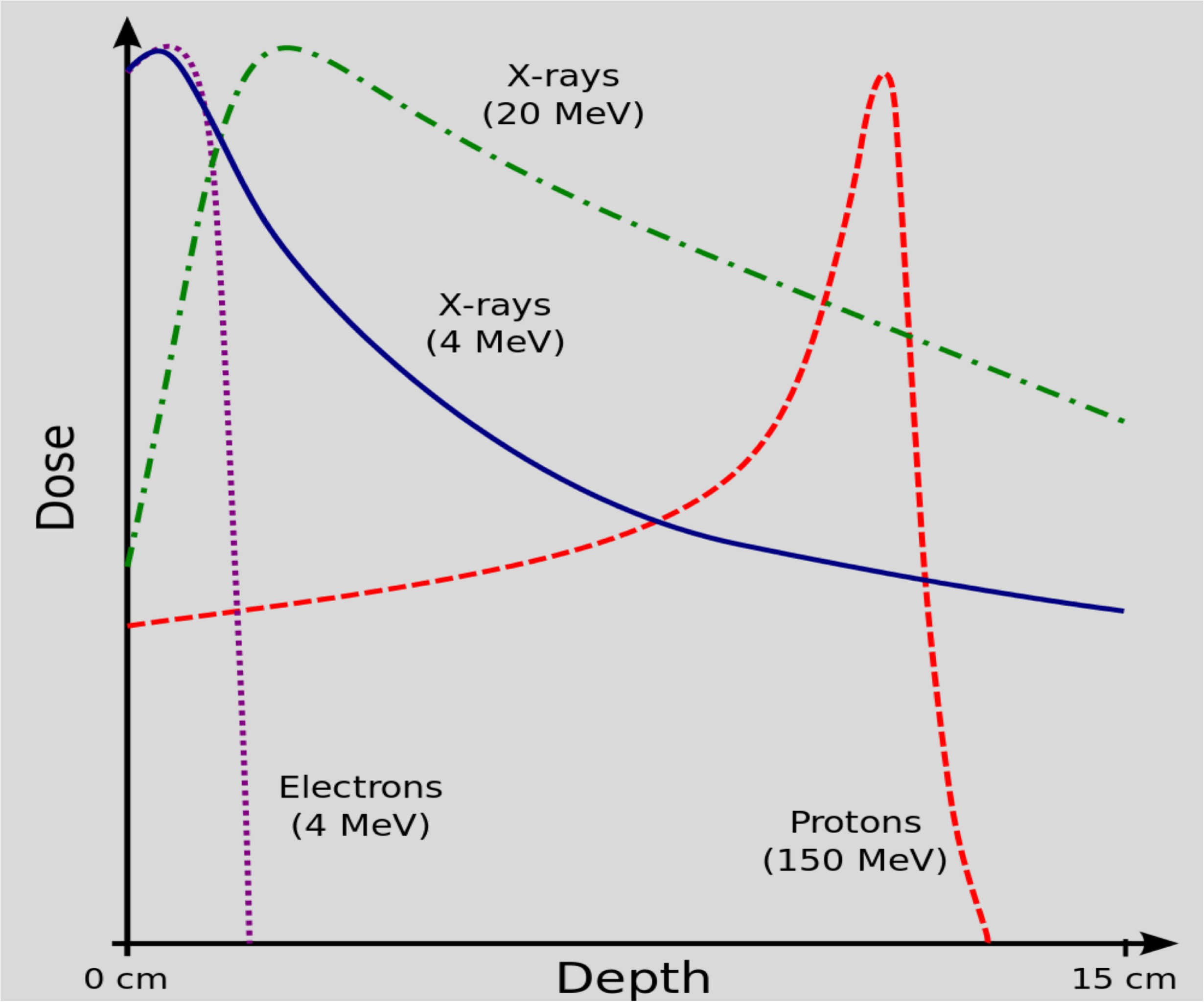
$$\rho_{Pb} = 11{,}35 gcm^{-3}$$

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

Bragg curve and Bragg peak:

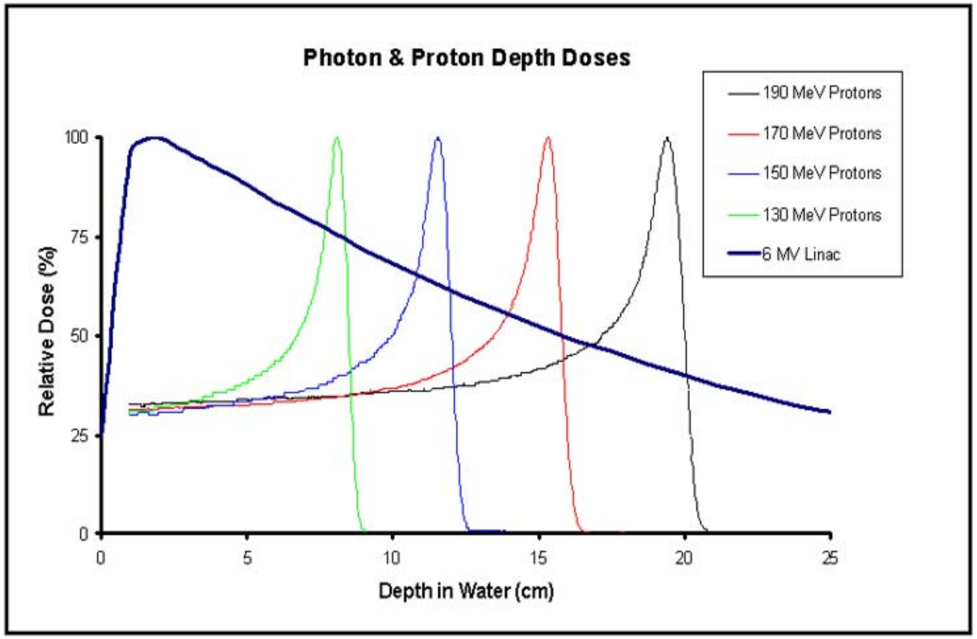


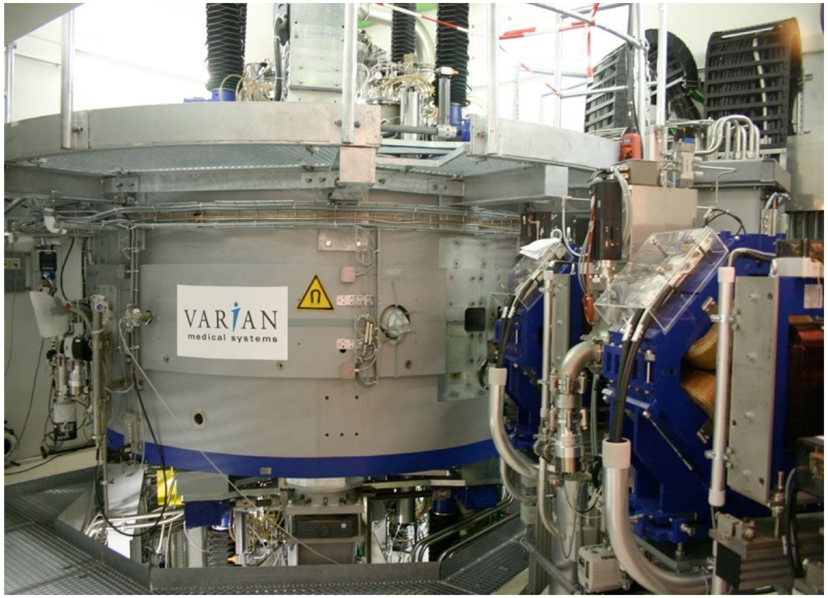
Bragg curve: Different for X-rays and heavy particles

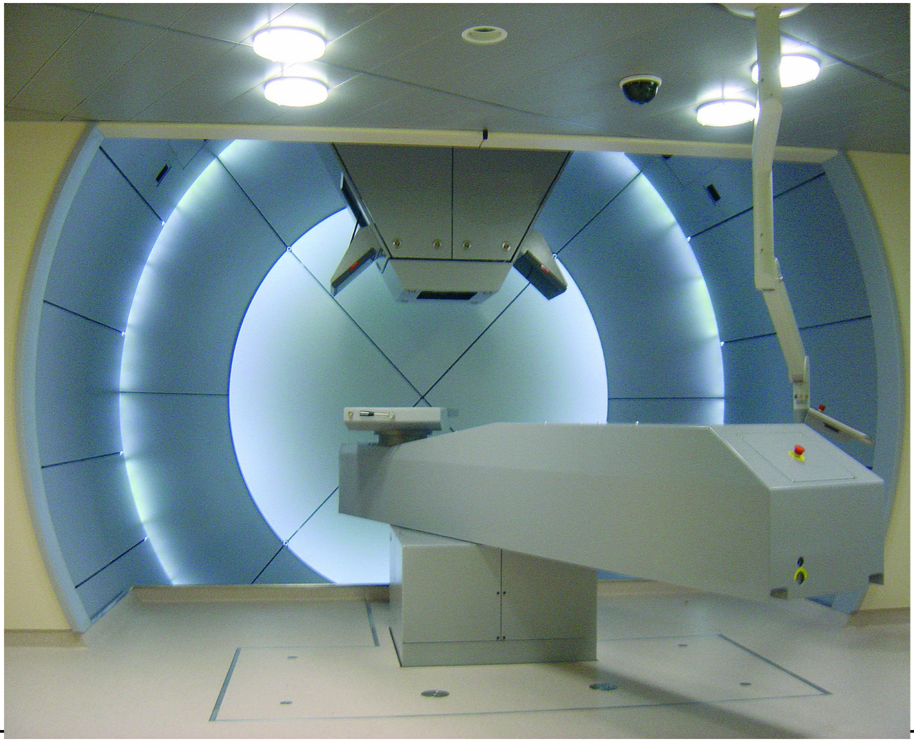


Application:

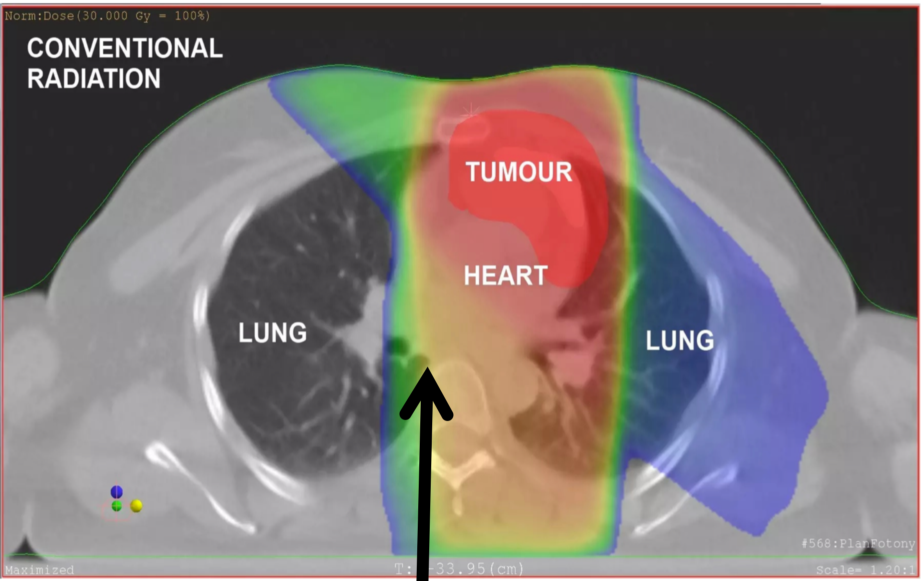
- Proton or
- Heavy Ion Therapy

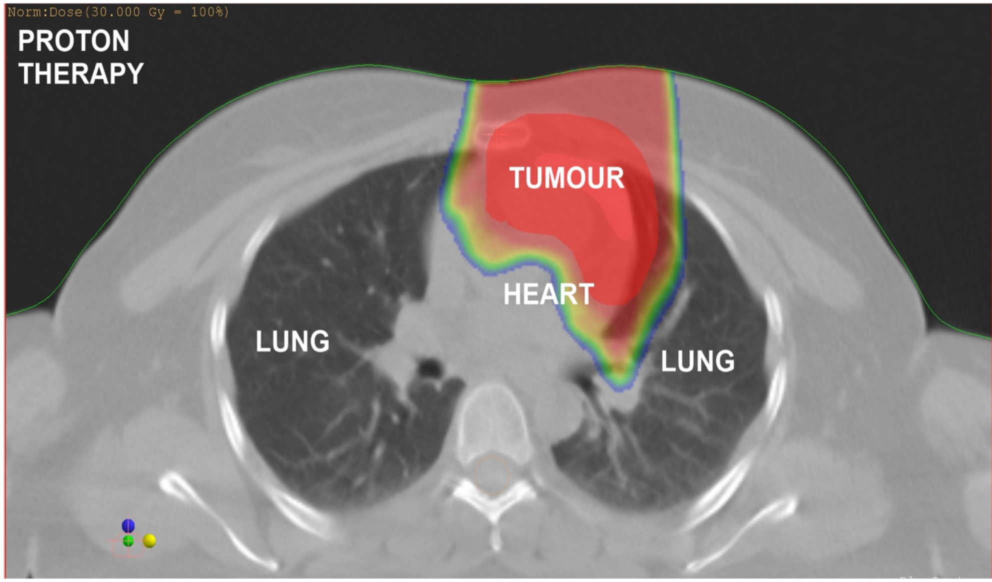






Advantage for tumor treatment





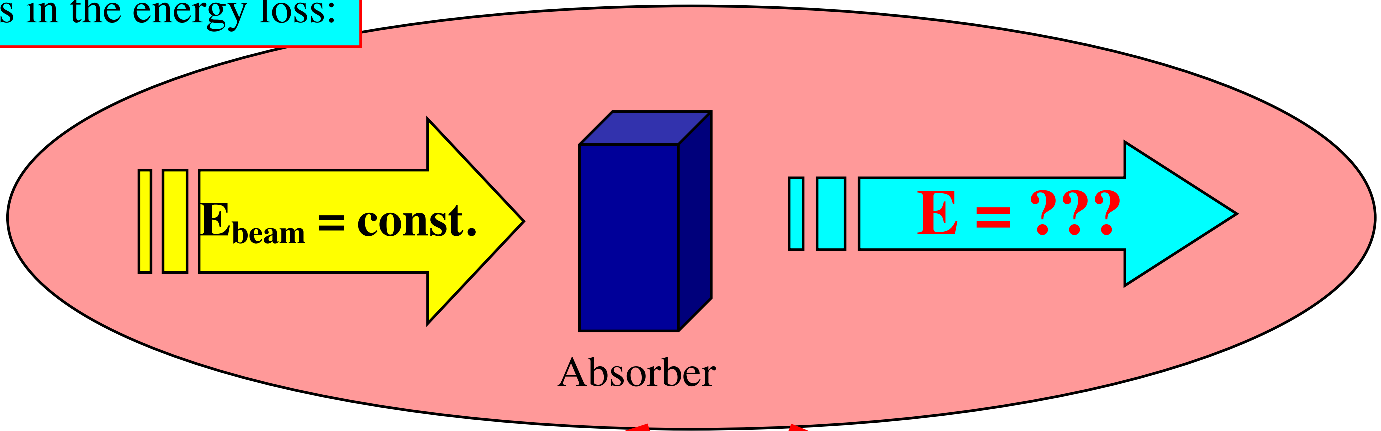
Higher irradiation of surrounding organs

