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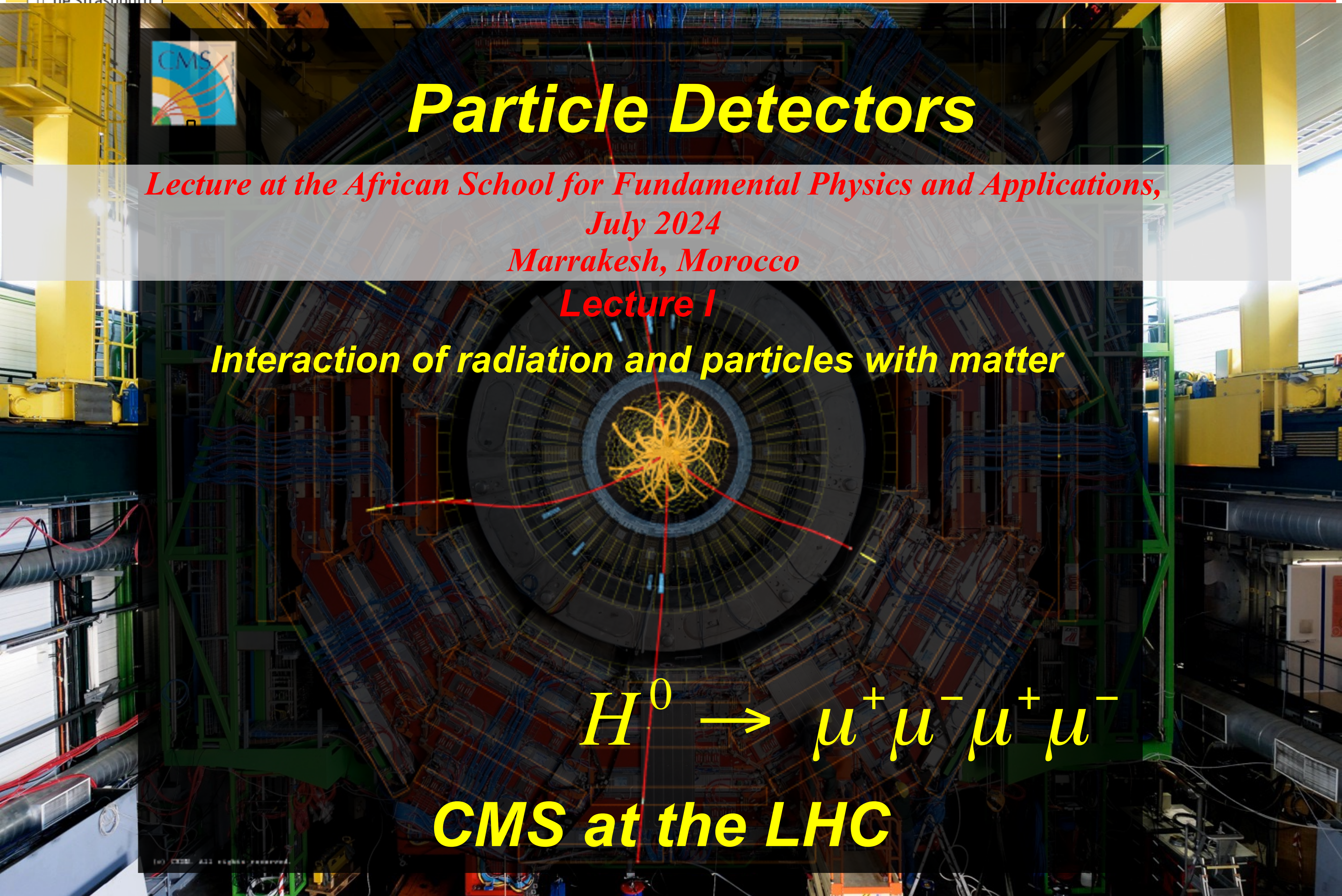


# Particle Detectors

*Lecture at the African School for Fundamental Physics and Applications,*
*July 2024*
*Marrakesh, Morocco*

**Lecture I**

***Interaction of radiation and particles with matter***

$$H^0 \rightarrow \mu^+\mu^-\mu^+\mu^-$$

## CMS at the LHC

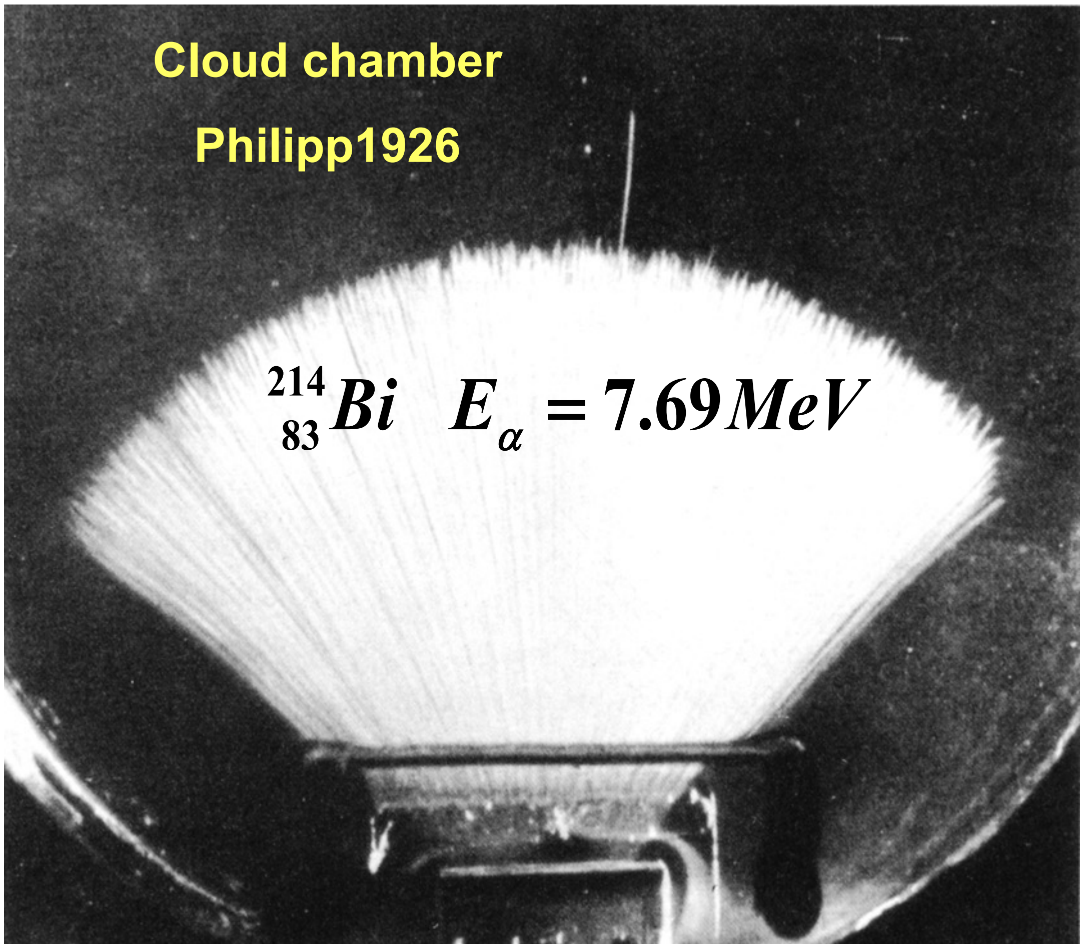


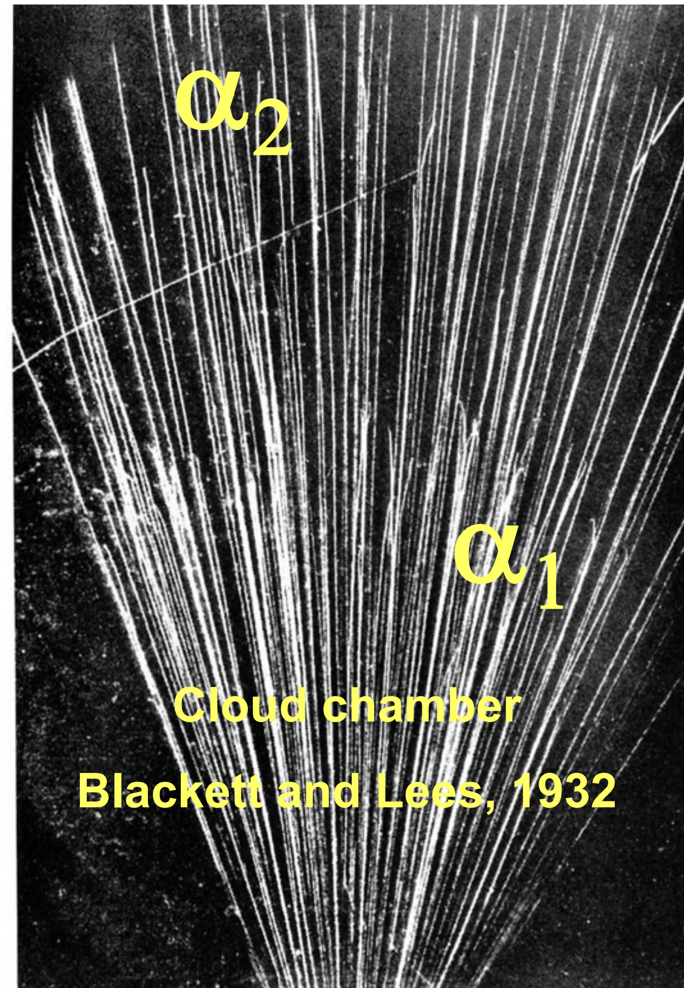
IPHC Institut Pluridisciplinaire Hubert Curien Strasbourg

# Cloud Chamber

$$^{212}_{82}Pb \xrightarrow{\beta^-} {}^{212}_{83}Bi \quad E_\alpha = 6.09\,MeV$$

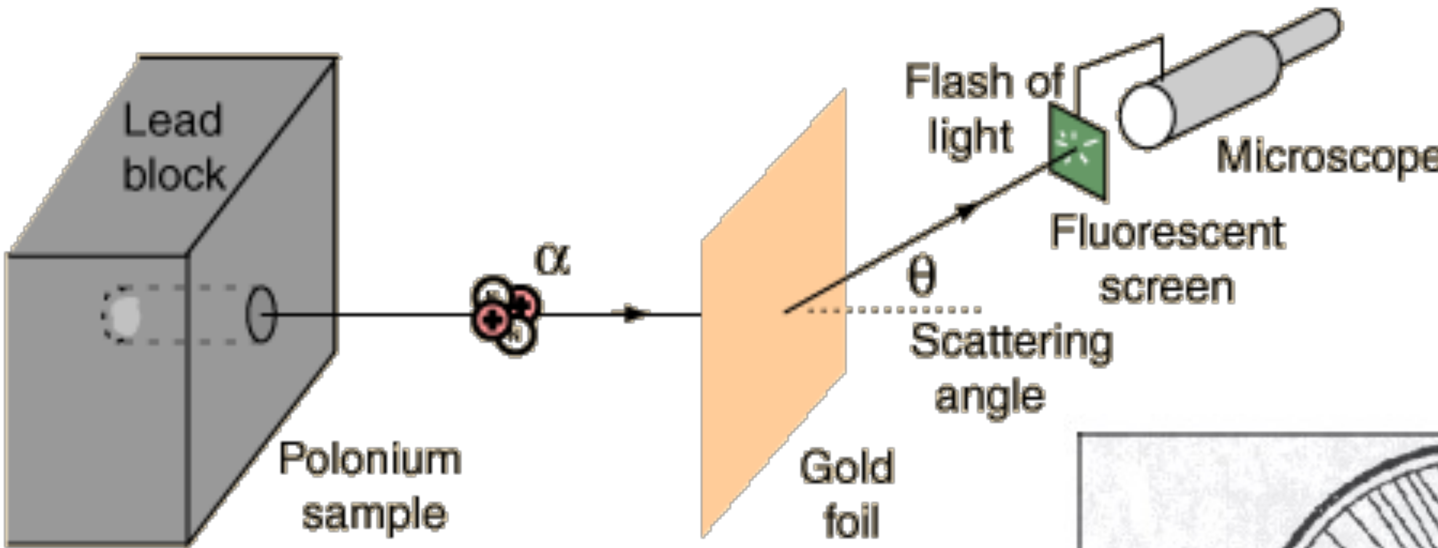
$$\xrightarrow{\beta^-} {}^{212}_{84}Po \quad E_\alpha = 8.78\,MeV$$

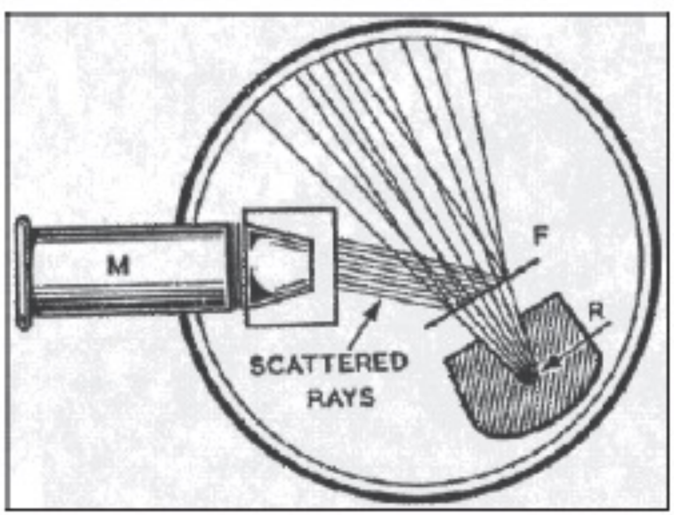


# Seeing particles: Rutherford scattering

## Experiment by Hans Geiger and Ernest Marsden 1909



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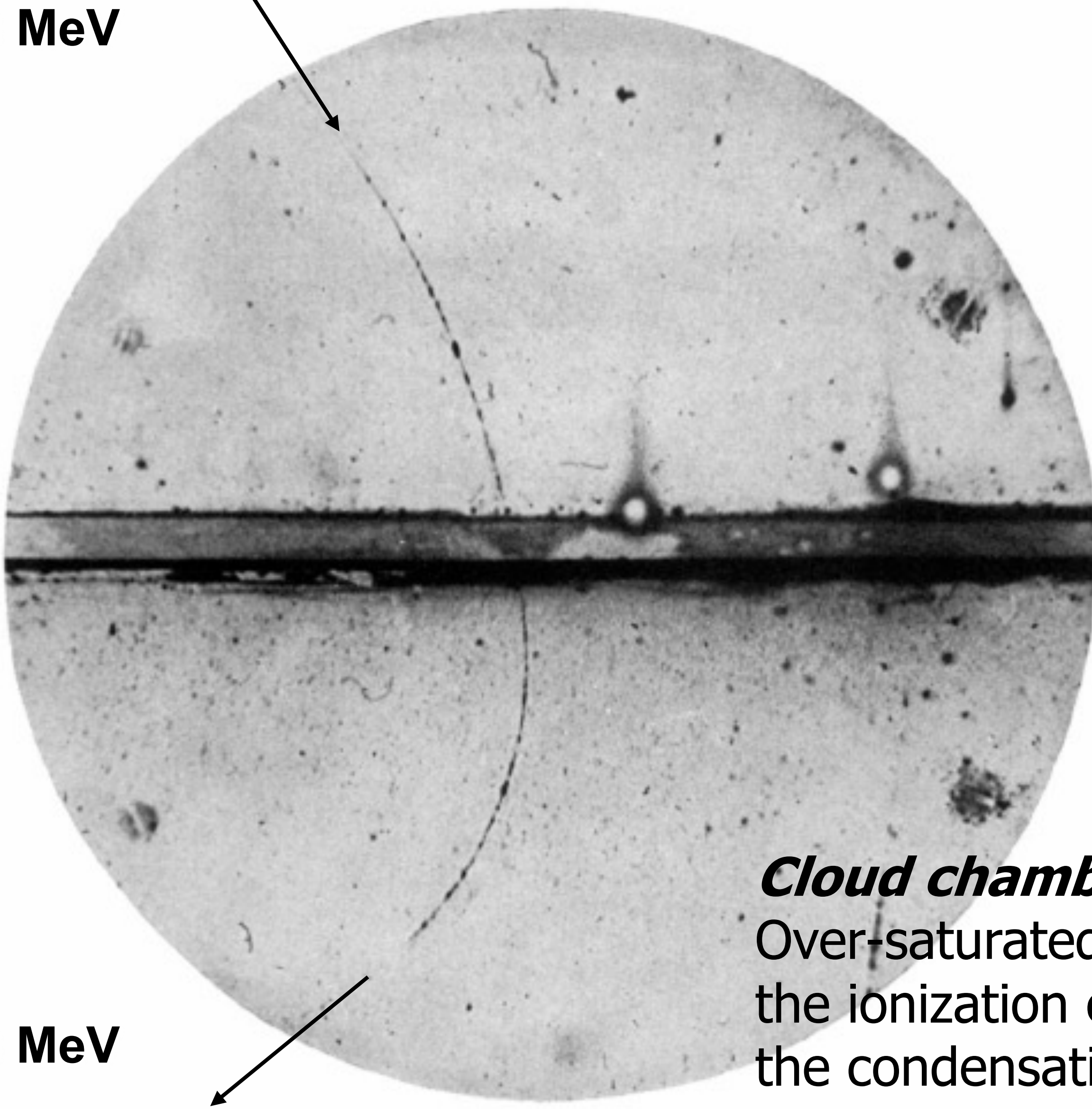
**$e^+$ 63 MeV**



**$e^+$ 23 MeV**

# 1932 Discovery of the positron by C.D.Anderson

6 mm Pb

***Cloud chamber (C.T.R. Wilson)***

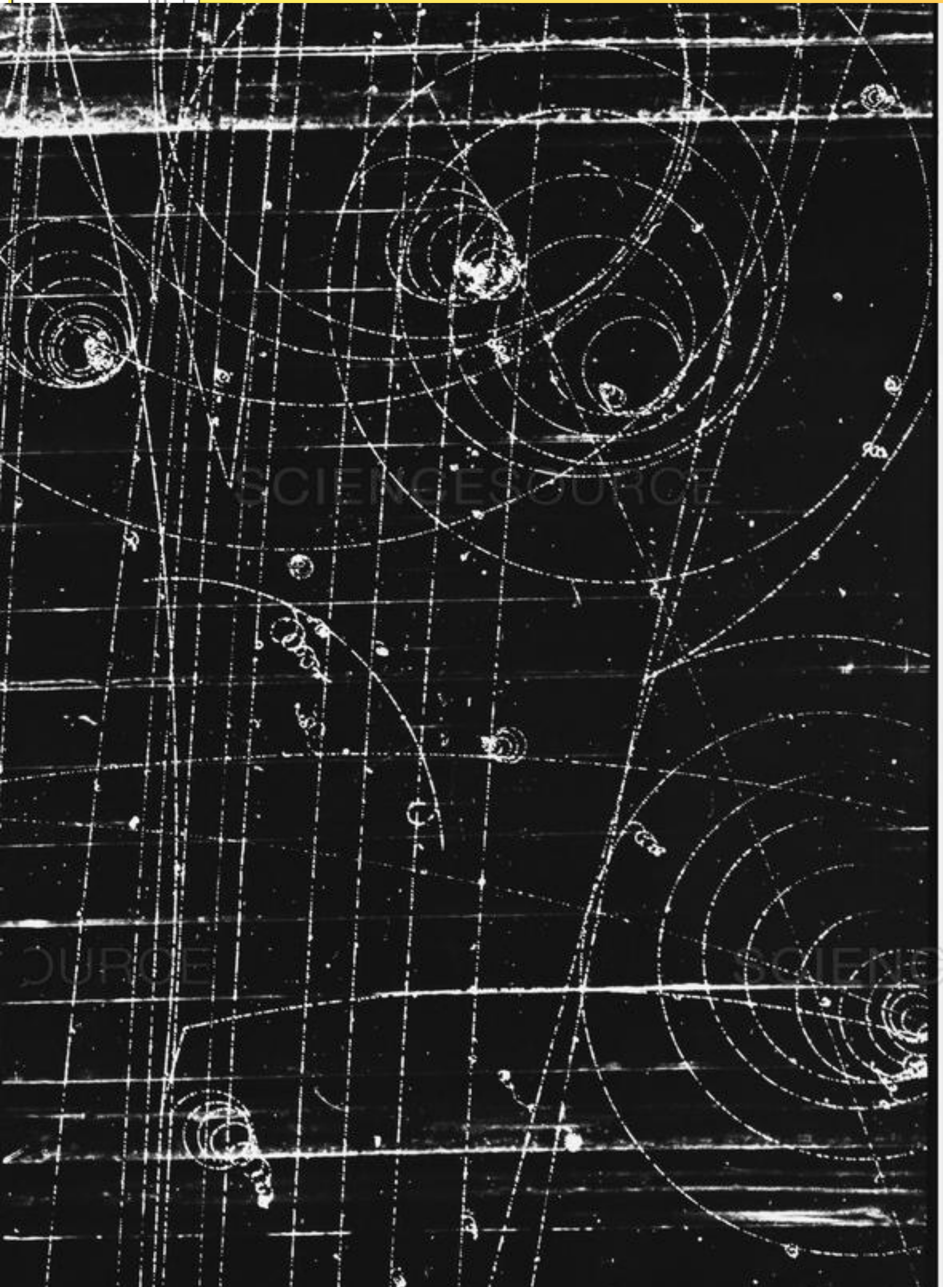
Over-saturated vapour :
the ionization clusters become the condensation nuclei

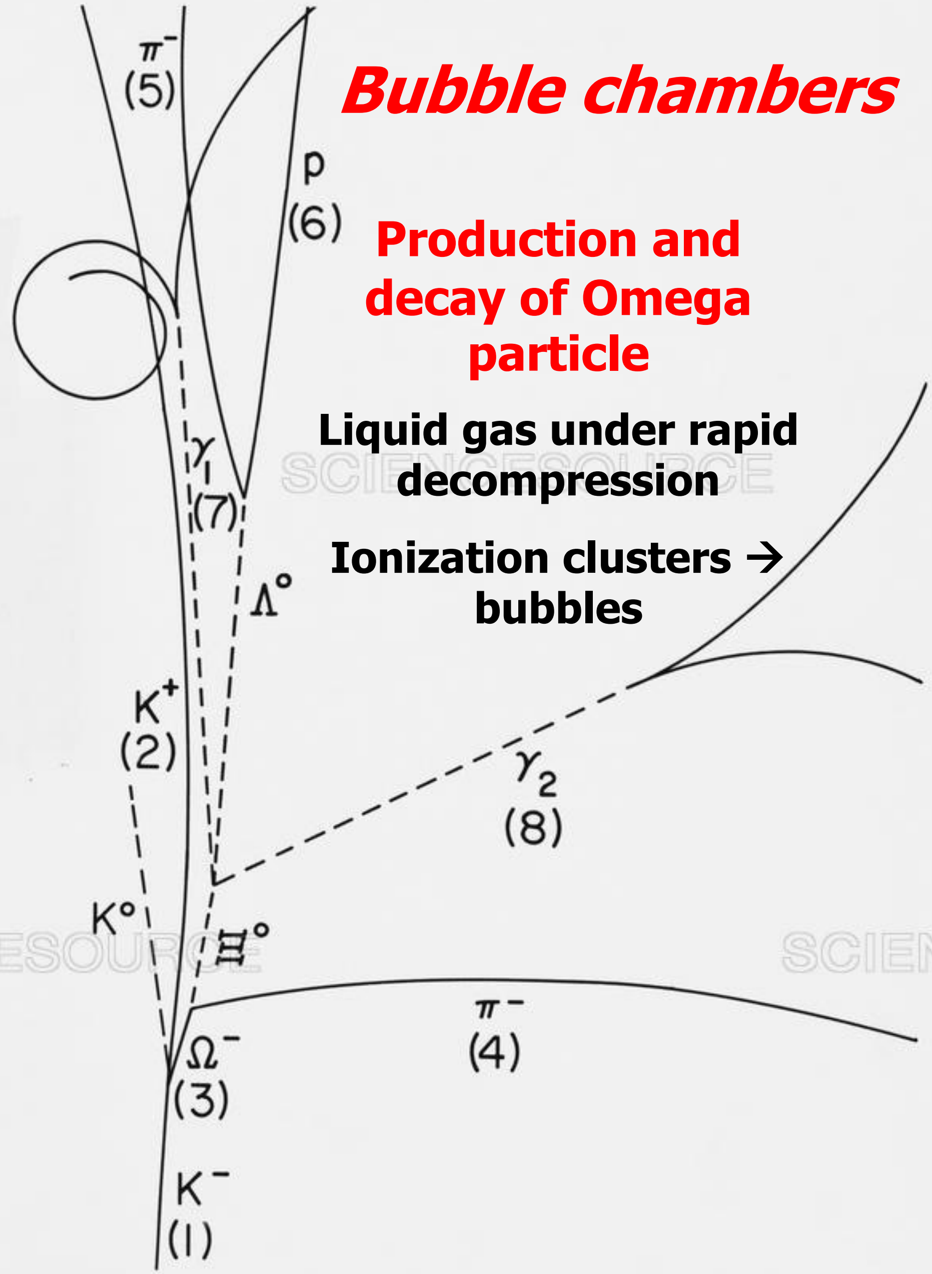
# *Bubble chambers*

## Production and decay of Omega particle

**Liquid gas under rapid decompression**

**Ionization clusters → bubbles**





# Particle Detectors

*Lecture at the African School for Fundamental Physics*
*Marrakesh, Morocco, July 2024*

**Goal of these lectures:**

**to understand how nuclear and particle physics detectors work**

## Lecture I

- Introduction
- Interaction of radiation and particles with matter

## Lecture II + III. Given by Sally Seidel

- The basics of detectors

## Lecture IV (tentative programme)

- High purity segmented Ge-detectors for Nuclear physics
- Recent developments of CMOS pixel detectors
- Fast detectors for time of flight measurements
- High granularity calorimeters
- Dark Matter detectors and other Exotics

# *Particle Detectors*

*Lecture at the African School for Fundamental Physics*
*Nelson Mandela University in Gqeberha, 2022*

## *1st Lecture*

- **Introduction**
  - **The goal: measuring subatomic particles (E, p, charge,, mass, ….**
  - **Detection of particles, how do they interact with matter, what does the interaction depend on (E, p, charge,, mass, beta, gamma ….**
- **Interaction of particles and radiation with matter**
  - **Photons: PE, Compton, Pair creation**
  - **Ionization/excitation, Bethe Bloch formula, range of particles, Bragg peak**
  - **Electrons, Bremsstrahlung, critical energy, radiation length**
  - **Electromagnetic showers of electrons and photons, (muons)**
  - **Hadronic interactions → showers, interaction length, solid and atmospheric absorbers**
  - **Multiple scattering**
  - **Cerenkov, Transition radiation**

- ***Exercises for the evening !!!!!***

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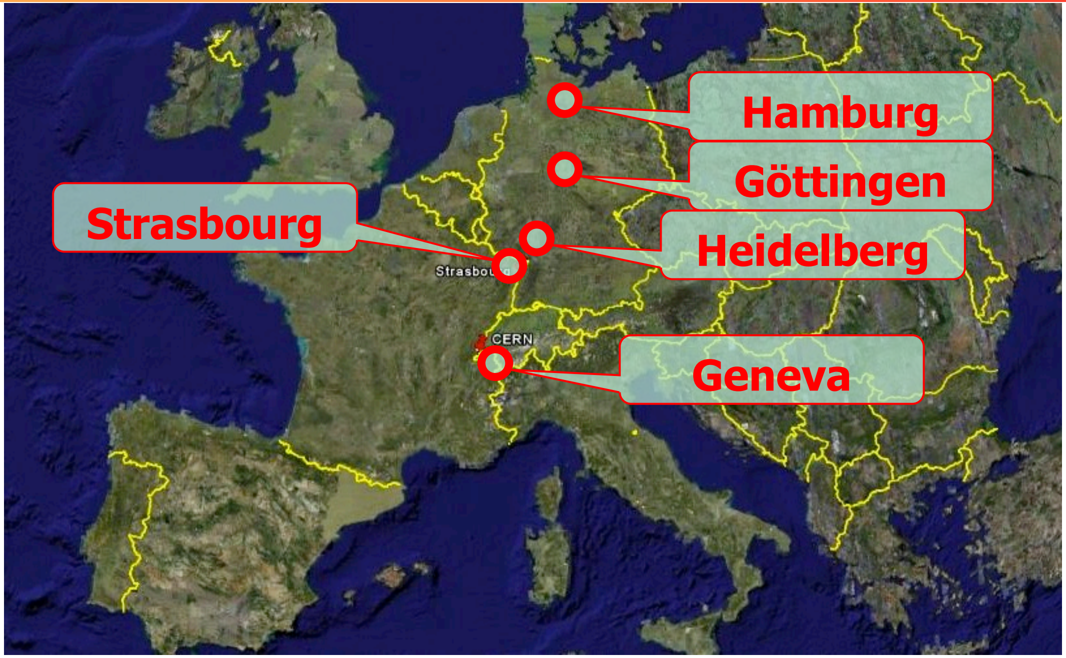
# *Who am I?*

## *Ulrich Goerlach*




- Born in Göttingen, Germany
- Physics (and Math) studies at the Universities Göttingen and Heidelberg
- Diploma (now Master) and PhD at the Max Planck Institute for Nuclear Physics in Heidelberg
- Post-doc (particle physics) at CERN, Geneva
- Researcher at University Heidelberg
- Researcher(staff) at CERN Geneva
- Researcher(staff) at DESY, Hamburg
- University Professor at the Unistra, (Université de Strasbourg)
- Professor émérité since 01/09/2022

Ulrich.Goerlach@iphc.cnrs.fr, ASP Particle detectors

# Bibliographie

**Text books :**

– C. Grupen, Particle Detectors, Cambridge University Press, 1996, 2011
– G. Knoll, Radiation Detection and Measurement, 3rd ed. Wiley, 2000
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– R. Wigmans, Calorimetry, Oxford Science Publications, 2000

**Review Articles**

– Experimental techniques in high energy physics, T. Ferbel (editor), World Scientific, 1991.
– Instrumentation in High Energy Physics, F. Sauli (editor), World Scientific, 1992.
– Many excellent articles can be found in Ann. Rev. Nucl. Part. Sci.

