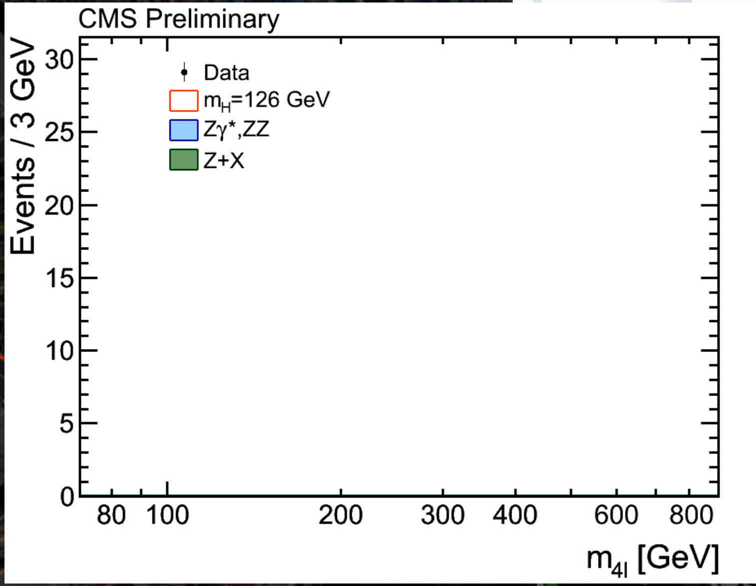
Particle Detectors

Lecture at the African School for Fundamental Physics
Dakar, Senegal 2014



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

CMS at the LHC

Particle Detectors

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Goal of my lecture:

to understand how particle physics experiments are being built

Main focus on the example LHC

Lecture I

- Introduction
- Interaction of radiation with matter
- Simple particle identification

Lecture II

- Concepts and strategies of (LHC) experiments
- The basic "building blocks", the detectors
- Conclusions or recommendations

Exercises!!!!!

Particle Detectors

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First Lecture

- **Introduction**
  - how are particle physics experiments are being built ?
  - The goal: measuring subatomic particles (E, p, charge,, mass, ….
  - Collisions of proton-proton, electron-positron, CR, neutrinos, dark matter….
  - Detection of particles, how do they interact with matter, what does the interaction depend on (E, p, charge,, mass, beta, gamma ….
- **Interaction of radiation with matter**
  - Photons: PE, Compton, Pair creation
  - Ionization/excitation, Bethe Bloch formula, range of particles, Bragg peak
  - Multiple scattering
  - Cerenkov, Transition radiation
  - Electrons, Bremsstrahlung, critical energy, radiation length
  - Electromagnetic showers of electrons and photons, (muons)
  - Hadronic interactions → showers, interaction length, solid and atmospheric absorbers
- **Simple particle identification (dE/dx, e/p, e/h/μ, TOF, Cerenkov/ TR**
- ***Exercises for the WE !!!!!***

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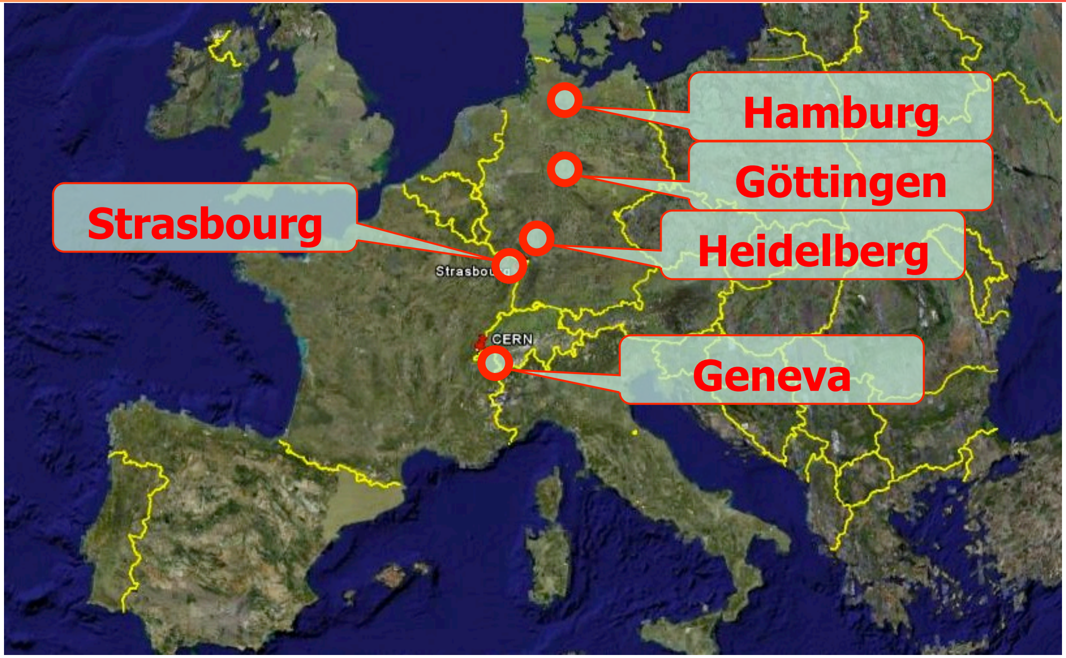
Second Lecture

- Detector systems, some examples, strategies
  - Experimental conditions, fixed target or collider, neutrinos, dark matter…
  - Experiments at the LHC (Atlas and CMS, ALICE, LHCb ?
- The basic "building blocks", characteristics (efficiency, resolution)
  - Gas detectors
  - Scintillators
  - Semiconductors
  - Calorimeters
  - Cerenkov and transition radiation detectors
- System aspects
- Conclusions or recommendations

- *Exercises for Thursday !!!*

Who am I?

Ulrich Goerlach



- Born in Göttingen, Germany

  interested in science at the age of about 14
- 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 at CERN Geneva
- Researcher at DESY, Hamburg
- University Professor at the UdS, (Université de Strasbourg)
- Responsible for the Master in subatomic Physics

Bibliographie

Text books :

– C. Grupen, Particle Detectors, Cambridge University Press, 1996
– G. Knoll, Radiation Detection and Measurement, 3rd ed. Wiley, 2000
– W. R. Leo, Techniques for Nuclear and Particle Physics Experiments, Springer, 1994
– K. Kleinknecht, Detectors for particle radiation , 2nd edition, Cambridge Univ. Press, 1998
- D. Green, The physics of <<<particle Detectors, Cambridge Univ. Press 2000
- S. Tavernier, Experimental Techniques in Nuclear and particle Physics, Springer 2010
- G. Lutz, Semiconductor Radiation Detectors, Springer, 1999
- W. Blum, L. Rolandi, Particle Detection with Drift Chambers, Springer, 1994
– 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.
……

Summer student lectures and academic training

- Particle Detectors - Principles and Techniques: C. D'Ambrosio, T. Gys, C. Joram, M. Moll and L. Ropelewski, CERN Academic Training Programme 2004/2005 …..
- Summer Student Lectures 2010, Werner Riegler, CERN,
- Summer Student Lectures 2012, Detectors for Particle Physics, D. Bortoletto, Purdue University
- Particle detection and reconstruction at the LHC (I), African School of Physics, Stellenbosch, South Africa, August 2010 (D. Froidevaux, CERN)
- Particle detectors and large HEP experiments, L. Serin LAL/Orsay & IN2P3/ CNRS, lecture at the European Summer Campus 2011, Strasbourg France
- Physics of Particle Detection, ICFA, Instrumental school, South Africa 2001, Claus Grupen, University of Siegen
- ….

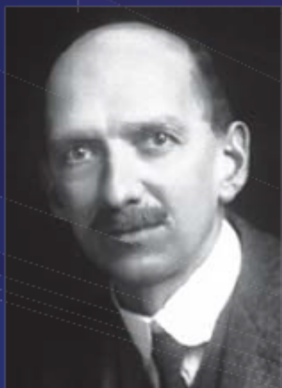
Acknowledgements

- 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

NOBEL PRIZES FOR INSTRUMENTATION

http://www.lhc-closer.es/php/index.php?i=1&s=9&p=2&e=0

D. Bortoletto

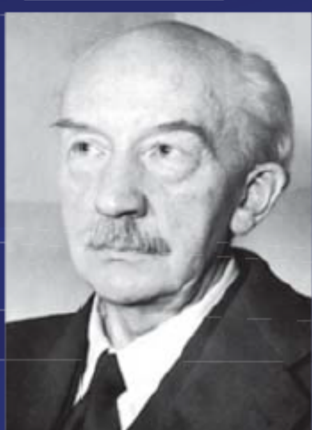


1927: C.T.R. Wilson, Cloud Chamber

1939: E. O. Lawrence, Cyclotron

1948: P.M.S. Blacket, Cloud Chamber

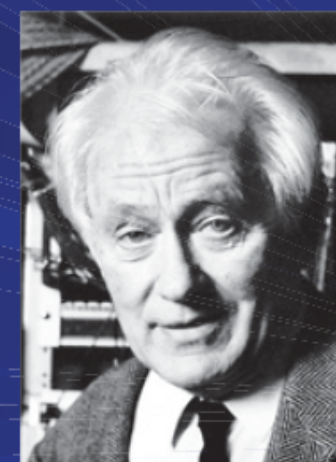
1950: C. Powell, Photographic Method



1954: Walter Bothe, Coincidence method

1960: Donald Glaser, Bubble Chamber

1968: L. Alvarez, Hydrogen Bubble Chamber



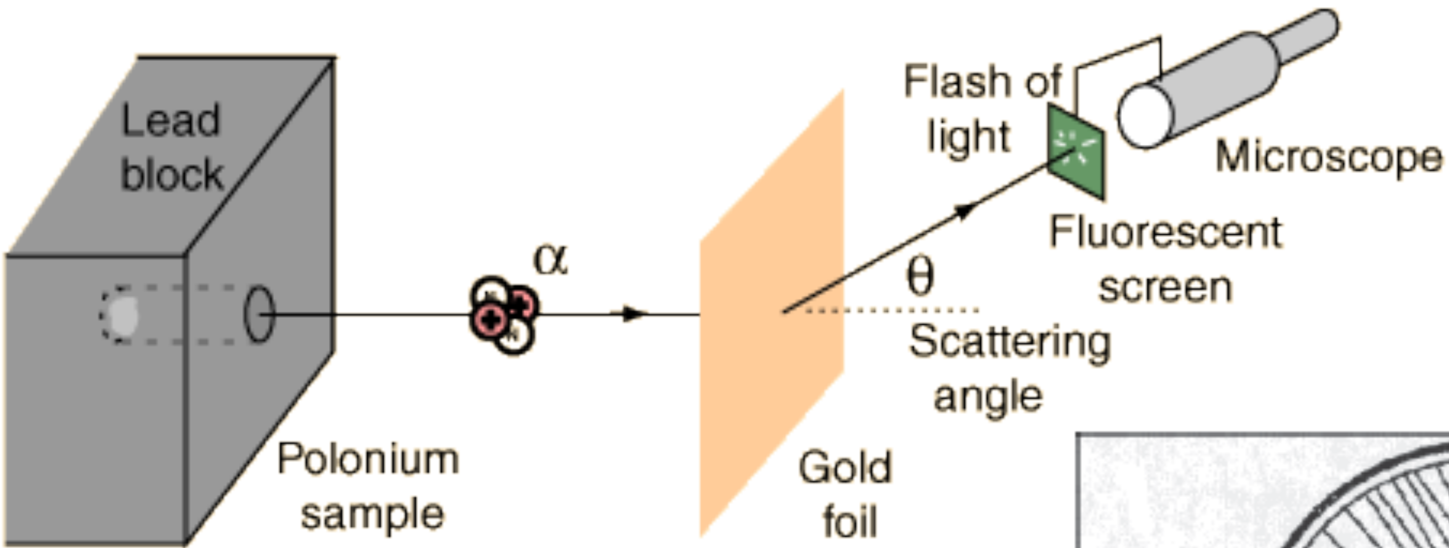
1992: Georges Charpak, Multi Wire Proportional Chamber

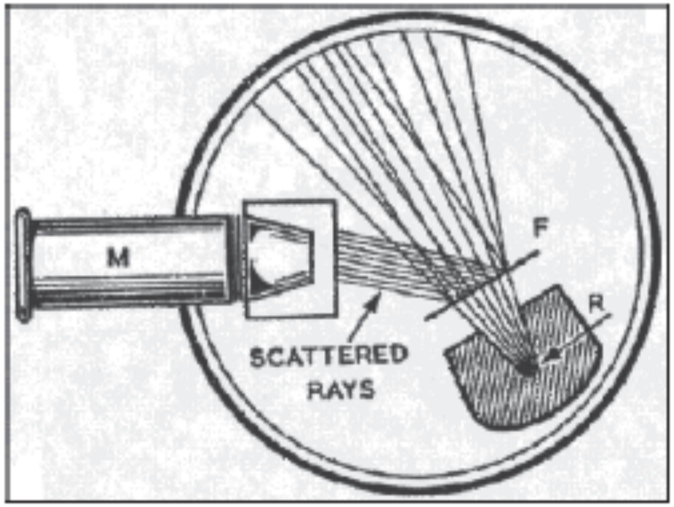
What do we want to observe?

- Collisions, interactions, creation and decay of particles (elementary or composed), which are invisible from first principles, even under a big microscope
- These particles are characterised by their masses, electric charges, spin, polarization.
- Their energy can vary from keV (Dark Matter searches, Nuclear physics) to GeV or TeV (particle physics) up to ZeV (10^{21}eV cosmic rays)
- Measure precisely the particle 4-vectors $\left(E/c, \vec{p}\right)$ and all other quantities

Seeing particles: Rutherford scattering

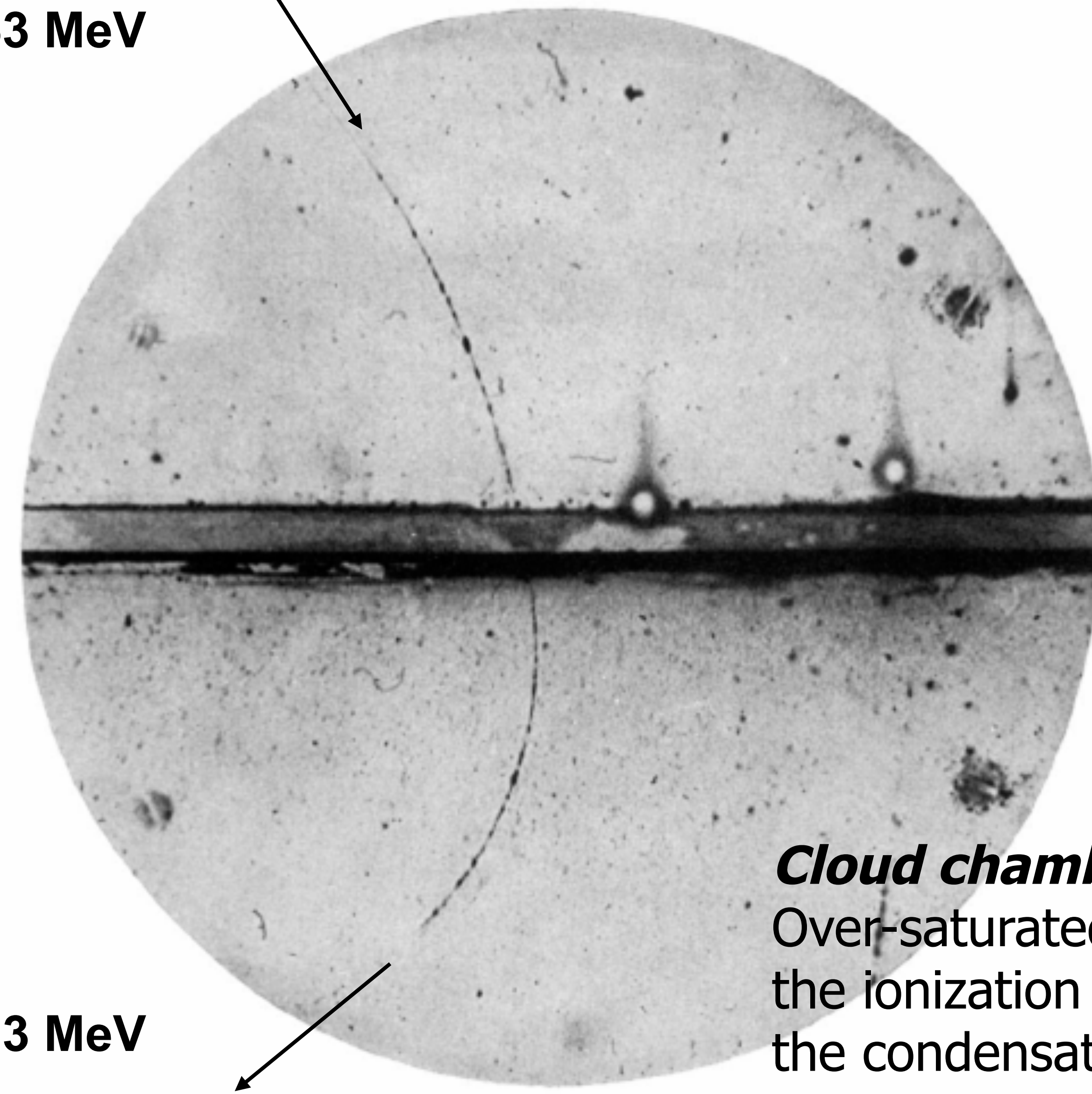
Experiment by Hans Geiger and Ernest Marsden 1909





1932 Discovery of the positron by C.D.Anderson

e^+ 63 MeV



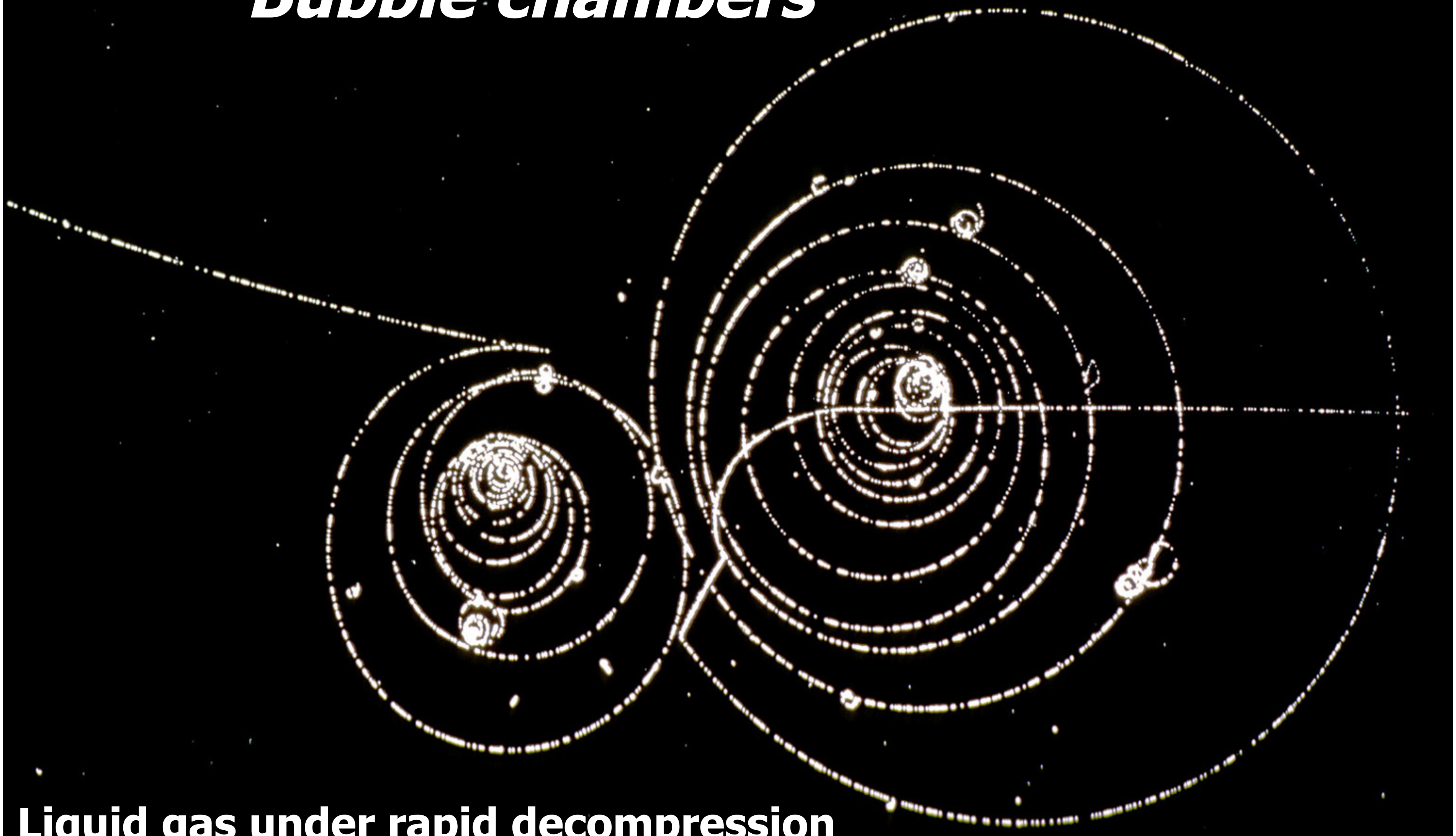
e^+ 23 MeV

6 mm Pb

Cloud chamber (C.T.R. Wilson)

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

Bubble chambers



Liquid gas under rapid decompression

Ionization clusters → bubbles

Some basics of particle detection

- Gammas: Photo effect, Compton scattering and conversion of gammas to electron-positron pairs
- Charged "heavy" particles: Energy loss by ionization
  - Non-relativistic, minimum ionizing and relativistic
- Multiple scattering
- Cerenkov effect and transition radiation
- Bremsstrahlung of electrons (and muons)
  - Critical energy and radiation length $\Rightarrow$ electromagnetic showers
- Nuclear interactions of hadrons (nuclear interaction length)
  - $\Rightarrow$ hadronic showers
- Neutrinos
- Dark Matter ?

photons

Interaction of photons with matter

- **Photo-electric effect** — Absorption of γ
  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 γ $E_\gamma \geq 1.022$ MeV

Nuclear photo-electric and photo-nuclear reaction are very rare!