With protons or heavy ions:

For Photons X et γ: $I = I_0 e^{-\mu x}$

Heavy particles = less dispersion = better focused
dE/dx → Bragg peak → energy concentrated in tumor cells

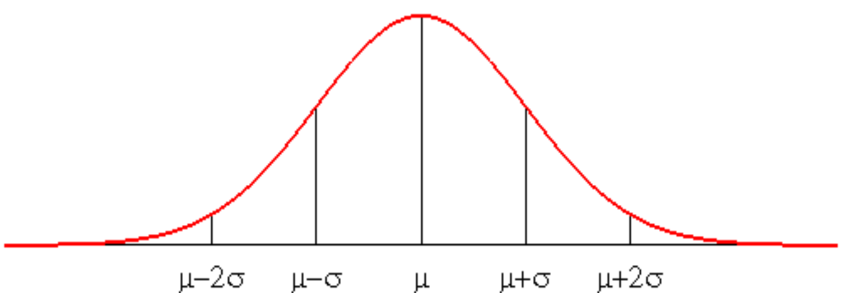
Fluctuations in the energy loss:



Thick Absorber:

Large number of collisions

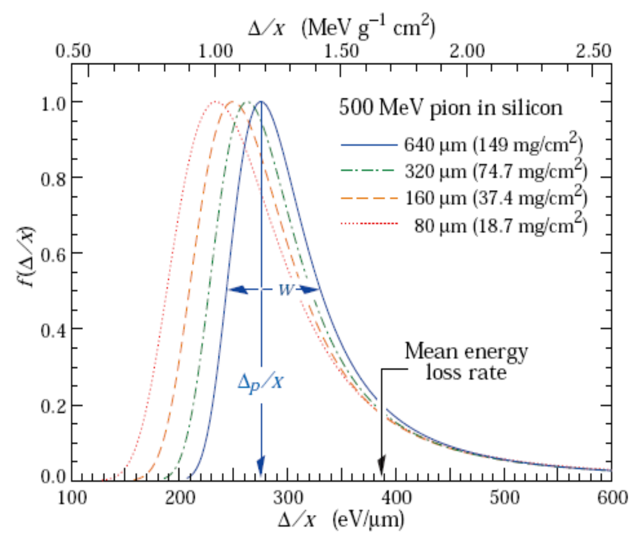
Gauss



Thin Absorber:

Small number of collisions

Landau Distribution

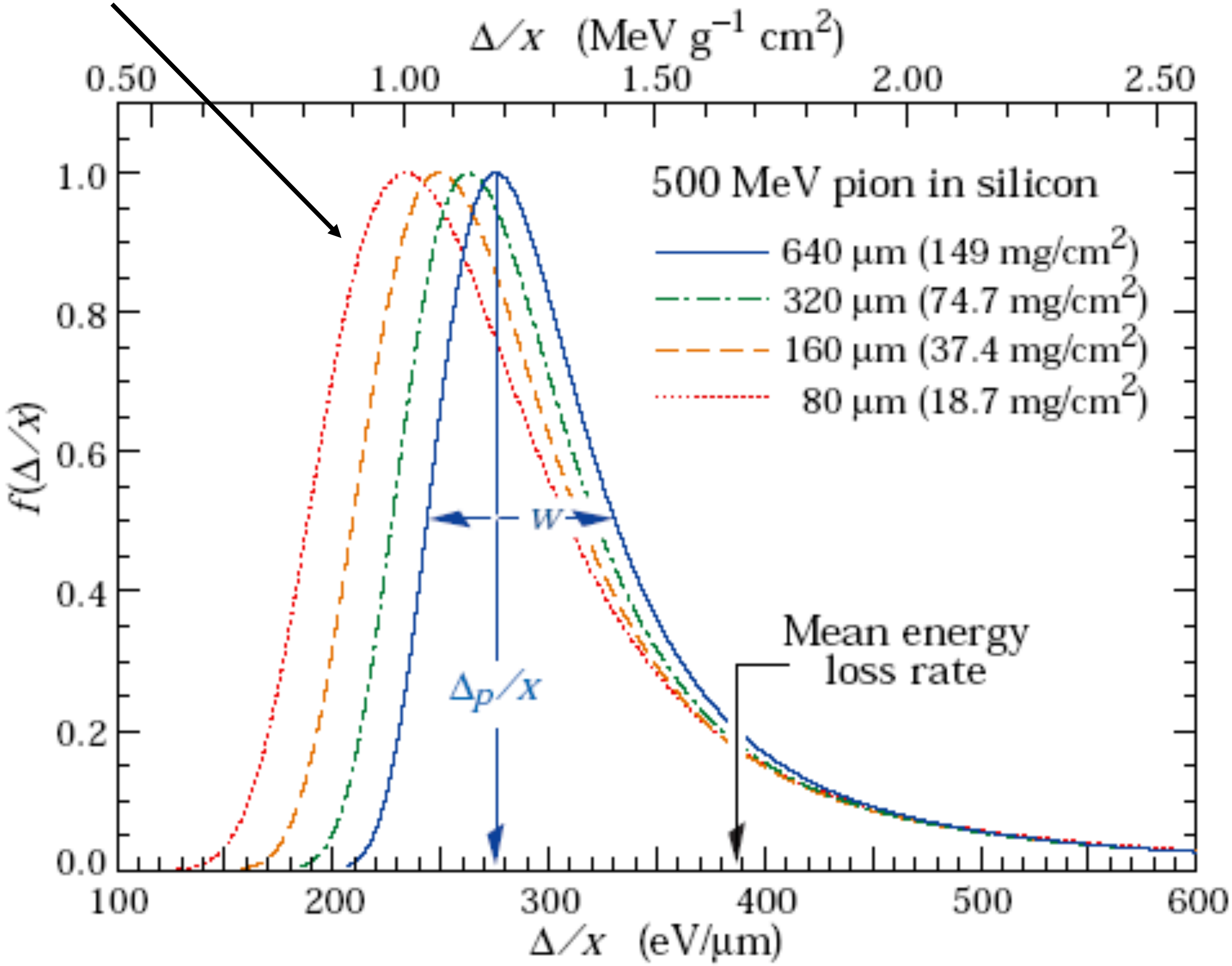


Straggling (1)

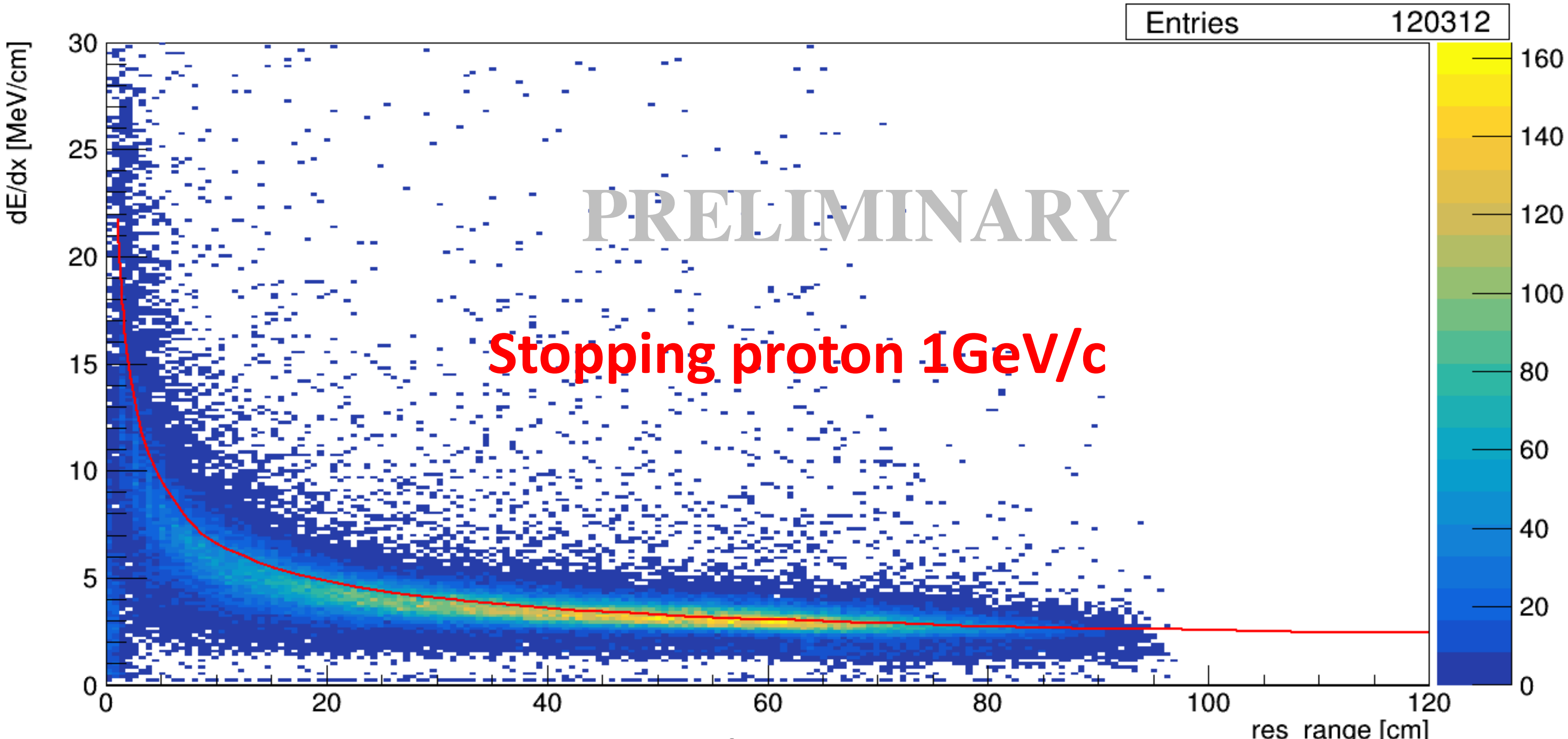
- So far we have only discussed the mean energy loss
- Actual energy loss will scatter around the mean value
- Difficult to calculate
  - parameterization exist in GEANT and some standalone software libraries
  - From of distribution is important as energy loss distribution is often used for calibrating the detector

Straggling (2)

Landau-Vavilov

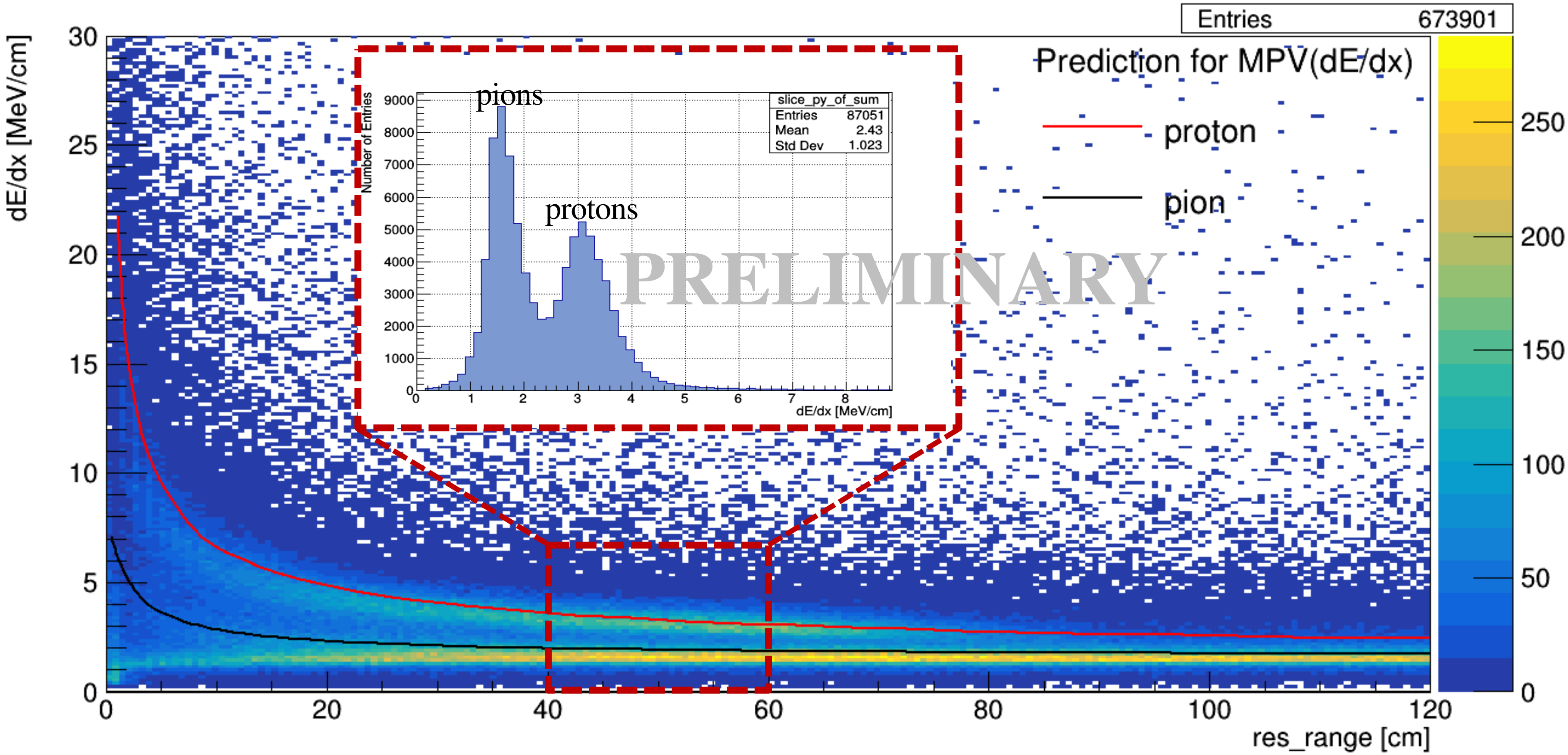


Energy deposit dE/dx in the LArTPC



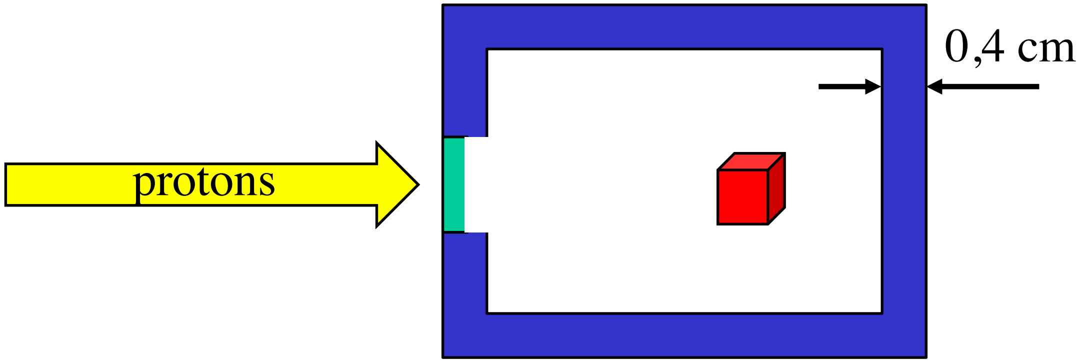
Red curve : **Most probable energy loss (Δ_p/x) from Landau-Vavilov distribution**

