Passage of particles through matter and applications to detectors

B. Laforge
LPNHE Paris
Sorbonne University

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DEPARTMENT OF PHYSICS AND CHEMISTRY - EMILIO SEGRÉ

LPNHE PARIS

Disclaimer

- **Particle and nuclear physics detectors are very complex, a lot of physics is behind the detection of particles**
    - ❖ particle/nuclear/astroparticle physics
    - ❖ material science
    - ❖ electronics
    - ❖ mechanics, …

- **To get a good understanding, one needs to work on a detector project**

- **This lecture can only give a glimpse at the physics of detectors and cannot cover everything and biased by a necessary selection given the time of the lecture !**

Useful sources and acknowledgement

- **Lectures strongly inspired from our LPNHE lectures on physics (F. Derue)**
- **These lectures are based upon**
  - lectures (in French) at the École IN2P3 « De la physique au détecteur » *2020/21* and *2022*, in particular the ones of P. Puzo and L. Chevalier
  - lectures (in French) at the École IN2P3 « Techniques de base des détecteurs », *2022*, in particular the ones from J. Peyré and E. Petit
  - lectures of « The European School in Instrumentation for Particle and Astroparticle Physics (ESIPAP) », *2022*, in particular the ones of M. Delmastro, L. Di Caccio and G. Unal
  - lectures for CERN summer students, *2022*, in particulat the ones from W. Riegler
  - lectures for DESY summer students, *2022*, in particular the ones of I-M. Gregor
  - many more ....

- **Books and reviews**
  - Reviews in *Particle Data Group*
    - section on passage of particles through matter
    - section on particle detectors at accelerators
  - Techniques for nuclear and particle physics experiments, W. R. Leo [*pdf*]
  - Particle Physics Reference Library, Volume 2: Detectors for Particles and Radiation, 2020 [*link*]

Overview

1) Introduction
. Generalities
. A bit of history

2) Interaction particle-matter
. Charged particles
. Neutral particles

3) Particle detection
. Gaseous ionization detectors
. Scintillation detectors
. Semiconductor detectors
. Calorimeters/bolometers

4) Measurement of some particle properties
. Track and charge reconstruction
. Energy measurement
. Particle identification

5) Quantum sensors

Part 1 - Generalities

What are the characteristics of a particle ?

- **Particles are characterized by :**
  - mass [Unit : eV/c^2 or eV]
  - charge [Unit : e ($1.6\ 10^{-19}$ C)]
  - energy [Unit : eV]
  - momentum [Unit : eV/c or eV]
  - [+ Spin, Lifetime ...]

- **Particles are characterized via the measurements of :**
  - $(E, \vec{p}, Q)$ or $(\vec{p}, \beta, Q)$
  - $(\vec{p}, m, Q)$ .....

In addition to the identification of their interaction properties

- **Relativistic kinematics states :**

$$\beta = \frac{v}{c} \qquad \gamma = \frac{E}{m} \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}} \qquad \vec{\beta} = \frac{\vec{p}c}{E}$$

$$E = m\gamma c^2 = mc^2 + E_{kin} \qquad E^2 = \vec{p}^2c^2 + m^2c^4$$

$$\vec{p} = m\gamma\vec{\beta}c$$

1 *eV* is a small energy !

$1\ eV = 1.6\ 10^{-19}\ J$

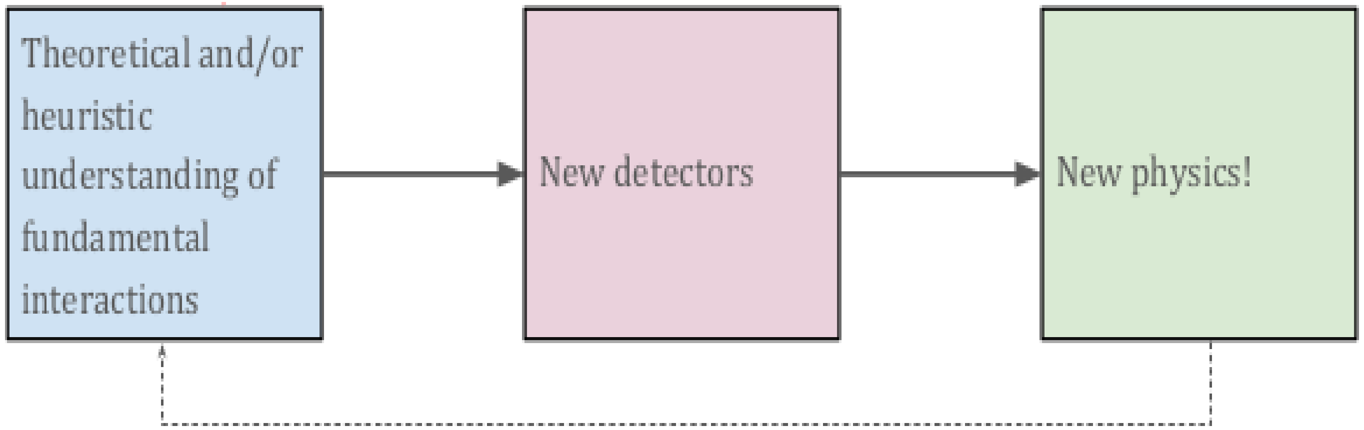
$M_{bee} = 1\ g = 5.6\times10^{32}\ eV$
$v_{Bee} = 1\ m/s$
$E_{Bee} = 10^{-3} J = 6.2\times10^{15}\ eV$

$E_{LHC} = 14\ TeV = 14\times10^{12}\ eV$
LHC has a total stored energy of 10^{14} protons x $14.10^{12}\ eV = 2.2\times10^{8}\ J$
which corresponds roughly to a 100*t* truck with speed of 100 *km/h* ....

Why study detector physics ?

- **Particle, nuclear, astro-particle physics discoveries are driven by detector (and accelerator) innovations**

- **and you need fundamental understanding to drive innovation**



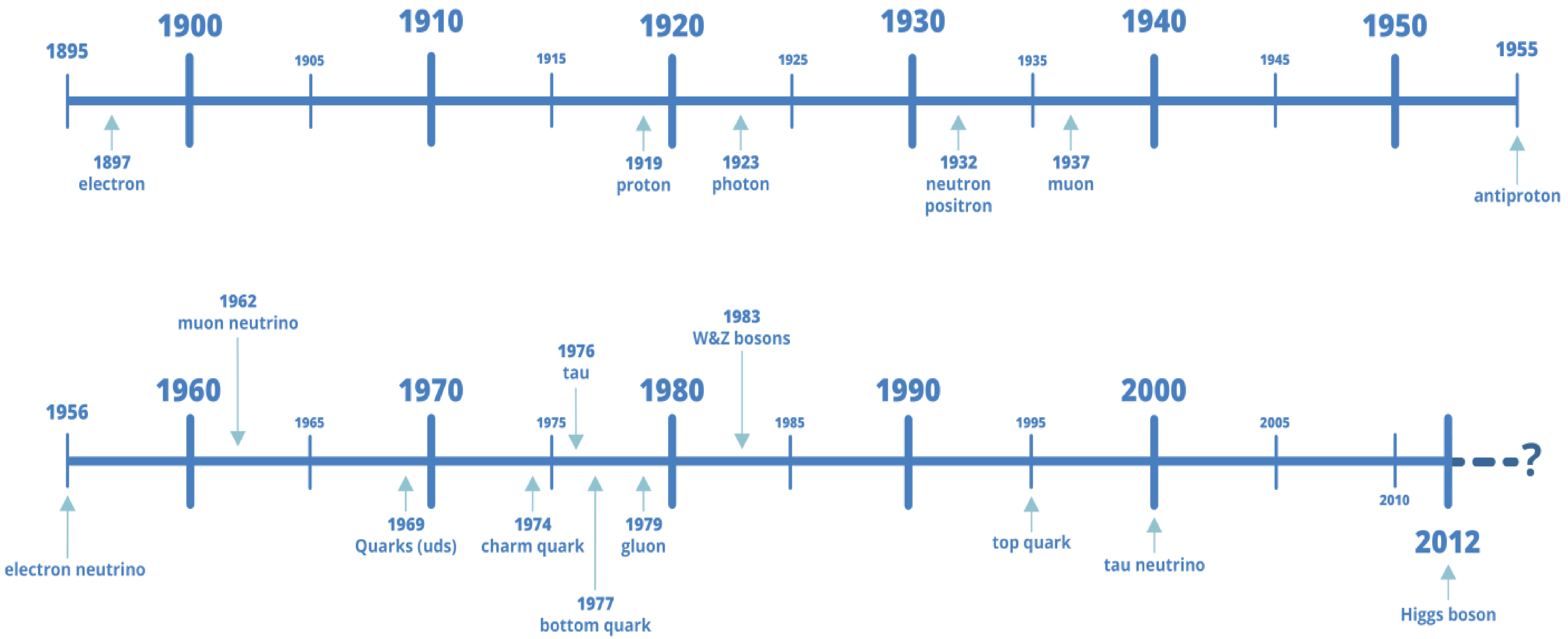
- **Instruments = Detectors**

For particle physics / photon science / medicine / societal applications, a good data analysis requires to have a clear idea of :

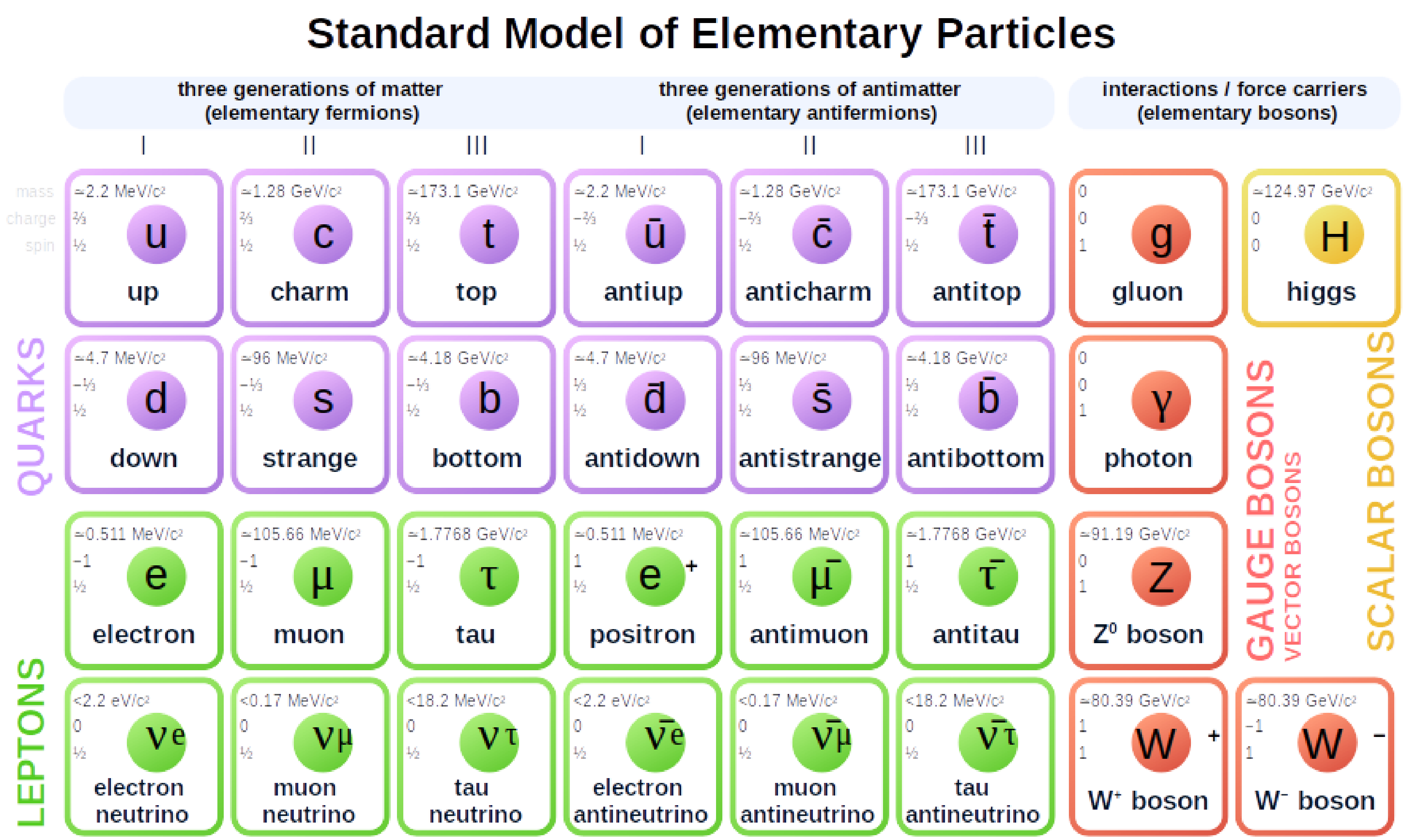
- what is the underlying principle of the detector of the data being analyzed ?
- how do they work from the physics to the provided measurement?
- how precise and unbiased are the measurements ?

ATLAS EXPERIMENT

Key particle discoveries



What particles do we need to detect ?

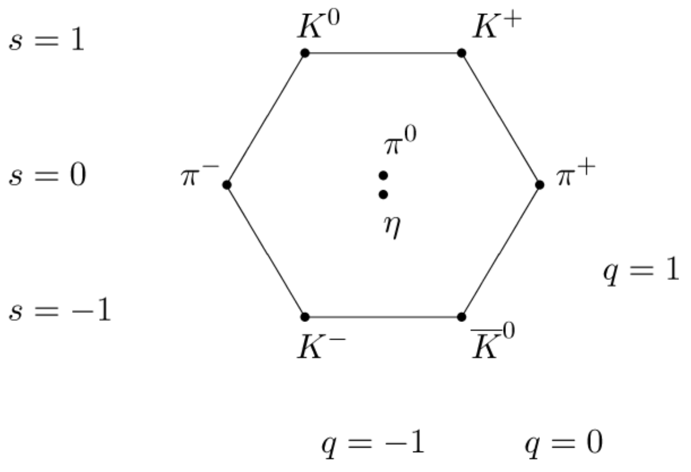


But unfortunately, the problem is a bit more complicated because particle aggregates :

- No free quarks,
- p, n form nuclei
- nuclei and e form atoms
- Atoms form molecules
- ...

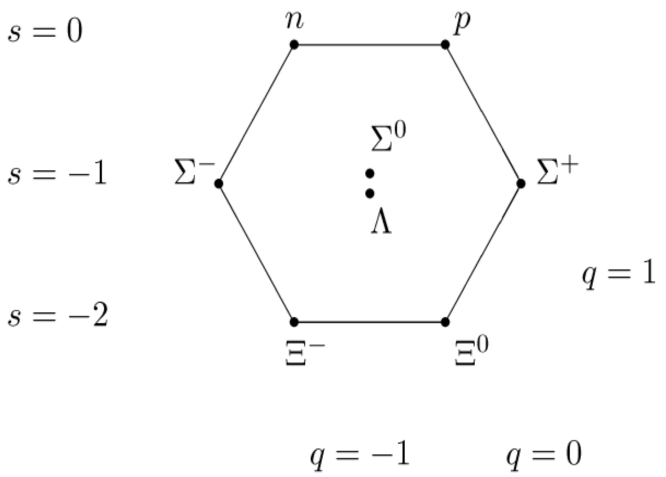
Quarks do not live alone : we need to address the hadron mess !

With the first three lighter quarks (u,d,s), we need to handle :

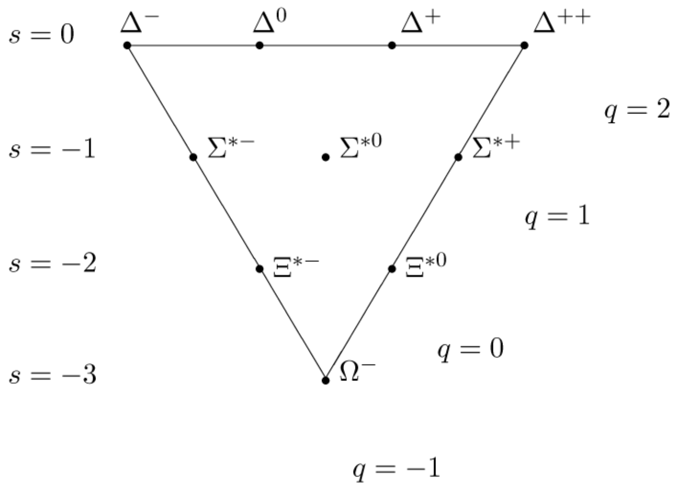


The meson octet (q-qbar states).

Particles along the same horizontal line share the same strangeness, s, while those on the same left-leaning diagonals share the same charge, q (given as multiples of the elementary charge).



The J = 1/ 2 baryon octet



The J = 3/ 2 baryon decuplet

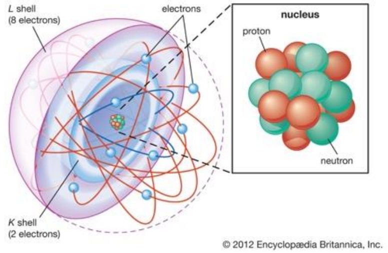
More than 200 mesons have been produced and characterized, most in high-energy particle-accelerator experiments.

Baryons need 3 quarks to maintain color neutrality (1 red, 1 blue, 1 green) and with 6 types of quarks, that's 216 possible combinations, but the top quark doesn't hadronize, so that leaves 75 possible Baryons (and their antiparticles)

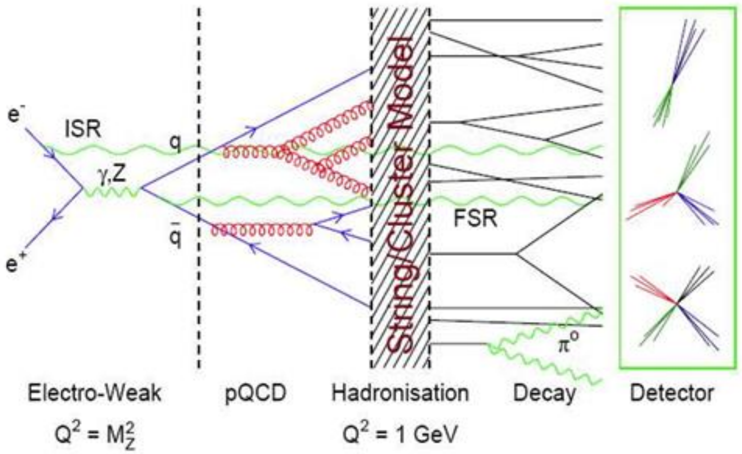
Tetra-quarks and penta-quarks have been observed but have a so short live time that they are not important for detectors

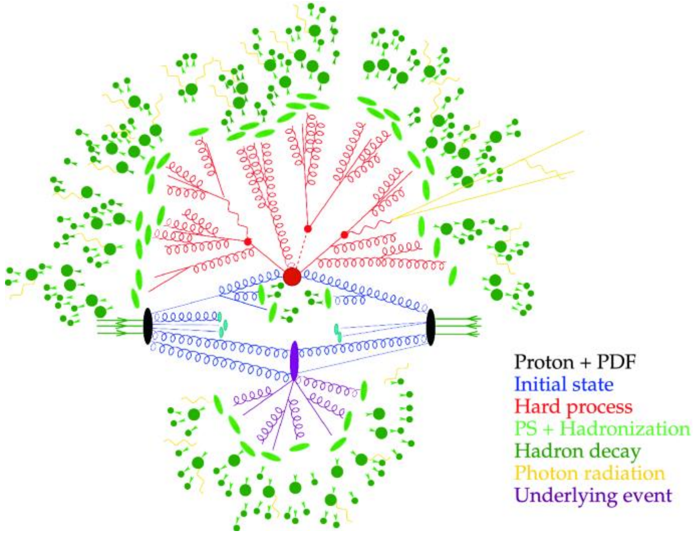
What type of particles do we face in experiments ?

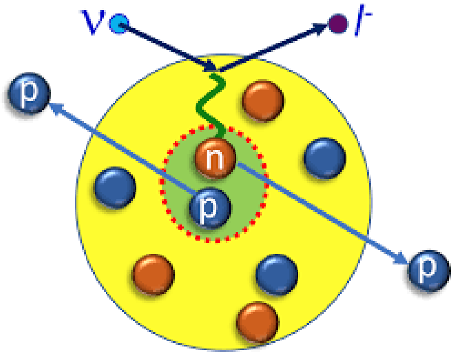
- The detector is made of mostly stable particles (except radioactive elements)
  - Usual matter is made of nuclei (protons + neutrons) and electrons



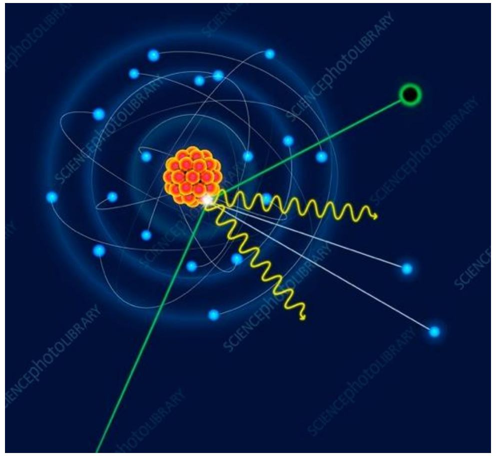
- The particles of scientific interest to be detected are :
  - Elementary of not (hadrons, long-lived resonances, ions)
  - Stable or not : e^+, e^-, p, n, pions (π^0, π^+, π^-), α, kaons (K_s, K_L, $K^{+/-}$), mesons or baryons (Δ, Λ,...), ...







ν interaction



DM interaction ?

- Three interactions are involved in their interaction with detector matter:
  - Electromagnetic, weak and strong interaction but never gravity
- We are interested only in particles with typical E>100 keV
  - Lower energies are the domain of ionic physics, molecular physics, etc.

Properties of the main usual particles

Particles	Mass mc^2	Charge	Mean Lifetime	Main interaction
electron	$m_e = 511$ keV	-1	stable	Electromagnetic (EM)
muon	$m_\mu = 206.6\, m_e = 105.66$ MeV	-1	2.2 μs	EM /decay = weak
photon	0	0	stable	EM
neutrino	<0.8 eV	0	stable	weak
proton	$m_p = 1836\, m_e = 938.27$ MeV	+1	stable	strong
neutron	$m_n = 1838\, m_e = 939.56$ MeV $m_n > m_p$	0	878 s In nuclei=long	strong
charged pion Neutral pion	$m_{\pi^{+/-}} = 140$ MeV $m_{\pi^0} = 135$ MeV	-1,1 0	10^{-8}s 10^{-17}s	EM/strong Decay EM (loop)
other hadrons	$m_h > m_\mu >> m_e$	-1 ; 0 ; 1 ; 2 (Δ^{++})	usually $<10^{-20}$s With few exceptions K_L, B_0, D_0	strong
nuclei	m_p to $\backsim$ $(A-Z)m_n + Z\, m_p$	1 to Z	usually stable	strong

Some numbers to keep in mind

m_e = 511 keV ; m_μ= 105 MeV ; m_π= 140 MeV ; $m_{p,n}$ = 2000 m_e = 0,94 GeV

- **Time and distances**
  - in 1 ns, a particle with *v*=c travels 30 cm (c= 3×10^8 m/s)
  - in 1 ms, an ionisation electron travels 5 cm in gas
  - in 1 ms, a proton travels 11 times in the LHC (about 300 km)

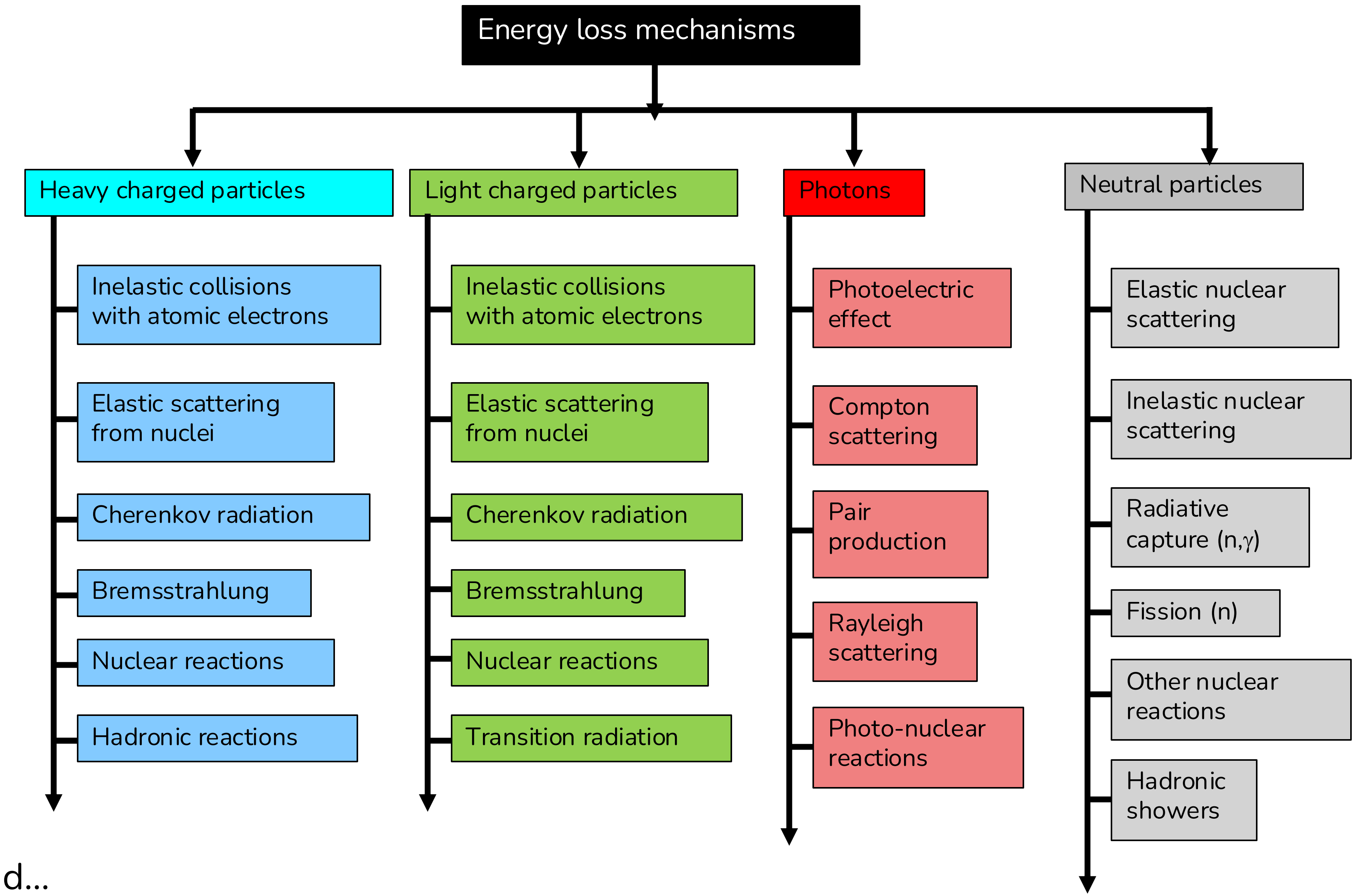
- **Mean lifetime and path**
  - for a detector, muons are stables, B mesons cannot be detected before they decay
  - stable particles are detected, unstable particles are reconstructed

	muon	**pion**	**B meson**
Mean Lifetime	2.2 μs	26 ns	1 ps
Mean path	660 m	7.8 m	300 μm

Of course with special relativity, this depends also on γ → time dilatation in the lab frame provide larger path

So stability of a particle is a question to be revisited experiment by experiment !

The different particles do not interact the same way



To keep in mind…

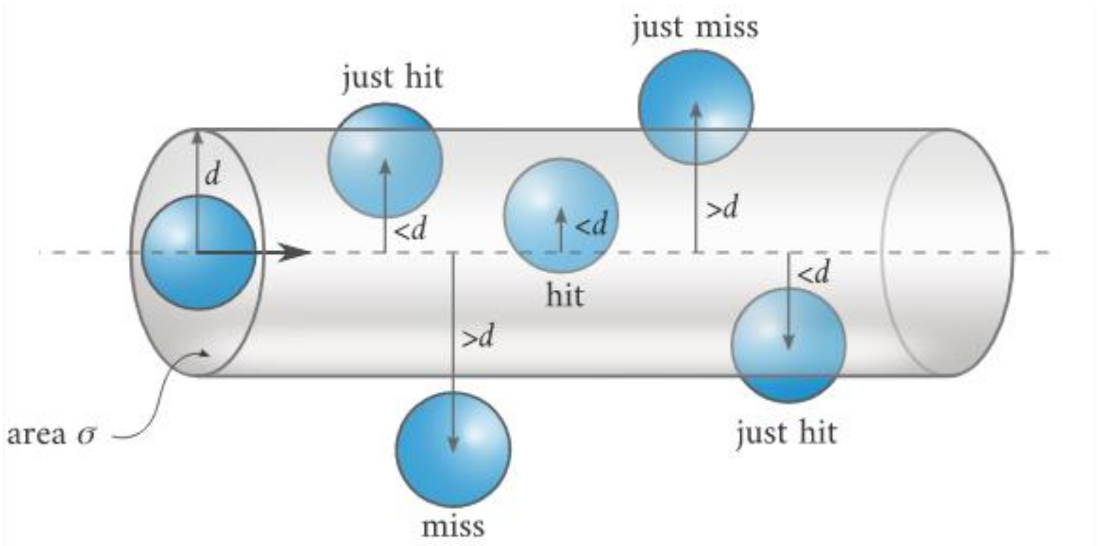
The different particles do not interact the same way

- **All effects** mentioned on the previous slide are strongly dependent on the type and momentum of the incident particle

- **Only a few mechanisms lead to significant energy loss** at typical energies relevant in particle physics
  - ionization, excitation, pair production, interactions with the absorber material's nuclei

- **In spite of this,** the other effects are important, because they allow us to build detector parts for particle identification
  - example : Cherenkov detectors, transition radiation detectors

Cross-section and effective size of a particle



$$dN_{coll} = \pi d^2 \times n\, v\, dt$$

Cross-section related to the probability of interaction :

$$\sigma = \pi d^2$$

$$E = h\nu = \frac{hc}{\lambda} \longrightarrow \lambda = \frac{hc}{E}$$

De Broglie Wavelength is decreasing like 1/E

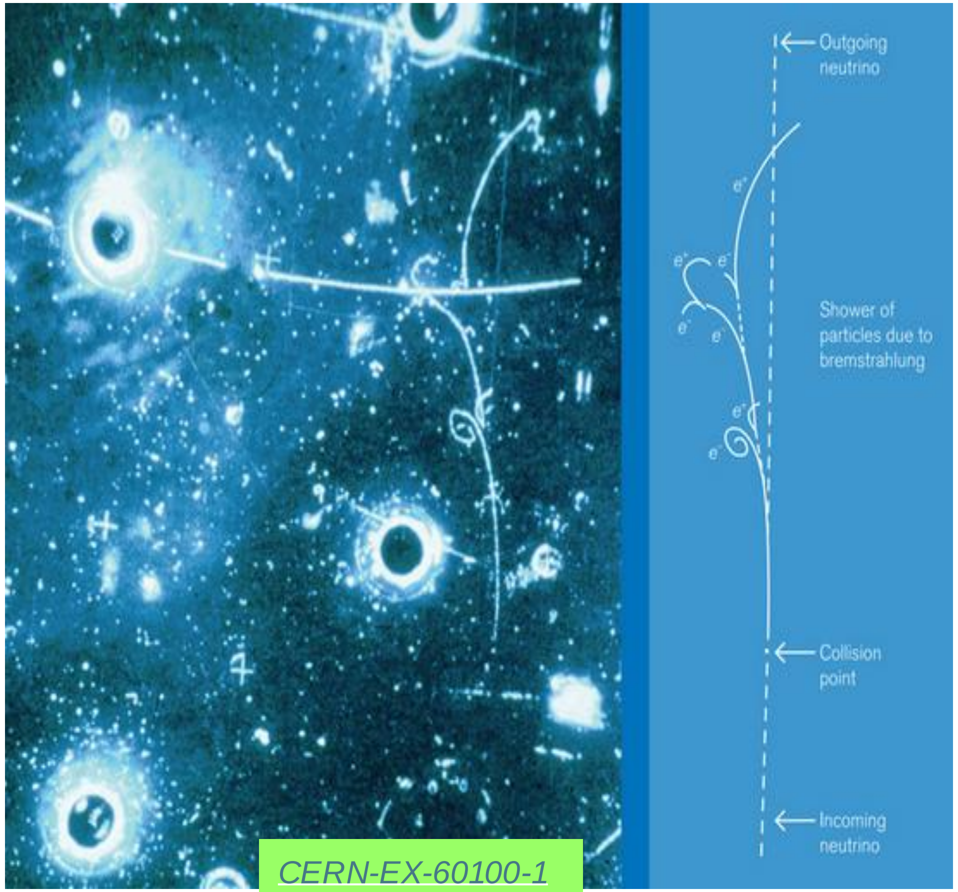
So higher energies probe shorter distances

Part 1 – A bit of history

I have no time to discuss old technics (Cloud chambers, Spark Chambers, Bubble chambers, …) unfortunately.