Statistical process governed by a cross section σ_i:

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

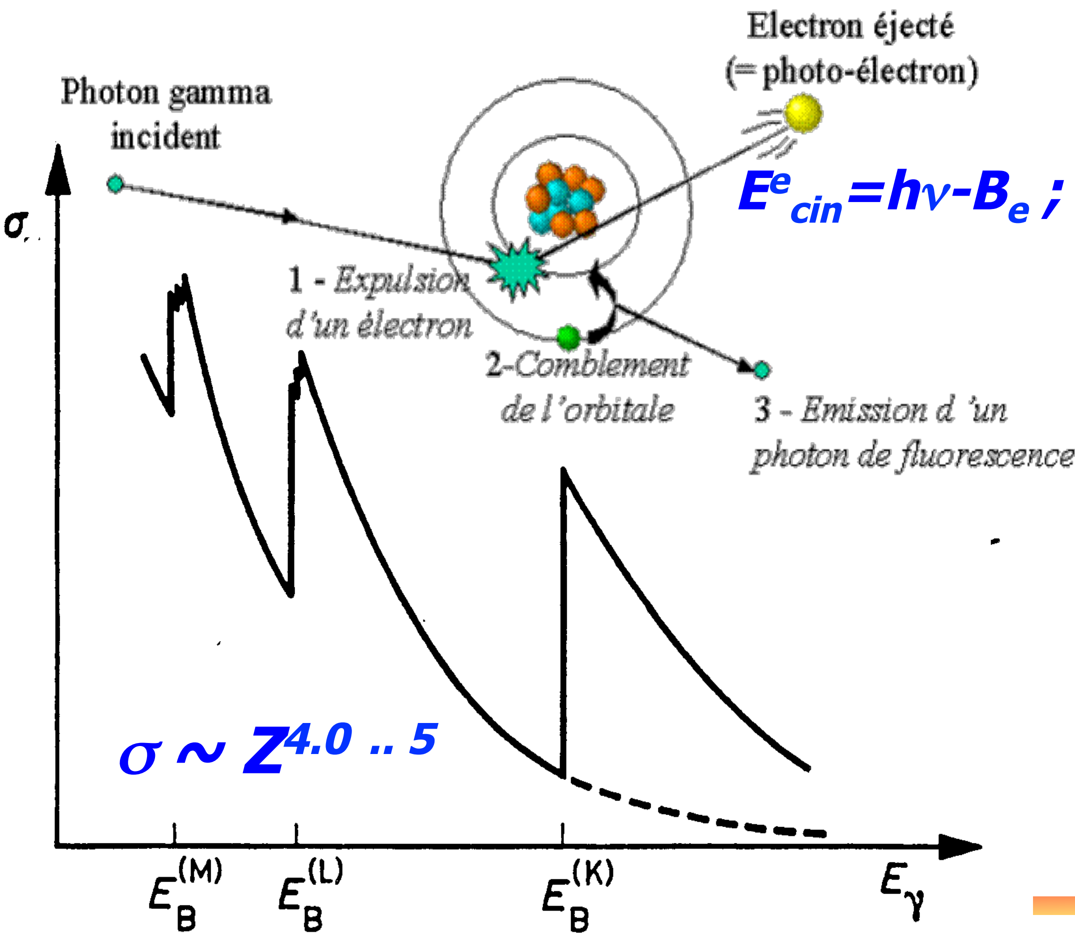
$I = I_o \exp(-\mu x)$

μ = 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

Photo-electric effect

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

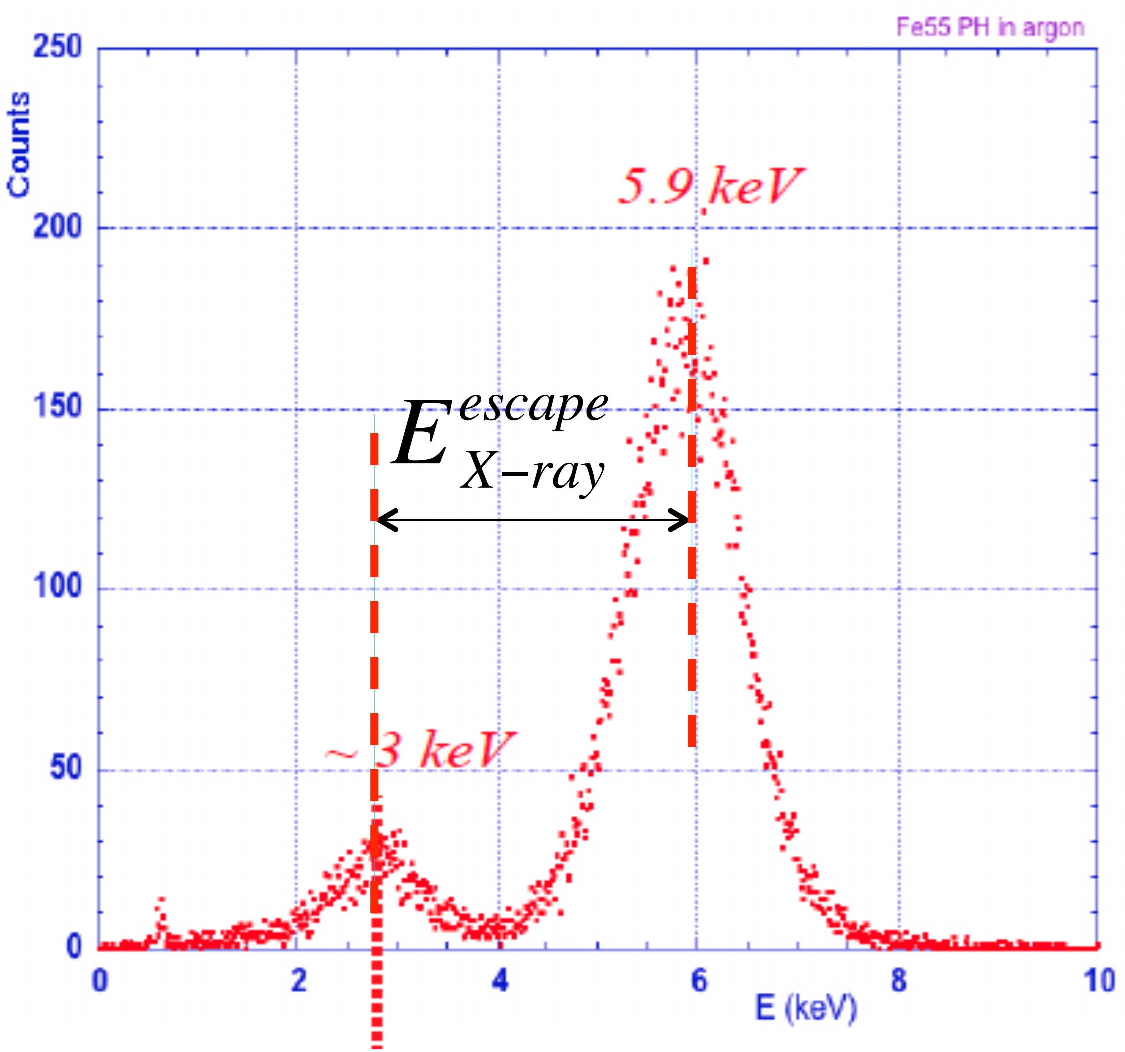


- At high *Z*, the hole in the K-shell is filled by an electron under the emission of a fluorescence x-ray of energy $E_\gamma = E_K - E_{L,M,N}$
- At low Z, Auger electrons occur: electrons of higher shells (L) are ejected with energy

$E_{Auger} = E_K - 2E_L$

X-RAY ABSORPTION SPECTRUM

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



Escape of the fluorescence x-ray of energy

$$E_X = E_K - E_{L,M,N} \approx E_K$$

Compton-effect

Scattering of a gamma on a "free" electron

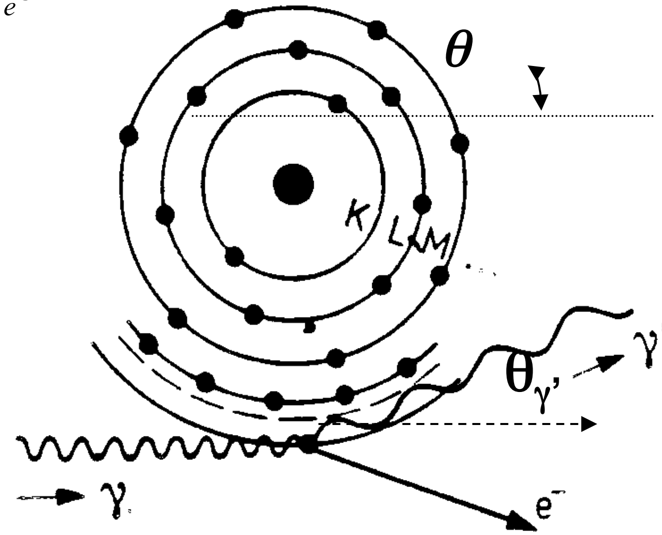
$$h\nu' = \frac{h\nu}{1+\varepsilon(1-\cos\theta_{\gamma'})};$$

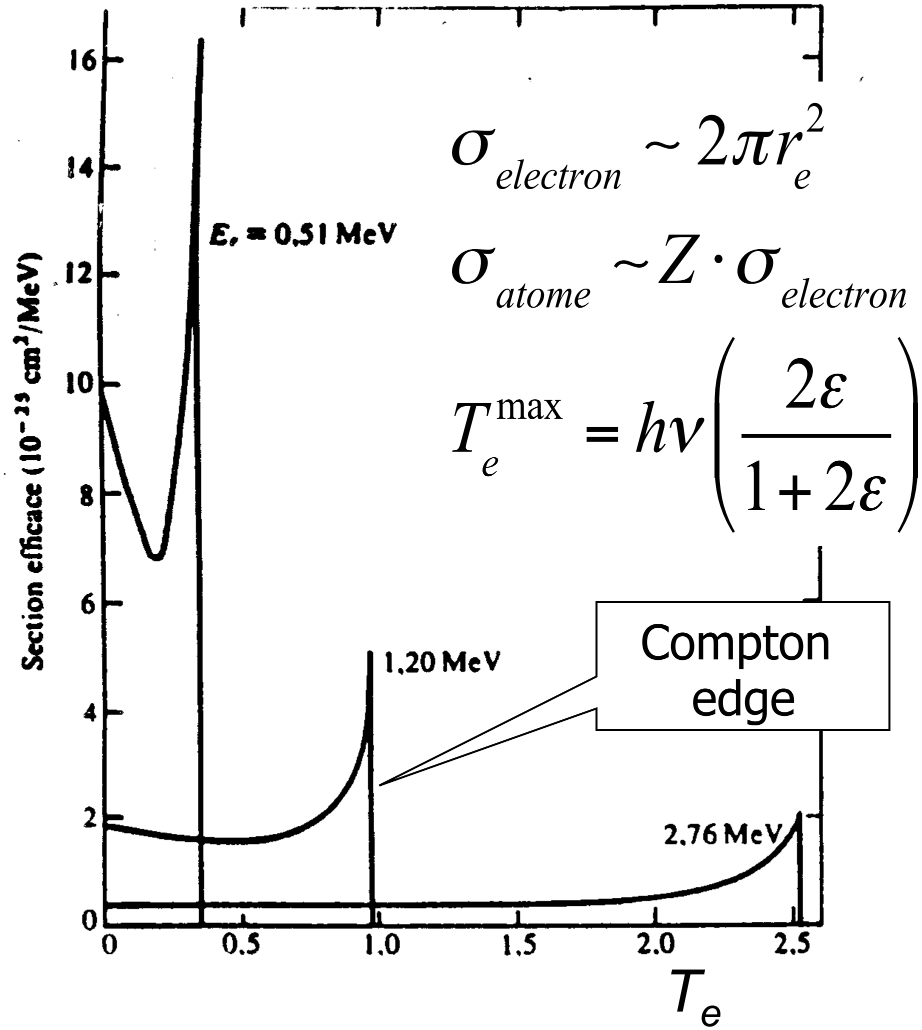
$$\varepsilon = h\nu / m_e c^2$$

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

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

$$\lambda_c = \frac{\hbar c}{m_e c^2}$$ Compton wave lenth of an electron





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

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

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

Kinematics of Compton scattering

longitudinal :

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

transversal :

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

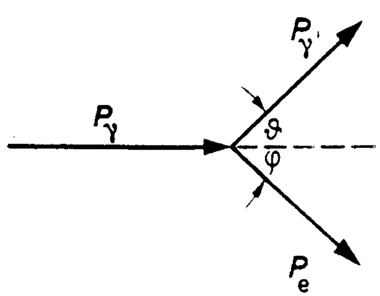
$$T_e = h\nu - h\nu'$$

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

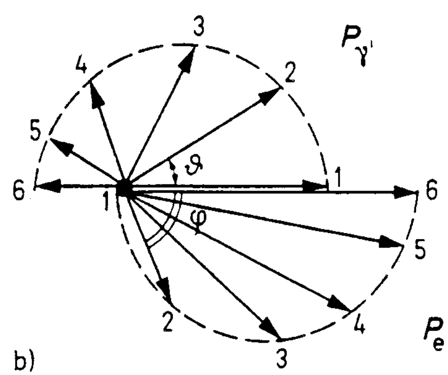
$$\varepsilon = h\nu / m_e c^2$$

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

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

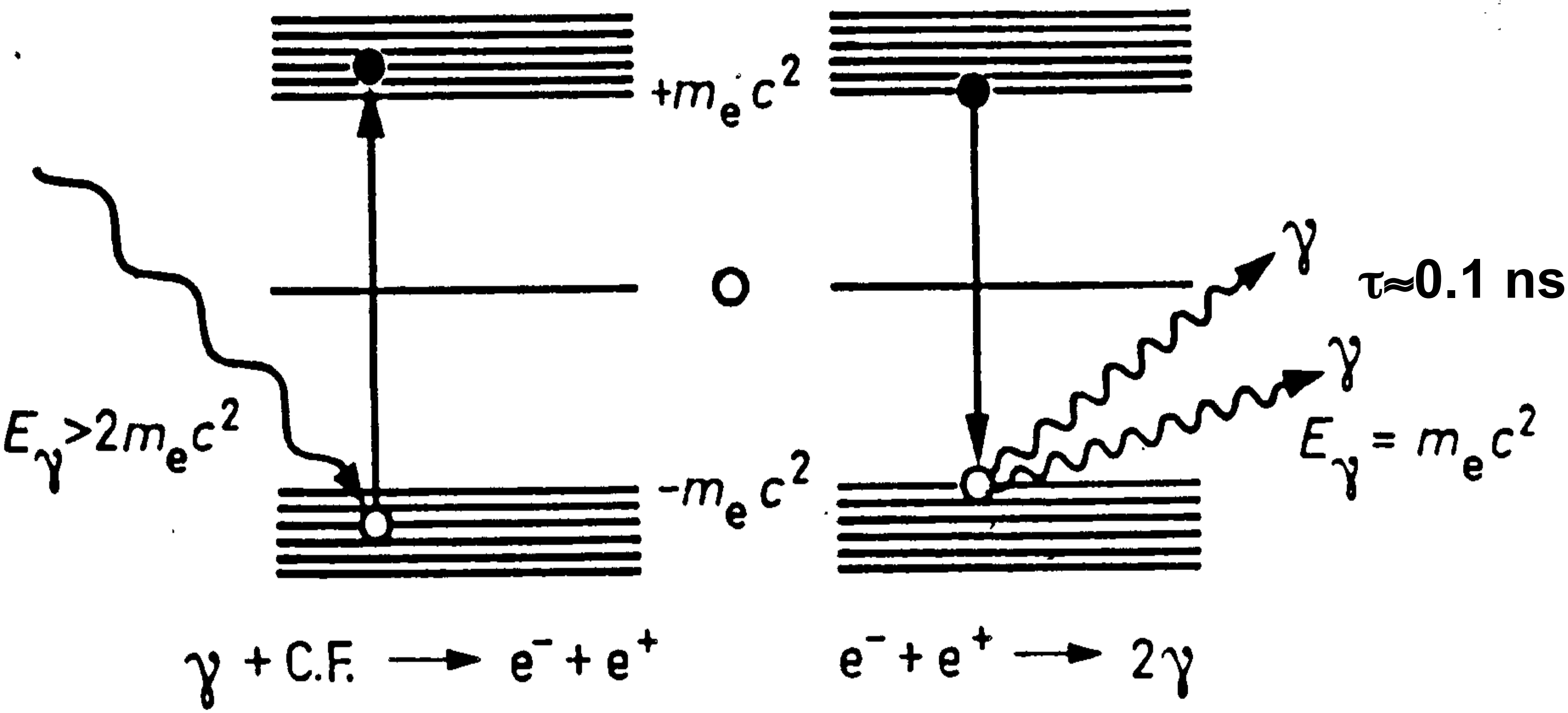


a)



b)

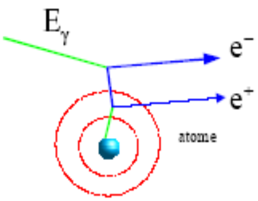
Creation and annihilation of electron positron pairs