…

- CERN-Summer student lectures and academic training…

# Acknowledgements


- Many thanks to all my colleagues who have prepared lectures like this one in the past and from which I profited a lot!!!
- I tried to quote the authorship of the slides I took from theses lectures and I apologize for the cases in which I forgot or could not trace them anymore

# Photons at low energy

# Interaction of photons with matter

- **Photo-electric effect** Absorption of $\gamma$; dominant for $E_\gamma \leq 0.1\text{-}1$ MeV
- **Compton effect** Diffusion $\gamma \rightarrow \gamma'$ Dominant for $0.1 \leq E_\gamma \leq 10$ MeV
- **Creation of ($e^+e^-$)-pairs** Absorption de $\gamma$ $E_\gamma \geq 1.022$ MeV
- **Nuclear photo-electric and photo-nuclear reaction are very rare!**

***Statistical processes governed by a cross section:***

(reaction rate per unit of flux) $\sigma_I$ (1 barn = $10^{-24}$ cm$^2$):

Intensity (number of $\gamma$ behind an absorber of depth x, [x]=g/cm$^2$)

$$I = I_o \exp(-\mu x) \quad ( dI = -I \mu dx )$$

$\mu$ = Attenuation or/and absorption coefficient; [$\mu$]=cm$^2$/g

$\mu = N_A/A(g) \cdot \Sigma_i \sigma_i$ ; $N_A$ Avogadros number, A=atomic weight in gramme

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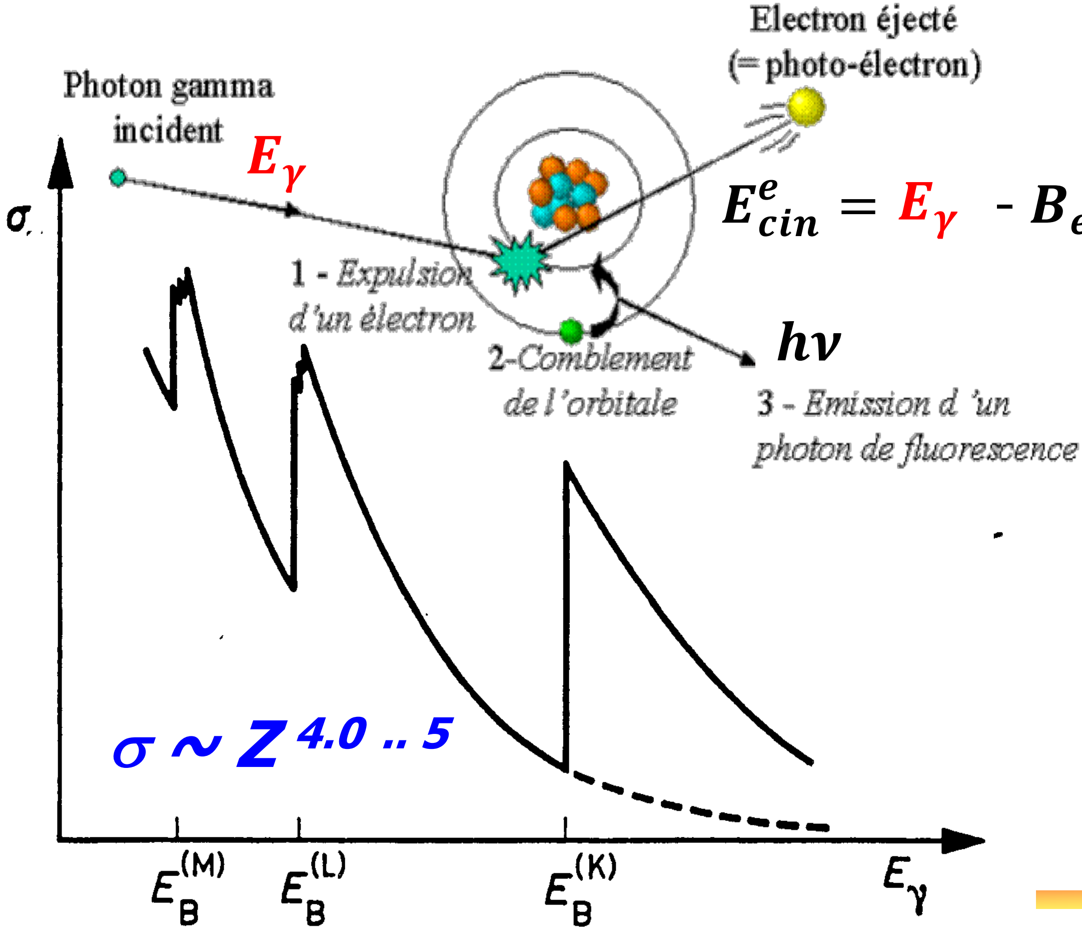
# Photo-electric effect

$$\sigma^{K}_{p.e.}\Big|_{atom} = \sqrt{\frac{32}{\left(E_\gamma / m_e c^2\right)^7}} \cdot Z^5 \alpha^4 \times \underbrace{\left(\frac{8}{3}\pi r_e^2\right)} \times \text{corrections}$$

$$r_e = \frac{e^2}{4\pi\varepsilon_0 m_e c^2}$$

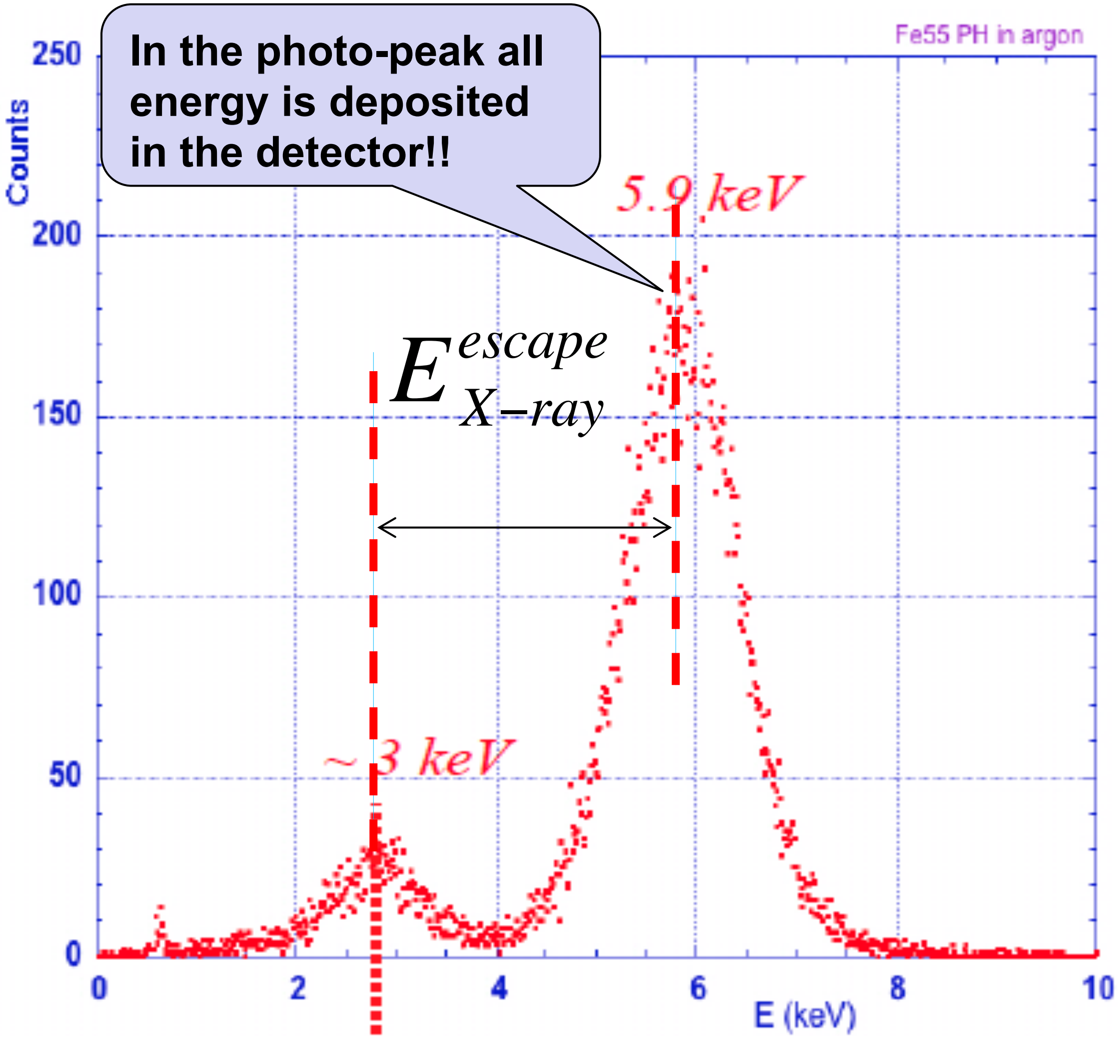


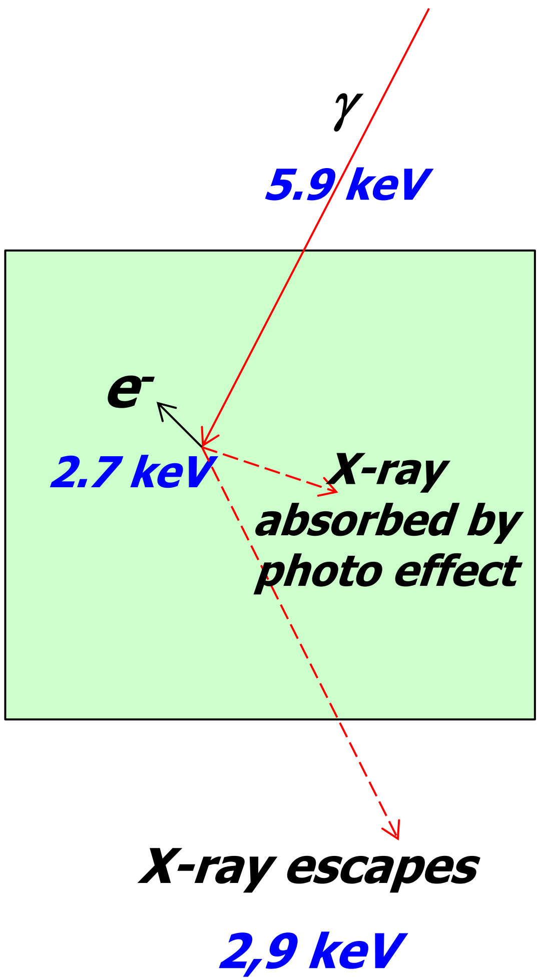

- **At high *Z*, the hole in the K-shell is filled by an electron under the emission of a fluorescence x-ray of energy $E_{h\nu}=E_K-E_{L,M,N}$**
- **At low Z, Auger electrons occur: electrons of higher shells (L) are ejected with energy**

**$E_{Auger}=E_K-2E_L$**

# X-RAY ABSORPTION SPECTRUM

$^{55}$Fe X-Rays (5.9 keV) in Argon:




**$E_K$=3,2 keV**

**$E_L$≈0.3 keV**

**Escape of the fluorescence x-ray of energy**

**$E_X = E_K - E_{L,M,N} = 3.2 - 0.3 = 2.9$ keV**

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# Compton-effect

## Scattering of a gamma on a “free” electron

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

$$\varepsilon = h\nu / m_e c^2$$

$$T_e = h\nu - h\nu'$$

$$\Delta\lambda = \lambda' - \lambda = \frac{hc}{m_e c^2}\left(1-\cos\theta_{\gamma'}\right)$$

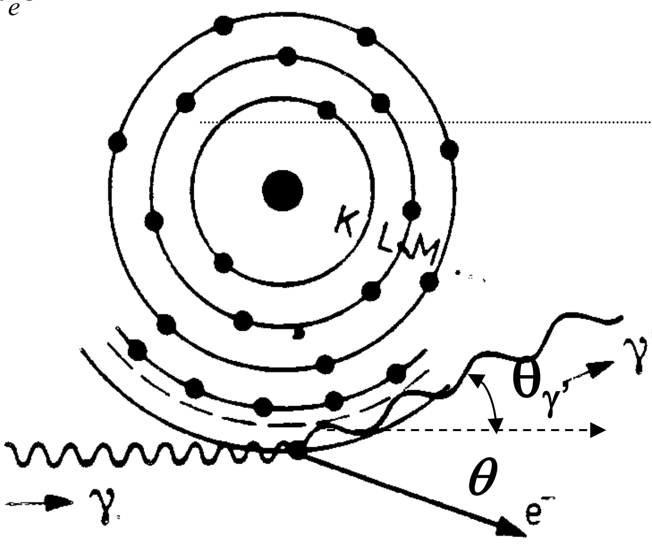
$$\lambda\!\!\!^-_c = \frac{\hbar c}{m_e c^2}$$ Compton wave length of an electron

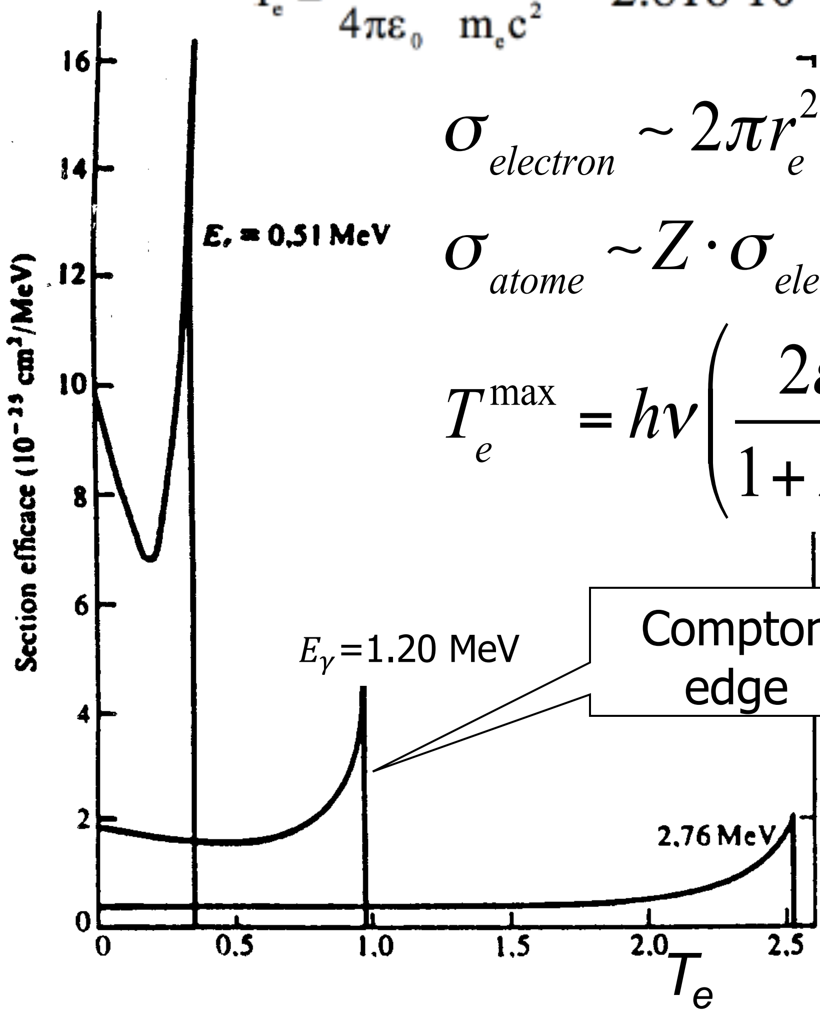
$$r_e = \frac{1}{4\pi\varepsilon_0}\cdot\frac{e^2}{m_e c^2} = 2.818\ 10^{-15}\ \mathrm{m}$$

$$\sigma_{electron} \sim 2\pi r_e^2$$

$$\sigma_{atome} \sim Z\cdot\sigma_{electron}$$

$$T_e^{max} = h\nu\left(\frac{2\varepsilon}{1+2\varepsilon}\right)$$



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# Kinematics of Compton scattering
## exercise !!

*longitudinal momentum conservation* :

$$p_\gamma = \frac{h\nu}{c} = \frac{h\nu'}{c}\cos\theta_{\gamma'} + \left|\vec{p}_e\right|\cos\theta_{e'}$$

*transversal momentum conservation* ::

$$0 = \frac{h\nu'}{c}\sin\theta_{\gamma'} - \left|\vec{p}_e\right|\sin\theta_{e'}$$

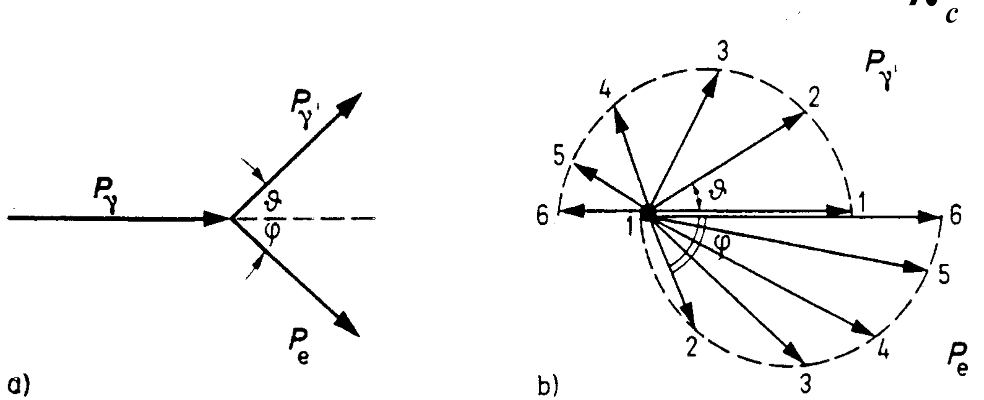
*Energy conservation* : $T_e = h\nu - h\nu'$

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

$$\varepsilon = h\nu / m_e c^2$$

$$\Delta\lambda = \lambda' - \lambda = \frac{hc}{m_e c^2}\left(1-\cos\theta_{\gamma'}\right)$$

$$\lambda_c = \frac{\hbar c}{m_e c^2}$$ longueur d'onde de Compton d'un électron



The Klein-Nishina formula

$$\frac{d\sigma}{d\omega} = Zr_0^2\left(\frac{1}{1+\alpha(1-\cos\theta)}\right)^2\left(\frac{1+\cos^2\theta}{2}\right)\left(1+\frac{\alpha^2(1-\cos\theta)^2}{(1+\cos^2\theta)[1+\alpha(1-\cos\theta)]}\right)$$

$$h\nu' = \frac{h\nu_0}{1+\alpha(1-\cos\theta)} \quad \text{with} \quad \alpha = \frac{h\nu_0}{m_0c^2}$$

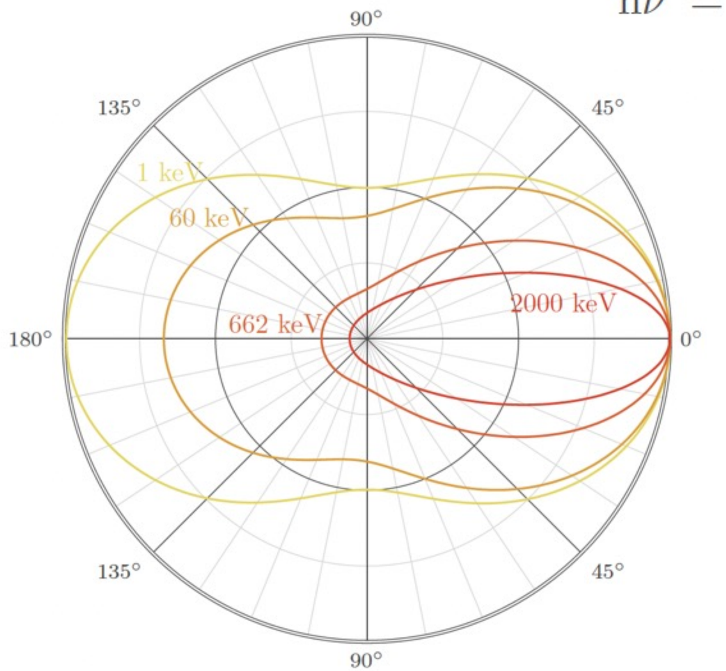
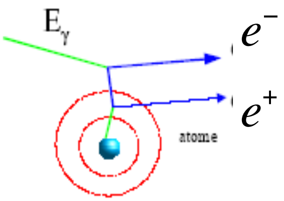



Figure 1.2: Probability of Compton scattering as a function of the scattering angle $\theta$ for an incident $\gamma$-ray coming from the left. The different curves correspond to various initial energies.