Detection techniques used to discover new particles in HEP

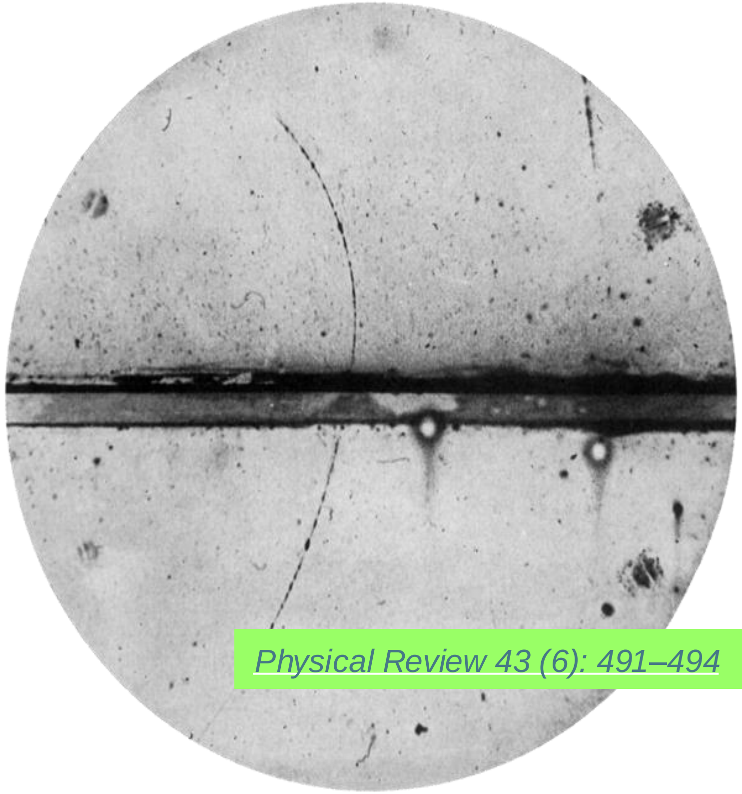
- fluorescent screen : 1897 e^- (Crookes tube), 1912 nucleus (Zn sulfur, Rutherfford)
- ionization chamber : n
- cloud chamber : e^+, $\mu^{+/-}$, K^0, Λ^0, Ξ^-, Σ^-
- nuclear emulsions : $\pi^{+/-}$, Σ^+, $K^{+/-}$, K^-, (Opera, Faser, ...)
- bubble chambers : Ξ^-, Σ^-, Ω^-, neutral currents, ...
- electronic techniques : anti-n, anti-p, π^0, W/Z, top, H ....



CERN-EX-60100-1

Weak Neutral Currents, 1973

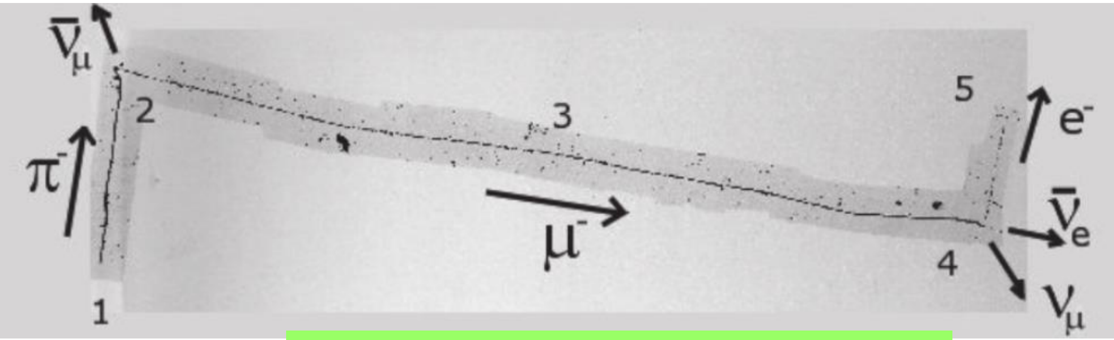
Positron, 1932



Physical Review 43 (6): 491–494

Pion, 1947

BNL timeline

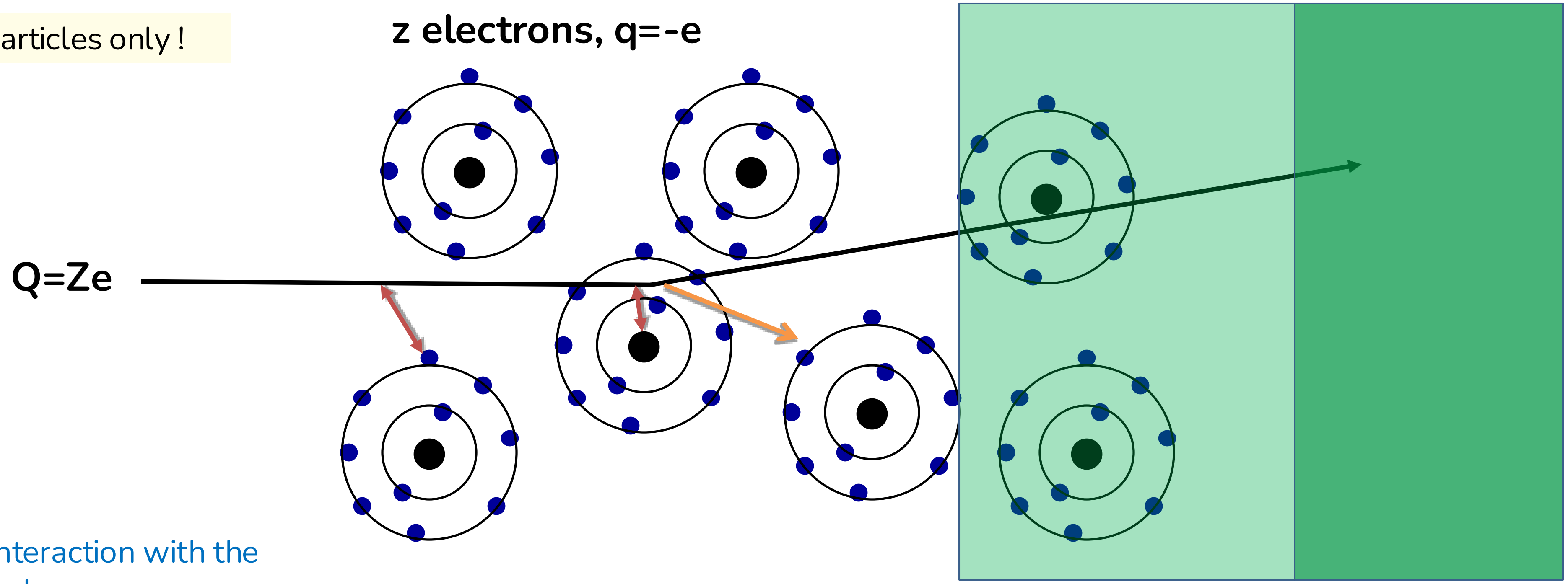


Nature volume 159, pages 694–697 (1947)

Part 2 – Interactions of particles in matter
Charged particle interactions

Electromagnetic interaction of charged particles in matter

charged particles only !

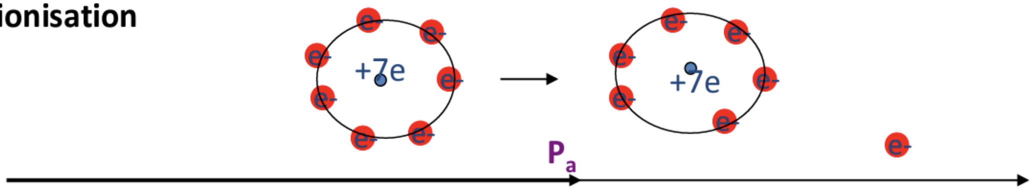


Inelastic interaction with the atomic electrons.
The incoming particle loses energy and the atoms are (soft collisions) excited
or are (hard collisions) ionised.

Exited atoms get back to their ground state by reorganizing their electron cloud (light emission)

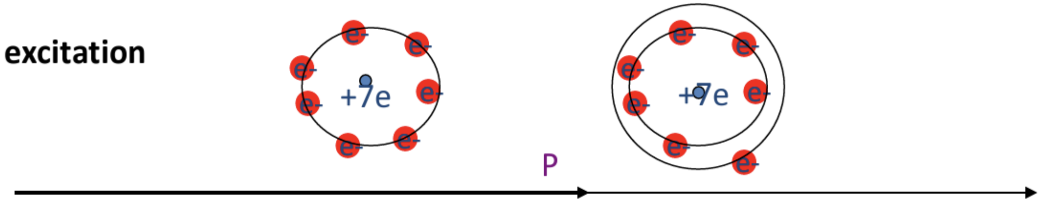
Inelastic interaction with the atomic electrons

- **ionisation**



P_a + atom ---> $atom^+ + e^- + P_a$

- **excitation**



P_a + atom ---> atom* + P_a

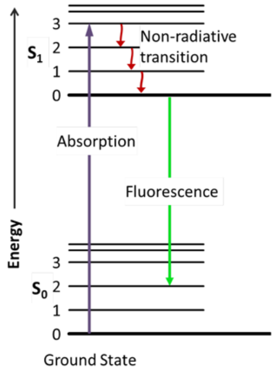
↳ atom + γ

- Both processes together (**ionization & excitation**) can also happen

General definition of fluorescence

Emission of light (UV to near infrared) by an atom, molecule that has absorbed light or other electromagnetic radiation, within the range of 0.5 to 20 nanoseconds

Energy levels in a molecule :



Important for scintillators !

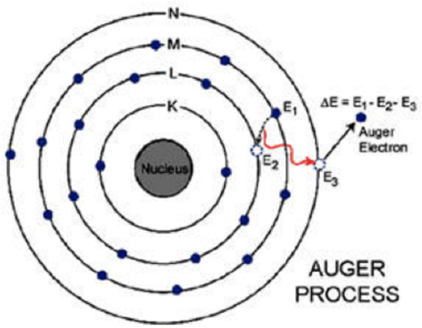
Atom de-excitation (after photoelectric effect)

Following the emission of a "photoelectron", the atom is in an excited state

De-excitation occurs via two effects (time scale: ~10^{-16} s)

- Fluorescence: $Atom^{*+}$ → $Atom^{+}$ + γ → **X rays**
- Auger effect $Atom^{*+}$ → $Atom^{++}$ + e- → **Auger electron**

Observed first by Lisa Meitner

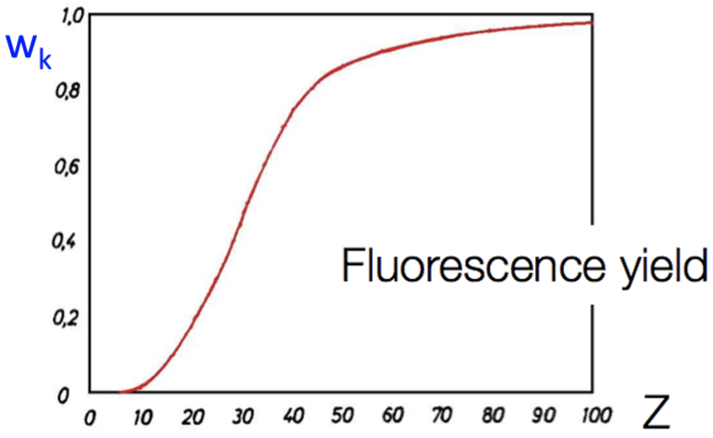


Auger electrons deposit energy locally (small energy < ~ 10 KeV)

Used for surface Spectroscopy (AES)

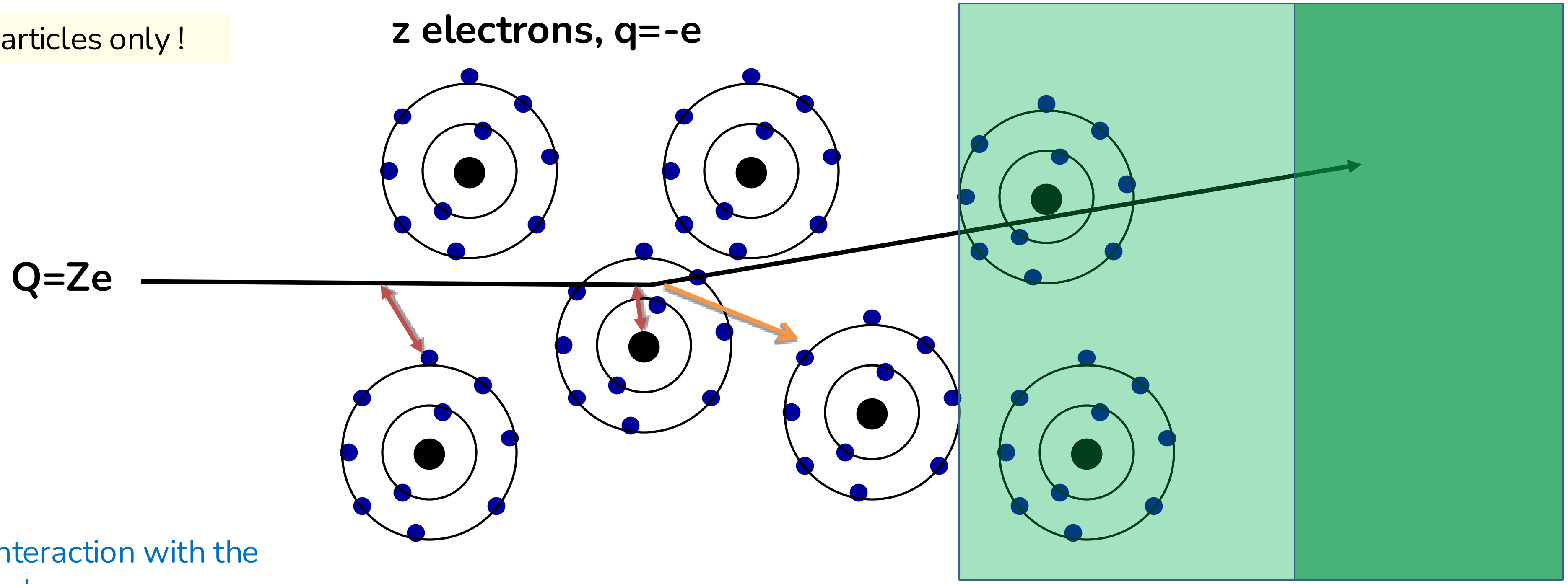
Fluorescence yield :

$$W_k = \frac{\text{Prob (fluorescence)}}{\text{Prob (florescence) + Prob (Auger)}}$$



Electromagnetic interaction of charged particles in matter

charged particles only !



Inelastic interaction with the atomic electrons.
The incoming particle loses energy and the atoms are (soft collisions) excited or are (hard collisions) ionised.

Exited atoms get back to their ground state by reorganizing their electron cloud (light emission)

Elastic interaction with the atomic nucleus.
The particle is deflected (scattered) causing multiple scattering of the particle in the material. During this scattering, a Bremsstrahlung photon can be emitted.

In case the particle's velocity is larger than the velocity of light in the medium, the resulting electromagnetic shock wave manifests itself as Cherenkov Radiation.

When the particle crosses the boundary between two media, there is a probability of the order of 1% to produce an X ray photon, called Transition radiation.

EM interaction of Heavy charged particles in matter

- **Heavy charged particles**
  - particles having $m \gtrsim m_\mu \approx 200\ m_e$, i.e everything but electrons : $\mu^{+/-}$, $\pi^{+/-}$, α, p, $K^{+/-}$ ...

- **A charged particle go through a material of thickness Δx**
  - the energy of the particle decreased by ΔE
  - the deposited energy ΔE will depend on :
    - material thickness (Δx) and material density (ρ)
    - particle mass (m), charge of the nuclei in the material (Ze), kinetic energy (T or E_c) and velocity (β)

- **The cross-section of inelastic collisions** is very small ($\sigma \approx 10^{-16}$ - 10^{-17} cm^2)
  - but the number of atoms is very high ($N \approx 10^{23}$ atoms/cm^3)
  - a 10 *MeV* proton losses all its energy in 0.25 *mm* of copper

- **The number of interactions** is ruled by statistics but is very high (because of the norm of Avogadro number !)
  - relative fluctuations are small (central limit theorem, large number rules)
  - in practice one observes a continuous diminishing of the energy down to the thermal energy (kinetic motion energy) of atoms in the medium
  - The mean energy loss by unit of length during the path is a central number for detector physics:

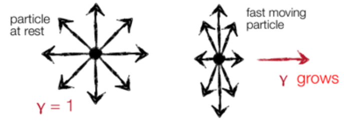
$$\left[\left\langle\frac{dE}{dx}\right\rangle\right] \equiv \left[\frac{1}{\rho}\left\langle\frac{dE}{dx}\right\rangle\right], \text{usually expressed in } MeV.g^{-1}.cm^2.$$ (MeV/cm x (g/cm^3)$^{-1}$)

Bethe-Heitler Formula for Mean Energy loss by ionisation for Heavy charged particles in matter

- **Quantum relativistic mechanics** allows to derive the Bethe-Bloch formula describes the mean energy lost by heavy particles in matter by ionization:

$$\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[ln\left(\frac{2m_e c^2 \gamma^2 \beta^2 W_{max}}{I^2} \right) - \beta^2 - \frac{\delta}{2} - \frac{C}{Z} \right]$$

heavy charged particles
(not valid for electrons)



logarithmic rise is due to lateral extension of electric field increases due to Lorentz transform of the electric filed E $\rightarrow \gamma$E

Material : z/A is the fraction of nucleons that are protons

Properties of the particle

W_{max} maximum kinetic energy which can be transfered to the electron in a single collision

I : mean excitation energy of the medium

$\frac{\delta}{2}$ density term due to polarization effects leads to saturation at higher energies

$\frac{C}{Z}$ shell correction term, only relevant at lower energies

$K = 4\pi N_A r_e^2 m_e c^2$
$\approx 0.307 MeV\, g^{-1} cm^2$

r_e : classical electron radius

$$r_e = \frac{e^2}{4\pi\varepsilon_0 m_e c^2} \approx 2.8 fm = 2.8 \times 10^{-15} m$$

m_e : electron mass
N_A : Avogadro's number 6.02 x 10^{23} mol^{-1}

A : atomic weight of absorbing material [g mol]
ρ : density of absorbing material
z : charge of incident particle in units of e
Z : charge of the nucleus of the material
β : v/c of the incident particle

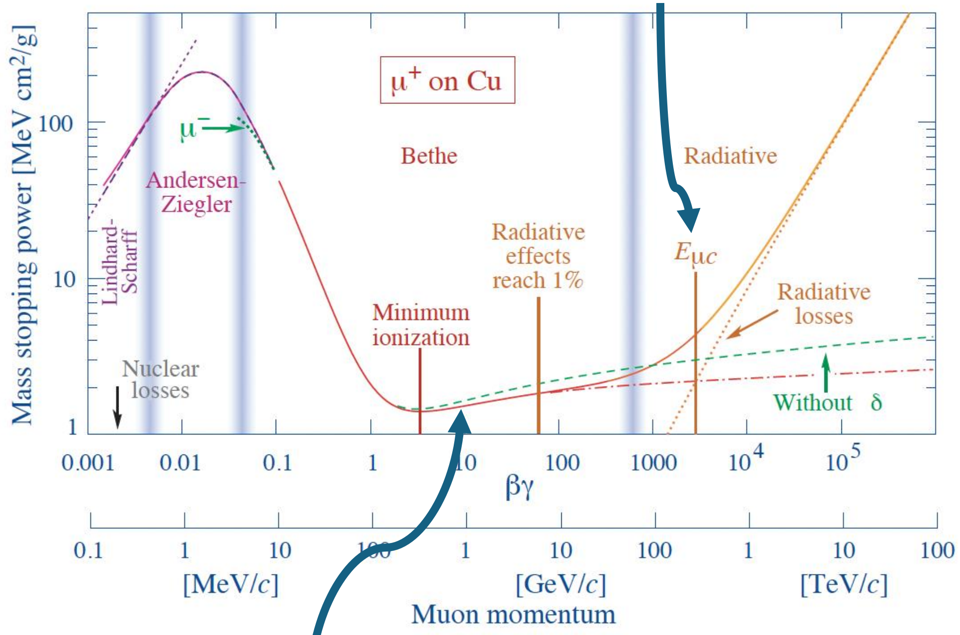
Bethe-Heitler Formula for Mean energy loss by ionisation for Heavy charged particles in matter

$$\frac{1}{\rho}\left\langle\frac{dE}{dx}\right\rangle = -4\pi N_A r_e^2 m_e c^2 \frac{Z}{A}\cdot\frac{z^2}{\beta^2}\left[\ln\left(\frac{2m_e c^2\gamma^2\beta^2 W_{max}(m)}{I^2}\right) - \beta^2 - \frac{\delta(\beta\gamma)}{2} - \frac{C(\beta)}{Z}\right]$$

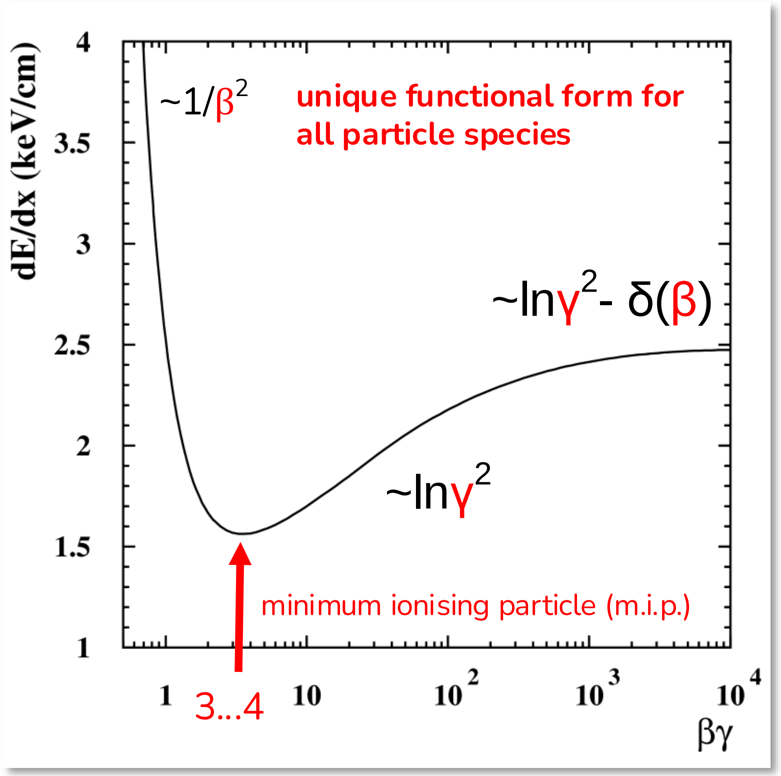
heavy charged particles (not valid for electron)

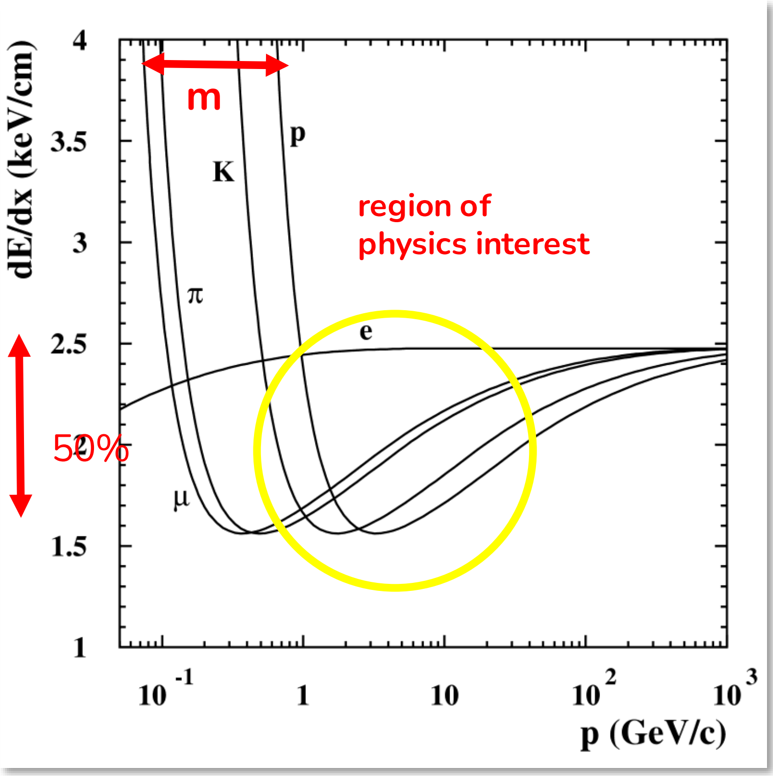
$\beta^2 \ll \ln\left(\frac{2m_e c^2\gamma^2\beta^2 W_{max}}{I^2}\right)$

At very high energy (E>Ecritic), radiation loss dominates



MIP - plateau





$W_{max}(m) \propto \frac{1}{1+2\gamma\frac{me}{m}+\left(\frac{me}{m}\right)^2}$

Bethe-Heitler Formula for Mean energy loss by ionisation for electrons in matter

Bethe-Bloch formula needs modification:

- Incident and target electron have same mass m_e Wmax = T/2
- Scattering of identical, undistinguishable particles
- New processes to be considered

$$-\left\langle\frac{dE}{dx}\right\rangle = 4\pi N_A r_e^2 m_e c^2 \rho \frac{Z}{A}\frac{1}{\beta^2}\left[ln\left(\frac{2m_e c^2\gamma^2\beta^2 T}{2\,I^2}\right) + \mathrm{F}(\gamma)\right]$$

(T = kinetic energy of the electron)

Remark: different energy loss for electrons and positrons at low energy as positrons are not identical to electrons and some annihilation finally occurs with usually 2 γ of 511 keV

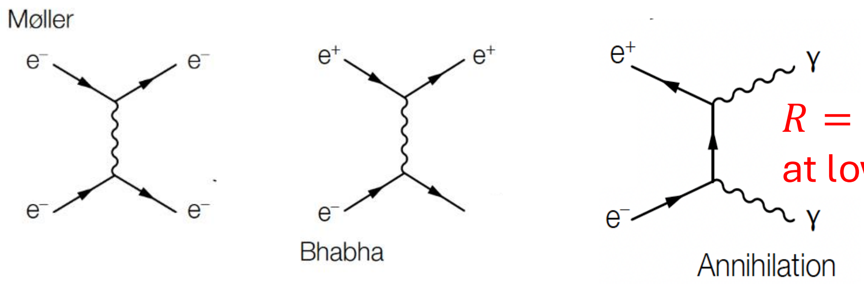
But importantly, $e^{+/-}$ are low mass and their energy loss is very early dominated by bremsstrahlung effect !

Bethe-Heitler Formula for Mean energy loss by ionisation for electrons in matter

Bethe-Bloch formula needs modification:

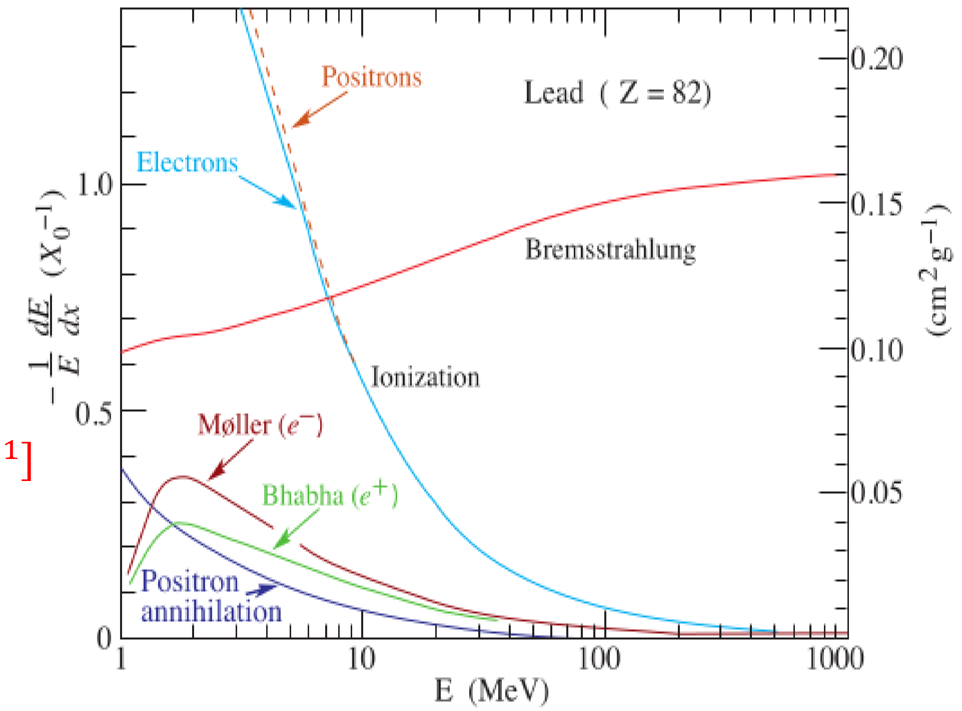
- Incident and target electron have same mass m_e so
  Wmax = T/2
- Scattering of identical, undistinguishable particles
- New processes to be considered

$$\sigma_{an} = Z\pi\, r_e^2/\gamma$$



$R = \rho\, N_A/A\, Z\pi r_e^2\, c[s^{-1}]$
at low E

This rate corresponds to a lifetime in lead (Pb) of about 10^{-10} s

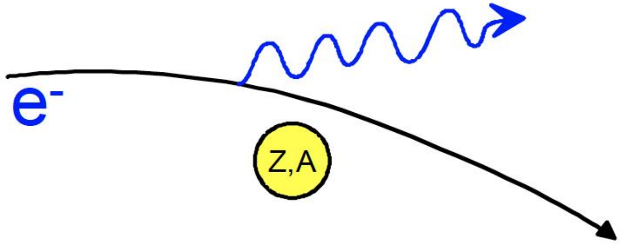


Electrons : $\frac{-dE}{dx} = K\frac{Z}{A}\frac{1}{\beta^2}\left\{ln\frac{\gamma m_e c^2\beta\sqrt{\gamma-1}}{I\sqrt{2}} + \frac{1}{2}(1-\beta^2) - \frac{2\gamma-1}{2\gamma^2}ln2 + \frac{1}{16}\left(\frac{\gamma-1}{\gamma}\right)^2\right\}(MeV/(g/cm^2))$

Positrons : $\frac{-dE}{dx} = K\frac{Z}{A}\frac{1}{\beta^2}\left\{ln\frac{\gamma m_e c^2\beta\sqrt{\gamma-1}}{I\sqrt{2}} - \frac{\beta^2}{24}\left(23+\frac{14}{\gamma+1}\right) + \frac{10}{(\gamma+1)^2} + \frac{4}{(\gamma+1)^3}\right\}(MeV/(g/cm^2))$

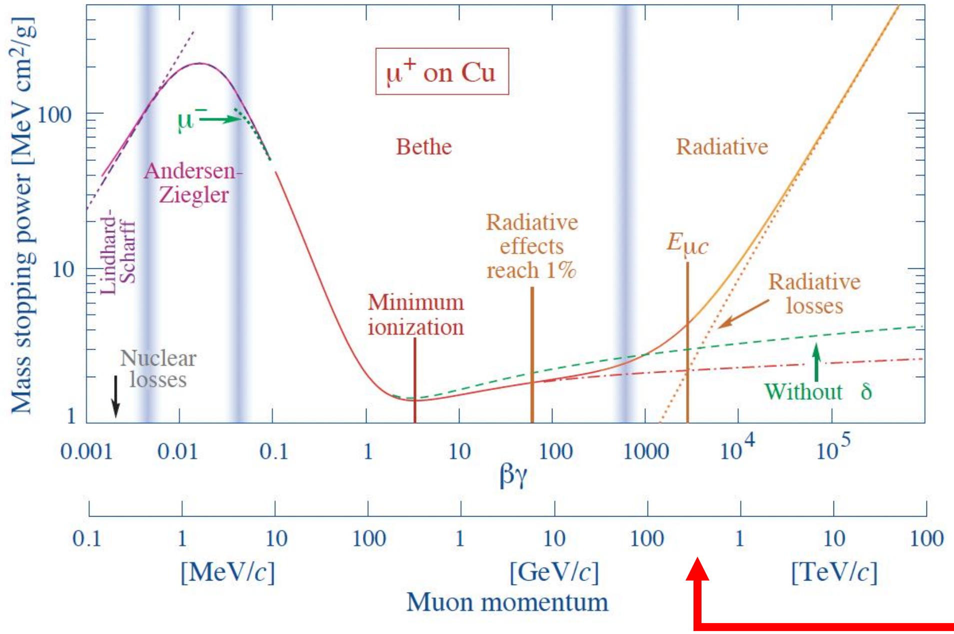
Mean energy loss by bremsstrahlung in matter