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

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

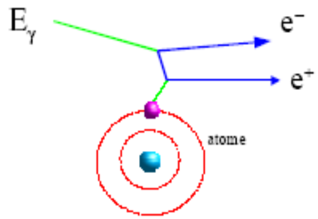
Creation of electron positron pairs



Dans le champ du noyau

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

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

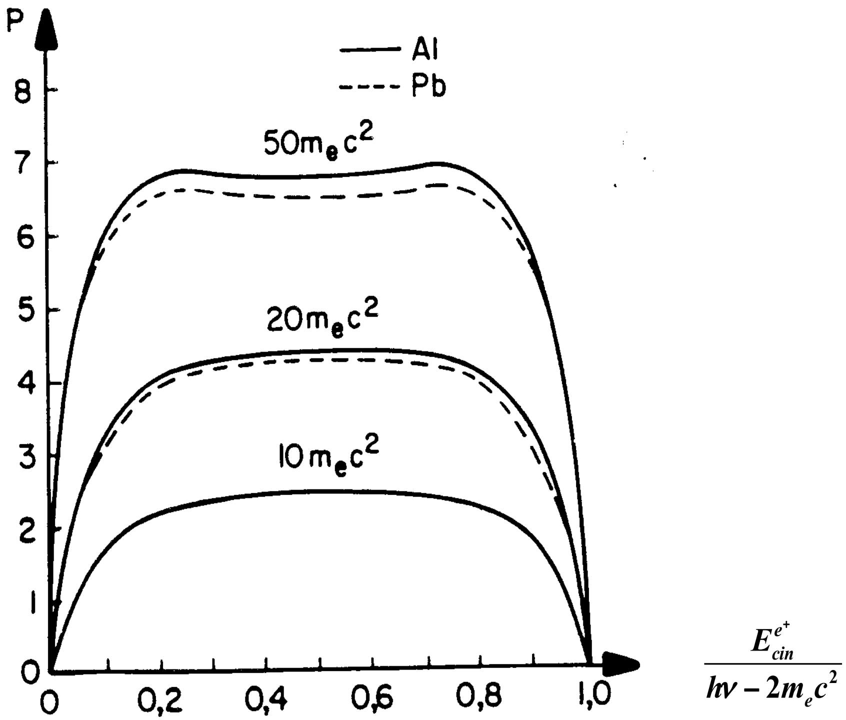


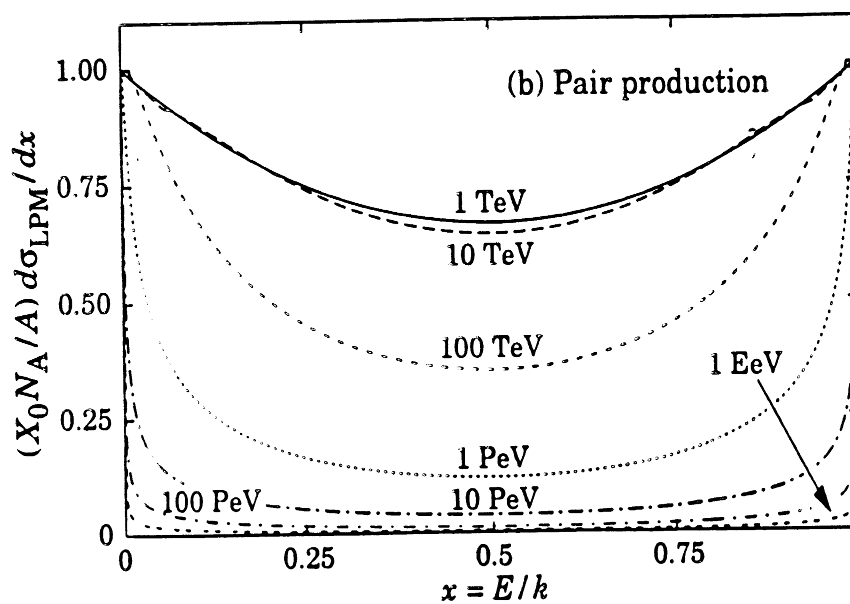
Dans le champ d'un électron

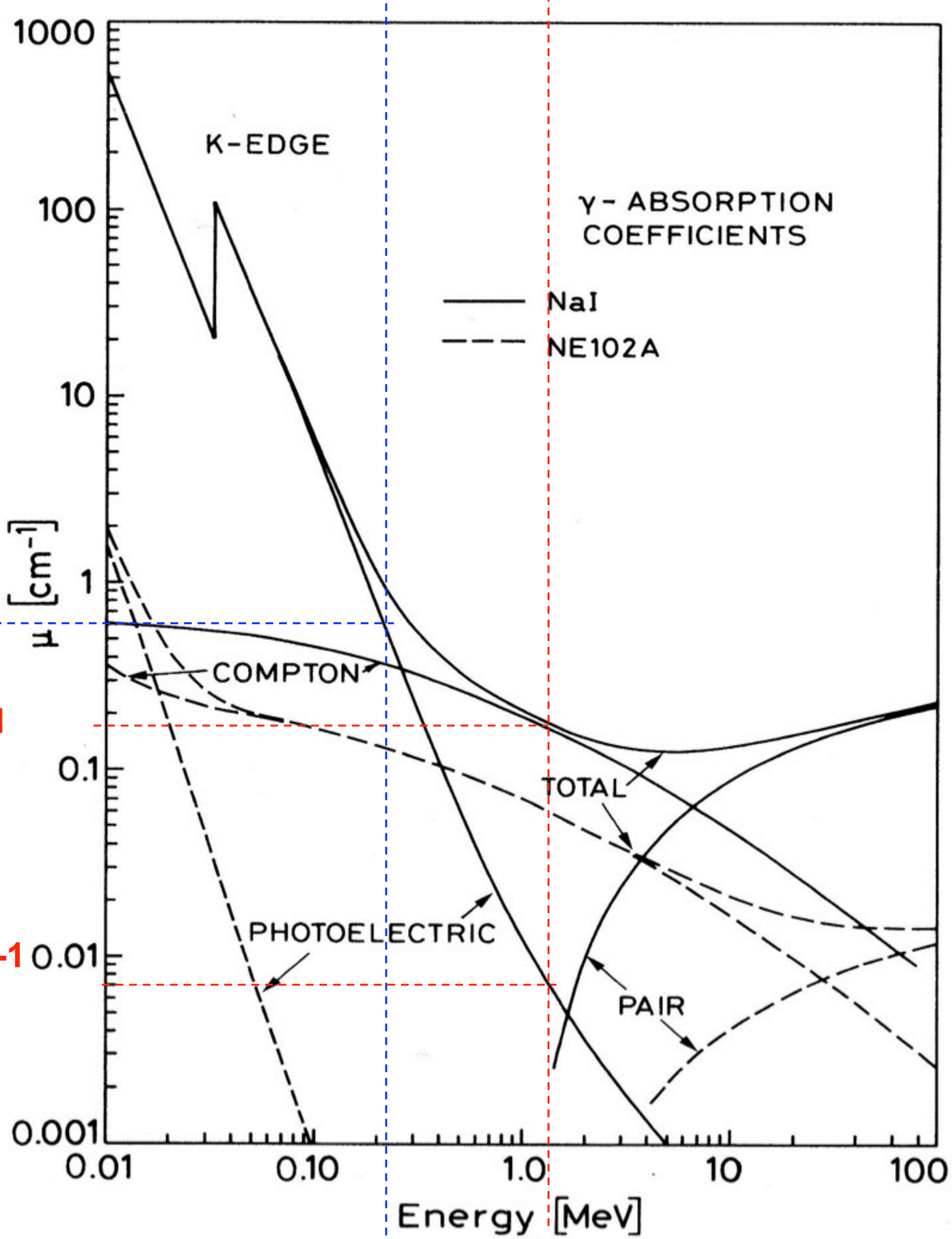
$$E_\gamma \geq 4m_e$$

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

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







$\mu = 0.6\ cm^{-1}$

$\mu = 0.18\ cm^{-1}$

$\mu = 0.007\ cm^{-1}$

Photo-electric effect

Absorption of γ

Compton scattering

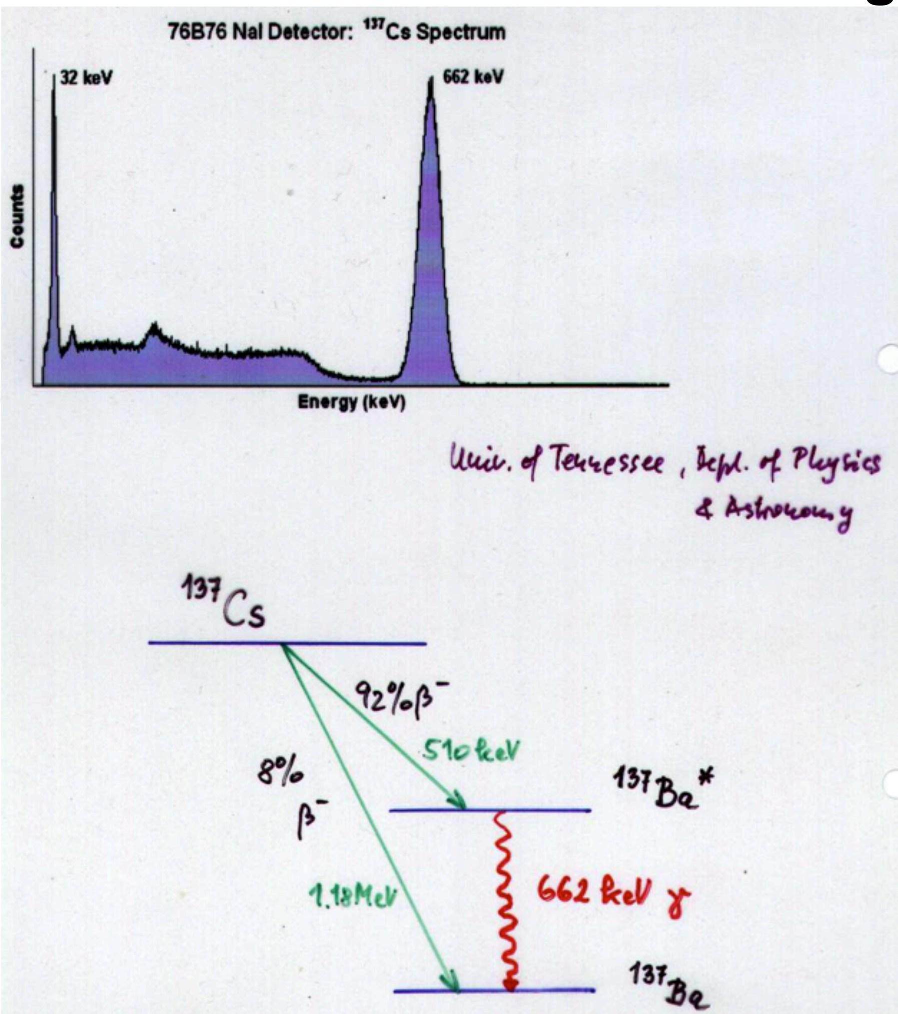
scattering $\gamma \rightarrow \gamma'$

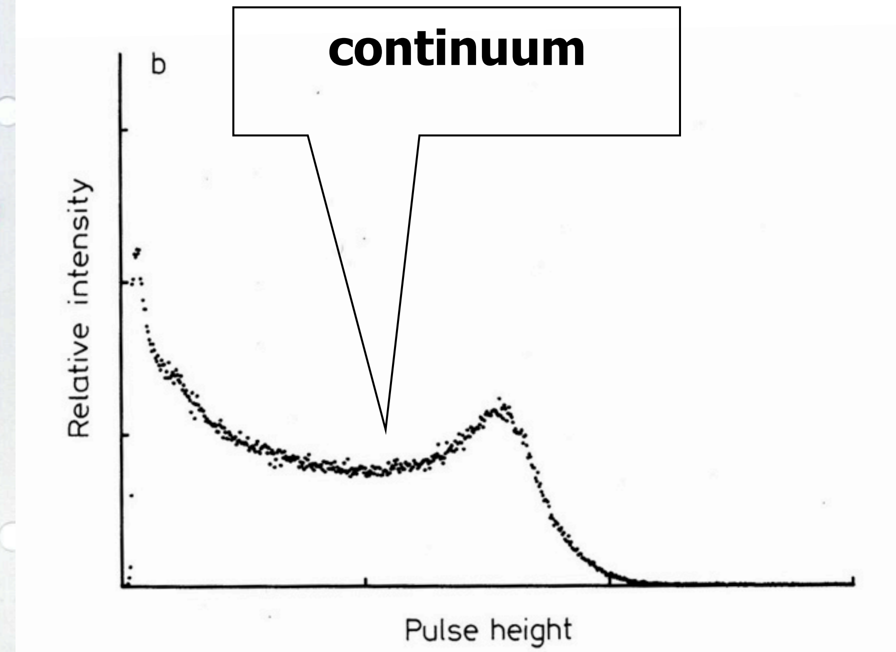
Creation of (e^+e^-) pairs

Absorption of γ

Response function of a Scintillator

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

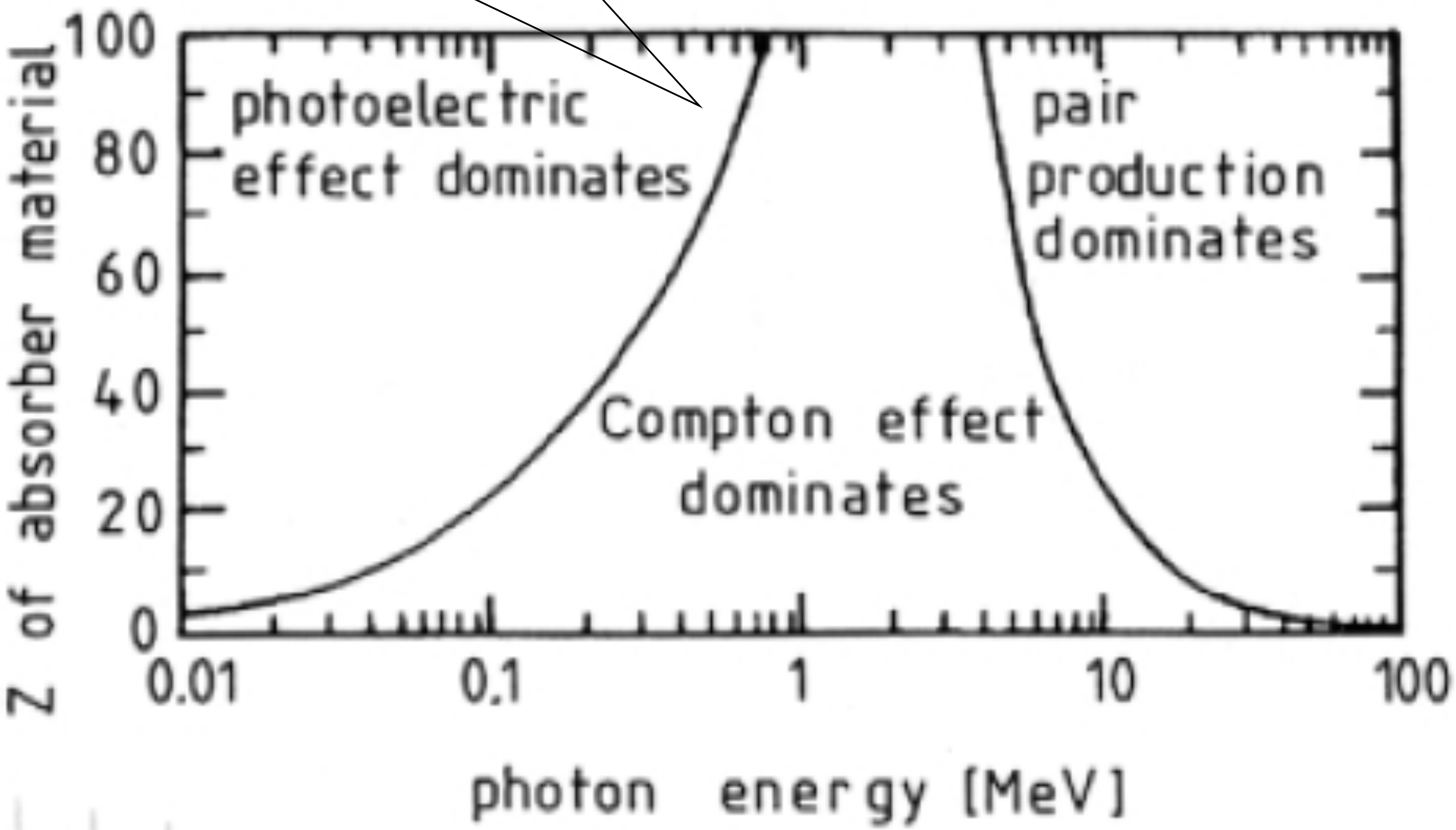




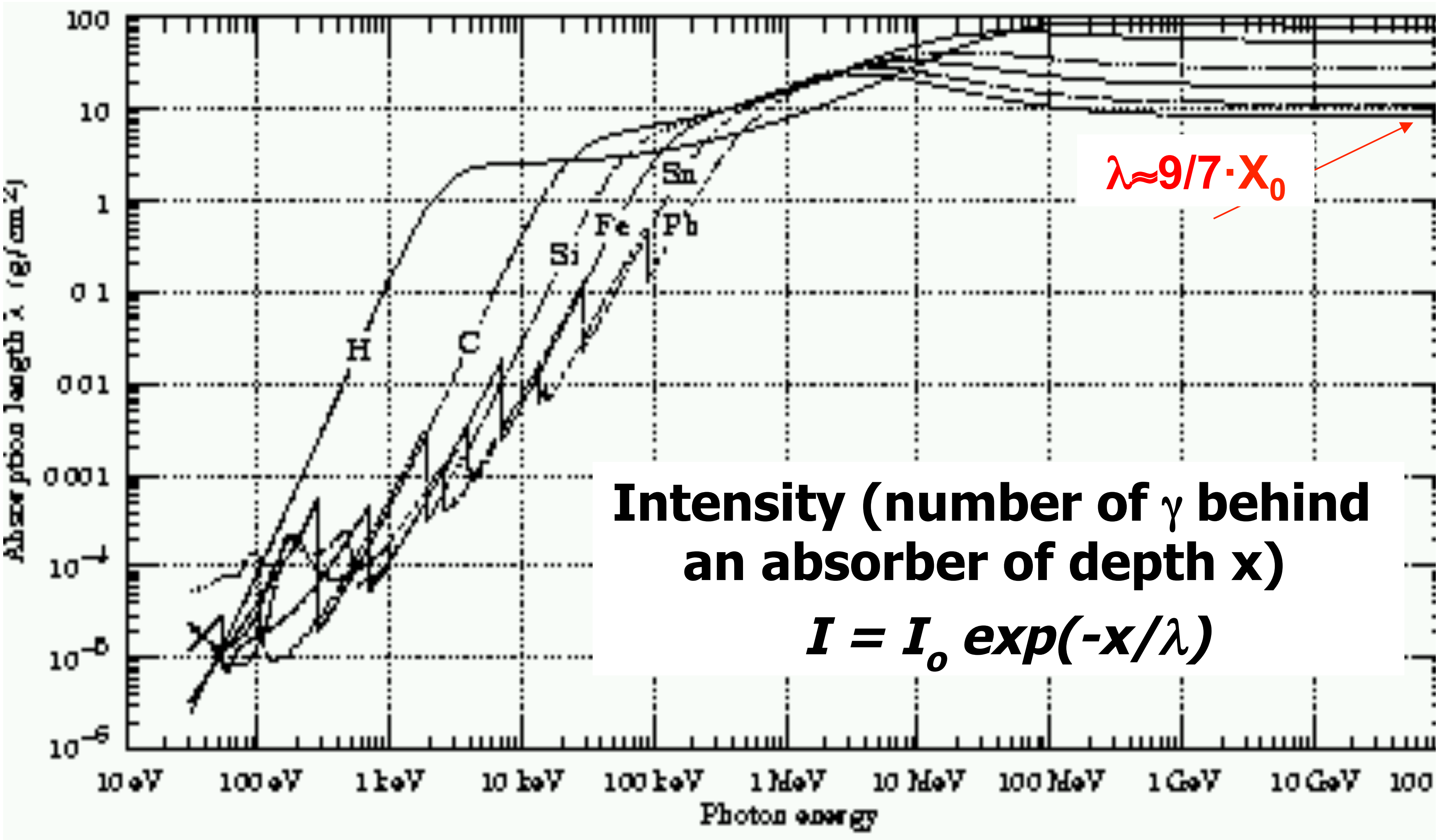
Plastic Scintillator

Interaction of photons with matter

Regions where one process is dominant, not exclusive !