Protons & pions



Application:

Typical setup to test detectors at CERN:
Purpose: measurement of the response of Si detectors
Test beam: protons with E = 20 MeV
Setup: Si detector (2 mm x 3 mm x 500 μm thick) inside an Aluminum box with an entrance window made of Beryllium (2 mm thick)

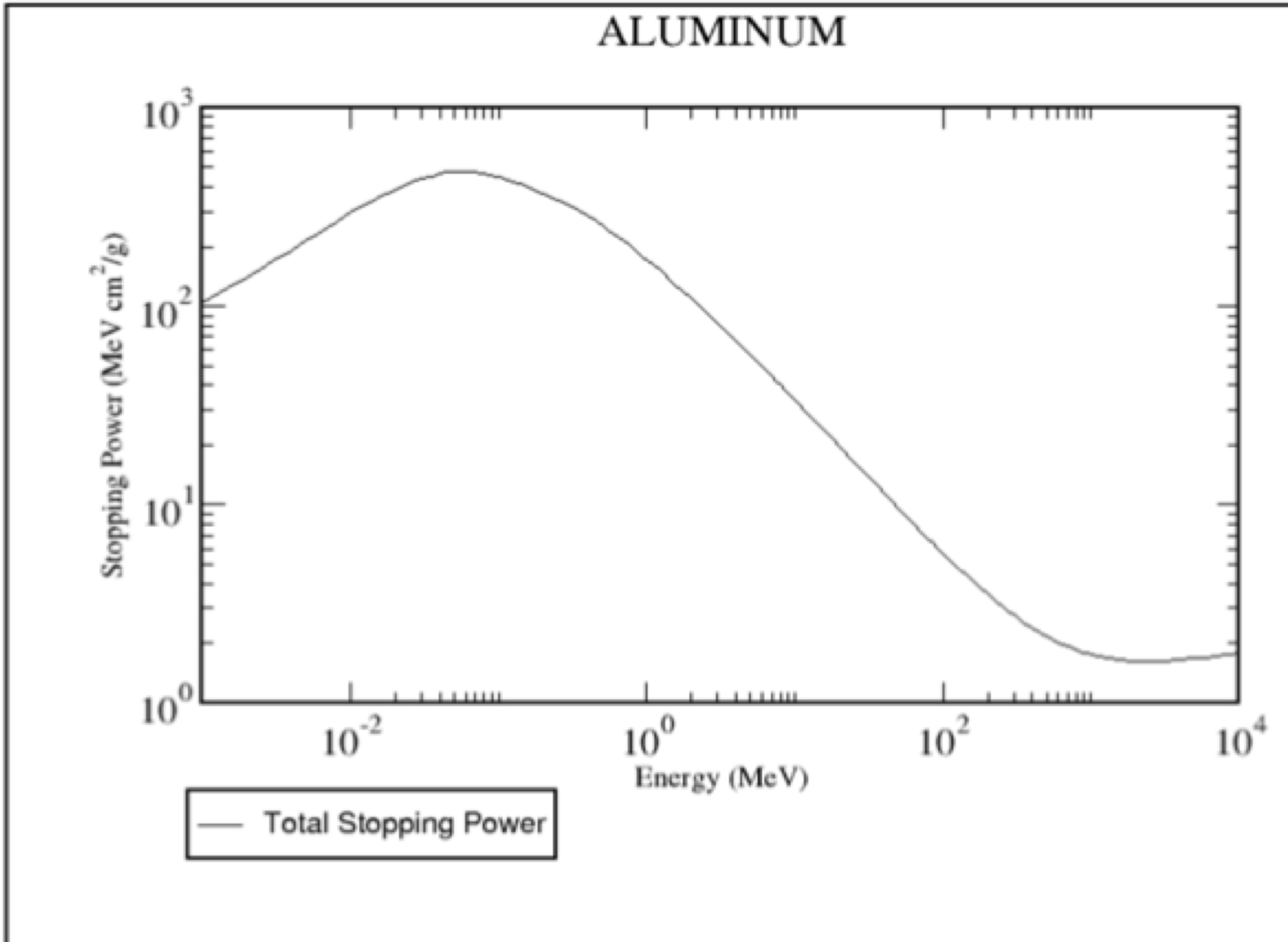


$\rho_{AL} = 2{,}6989\ \mathrm{g/cm^3}$

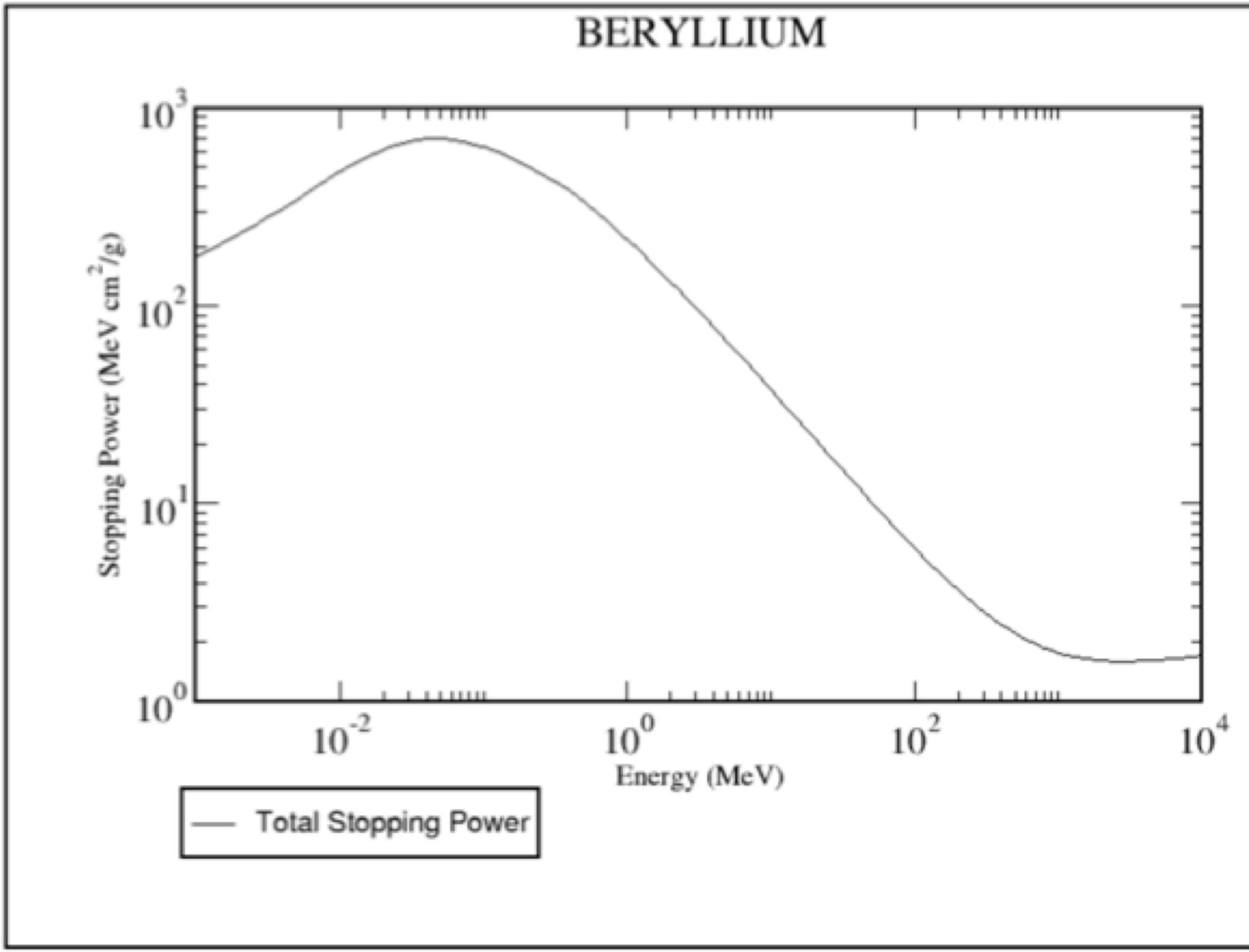
$\rho_{Be} = 1{,}848\ \mathrm{g/cm^3}$

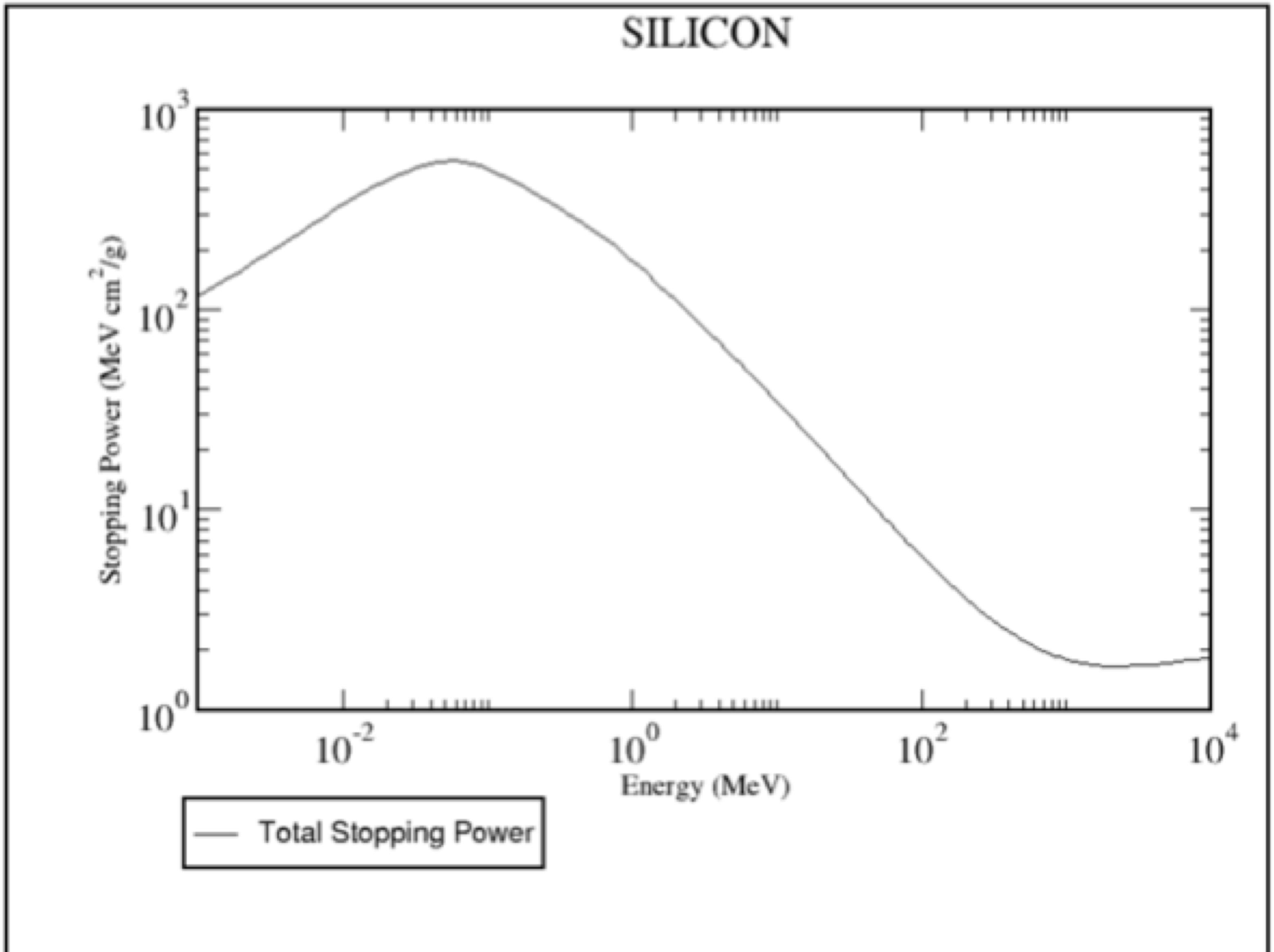
$\rho_{Si} = 2{,}33\ \mathrm{g/cm^3}$

Energy of the proton beam after the Be window?
Energy left in the Si detector?
Does the proton beam exits the Al box? (relevant for safety)



ALUMINUM
Stopping Power (MeV cm²/g)
10³
10²
10¹
10⁰
10⁻²
10⁰
10²
10⁴
Energy (MeV)
Total Stopping Power


BERYLLIUM
Stopping Power (MeV cm^2/g)
10^3
10^2
10^1
10^0
10^{-2}
10^0
10^2
10^4
Energy (MeV)
Total Stopping Power


SILICON
Stopping Power (MeV cm²/g)
10³
10²
10¹
10⁰
10⁻²
10⁰
10²
10⁴
Energy (MeV)
Total Stopping Power

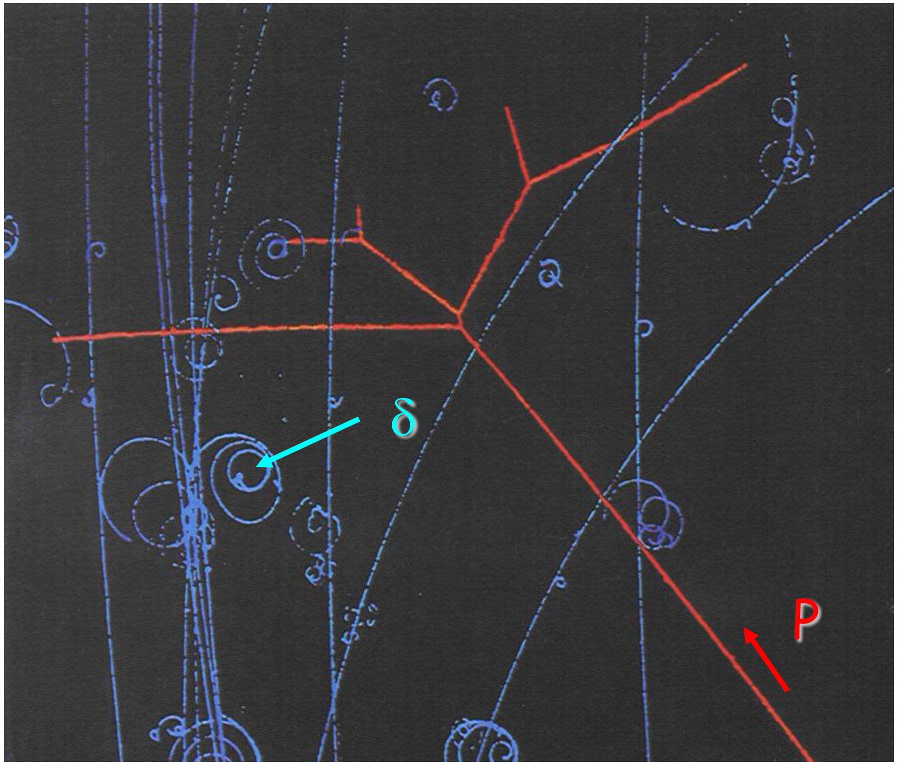
δ-Rays

- Energy loss distribution is not Gaussian around mean.
- In rare cases a lot of energy is transferred to a single electron