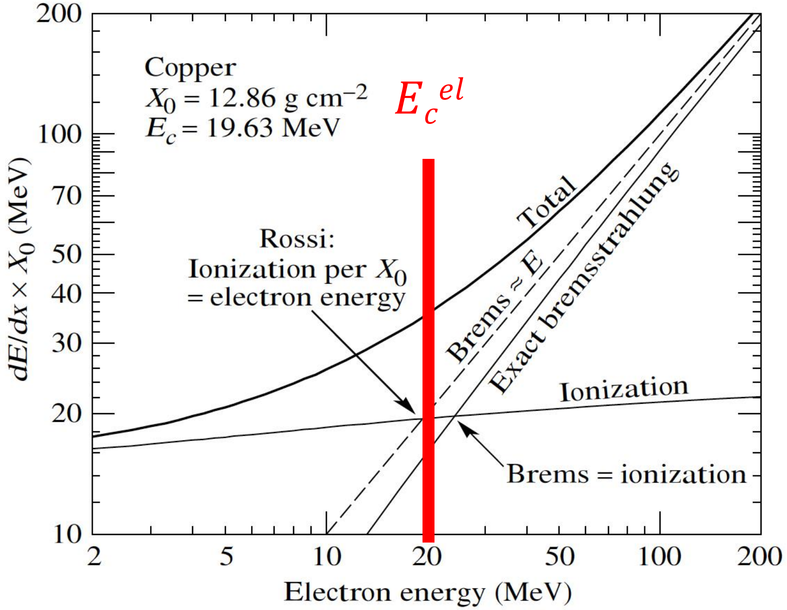
Bremsstrahlung arises if particles are accelerated in Coulomb field of nucleus :



$$\left\langle \frac{dE}{dx} \right\rangle = 4\,\alpha\, N_A \frac{z^2 Z^2}{A} \left(\frac{1}{4\pi\varepsilon_0} \frac{e^2}{m\,c^2} \right)^2 E \ln \frac{183}{Z^{1/3}} \sim \frac{z^2 E}{m^2}$$

i.e. energy loss proportional to $1/m^2$ → main relevance for electrons or ultra-relativistic muons





Mean energy loss by bremsstrahlung : definition of the critical energgy

Critical energy:

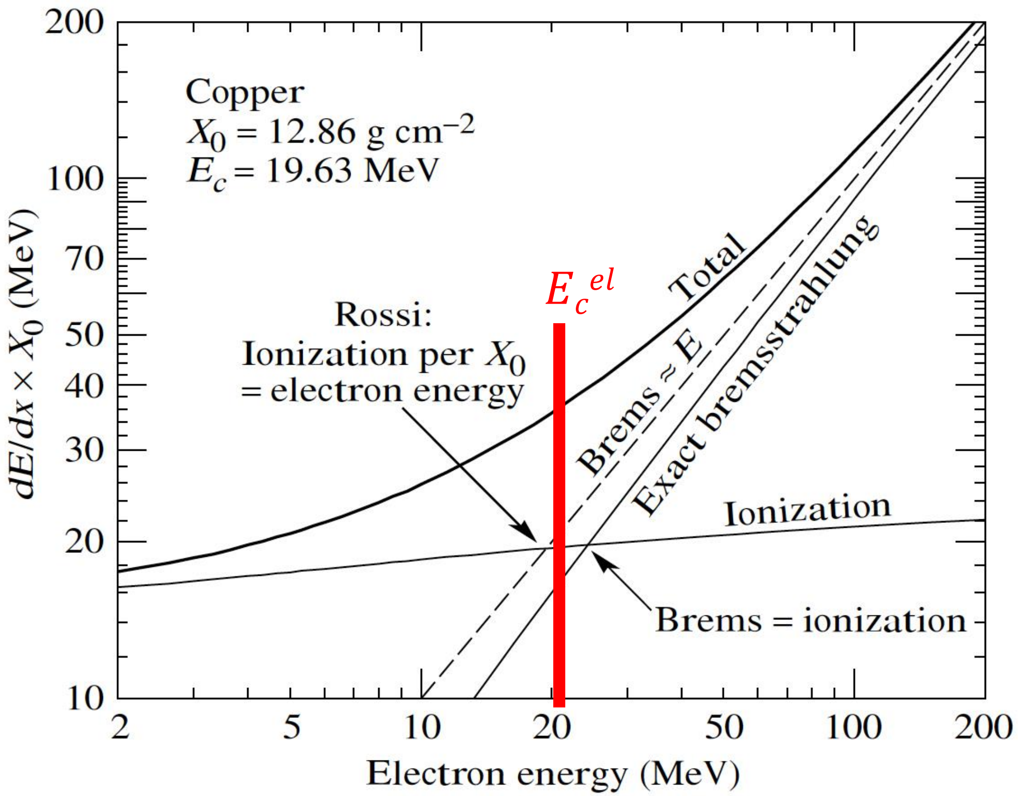
$$\frac{dE}{dx}(E_c)\Big|_{\text{Brems}} = \frac{dE}{dx}(E_c)\Big|_{\text{Ion}}$$

Empiric evolution with Z for electrons :

$$E_c^{\text{Gas}} = \frac{710\ \text{MeV}}{Z + 0.92}$$

$$E_c^{\text{Sol/Liq}} = \frac{610\ \text{MeV}}{Z + 1.24}$$

$$\left(\frac{dE}{dx}\right)_{\text{Tot}} = \left(\frac{dE}{dx}\right)_{\text{Ion}} + \left(\frac{dE}{dx}\right)_{\text{Brems}}$$



Example Copper: $E_c \approx 20$ MeV

Mean energy loss by bremsstrahlung : radiation length

Beyond the critical energy, electron interaction is fully dominated by radiation

$$\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 \cdot E \ \ln \frac{183}{Z^{\frac{1}{3}}}$$

$$\frac{dE}{dx} = \frac{E}{X_0} \qquad \text{with} \quad X_0 = \frac{A}{4\alpha N_A \ Z^2 r_e^2 \ \ln \frac{183}{Z^{\frac{1}{3}}}}$$

[Radiation length in g/cm^2]

$$\rightarrow E = E_0 e^{-x/X_0}$$

After passage of one X_0 electron has lost all but $(1/e)^{th}$ of its energy

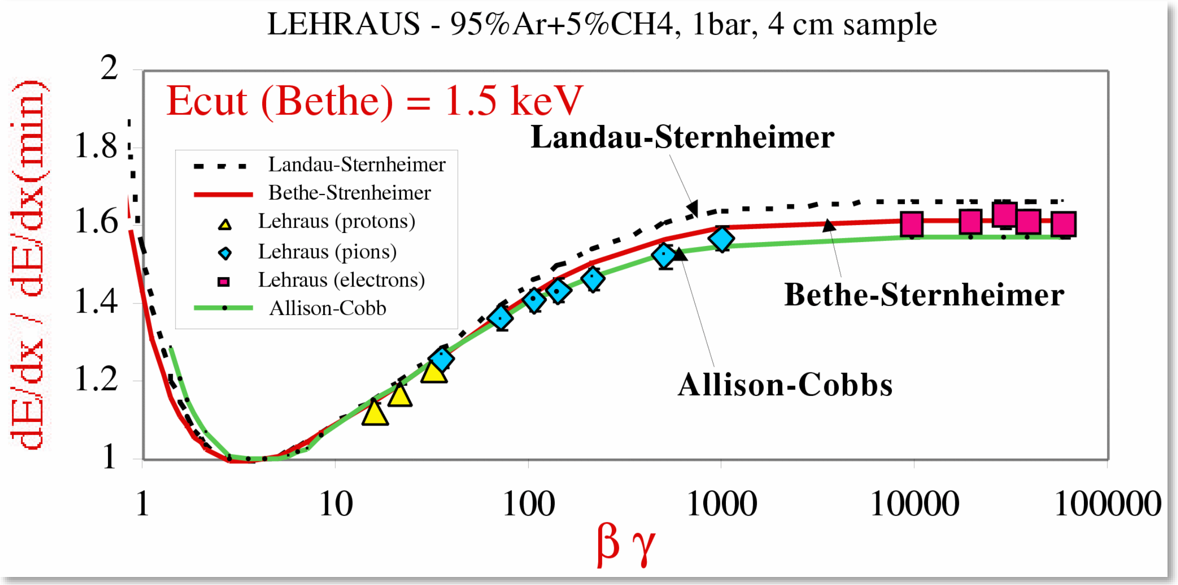
[i.e. 63%]

Precision of the mean ionization prediction ?

Bethe-Bloch calculations are difficult, different models exist

- Landau-Sternheimer calculation
- Bethe-Sternheimer calculation
- Allison-Cobb Monte Carlo Ann. Rev. Nucl. Sci., 30 (1980) 253

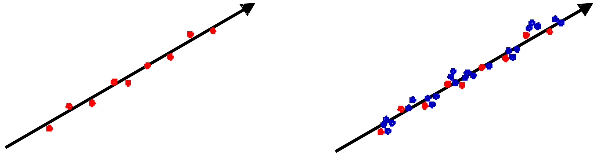
Level of (dis)agreement: ~3% in relativistic rise



Common problem

- what E_{cut} to be used? What's E_{cut} at all?

- Tracking detectors usually DON'T measure the full energy loss of a particle!
- Secondary electrons with sufficient energy may escape from track, e.g. to adjacent drift cell, pad etc.
  - may be recognized as separate hit, not associated to track
  - detectors measure RESTRICTED energy loss instead of full energy loss



Total ionization = primary + secondary ionization

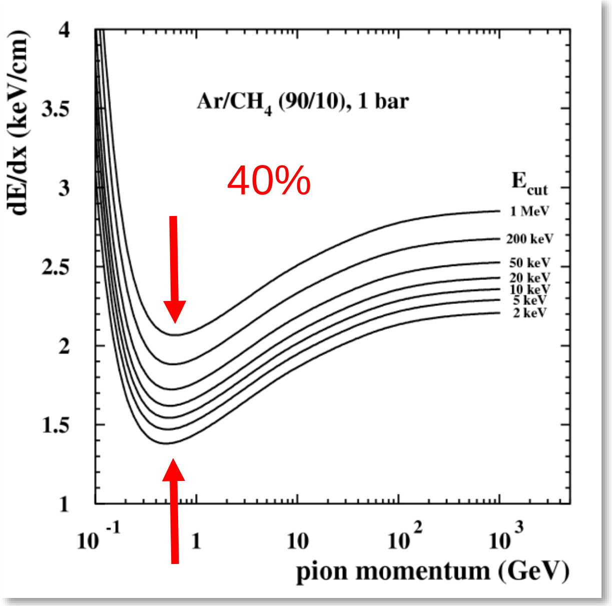
- Cut-off energy E_{cut} defines maximum energy of an electron still associated to a track
  - depends on detector geometry, double hit resolution, magnetic field, diffusion and more
  - typical E_{cut} is a few keV corresponding to some 100 μm – 1 mm range

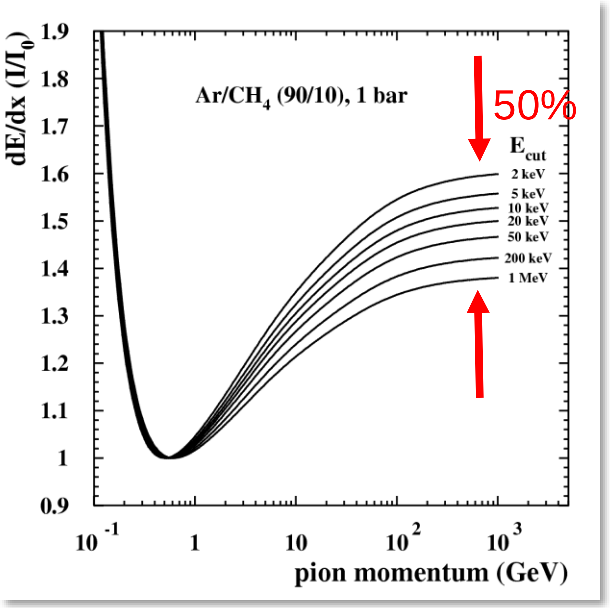
E_{cut} dependance

- E_{cut} is difficult to determine, basically a free parameter

- Impossible to make calculations of Bethe-Bloch function to percent level or even better

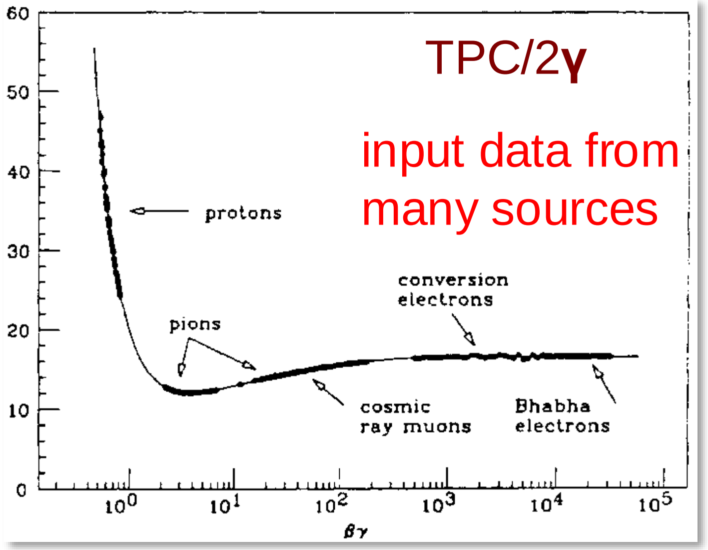
- results depend on E_{cut} a lot





relativistic rise variation up to 50%

Empirical parameterization used in practice



$$\chi^2(e,\mu,\pi,K,p) = \left[\frac{dE/dx_{measured} - dE/dx(e,\mu,\pi,K,p)_{predicted}}{\sigma\,(dE/dx)}\right]^2$$

Residuals < ±0.2%

[M. Hauschild, RD51 workshop on Gazeous detector contributions to PID]

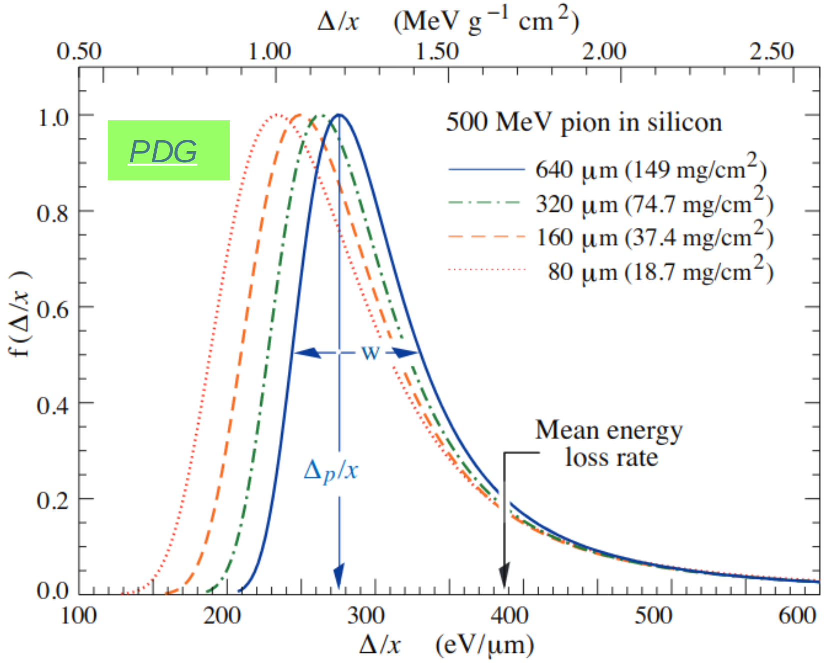
Fluctuations on the ionization path

- **Real detector measures the energy DE deposited in a layer of finite thickness Dx**

$$\Delta E = \sum_{n=1}^{N} \delta E_n$$

with N, the number of collisions,
δE, the energy loss in a single collision

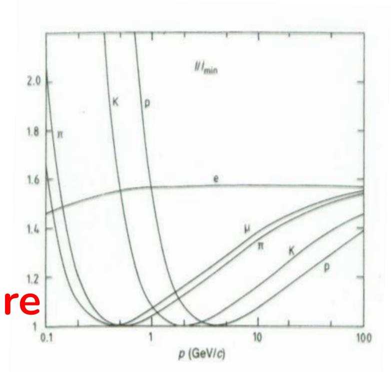
  - ionisation loss dE distributed statistically
  - so called energy loss « straggling »

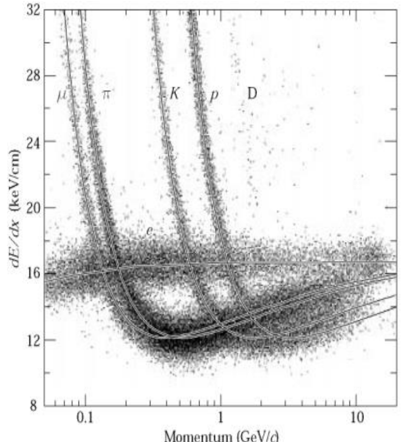


Straggling functions in silicon for 500 MeV pions

- **Small thickness or low-density materials**
  - few collisions, but some of them can have large energy transfer
  - fluctuations (due to δ electrons) become important
  - *dE/dx* distributions show large fluctuations for high losses (Landau tails) leading to asymmetric distributions

- **Large thickness, or high-density materials**
  - many collisions
  - central limit theorem: *dE/dx* distributions are Gaussian





By measuring the particle momentum and its energy loss, one can measure the particle mass (i.e. particle identification)

How to improve the identification power of dE/dx ?

Important for physics is the separation power to identify particles

- **particle separation power in relativistic rise**

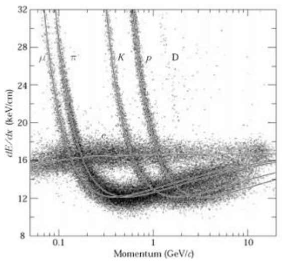
$$\text{separation power} = \frac{\text{separation}}{\text{resolution}}$$

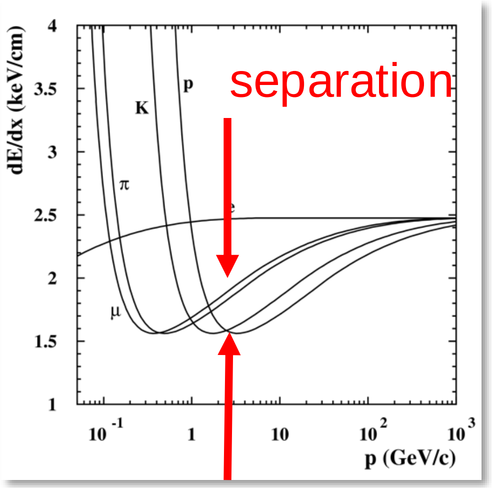
- **dE/dx resolution is not the most important!**

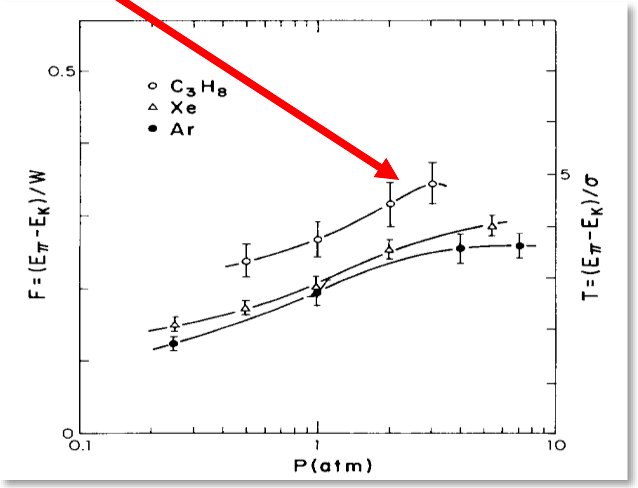
- Higher pressure reduces separation in relativistic rise

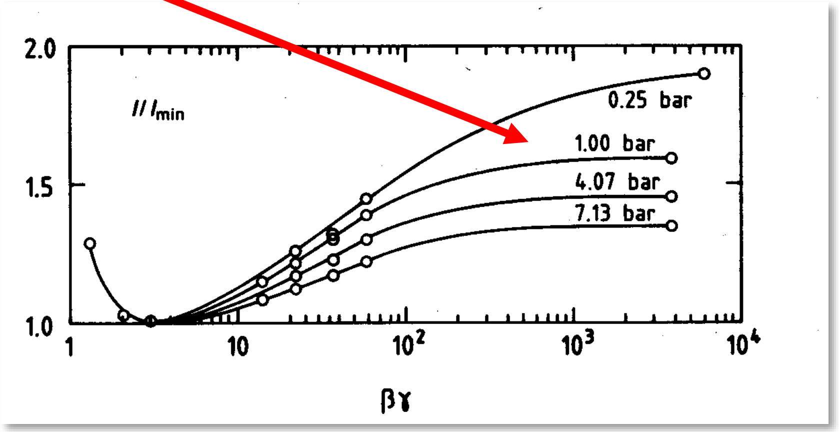
- Optimal separation power at 3 - 4 bars

- **also less diffusion, but…**
- **pressure vessel needed..**









Typical (average) particle separation power at LEP

- **e/π** > 2σ up to 12…14 GeV
- **π/K** > 2σ up to 8…20 GeV (max. 2.5 – 3.5 σ)
- **p/K** always below 2σ (max. 1 – 1.7 σ)

[M. Hauschild, RD51 workshop on Gazeous detector contributions to PID]

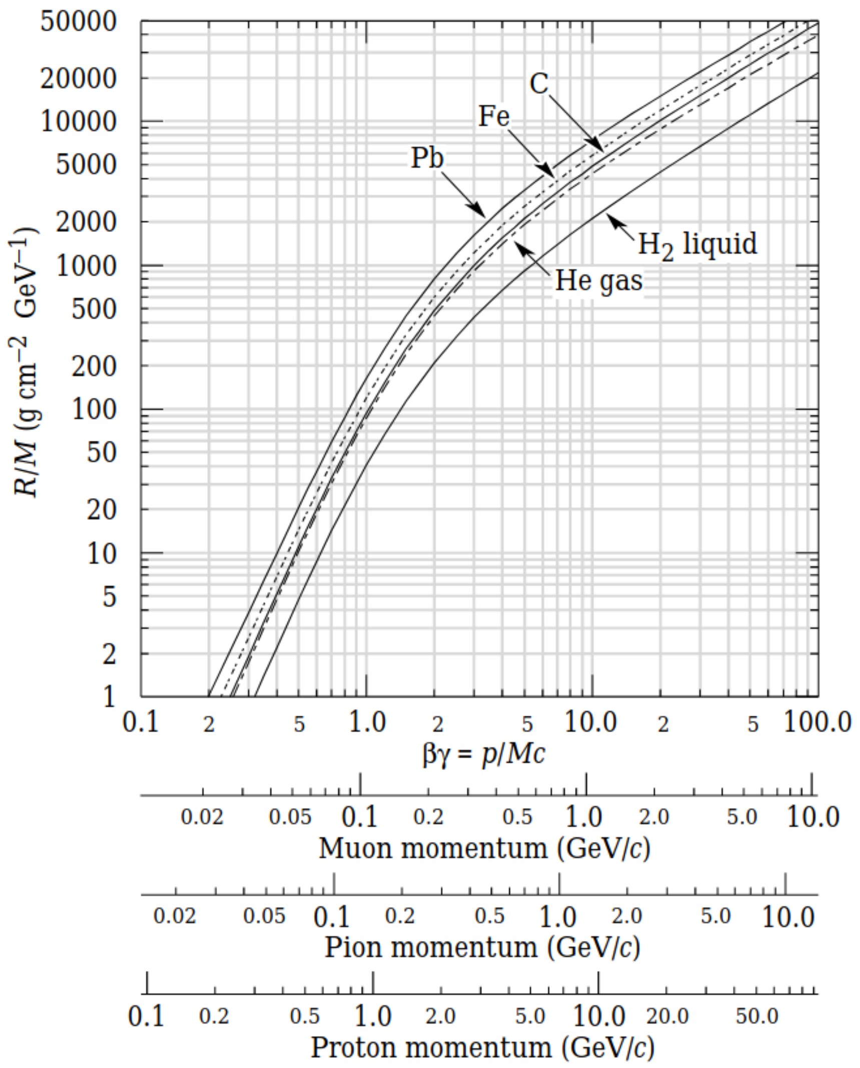
How far a heavy charged particle goes ?

- **Range R is the distance traveled (depth) in the medium by a particle until it stops**

$$R(E_0) = \int_0^{E_0} \frac{1}{dE/dx} dE$$

- **Calculation shows that R/M is a universal function of βγ**

- **Example :**
  - consider proton with momentum of 1 *GeV* on a Pb target (ρ=11.3 *g/cm*)
  - from the figure we can read
    - R/M~200 *g* cm^{-2} GeV^{-1}
    - R = 200/11.3 *1GeV ~18 *cm*

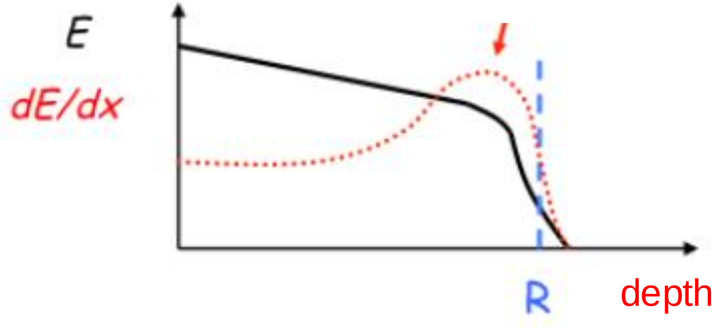


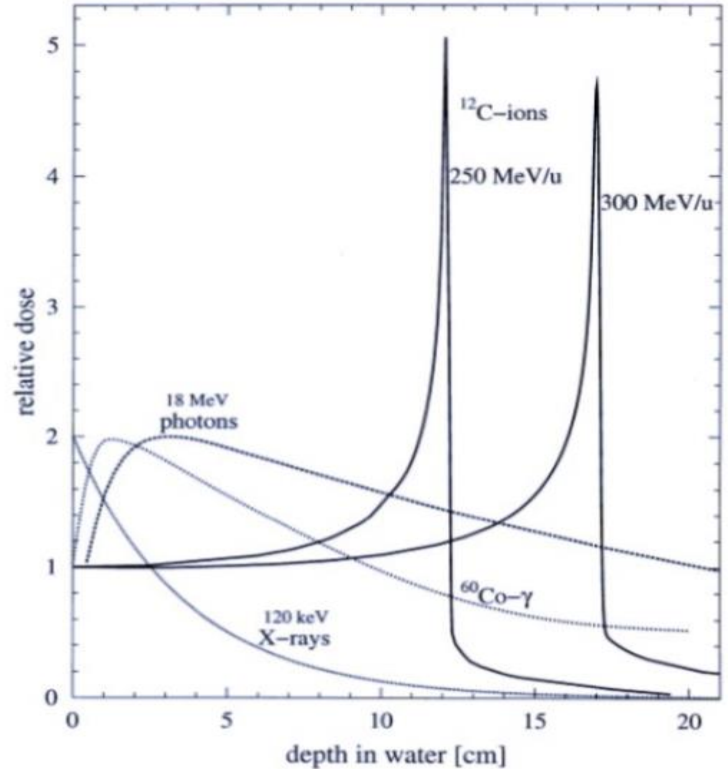
Note : this curve is only valid for particles which lose energy only by ionization and atomic excitation
- low energy hadrons
- muons up to a few hundred *GeV*

Bragg curve for charged heavy particles

- **Bragg curve is the relation between the depth (distance traveled) and *dE/dx***

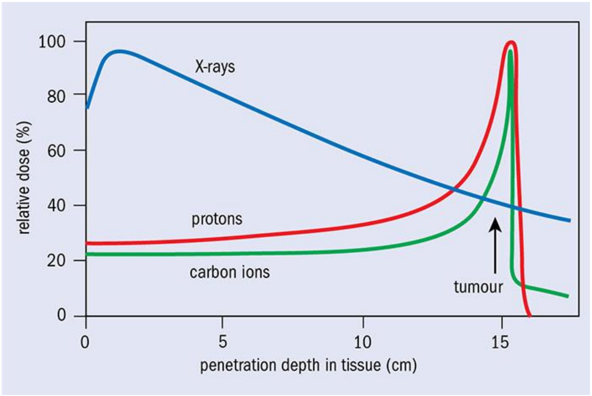
Braking due to the increase of *dE/dx* in $\beta^{-5/3}$





  - ○ most of the energy is deposited near the end of the traveled distance : Bragg peak
  - ○ the peak position (and the height of the plateau) depends on the type of particle and its energy

- **Application :**
  - ○ tumor therapy with protons and heavy ions
  - ○ adjust beam energy to place Bragg peak inside tumor

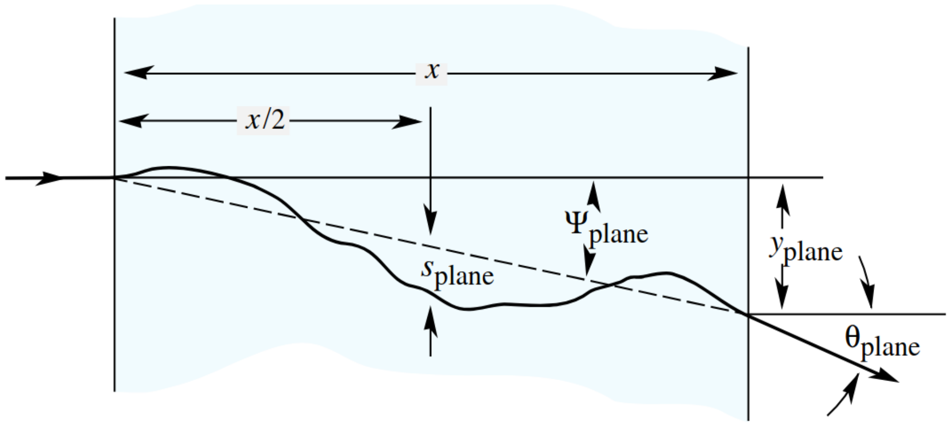


CERN courrier 2016

effective relative dose versus tissue depth for different forms of radiation

Multiple Scattering

- **A charged particle going through a medium will be deflected by numerous interactions at large distance with atomic nuclei**



- **Originated from Coulombian scattering on nuclei which cross-section is :**

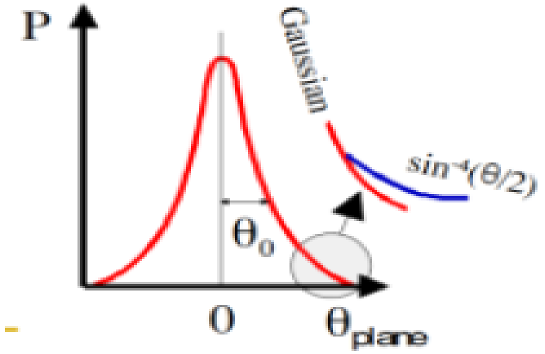
$$\frac{d\sigma}{d\theta} = 4\pi\left(zZr_0\frac{m_ec^2}{p\beta c}\frac{1}{tan^2(\theta/2)}\right)^2$$

- **Width θ of the distribution is given by :**

$$\theta_0 = \frac{13.6MeV}{\beta cp} z\sqrt{(x/X_0)}[1 + 0.038ln(x/X_0)]$$

  - where X is the radiation length, characteristics of the material
  - precise value, better than 10% for 10 <x/X <100

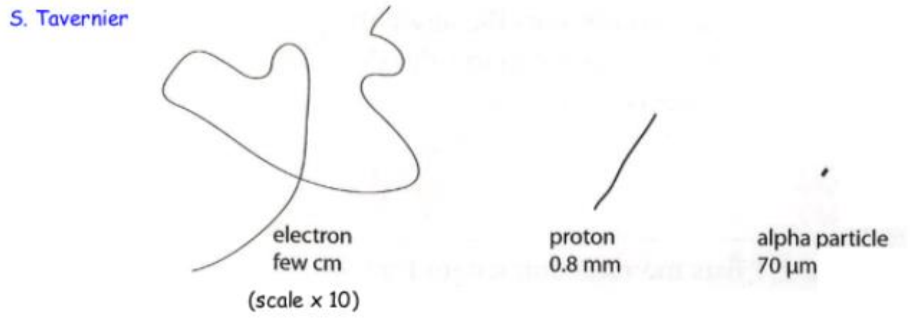
For large values of θ, the curve deviates from a Gaussian and has a shape in $\sin^{-4}(\theta/2)$



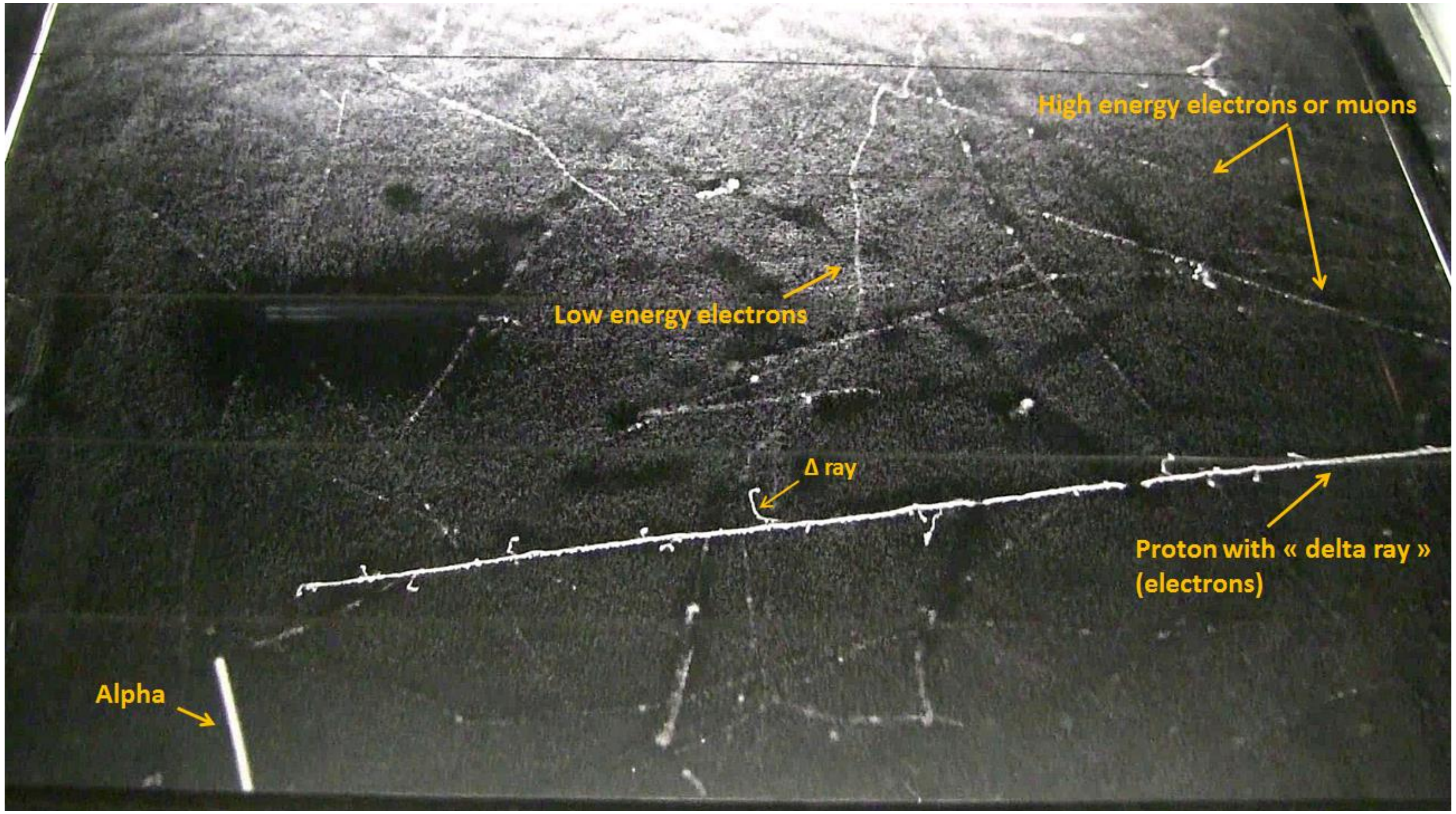
- **If there are many collisions, the mean scattering angle is zero**