Attenuation length of photons

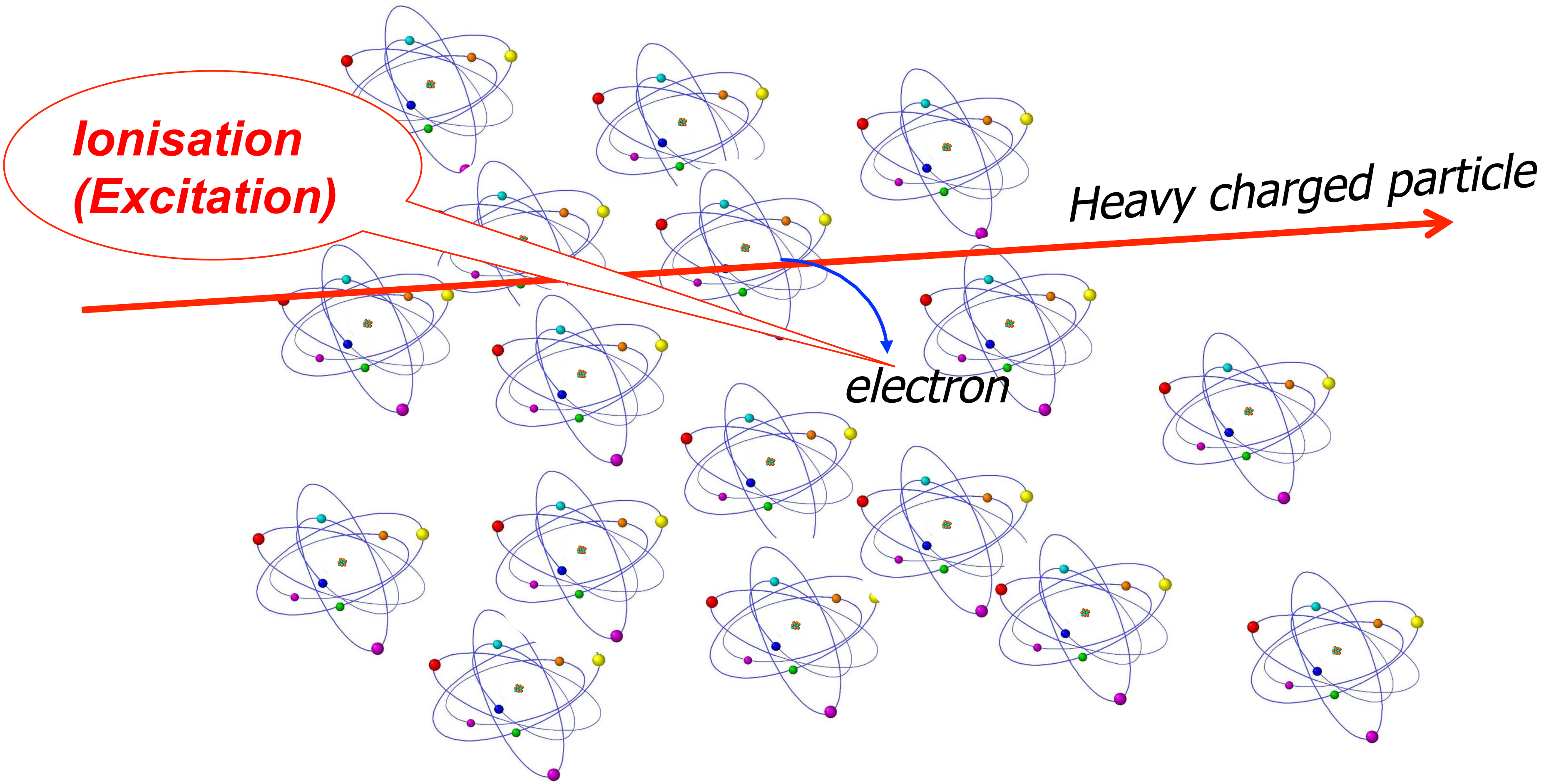


Intensity (number of γ behind an absorber of depth x)

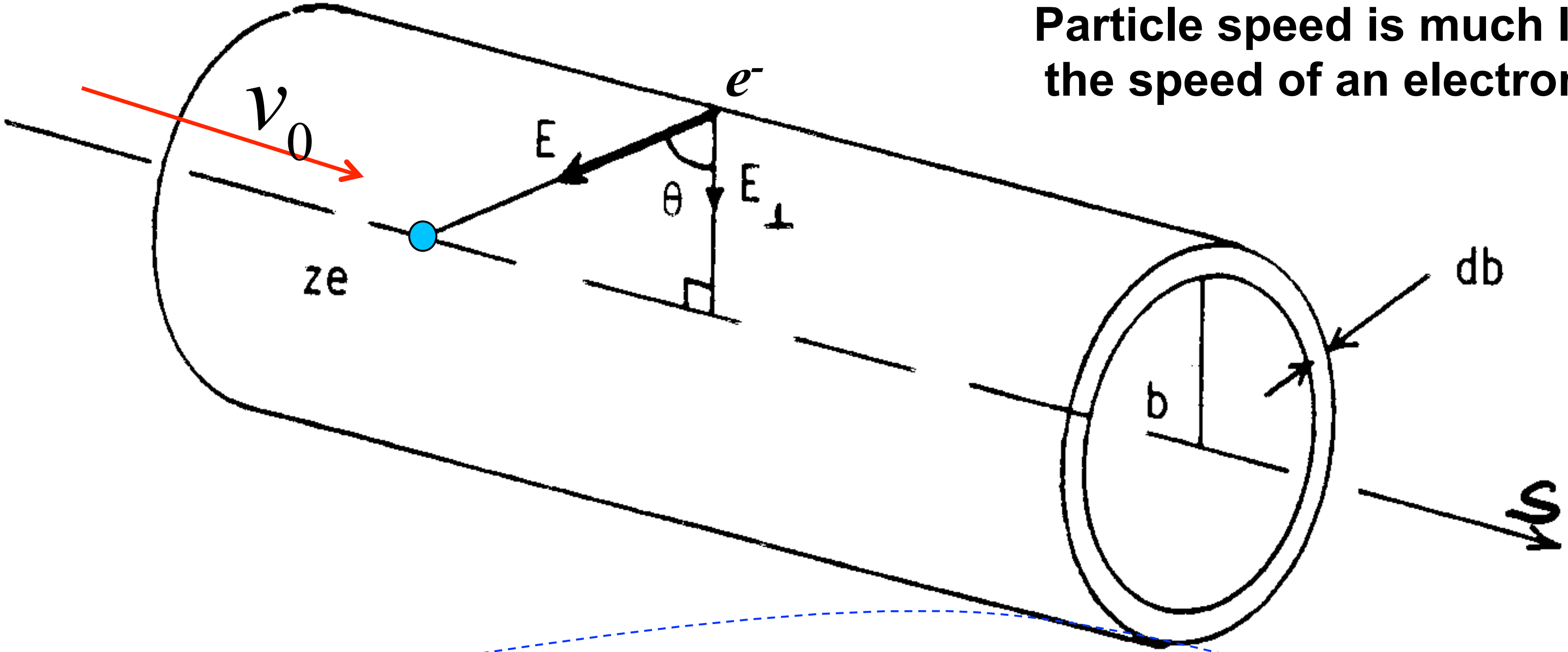
$$I = I_o \exp(-x/\lambda)$$

Charged « heavy particles »

Coulomb interaction

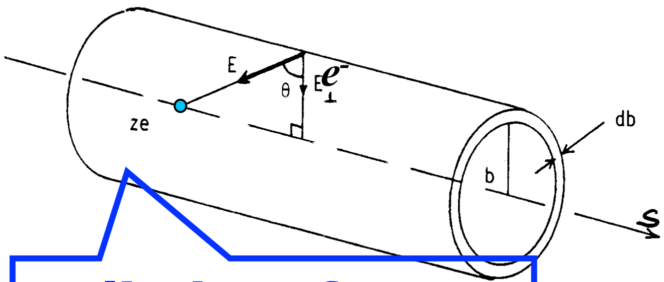


Interaction of charged "heavy" particles with the electrons of matter



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

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



Cylinder of surface *A* and volume *V*

Classical calculation by Bohr:

Momentum transfer Δp to the electron;

Energyloss of particle = - energy transfer to electron ΔE;

n_e = electron density

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

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

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

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

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

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

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

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

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

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

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

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

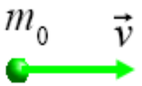
$b_{\max}$: interaction time $\ll$ Orbit time $\bar{T}$

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

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

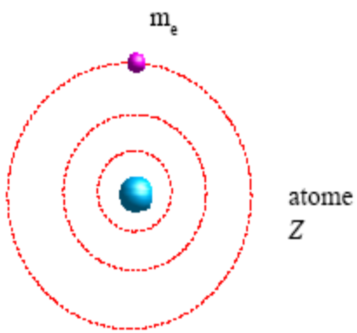
$$-\frac{dE}{ds} = -\int_0^\infty \frac{dE}{db} db = \frac{4\pi z^2 e^4 k^2}{m_e v_0^2} n_e \ln \frac{\gamma^2 m_e v_0^3 \bar{T}}{z^2 e^2 k^2}$$

Maximal energy transfer of charged "heavy" particles to the electrons of matter



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

E



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

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

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

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

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

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

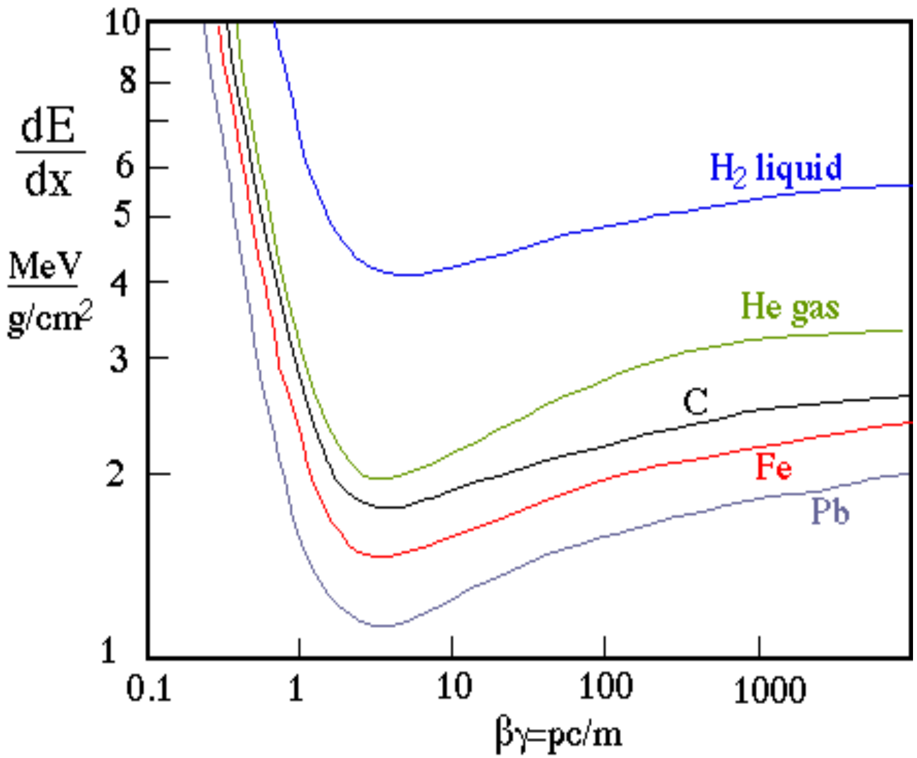
$$m_0 \gg m_e; \; 2\gamma m_e / m_0 \ll 1$$

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

$$m_0 = m_e$$

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

Bethe – Bloch formula



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

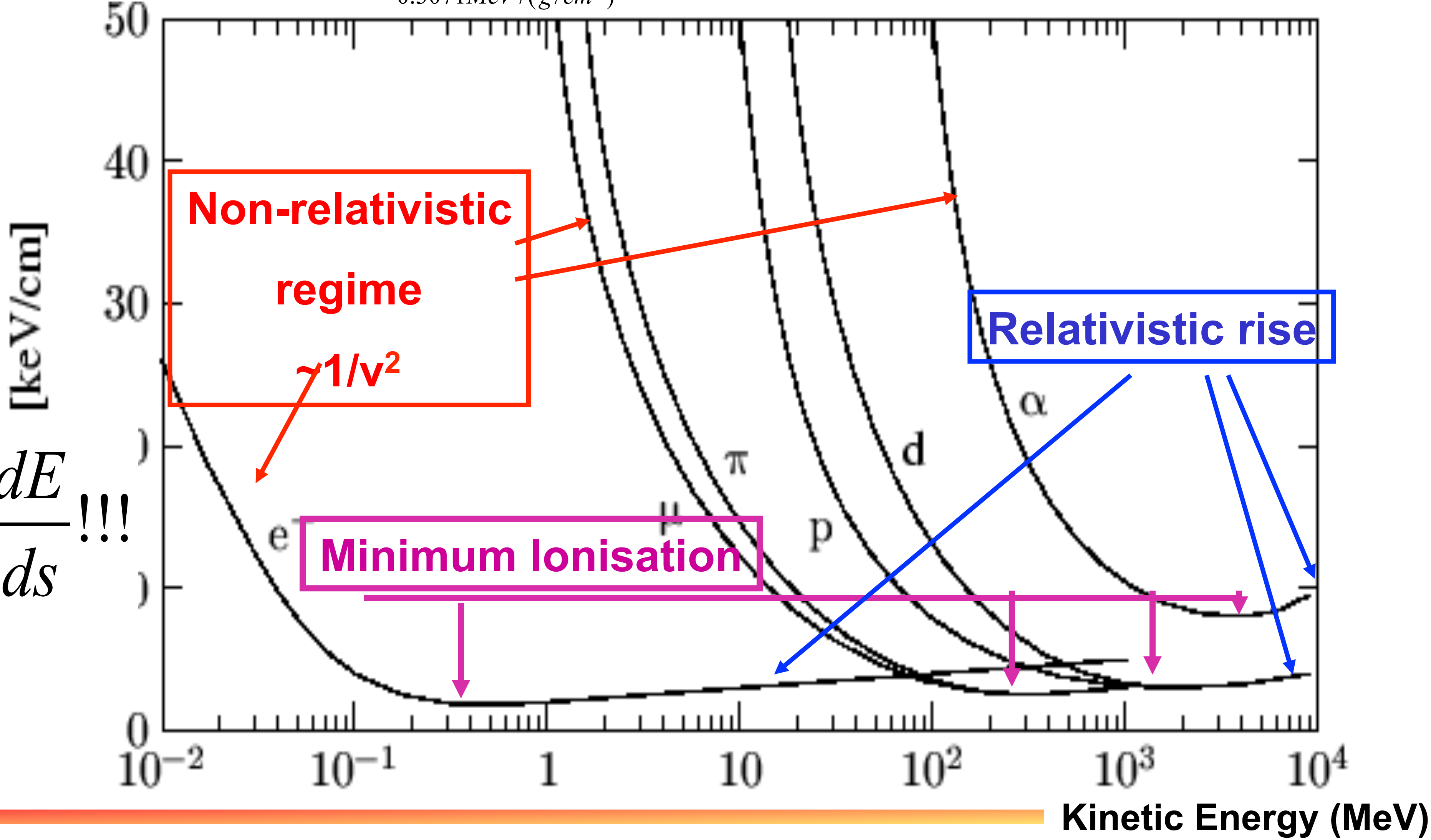
$$n_e = N_A \cdot \rho \cdot \frac{Z}{A}$$

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

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

Density- *shell correction*

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



$$\frac{dE}{ds}!!!$$

$$\frac{dE}{ds}!!!$$

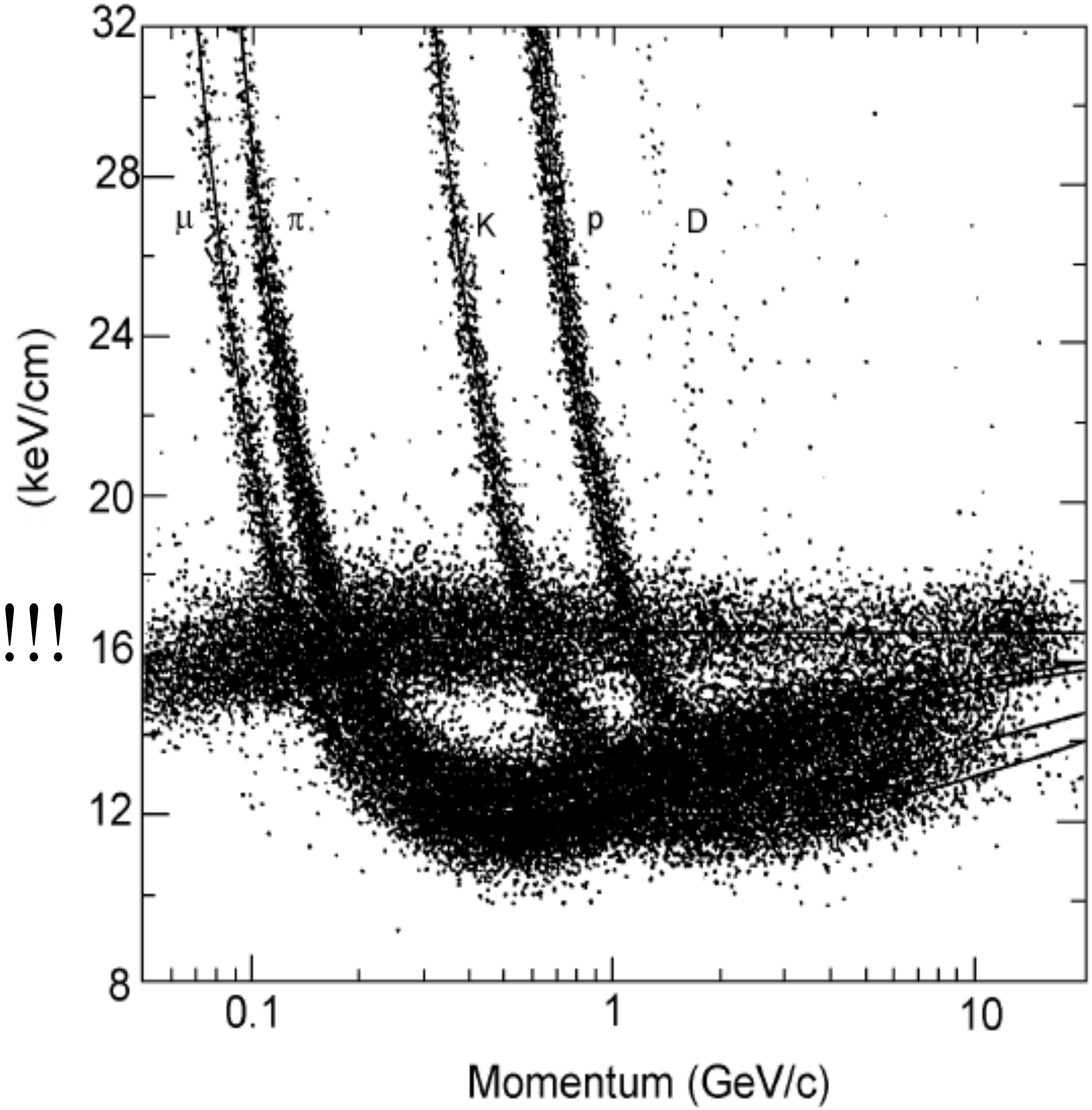
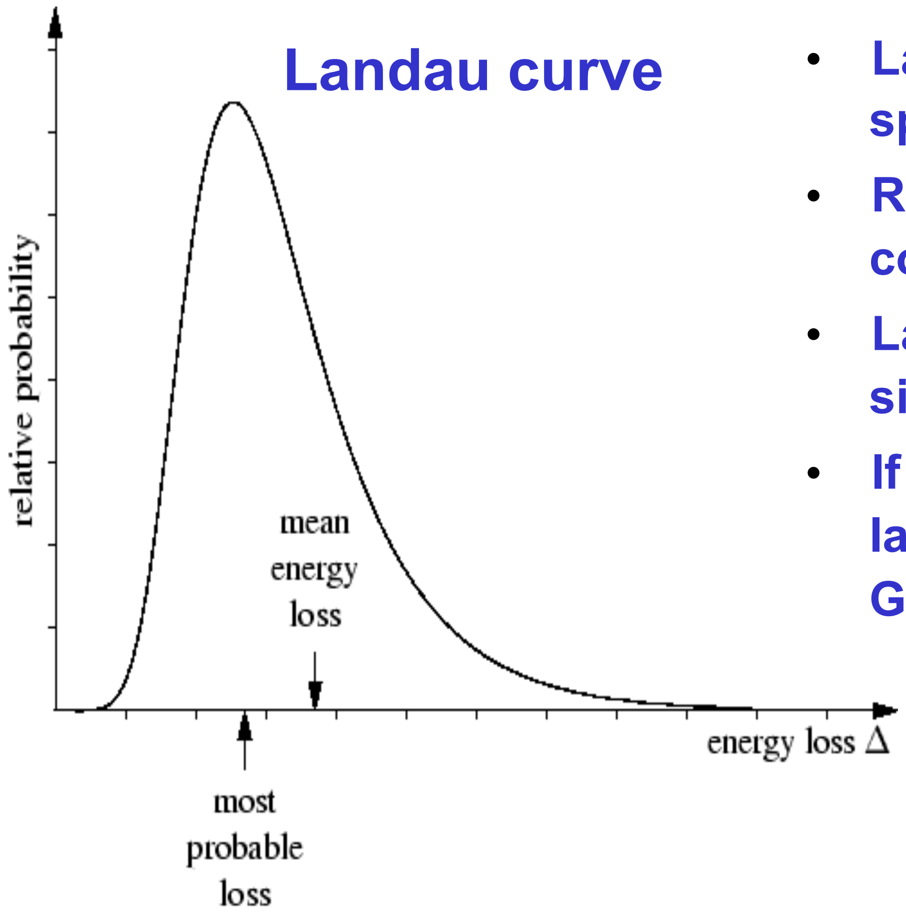
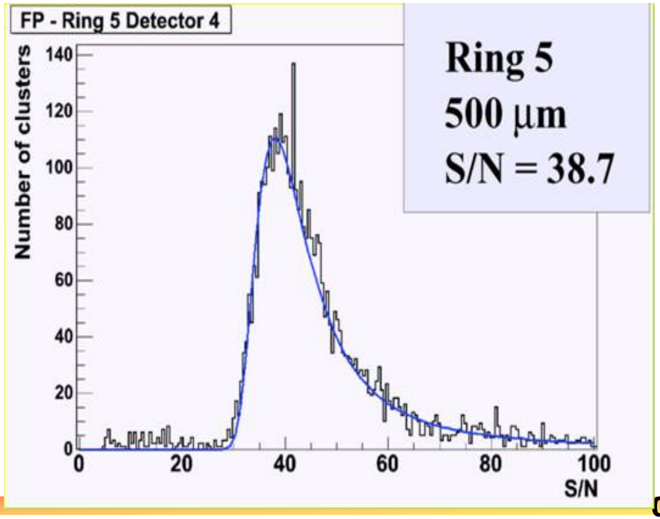


FIGURE 7. Measured ionization energy loss of electrons, muons, pions, kaons, protons and deuterons in the PEP4/9-TPC ($Ar–CH_4 = 80 : 20$ at 8.5 atm) [13]

Fluctuations of energy loss by charged particles



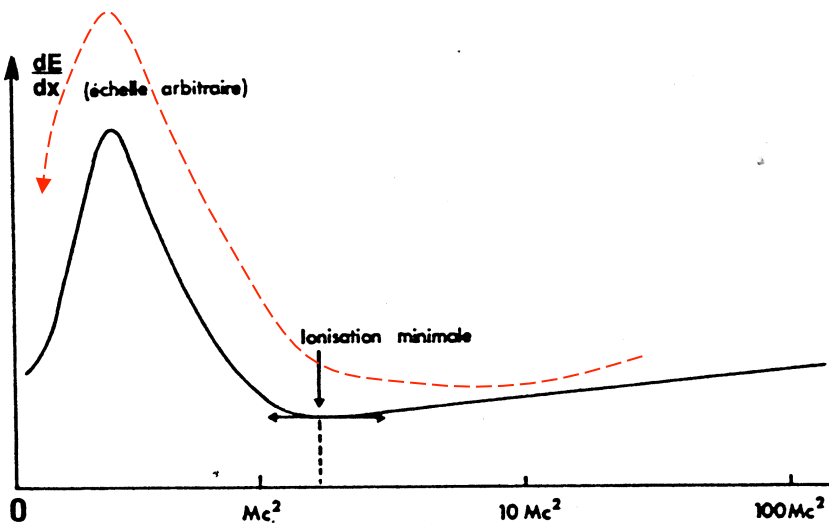
- Large fluctuations of energy loss, specially in thin layers
- Results from the stochastic nature of collisions.
- Large transfer of energy can occur in a single collision
- If the number of collisions becomes very large the distribution approaches a Gaussian (Central Limit Theorem).