$\boxed{\delta\text{-Ray}}$

- If one excludes δ-rays, the average energy loss changes
- Equivalent of changing E_{max}

Emission de rayons delta (électrons)

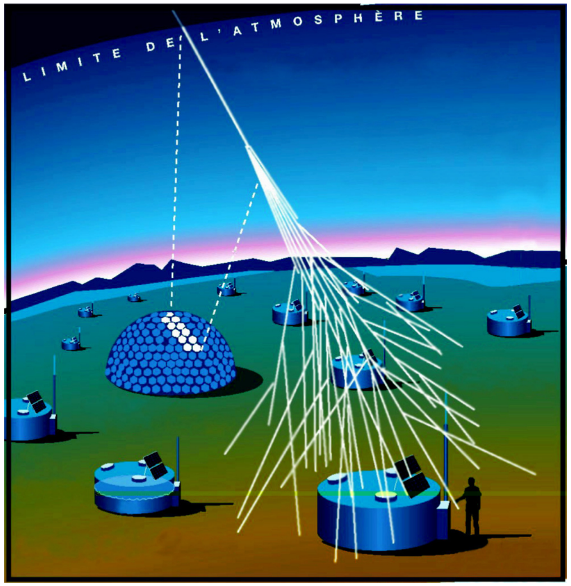


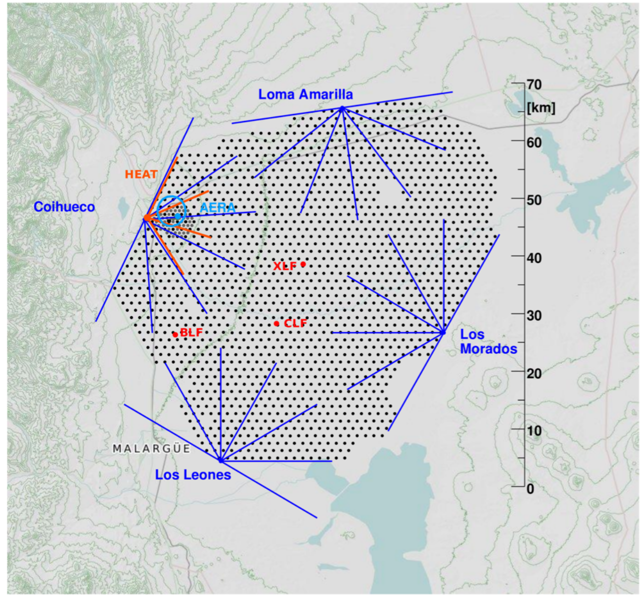
$$\frac{dN}{dx} \approx \boxed{\frac{1}{2} K z^2 \frac{Z}{A}} \frac{1}{\beta_\mu} \int_{T_{min}}^{T_{max}} \frac{dT}{T^2} = \frac{\boxed{0.08445}}{\beta_\mu} \left(\frac{1}{T_{min}} - \frac{1}{T_{max}} \right)$$

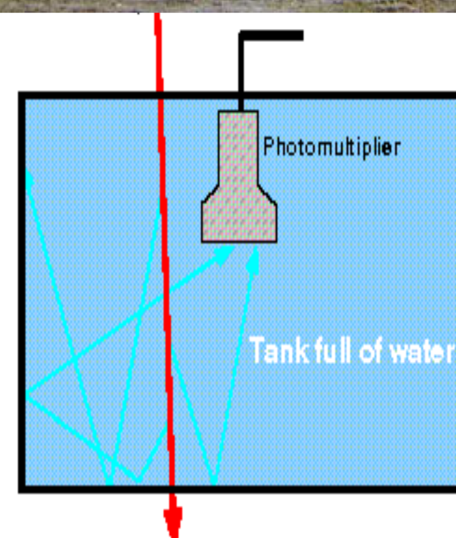
In Water

Exemple: un μ de 1 GeV qui traverse une cuve d'eau de 120 cm verticalement (expérience AUGER)

Quel est le nombre et l'énergie de rayons δ de plus de 15 keV?







$$\frac{dN}{dx} \approx \frac{1}{2} K z^2 \frac{Z}{A} \frac{1}{\beta_\mu} \int_{T_{min}}^{T_{max}} \frac{dT}{T^2} = \frac{0.08445}{\beta_\mu} \left(\frac{1}{T_{min}} - \frac{1}{T_{max}} \right)$$

T_{min} = 15 KeV, $T_{max} = 2\, m_e c^2\, ß^2 \gamma^2$

= 2 x 0,511 MeV x 1 x 1 GeV/0,105 GeV = 9,52 MeV

N = 5,6 x 120 cm = 674

Multiple scattering through small angles

•Charged particles traversing a medium are deflected by many small angle scatters.

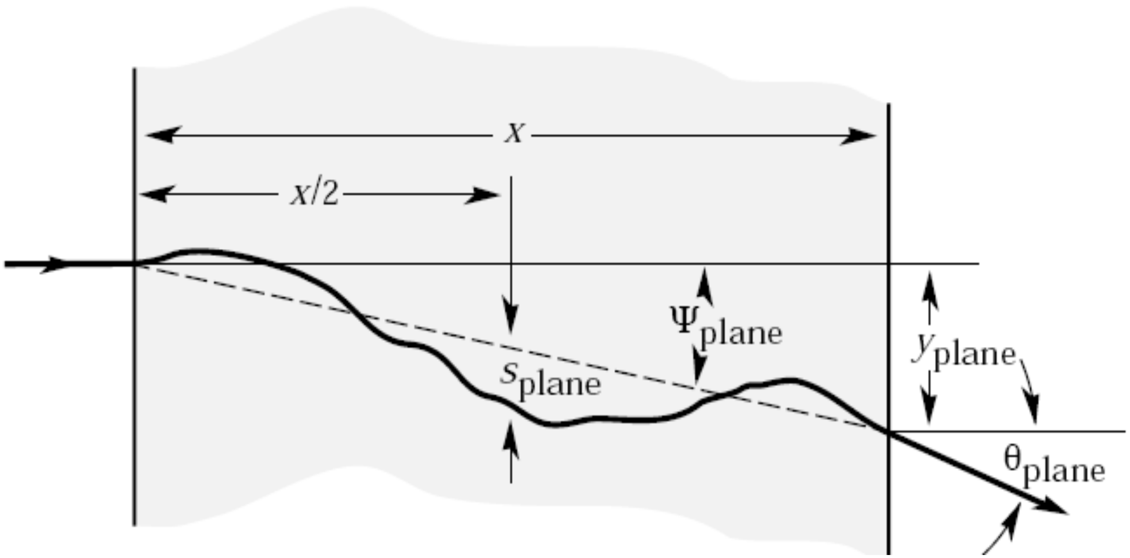
•Scattering is mostly due to Coulomb scattering from nuclei. (for hadrons strong interaction also contributes)

•Angular distribution described by Molière theory and is in first approximation Gaussian.

•For large angles = Rutherford scattering (larger tails than the Gaussian distribution).

Gaussian approximatio

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



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

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

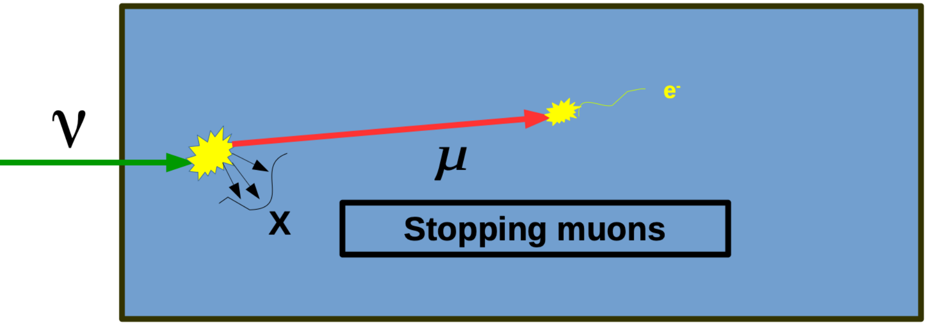
Application 1: Use MCS to measure momentum

Here momentum is determined by range

Multiple Coulomb Scattering
Why?

Charged-current event

$$\boxed{\nu + Ar \rightarrow \mu + X}$$

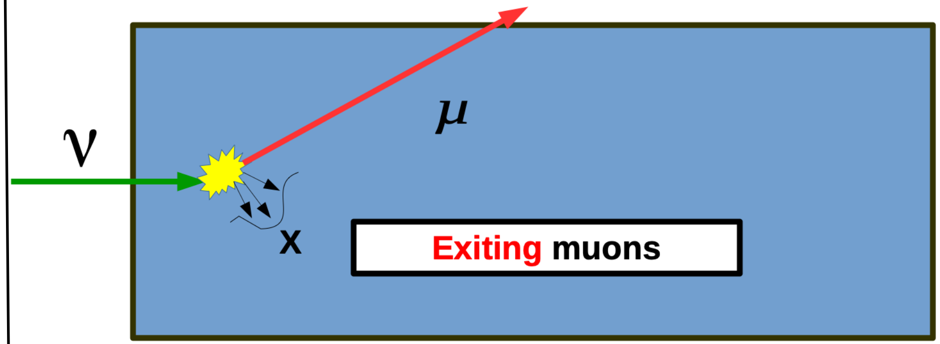


Here the muon left the detector ->
Range measurement does NOT work
-> use MCS

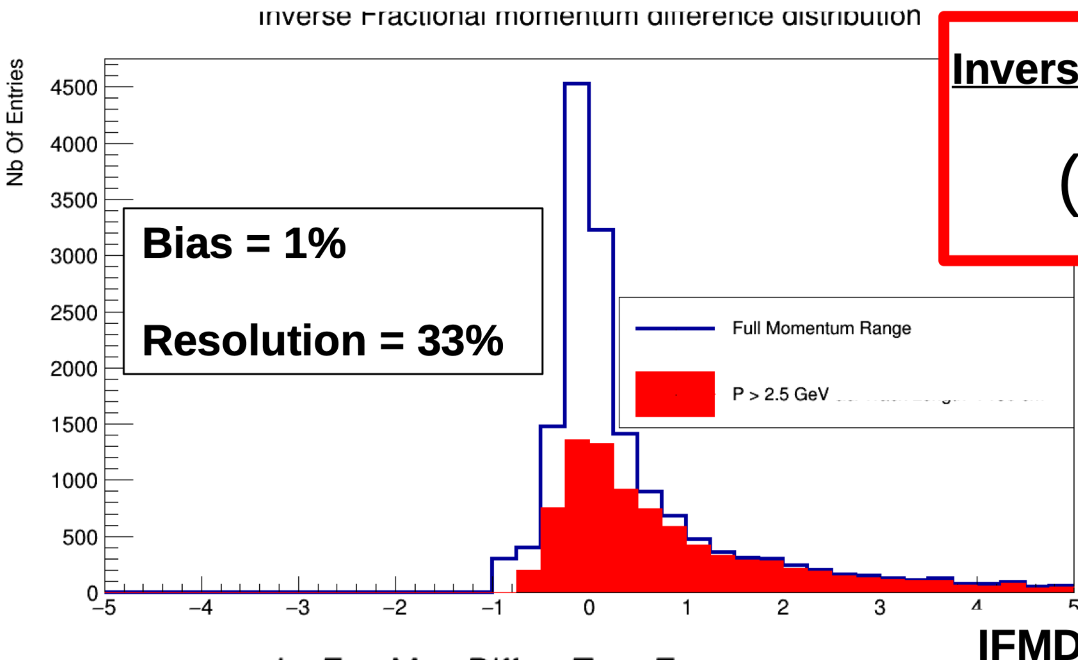
Multiple Coulomb Scattering
Why?

Charged-current event

$$\boxed{\nu + Ar \rightarrow \mu + X}$$



Results on CORSIKA sample

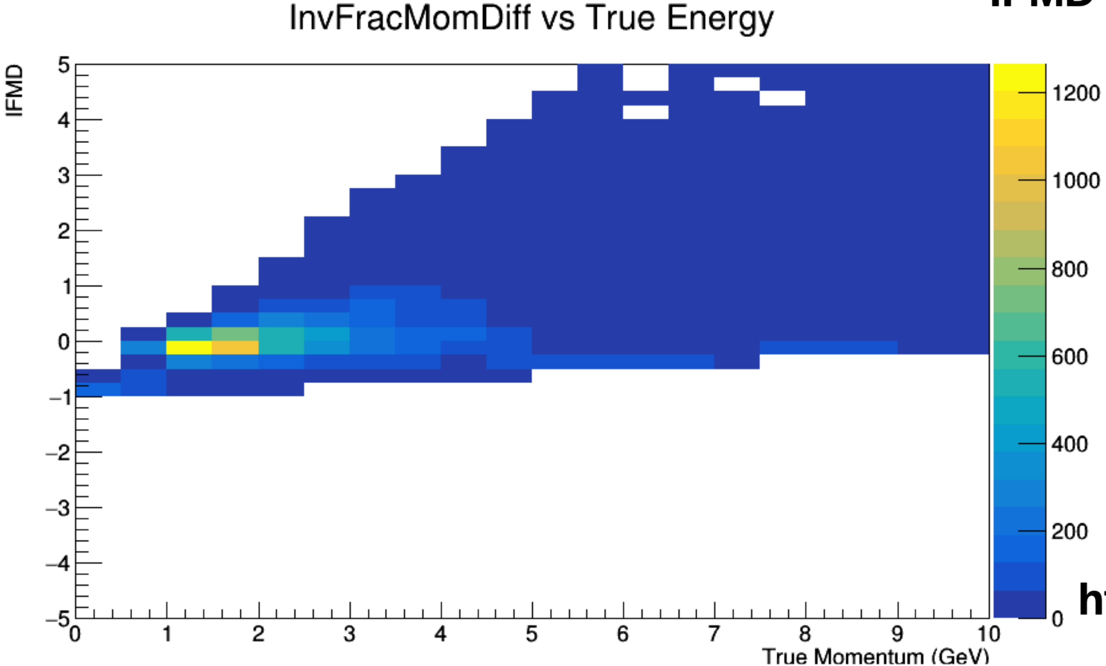


<u>Inverse</u> <u>fractional momentum difference = IFMD</u>

$$(1/p_{reco} - 1/p_{true}) / (1/p_{true})$$

Keeping only P < 2.5 GeV

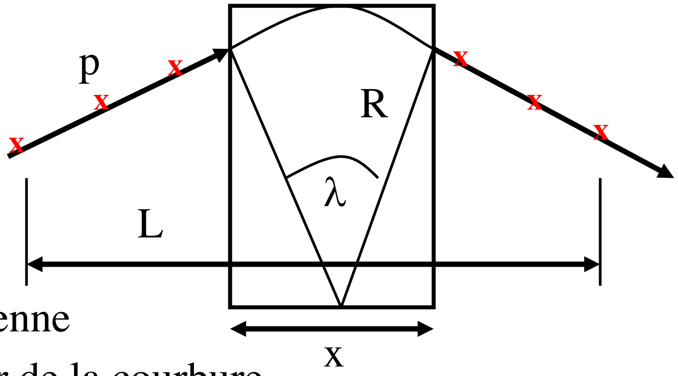
Resolution value falls to 20% !!