Multiple Scattering

- **At small energies (p~1 *MeV/c*), after 1 X_0, the information on the initial direction is lost**



Typical trajectories for an e , a proton and an α of 10 MeV in silicium



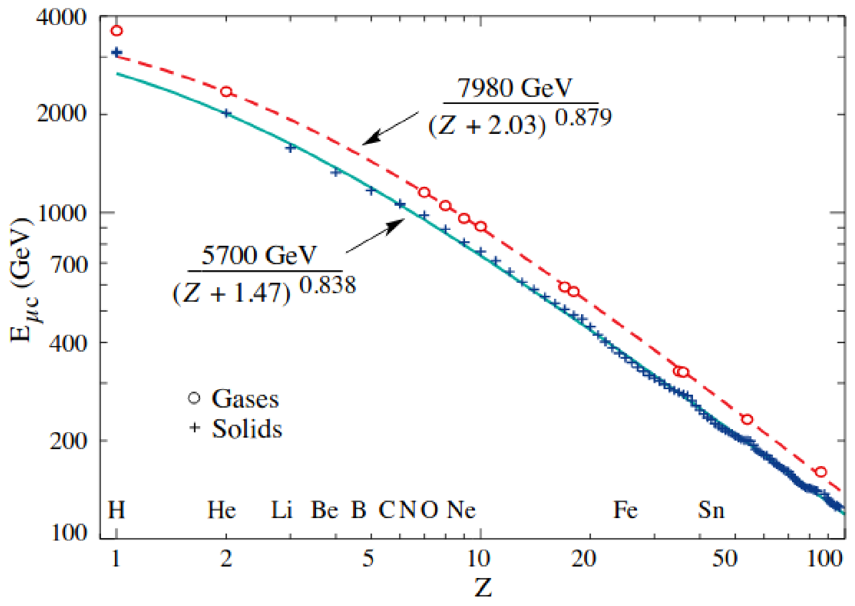
A particle of high energy which stops in matter always ends up to be concerned by multiple scattering

High energy muons

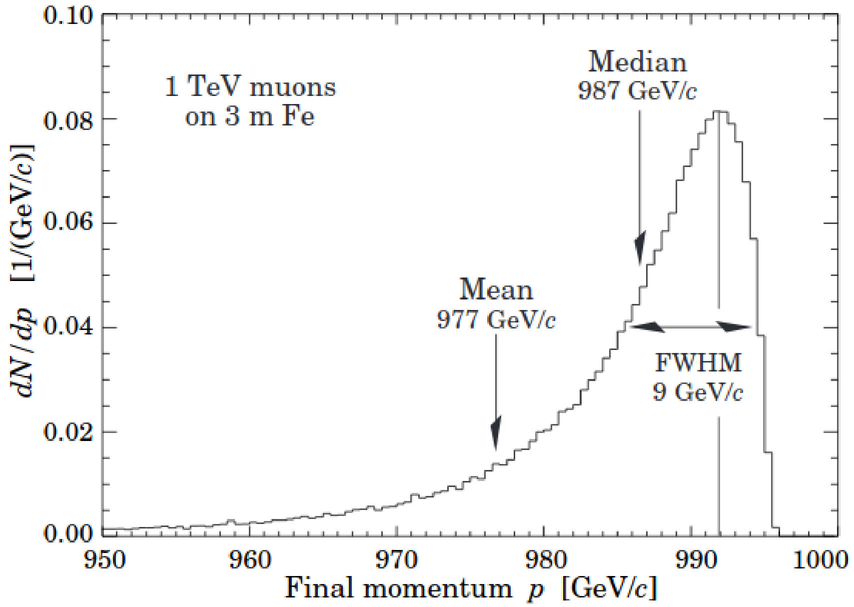
- **Critical energy for $\mu^{\pm}$ changes with the material**
  for iron (Z=26), E_c(e) : 22.4 *MeV*, $E_c(\mu)$ ~ 100-200 *GeV*

- **Interaction of μ with matter can then be modeled with three parts in the spectrum:**
  - the most probable loss is 8 *GeV/c* (3.4 MeV g   cm)
  - full width at half-maximum is 9 *GeV/c* (resolution is 9/992~0.9%)
  - the tail of the distribution is due to Bremsstrahlung

High energy muons are highly penetrant



Muon critical energy for the chemical elements



The momentum distribution of 1 TeV/c muons after traversing 3 m of iron

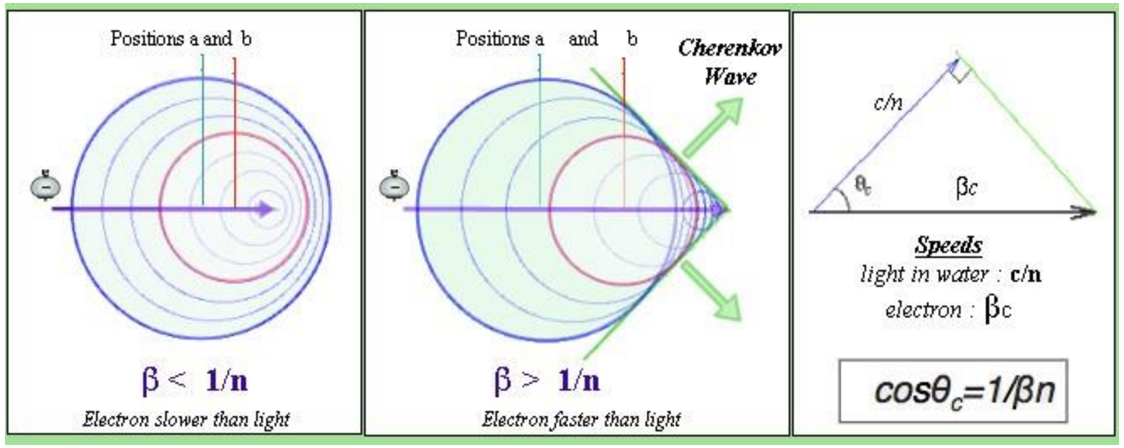
Čerenkov radiation

A charged particle radiates a γ when traversing a medium, if its velocity β is larger than the local phase velocity v of light in the material

Mechanism : the field E polarizes the medium. After the passage of the particle, it returns to its initial state

- the change of polarization is an EM perturbation moves at velocity c/n
- refractive index n=c/v
- if v<c/n, the EM signal propagates faster than the particle
- at a given point of space, these signals arrive in random way

$$v_{th} \geq \frac{c}{n} \Rightarrow \beta_{th} \geq \frac{1}{n}$$



- *if v>c/n, the EM signal propagates slower than the particle*
- *at a given point of space, elementary perturbations will sum up in a single wave front*

- the light is emitted in a cone with a characteristic opening angle, the Čerenkov angle q, which depends on the velocity of the particle and the refractive index

$$cos(\theta_C) = \frac{(c/n)t}{vt} = \frac{c}{nv} = \frac{1}{\beta n}$$

Čerenkov radiation

- **Threshold energy and refractive index**
  - threshold kinetic energy is : $E_{th} = mc^2\left(\sqrt{\left(\frac{n^2}{n^2-1}\right)} - 1\right)$
  - in water : n~1.33. E_{th} = 264 keV for $e^{\pm}$ and 486 MeV for p

- **Intensity of the radiation can be calculated thanks to Maxwell equations**

$$\frac{d^2\varepsilon}{d(\hbar\omega)dx} = \hbar\omega\frac{Z^2\alpha}{\hbar c}\left(1 - \frac{1}{n^2\beta^2}\right)$$

  - where ε is the energy emitted by photons of energy $\hbar\omega$ and Z the charge of the particle
  - by dividing by $\hbar\omega$ one obtains the number of photons
    - high energy $e^{\pm}$ produce ~220 photons/cm in water and ~30/m in the air

- **This effect exists in all material but is negligible compared to ionisation**
  - proton with E_{kin} = 1 *GeV* passing through 1 *cm* water
    β=p/E ≈ 0.875 ; cosθ = 1/nβ = 0.859 ➛ θ_C = 30.8°
    $d^2N/(dEdx) = 370 \sin 2\theta_C$ $eV^{-1}.cm^{-1} \approx 100$ $eV^{-1}.cm^{-1}$
    ΔE_{loss} = <E> $d^2N/(dEdx)$ ΔE Δx= 2.5 *eV* x 100 $eV^{-1}.cm^{-1}$ x 5 eV^{-1} *cm* = 1.25 *keV*

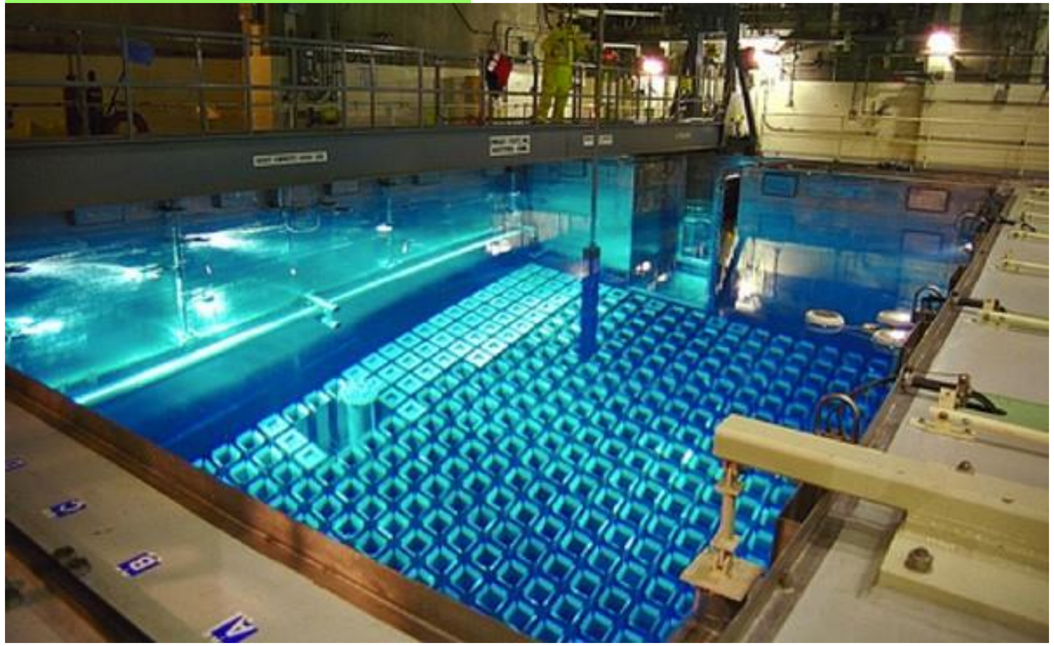
- **It is used for the particle identification, not for *dE/dx* measurements**

Čerenkov radiation

- **Most of light is emitted in the blue / ultraviolet region**

- **Needs to be considered when thinking about detecting Čerenkov photons**
  - glass (photomultiplier window) absorbes UV light

https://radioactivity.eu.com



The blue tint of the water that bathes the fuel assemblies in the storage pools is due to the Cherenkov effect.
The electrons are produced by the Compton effect in the water by gamma rays from the radioactive disintegrations which occur in the fuel rods and which have come out of the sheaths encasing this fuel. © NRC

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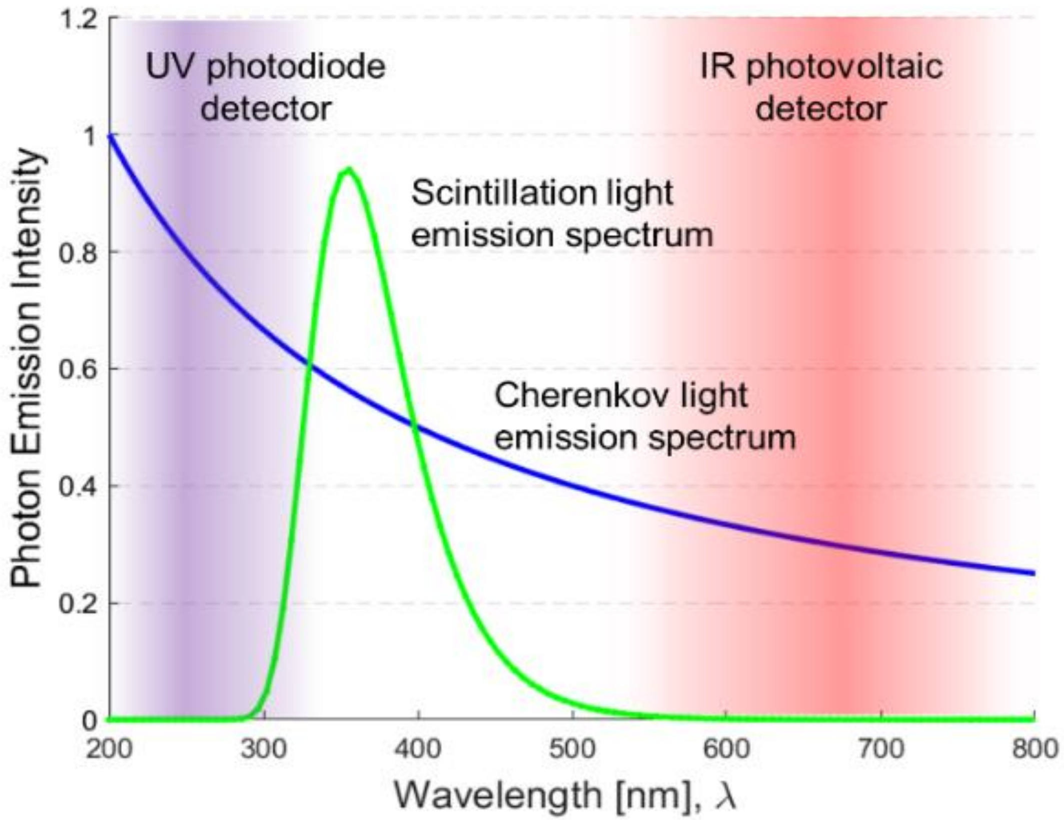
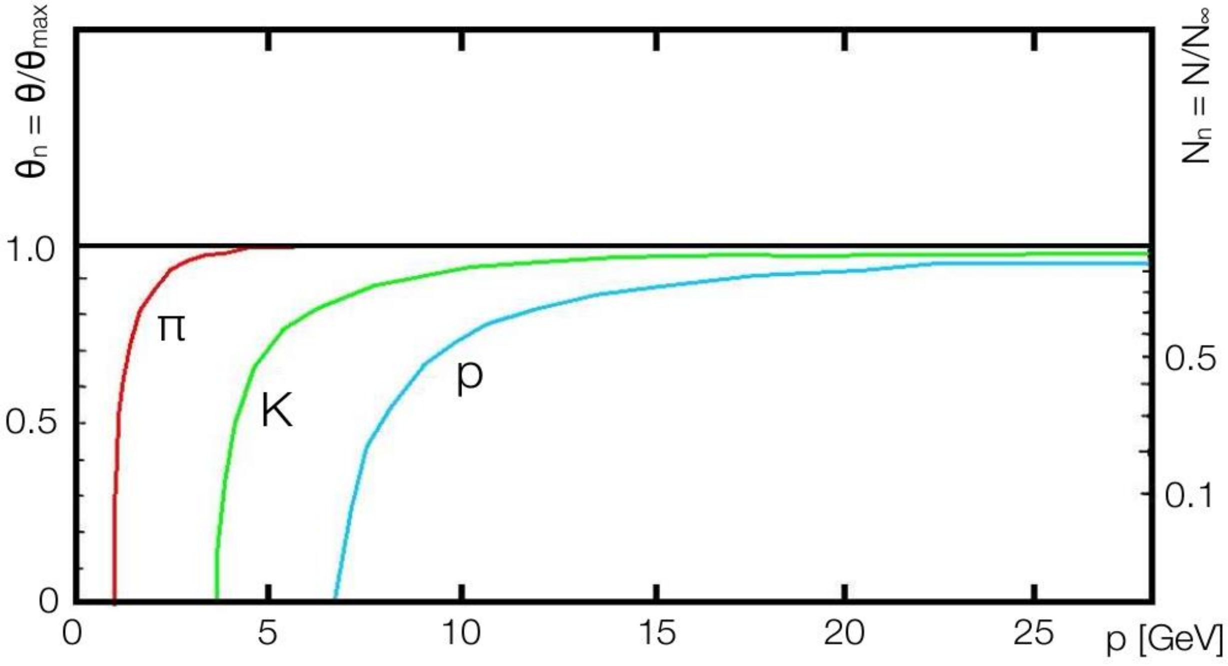


Material dependence of Čerenkov radiation

Medium	n	β_{thr}	θ_{max} [β=1]	$N\gamma$ [eV^{-1} cm^{-1}]
Air	1.000283	0.9997	1.36	0.208
Isobutane	1.00127	0.9987	2.89	0.941
Water	1.33	0.752	41.2	160.8
Quartz	1.46	0.685	46.7	196.4

- Gases have a very high β_{thr} due to their low density and are suitable for electron identification
- Drawback : small number of Čerenkov photons, need large path in the material

Material dependence of Čerenkov radiation



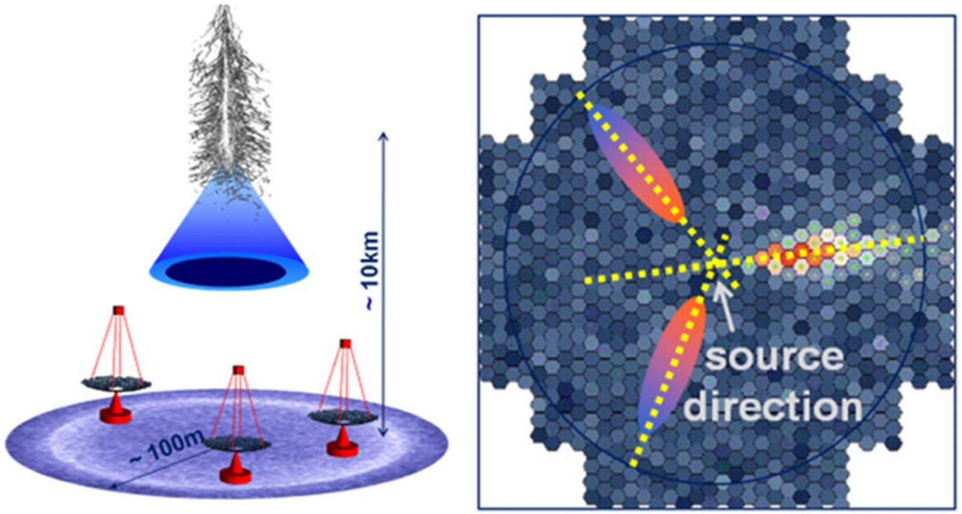


Fig. 1. Left: detection of a TeV gamma-ray with an array of Cherenkov telescopes (not to scale). Right: example for shower images seen in the camera's focal plane, and the principle of stereoscopy.

- **Particles of different mass have different Čerenkov thresholds and reach the asymptotic region at different momenta**

Also used in CTA to detect high energy cosmic rays

- **If we know the momentum, we can identify the particle type up few GeV**
  - threshold Čerenkov detectors
  - ring imaging Čerenkov detectors, need to select material with suitable index of refraction for the desired momentum region

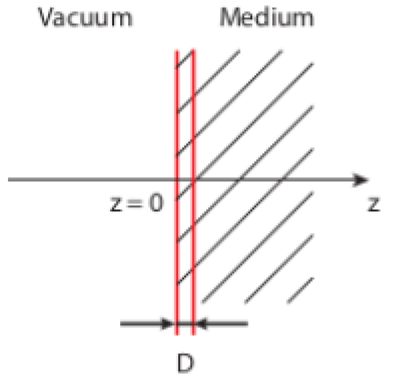
Transition radiation

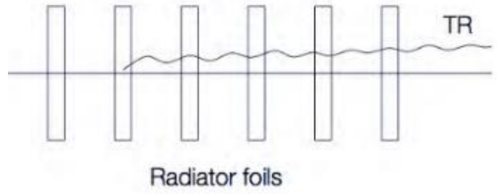
- **Transition radiation occurs when a relativistic charged particle passes the boundaries between two media with different refractive indices**

- **Some complex EM calculations show that :**
  - angular distribution of the radiation strongly forward peaked [Interference; coherence condition] $\theta \leqslant 1/\gamma$
  - coherent radiation is generated only over a very small formation length $D = \gamma\, c/\omega_p$ ← plasma frequency [from Dude model]
  - the number of photons emitted at each transition is very small
  - the energy emitted at each transition is $\hbar\omega_P$~10-50 eV : X-rays $E = \dfrac{\alpha Z^2 \gamma \hbar \omega_P}{3}$
  - maximum energy of radiated photons limited by plasma frequency … $E_{max} = \gamma \hbar \omega_p$
  - $e^{\pm}$ are the only particles which will emit a transition radiation so are used to do e/π separation
  - Typical values : D = 10 mm   (d>D : absorption dominates)

    CH_2 : $\hbar\omega_P$ ~ 20 eV, γ=10

    Air : $\hbar\omega_P$ ~ 0.7 eV





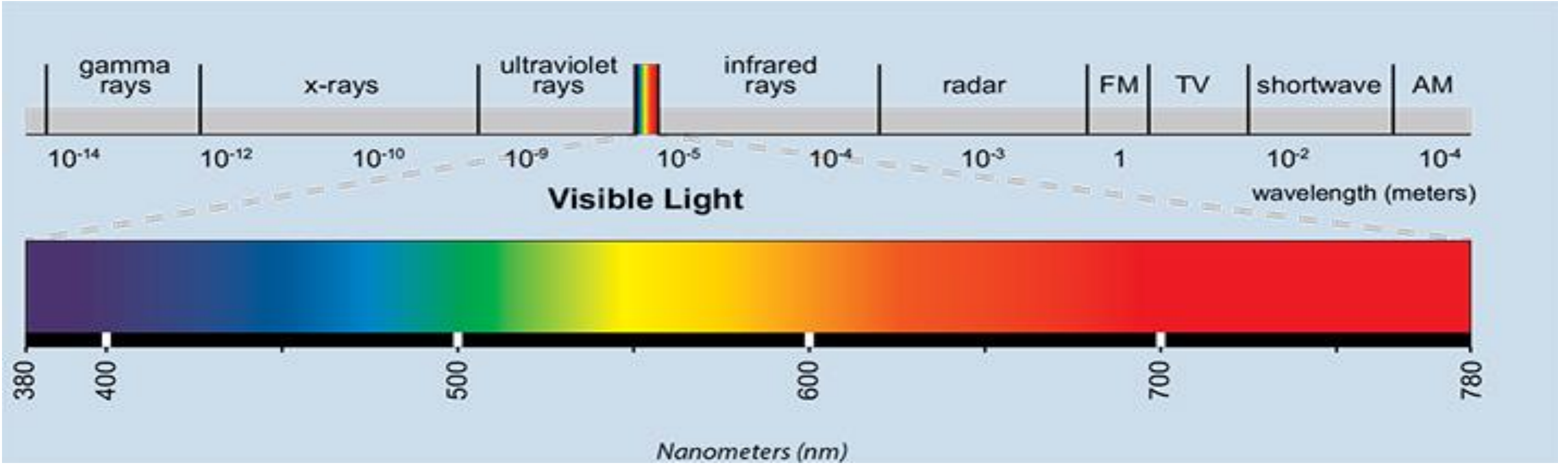
Part 2 – Interactions of particles in matter
Neutral particle interactions

- photons
- neutrons
- neutrinos

Photon detection

γ-ray is an electromagnetic radiation at high frequency which has no mass, no electric charge.

γ-rays travel at the speed of light of the medium they go through c/n, where c=299 792 458 ms^{-1} is the speed of light in vacuum and n is the refractive index of the medium. They do not let track of their trajectory. They are not deviated by electromagnetic fields.



Photons are characterized by :

- their wave length : λ[m] in vacuum
- their frequency : ν[Hz] ; λν=c or λ = c T
- their energy : E = hν= hc/λ

  where h is the Planck constant : h = 6.626×10^{-34} *J.s*

$$E[eV] \approx \frac{1240}{\lambda[nm]}$$

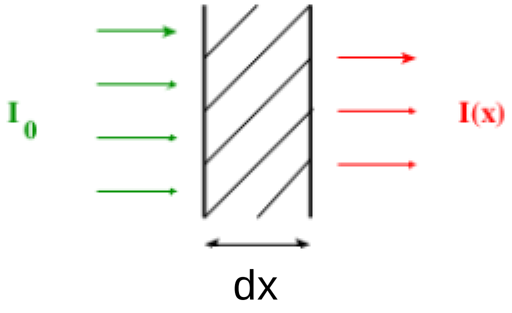
Photon flux in matter

Consider beam of monoenergetic γ with intensity I hitting an absorber. **Despite many known mechanisms of interaction are possible, only three play an important role for radiation measurements :**

- photoelectric effect
- Compton scattering
- pair production
- other processes :
  - Rayleigh Scattering (γA ➛ γA; A = atom; coherent)
  - Thomson Scattering (γe ➛ γe; elastic scattering)
  - Nuclear Photon Absorption (γN ➛ pN'/nN) (the absorbed photon kicks off a neutron or a proton from the nucleus N)
  - Nuclear Resonance Scattering (γN ➛ N* ➛ γN)
  - Delbruck Scattering (γN ➛ γN)
  - Hadron Pair photo-production (γN ➛ $h^+ h^-$ N)

$$dI = -\mu I dx$$

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



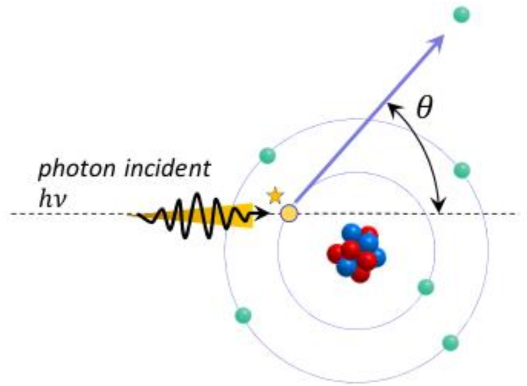
with λ=1/μ is the mean free path

μ absorption coefficient (cm^2/g)

- **A single interaction remove the photon from the beam**
  - all these processes lead to a partial or complete transfer of the energy of the photon to electrons
  - they lead to sudden and abrupt changes in the photons history, as they entirely disappear or are scattered with high angle
  - this behaviour is dramatically different from what happen to charged particles which gradually slow down by continuous and simultaneous interactions with many absorbing atoms

Photo electric effect

- **Mechanism : γ + atom → atom + e**
  - occurs when a photon is absorbed by an inner shell electron causing the electron to gain sufficient energy to be ejected from the atom
  - concerns essentially e^- from the K layer
  - after ejection of the inner shell electron, the missing electron must be replaced by an outer shell (higher energy) electron. For this to happen, the outer shell electrons must loose energy by emission of a characteristic X-ray and/or an Auger Electron.