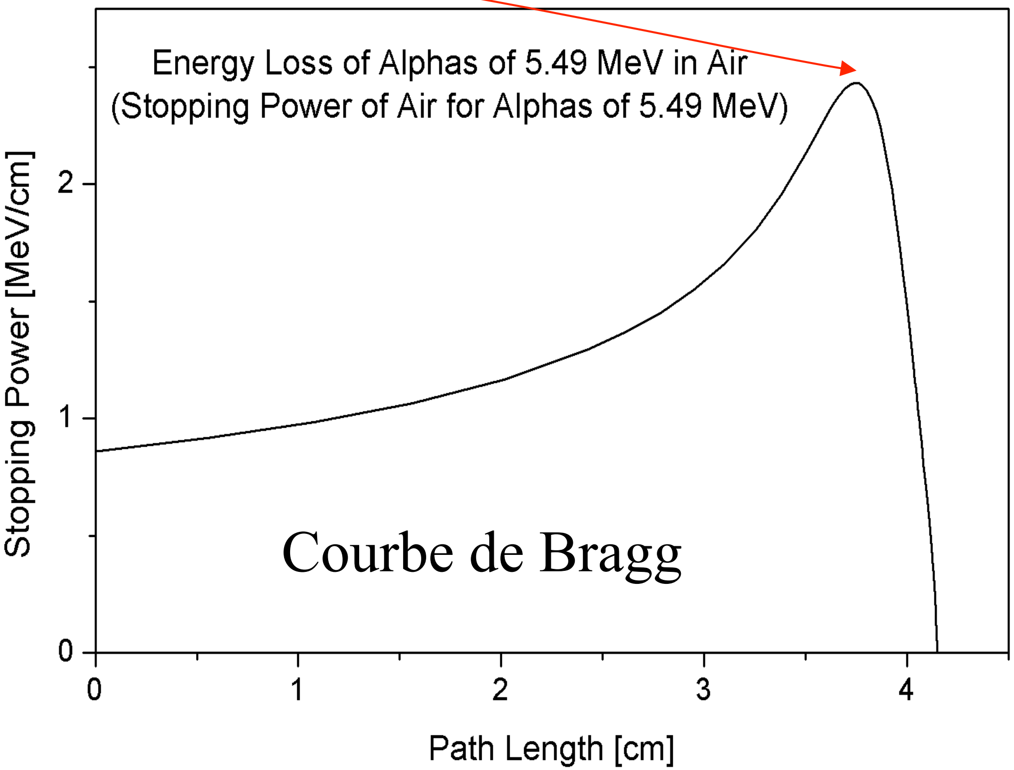


Range of charged particles

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

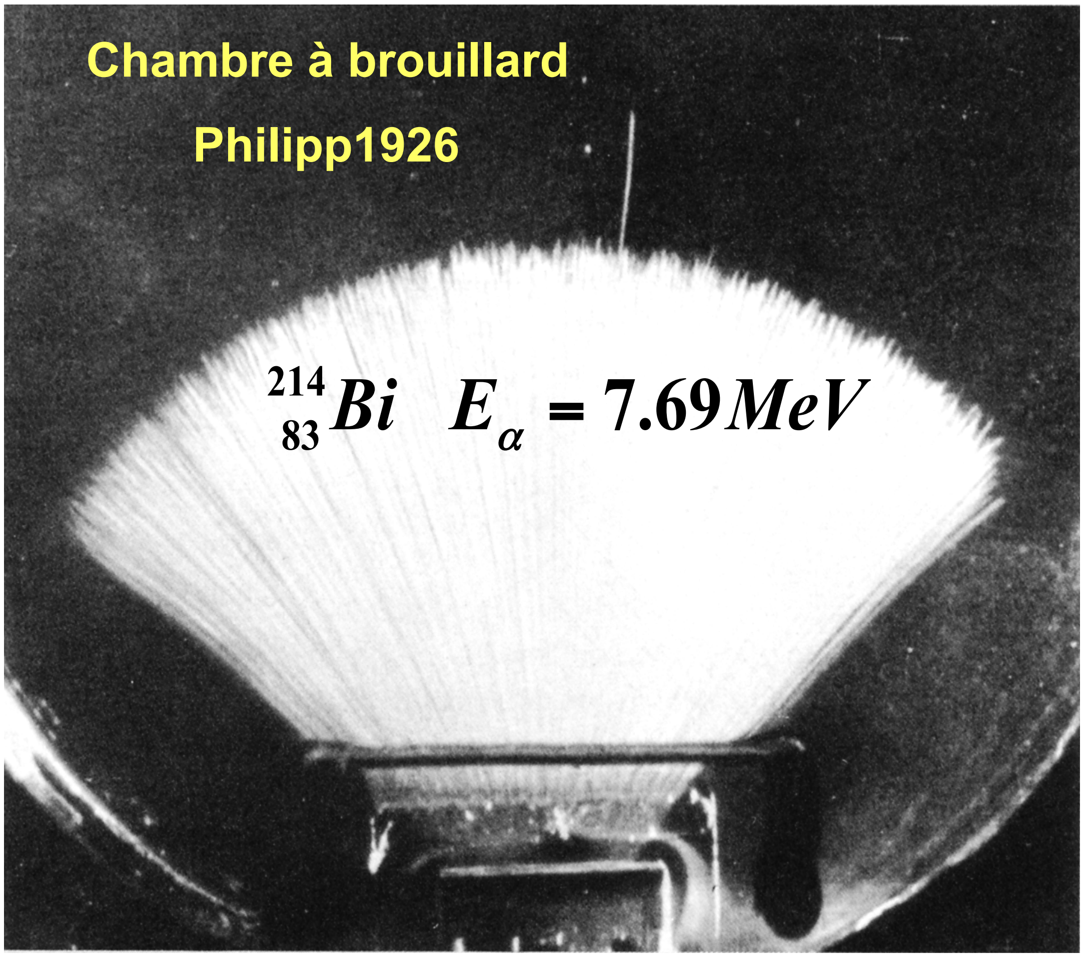
$$\frac{< R > \rho}{Mc^2} \sim \frac{1}{z_0^2} \frac{A}{Z} f\left(\beta_0 \gamma_0\right)$$

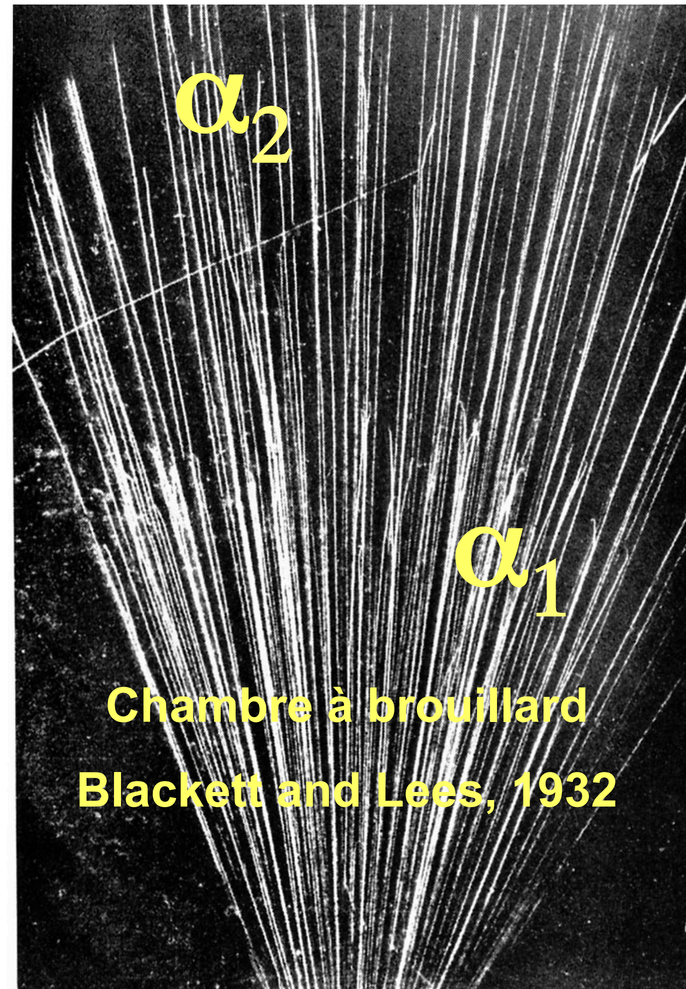




Cloud Chamber

$${}^{212}_{82}Pb \xrightarrow{\beta^-} {}^{212}_{83}Bi \quad E_\alpha = 6.09\,MeV \xrightarrow{\beta^-} {}^{212}_{84}Po \quad E_\alpha = 8.78\,MeV$$

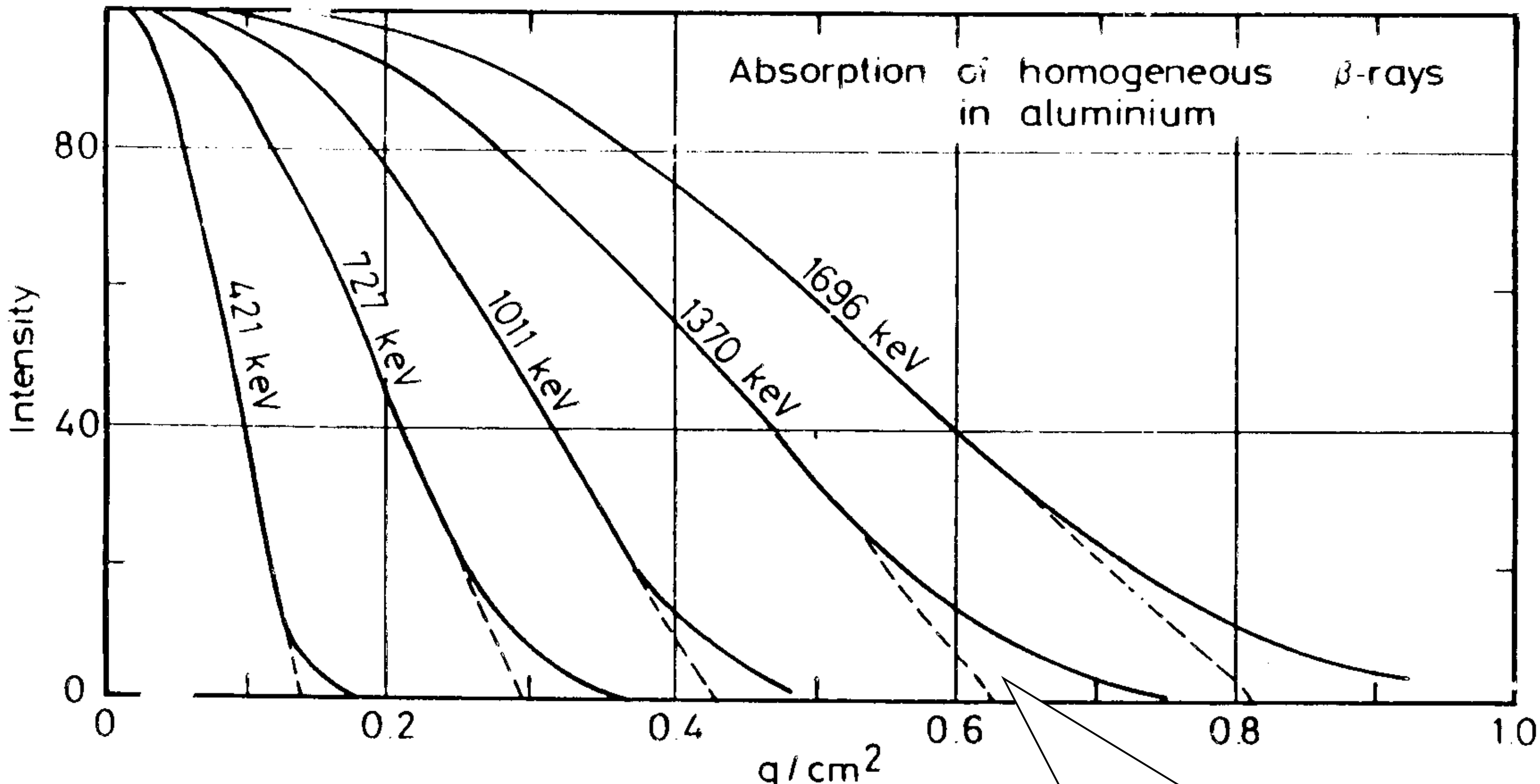




Electrons

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

Low energy electrons

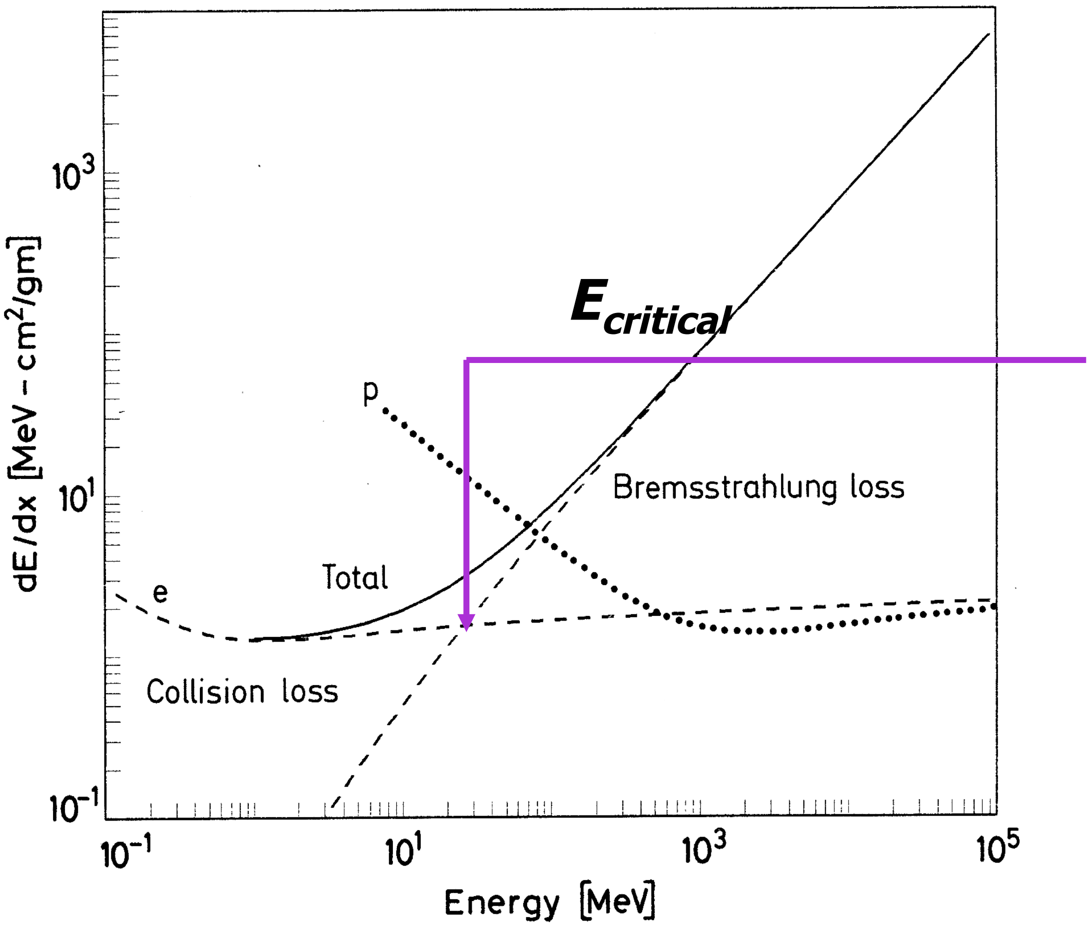


Definition of an efective range

High energy electrons: Bremsstrahlung

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

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

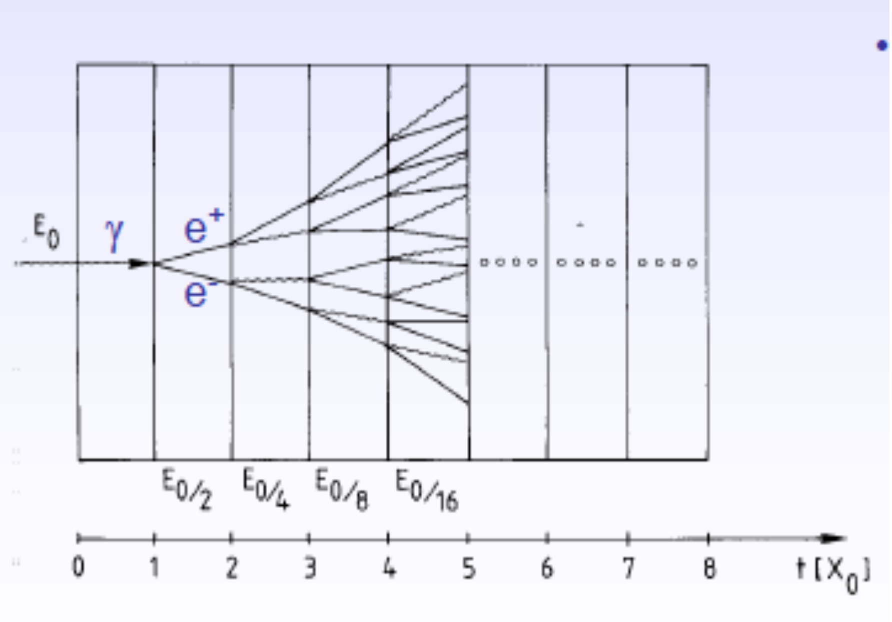
$$E_c = \frac{710 \ \ MeV}{Z + 0{,}92}$$ Gas

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



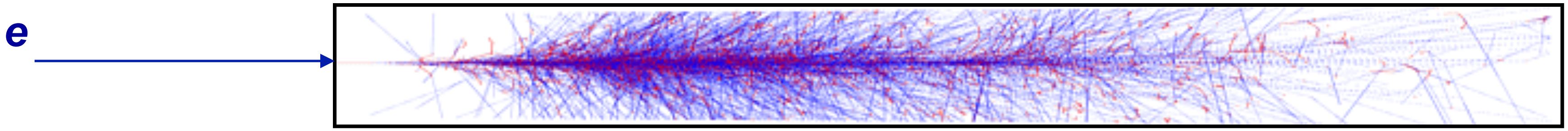
$N(t) = 2^t \qquad E(t)/\,particle = E_0 \cdot 2^{-t}$