→ The higher the energy the higher the IFMD

https://arxiv.org/pdf/1703.06187.pdf

Application 2: Error induced by MCS when measuring the particle momentum in a magnetic field:



$P\cos\lambda = 0.3\, z\, B\, R$

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

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

$$(\delta k)^2 = (\delta k_{res})^2 + (\delta k_{ms})^2$$

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 :

$$\delta k_{res} = \frac{\sigma(x)}{L^2}\sqrt{\frac{720}{N+4}}$$

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

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

Et aussi: $\delta k_{ms} \approx 8 s_{plane}^{rms} / L^2$

Résolution pour l 'impulsion

$$\left|\frac{\Delta p}{p}\right| = \frac{p}{0.3B}\,\delta k$$

Mesure de l 'impulsion en champ magnétique

Exemple: expérience CHORUS (CERN)

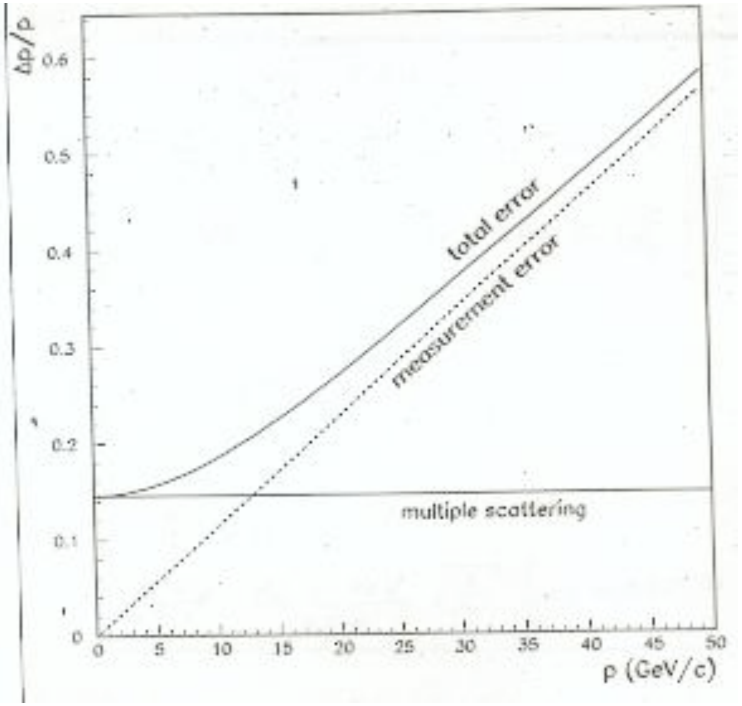
$\sigma(x) = 1$ mm = 10^{-3} m, L = 1,3 m, x = 0,5 m, B = 1,65 T, 4 points de mesure

$$\delta k_{res} = \frac{\sigma(x)}{L^2}\sqrt{\frac{720}{N+4}} = \frac{10^{-3}}{1.69}\sqrt{\frac{720}{8}} = 5.61\times 10^{-2}$$

$$\left|\frac{\Delta p}{p}\right|_{res} = \delta k_{res} \times \frac{p}{0.3\times 1.65} = 1.13\times 10^{-2}\times p$$

$$\delta k_{ms} = \frac{1}{L^2} 8 \frac{1}{4\sqrt{3}} x\theta_0\left(\frac{1}{p}\right) = \frac{1.154}{1.69}\times 0.5\times 0.2112\left(\frac{1}{p}\right) = 0.0721\left(\frac{1}{p}\right)$$

$$\left|\frac{\Delta p}{p}\right|_{ms} = \delta k_{ms}\frac{p}{0.3\times 1.65} = 0.1456$$



Erreur totale:

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

Electrons

Energy loss of Electrons and Positrons

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

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

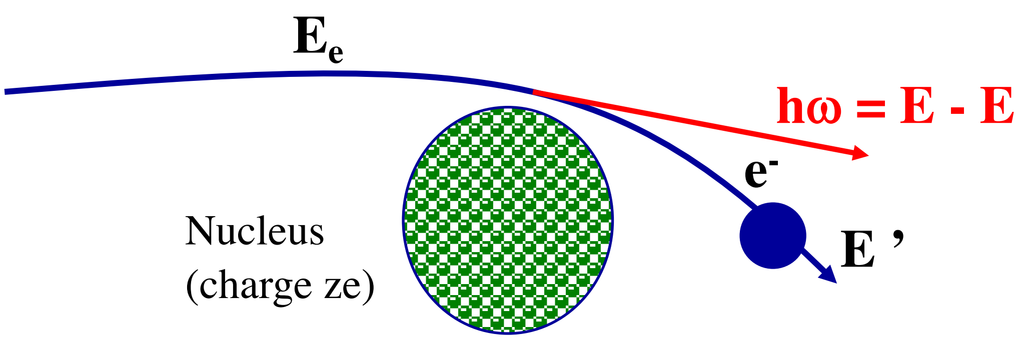
Two modifications needed in the equation

- 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

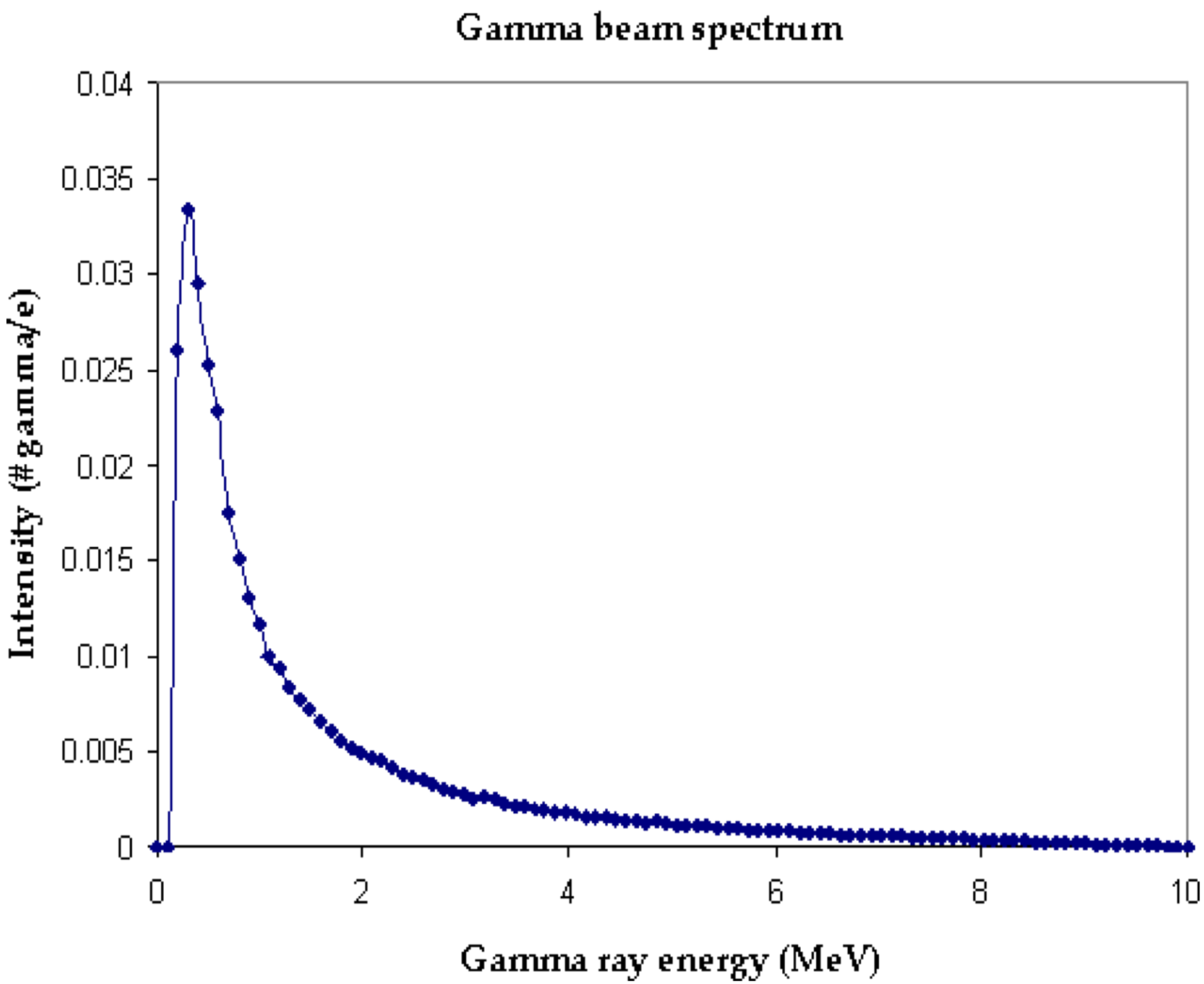
Classical interpretation::
Radiation from the acceleration of an electron or positron in the field of the nucleus.



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

With k = Energy of the radiation (photons)

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

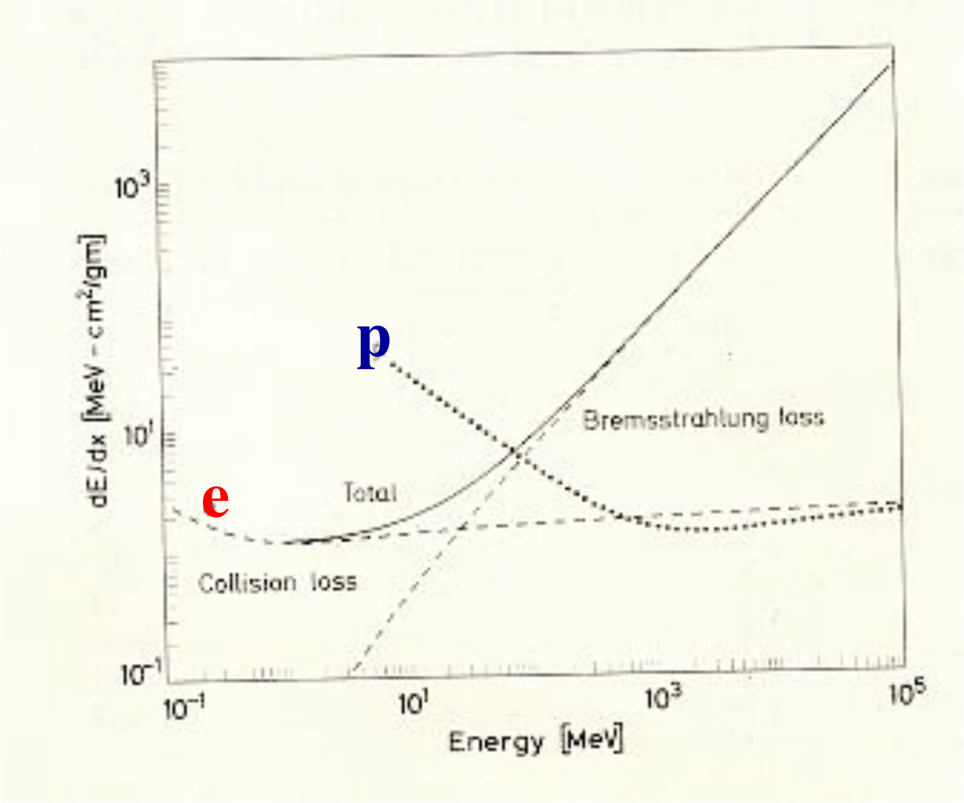


Energy loss of Electrons and Positrons

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

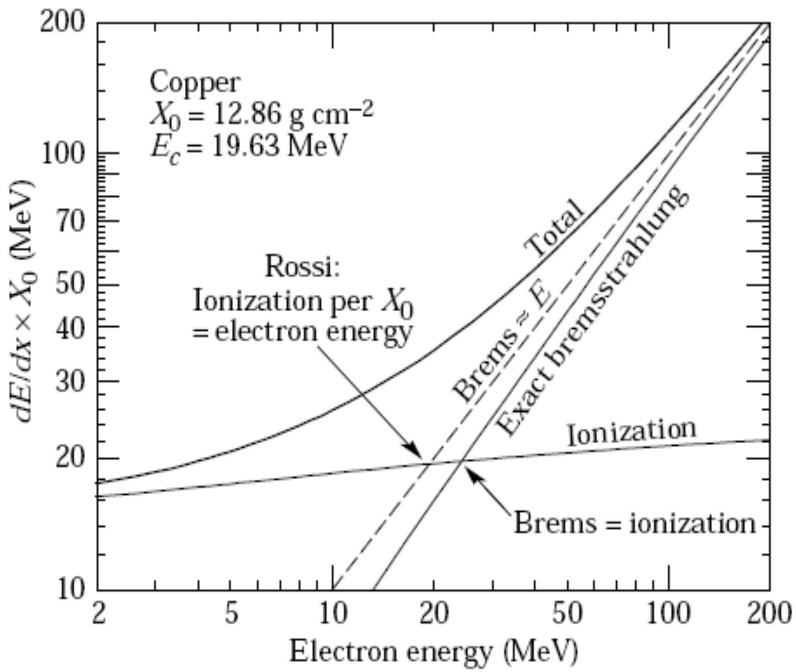
- For a muon (M = 106 MeV) σ_{brems} is **40000** times smaller than for an electron!
- For a proton σ_{brems} is roughly **4 million** times smaller!!!