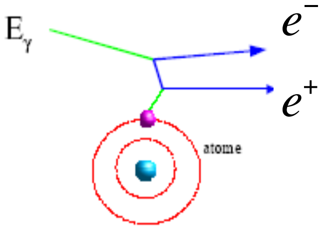
# Creation of electron positron pairs




In the field of a nucleus

$$E_\gamma \geqslant 2m_e + \frac{2m_e^2}{m_N}$$

$$m_N \gg m_e \Rightarrow E_\gamma \geqslant 2m_e$$



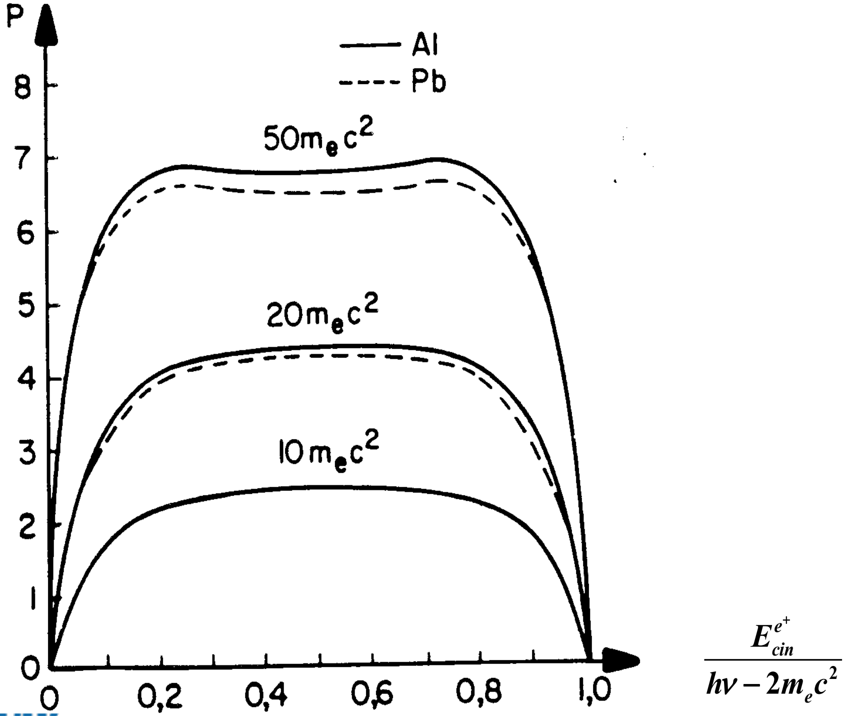

In the field of an electron

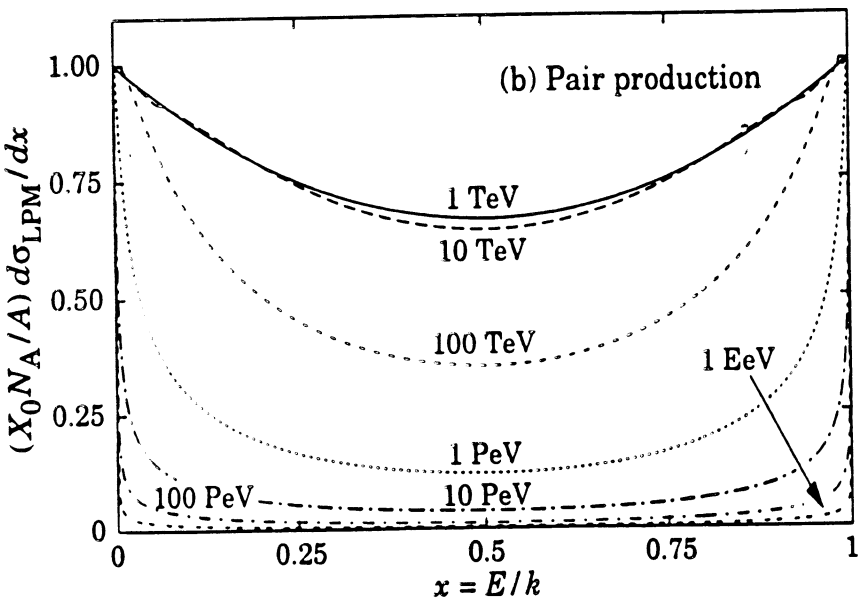
$$E_\gamma \geqslant 4m_e$$

$$\sigma_{pair} \approx \frac{7}{9}\frac{A(g)}{N_A}\cdot\frac{1}{X_0} \sim Z(Z+1)$$

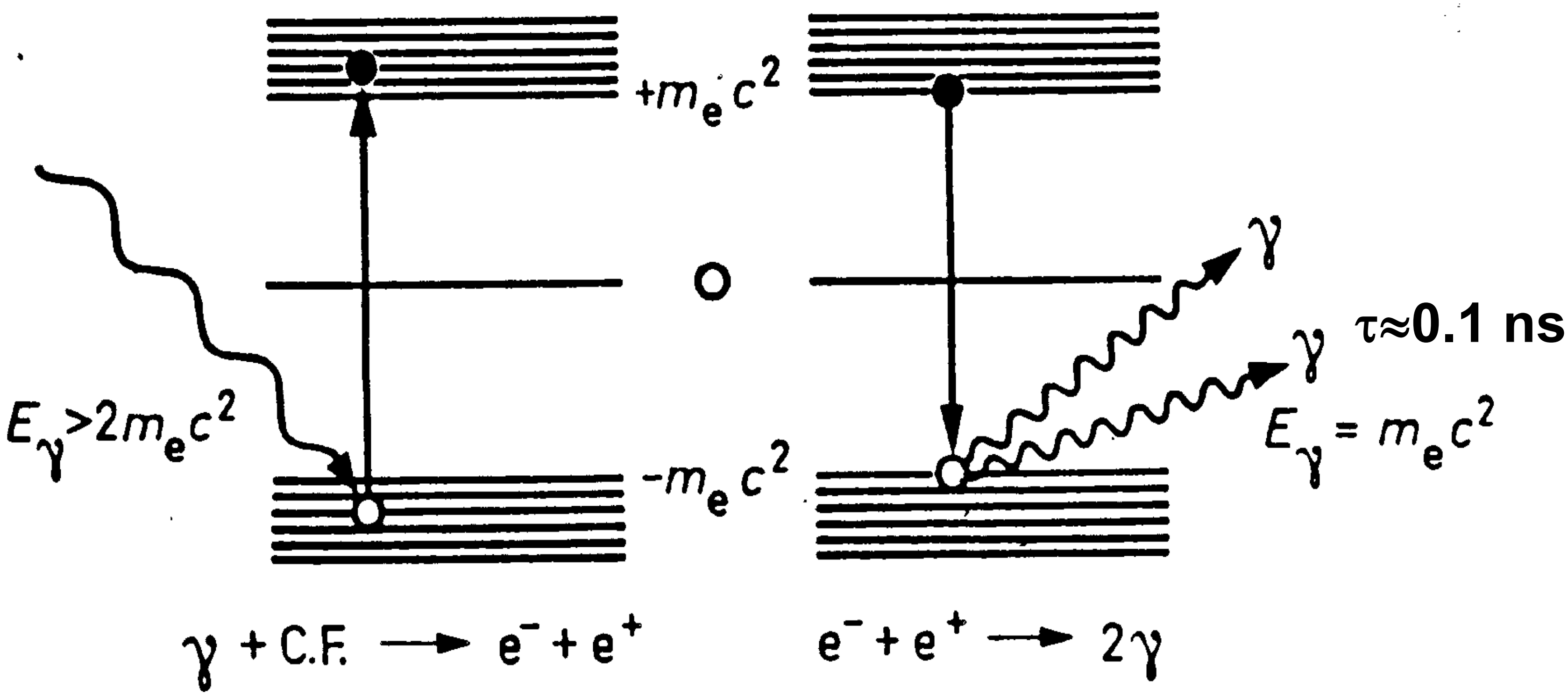
$$\mu_{pair} = \frac{N_A}{A}\sigma_{pair} \approx \frac{7}{9}\frac{1}{X_0} \; ; \; \lambda_{pair} = \frac{1}{\mu_{pair}} = \frac{9}{7}X_0$$

$X_0$ = radiation length



# Creation and annihilation of electron positron pairs




**Only in the presence of a nucleus, cannot occur in free space !**

$$!!!! \quad \gamma \not\rightarrow (e^+e^-): \; photon(E_\gamma = h\nu, P_\gamma = h\nu / c); \; E_\gamma = E_{ee}!$$

$$electron - pair: E_{ee} = 2\gamma m_e c^2, \; P_{ee} = 2\gamma m_e v_e = \frac{h\nu}{c}\frac{v}{c} = \frac{h\nu}{c}\beta \neq P_\gamma$$

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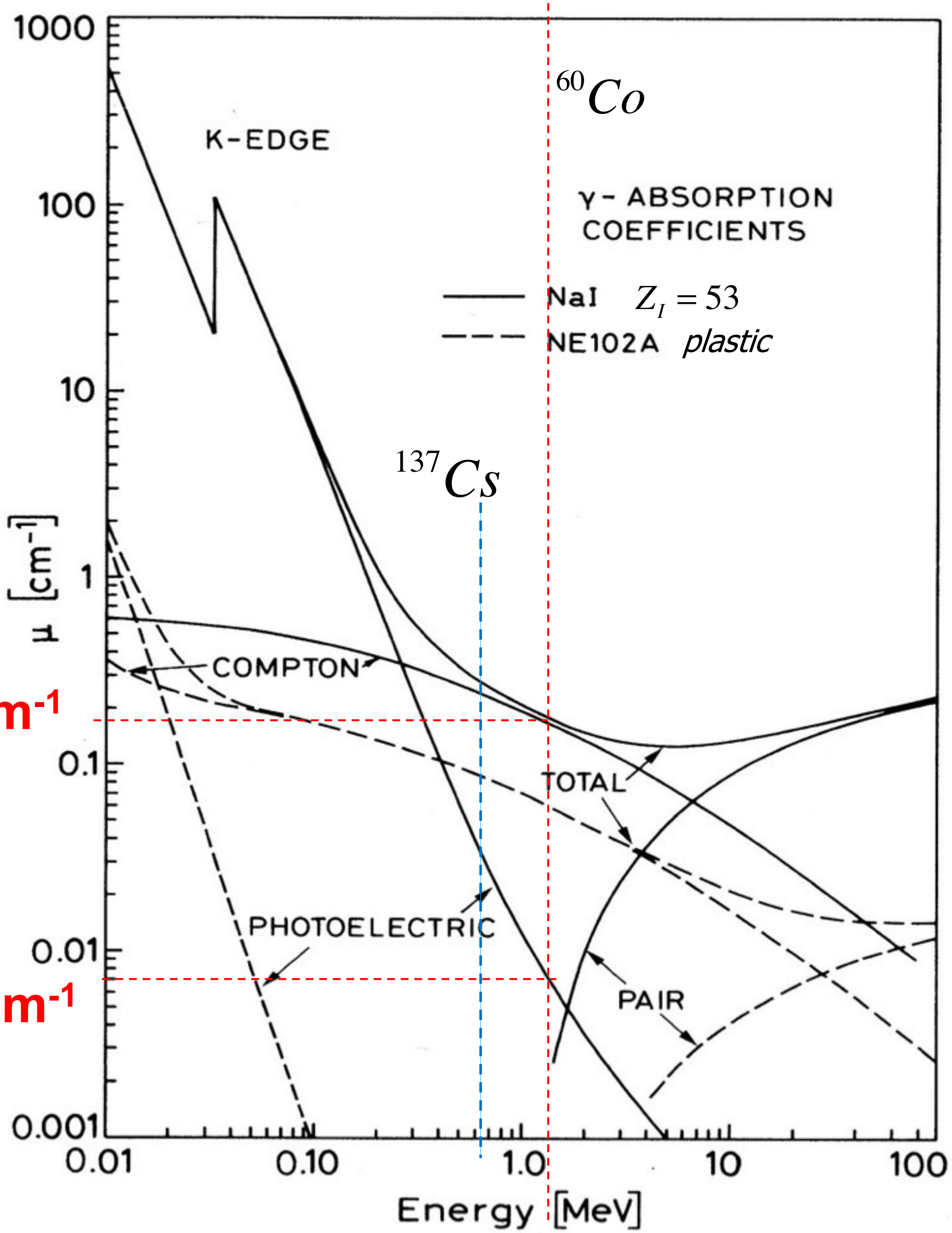


μ = 0.18 cm$^{-1}$

μ = 0.007 cm$^{-1}$

**Photo-electric effect**

**Absorption of γ**

**Compton scattering**

**scattering γ –> γ'**

**Creation of ($e^+e^-$) pairs**

**Absorption of γ**

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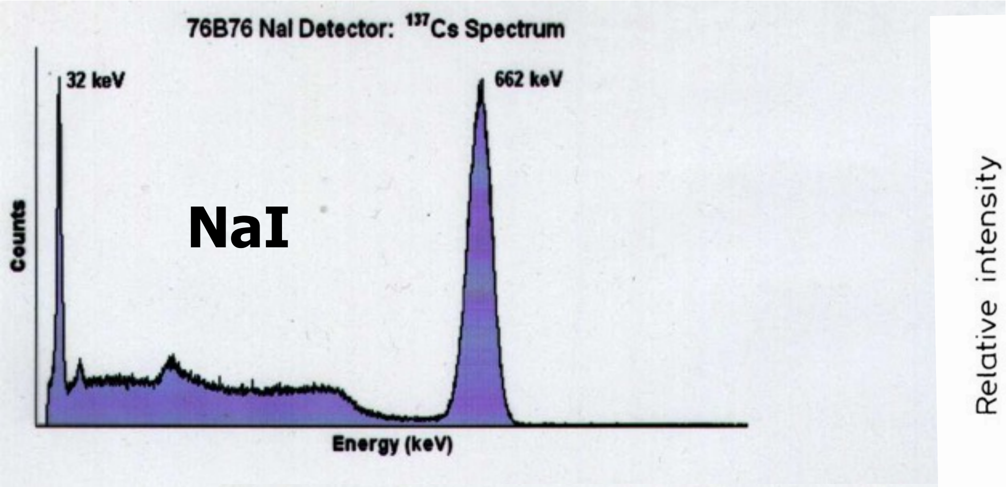
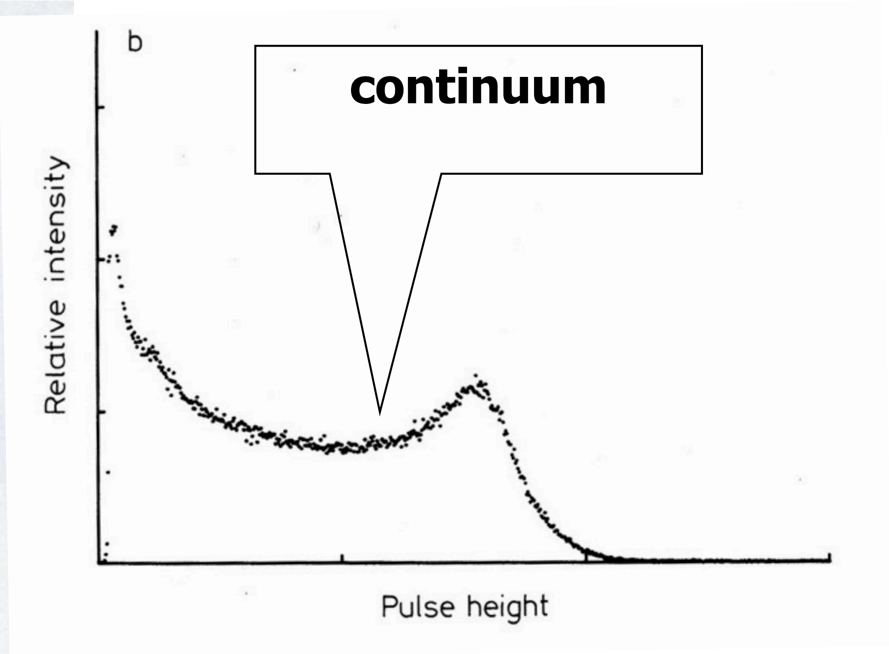
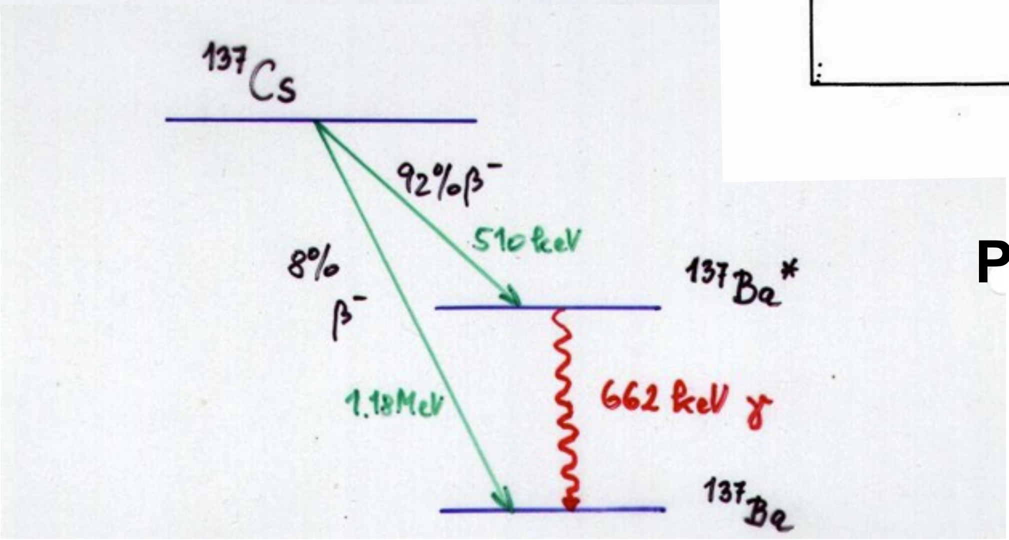
# Response function of a Scintillator

## Two examples of how a scintillator responds to mono-energetic photons




**Plastic Scintillator**

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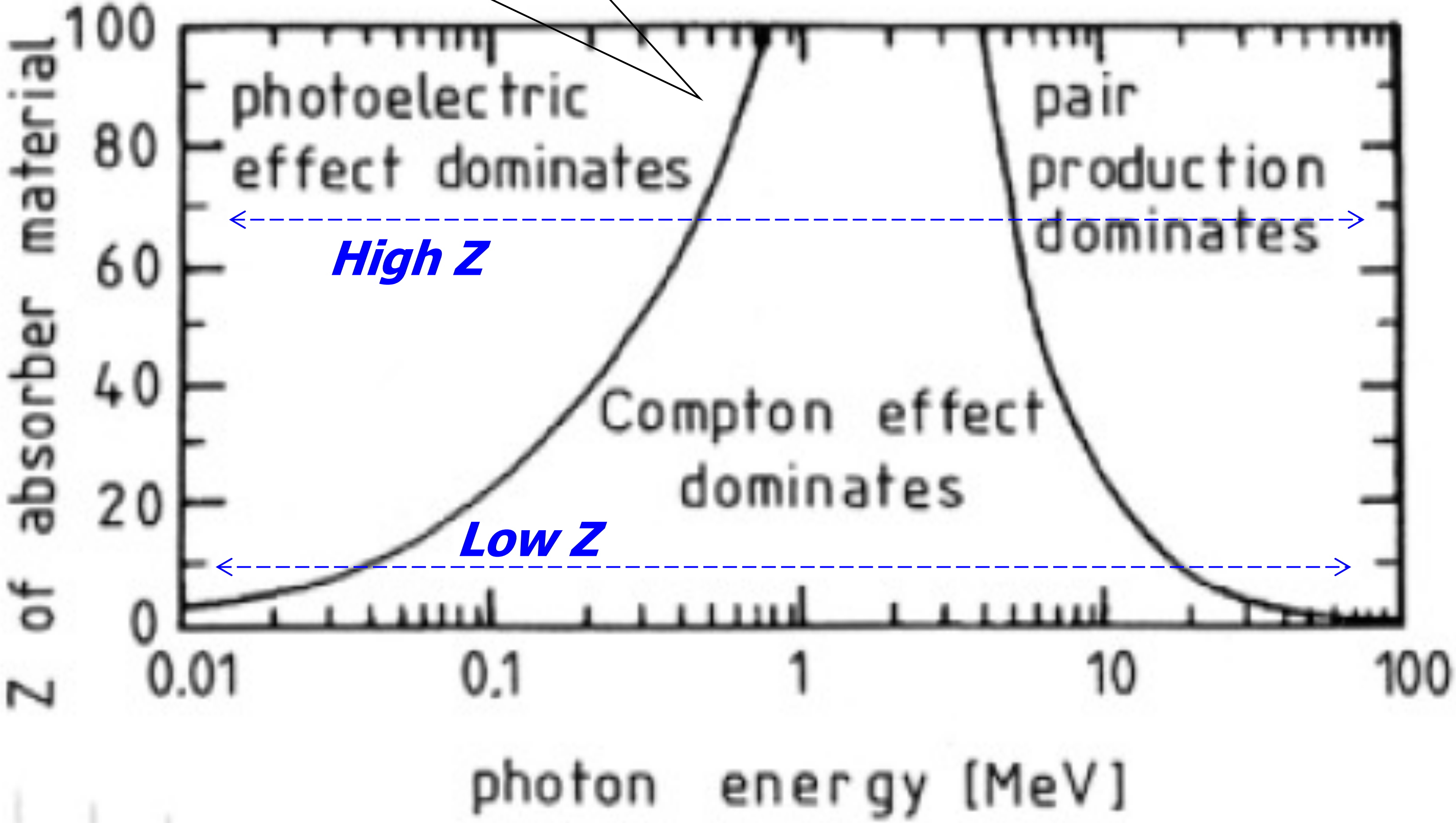
# Interaction of photons with matter

**Regions where one process is dominant, not exclusive !**



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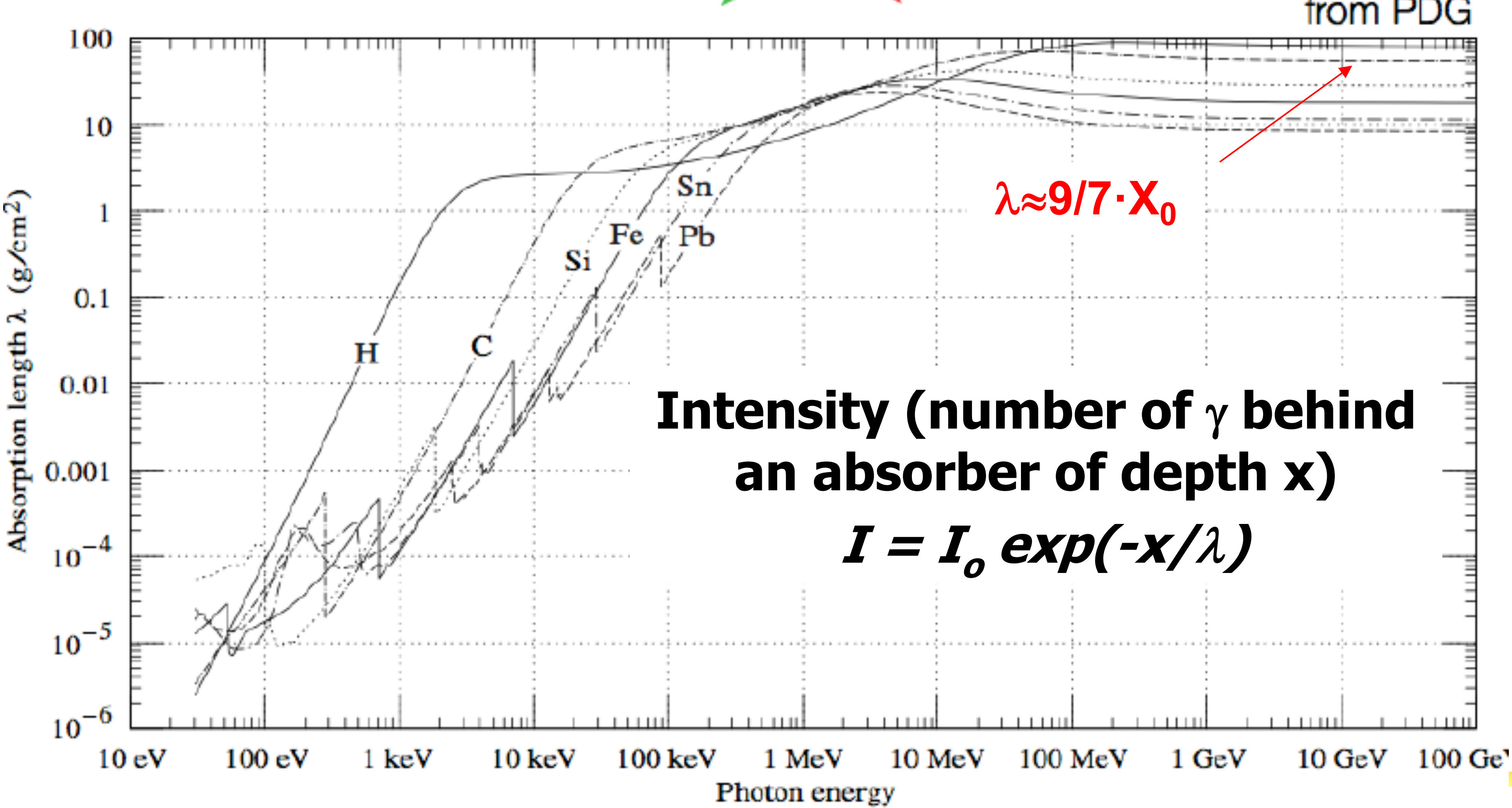
Ulrich.Goerlach@iphc.cnrs.fr, ASP Particle detectors

# Attenuation length of photons

Mass absorption coefficient $\lambda = 1/(\mu/\rho)$ [g.cm²] with $\mu = N_A.\sigma/A$

$\sigma_{Ph} \propto \frac{Z^5}{E^{3.5}}$ $\quad \sigma_{Compton} \propto \frac{\ln E}{E} \cdot Z$ $\quad \sigma_{Pair} \propto Z^2$



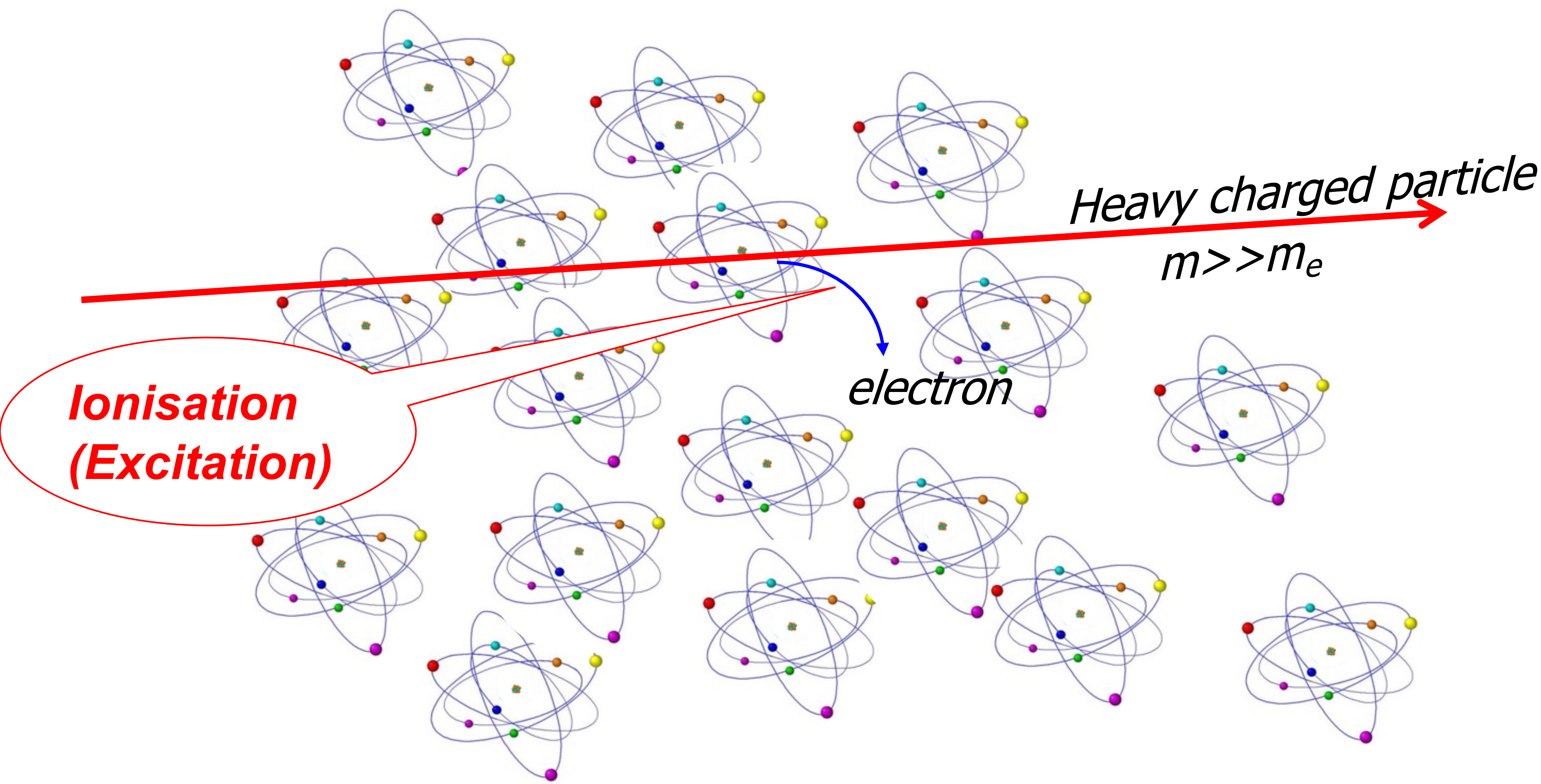

**Intensity (number of γ behind an absorber of depth x)**

$$I = I_o \exp(-x/\lambda)$$

# *Questions ???*

# Charged « heavy particles »

## Coulomb interaction



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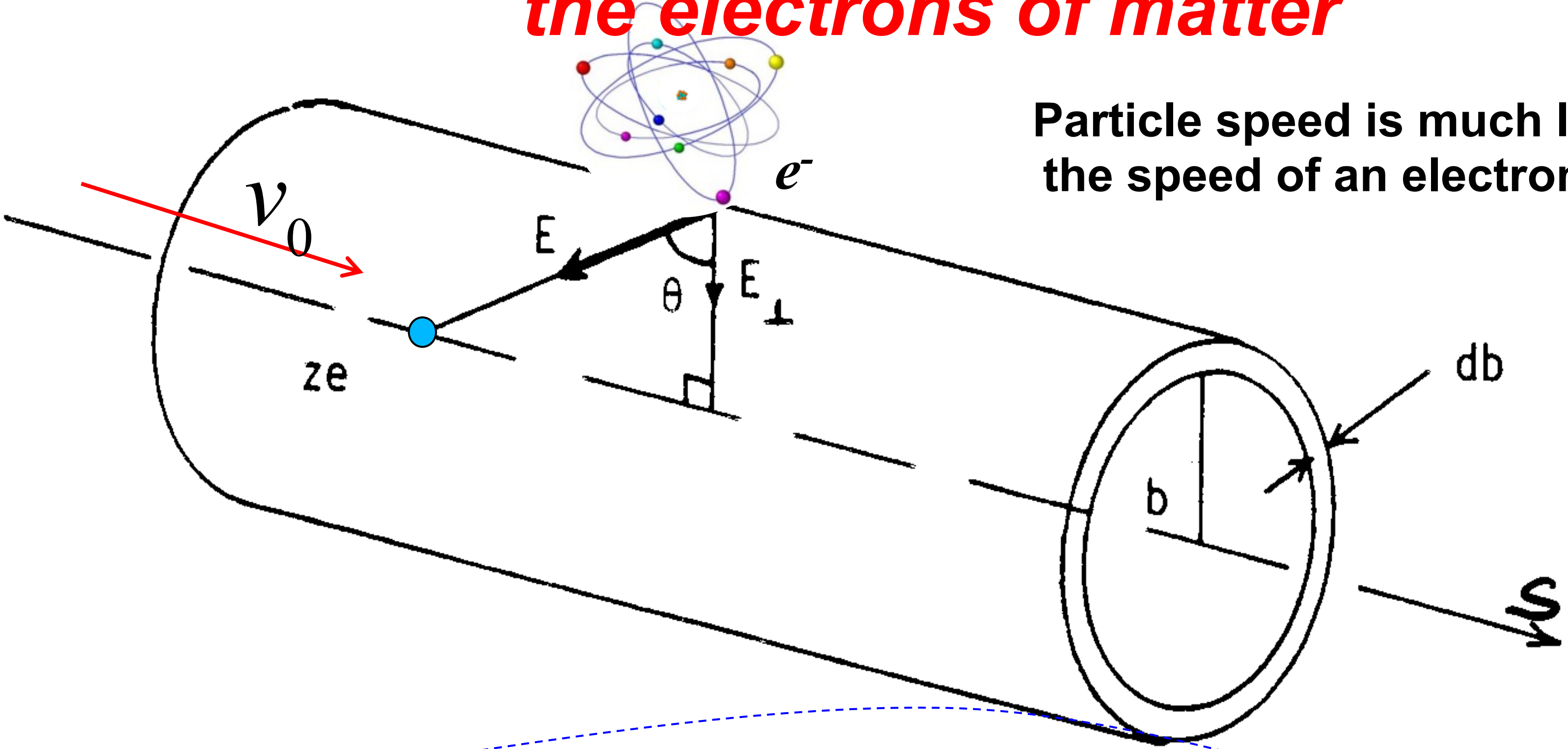
# Interaction of charged "heavy" particles with the electrons of matter