Process continues until $E(t)<E_c$

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

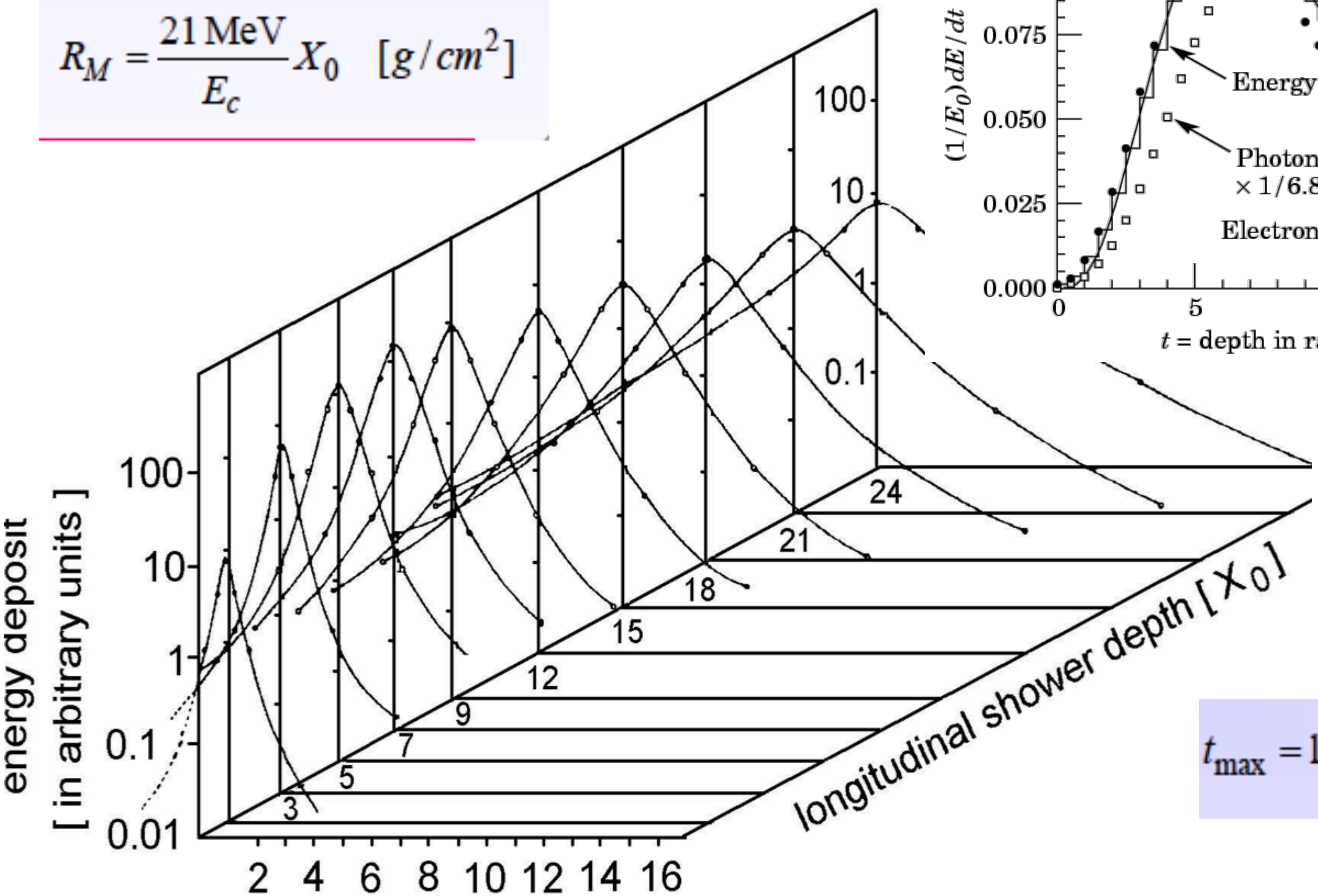
$$t_{max} = \frac{\ln E_0/E_c}{\ln 2}$$

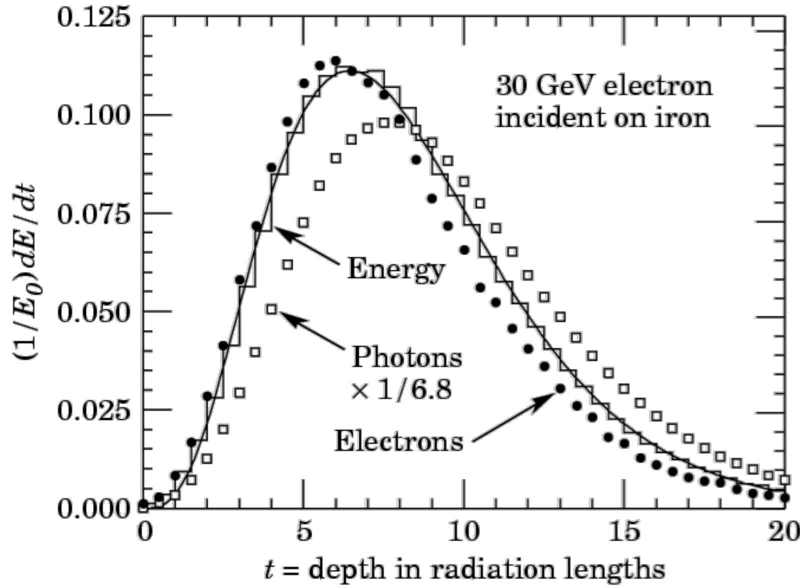
$PbW0_4$ CMS, X_0=0.89 cm



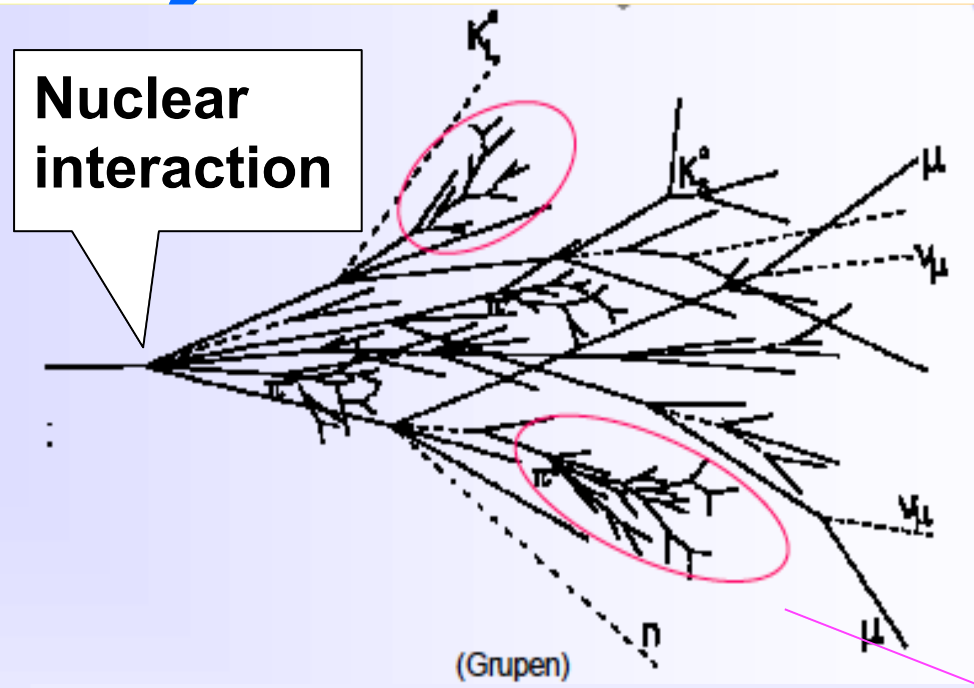
95% in a cone of R_M

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





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



Hadronic showers

This is NOT(!)

a parton shower !!!

hadronic + electromagnetic

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

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

neutral pions $\rightarrow 2\gamma$

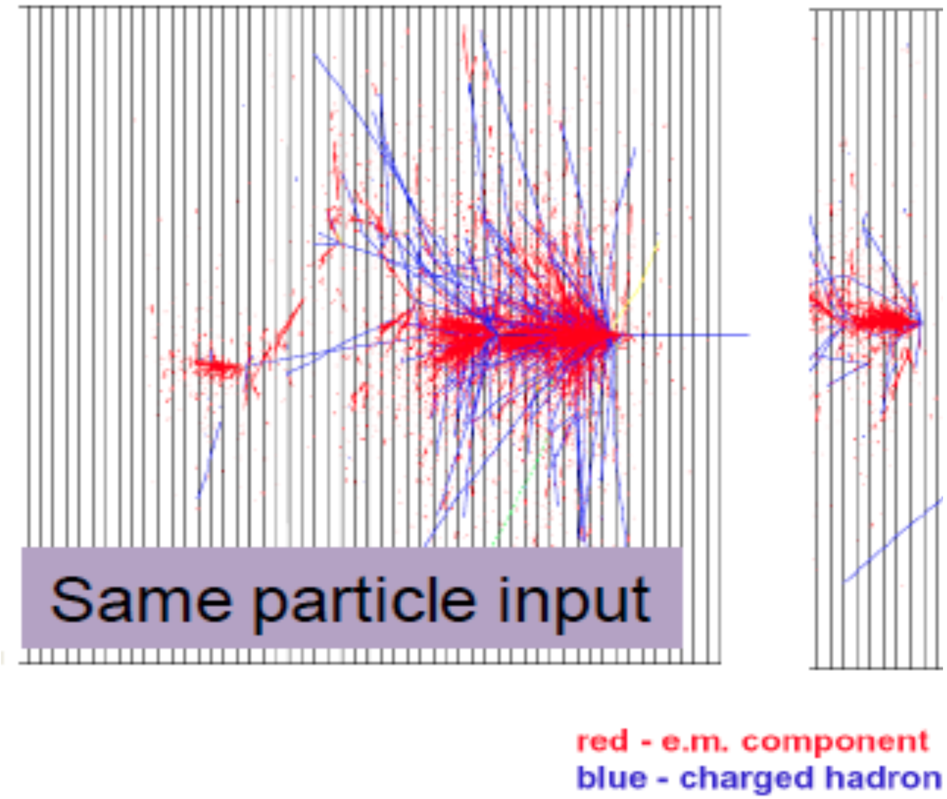
$\rightarrow$ electromagnetic cascades

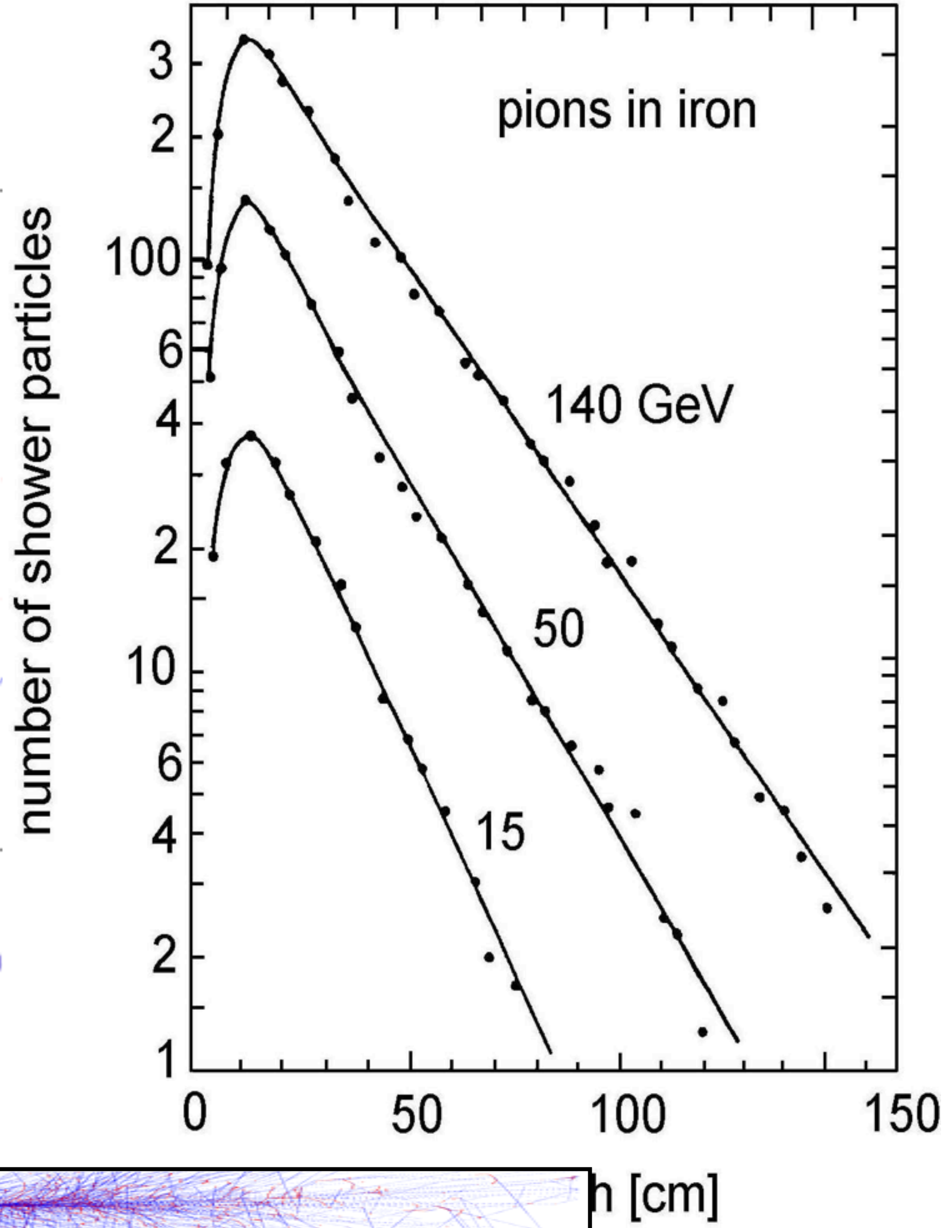
$$n(\pi^0) \approx \ln E(GeV) - 4.6$$

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

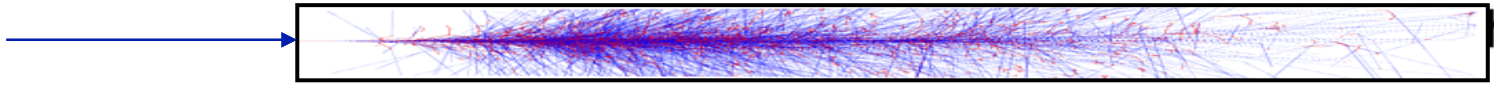
invisible energy $\rightarrow$ large energy fluctuations $\rightarrow$ limited energy resolution

Hadronic shower





Comparison elm shower:



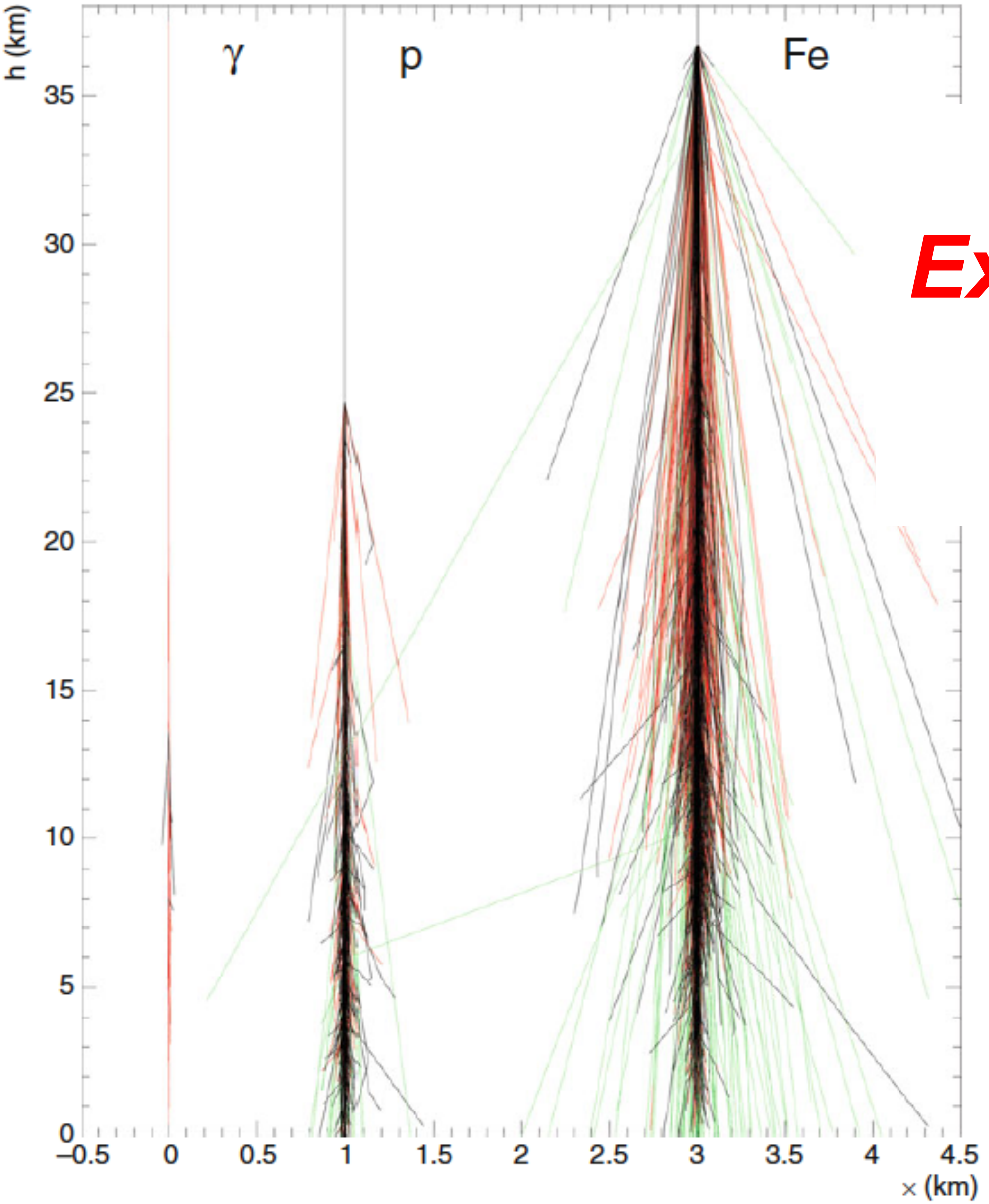


Fig. 1.11 Side view of trajectories of particles of energy ≥10 GeV of a photon, a proton and an iron nucleus initiated shower having a total primary energy of 10^5 GeV each. The electromagnetic component is shown in *red*, hadrons are *black* and muons *green*. The widely spread particles in the lower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

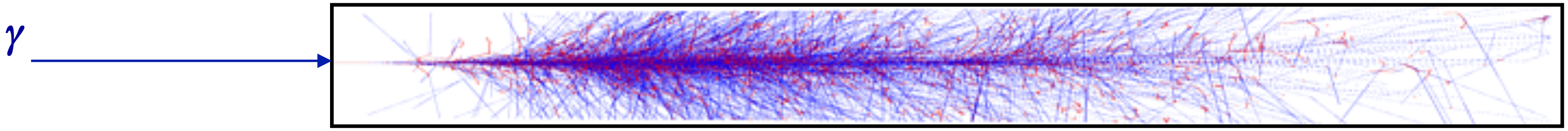
Summary
Particle interaction with matter

Photons :

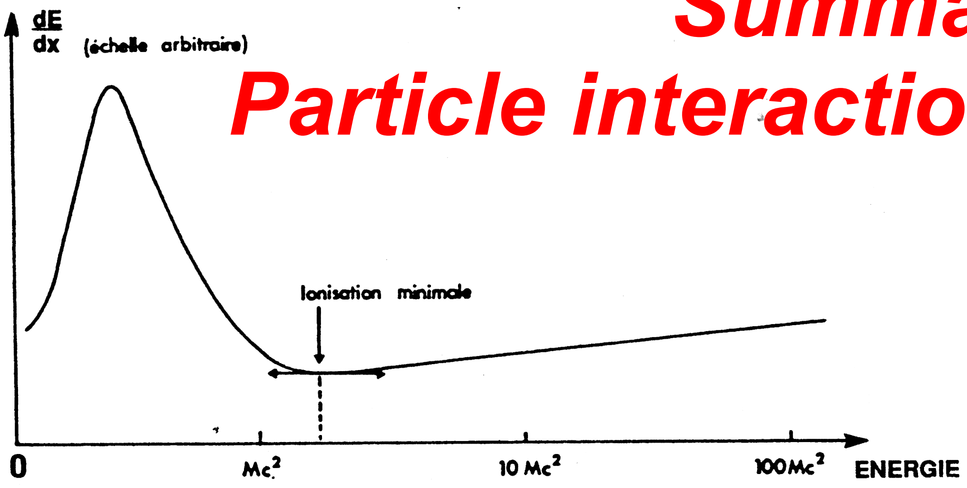
- **At low energy (< 10 MeV) photons are absorbed by a single interaction (photoelectric, Compton effect or pair creation). The number of photons is attenuated exponentially, the energy of the remaining photons is not changed, however by the Compton effect lower energy photons are created.**

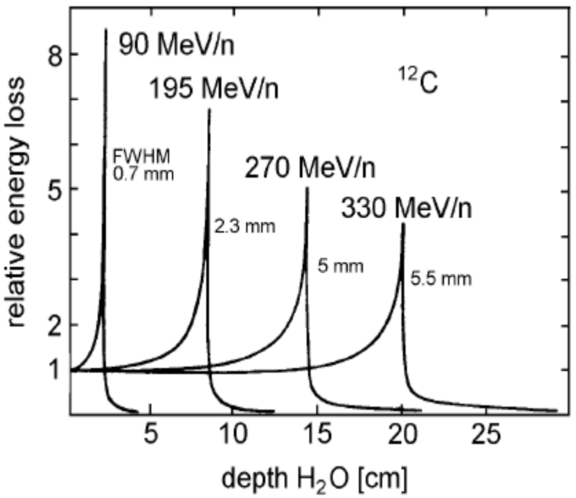
$$N(x) = N_0 \exp\left(-x/\lambda\right) \; ; \quad \frac{1}{\mu} = \lambda_{\text{specific process}} = \text{attenuation length}; \quad x = \text{thickness}$$