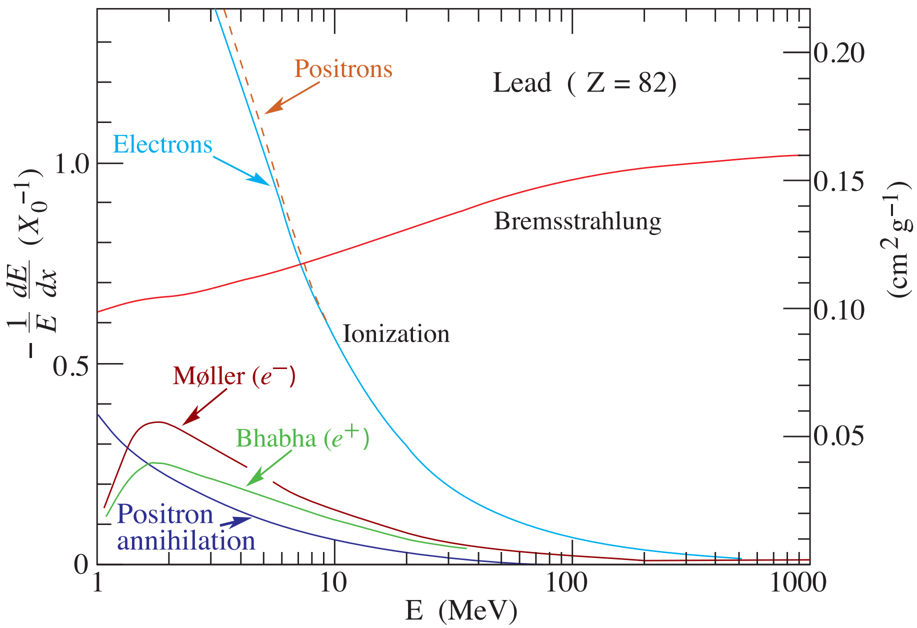
In first order, Energy loss by Bremsstrahlung is only relevant for electrons



Energy loss of Electrons and Positrons

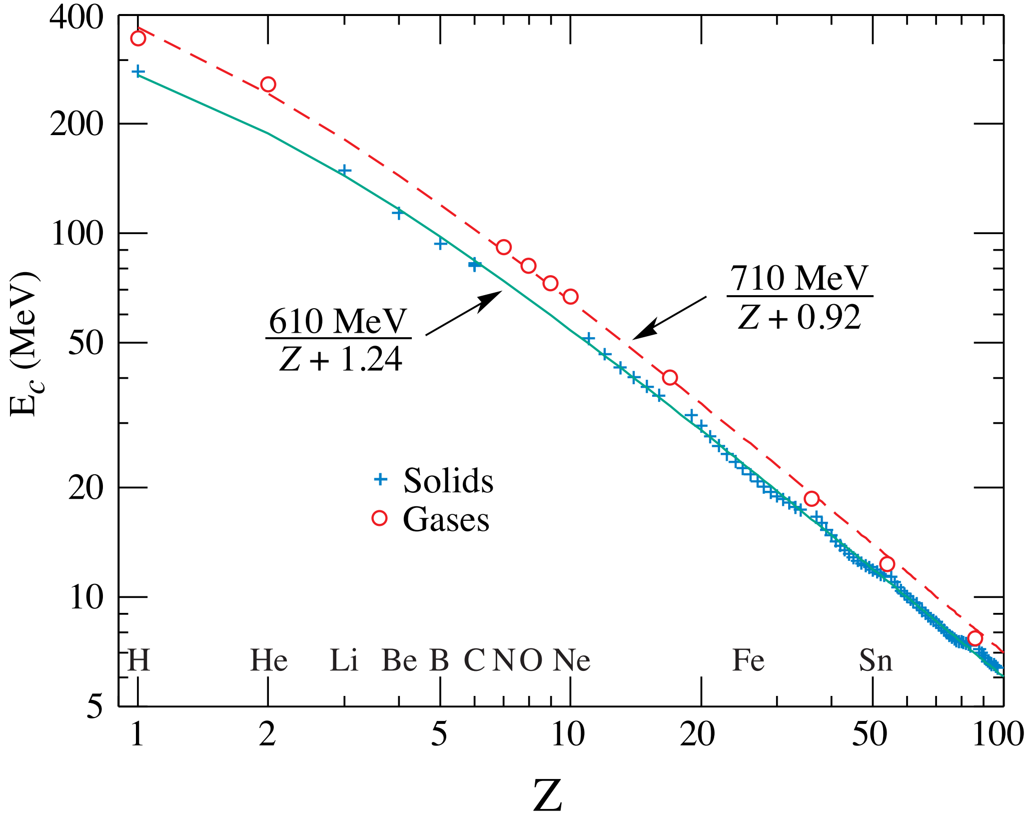
Definition of radiation length: X_0 = Average distance traveled by an electron before loosing 1/e of its energy by Bremsstrahlung.





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

Electron critical energy



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

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

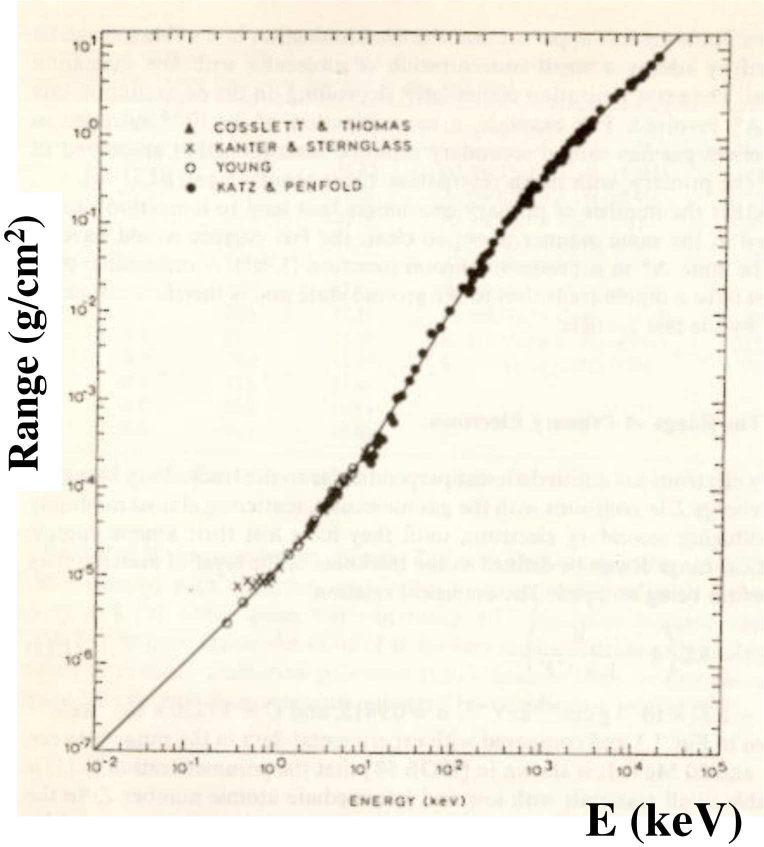
(Valid for small and medium Z)

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

$B = 0.9815$

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

300 eV < T < 20 MeV



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

Electromagnetic Cascades:

High Energy Photon or Electron

Pair production and Bremsstrahlung

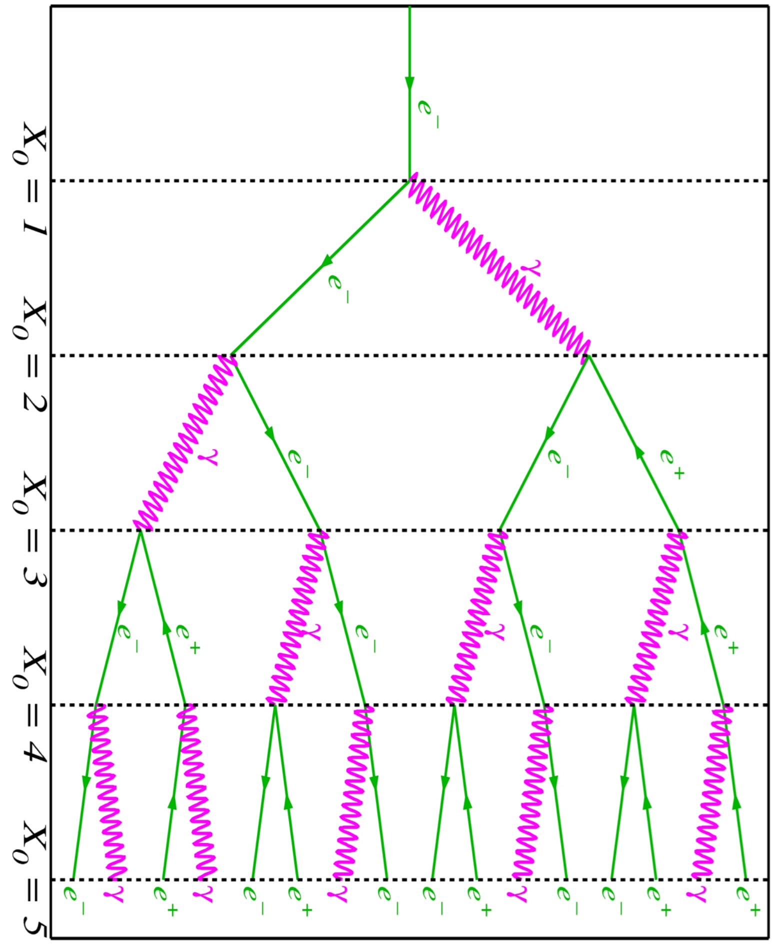
Generation of many electrons and photons of lower energy

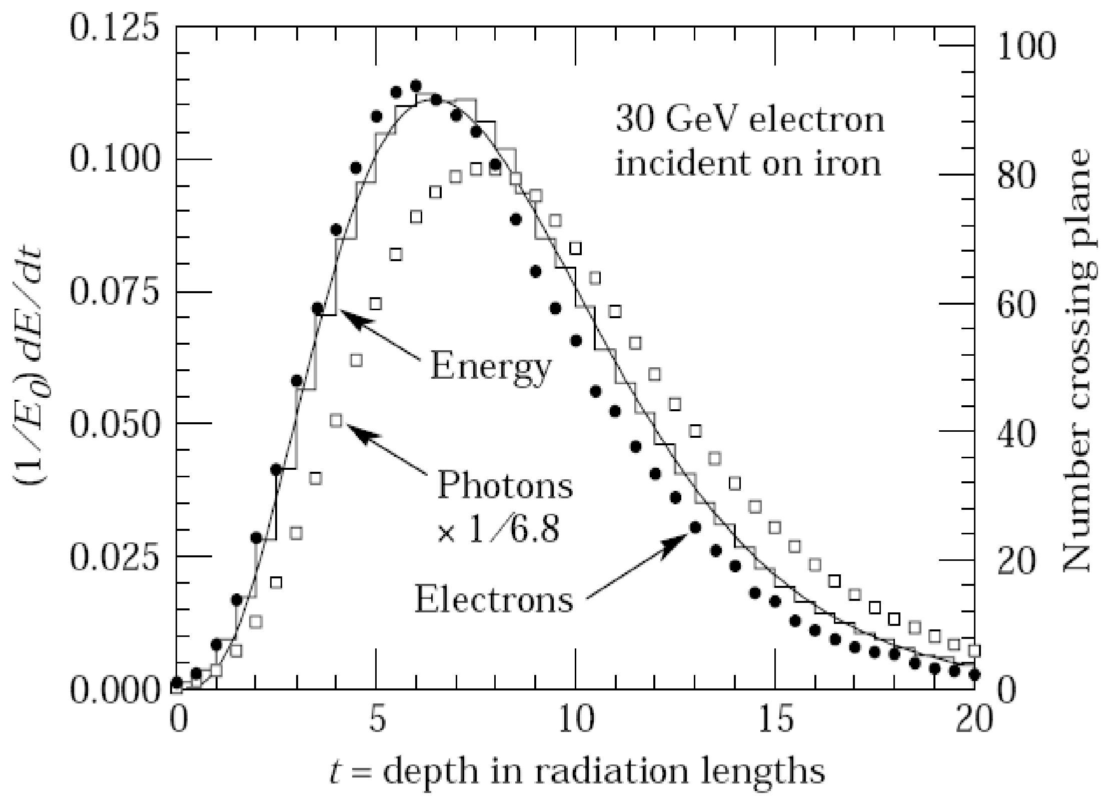
Pair production and Bremsstrahlung

Generation of many electrons and photons of lower energy

$E = E_{critique}$

Cascade stops → dE/dx by ionization




30 GeV electron
incident on iron
Energy
Photons
× 1/6.8
Electrons
$(1/E_0)\, dE/dt$
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

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:

$E(t_{max}) = E_0 / 2^{tmax} = E_c$

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

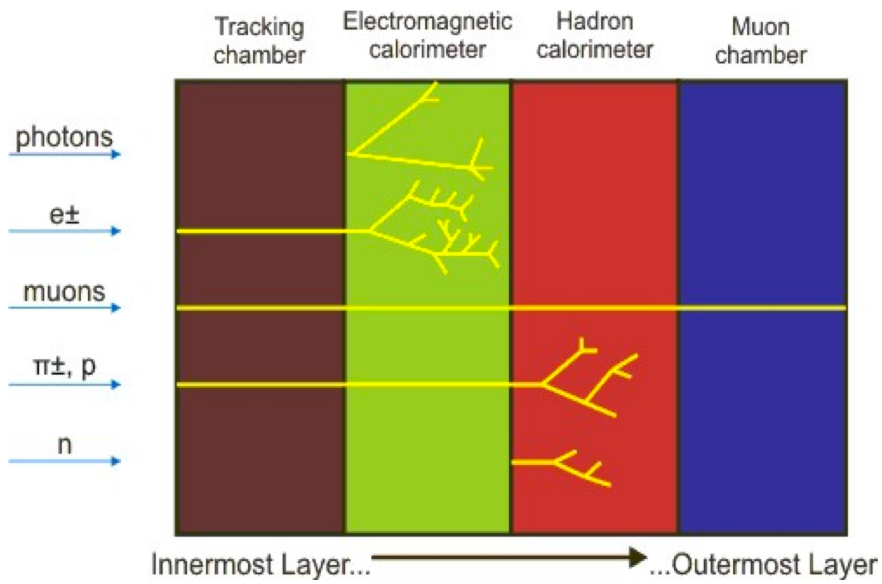
2/ Transversal dimensions:

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

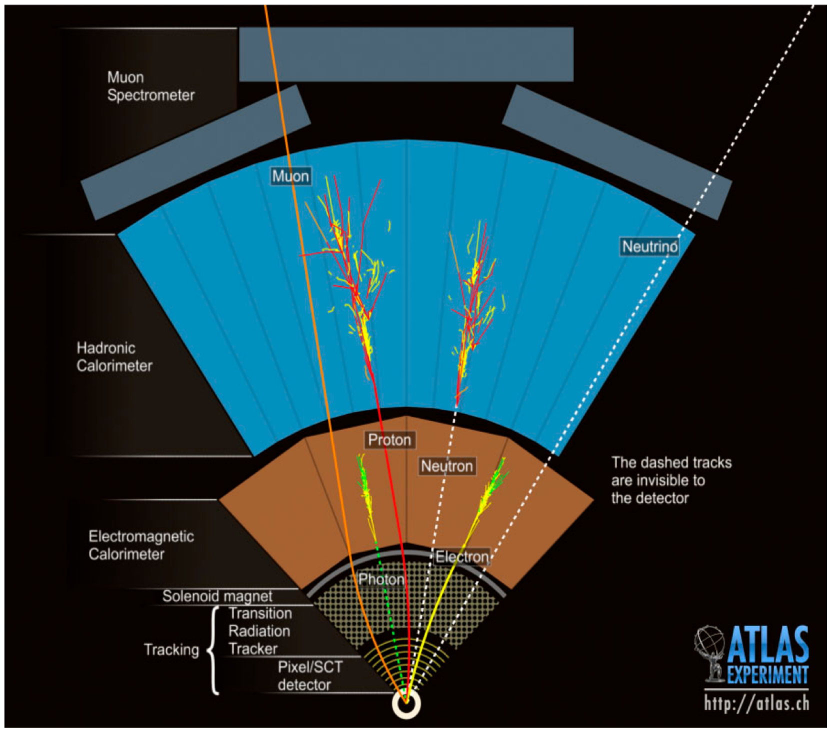
90% of the particles stay inside a cylinder with R_M around the shower axis.