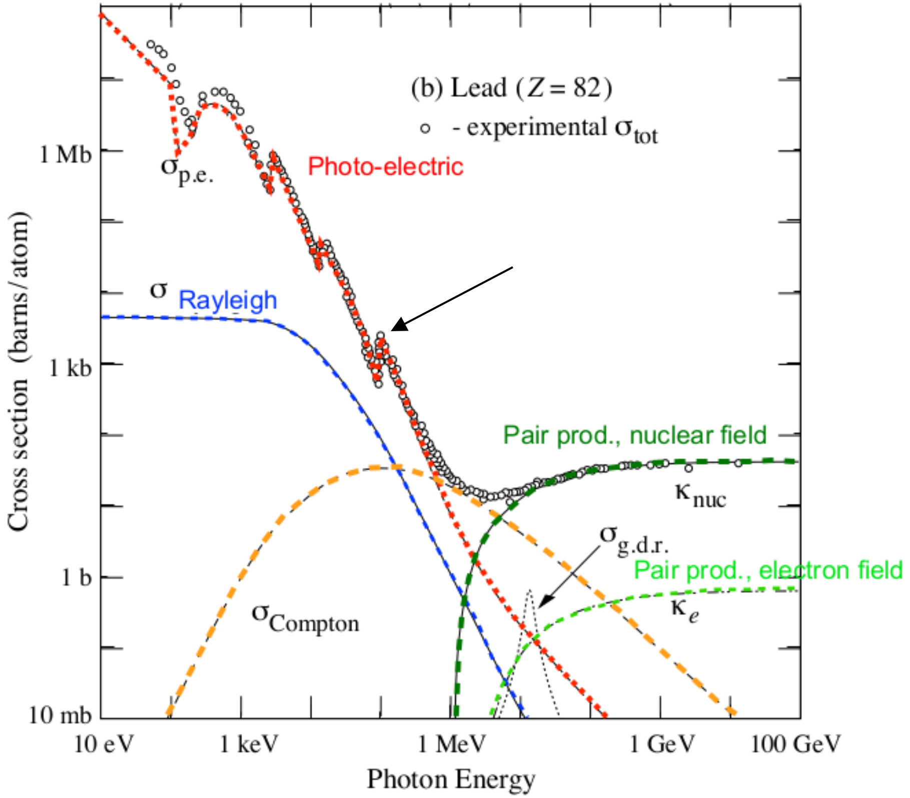


- **Energy :**
  - energy threshold (minimum required energy) equals to the binding energy of the orbital electron : $E_e = h\nu - E_b$

- **Cross-section is** characterized by discontinuities (absorption edges) as thresholds for photo-ionisation of various atomic levels are reached

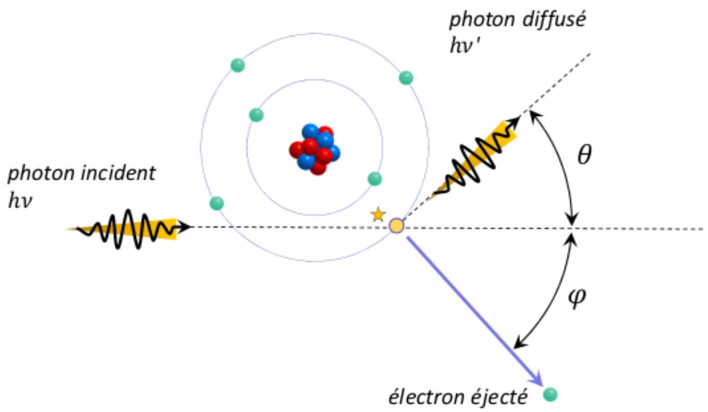
$$\sigma_{Photoelectric} \approx 4\sqrt{2}\alpha^4 Z^5 \left(\frac{m_e c^2}{E_\gamma}\right)^{7/2} \sigma_{Thomson}$$

$$with\ \sigma_{Thomson} = \frac{8}{3}\pi r_e^2 \approx 665 mb$$



Photon detection

- **Mechanism : γ + e → γ' + e'**
  - it is an inelastic scattering event in which the incident photon interacts with a single electron
  - because the interaction is inelastic, the photon transfers some of its energy to the electron during the interaction
  - the electron is ejected from its orbital



- **Energy :**
  - after scattering, the energy is shared between the electron and the scattered photon minus the binding energy of the electron

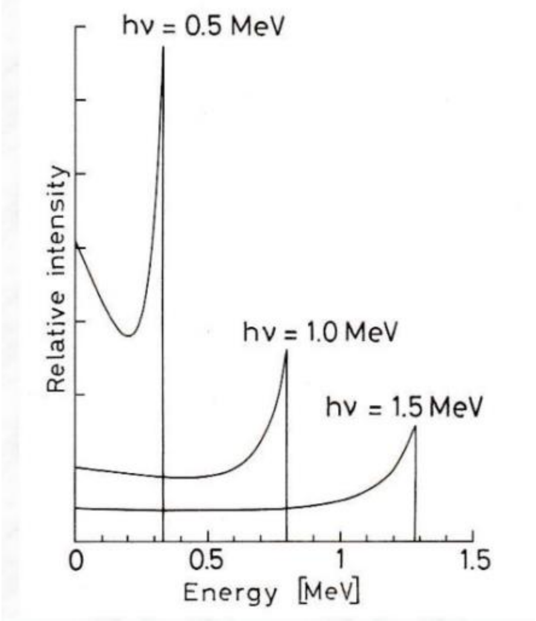
$$E_\gamma{}' = \frac{E_\gamma}{1 + \epsilon\left(1 - cos(\theta_\gamma)\right)} \qquad \epsilon = \frac{E_\gamma}{m_e c^2}$$

  - maximal energy transfer to the electron for q=p

$$E_{elec} = E_\gamma - E_{bind}$$

  - corresponds to a maximal electron energy

$$E_{\gamma'}^{min} = E_\gamma \frac{1}{1 + 2\varepsilon} \qquad E_{elec}^{max} = E_\gamma - E_{\gamma'}^{min} = E_\gamma \frac{2\varepsilon}{1+2\varepsilon} < E_\gamma$$

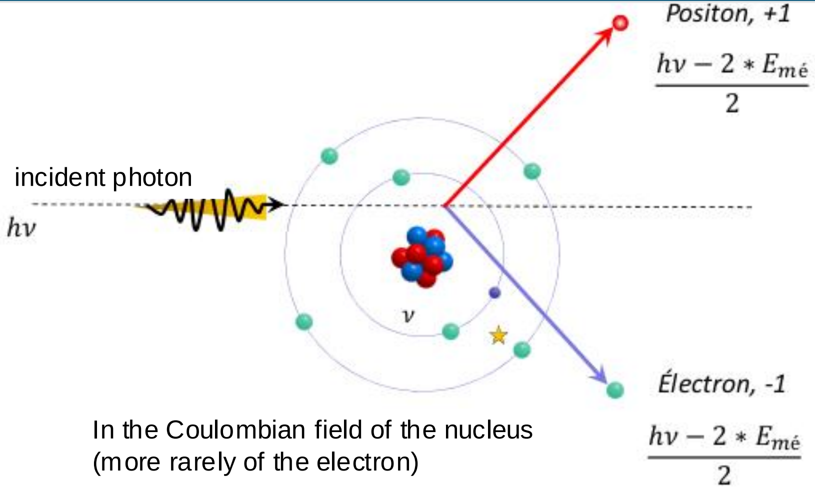


- **Cross-section :**
  - decreases when the energy of the photon increases

$$\sigma_C^e \approx \frac{ln(\epsilon)}{\epsilon}; \sigma_C^{atom} \approx Z\sigma_C^e$$

Pair production

- **Mechanism : γ + nucleus → e^-+e^+ + nucleus**
  - a photon transitions to an electron/positron pair. The presence of a massive particle is required. This allows for conservation of energy and momentum as the massive particle is able to absorb some recoil energy



In the Coulombian field of the nucleus (more rarely of the electron)

- **Energy :**
  - occurs in the Coulombian field of the nucleus only if $E_\gamma > 2m_ec^2\left(1+\frac{m_e}{m_n}\right)$ $\approx 1MeV$

- **Cross-section :**
  - for E >> m_ec^2 it is independant of the energy :

$$\sigma_{pair} \approx \frac{7}{9}\left(4\alpha r_e^2 Z^2 ln\frac{183}{Z^{1/3}}\right) \approx \frac{7}{9}\frac{A}{N_A}\frac{1}{X_0}$$

	ρ [g/cm3]	X_0 [cm]
H	0.071	865
C	2.27	18.8
Fe	7.87	1.76
Pb	11.35	0.56
Air	1.2×10^{-3}	30×10^3

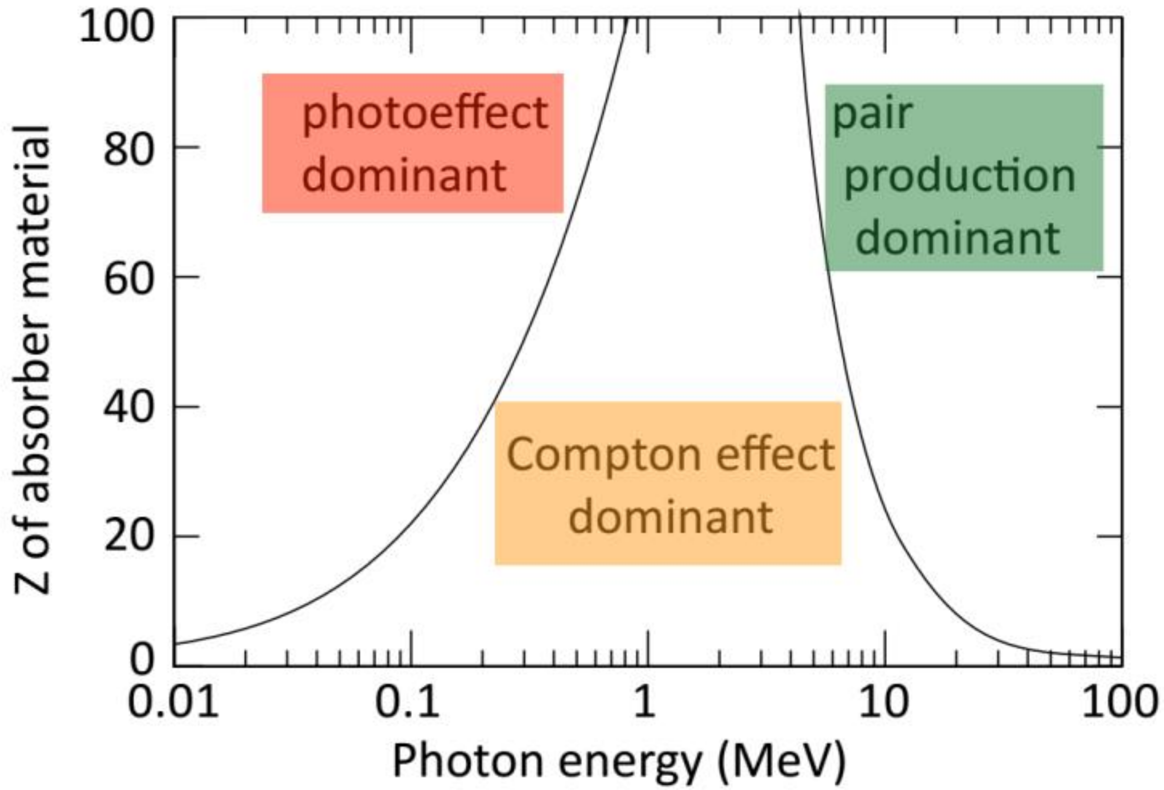
- **One introduces :**
  - μ : absorption coefficient,
  - λ_{pair} = 1/μ. On average, a high energy g will convert into a e e pair after ~1 X_0

$$\lambda_{pair} = \frac{9}{7}X_0$$

Interaction of photons with matter

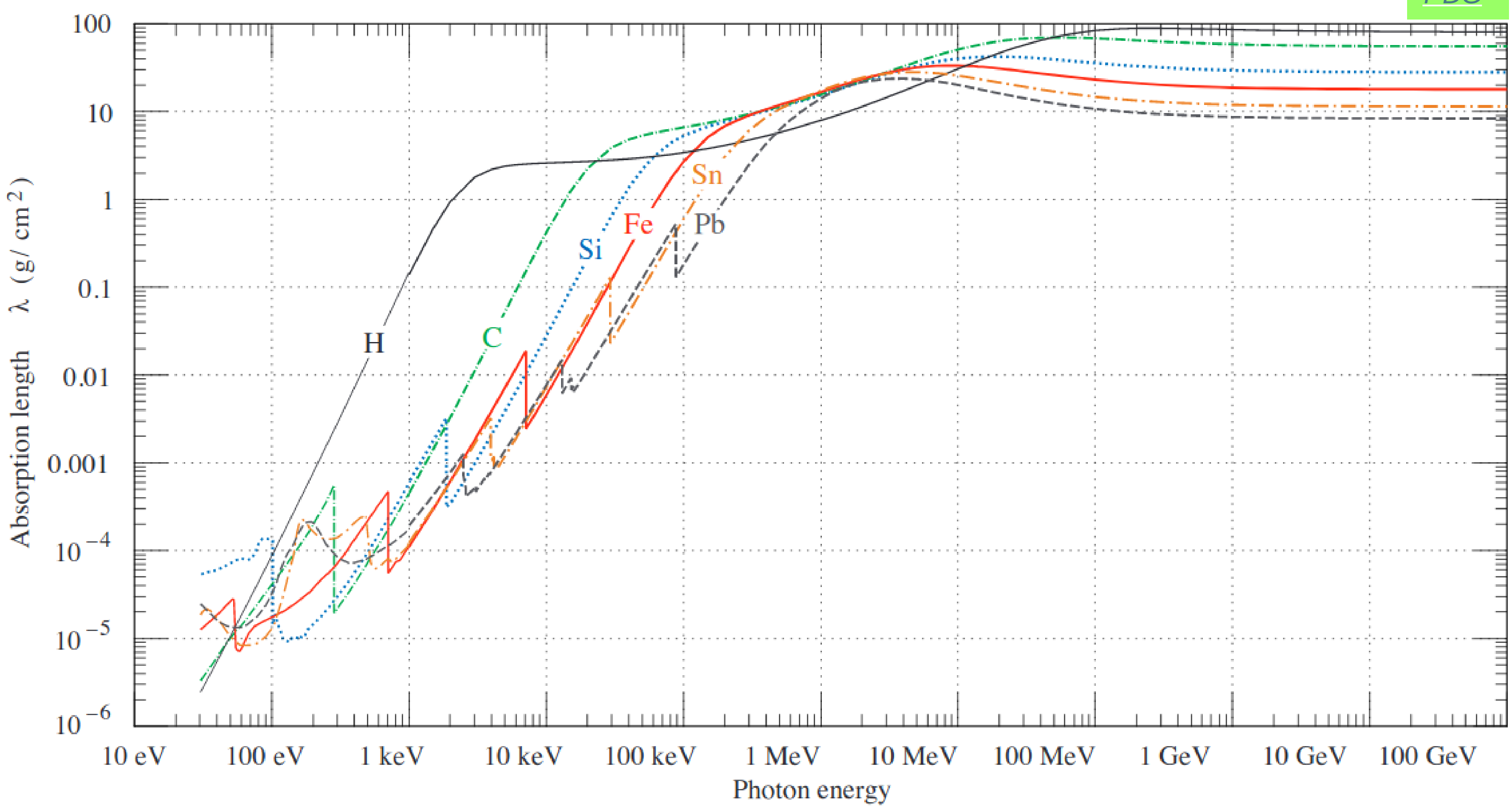
These three effects create charged particles and/or transfer energy to charged particles which are then detected:

- photoelectric effect : dominant for E <100 *keV*
- Compton scattering : dominant for E ~1 *MeV*
- pair production : dominant for E >1 *MeV*



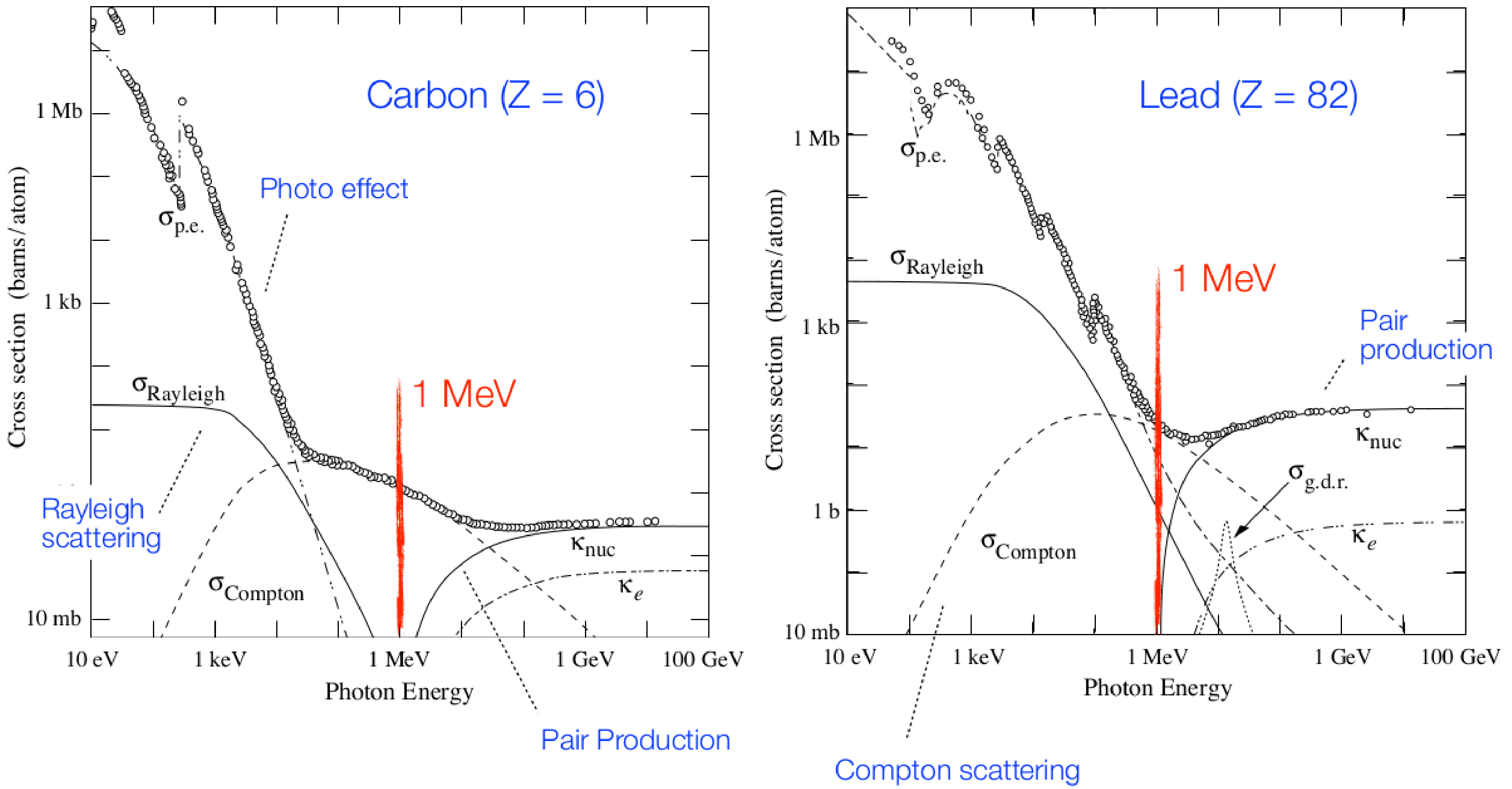
Absorption length of photons in matter

PDG



Photon cross-sections (Z and E dependence)

PDG



Absorption of a photon or an electron in a dense environment leads to the creation of an electromagnetic shower (calorimeter)

Neutron interaction in matter

The neutrons was discovered by Chadwick in 1932. Nuclear fission, induced by the capture of a slow neutron in ^{235}U was discovered by Hahn and Strassman in 1939.

The fact that several neutrons emitted when fission takes place suggested that a self-sustaining chain reaction might be possible.

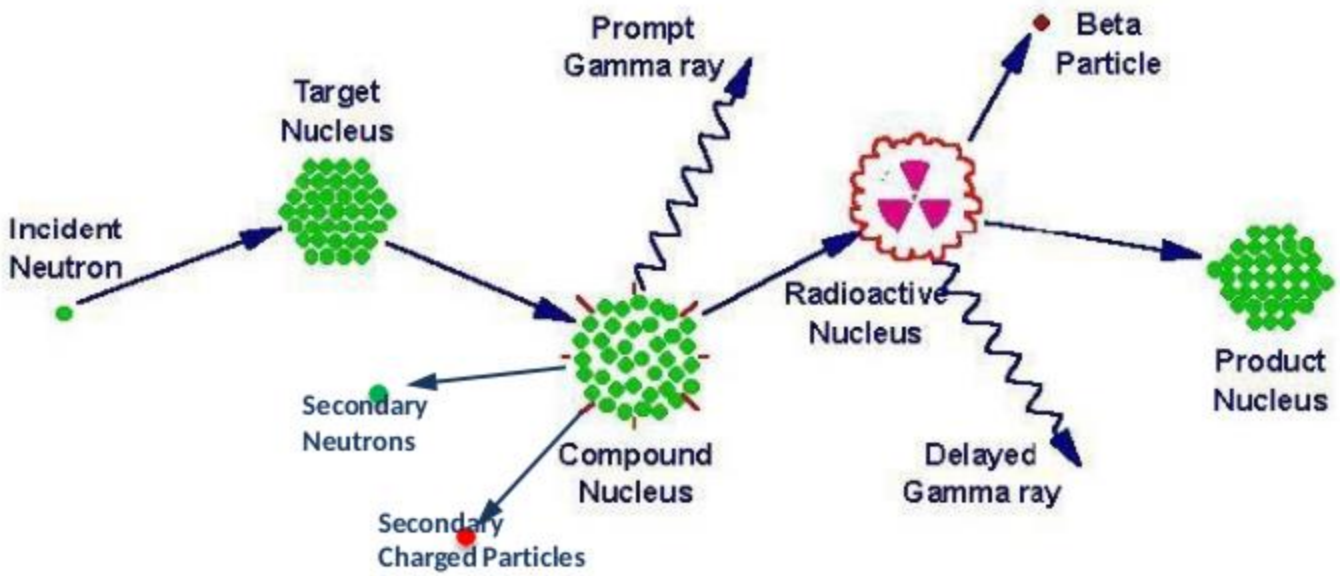
Under Fermi's direction, the world's first man-made nuclear reactor went critical on Decembe 2, 1942

In terms of interaction :

Neutrons can interact with a atomic nuclei through:
- Elastic scattering: the total kinetic energy is conserved – the energy loss by the neutron is equal to the kinetic energy of the recoil nucleus.
- Inelastic scattering: the nucleus absorbs some energy internally and is left to an excited state.
- (Thermal) neutron capture: the neutron is captured or absorbed by a nucleus, leading to a reaction such as (n,p), (n,2n), (n,a) or (n,g). The reaction changes the atomic number and/or atomic mass number of the struck nucleus.

Neutron interaction in matter

- **Neutron detectors do not detect neutrons but products of neutron interactions !**



Almost all detector types can be made neutron sensitive:

- external converter (radiator to go to low energy)
- converter = detector

see also lectures from I-M. Gregor, 2022

Neutron interaction in matter at high energy

- **Neutron detectors do not detect neutrons but products of neutron interactions !**

At high energies (>100 MeV) they also behave like any hadron when meeting a nucleus

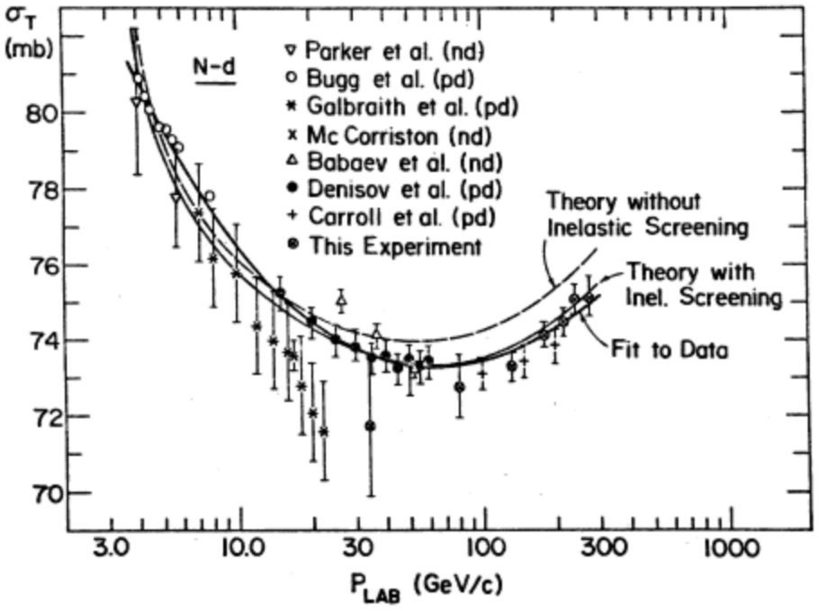


Fig. 2. Neutron-deuteron total cross section data above 4 GeV/c. Total errors, including scale errors, are shown on all points. The heavy solid curve is a fit to the data. The light solid and dashed curves are theoretical curves calculated with and without inelastic screening corrections.

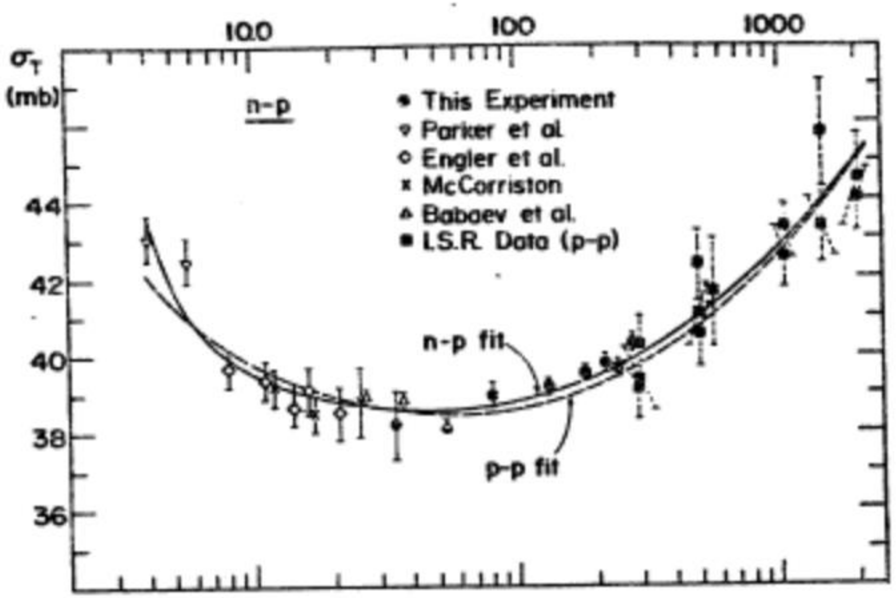
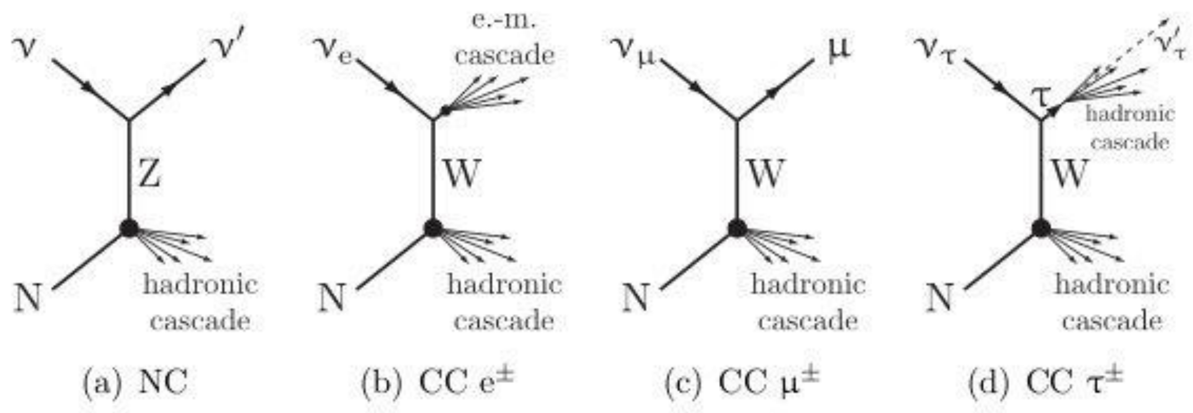


Fig. 1. Neutron-proton total cross sections from this experiment and previous measurements with neutron beams above 4 GeV. Some p-p data are shown with dashed error bars for comparison.

Neutrino interaction in matter

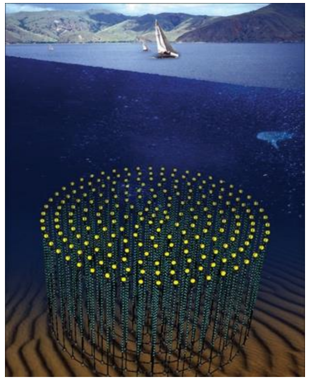
- **Neutrinos are sensitive only to weak interaction**
  - cross-sections are very small
  - neutrino beams can be built from π decay

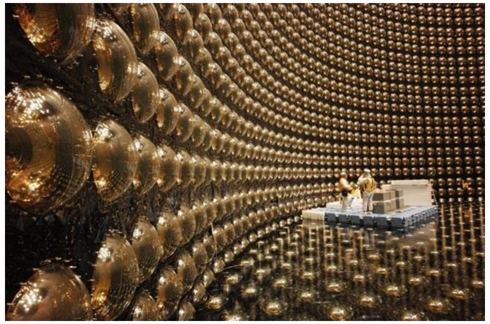


- **To detect them, they need to interact**

$$\begin{cases} \nu_\ell + n \longrightarrow \ell^- + p \\ \bar{\nu}_\ell + p \longrightarrow \ell^+ + n \end{cases} \quad \text{with} \quad \begin{aligned} \ell^- &= e^-, \mu^-, \tau^- \\ \ell^+ &= e^+, \mu^+, \tau^+ \end{aligned}$$

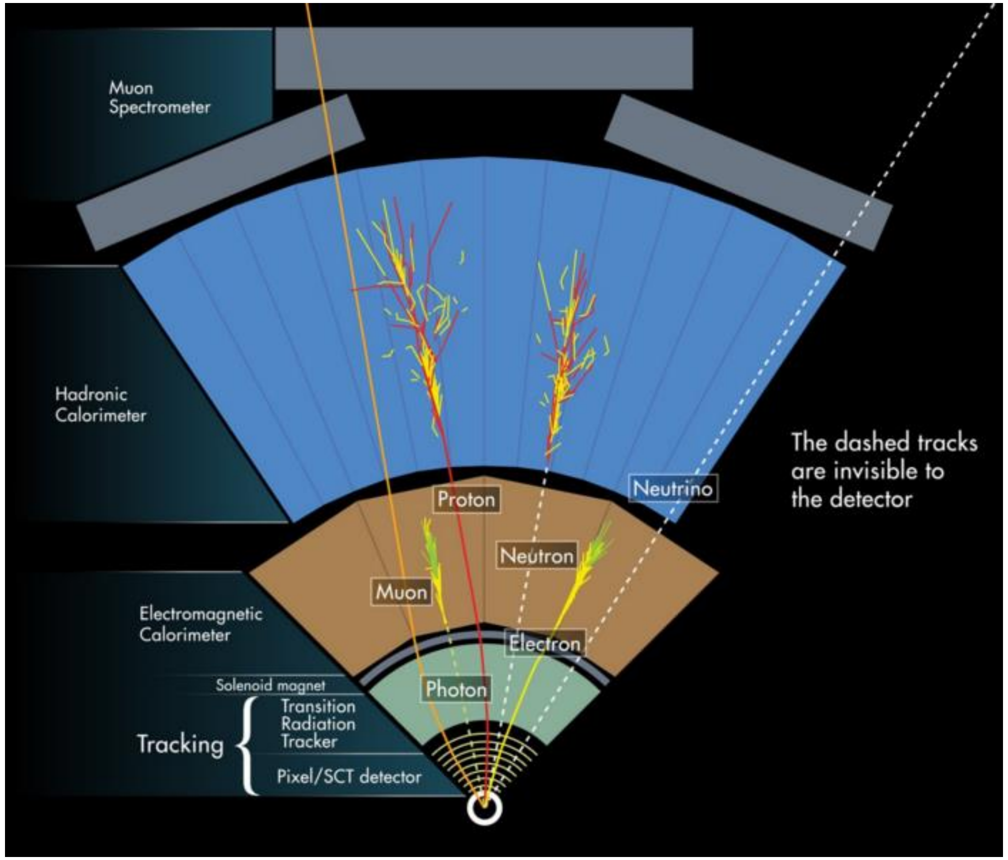
- **Typically, detection efficiencies are of the order of 10^{-17} in 1 *m* of iron**
  - detectors specialized for neutrinos need to be enormous (Km3net !!!!) and accept very high fluxes





Neutrino interaction in matter

In collider detectors, neutrinos are « seen » through the missing energy reconstructed in the Detector (but can also be DM ! Or any low-interacting particles!)



Part 3 – Particle detection

A typical measurement block diagram

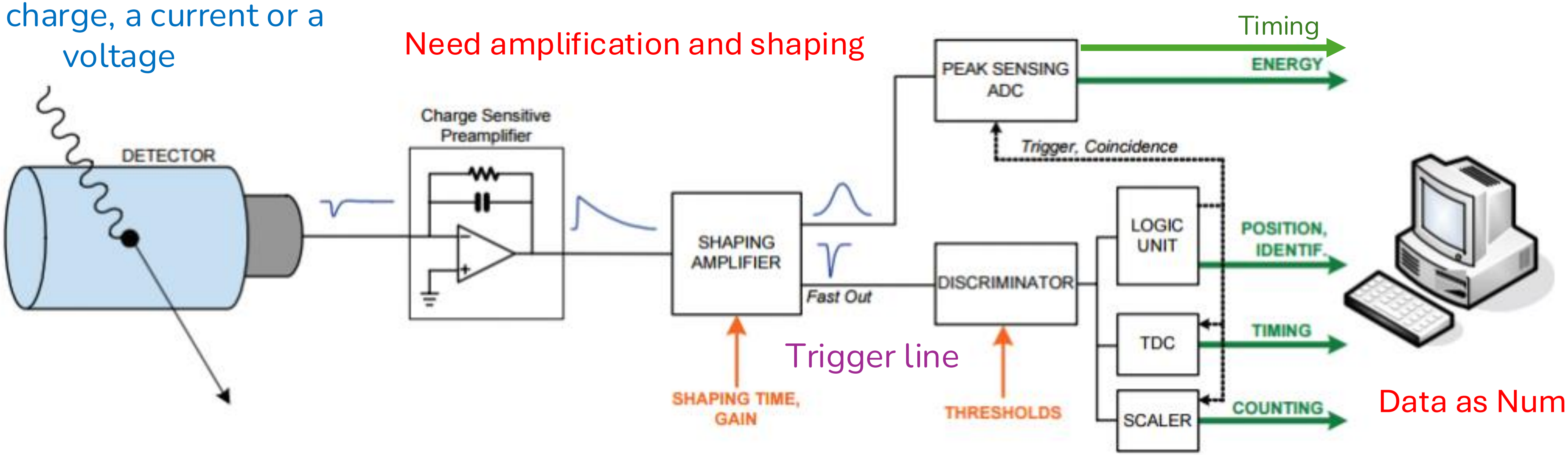
Typical measurement block diagram

Need a mechanism to transform the physical effect into a charge, a current or a voltage

Need amplification and shaping

Need Analog digital convertion

Precision measurement

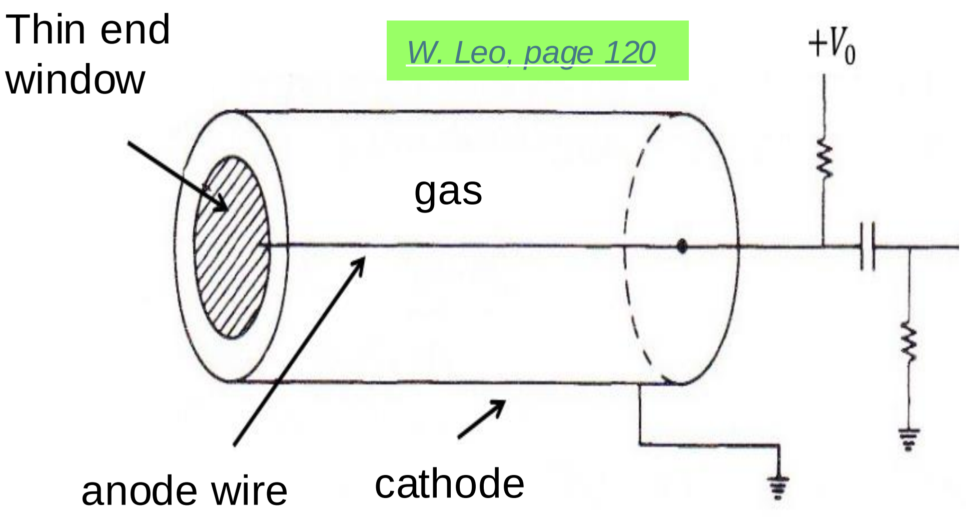


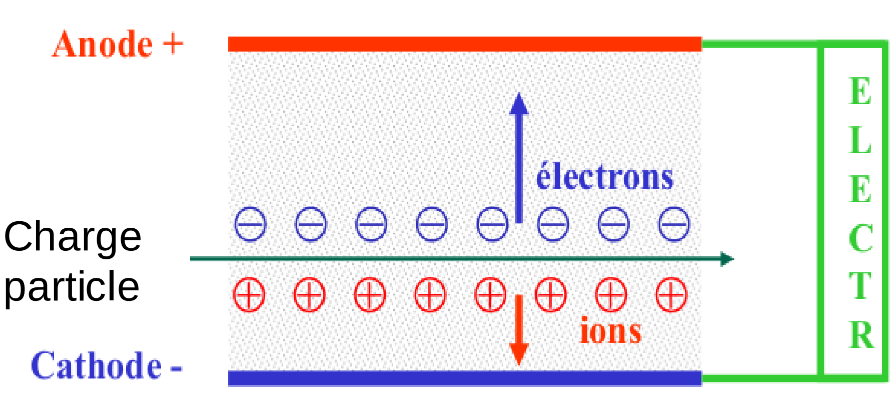
- Ionisation provides a charge, need for an electrical field to collect the charge
- Light emission requires a mecanism to use the photons to provide electrons or positrons (photoelectric effect, Compton effect, pair creation, auger electrons)
- Hadronic collisions : charged particles providing ionisation, atomic reorganization (photons)
- Transition in a magnetic cavity → current induction