- **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"**



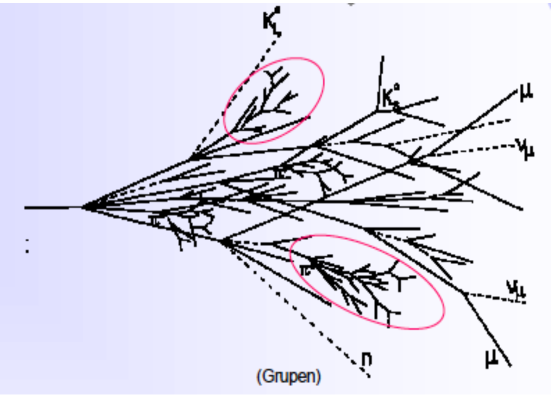
Summary
Particle interaction with matter





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 :



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

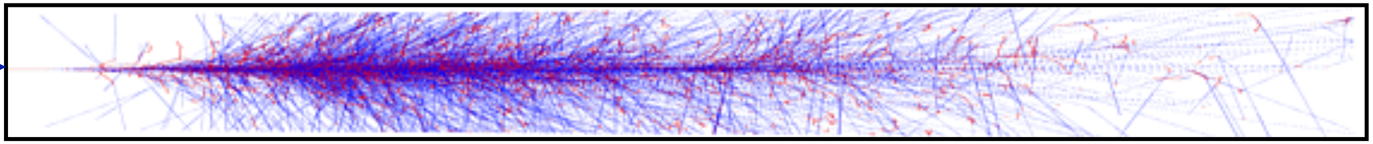
Summary (I)
Particle interaction with matter

Electrons

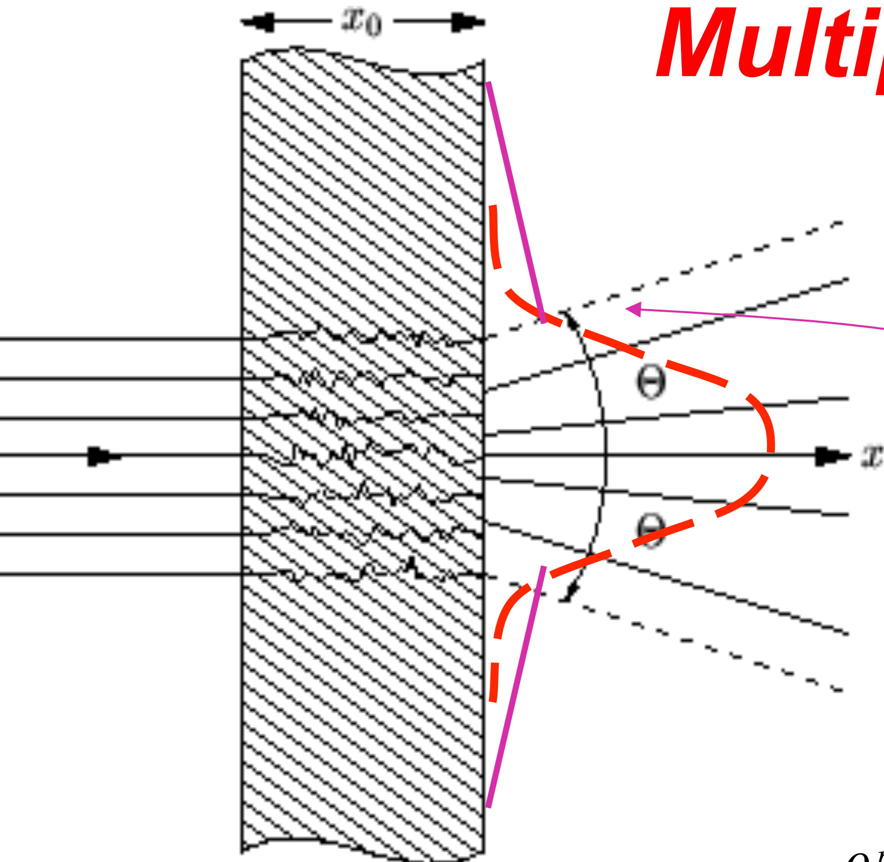
- also loose their energy by ionization but with much larger fluctuations in the energy loss and deflections leading to a badly defined range in matter.
- At energies higher than a critical energy Bremsstrahlung is emitted. This process becomes rapidly dominant.
- Multiple pair creation and Bremsstrahlung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

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

e



Multiple scattering

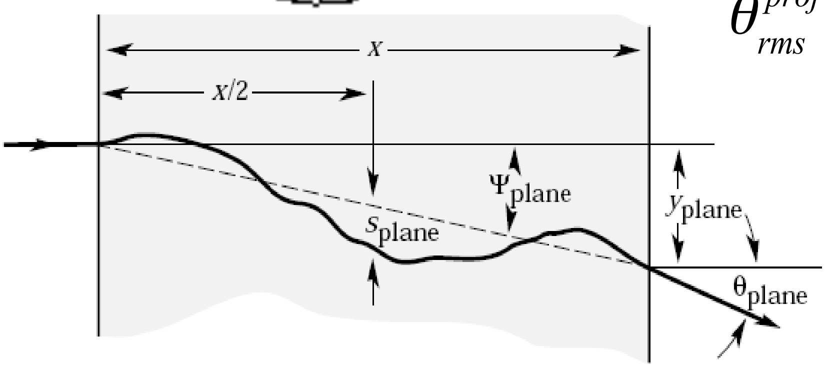


Scattering in the coulomb field of the nucleus (Rutherford)

Gaussian (θ) distribution for small angles θ,

Violant scatters can lead to large values of θ

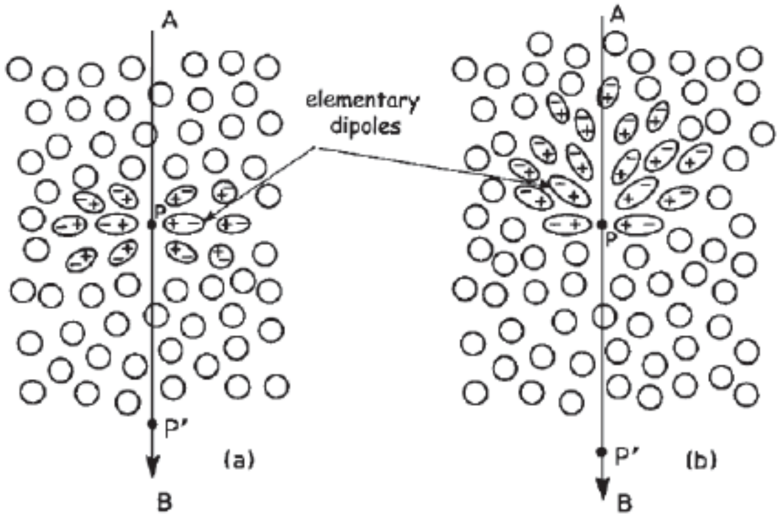
$$\theta_{rms}^{proj} = \frac{13.6 MeV/c}{p \cdot \beta} Z_0 \sqrt{\frac{x}{X_0}} \left(1 + 0.038 \ln(x/X_0)\right)$$



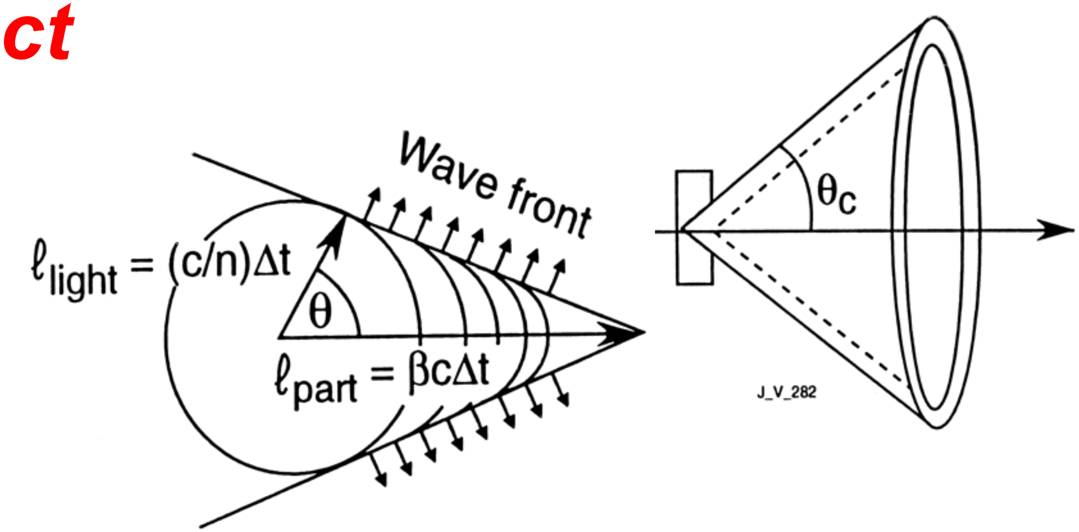
X_0=radiation length

Cerenkov and Transition radiation

Cerenkov effect



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



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

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

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

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

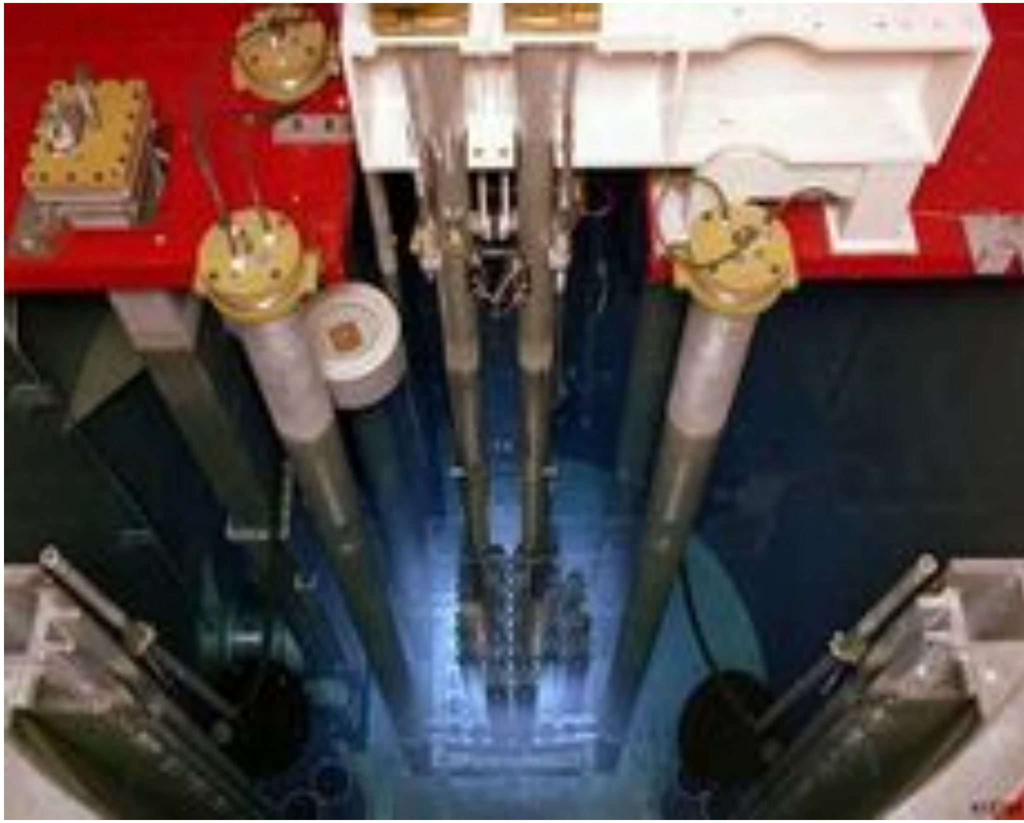
$$\lambda_{photons} \approx 200 - 700\,nm$$

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

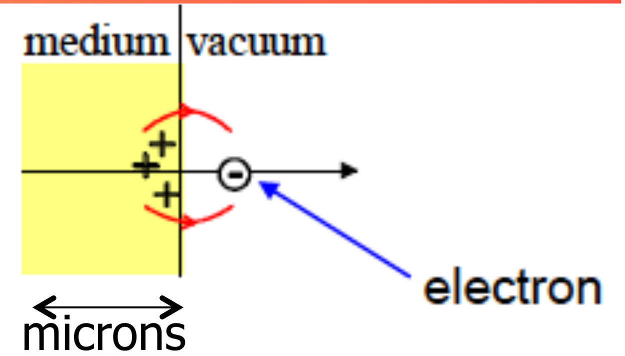
Exercise

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**



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

$$\omega_{pl} = \sqrt{\frac{N_e e^2}{\varepsilon_0 m_e}} \; ; \left\{ \begin{array}{c} \text{plasma} \\ \text{frequency} \end{array} \right\}$$

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

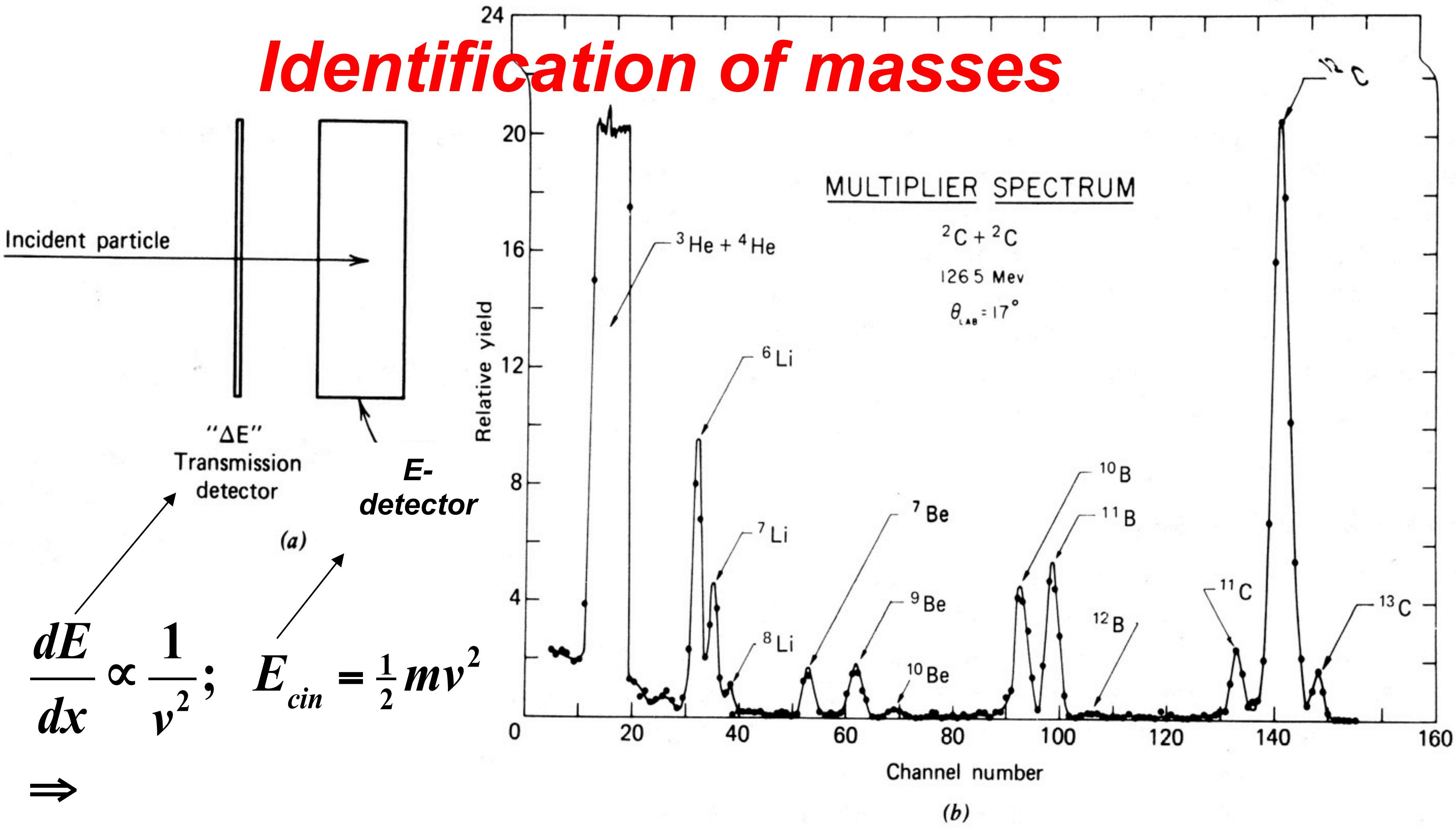
- Energy of emitted photons (X-rays) $\hbar\omega \approx \frac{1}{4}\hbar\omega_{pl}\gamma \rightarrow keV\ \ range$
- Number of emitted photons: $N_{ph} \approx \frac{W}{\hbar\omega} \sim \alpha \approx \frac{1}{137}; \Rightarrow$ *many layers*
- X-rays are emitted at small angle $\theta_{X-ray} \sim 1/\gamma$

(Simple?) Particle Identification, (PID)

PID: charge, masse, leptons or hadrons, muons

- Measure Energy and dE/dx (β) at low energy
- Measure dE/dx (β) and momentum (B-field)
- Time of flight (TOF)
- Cerenkov (β) or Transition radiation (γ)
- Photon vs neutral hadron
- Electron vs hadron
- Hadrons vs muons
- Neutrons
- Neutrinos ?
- Dark matter ?

Identification of masses



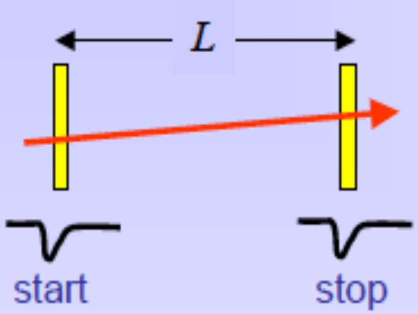
$$\frac{dE}{dx} \propto \frac{1}{v^2}; \quad E_{cin} = \frac{1}{2} m v^2$$

$\Rightarrow$

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

Figure 11-16 (a) A particle identifier arrangement consisting of tandem ΔE 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])

Particle ID using Time Of Flight (TOF)



$$t = \frac{L}{\beta c} \longrightarrow \beta = \frac{L}{tc}$$

Combine TOF with momentum measurement

$$p = m_0 \beta\gamma \longrightarrow m_0 = p\sqrt{\frac{c^2 t^2}{L^2} - 1}$$

Mass resolution $$\frac{dm}{m} = \frac{dp}{p} + \gamma^2\left(\frac{dt}{t} + \frac{dL}{L}\right)$$