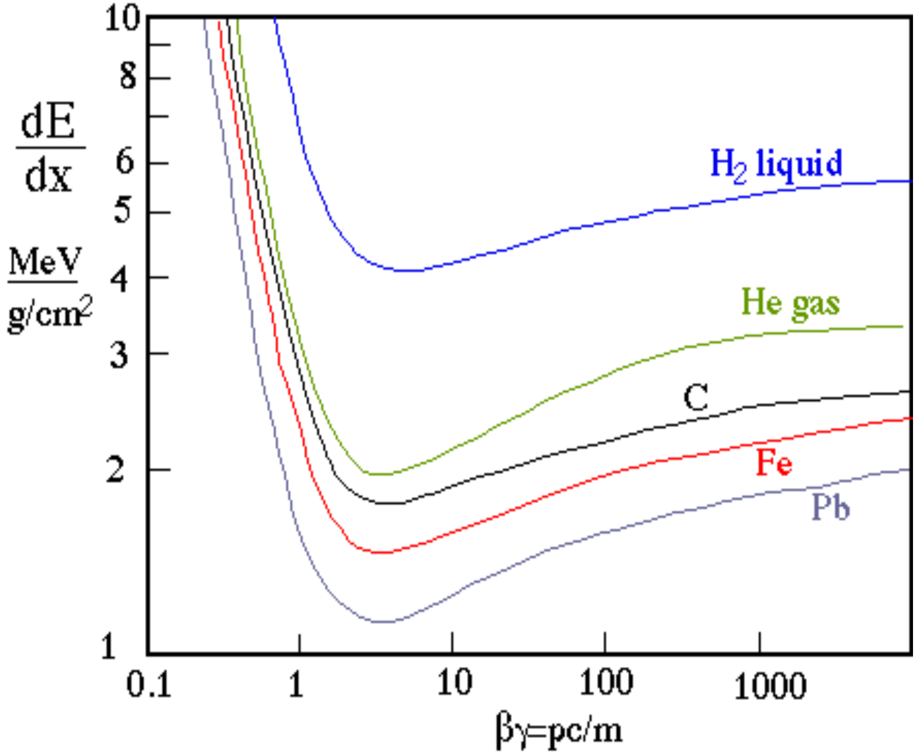



Particle speed is much larger than the speed of an electron bound to a nucleus

$$-\frac{dE}{ds} = -\int_0^\infty \frac{dE}{db} db = \frac{4\pi z^2 e^4 k^2}{m_e v_0^2} n_e \ln \frac{b_{max}}{b_{min}}$$

$$k = \frac{1}{4\pi\varepsilon_0}$$

# Bethe – Bloch formula




$x$ = surface density

$$-\frac{dE}{dx} = -\frac{1}{\rho}\frac{dE}{ds}$$

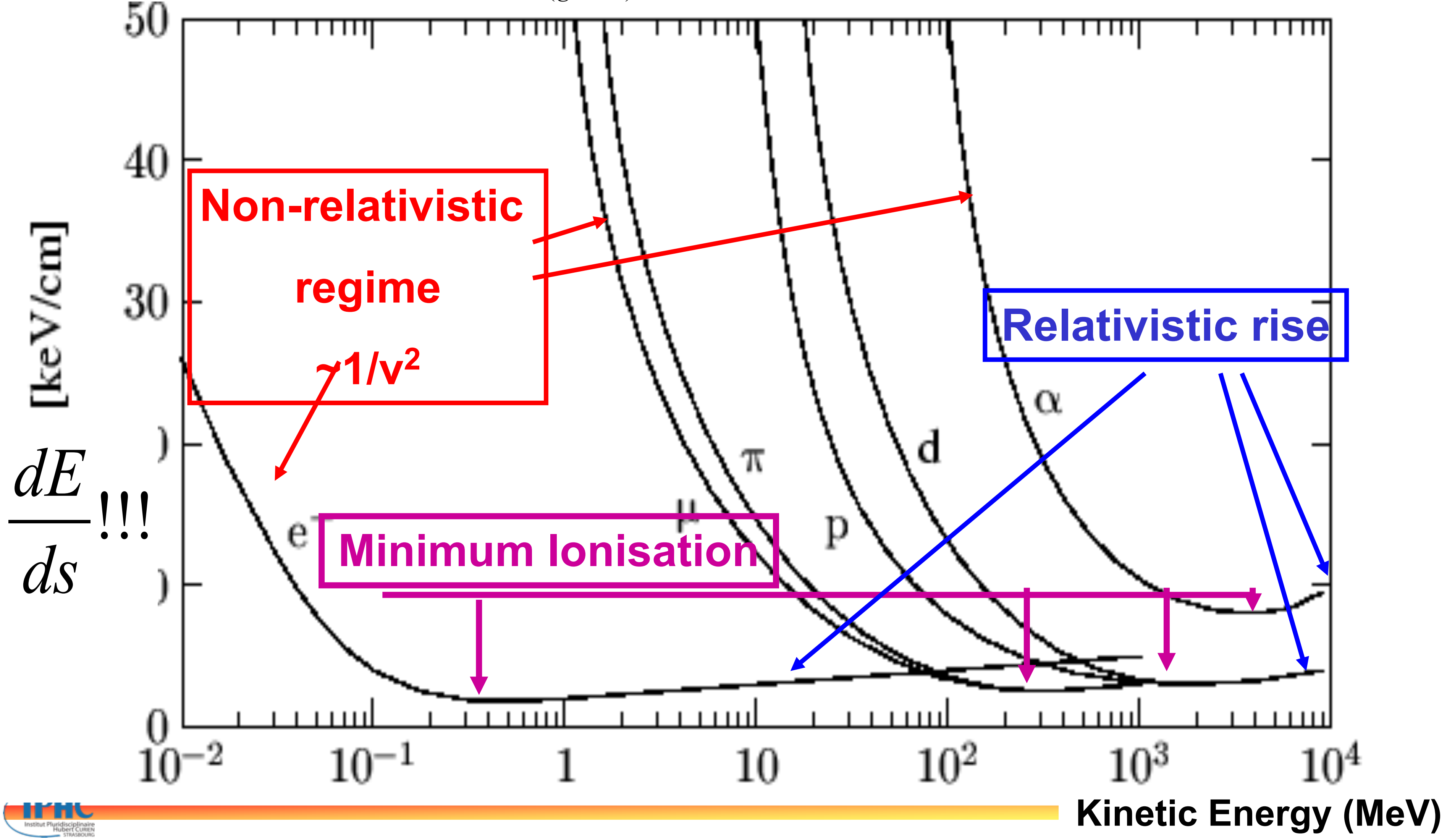
$$n_e = N_A \cdot \rho \cdot \frac{Z}{A}$$

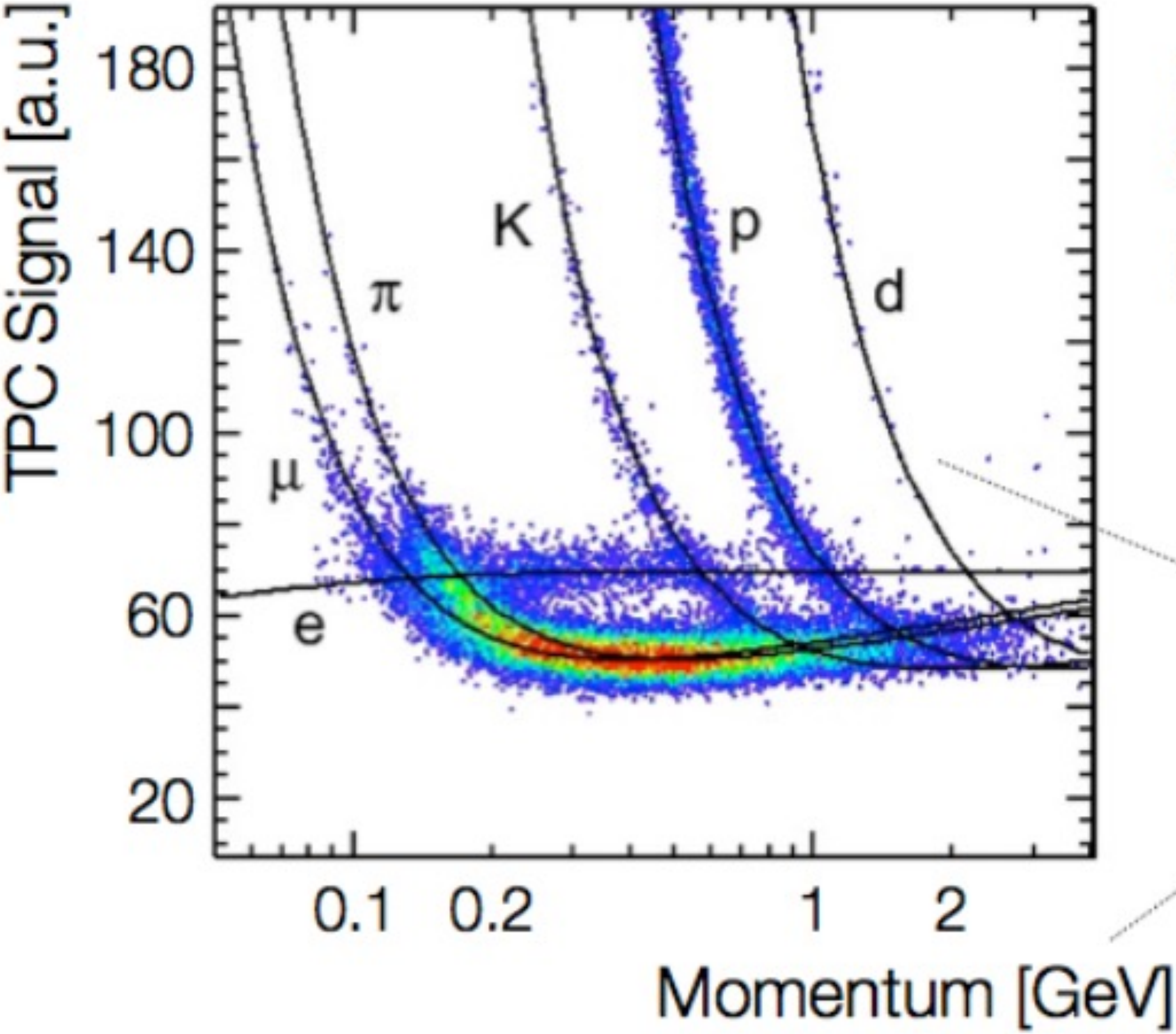
$$r_e = \frac{e^2}{4\pi\varepsilon_0 m_e c^2} = \frac{\alpha\hbar c}{m_e c^2}$$

$$-\frac{1}{\rho}\frac{dE}{ds} = -\frac{dE}{dx} = \underbrace{4\pi N_A r_e^2 m_e c^2}_{0.3071\, MeV/(g/cm^2)} \frac{Z}{A} z^2 \frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\gamma^2\beta^2 \cdot T_e^{\max}}{I^2} - \beta^2 - \frac{\delta}{2} - \frac{C}{Z}\right]$$

*Density-* *shell correction*

$$-\frac{1}{\rho}\frac{dE}{ds} = -\frac{dE}{dx} = \underbrace{4\pi N_A r_e^2 m_e c^2}_{0.3071\,MeV/(g/cm^2)} \frac{Z}{A} z^2 \frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\gamma^2\beta^2\cdot T_e^{\max}}{I^2} - \beta^2 - \frac{\delta}{2} - \frac{C}{Z}\right]$$





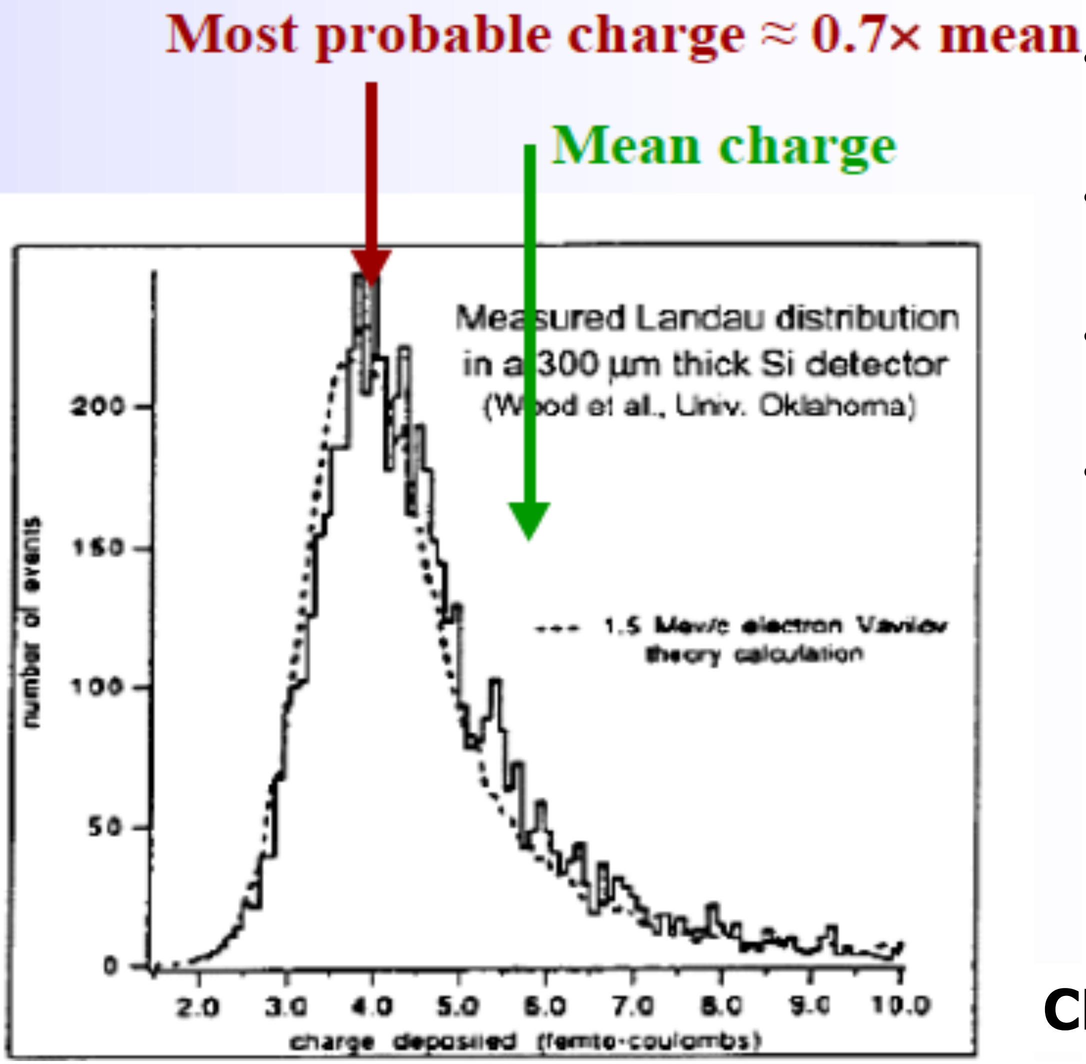

Measured
energy loss

[ALICE TPC, 2009]

Bethe-Bloch

Remember:
dE/dx depends on β!

# Fluctuations of energy loss by charged particles




**Mean / average energy loss is predicted by Bethe-Bloch formula**

- Large fluctuations of energy loss, specially in thin layers
- Results from the stochastic nature of collisions.
- Large transfer of energy can occur in a single collision
- If the number of collisions becomes very large the distribution approaches a Gaussian (Central Limit Theorem).

**CMS silicon detector**

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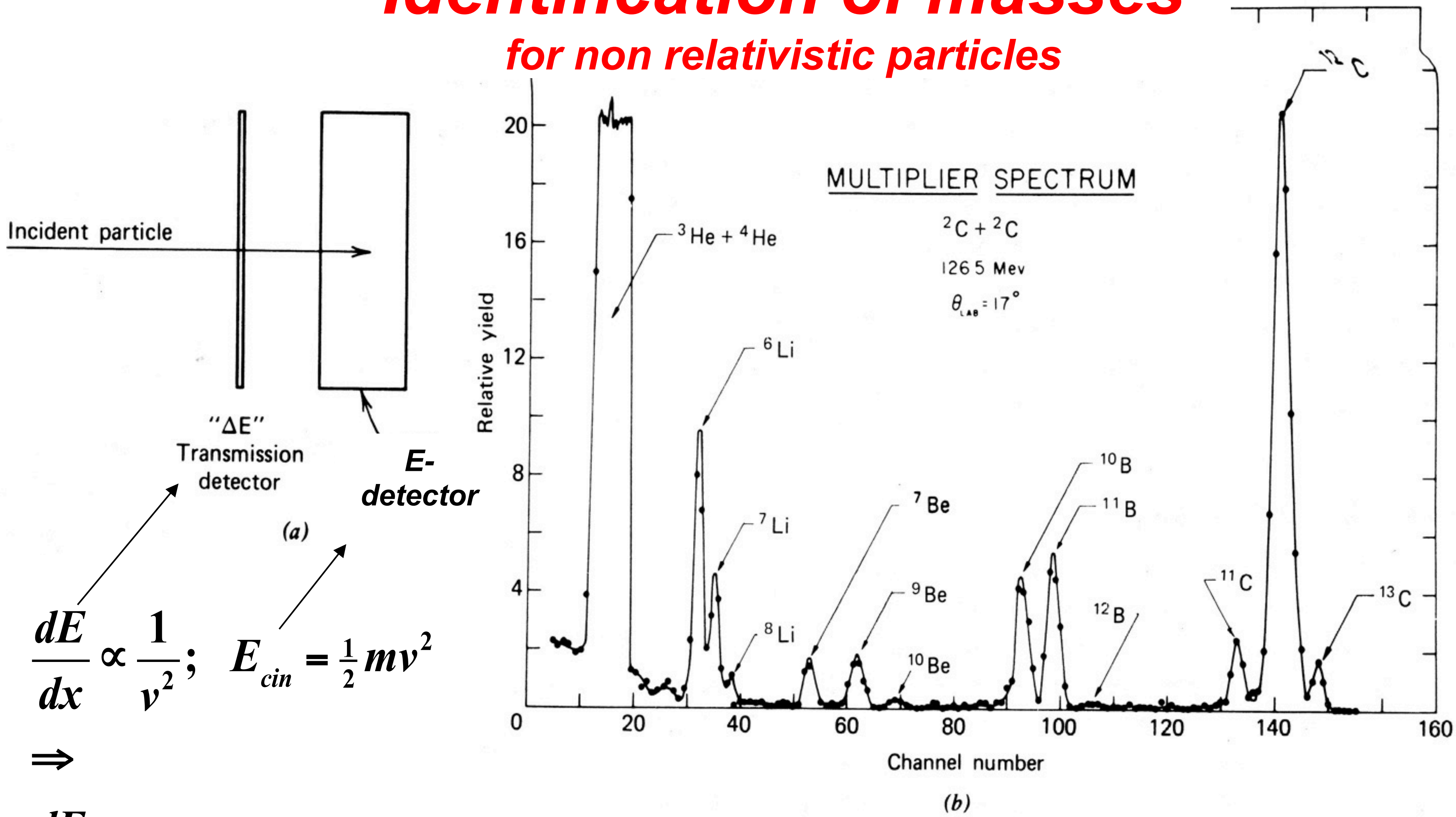
# Identification of masses

## for non relativistic particles




$$\frac{dE}{dx} \propto \frac{1}{v^2}; \quad E_{cin} = \frac{1}{2} m v^2$$

$$\Rightarrow$$

$$\frac{dE}{dx} \times E_{cin} \propto m$$

**Figure 11-16** (a) A particle identifier arrangement consisting of tandem $\Delta E$ and $E$ detectors operated in coincidence. (b) Experimental spectrum obtained for the $\Delta E \cdot E$ signal product for a mixture of different ions. (From Bromley.[90])

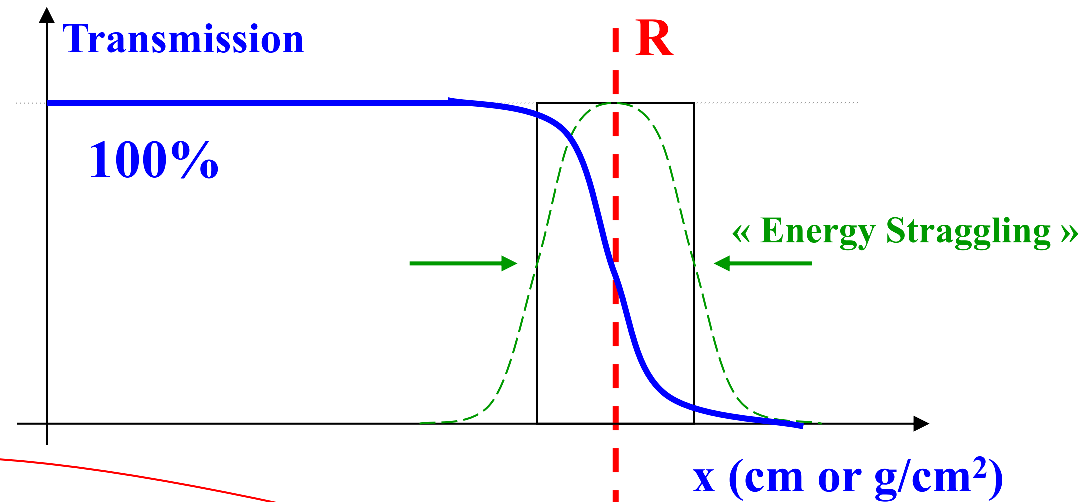
Ulrich.Goerlach@iphc.cnrs.fr, ASP Particle detectors

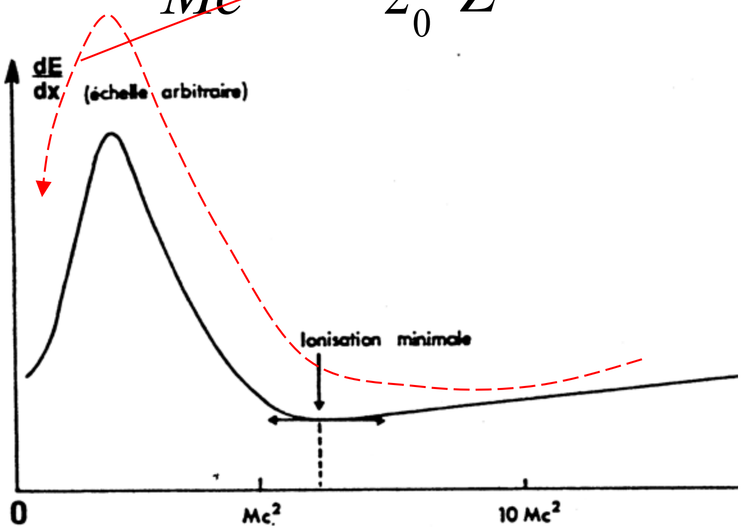
# Range of charged particles is a very well defined quantity