Part 3 – Particle detection

Gaseous ionization detectors

Gazeous detector principle : ionizing particle





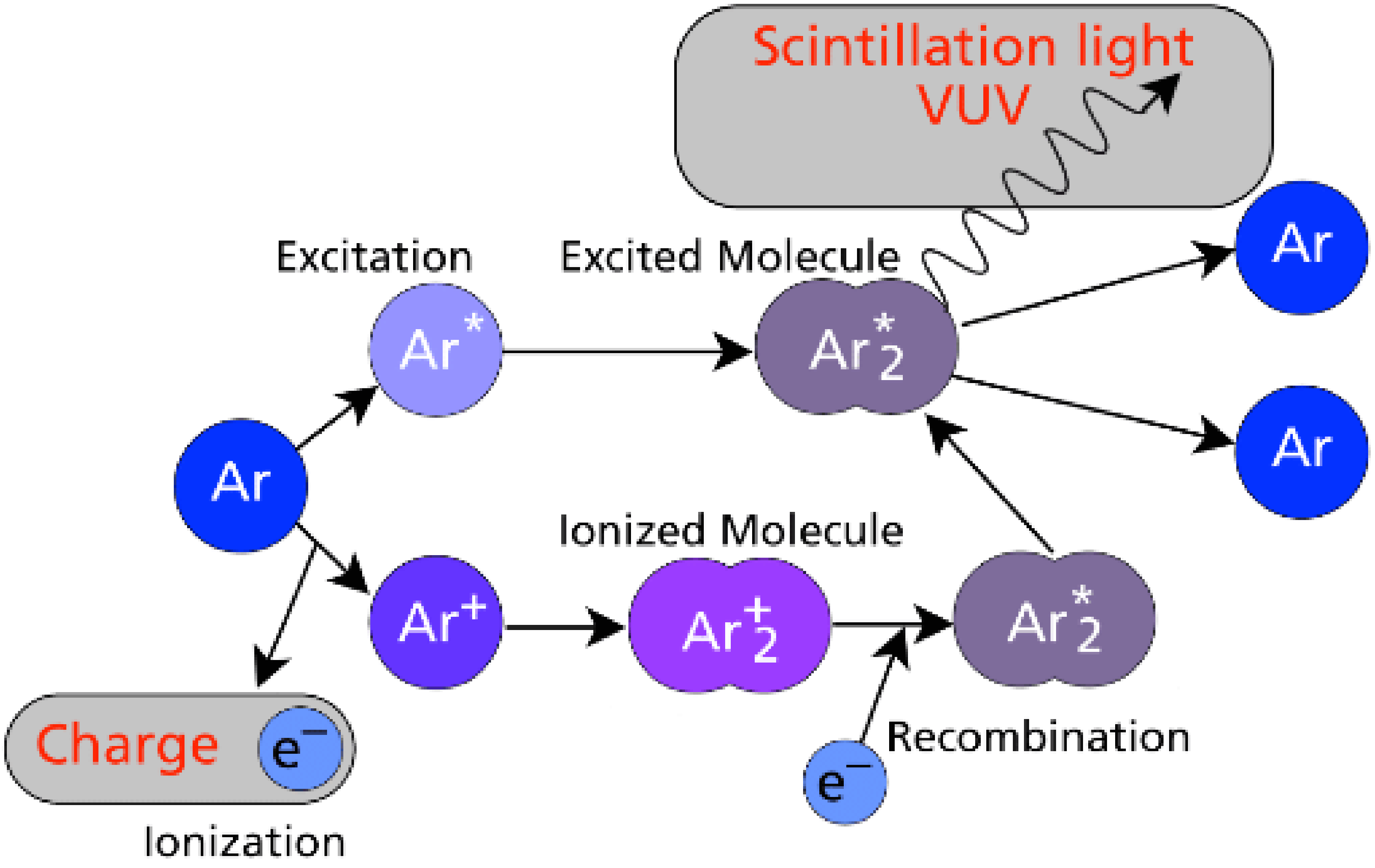
- **Primary ionisation**
  - creation of electrons/ions pairs
- **Movement of electrons and ions**
  - moving in an electric field
- **Multiplication (possibly)**
  - avalanche in the gas
    (if field is strong enough)

- **Charge collection**
  - creation of the signal with a E Field
- **Electronics reading**
  - signal treatment

Part 3 – Particle detection

Scintillation detectors

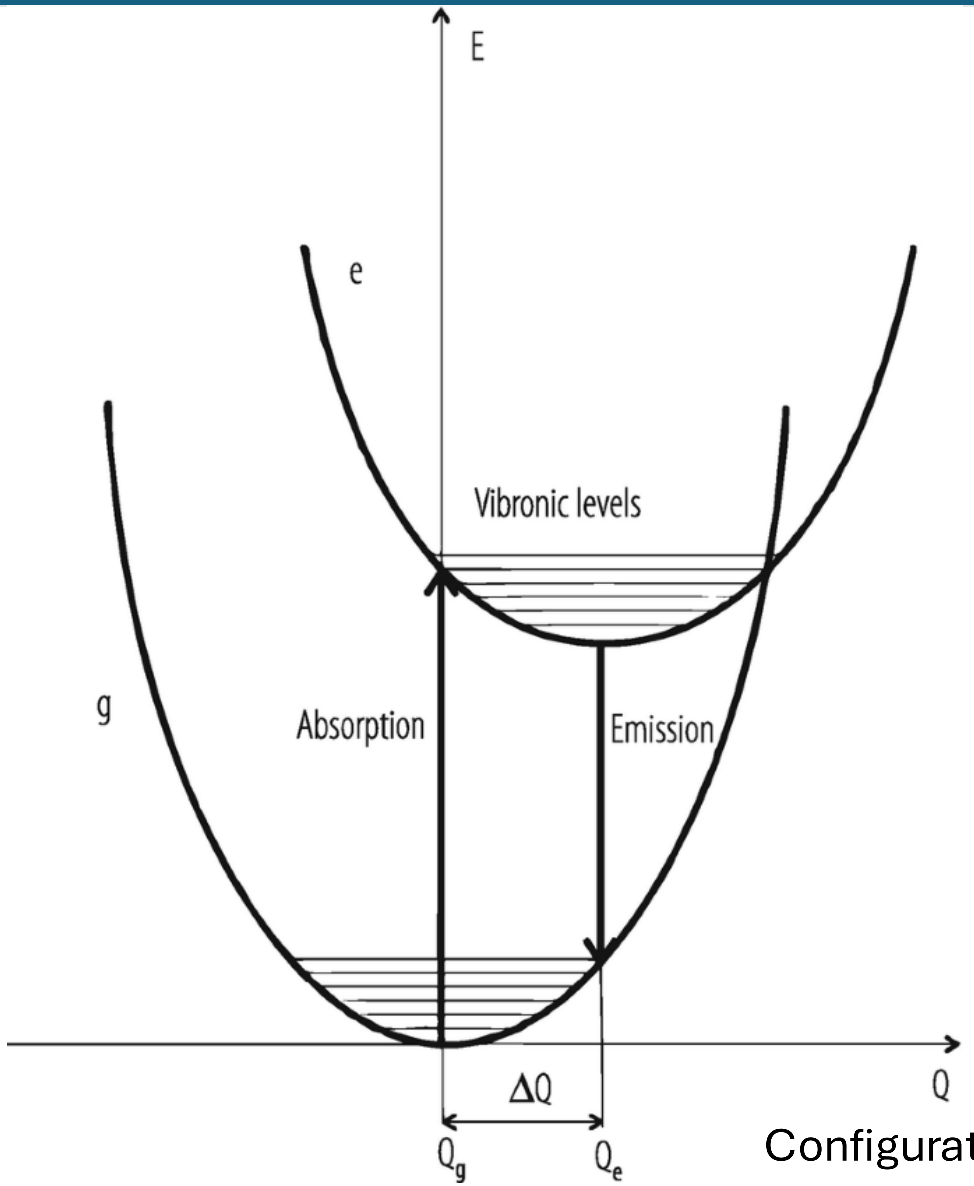
Molecular scale effects : the example of Liquid Argon



This molecular photon emission has a wavelength that is different from the ones between two atomic levels : liquid argon is transparent to it scintillation light

Competition between light emission and ionization

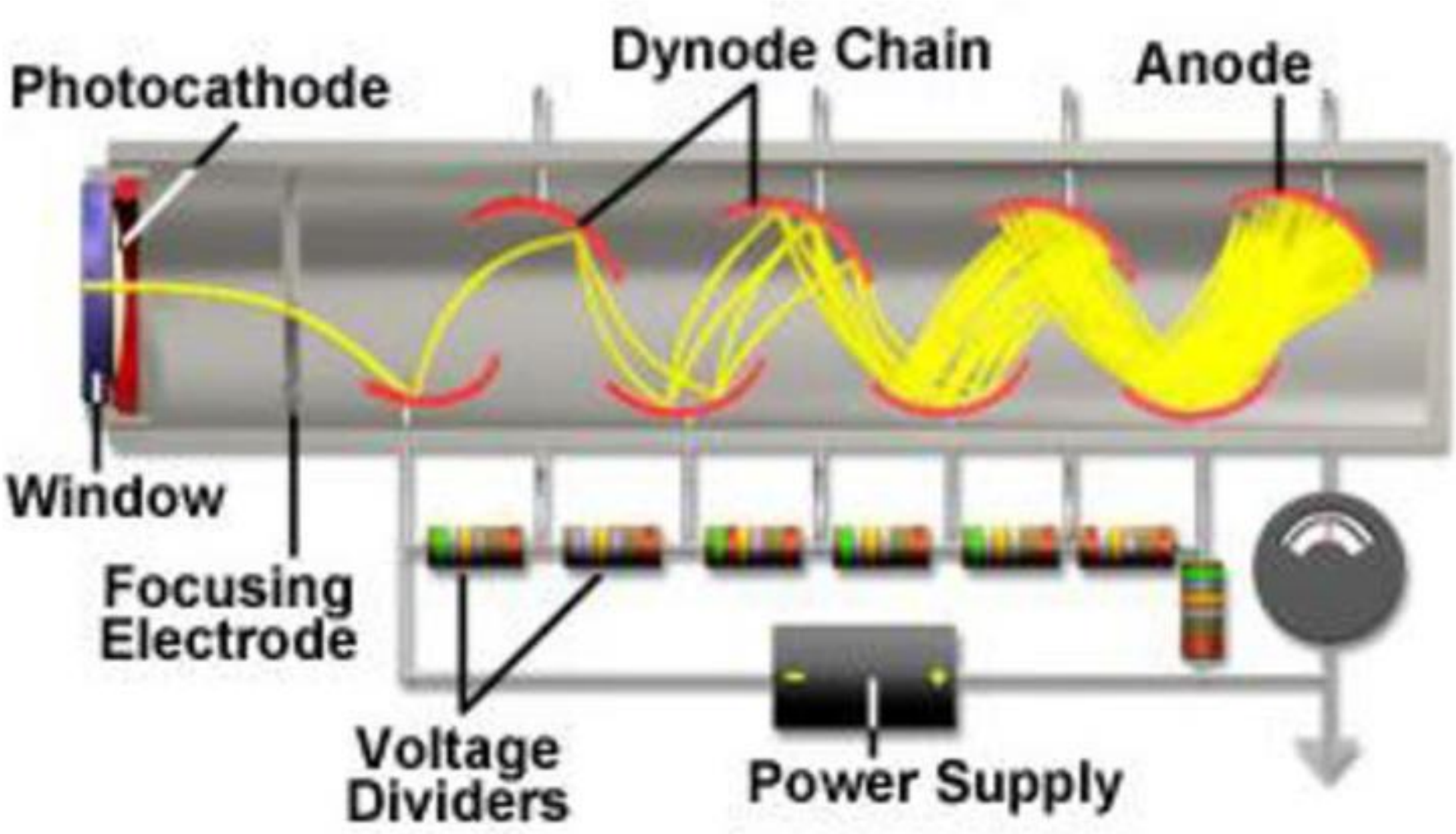
Multi-atomic scale effects : example of scintillation in a cristal



In a crystal, absorption of a photon induces a vibrational state in a different local configuration of two neighbor atoms.

The crystal is transparent to its own emission light !

scintillation light to a charge or a current : the photomultiplier



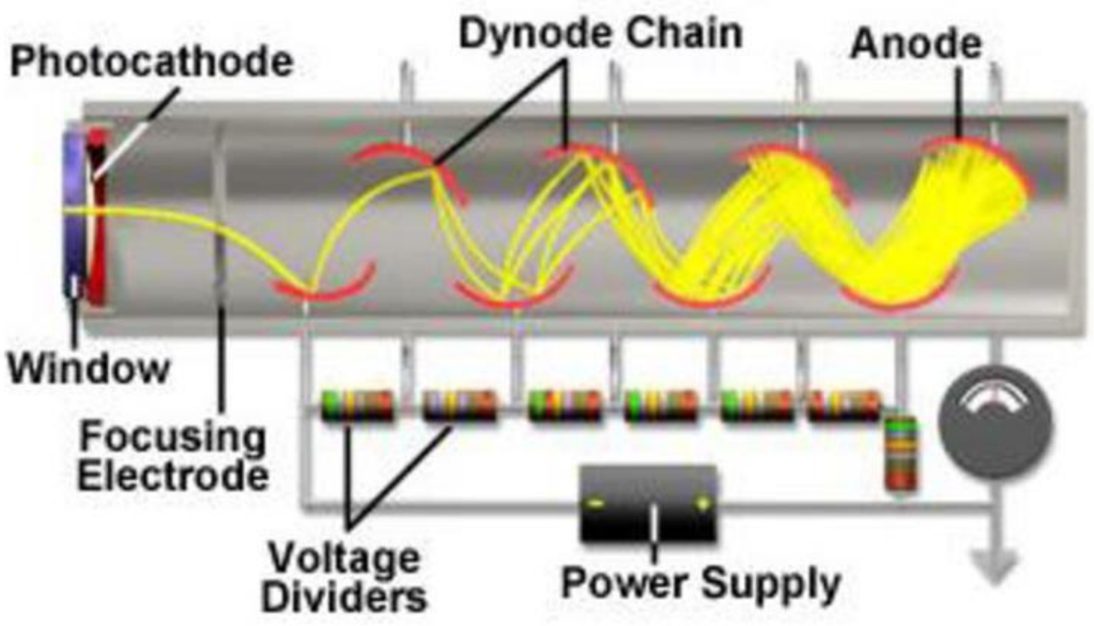
Photoelectric effect in the material of the photocathode provide a charge which is accelerated in the field of the dynodes (avalanche = amplification)

Part 3 – Particle detection

Semiconductor detectors

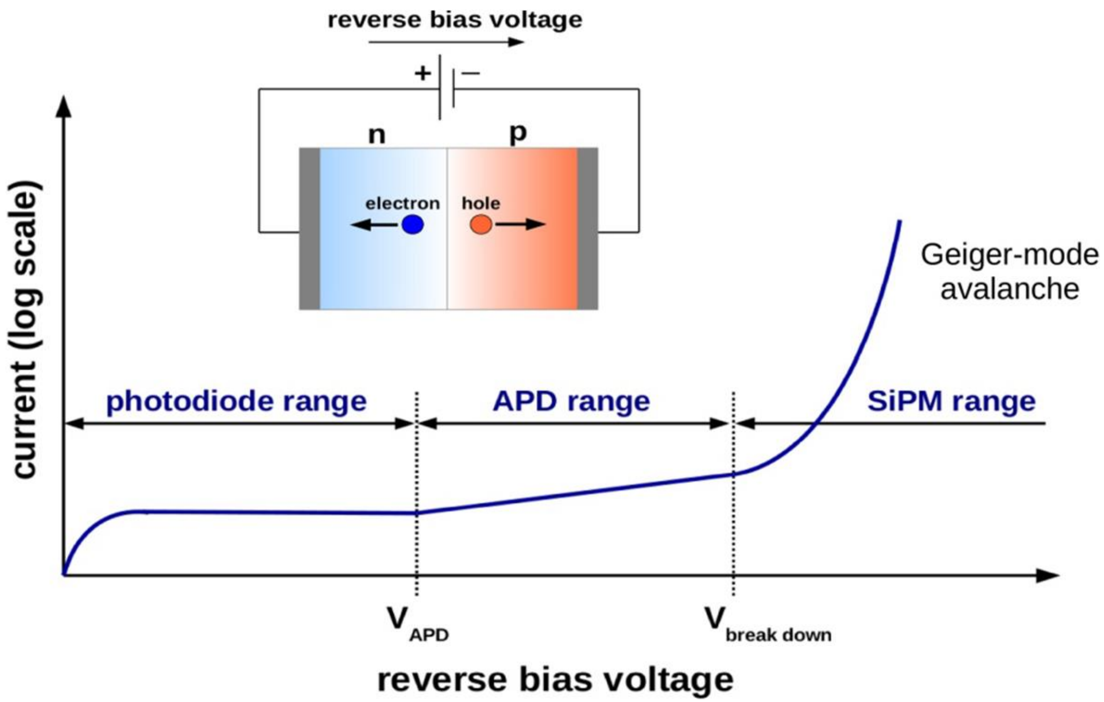
scintillation light to a charge or a current ?

Photomultipliers



Photoelectric effect in the material provide a charge which is accelerated in the field of the dynodes (avalanche = amplification)

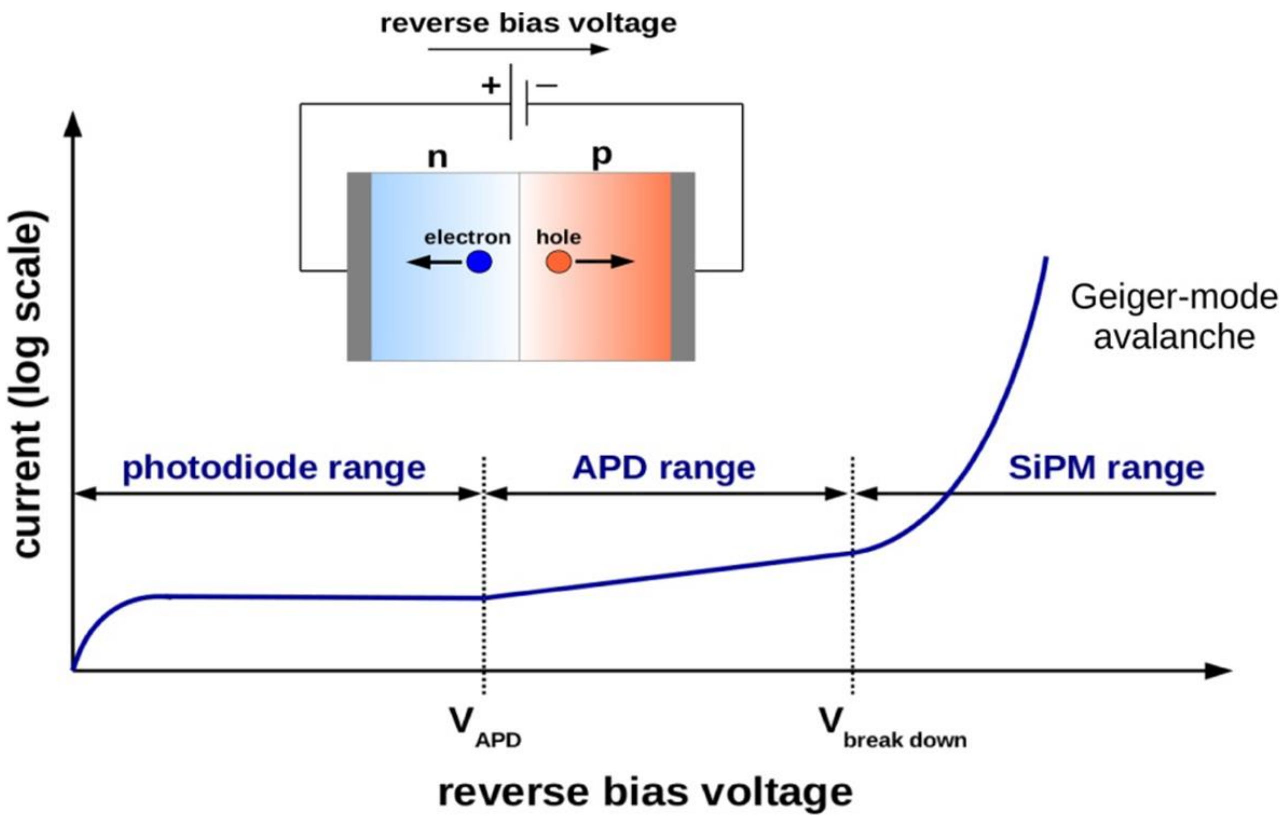
Silicon detectors

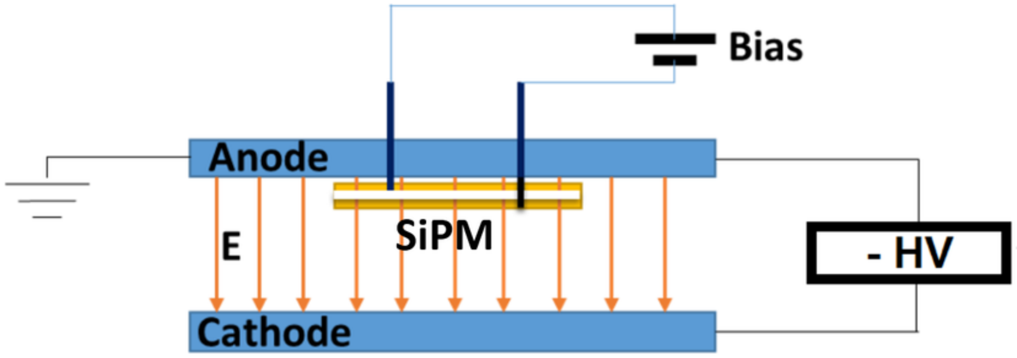


Photoelectric effect in the material provide a charge which is accelerated in the field of the depleted zone (avalanche = amplification)

ionisation to a current ?

Silicon detectors





Ionisation in the material provide an e/hole that migrate in opposite direction.
If the field in the junction is large enough, go to avalanche mode (amplification)

Part 3 – Particle detection

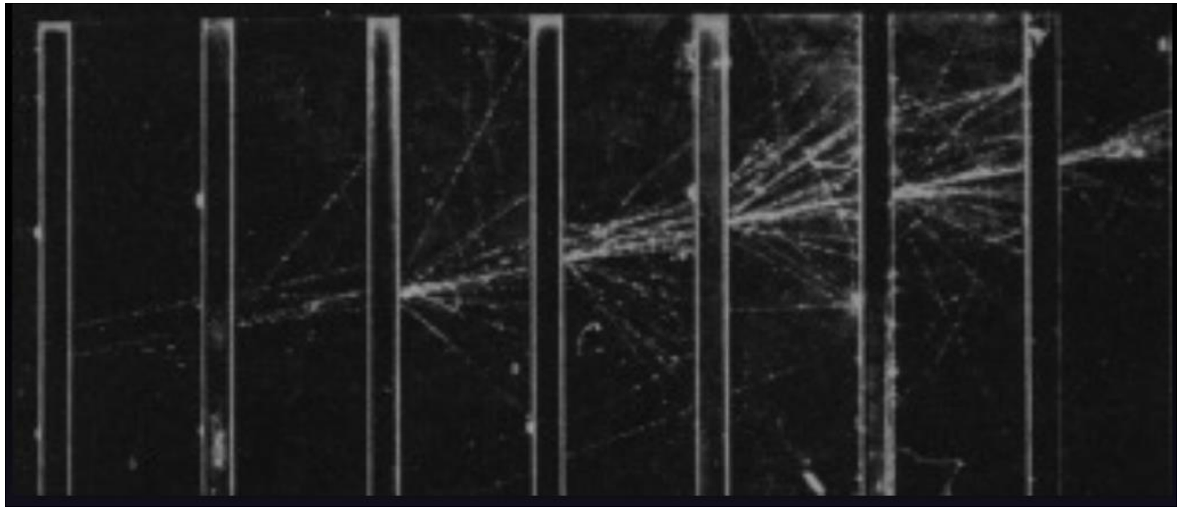
Calorimeters

What is a calorimeter ?

In nuclear and particle physics calorimetry means the detection of particles through their total absorption in a block of instrumented matter

Two types of calorimeters have been proposed :

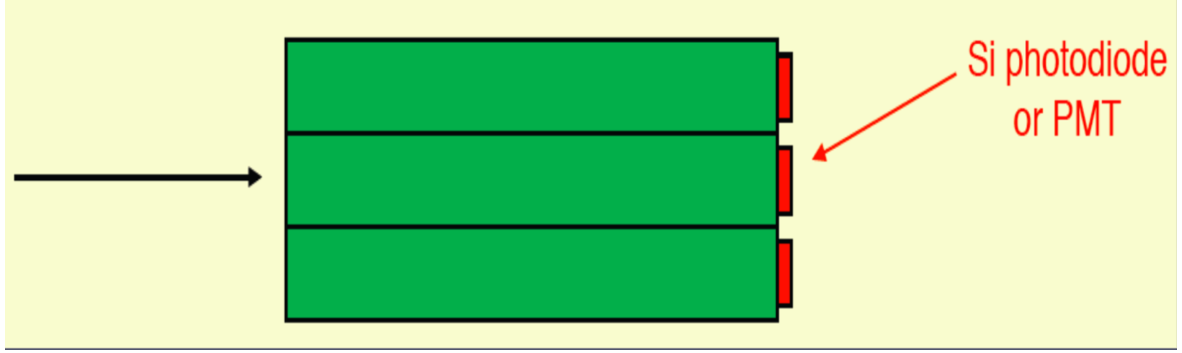
Sampling calorimeters



Absorbers are used to initiate the shower and measurement gaps (Lar, scintillators, …) are used to measure the effect of outcoming particles in the gap : ΔE.

$$E = \sum \Delta E \qquad f_{sampling} = \frac{E_{visible}}{E_{deposited}}$$

Total absorption (homogeneous) calorimeters

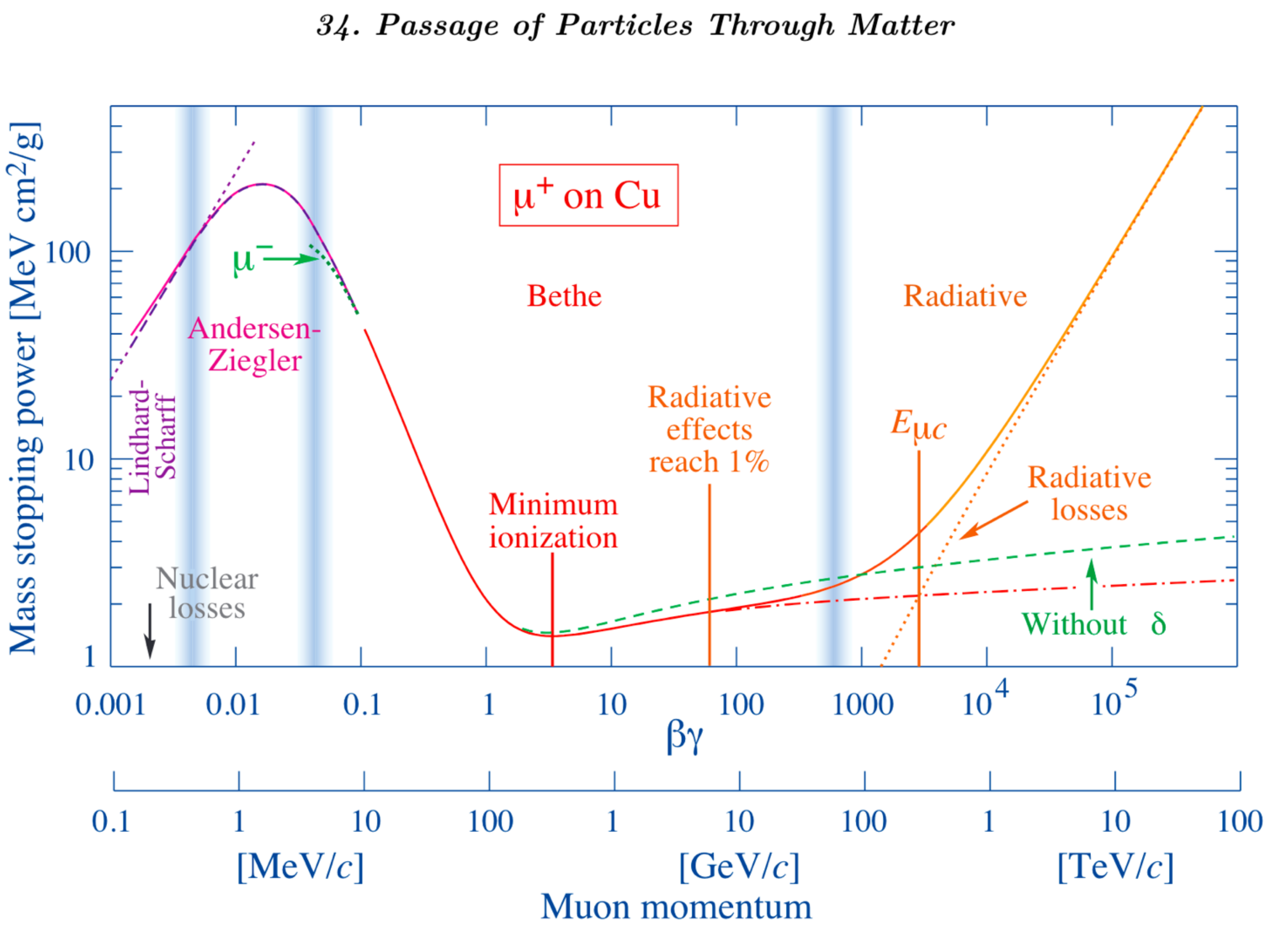


The incoming particles are fully arrested in the calorimeter volumes and produce n = E/W scintillation light (W is the threshold to produce scintillation).

$$\frac{\sigma_E}{E} = \frac{1}{\sqrt{n}} = \frac{1}{\sqrt{E/W}}$$

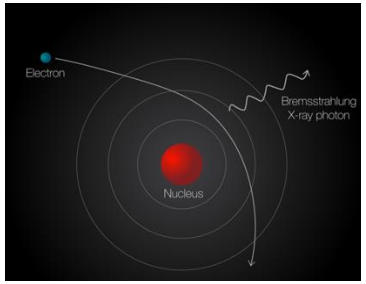
Interactions of particles through matter