Different interactions = different interaction length = typical HEP detector:

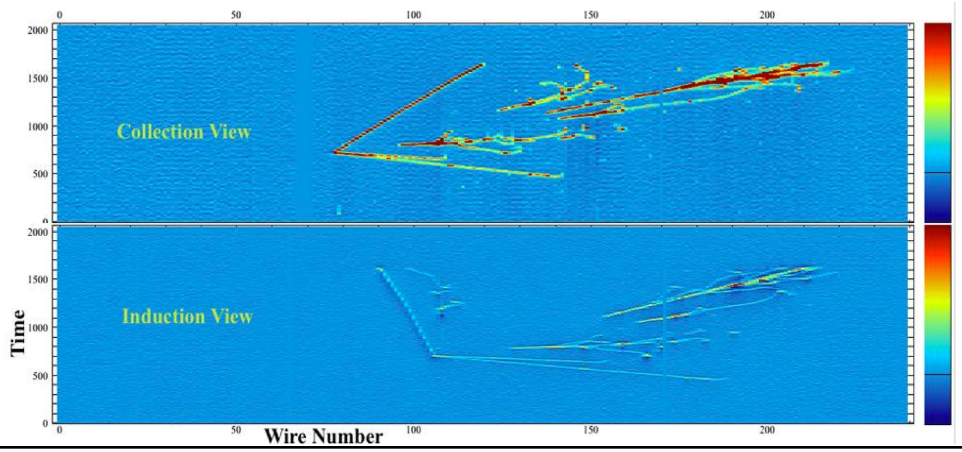
Generic detector:



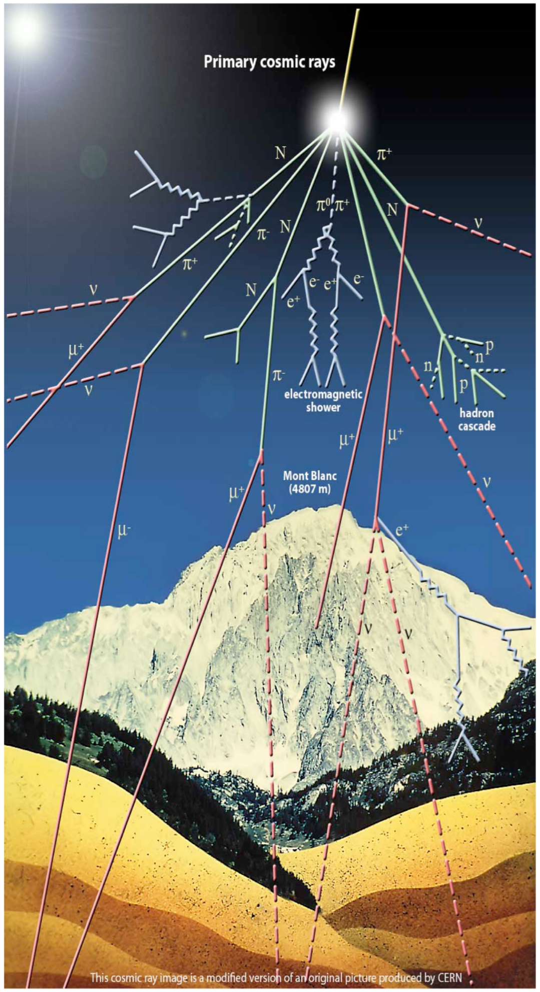
Atlas:



Neutrino event in a LAr detector:

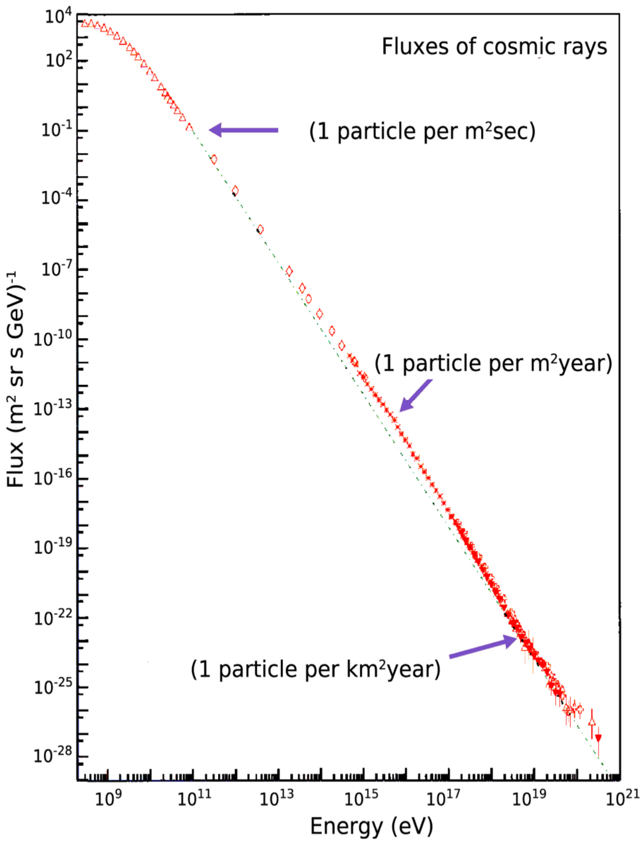


Use of atmospheric muons – a cheep and easy way for calibration…

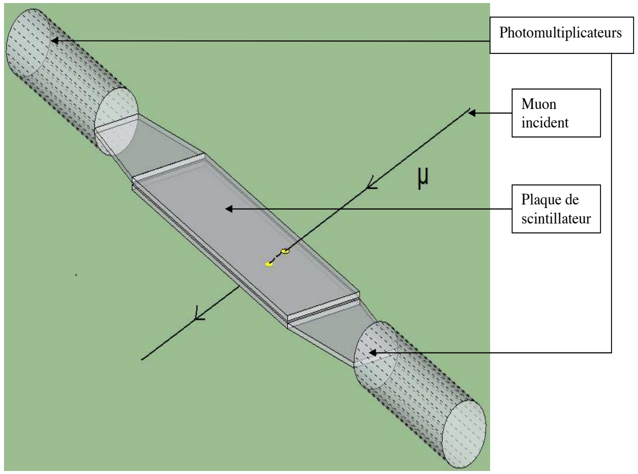


$$< E\mu_{atm} > \approx 4 \text{ GeV}$$

$$\text{Flux at ground} \approx 130 \text{ m}^{-2} \text{ s}^{-1}$$



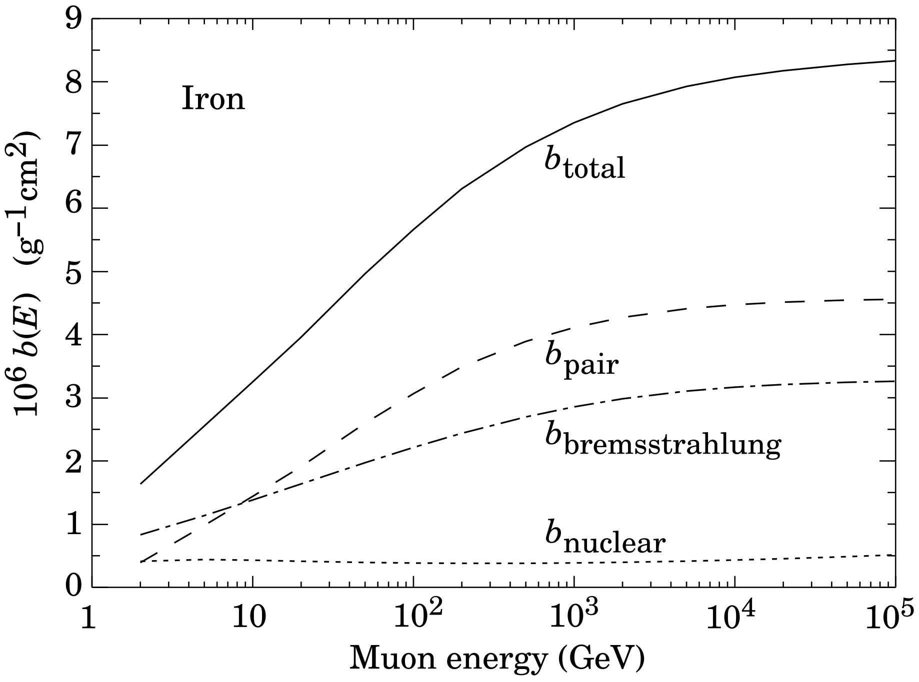
μ - hodoscope

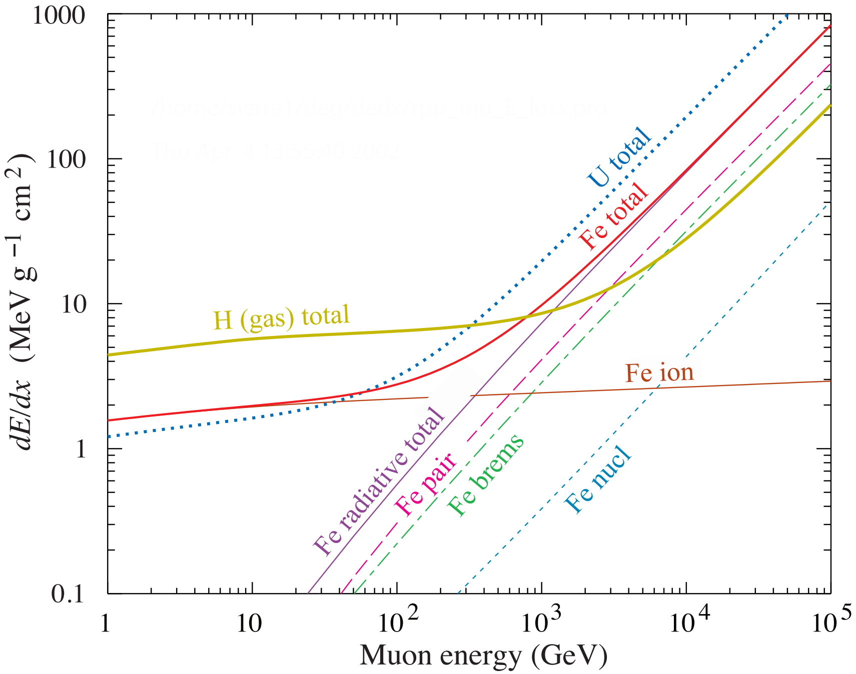


dE/dx for Muons

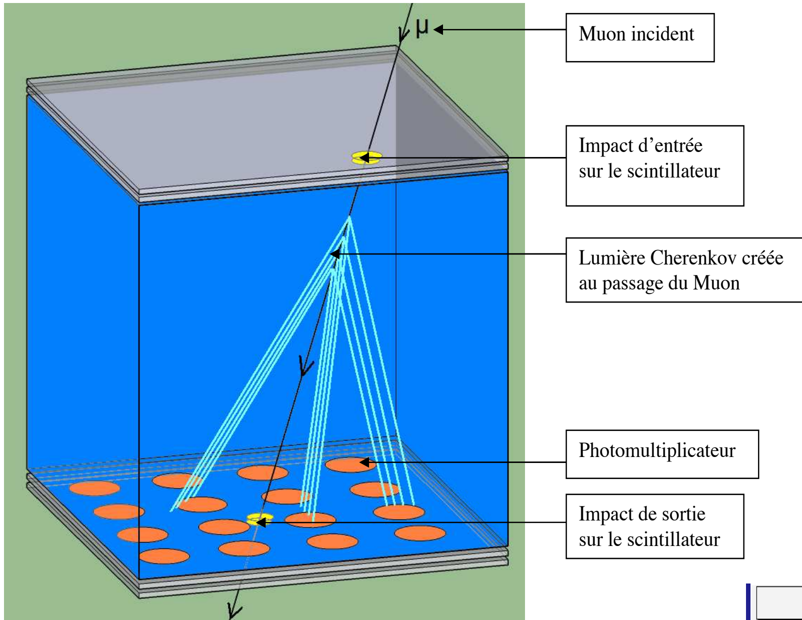
$-dE/dx = a(E) + b(E)E$

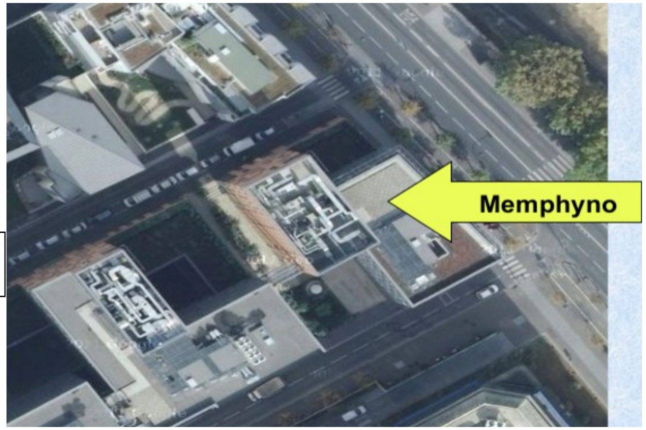
where a(E) is the ionization lass by Bethe-Block and b(E) are corrections (pair production, brems, etc)

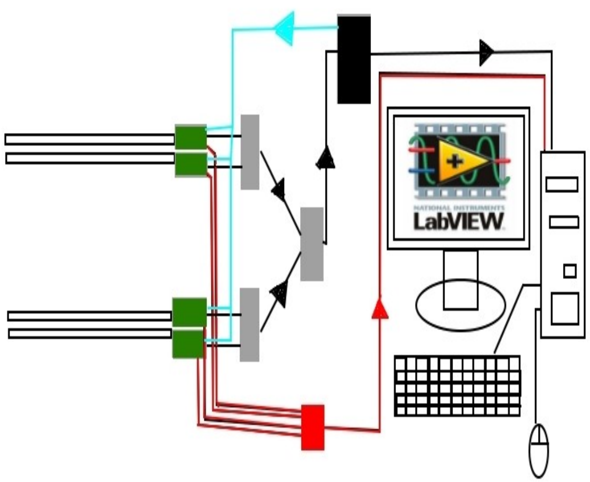


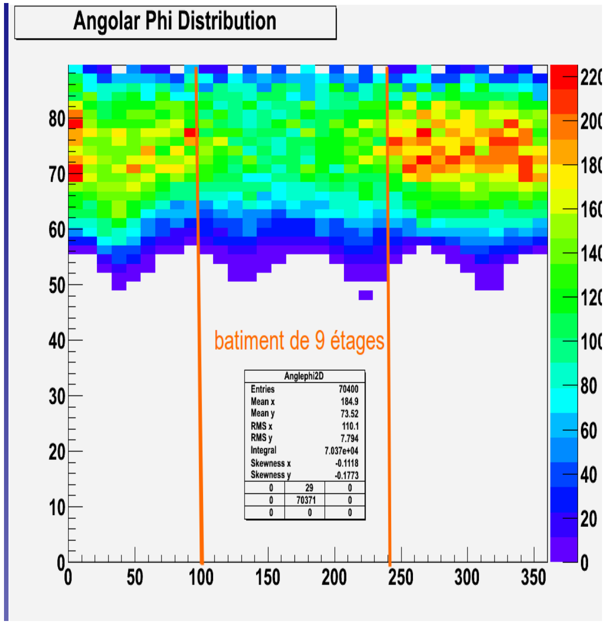


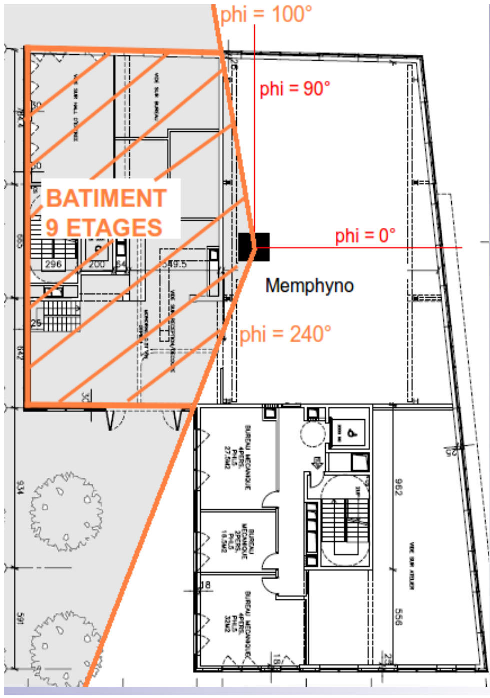
Use of atmospheric muons – a cheep and easy way for calibration…