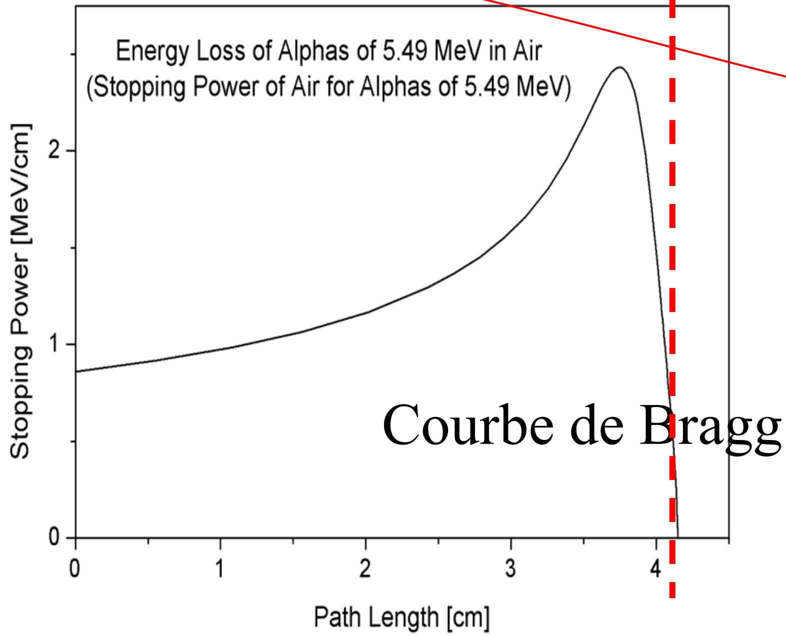
$$< R >= \int_{E_0}^{0} \left( \frac{dE}{dx} \right)^{-1} dE$$

$$\frac{< R > \rho}{Mc^2} \sim \frac{1}{z_0^2} \frac{A}{Z} f(\beta_0 \gamma_0)$$

## Range of heavy charged particle



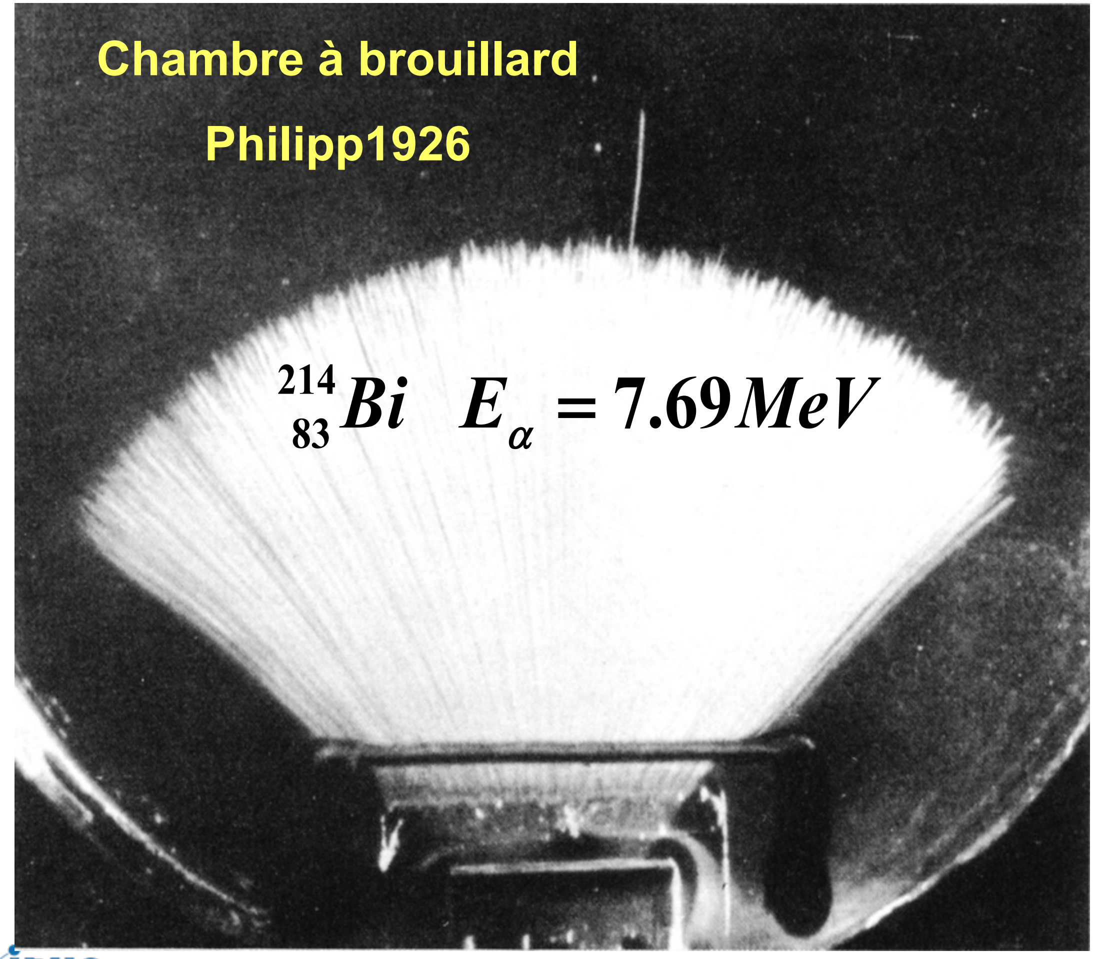



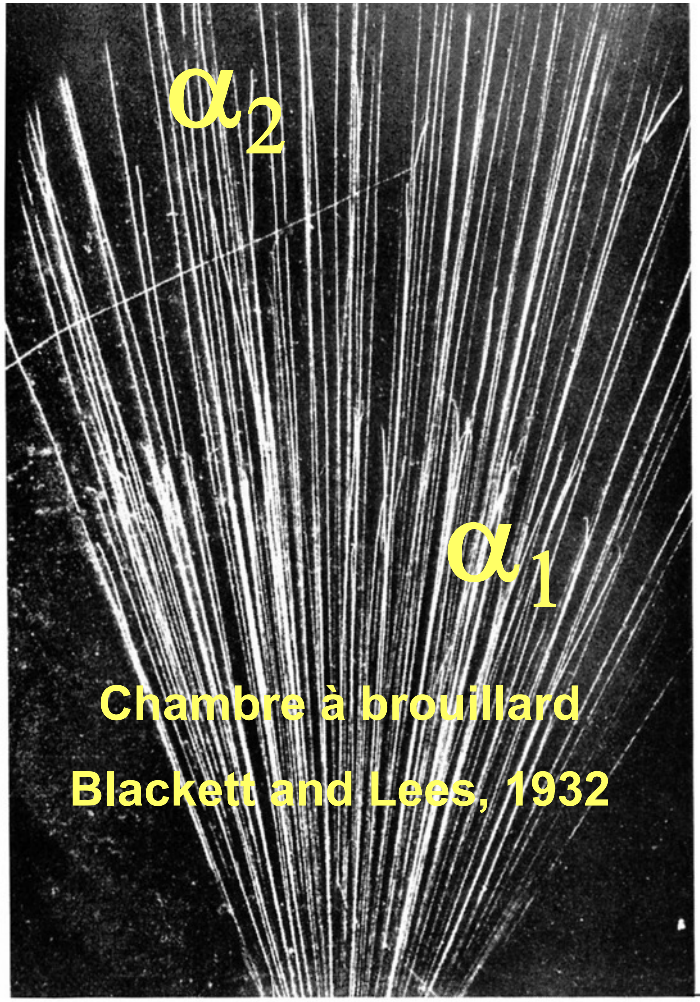
$$^{212}_{82}Pb$$

# Cloud Chamber

$$\xrightarrow{\beta^-} {}^{212}_{83}Bi \quad E_\alpha = 6.09\,MeV$$

$$\xrightarrow{\beta^-} {}^{212}_{84}Po \quad E_\alpha = 8.78\,MeV$$

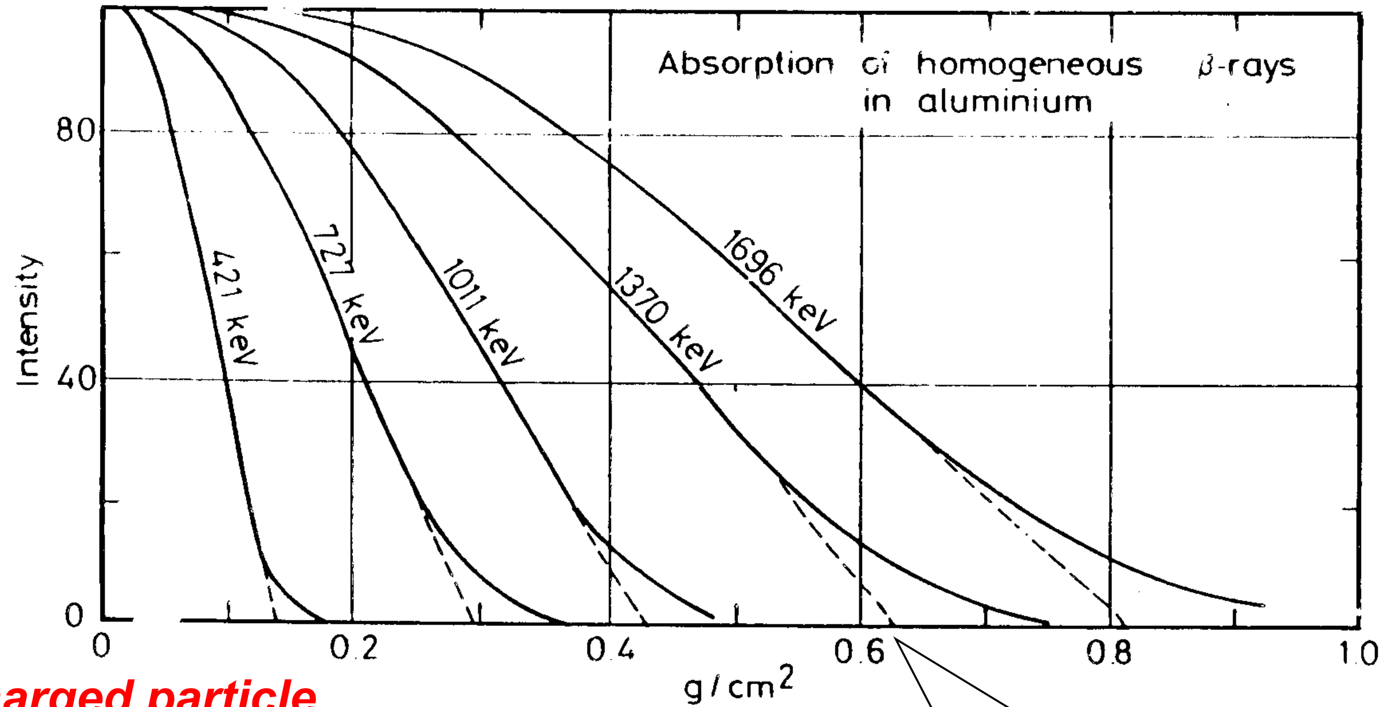


# Electrons

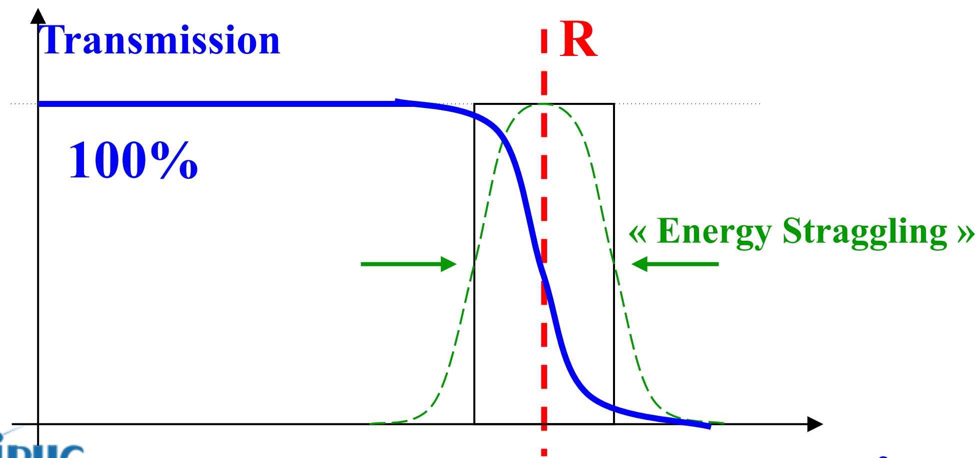
- Electron – electron collisions
- Identical particles / equal masses
- Higher energy transfer
- Larger directional changes
- Badly defined trajectory

# Low energy electrons




**Definition of an efective range**

*Range of heavy charged particle*



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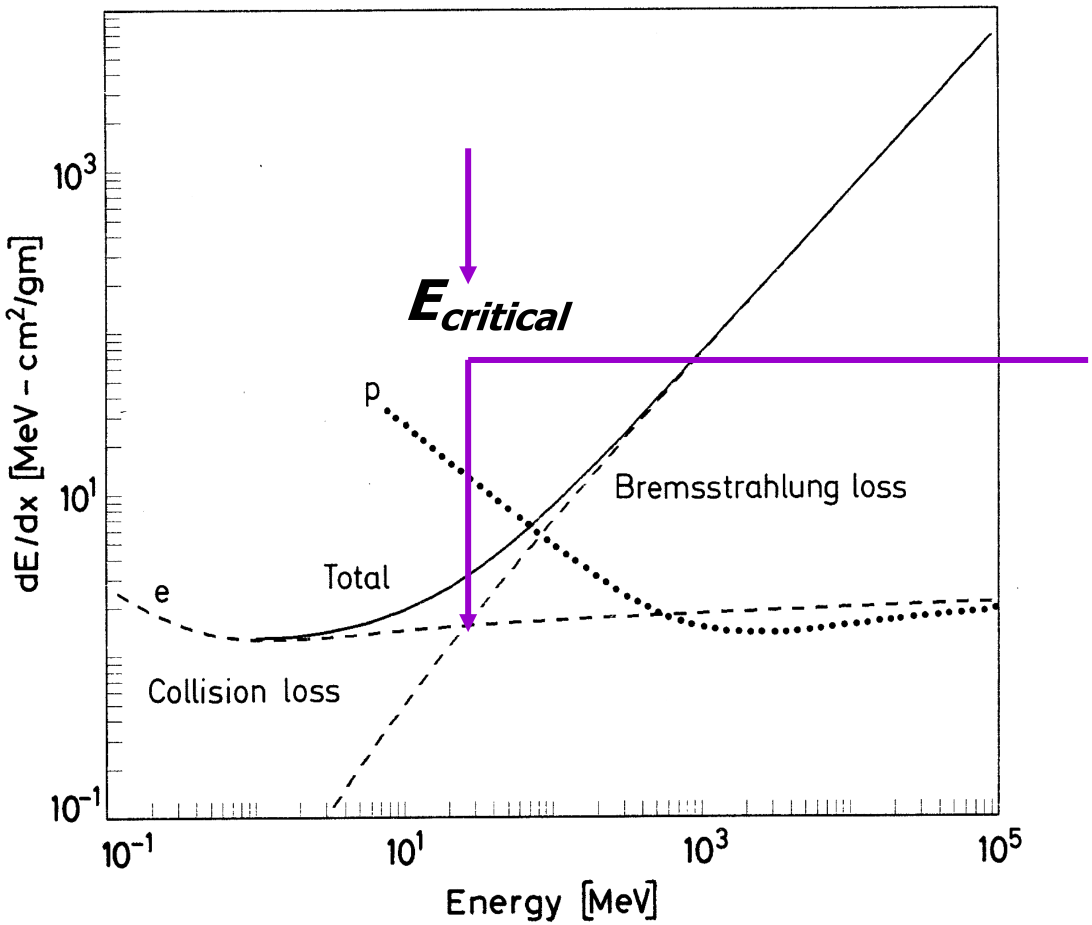
# High energy electrons: Bremsstrahlung

$$\frac{dE^{rad}}{dx} = -\frac{dE^{e^-}}{dx} = \frac{E^{e^-}}{X_0} \Rightarrow E^e(x) = E_0^e \exp(-x / X_0)$$

**$X_0$ = radiation length**




$$\frac{dE^{rad}}{dx} = 4\alpha N \frac{Z^2}{A} z^2 r^2 E \ln\left(\frac{183}{Z^{1/3}}\right)$$

$$r_e = \frac{e^2}{4\pi\varepsilon_0 m_e c^2}$$

$$E_{critical} \sim \left(\frac{m_{particle}}{m_{electron}}\right)^2 \frac{1}{Z}$$

For muons the critical energy is about 200 GeV !

$$E_c = \frac{610\ MeV}{Z+1{,}24}$$ Liquids and solids

$$E_c = \frac{710\ MeV}{Z+0{,}92}$$ Gas

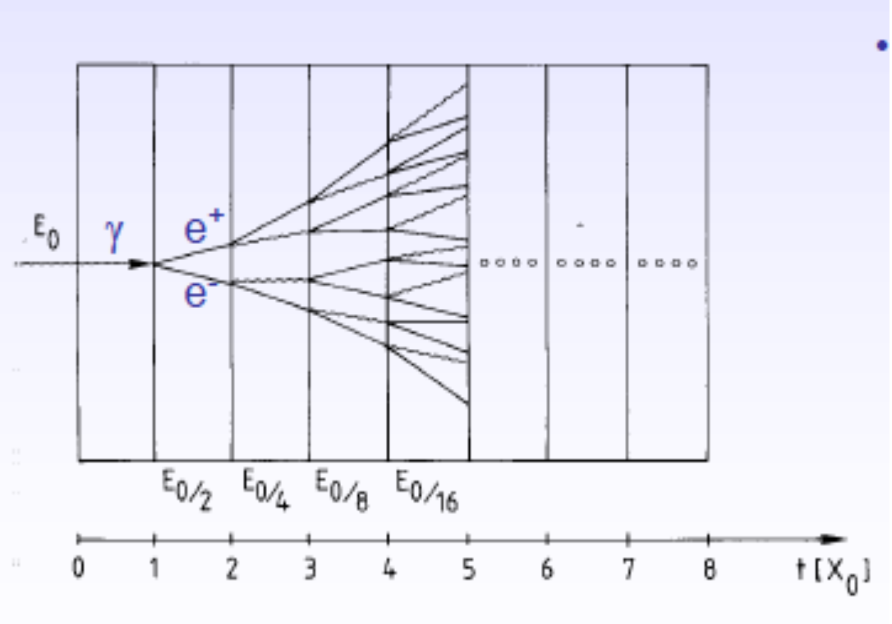
Ulrich.Goerlach@iphc.cnrs.fr, ASP Particle detectors

# Interaction of electrons:

# radiation length and critical energy

| *milieu* | *Z* | *A* | $X_0$ ($g/cm^2$) | $X_0$ (cm) | $E_C$ (MeV) |
|---|---|---|---|---|---|
| hydrogène | 1 | 1.01 | 63 | 700000 | 350 |
| hélium | 2 | 4 | 94 | 530000 | 250 |
| lithium | 3 | 6.94 | 83 | 156 | 180 |
| carbone | 6 | 12.01 | 43 | 18.8 | 90 |
| azote | 7 | 14.01 | 38 | 30500 | 85 |
| oxygène | 8 | 16 | 34 | 24000 | 75 |
| aluminium | 13 | 26.98 | 24 | 8.9 | 40 |
| silicium | 14 | 28.09 | 22 | 9.4 | 39 |
| fer | 26 | 55.85 | 13.9 | 1.76 | 20.7 |
| cuivre | 29 | 63.55 | 12.9 | 1.43 | 18.8 |
| argent | 47 | 109.9 | 9.3 | 0.89 | 11.9 |
| tungstène | 74 | 183.9 | 6.8 | 0.35 | 8 |
| plomb | 82 | 207.2 | 6.4 | 0.56 | 7.4 |
| air | 7.3 | 14.4 | 37 | 30000 | 84 |
| silice ( $SiO_2$) | 11.2 | 21.7 | 27 | 12 | 57 |
| eau | 7.5 | 14.2 | 36 | 36 | 83 |

# Electromagnetic shower




$N(t) = 2^t \qquad E(t)/particle = E_0 \cdot 2^{-t}$

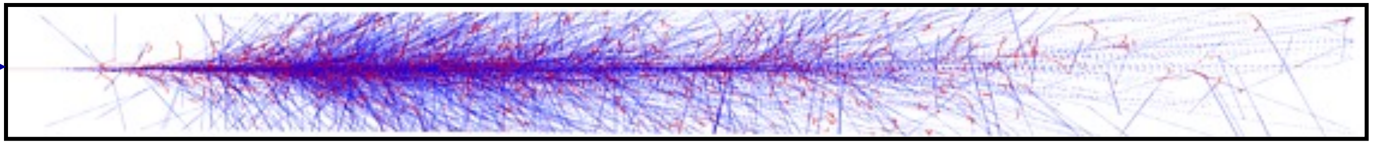
Process continues until $E(t)<E_c$

$$N^{total} = \sum_{t=0}^{t_{max}} 2^t = 2^{(t_{max}+1)} - 1 \approx 2 \cdot 2^{t_{max}} = 2\frac{E_0}{E_c}$$

$$t_{max} = \frac{\ln E_0/E_c}{\ln 2}$$

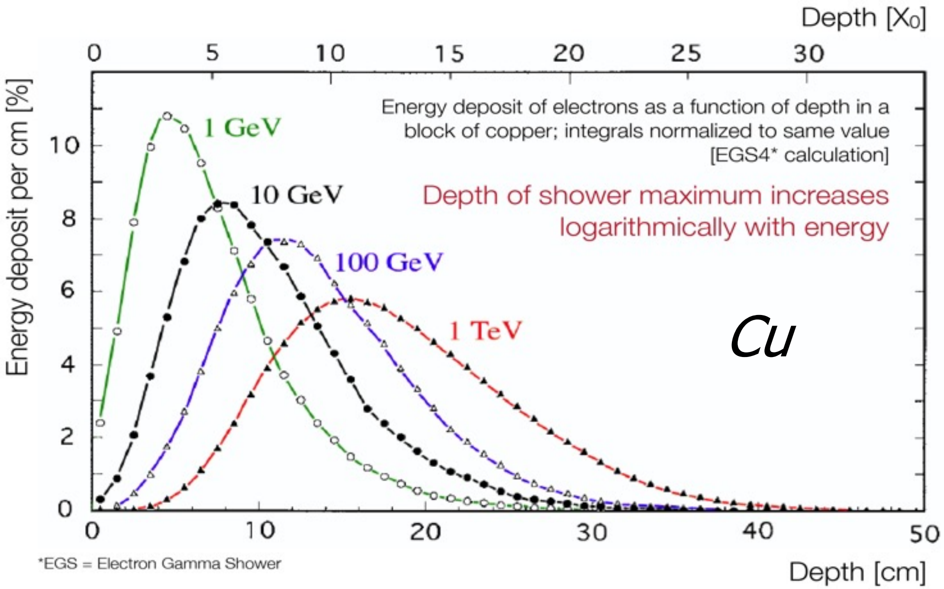
**$PbW0_4$ CMS, $X_0$=0.89 cm**

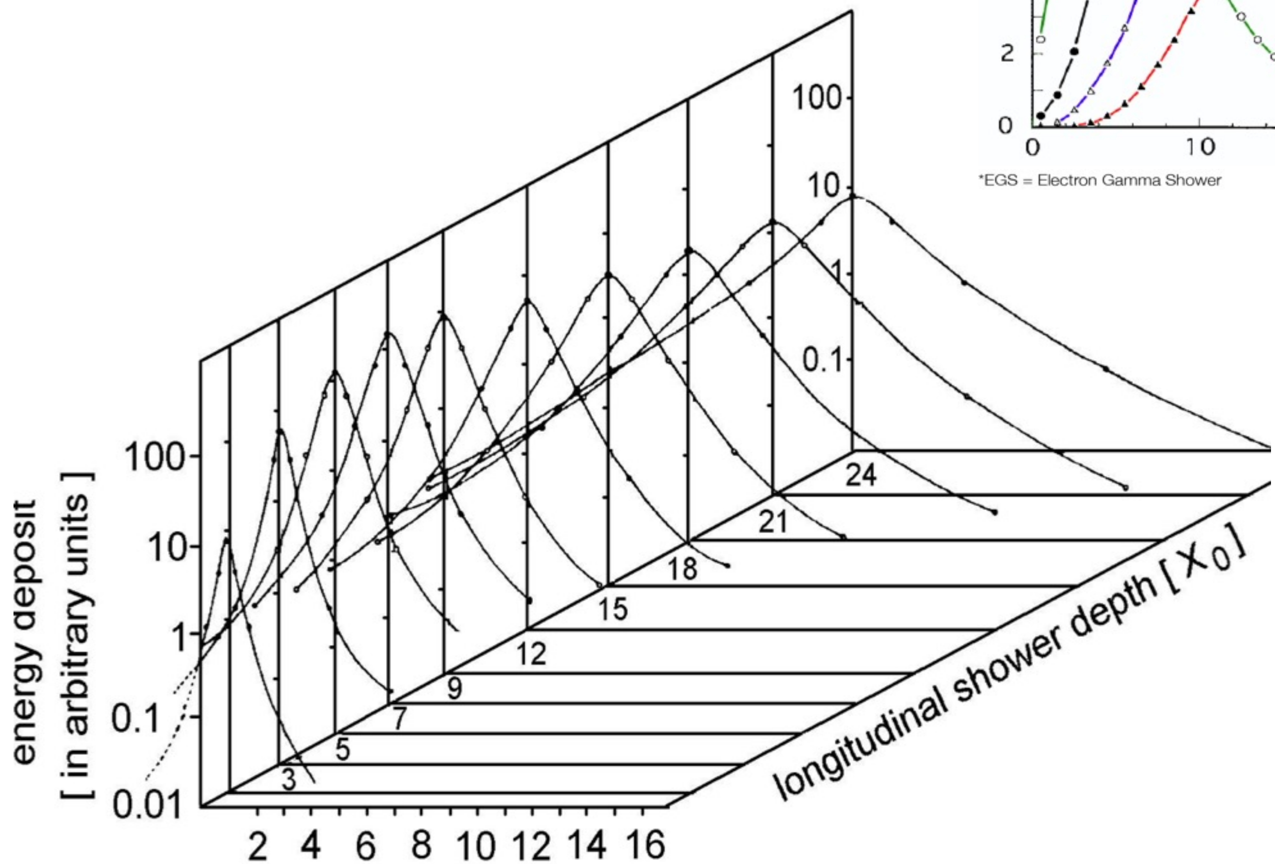
*e, γ*



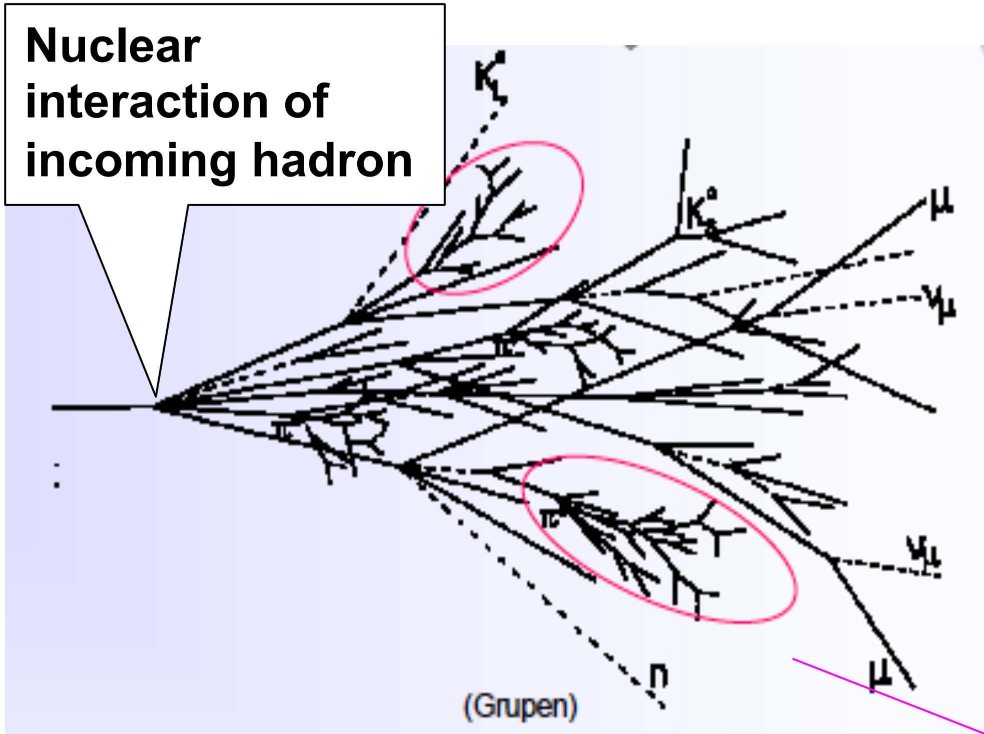
# 95% in a cylinder of $R_M$

$$R_M = \frac{21\,\text{MeV}}{E_c} X_0 \quad [g/cm^2]$$




$$t_{max} = \ln\frac{E_0}{E_c}\frac{1}{\ln 2}$$




# Hadronic showers

**This is NOT(!) a parton shower !!!**

hadronic + electromagnetic

$$N(x) = N_0 \exp(-x/\Lambda) \; ; \; \frac{1}{\Lambda} = \sigma_{int} \cdot n_b$$

$$\Lambda \gg X_0$$

- charged hadrons p, $\pi^{\pm}$, $K^{\pm}$,
- nuclear fragmets ….
- breaking up of nuclei (binding energy)
- neutrons, neutrinos, soft $\gamma$'s, muons