Charged particle interaction as a function of its Energy

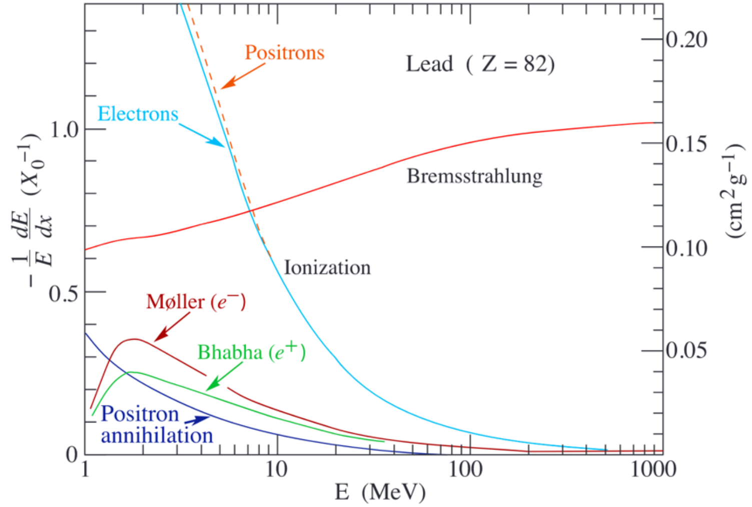


The critical energy that triggers the radiative process (Bremsstrahlung) depends on the mass of the charged particle. For an electron it is about:

$$dE \sim \frac{2Z^2e^6}{3b^3m_e^2c^4}\gamma^2$$

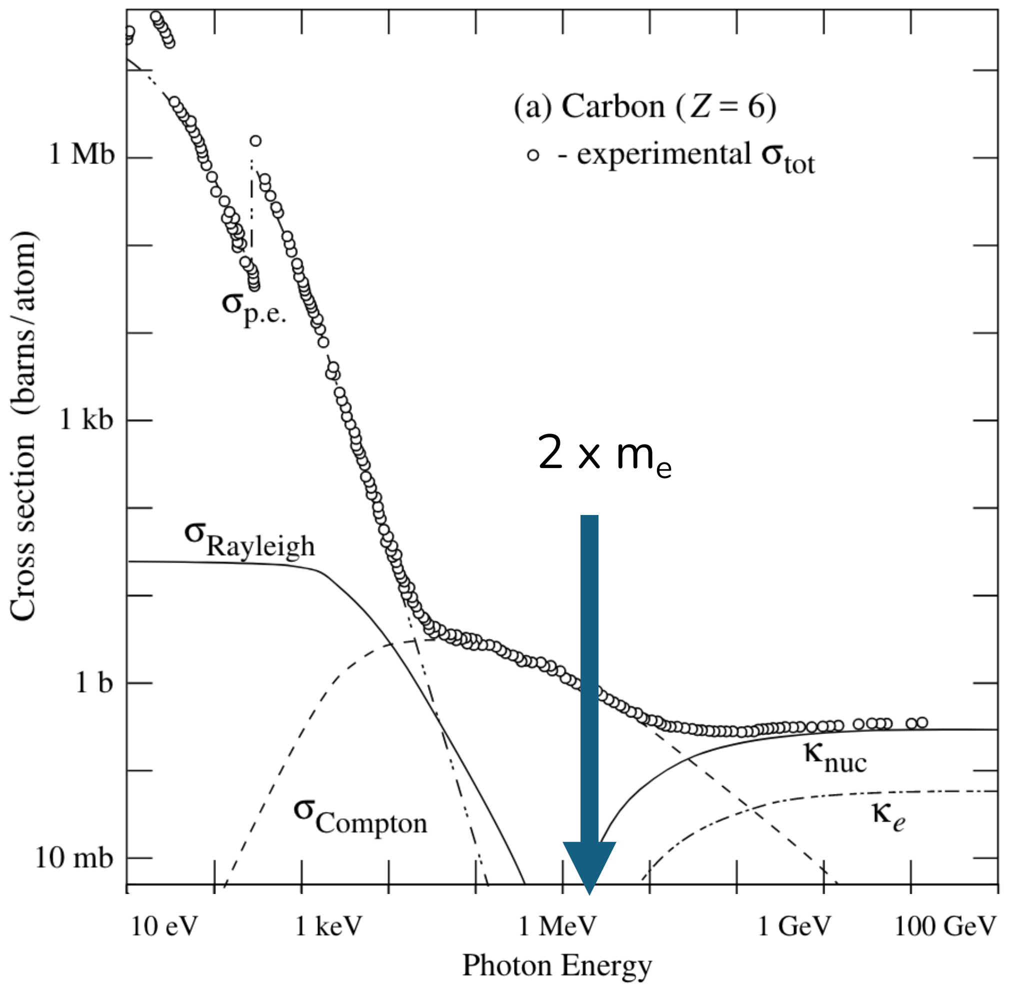


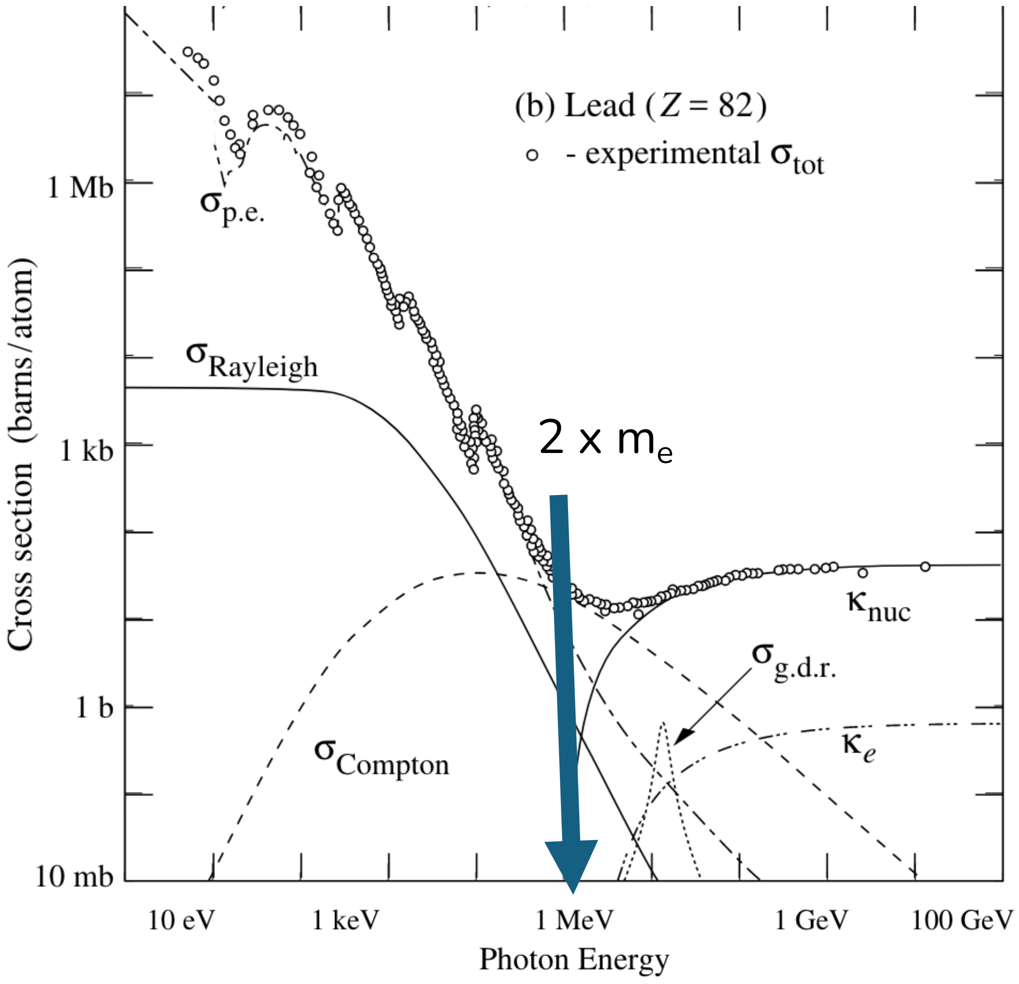
So that light particles can have their energy loss dominated by radiation : few MeV electron do EM showers



Interactions of particles through matter

Photon interaction as a function of its Energy



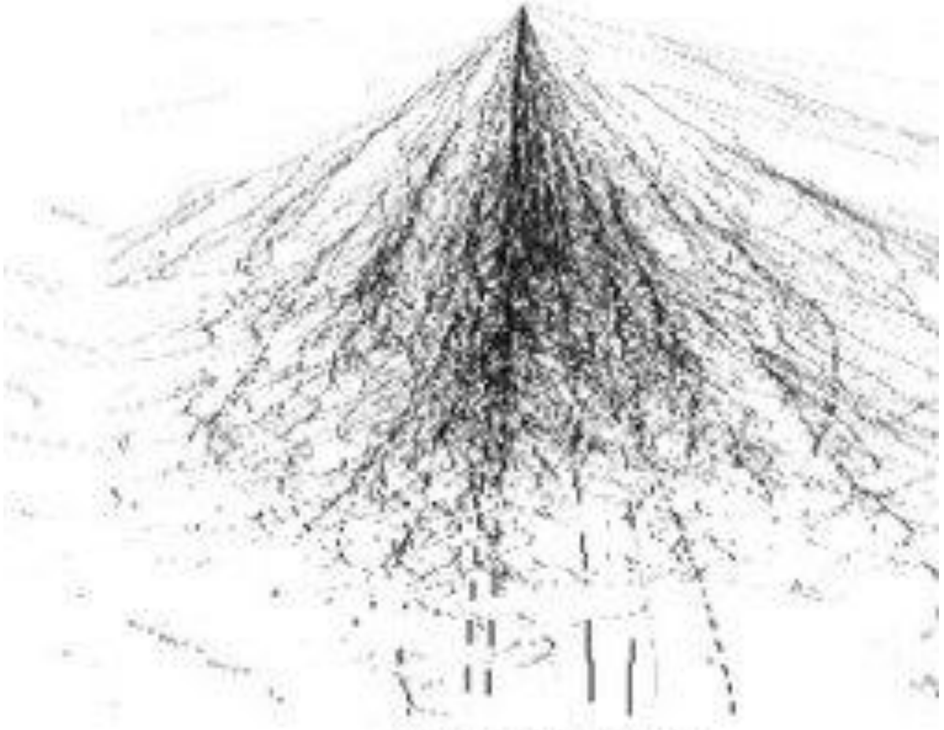


High energy photon interaction is dominated by electron-positron pair creation and is higher at high Z

Calorimetric showers require two types of calorimeters

At high energy, photon and electron are mainly governed by bremsstrahlung and pair conversion while hadronic showers correspond mostly to interaction with the nuclei and the subsequent decay of the unstable hadrons produced.

Gamma shower



Hadronic shower

$$X_0 \sim \frac{A}{Z^2}$$

$$\lambda_{\text{int}} \sim A^{1/3}$$

$$\rightarrow \frac{\lambda_{\text{int}}}{X_0} \sim A^{4/3}$$

$$\lambda_{\text{int}} \gg X_0$$

2 different calorimeters are required for EM and HAD showers.

EM showers of electrons and photons

Shower development depends on the material and can be characterised by the attenuation factor X_0

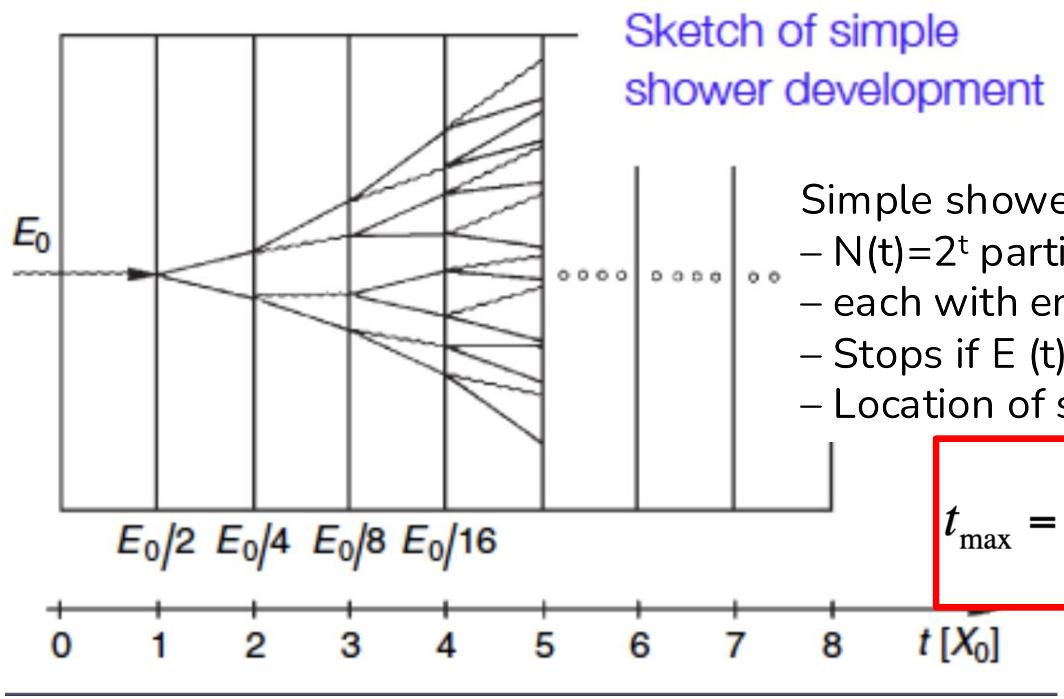
$$X_0\ (\mathrm{g/cm^2}) \simeq \frac{716\ \mathrm{g\ cm^{-2}}\, A}{Z(Z+1)\ \ln(287/\sqrt{Z})}$$

Electrons :

$$\langle E(x)\rangle = E_0\, e^{-\frac{x}{X_0}}$$

Photons :

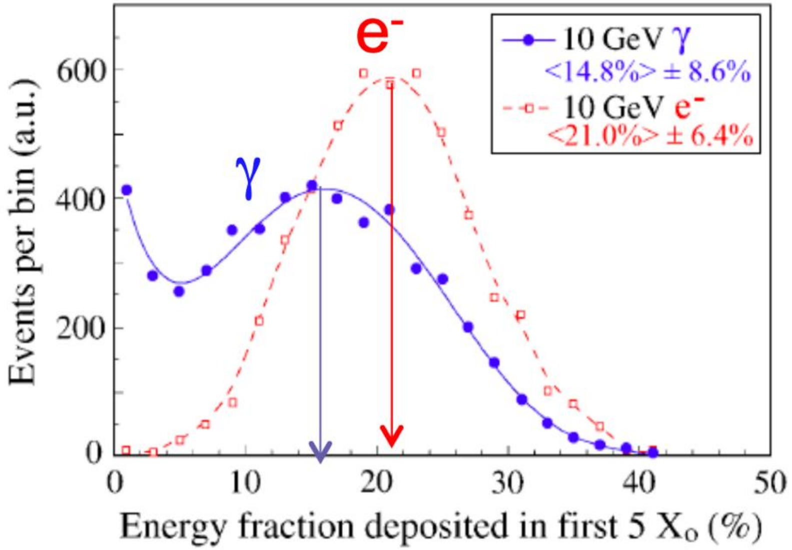
$$\langle I(x)\rangle = I_0\, e^{-\frac{7}{9}\frac{x}{X_0}}$$



Simple shower model:

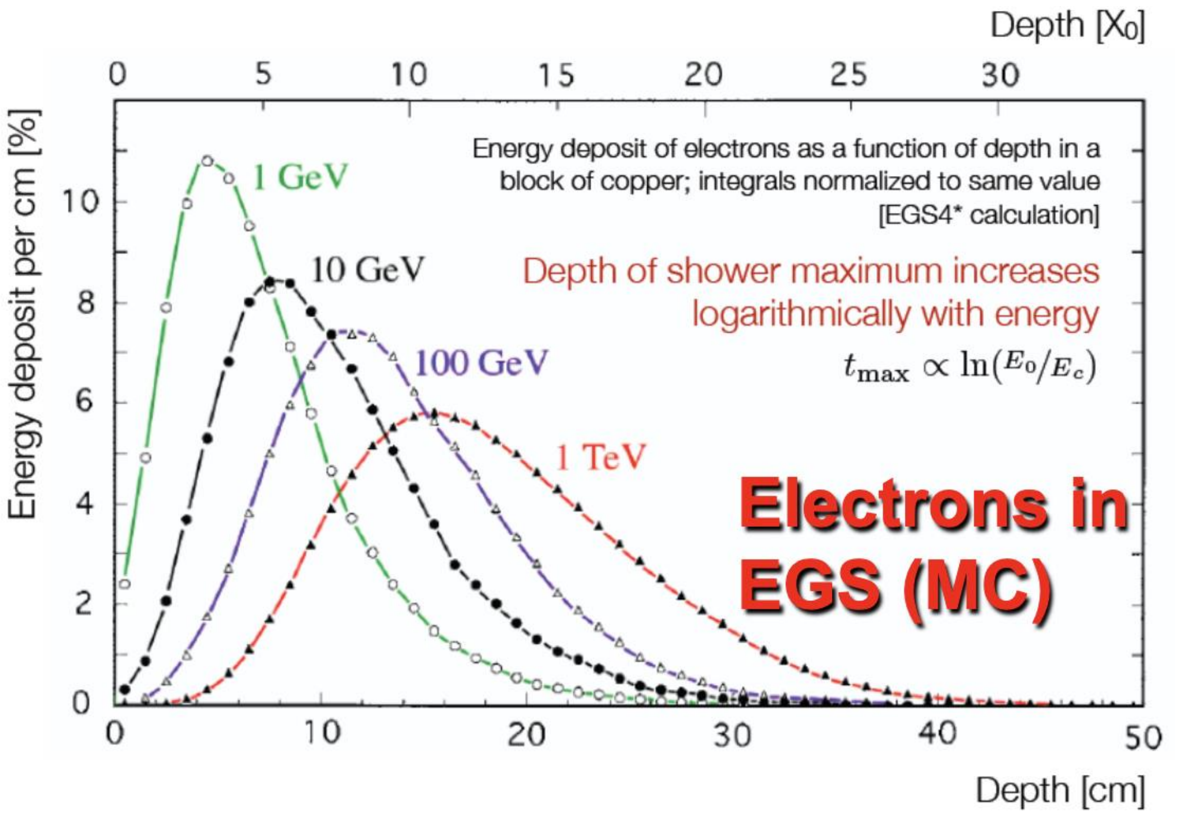
– $N(t)=2^t$ particles after $t = x/X_0$
– each with energy $E(t)=E0/2^t$
– Stops if E (t) < Ec=E02tmax
– Location of shower maximum at

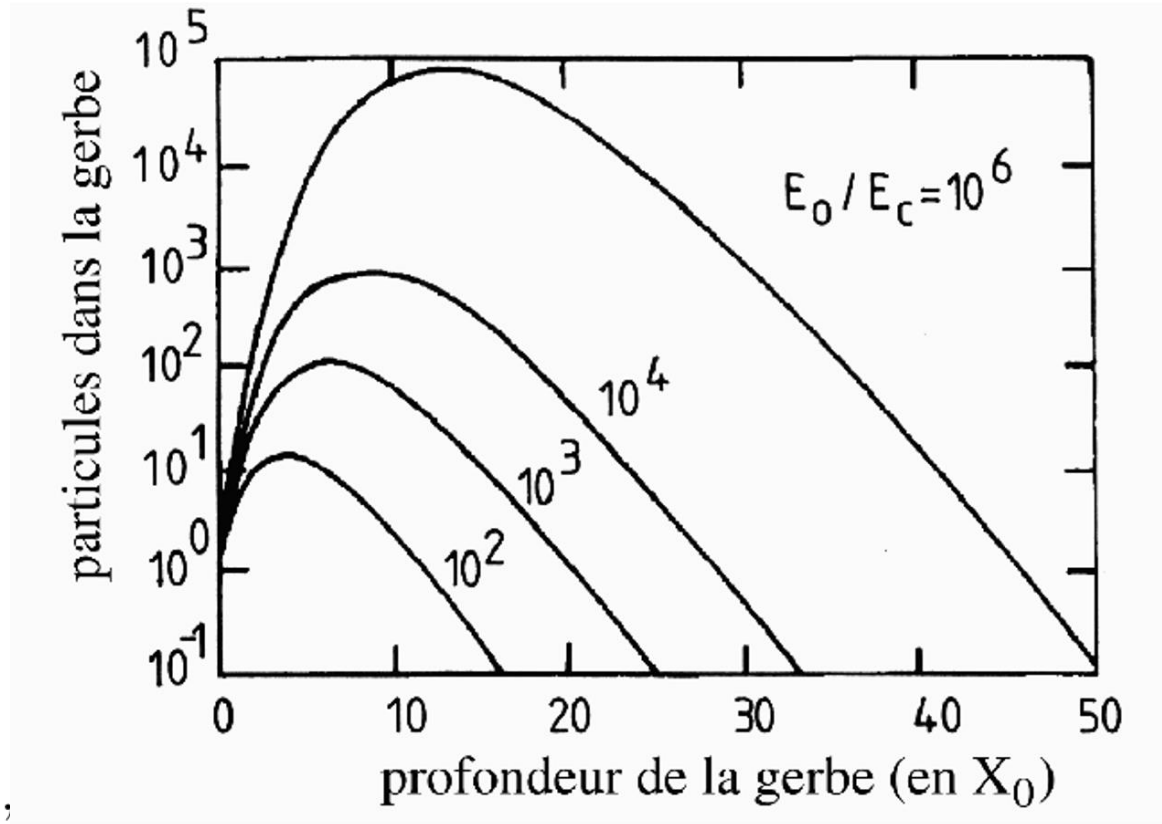
$$t_{\max} = \frac{\ln(E/Ec)}{\ln 2} \propto \ln\left(\frac{E}{E_c}\right)$$



Mean free path of a γ is $9/7\ X_0$

EM showers longitudinal development





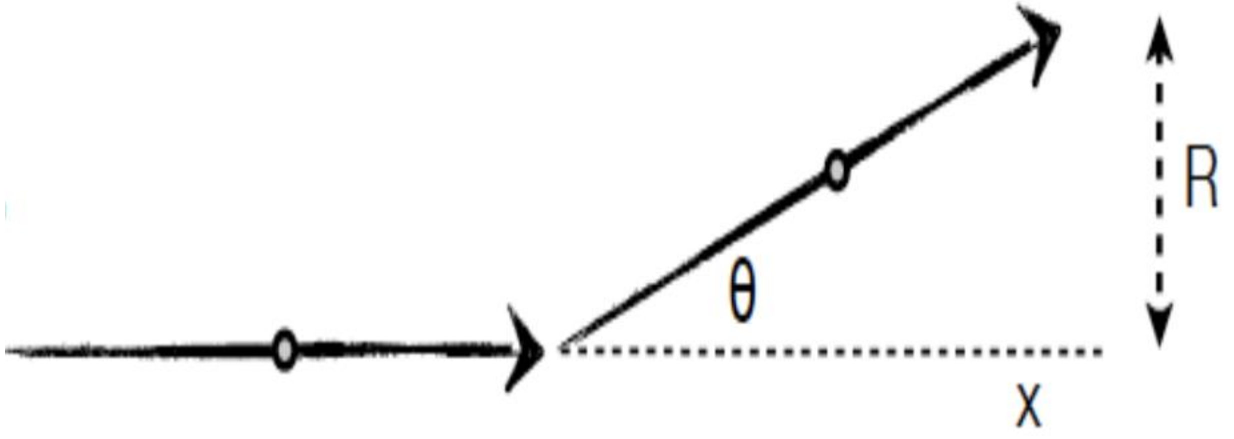
$$t_{\max} = (a-1)/b = 1.0 \times (\ln y + C_j), \qquad j = e, \gamma,$$

$$\frac{dE}{dt} = E_0\, b\, \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)} \qquad t = x/X_0, \qquad y = E/E_c;$$

EM showers lateral development

Opening angle:
– bremsstrahlung and pair production:

$$\langle \theta^2 \rangle \approx \left(\frac{m_e c^2}{E_e} \right)^2 = \frac{1}{\gamma^2}$$



Lateral extension: $R = x \cdot \tan\theta \approx x \cdot \theta$, if θ small ...

- multiple coulomb scattering [Molière theory]

$$\langle \theta \rangle = \frac{E_s}{E_e} \sqrt{\frac{x}{X_0}} \quad \text{where} \quad E_s = \sqrt{\frac{4\pi}{\alpha}} \left(m_e c^2 \right) = 21.2 MeV$$

Main contribution from low energy electrons as $\langle\theta\rangle \sim 1/E_e$, i.e. for electrons with E < Ec

EM shower lateral development

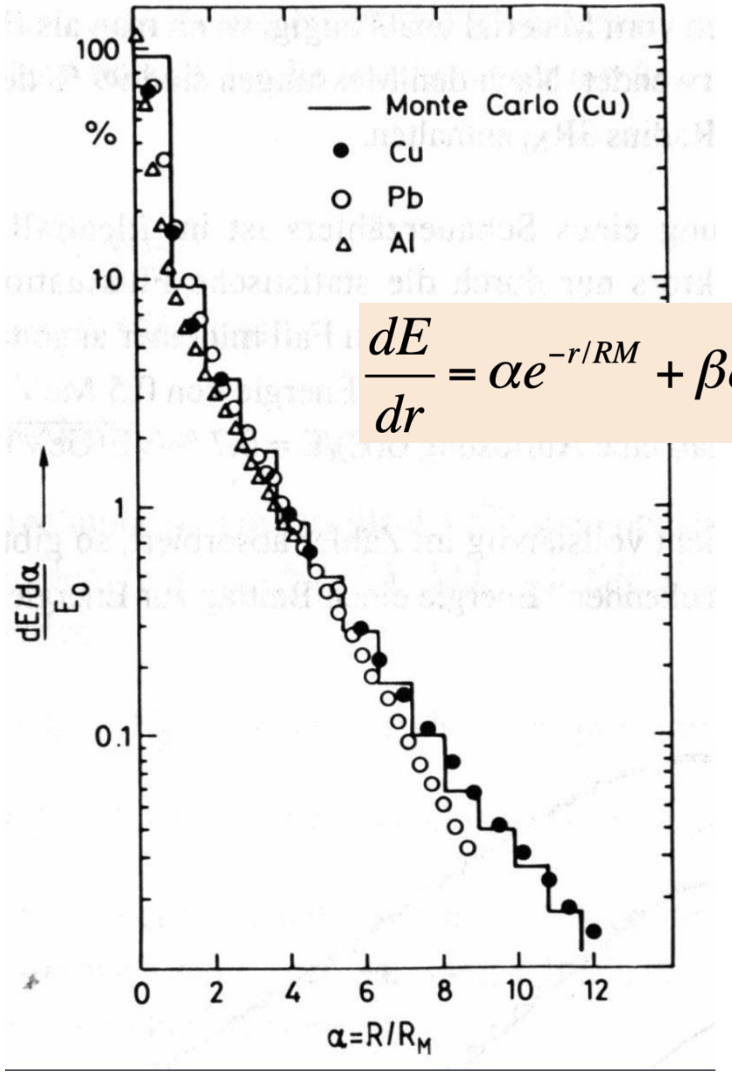
- Inner part is due to Coulomb's scattering of electron and positron
- Outer part is due to low energy γ produced in Compton's scattering, photo-electric effect etc.

– Predominant part after shower max especially in high Z absorbers

- The shower gets wider at larger depth
- An infinite cylinder of radius 2RM contains 95% of the shower

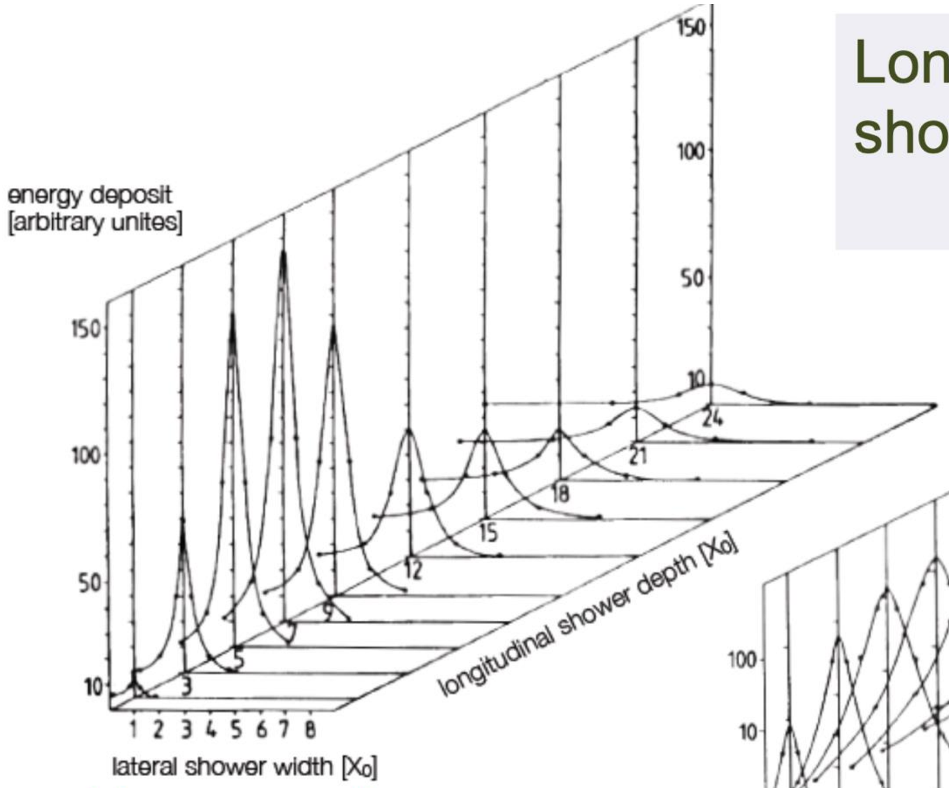
Molière Radius

$$R_M = \frac{E_s}{E_c} X_0 \approx \frac{21.2 MeV}{E_c} X_0$$

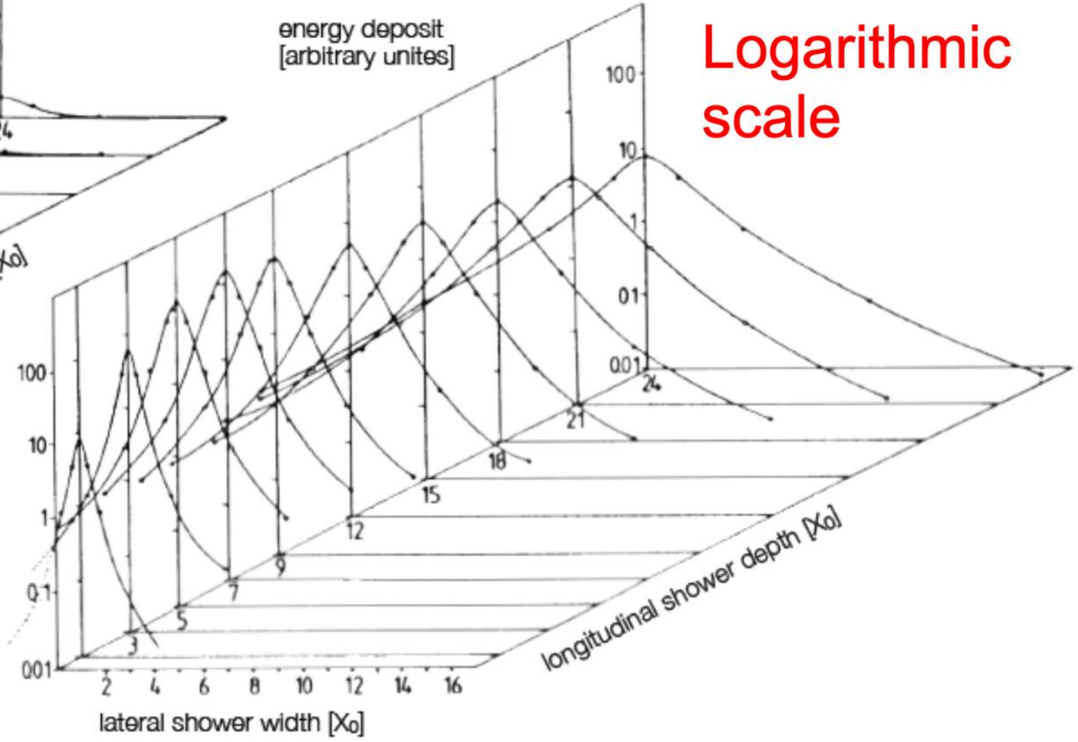


$$\frac{dE}{dr} = \alpha e^{-r/RM} + \beta e^{-r/\lambda_{\min}}$$

3D EM shower development



Longitudinal and transfer EM shower profile of 6 GeV e^- in Lead



Hadronic showers

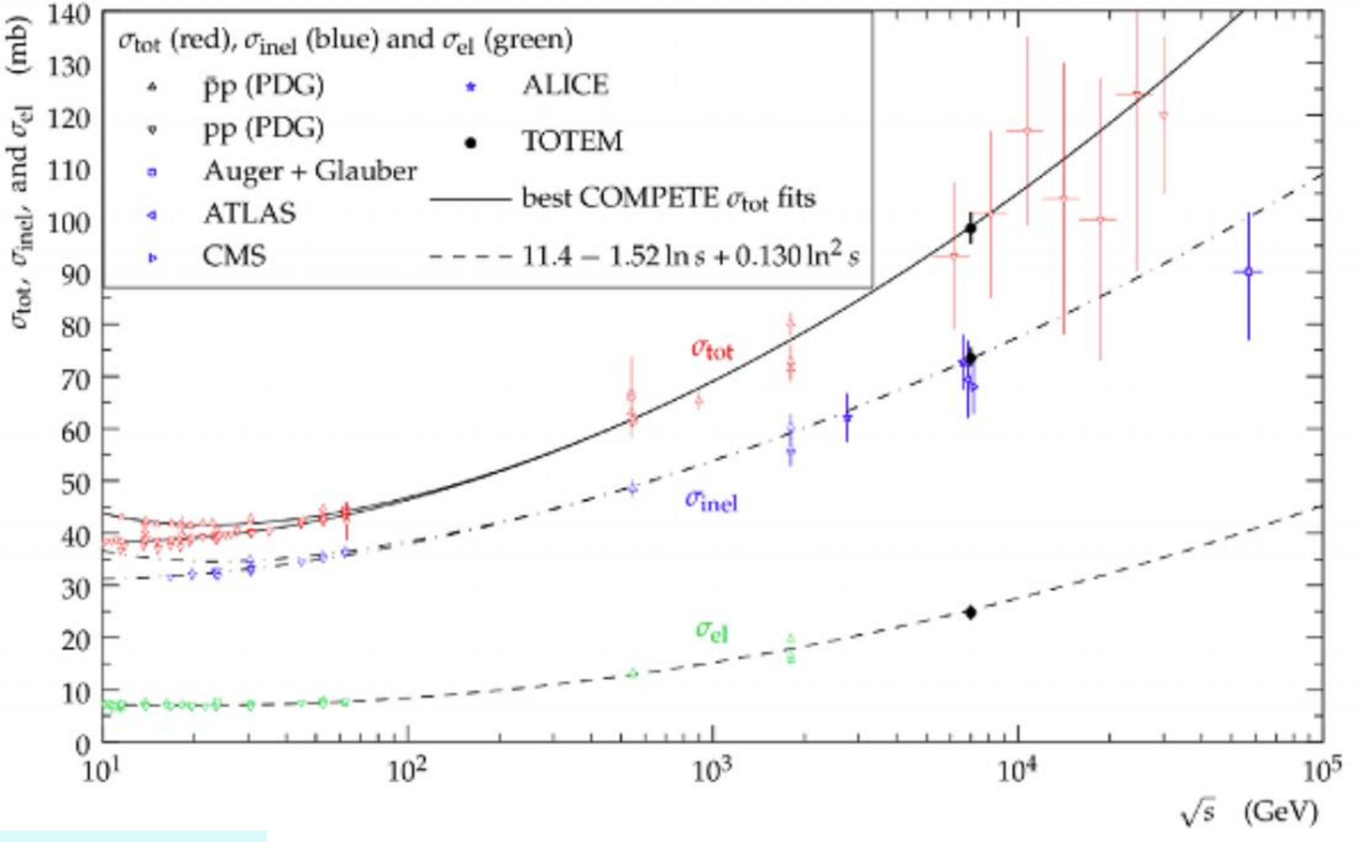
Hadronic interaction Cross section

$$\sigma_{Tot} = \sigma_{el} + \sigma_{inel}$$

$$\sigma_{el} \approx 10mb \qquad \sigma_{inel} \approx A^{2/3}$$

$$\sigma_{Tot} = \sigma_{tot}(pp)A^{2/3}$$

where: $\sigma_{tot}(pp)$ increases with $\sqrt{s}$



Hadronic interaction length

$$\lambda_{\text{int}} = \frac{1}{\sigma_{tot} \cdot n} = \frac{A\rho}{\sigma_{pp} A^{2/3} N_A} \approx \left(35g/cm^2\right) A^{1/3}$$

$$N(x) = N(0)\mathrm{e}^{-x/\lambda_{\text{int}}}$$

Hadronic showers and non-compensation

Hadronic showers produce neutral hadrons decaying to photons (h, π_0, …) so it is an heterogeneous shower with a fraction f_{em} collected from EM objects