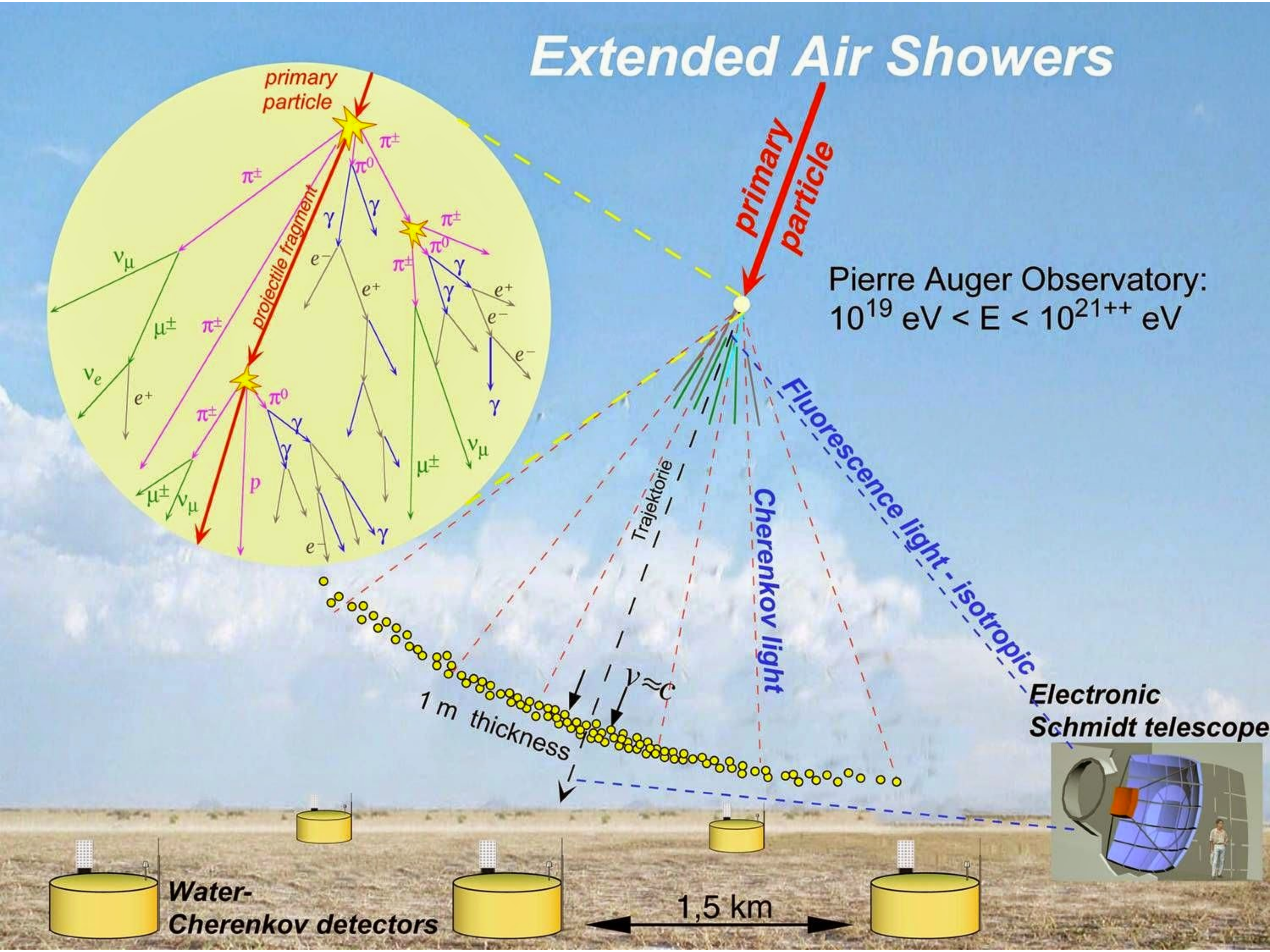






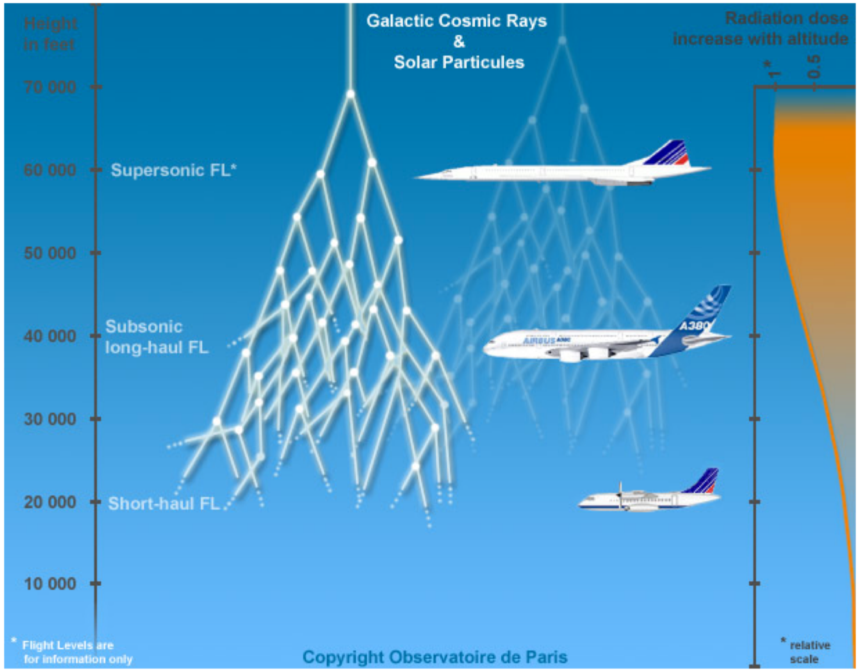




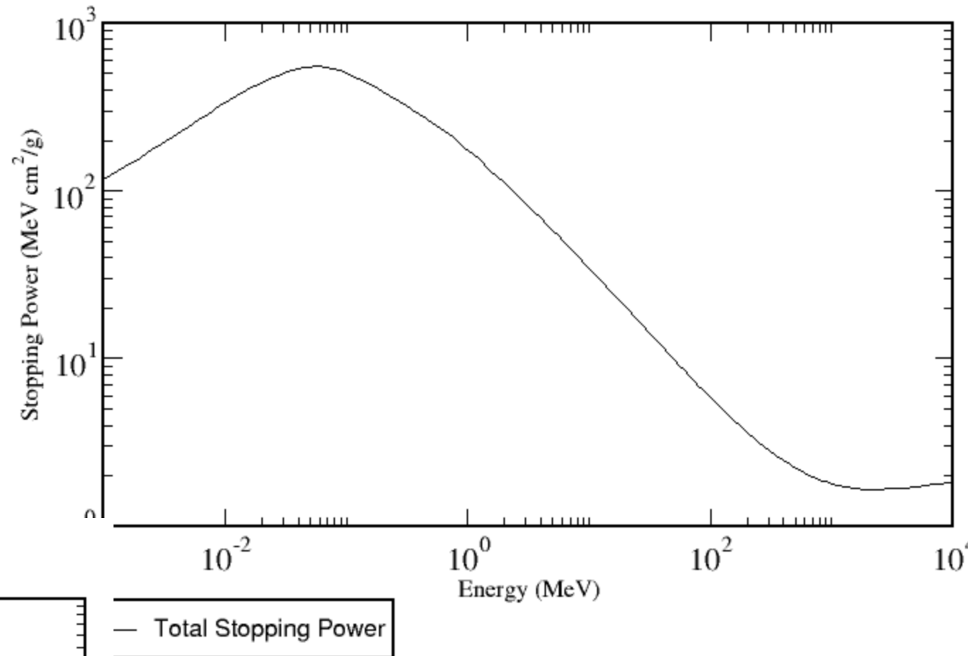


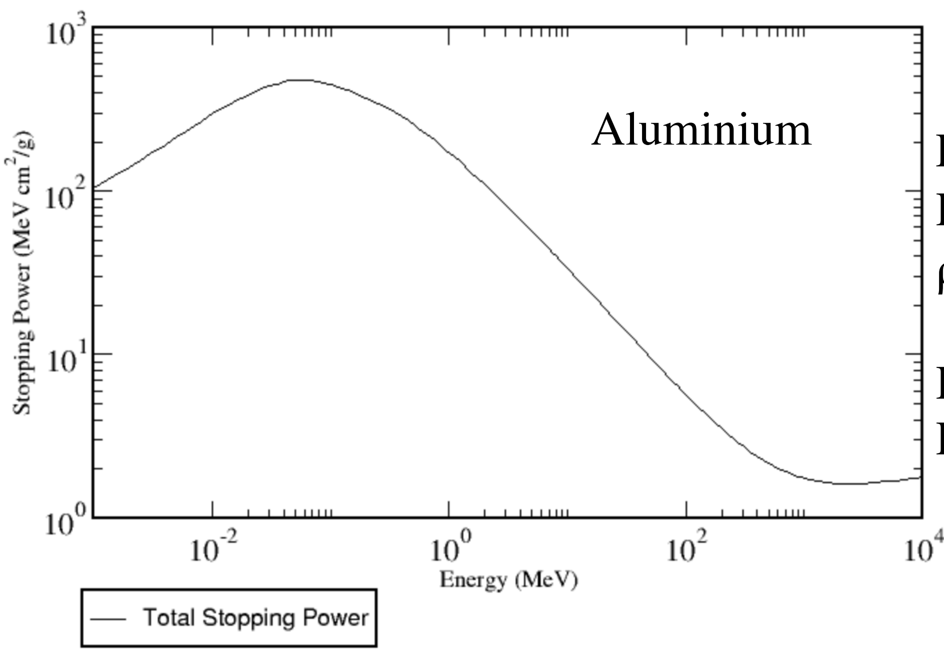
Extended Air Showers
primary particle
projectile fragment
primary particle
Pierre Auger Observatory:
10^{19} eV < E < 10^{21++} eV
Fluorescence light - isotropic
Cherenkov light
Trajektorie
$v \approx c$
1 m thickness
Electronic Schmidt telescope
Water-Cherenkov detectors
1,5 km

When cosmic rays and em/had showers strike aircrafts or satellites



SILICON





Example:

How far goes a 100 MeV proton in Aluminum?

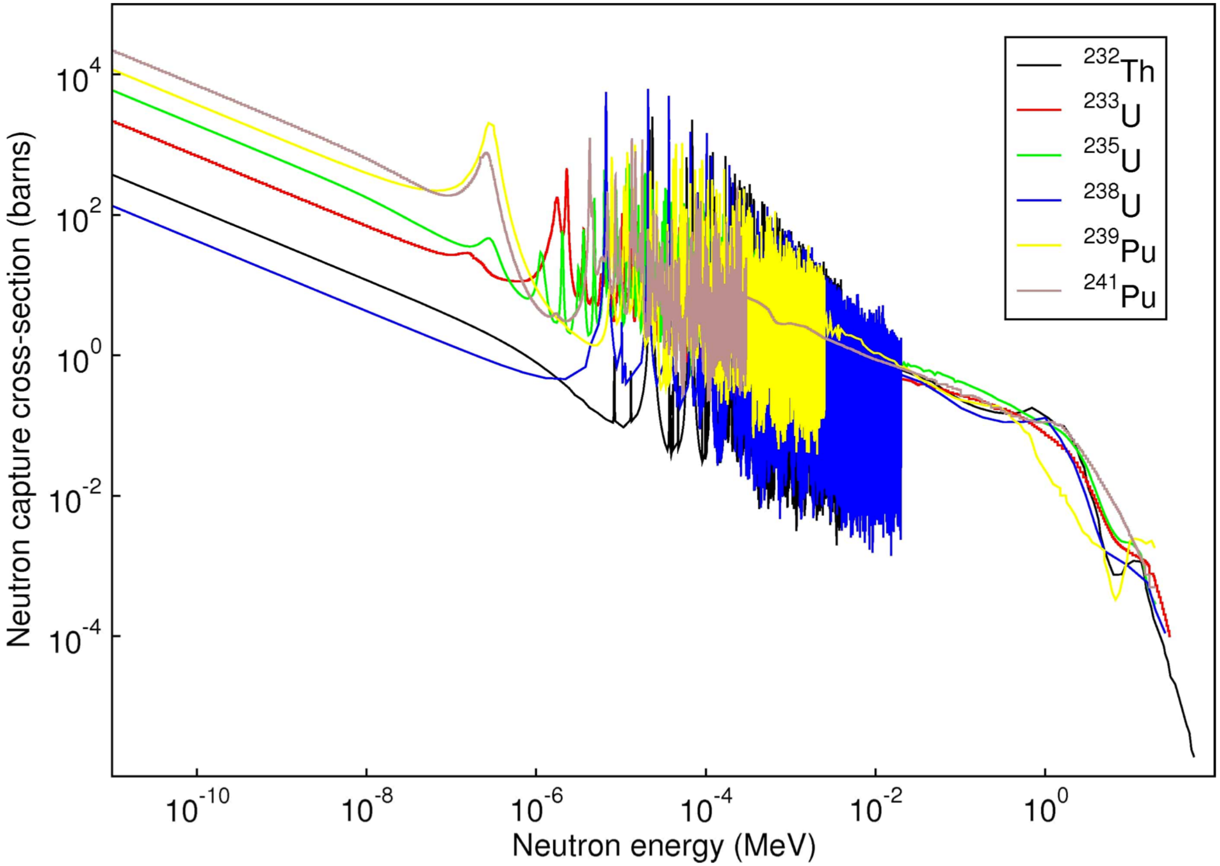
$\rho_{Al} = 2.7\ g/cm^3$

$D = \text{Energy} / (\text{stopping power} \times \rho_{Al})$

$D = 100 / (6 \times 2.7) = 6.2\ cm$

Neutrons

Neutrons are neutral and therefore do not ionize directly
Free neutrons scatter with the nucleus elastically
Very penetrating radiation, must be slowed down before absorption (e.g. Nuclear power plant)
In HEP experiments difficult for calorimetry



Neutron detectors in HEP:

Gas proportional detectors: Addition of nuclide with high neutron X-section

Helium-3, lithium-6, boron-10, uranium 235 commonly used for thermal neutrons

Scintillation neutron detectors: same principle:
Add high neutron X-section material to scintillators or scientillating fibers

Coated semiconductors

Neutron activation detectors

For fast neutrons, usually first slowed down and then detected.
Some He based noble gas detectors or scintillator detectors can distinguish pulse shape discrimination