**$\Lambda$ = nuclear interaction length**

neutral pions $\rightarrow 2\gamma$

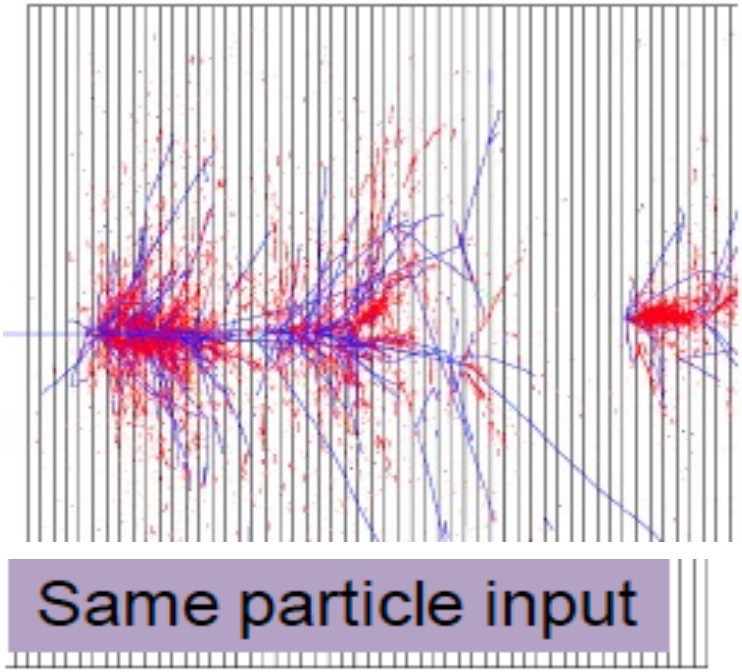
$\rightarrow$ electromagnetic cascades

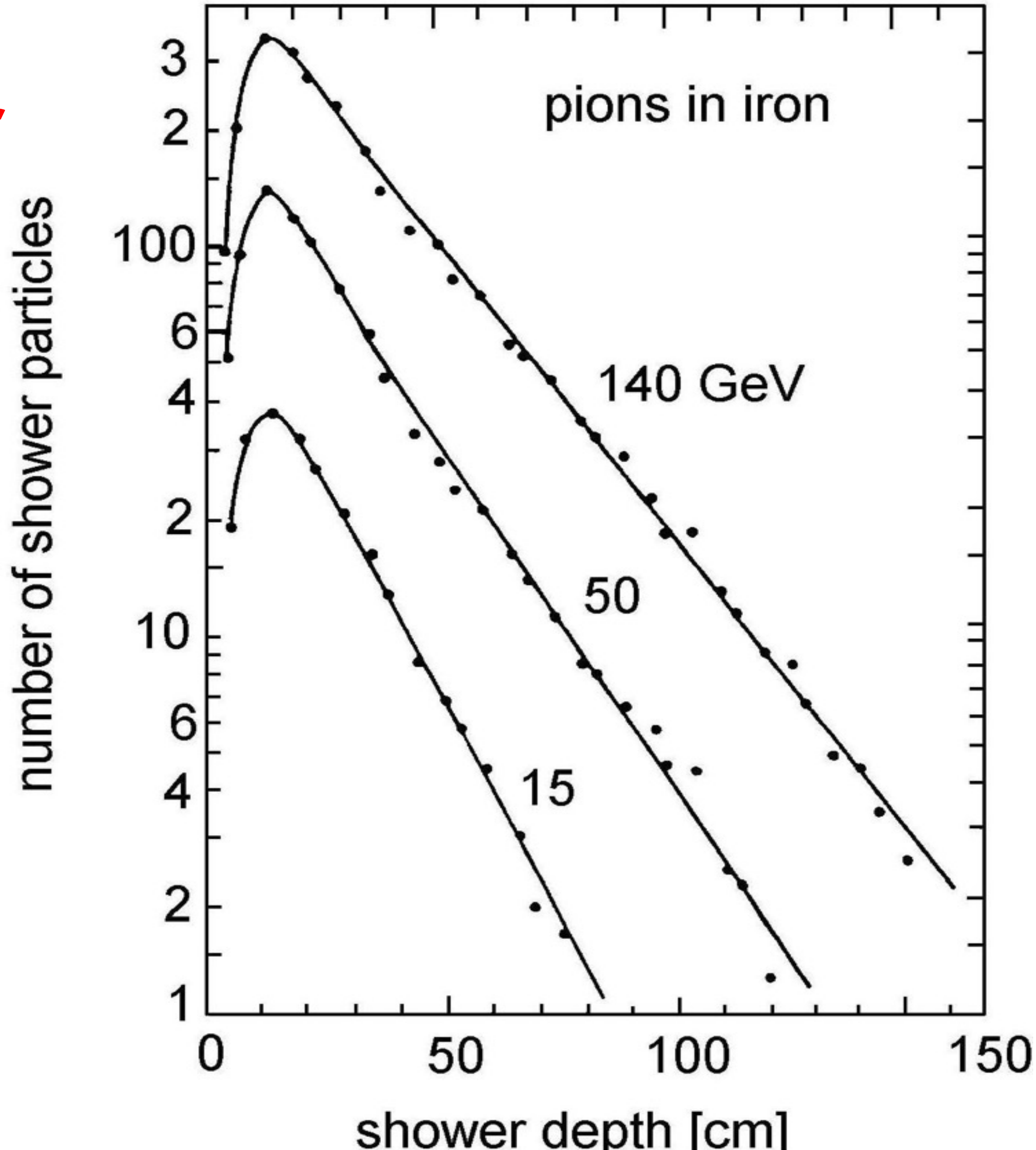
$$n(\pi^0) \approx \ln E(GeV) - 4.6$$

example $E = 100$ GeV: $n(\pi^0) \approx 18$

$\rightarrow$ invisible energy $\rightarrow$ large energy fluctuations $\rightarrow$ limited energy resolution

# Hadronic shower

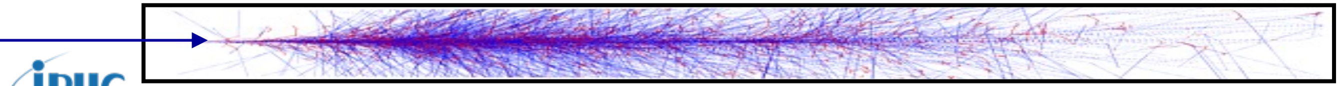



$\Lambda \gg X_0$

red - e.m. com
blue - charged

**Comparison elm shower:**



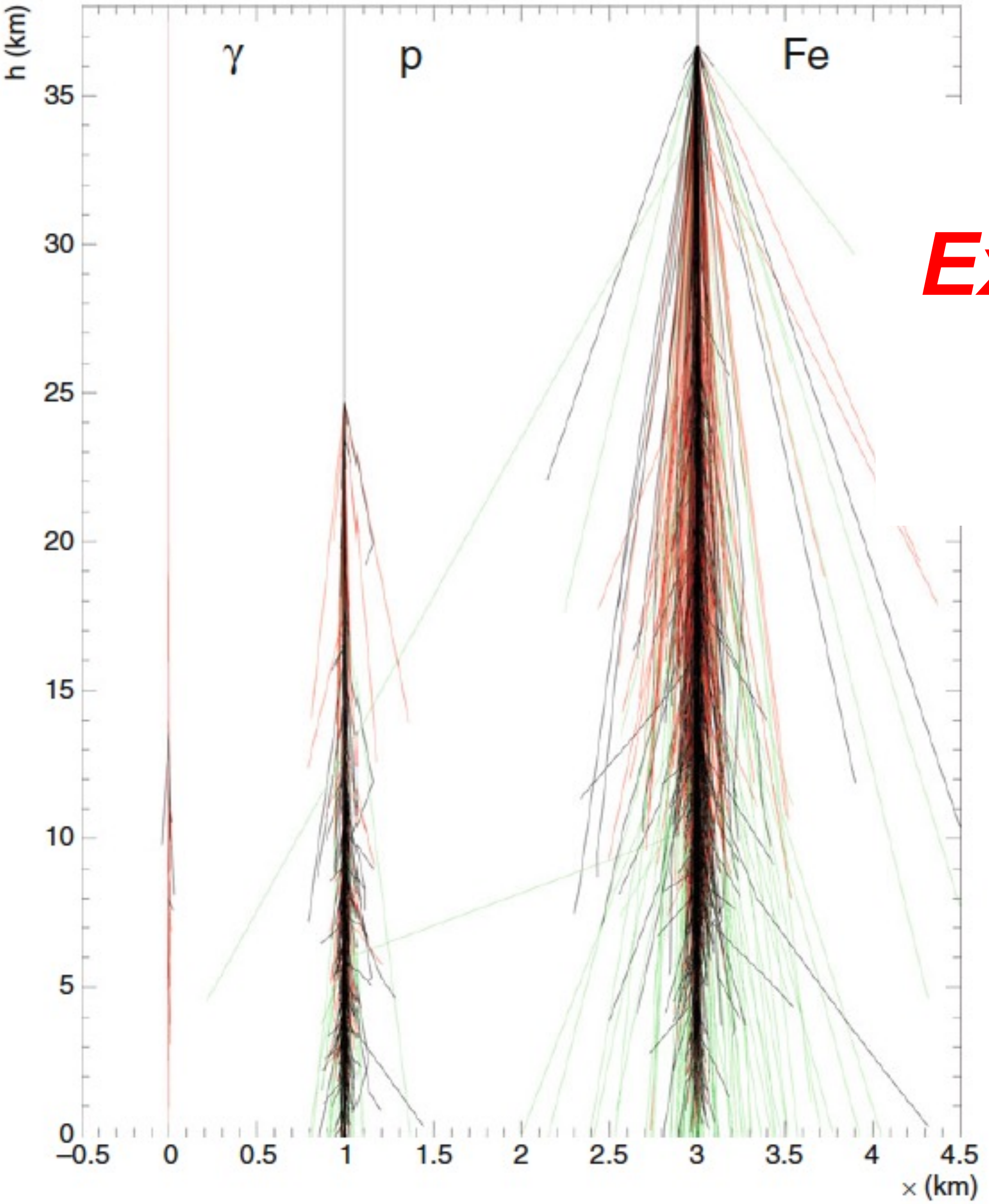


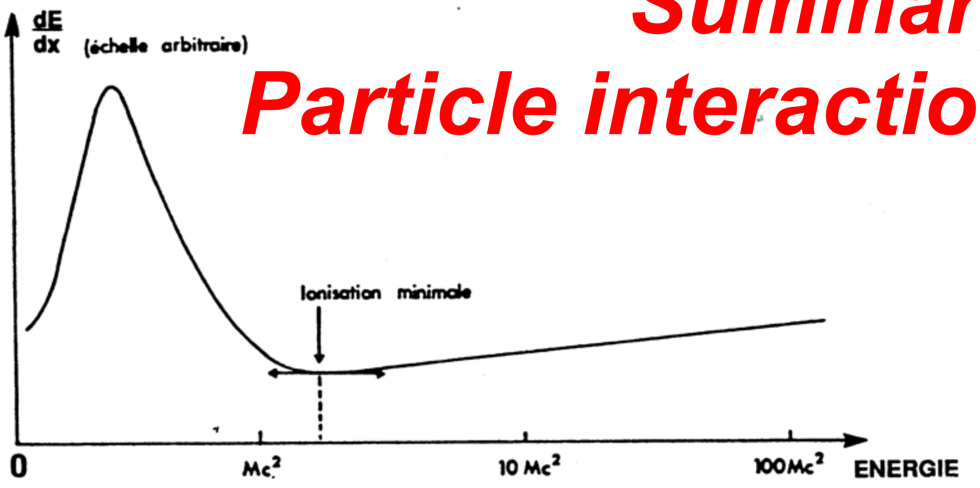

**Fig. 1.11** Side view of trajectories of particles of energy ≥10 GeV of a photon, a proton and an iron nucleus initiated shower having a total primary energy of $10^5$ GeV each. The electromagnetic component is shown in *red*, hadrons are *black* and muons *green*. The widely spread particles in the lower region of the atmosphere in the hadron showers are mostly muons (courtesy of KASCADE group)

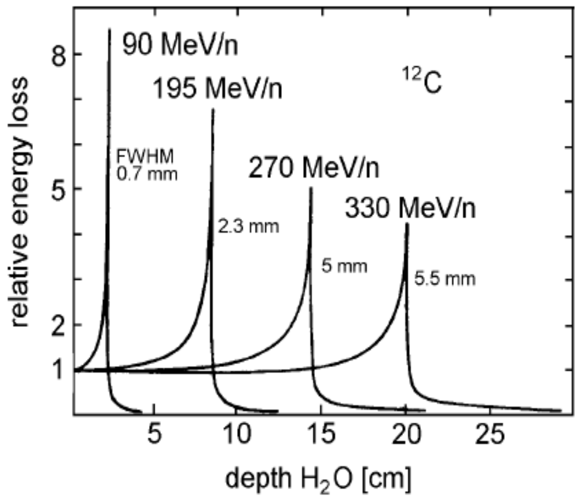
# Extensive Air shower $10^{14}$ eV

**The atmosphere as a big calorimeter**

**See lecture on astroparticles**

# Summary (I)
# Particle interaction with matter

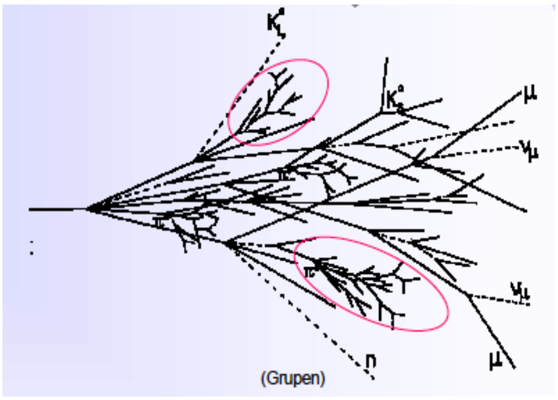



## Heavy charged particles

- loose continuously kinetic energy along their path (ionization) with small fluctuations until they are stopped after a well defined distance; until that point their number remains constant and they travel on a straight line.
- At high energies also hadronic interactions may occur, leading to an hadronic shower :

$$N(x) = N_0 \exp\left(-x/\Lambda\right) \;;\qquad \frac{1}{\Lambda} = \sigma_{\text{int}} \cdot n_b$$



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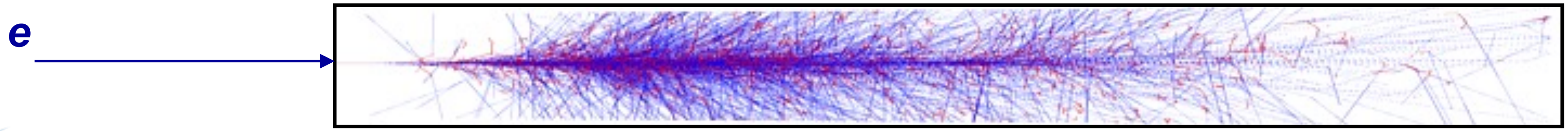
# Summary(II)
# Particle interaction with matter

## Electrons

- also loose their energy by ionization but with much larger fluctuations in the energy loss and deflections leading to a badly defined range in matter.
- At energies higher than a critical energy Bremsstrahlung is emitted. This process becomes rapidly dominant.
- Multiple pair creation and Bremsstrahlung will lead to extended electromagnetic showers characterized by the "radiation length $X_0$"
- The energy of the incoming electron (not the number !) decreases exponentially with the path length.

$$E^e(x) = E_0^e \exp(-x / X_0)$$



# *Summary (III)*
# *Particle interaction with matter*

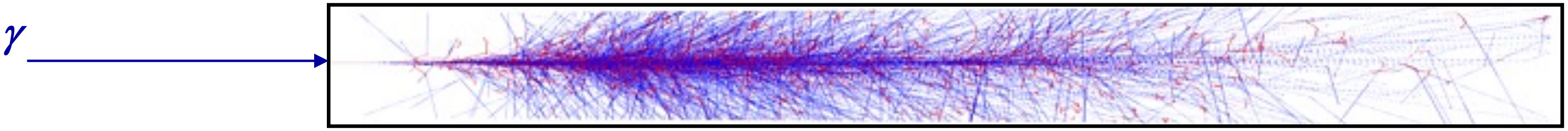
## Photons :

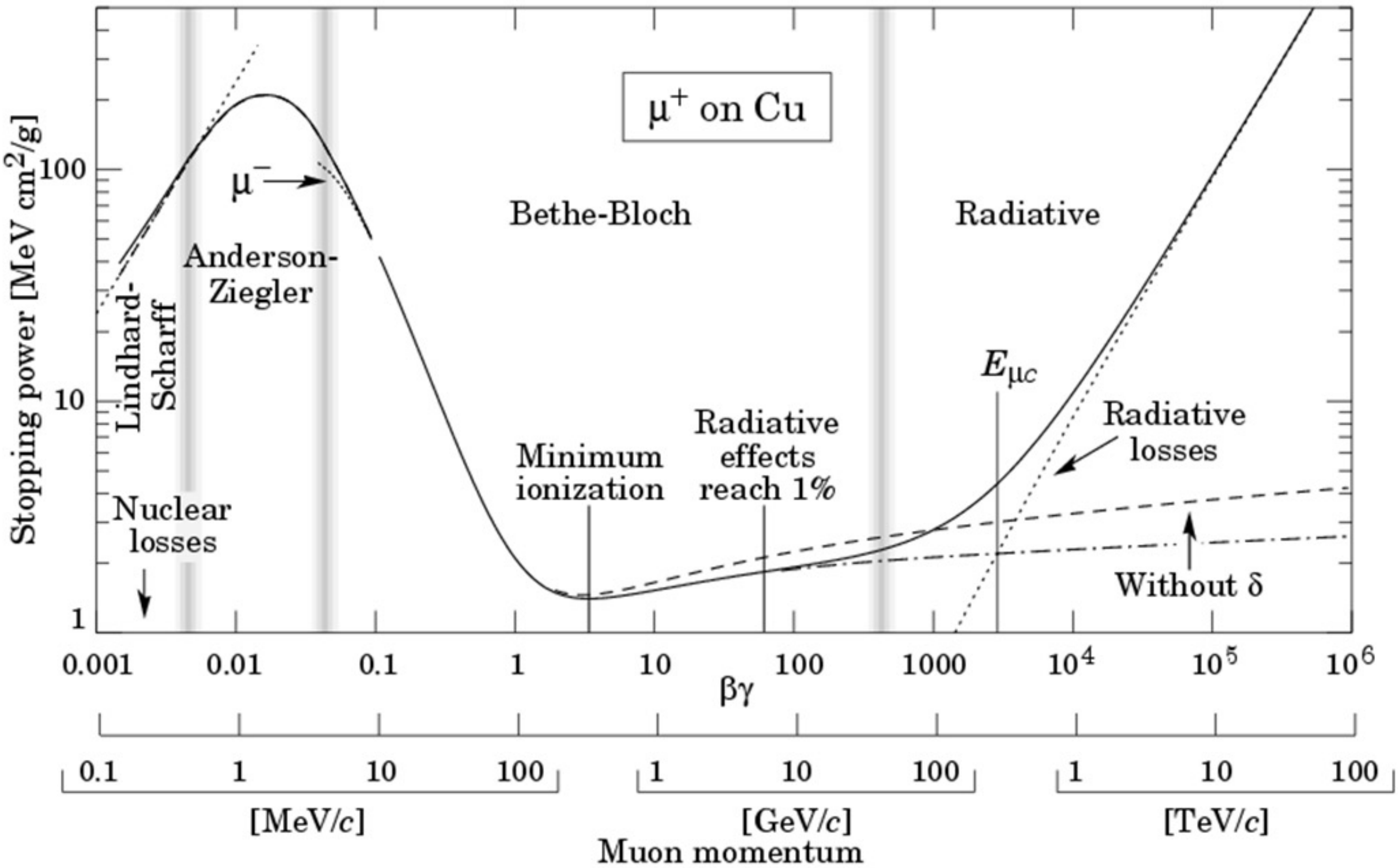
- At low energy (< 10 MeV) photons are absorbed by a single interaction (photoelectric, Compton effect or pair creation). The number of photons is attenuated exponentially, the energy of the remaining photons is not changed, however by the Compton effect lower energy photons are created.

$$N(x) = N_0 \exp(-x/\lambda) \; ; \quad \frac{1}{\mu} = \lambda_{\text{specific process}} = \text{attenuation length}; \quad x = \text{thickness}$$

- At high energy (E>> 10 MeV) successive pair creation followed by electron Bremsstrahlung will lead to extended elm showers characterized by the "radiation length $X_0$"

$\gamma$

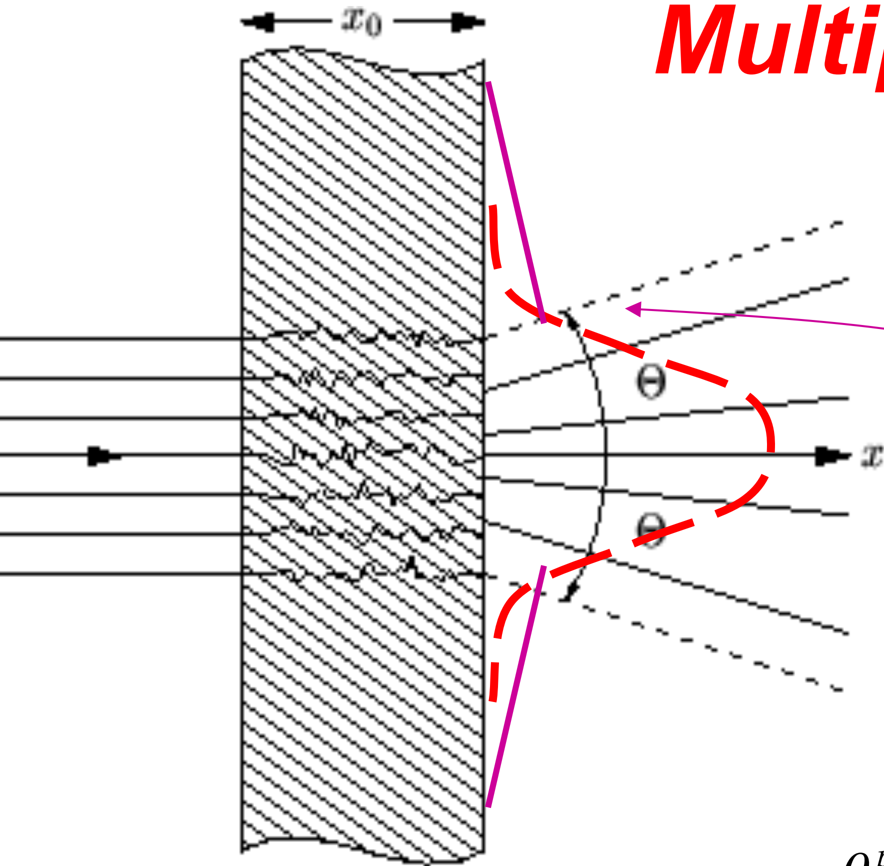



μ+ on Cu
Stopping power [MeV cm²/g]
100
10
1
Lindhard-
Scharff
Anderson-
Ziegler
μ−
Bethe-Bloch
Radiative
Nuclear
losses
Minimum
ionization
Radiative
effects
reach 1%
Eμc
Radiative
losses
Without δ
0.001
0.01
0.1
1
10
100
1000
10⁴
10⁵
10⁶
βγ
0.1
1
10
100
1
10
100
1
10
100
[MeV/c]
[GeV/c]
[TeV/c]
Muon momentum

# Other processes

- Multiple scattering
- Cerenkov radiation
- Transition radiation
- Neutrons
- Neutrinos
- Direct dark matter detection

# Multiple scattering




**Scattering in the coulomb field of the nucleus (Rutherford)**

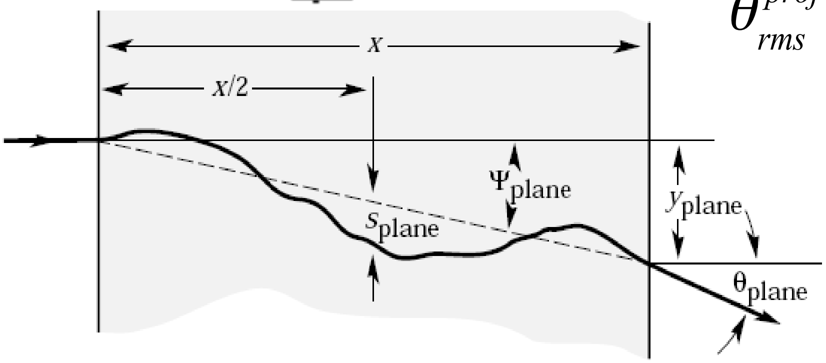
**Gaussian (θ) distribution for small angles θ,**

**Violant scatters can lead to large values of θ**

$$\theta_{rms}^{proj} = \frac{13.6 MeV / c}{p \cdot \beta} z \sqrt{\frac{x}{X_0}} (1 + 0.038 \ln(x / X_0))$$

*z of charged particle*

**$X_0$=radiation length**



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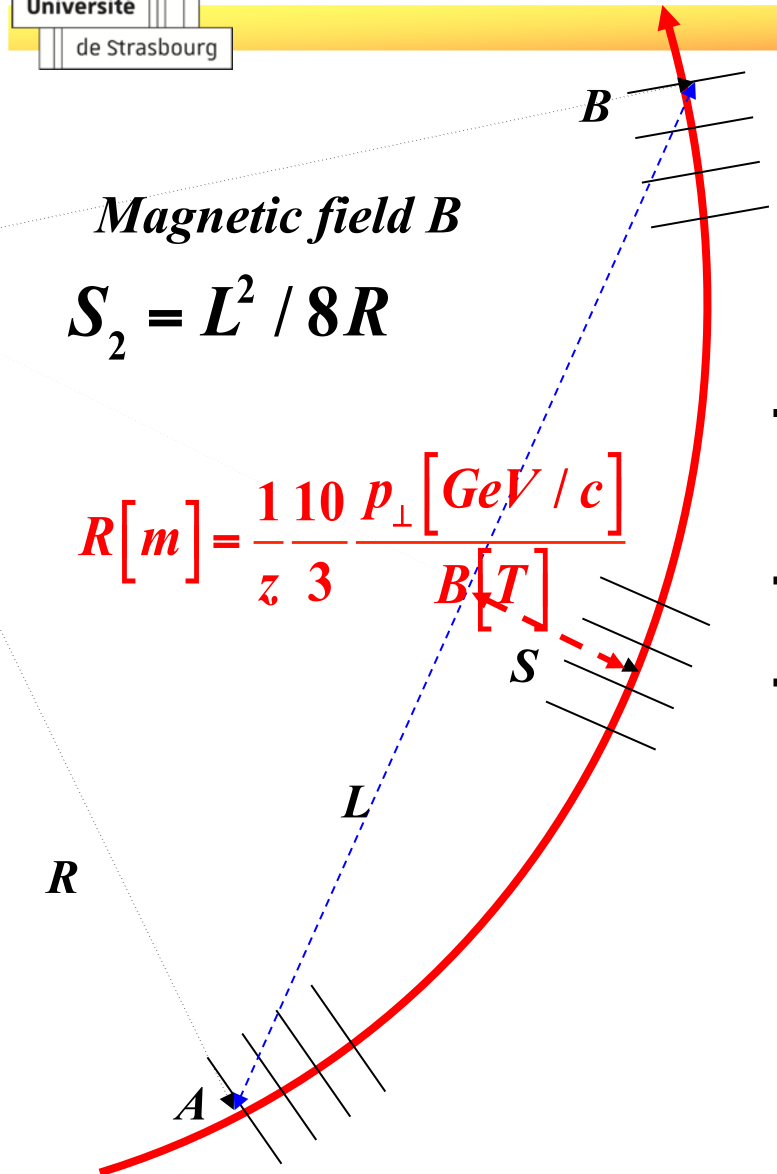
# Reconstruction of transverse momentum in a magnetic field

Exercise !!!




$$S_2 = L^2 / 8R$$

$$R[m] = \frac{1}{z}\frac{10}{3}\frac{p_\perp[GeV/c]}{B[T]}$$

- Movement of a charge $z$ in a uniform magnetic field
- Momentum resolution *dp/p*
- Spatial resolution of the sagitta *dS/S*

$$\frac{dS}{S} = \frac{dp_\perp}{p_\perp} = \frac{80}{3 \cdot z}\frac{1}{BL^2} p_\perp dS$$

$$[B] = Tesla; \ [L] = m; [p_\perp] = GeV/c$$

**If the trajectory is measured with *N* points:**

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma(x) \cdot p_T}{0.3 \cdot BL^2}\sqrt{720/(N+4)} \qquad \text{(for N} \geq \sim 10\text{)}$$

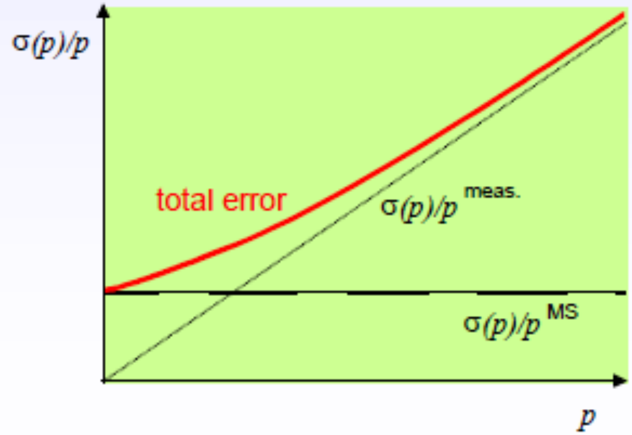
# Resolution and multiple scattering

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma(x)\cdot p_T}{0.3\cdot BL^2}\sqrt{720/(N+4)}$$ (for N ≥ ~10)

$$\left.\begin{array}{l}\dfrac{\sigma(p)}{p_T} \propto \sigma(x)\cdot p_T \\ \sigma(x)\big|^{MS} \propto \theta_0 \propto \dfrac{1}{p}\end{array}\right\} \quad \left.\frac{\sigma(p)}{p_T}\right|^{MS} = \text{constant}$$

, i.e. independent of p !