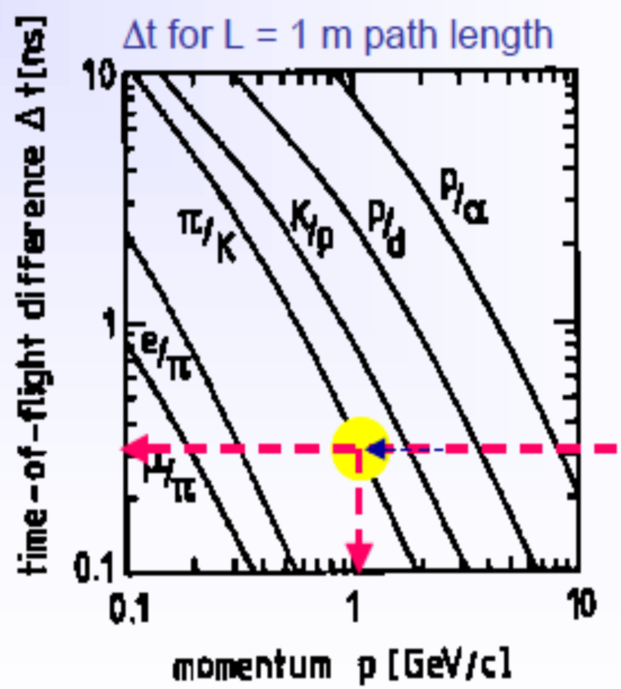
TOF difference of 2 particles as *f(p)*

$$\Delta t = \frac{L}{c}\left(\frac{1}{\beta_1} - \frac{1}{\beta_2}\right)$$

$$= \frac{L}{c}\left(\sqrt{1 + m_1^2 c^2 / p^2} - \sqrt{1 + m_2^2 c^2 / p^2}\right)$$

$$\approx \frac{Lc}{2p^2}\left(m_1^2 - m_2^2\right)$$

Δt for L = 1 m path length



σ_t = 300 ps
π/K separation
up to 1 GeV/c

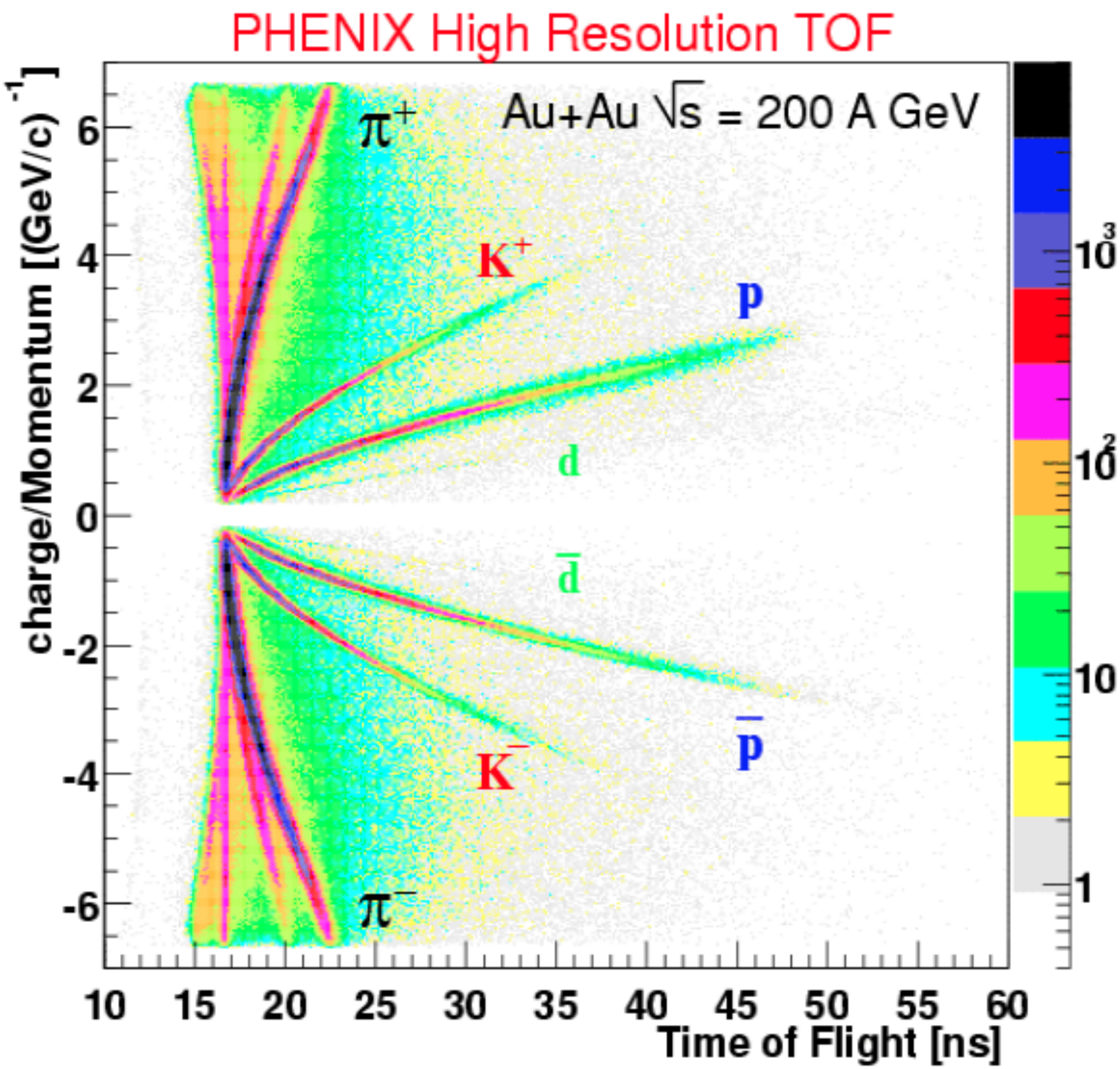
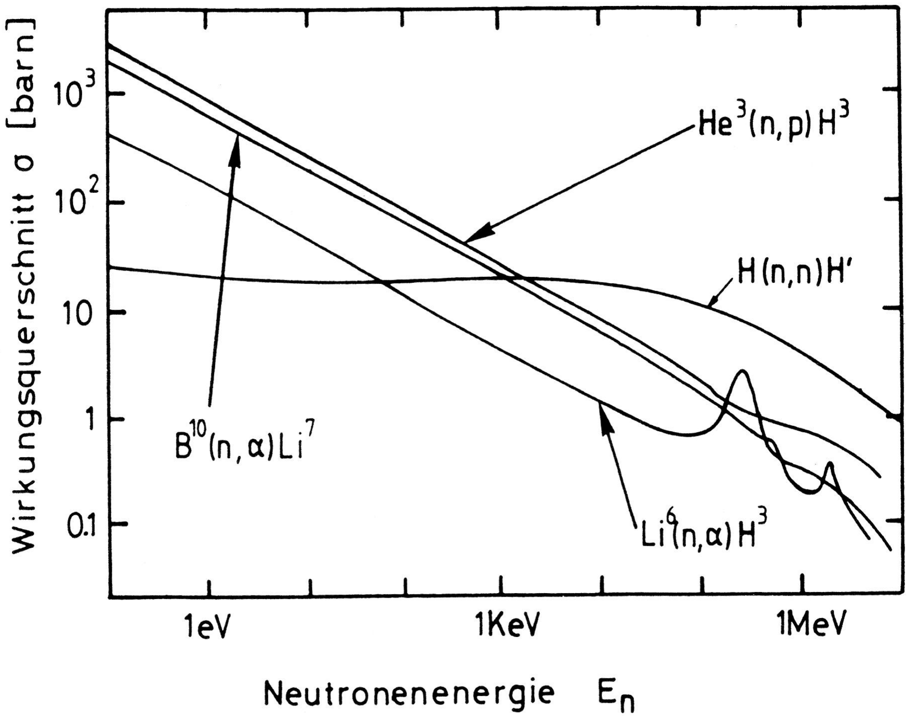


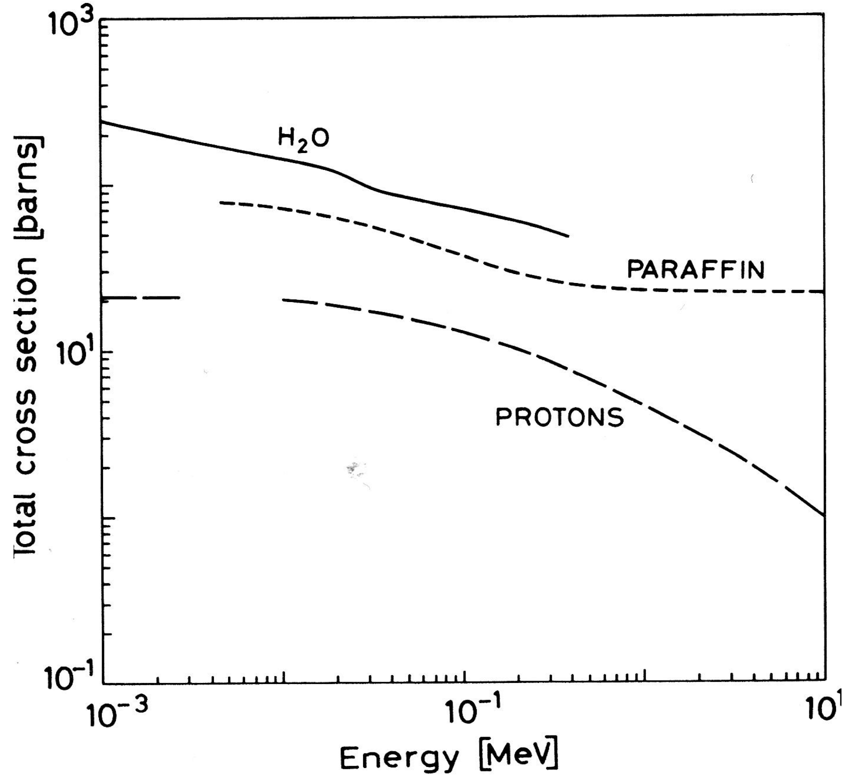
Figure 7. TOF-PID plot from PHENIX based on an Au-Au run in 2002.

Simple PID at high energy

- Photon vs neutral hadron
  - Electromagnetic or hadronic shower
- Electron vs hadron (electron or pion ?)
  - Ionization trace from the trajectory of a charged particle followed by a electromagnetic or hadronic shower
- Hadrons vs muons (electron, muon or pion)
  - Ionization trace of a charged particle, but no electromagnetic or hadronic shower, the muons can travers large quantities of very dense absorbers.

Neutrons



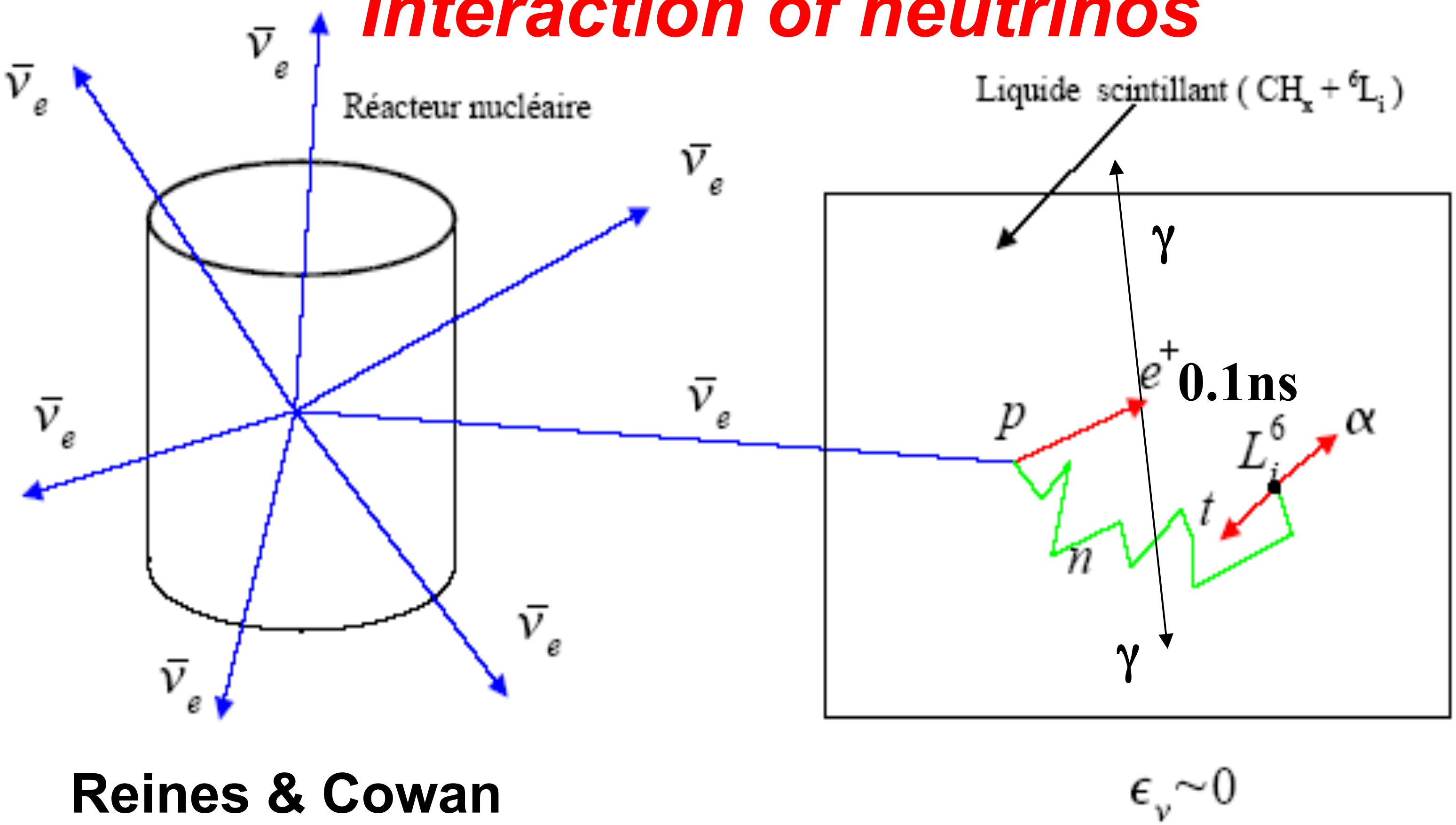


- **Elastic scattering off a nucleus $E_{neutron}$ < MeV**
- **Inelastic scattering $E_{neutron}$ > MeV**
- **Radiative capture σ~1/vitesse**
- **Nuclear reactions, fission**

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

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

Interaction of neutrinos

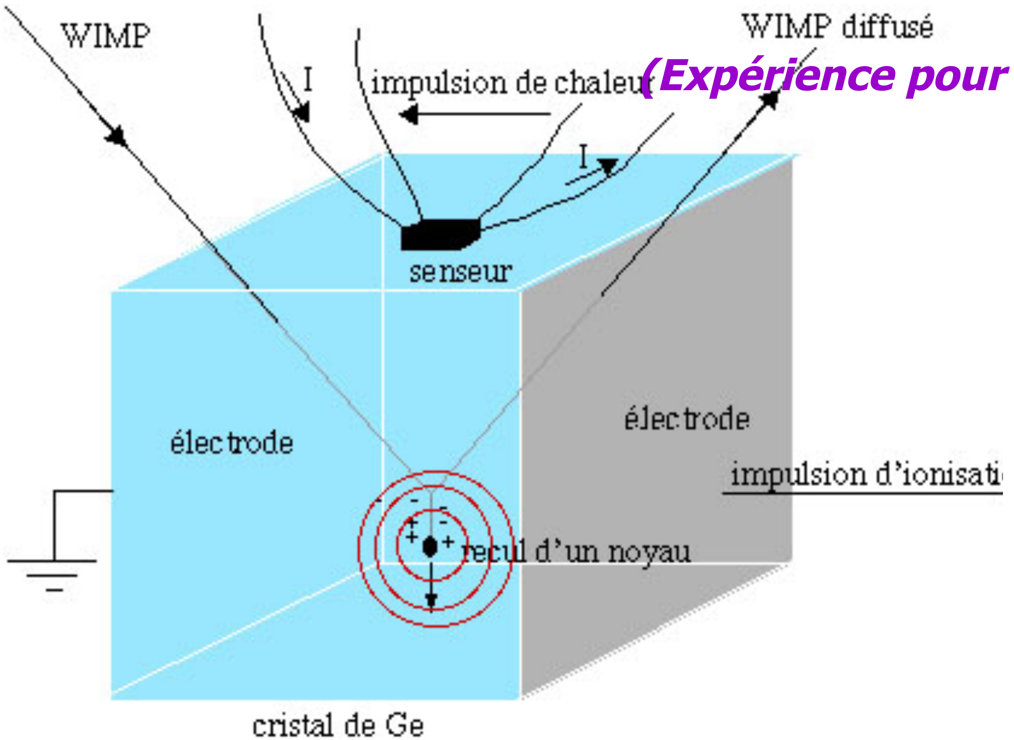


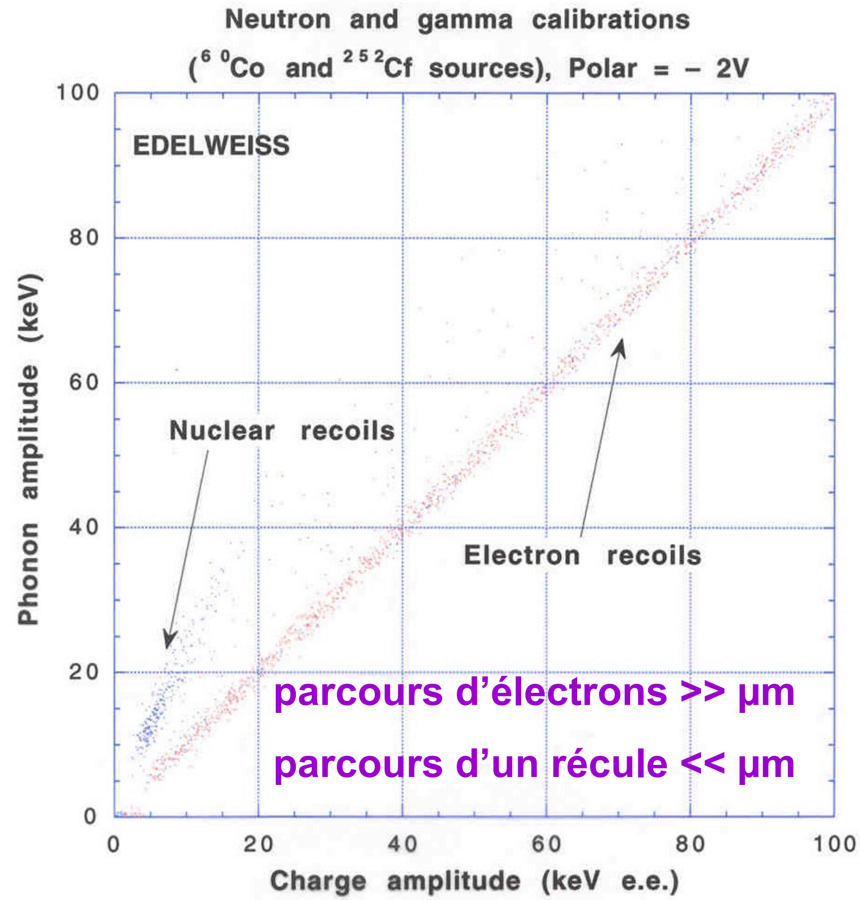
Reines & Cowan 1959

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 $\alpha - t$.

EDELWEISS

(Expérience pour Détecter Les Wimps en Site Souterrain)





parcours d'électrons >> μm

parcours d'un récule << μm

- **Cristal of very pure "Ge" 1Kg,**
- **Very rare events 1 event/Kg/year !!**
- **Ionisation**
  - **some keV**
- **Heat/ mechanical vibration of cristal**
  - **$\Delta T \approx$ 10-6 mK => cryostat(^3He-^4He) à 10 milli-Kelvin**

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 Estimate the nuclear interaction length in Iron

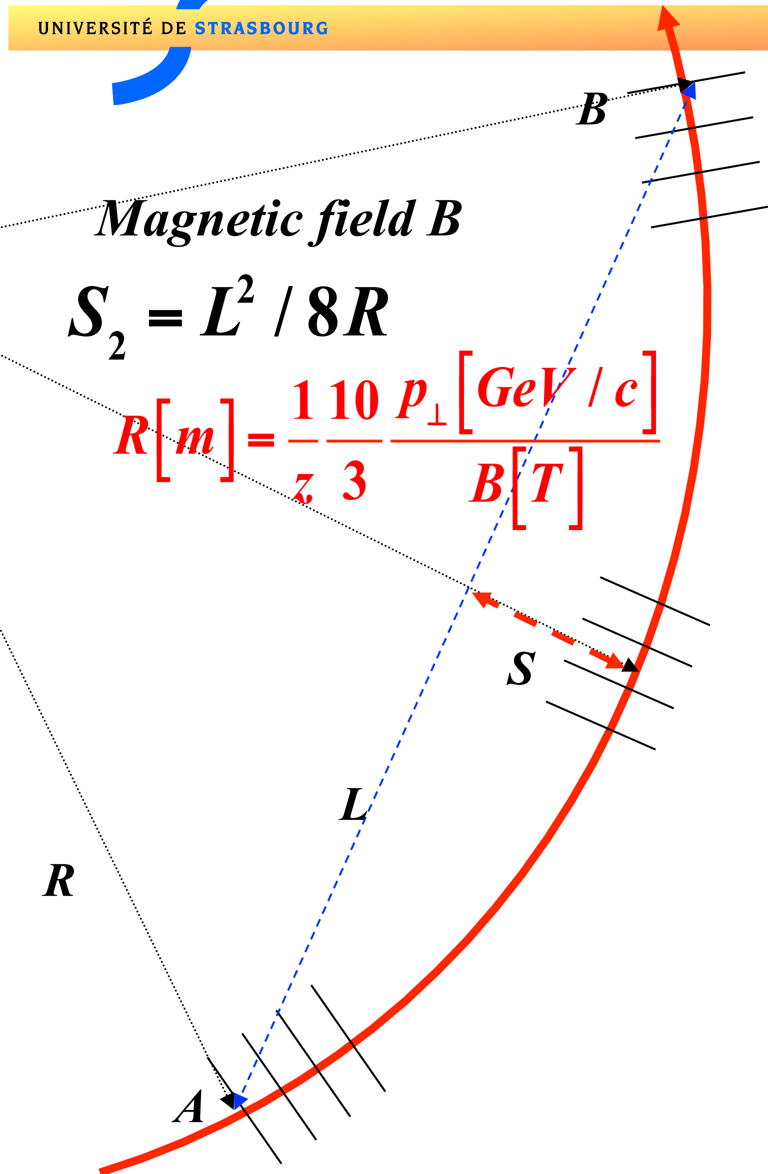
(Fe, A=56; ρ=7.8 g/cm^3)

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 ?

Reconstruction of transverse momentum in a magnetic field

Exercise !!!



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

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

- Mouvement 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:

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

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 lecture, how we can do this