More precisely: $\left.\frac{\sigma(p)}{p_T}\right|^{MS} = 0.045\frac{1}{B\sqrt{LX_0}}$



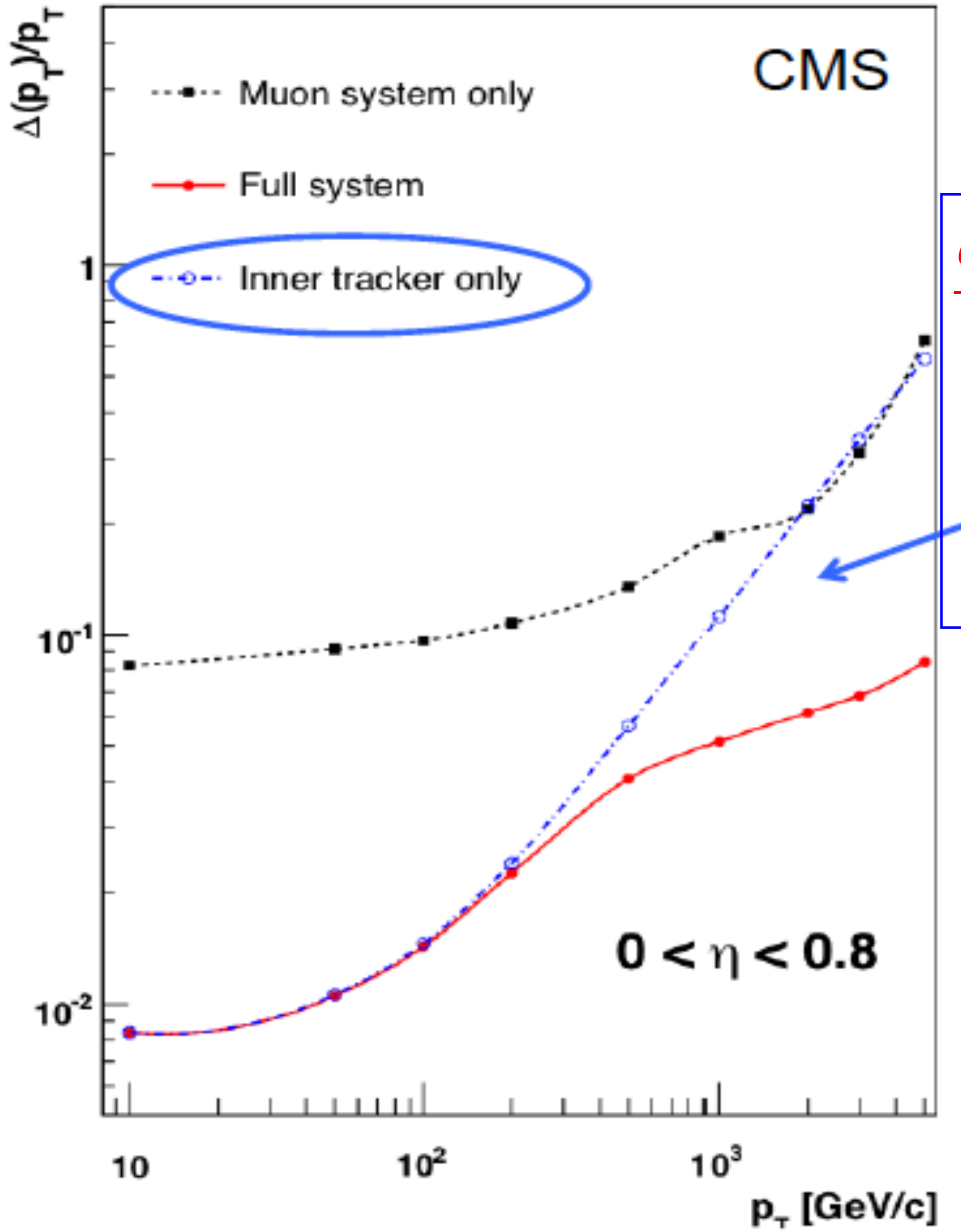

Example:

$p_t = 1$ GeV/c, $L = 1$m, $B = 1$ T, $N = 10$

$\sigma(x) = 200$ µm: $\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} \approx 0.5\%$

Assume detector (L = 1m) to be filled with 1 atm. Argon gas ($X_0$ = 110m),

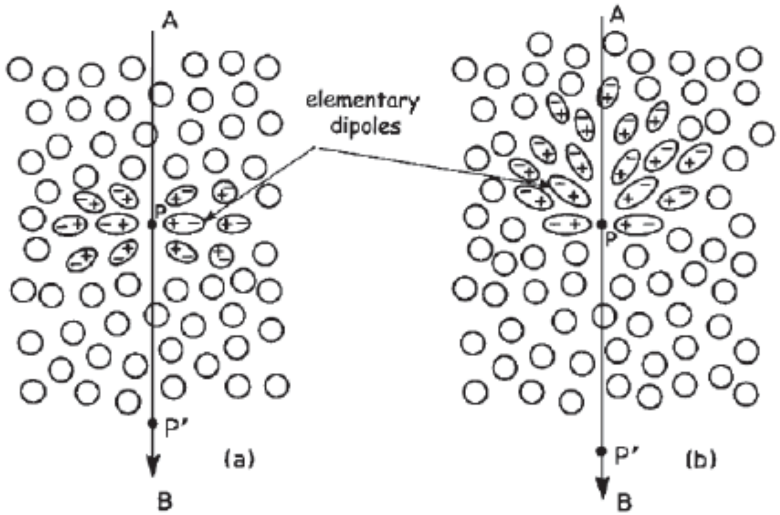
$$\left.\frac{\sigma(p)}{p_T}\right|^{MS} \approx 0.5\%$$



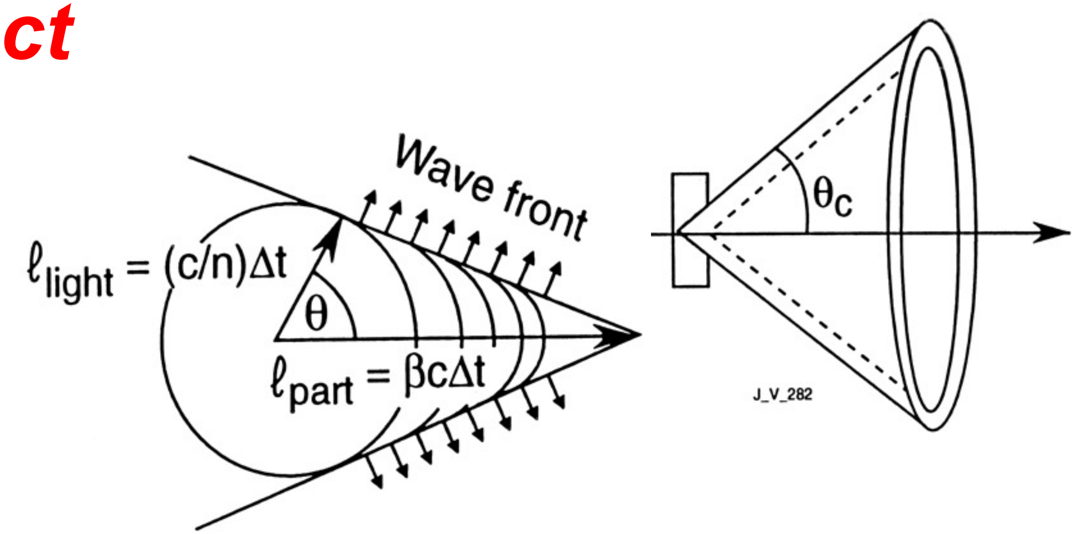

$$\frac{dp_\perp}{p_\perp} = \alpha \times p_\perp dS$$

$$\oplus \left( \begin{array}{c} \text{Multiple scattering} \\ \text{constant} \end{array} \right)$$

# Cerenkov effect




$v_p/c < c/n(\lambda)$ $v_p/c > c/n(\lambda)$




$$v = \beta c > c/n$$

$$\cos\theta_C = \frac{c \cdot \Delta t / n}{\beta c \cdot \Delta t} = \frac{1}{\beta n}$$

$$\Rightarrow \beta > \frac{1}{n}\,;\ \cos\theta_c^{\max} = \frac{1}{n}$$

$$\lambda_{photons} \approx 200 - 700\,nm$$

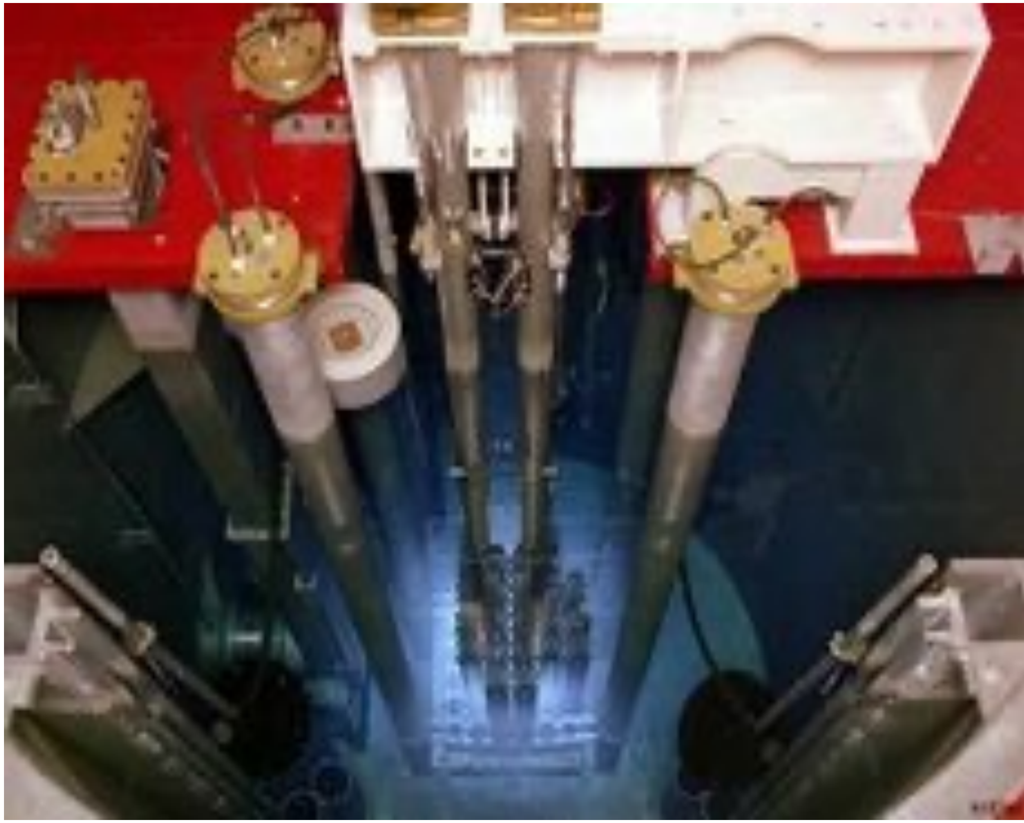
$$\frac{d^2 N_{h\nu}}{dE_{h\nu} dx} \approx 370 \sin^2\theta_C \; eV^{-1} cm^{-1}$$

- **Coherent superposition of the radiation of the atoms**
- **Mainly blue light**
- **Very few photons**
- **Very small energy loss**
- **Identification of particles!**

# Exercise

**Blue light in a reactor**

1. **What produces the light?**
2. **Water *n*=1.333. calculate the minimal energy of an electron to produce Cerenkov light**



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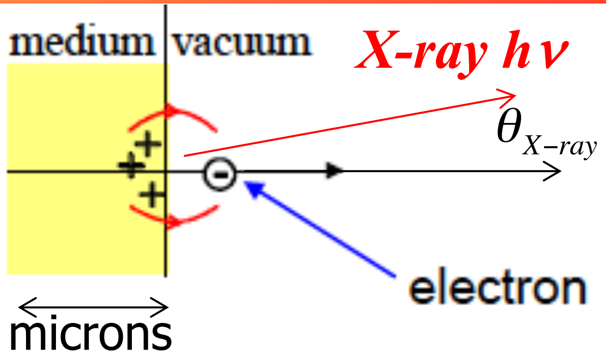
# Transition radiation




- **Elm. radiation is emitted when a charged particle traverses a discontinuity of refractive index, e.g. the boundary between vacuum and a dielectric layer.**
- **Radiated energy *W* / boundary:** $W = \frac{1}{3}\alpha\hbar\omega_{pl}\gamma \approx \gamma \;\; !!$
- **Plasma frequency** $\omega_{pl} = \sqrt{\frac{N_e e^2}{\varepsilon_0 m_e}} \; ; \left\{ \begin{array}{c} \text{plasma} \\ \text{frequency} \end{array} \right\}$

$$\hbar\omega_{pl} \approx 20 - 30 \; eV$$

- **Energy of emitted photons (X-rays)** $h\nu = \hbar\omega \approx \frac{1}{4}\hbar\omega_{pl}\gamma \;\rightarrow\; keV \; range$

**Proportionally to rel. gamma factor!**

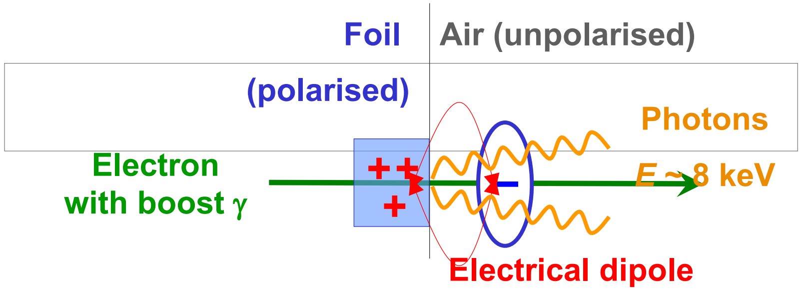
- **Number of emitted photons:** $N_{ph} \approx \frac{W}{\hbar\omega} \sim \alpha \approx \frac{1}{137}; \;\Rightarrow\; \begin{array}{c} many \\ layers \end{array}$
- **X-rays are emitted at small angle** $\theta_{X-ray} \sim 1/\gamma$

IPHC

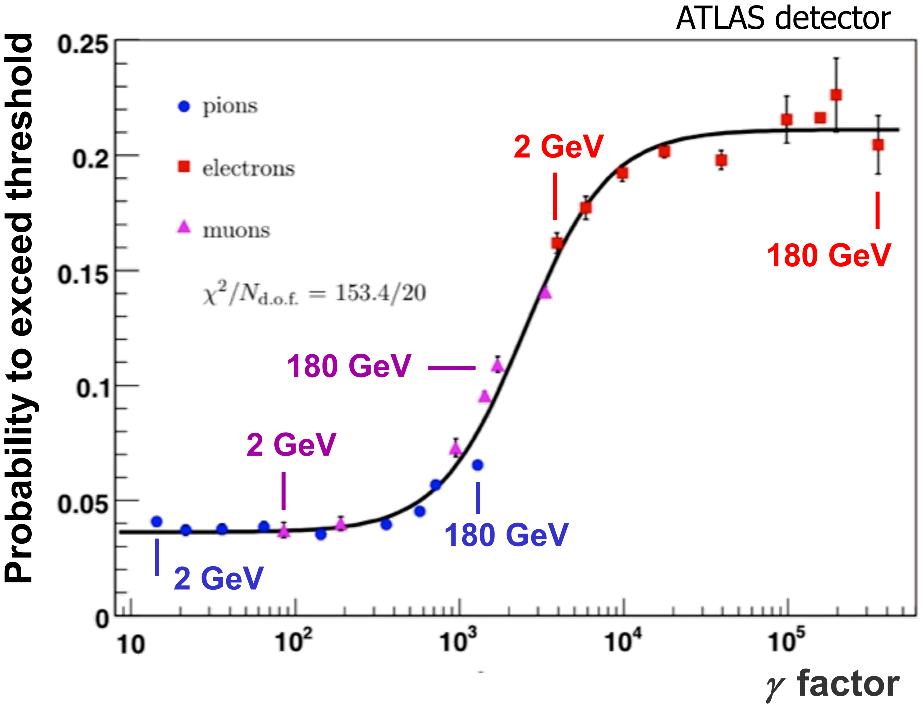
# Transition radiation

- Effect can be explained by re-arrangement of electric field
- A charged particle approaching a boundary creates a electric dipole with its mirror charge
- The time-dependent dipole field causes the emission of electromagnetic radiation

**Photon radiation when charged ultra-relativistic particles traverse the boundary of two different dielectric media (foil & air)**

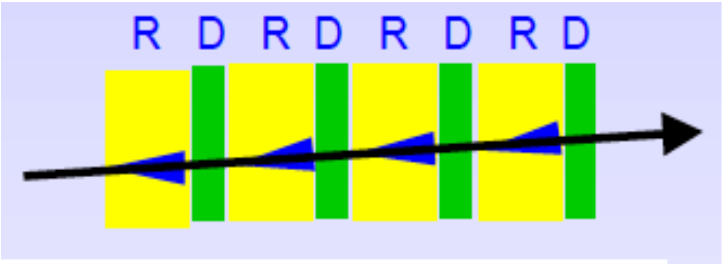


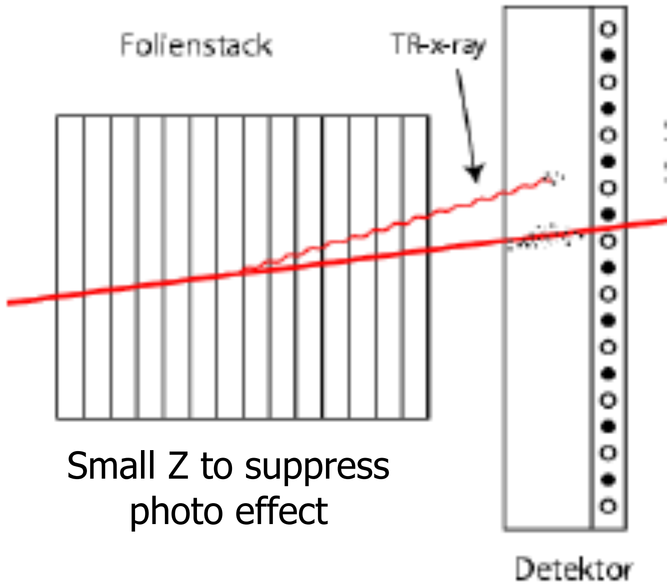

➡ **Significant radiation for $\gamma$ > 1000 and > 100 boundaries**



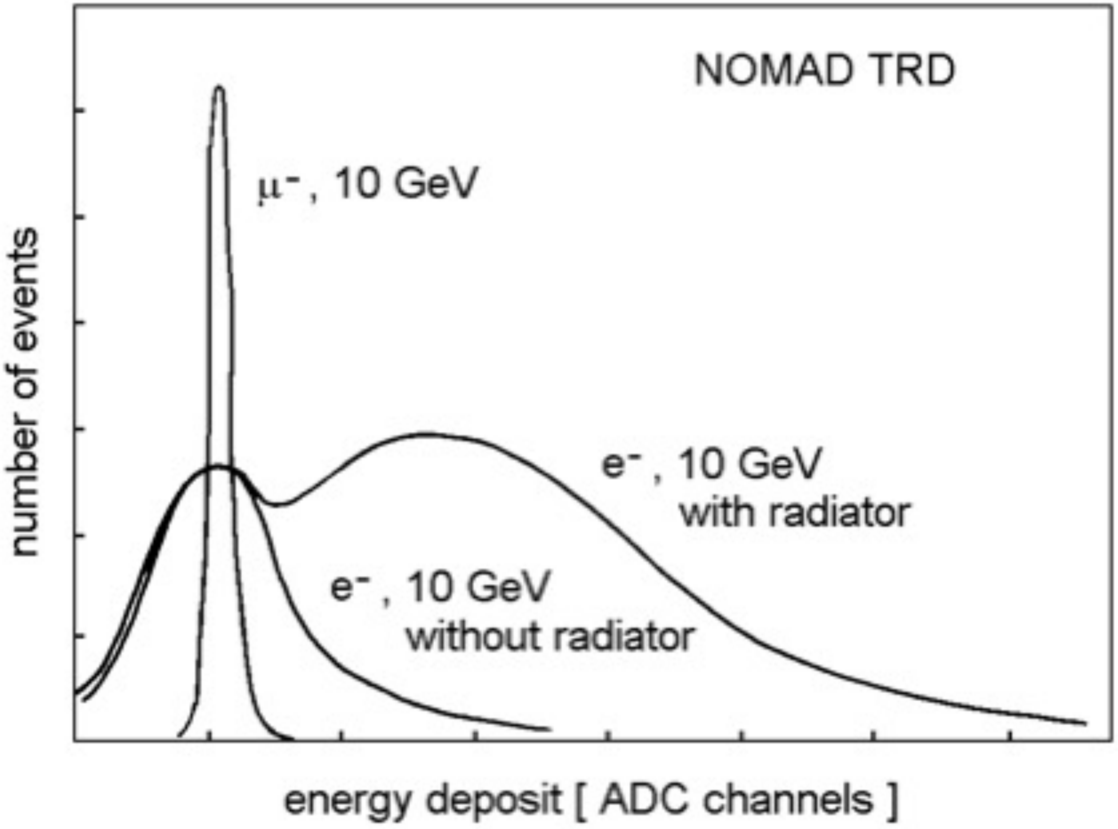

From D. Froidevaux, ASP 2010

# Transition Radiation Detectors




Small Z to suppress photo effect




$$W = \tfrac{1}{3}\alpha\hbar\omega_{pl}\gamma \approx \gamma \;\; !!$$

$$N_{ph} \approx \frac{W}{\hbar\omega} \sim \alpha \approx \frac{1}{137}; \;\Rightarrow\; \begin{matrix} many \\ layers \end{matrix}$$

$$\hbar\omega \approx \tfrac{1}{4}\hbar\omega_{pl}\gamma \;\; \rightarrow \;\; keV \;\; range$$

$$\theta_{X-ray} \sim 1/\gamma$$

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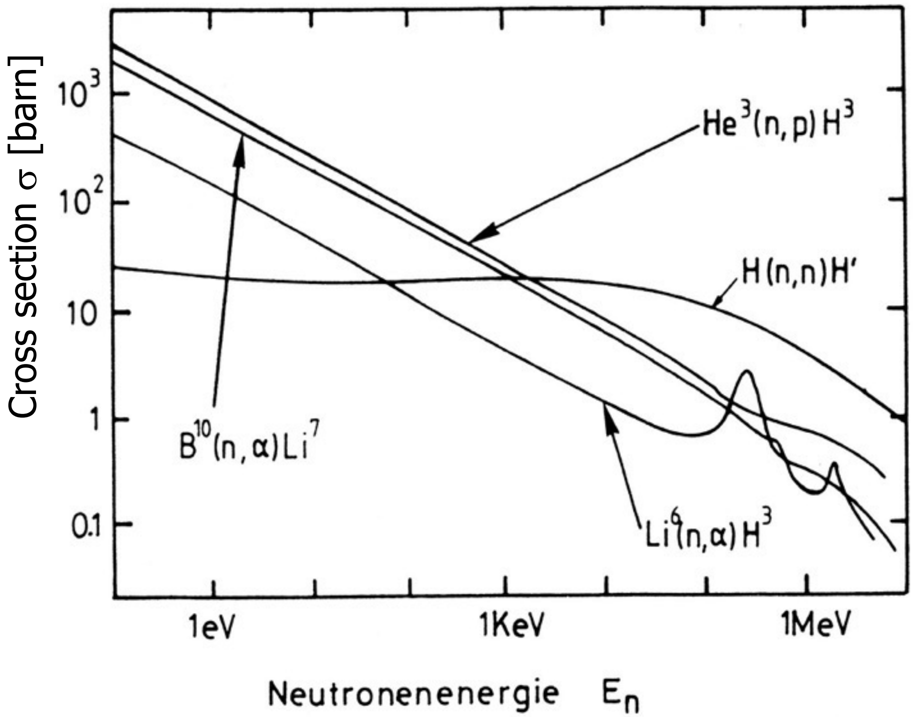
# Neutrons

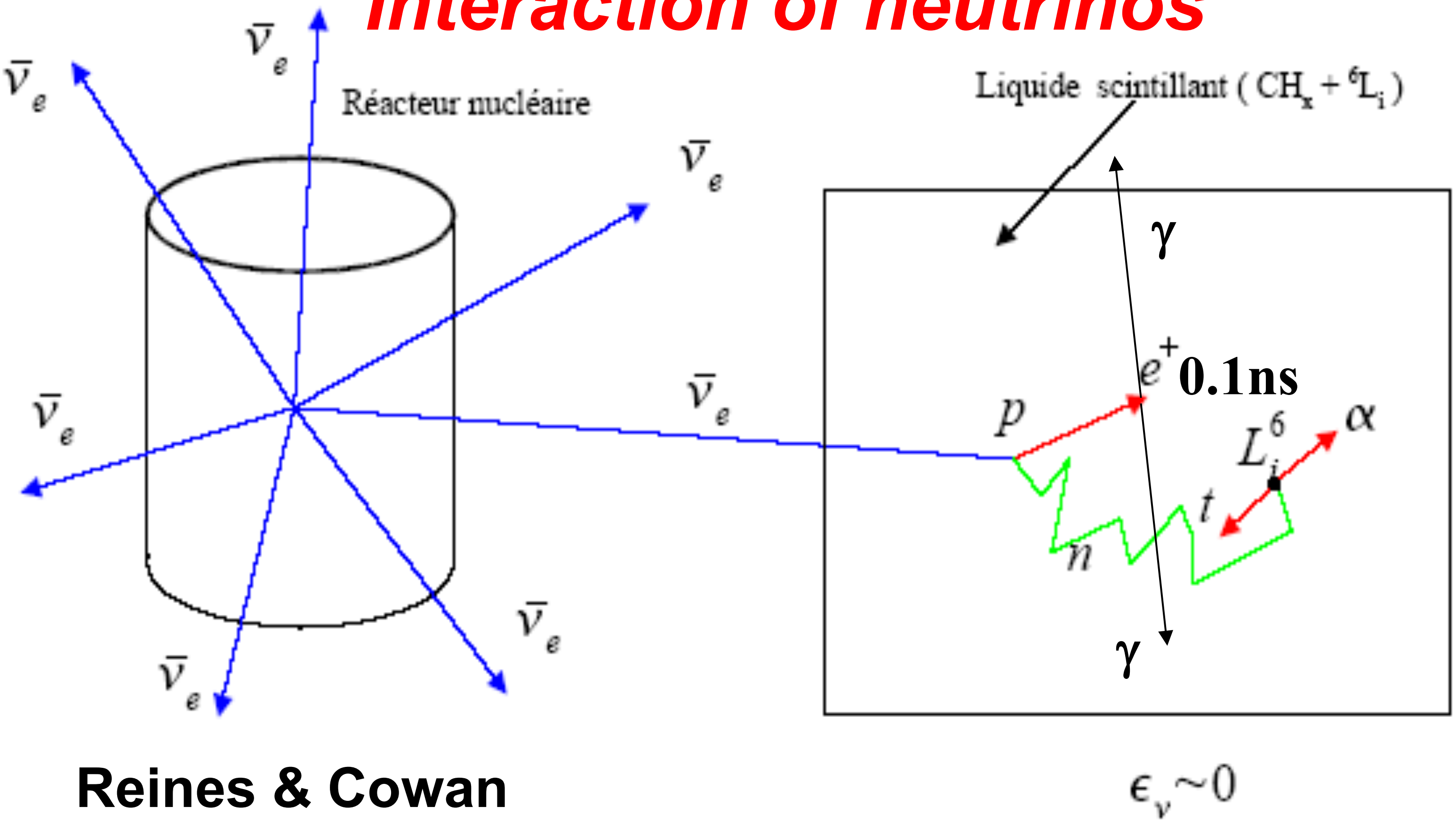



$$N = N_0 \exp(-x/\lambda);$$

$$\lambda^{-1} = N\sigma_{tot}$$

- Elastic scattering off a nucleus $E_{neutron} \approx$ MeV
- Inelastic scattering $E_{neutron} >$ MeV
- Radiative capture $\sigma \sim 1$ / velocitiy
- Nuclear reactions, fission

# Interaction of neutrinos




**Reines & Cowan 1959**

La réaction de détection est : $\bar{\nu}_e + p \rightarrow n + e^+$ , qui est rapidement ( 100 µs ) suivie de la capture du neutron sur un noyau de $L_i^6$ selon la réaction : $n_{th} + L_i^6 \rightarrow \alpha + t + 4{,}8\,MeV$ . Les particules chargées produisent des impulsions de scintillation en coïncidence . La signature de détection d'un neutrino correspond à l'enregistrement de deux impulsions lumineuses induites par le positon et la paire $\alpha - t$ .

# Conclusions

- All particle detectors in nuclear, particle and astroparticle physics are based on the physics of the interaction of particles and radiation with matter
- The interactions produce free electrical charges (ionization, excitations of the medium) or sometime light (Cerenkov)
- These products of the interactions can be used to derive (electronic) signals to indicate the presence of an invisible particle
- We will see in the next lectures, how we can do this

Ulrich.Goerlach@iphc.cnrs.fr, ASP Particle detectors

# Some recommended exercises

1 Look at the classical derivation of the the Bethe-Bloch formula

2 Kinematics of Compton scattering and (e+e-)-pair creation

3 Cerenkov threshold for electrons in water

4 Find the decay scheme of the $^{55}Fe$ source: where do the 5.9 keV gammas come from?

5 Estimate the nuclear interaction length in Iron

(Fe, A=56; $\rho$=7.8 g/cm$^3$)

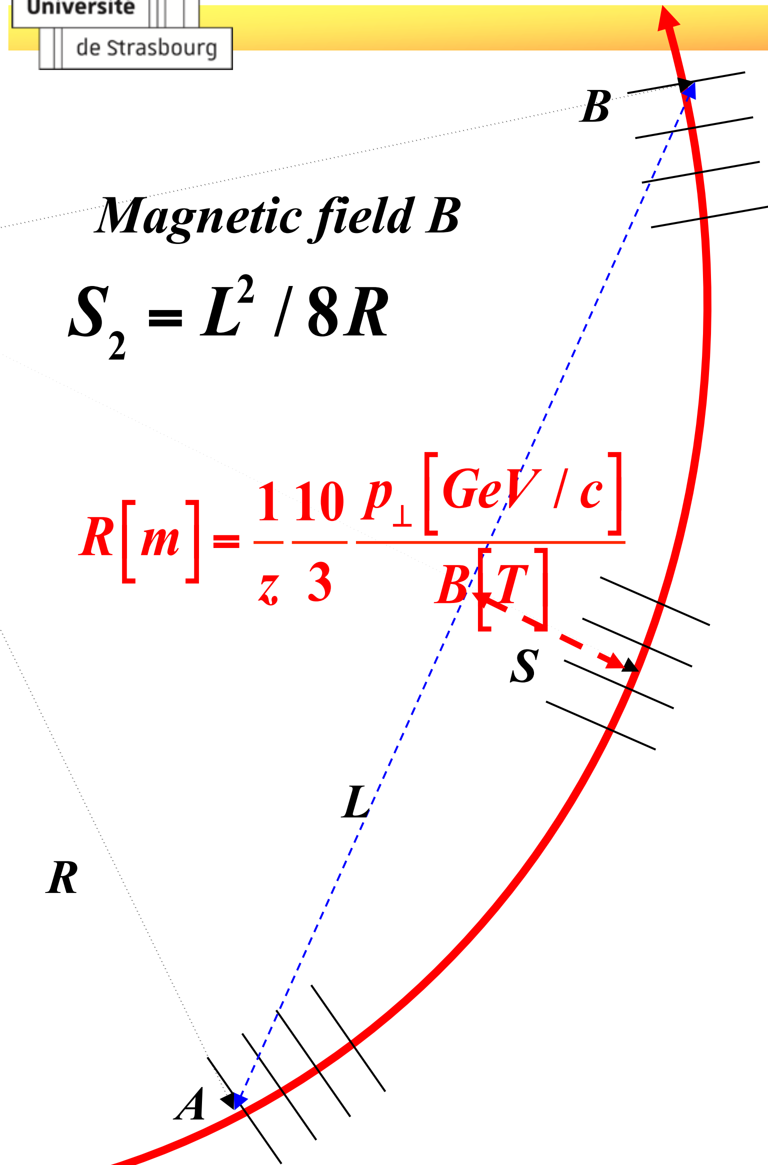
1 The number of particles in a elm shower is proportional to the Energy. If we can measure the number of particles in a shower, how will the energy resolution scale with energy ?

2 Movement of a charged particle in a magnetic field. If the curvature is measured, how well can we measure the momentum of the charged particle ?

*Ulrich.Goerlach@iphc.cnrs.fr, ASP Particle detectors*

# Reconstruction of transv… e momentum in a magn… field

**Exercise !!!**




*Magnetic field B*

$$S_2 = L^2 / 8R$$

$$R[m] = \frac{1}{z}\frac{10}{3}\frac{p_\perp[GeV/c]}{B[T]}$$

- **Movement of a charge $z$ in a uniform magnetic field**
- **Momentum resolution *dp/p***
- **Spatial resolution of the sagitta *dS/S***

$$\frac{dS}{S} = \frac{dp_\perp}{p_\perp} = \frac{80}{3\cdot z}\frac{1}{BL^2}p_\perp dS$$

$$[B] = Tesla;\ [L] = m; [p_\perp] = GeV/c$$

**If the trajectory is measured with *N* points:**

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma(x)\cdot p_T}{0.3\cdot BL^2}\sqrt{720/(N+4)} \qquad \text{(for N} \geq \sim 10)$$

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# Momentum reconstruction in a uniform magnetic field

$$R^2 = (L/2)^2 + (R-S)^2$$

$$0 = S^2 - 2RS + L^2/4$$

$$S_{1,2} = R\left(1 \pm \sqrt{1-(L/2R)^2}\right)$$

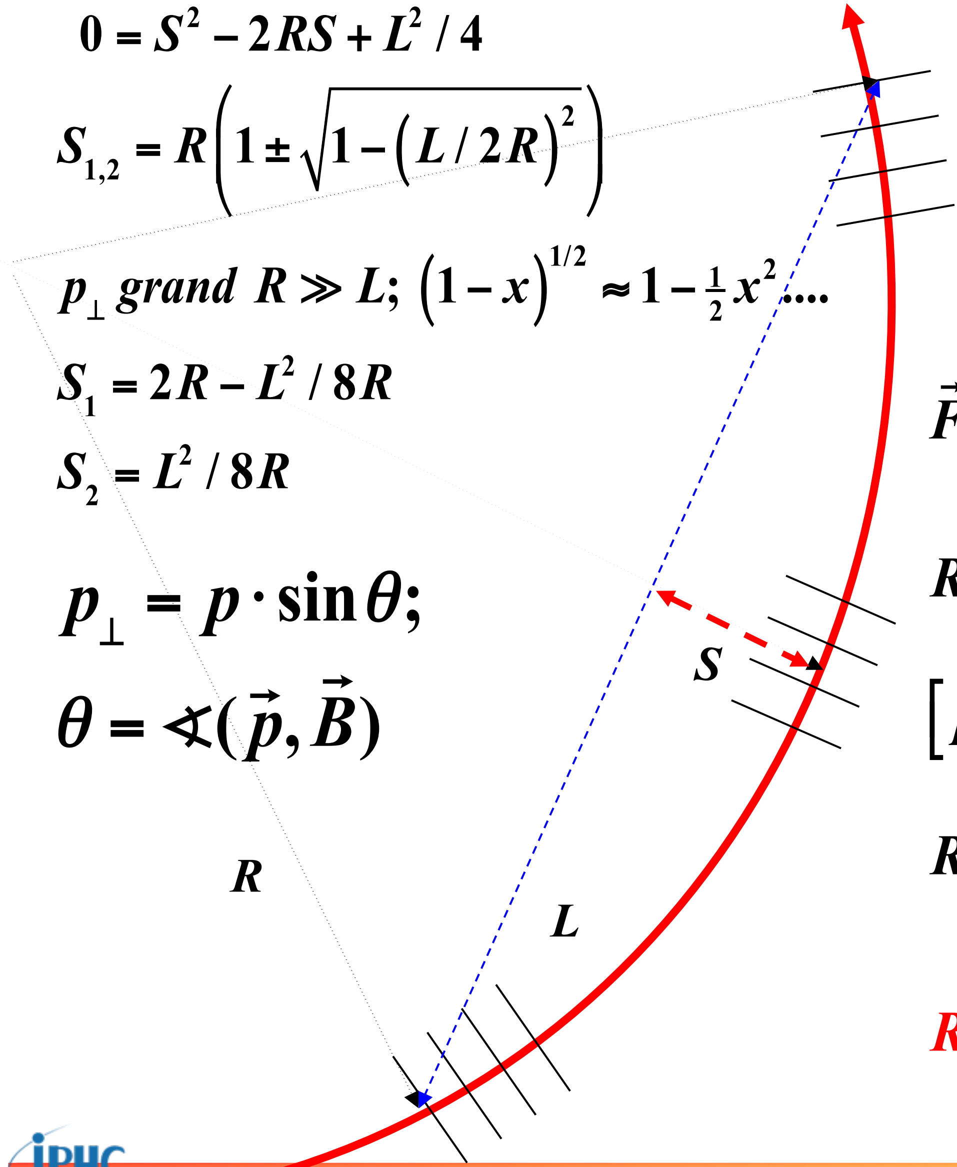
$$p_\perp \text{ grand } R \gg L; \ (1-x)^{1/2} \approx 1 - \tfrac{1}{2}x^2 \ldots.$$

$$S_1 = 2R - L^2/8R$$

$$S_2 = L^2/8R$$

$$p_\perp = p \cdot \sin\theta;$$

$$\theta = \measuredangle(\vec{p}, \vec{B})$$




$$\vec{F} = q \cdot (\vec{v} \times \vec{B}) = m\vec{a}_R = m\frac{v^2}{R}; \ \vec{v} \perp \vec{B}$$

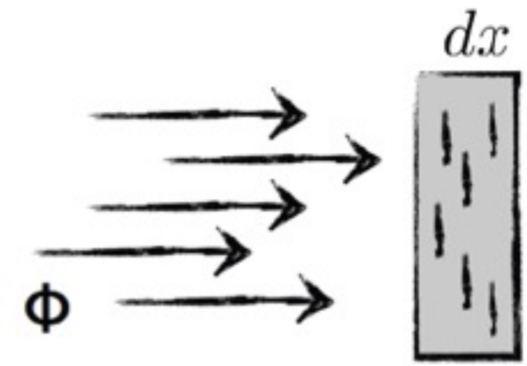
$$R = \frac{m}{q}\frac{v}{B} = \frac{p_\perp}{q \cdot B}$$

$$[p_\perp] = GeV/c; [q] = e \cdot z; [B] = T_{esla} = Vs/m^2$$

$$R = \frac{1}{z \cdot e}\frac{10^9 eV}{c}\frac{1}{Vs/m^2}; \ c = 3 \cdot 10^8 m/s$$

$$R[m] = \frac{1}{z}\frac{10}{3}\frac{p_\perp[GeV/c]}{B[T]}$$

# INTERACTION CROSS-SECTION




Flux $\Phi = \frac{1}{S}\frac{dN_i}{dt}$ [$L^{-2} t^{-1}$]

*area obscured by target particle*

Reactions per unit of time $\frac{dN_{\text{reac}}}{dt} = \Phi \sigma N_{\text{target}} dx$ [$t^{-1}$]

[$L^{-2} t^{-1}$] [?] [$L^{-1}$] [L]

Reaction rate per target particle $W_{if} = \Phi\sigma$ [$t^{-1}$]

Cross section per target particle $\sigma = \frac{W_{if}}{\Phi}$ [$L^2$] = reaction rate per unit of flux

1b = $10^{-28}$ m² (roughly the area of a nucleus with A = 100)

# CROSS-SECTION: ORDER OF MAGNITUDE

Standard
cross section unit: $[\sigma] = \text{mb}$ with $1\ \text{mb} = 10^{-27}\ \text{cm}^2$

or in
natural units: $[\sigma] = \text{GeV}^{-2}$ with $1\ \text{GeV}^{-2} = 0.389\ \text{mb}$
$1\ \text{mb} = 2.57\ \text{GeV}^{-2}$

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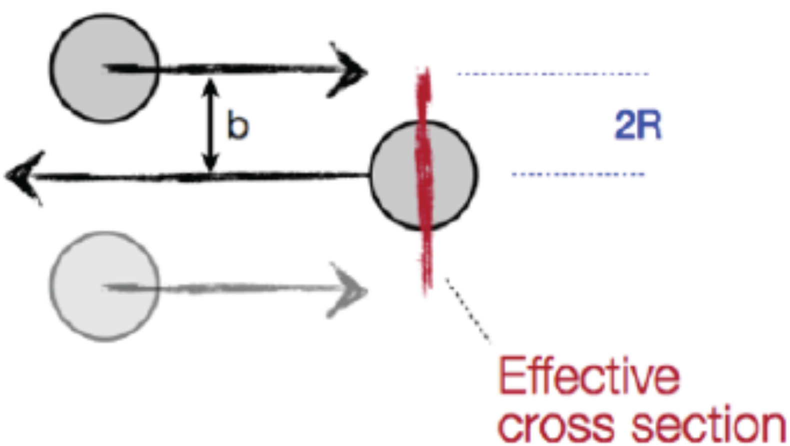
using: $\hbar c = 0.1973\ \text{GeV fm}$
$(\hbar c)^2 = 0.389\ \text{GeV}^2\ \text{mb}$

Estimating the
proton-proton cross section:




Proton radius: R = 0.8 fm
Strong interactions happens up to b = 2R

$$\sigma = \pi(2R)^2 = \pi \cdot 1.6^2\ \text{fm}^2$$
$$= \pi \cdot 1.6^2\ 10^{-26}\ \text{cm}^2$$
$$= \pi \cdot 1.6^2\ 10\ \text{mb}$$
$$= 80\ \text{mb}$$

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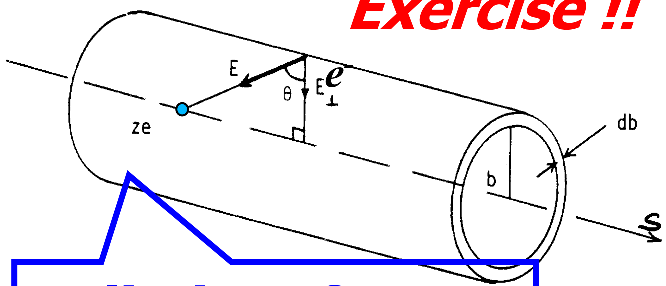
## Exercise !!




**Cylinder of surface $A$ and volume $V$**

**Classical calculation by Bohr:**

**Momentum transfer $\Delta p$ to the electron;**

**Energyloss of particle = - energy transfer to electron $\Delta E$;**

**$n_e$ = electron density**

$$\Delta p_e = \int_{-\infty}^{\infty} F\,dt = e\int_{-\infty}^{\infty} \mathfrak{E}_\perp\,dt = \frac{e}{v_0}\int_{-\infty}^{\infty} \mathfrak{E}_\perp\,ds; \quad \mathfrak{E}_\perp = \text{electric field}$$

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$$GAUSS: \iiint_V \operatorname{div}\vec{\psi}\,dx\,dy\,dz = \oint_A \vec{\psi}\,d\vec{a}; \quad \vec{\psi} = \text{ vector field}$$

$$\iint_A \mathfrak{E}_\perp\,da = \iiint_V \operatorname{div}\vec{\mathfrak{E}}\,dx\,dy\,dz = \frac{1}{\varepsilon_0}\iiint \rho\,dx\,dy\,dz = \frac{ze}{\varepsilon_0}; \quad \operatorname{div}\vec{\mathfrak{E}} = \frac{\rho}{\varepsilon_0}$$

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$$da = 2\pi b\,ds\ ; \quad 2\pi b\int_{-\infty}^{\infty} \mathfrak{E}_\perp\,ds = \frac{ze}{\varepsilon_0}$$

$$\Delta p_e = \frac{2}{4\pi\varepsilon_0}\frac{ze^2}{bv_0} = 2k\frac{ze^2}{bv_0}; \qquad k = \frac{1}{4\pi\varepsilon_0}$$

$$\Delta E = -\Delta E_e = -\frac{(\Delta p_e)^2}{2m_e} = -2\frac{z^2e^4}{b^2 m_e}\left(\frac{k}{v_0}\right)^2$$

$$-dE(b) = \Delta E(b) n_e dV = 4\pi n_e \frac{z^2e^4}{m_e}\left(\frac{k}{v_0}\right)^2 \frac{db}{b}ds; \quad (dV = 2\pi b\,db\,ds)$$

$$-\frac{dE}{ds} = -\int_0^{\infty}\frac{dE}{db}db = 4\pi n_e\frac{z^2e^4}{m_e}\left(\frac{k}{v_0}\right)^2 \ln\left(\frac{b_{max}}{b_{min}}\right)$$

# Classical calculation by Bohr, $b_{min}$ and $b_{max}$

$b_{\min}$ : Maximal energy transfer to electron

$$T_e^{\max} = 2m_e v_0^2 \gamma^2 = 2\frac{z^2 e^4}{b_{\min}^2 m_e}\left(\frac{k}{v_0}\right)^2$$

$$b_{\min} = \frac{z \cdot e^2 k^2}{\gamma m_e v_0^2}; \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}};\ \beta = \frac{v_0}{c};\ v_0 = \text{particle speed !}$$

$b_{\max}$ : interaction time $\cong$ Orbit time $\bar{T}$

$$\frac{b_{max}}{\gamma v_0} \ll \bar{T}$$

$$b_{max} = \gamma v_0 \bar{T}$$

$$-\frac{dE}{ds} = -\int_0^\infty \frac{dE}{db}\,db = \frac{4\pi z^2 e^4 k^2}{m_e v_0^2} n_e \ln \frac{\gamma^2 m_e v_0^3 \bar{T}}{z^2 e^2 k^2}$$

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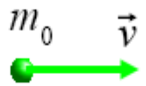
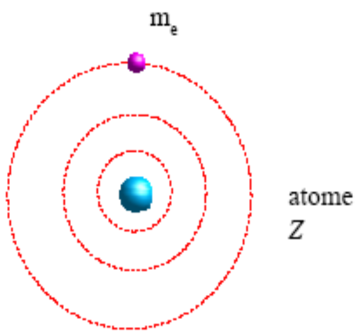
# Maximal energy transfer of charged “heavy” particles to the electrons of matter




$\vec{p} = \gamma m_0 \vec{v}$

$E$




$$T_e^{\max} = E_e^{\max} - m_e c^2 = \frac{2 m_e^2 c^2 \beta^2 \gamma^2}{\left(E_{CM} / m_0 c^2\right)^2}$$

$$v \gg v_e \simeq Z\alpha c$$

$$E_{CM} = \left(m_0^2 c^4 + m_e^2 c^4 + 2 m_e c^2 E\right)^{\frac{1}{2}}$$

$$p_e^{CM} = p \frac{m_e c^2}{E_{CM}}$$

$$E_e^{CM} = (E + m_e c^2) \frac{m_e c^2}{E_{CM}}$$

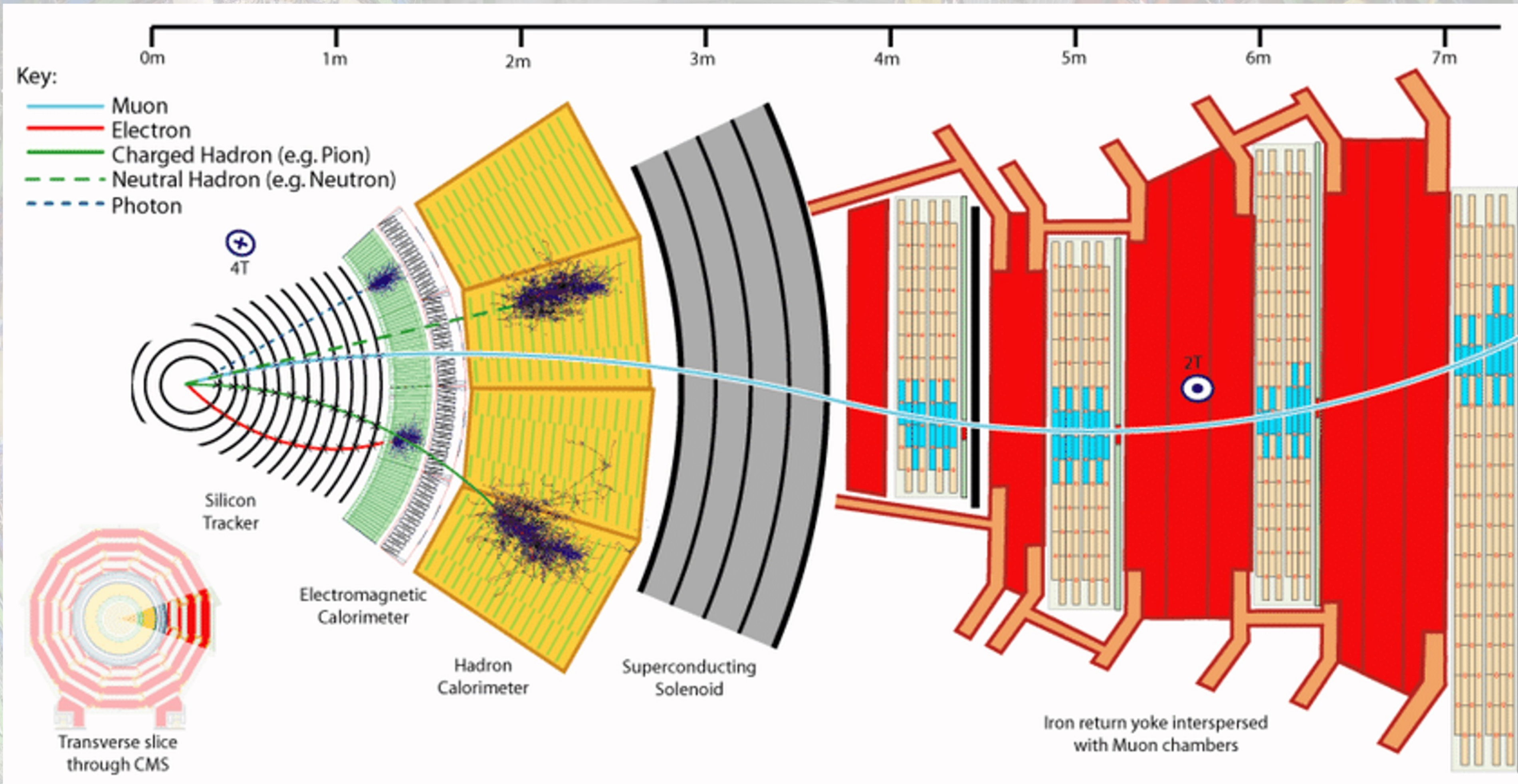
$$\gamma^{CM} = \frac{E + m_e c^2}{E_{CM}}; \;\; \beta^{CM} = \frac{pc}{E + m_e c^2}$$

$$m_0 \gg m_e; \; 2\gamma m_e / m_0 \ll 1$$

$$T_e^{\max} = 2 m_e c^2 \beta^2 \gamma^2$$

$$m_0 = m_e$$

$$T_e^{\max} = \frac{E^2 - m_e^2 c^4}{m_e c^2 + E} = E - m_e c^2 = T_e = T_0$$




**LHCb b-jet event**

**ATLAS dijet event**

**event**

https://... file/Raquel_Gomez-Ambrosio/... /Transverse-section-of-the-CMS-detector.png