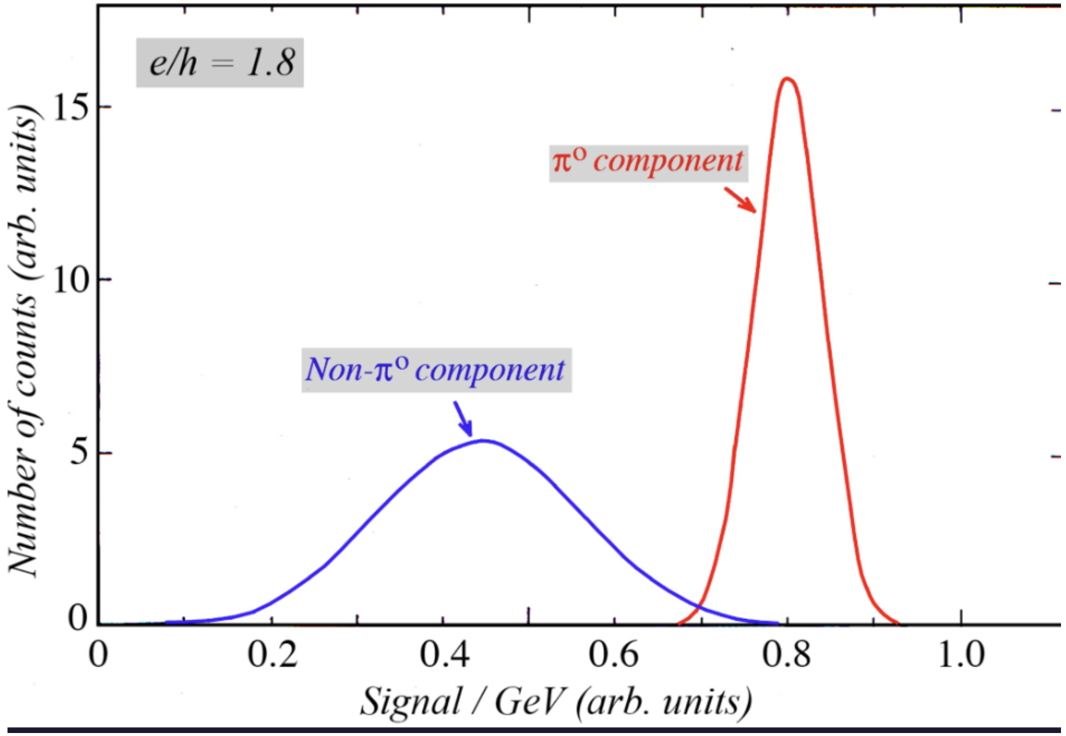
$$\pi = f_{em}\, e + (1-f_{em})\, h$$

Comparing pion and electron showers:

$$\frac{e}{\pi} = \frac{e}{f_{em}\, e + (1-f_{em})\, h} = \frac{e}{h} \cdot \frac{1}{1 + f_{em}(e/h-1)}$$

Calorimeters can be:

- Overcompensating $e/h < 1$
- Undercompensating $e/h > 1$
- Compensating $e/h = 1$



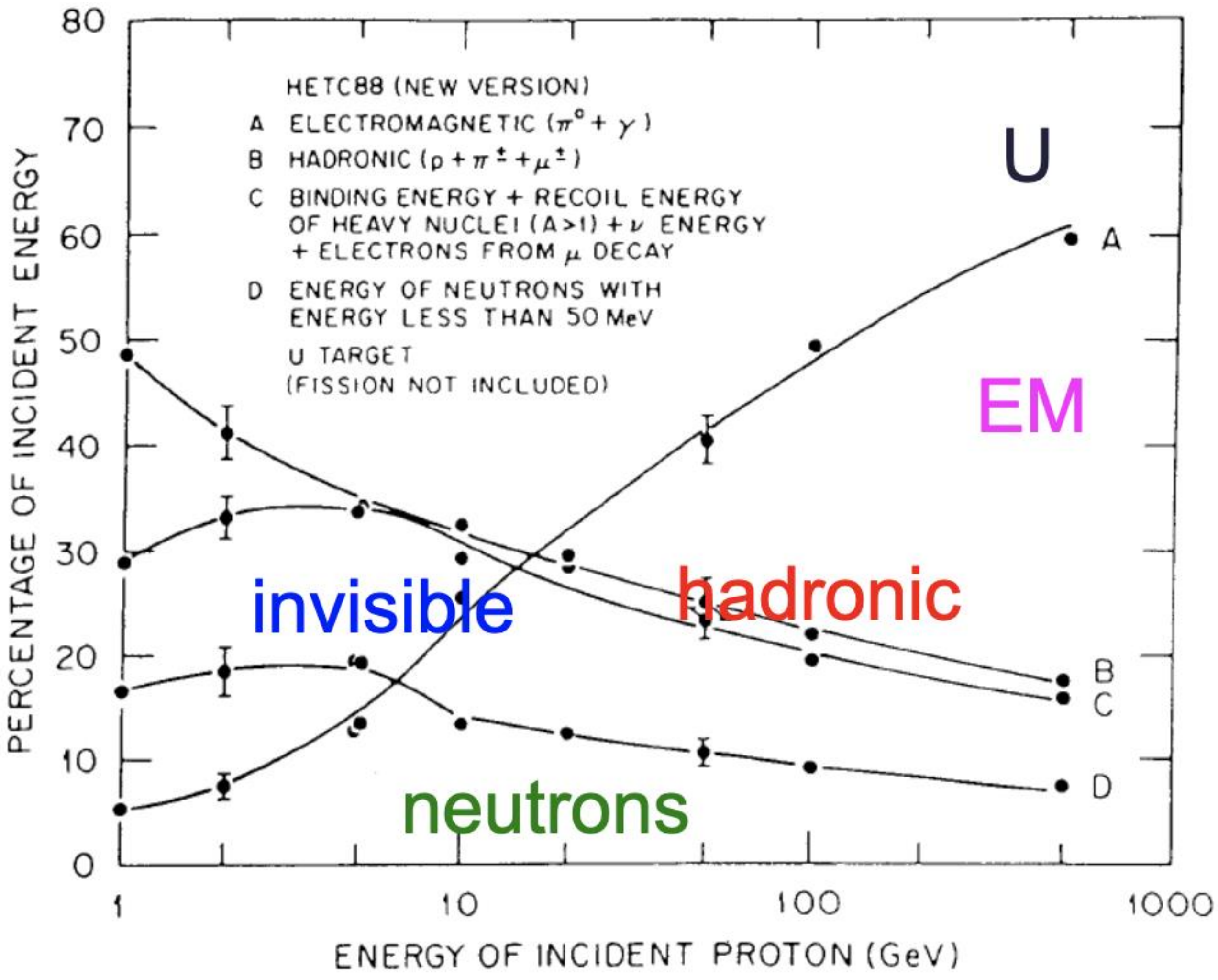
But hadronic component is heterogenous (e.g. neutron) which also introduce fluctuations

Hadronic showers and non-compensation

$$E_p = f_{em} e + (1 - f_{em}) h$$

$$h = f_{rel} \cdot rel + f_p \cdot p + f_n \cdot n + f_{inv} \cdot inv$$

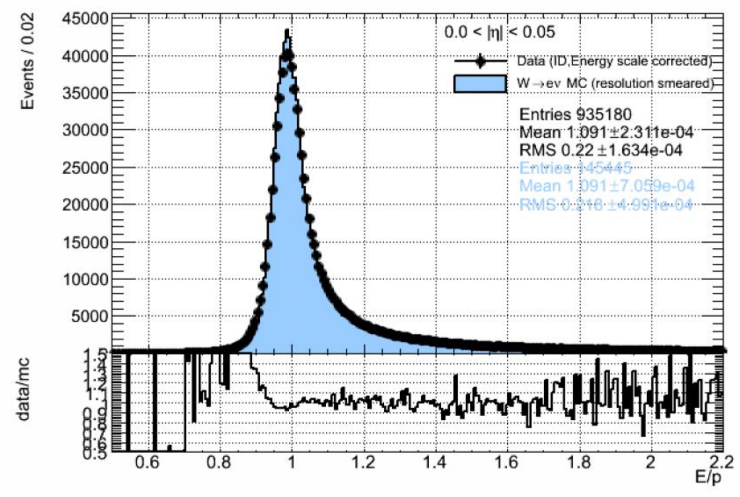
Compensation:
– Tuning the neutron response using hydrogenous active material (L3 Uranium/gas calorimeter)
– Compensation adjusting the sampling frequency

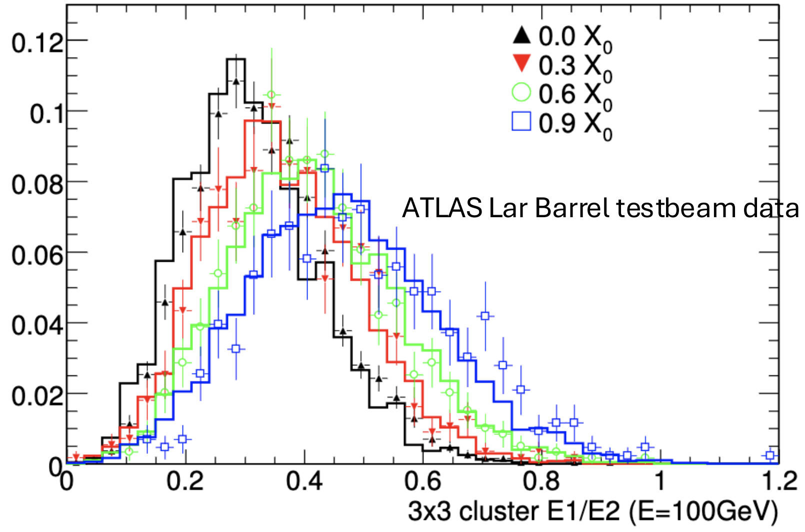


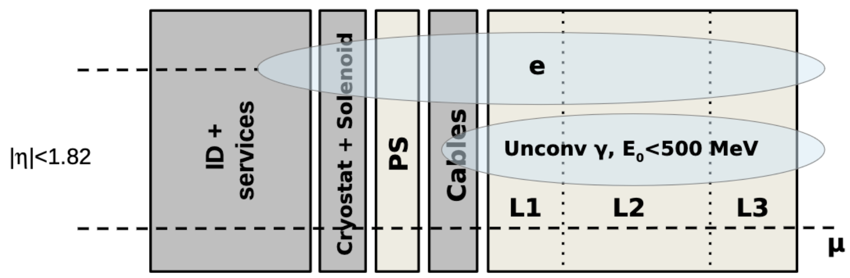
Impact of stochastic nature of the shower

Calbration:
– with a single cell to detect a whole shower, you have no other choice than affecting the most probable value of the measured distribution when you detect the same particle with the same energy at the same place

Resolution suffers from the stochastic nature of the shower : for instance the number of charges produced in the shower, the possible high energy photons that escaped the cell but also some parasitic effects (electronic noise, pileup and residual local non homogeneities in the construction of the detector)





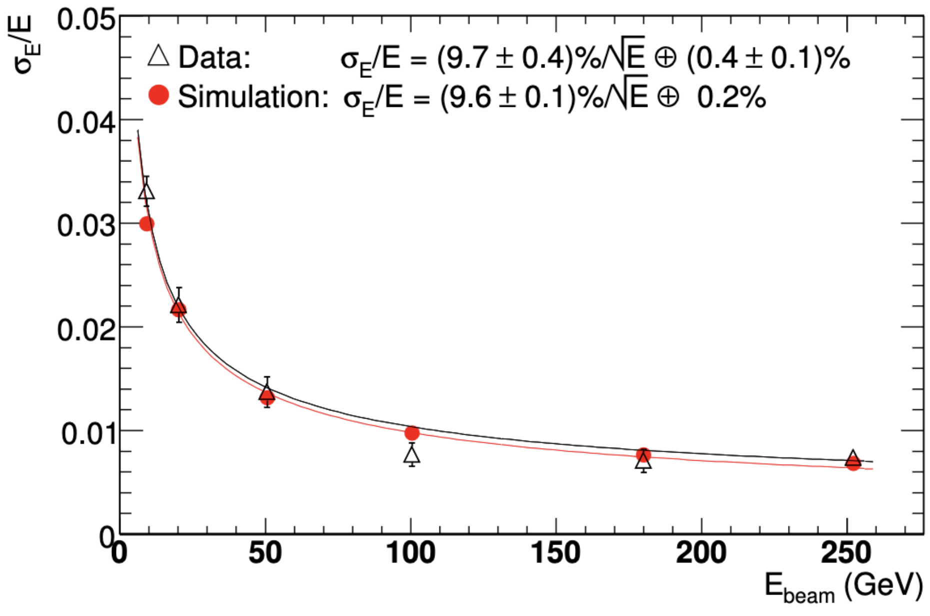


XIII International Conference on Calorimetry in High Energy Physics (CALOR 2008)

Impact of stochastic nature of the shower

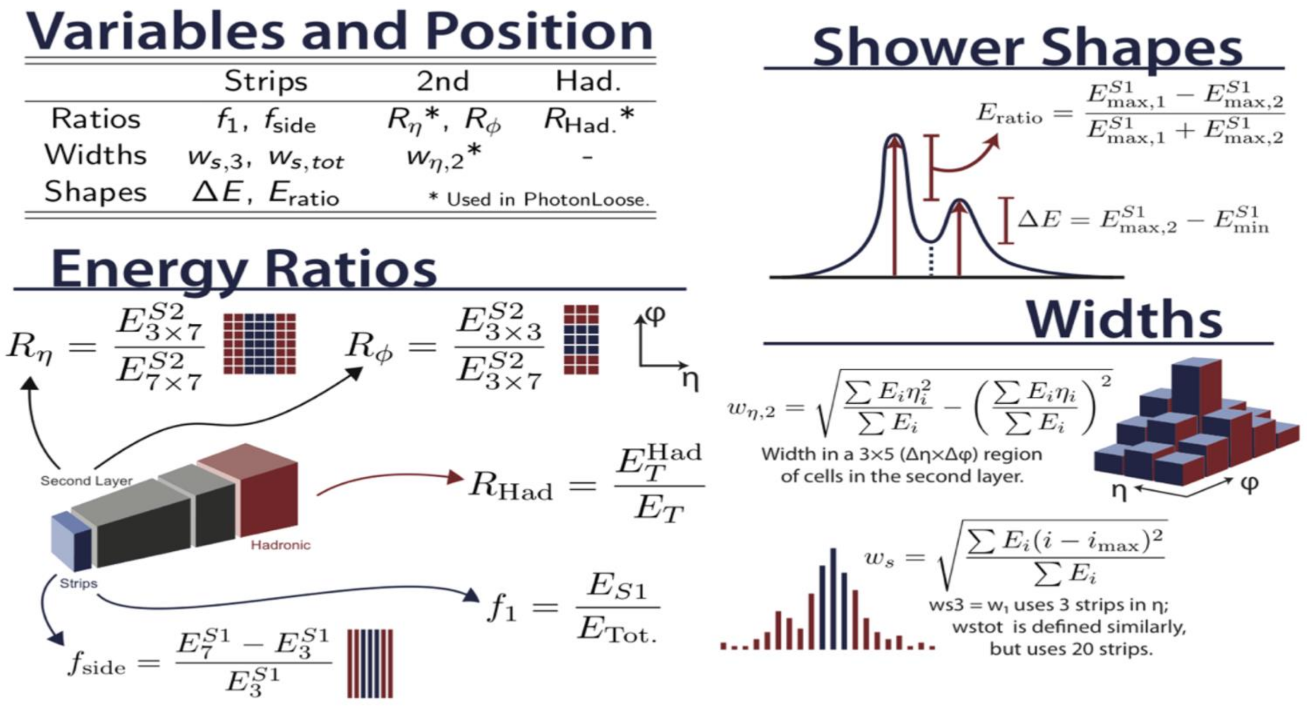
Calbration:
– with a granular calorimeter, you measure the shower development (the stochasiticity) which gives handle to correct further the energy beyond the most probable value

- You can use shower shape variables with ML to improve resolution



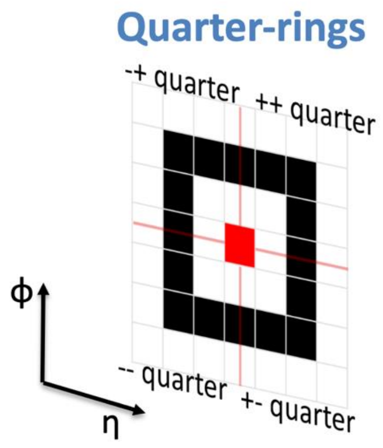
ATLAS Lar Barrel testbeam data

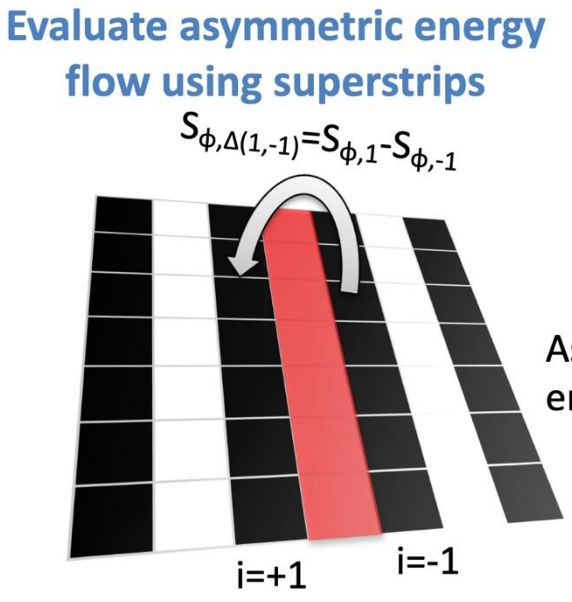
XIII International Conference on Calorimetry in High Energy Physics (CALOR 2008)

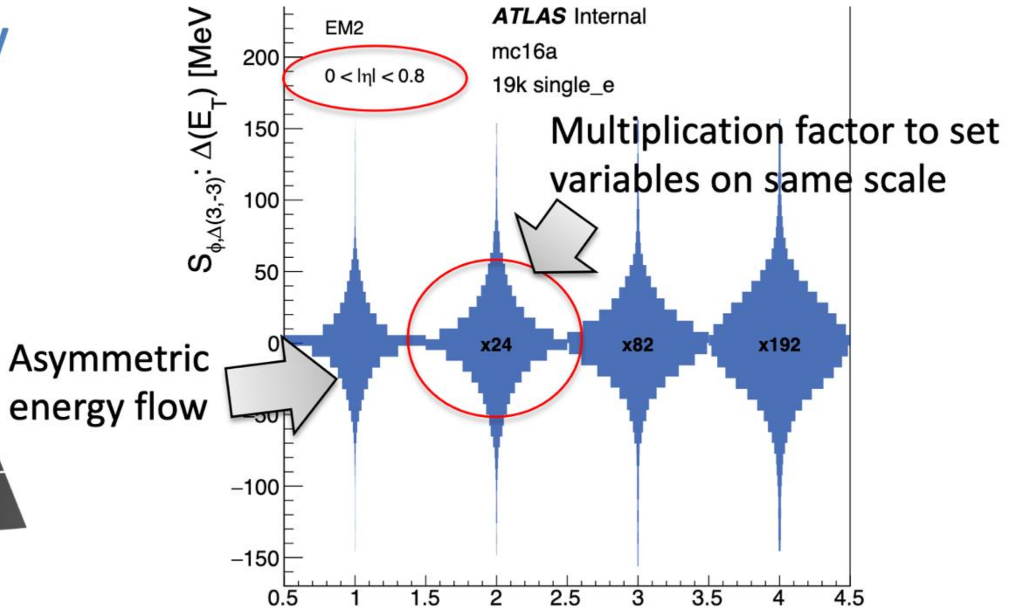


Impact of stochastic nature of the shower

Calbration:
– a step further : using shower asymetries measurements







Part 3 – Particle detection

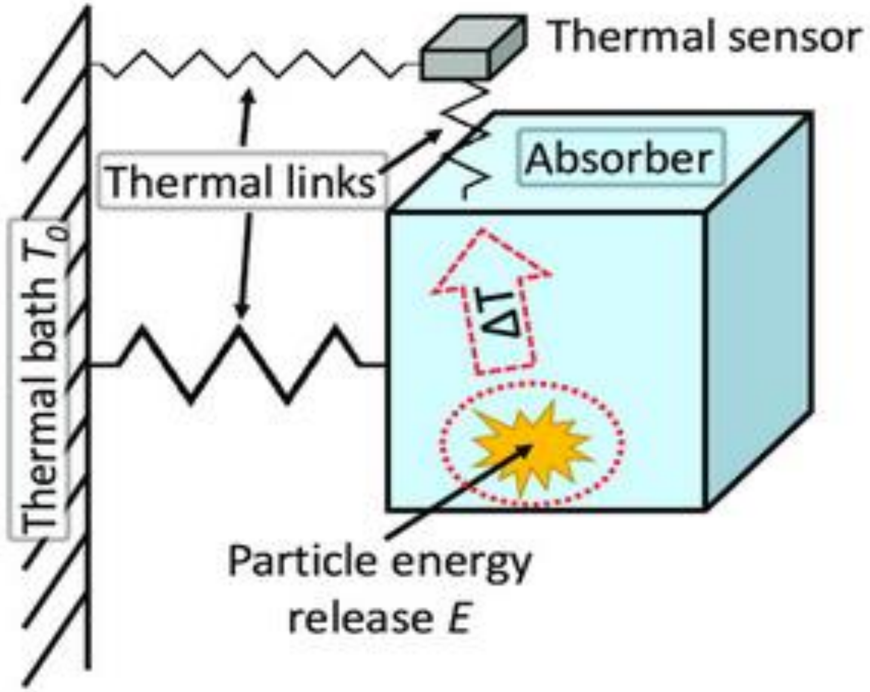
Bolometers

- **Principle : convert energy of the incident radiation to heat**
  - the incident power is absorbed by the right material
  - then measure the increase of temperature

- **Bolometers can cover a large spectrum of Energy but they are in general specialized to a certain domain of wave length**
  - ionising or non-ionising particles
  - energetic photons → gamma

- **Measurements**
  - from eV to 100 GeV
  - order of magnitude of sensitivities : commonly until 1 mK, i.e 10^{-16} W (E = kT) but can go down to 10^{-18} W
  - sensitivity : detection of a 100 W lamp at 300 000 km !

- **Ability**
  - Allow high resolution spectroscopy X, γ, α
  - measurements of absolute mK (cosmological black body)
  - measurement of lifetime of very rare radio-isotopes from 10^{19} à 10^{26} years
  - …



Temperature T
Internal energy U
Mass m

→ T' = T + ΔT
U' = U + E

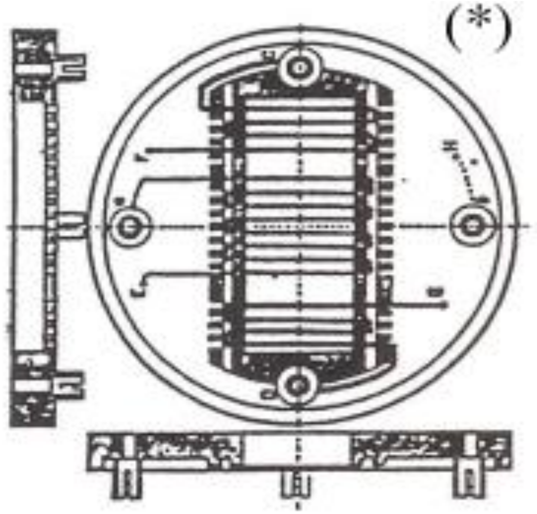
$$\Delta T = \frac{E}{C_{(T)}} = \frac{E}{m \times c_{(T)}}$$

Thermodynamics
$E = \Delta U = C_{(T)} \Delta T$
Heat capacity (J.K^{-1})
Specific heat capacity
$C_{(T)} = m \times c_{(T)}$
$\lim_{T \to 0} c(T) = 0$

A bit of history

- **1881 : 1st bolometer S. Langley**
  - etymology :
    - bolè = radiation, line, trajectory
      cf. discobolus, bolide, parabola, ballistics
    - metron = measure
- **1903 : radioactivity and heat**
  - measurements by P. Curie and A. Laborde
  - sensitivity limit ≈10^{-4} W

by thermic effect



Pierre Curie et André Laborde
CR Acad. Sciences, mars 1903

SUR LA

CHALEUR DÉGAGÉE SPONTANÉMENT

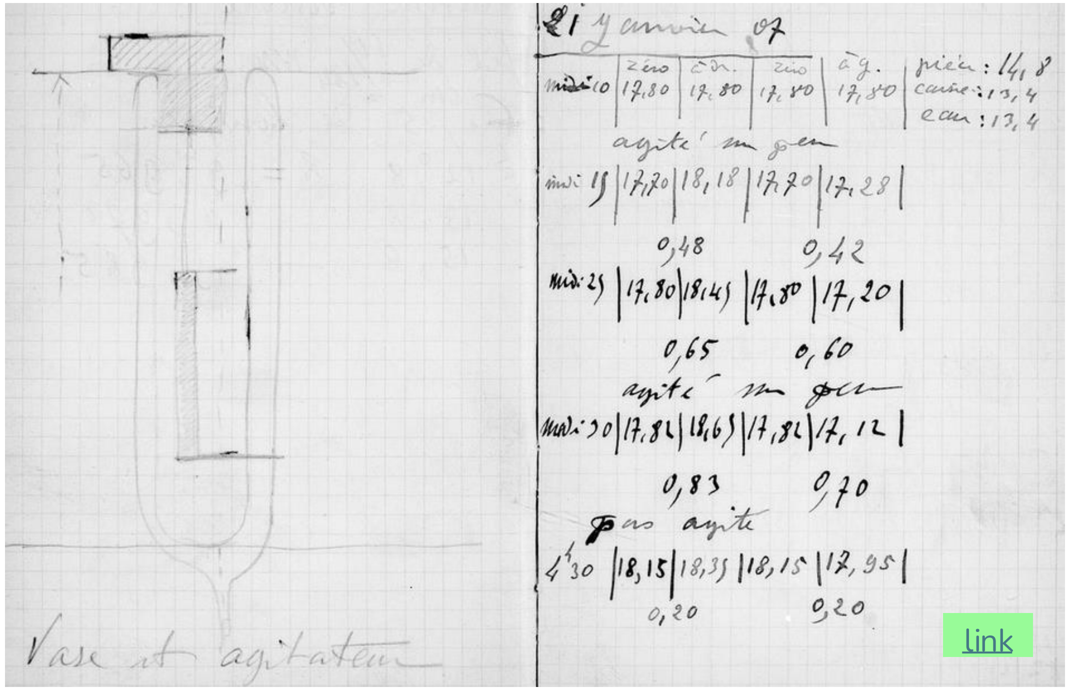
PAR LES SELS DE RADIUM.

En commun avec A. LABORDE.

Comptes rendus de l'Académie des Sciences, t. CXXXVI, p. 673, séance du 16 mars 1903.

Nous avons constaté que les sels de radium dégagent de la chaleur d'une manière continue.

Un couple thermo-électrique, fer-constantan, dont une des soudures est entourée de chlorure de baryum radifère, et dont l'autre est entourée de chlorure de baryum pur, accuse en effet une différence de température entre les deux corps.



link

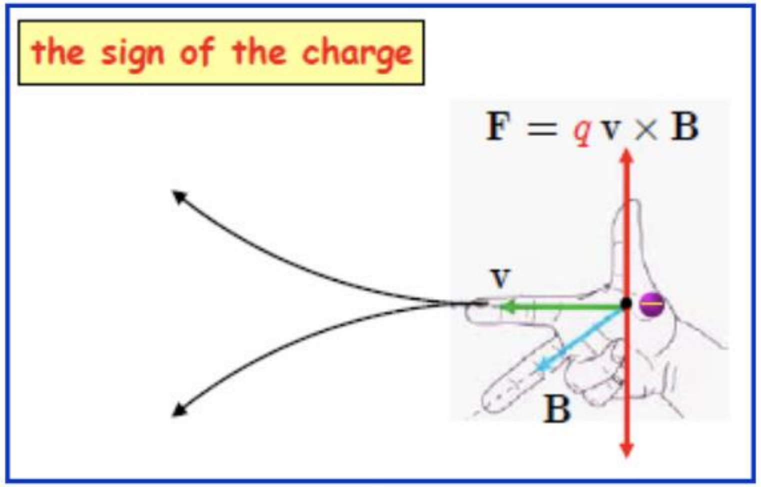
Notebook of P. Curie and A. Laborde

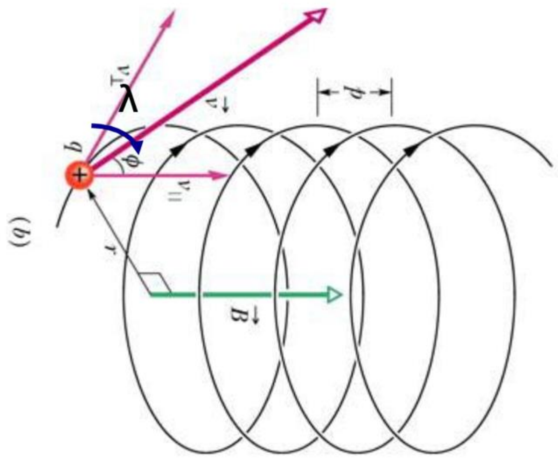
lecture of P. de Marcillac, ecole IN2P3

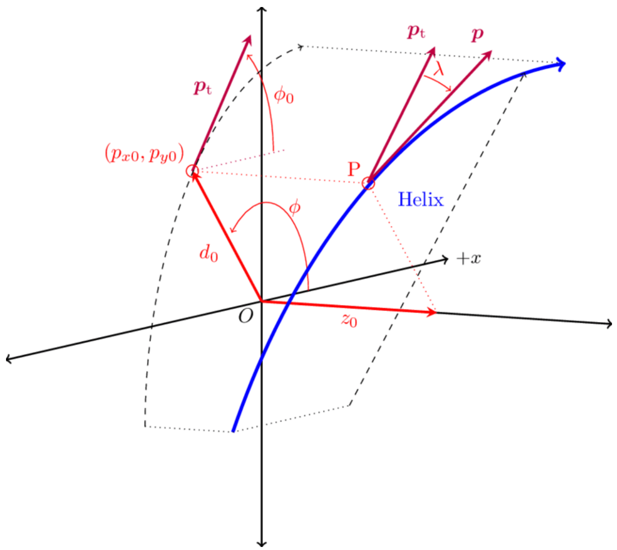
Part 4 – Measurement of particle properties

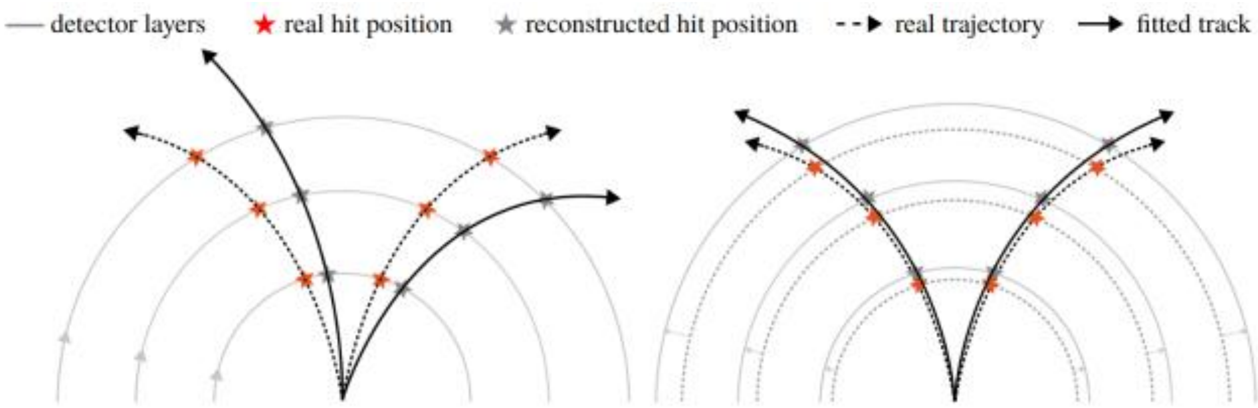
Track and charge reconstruction

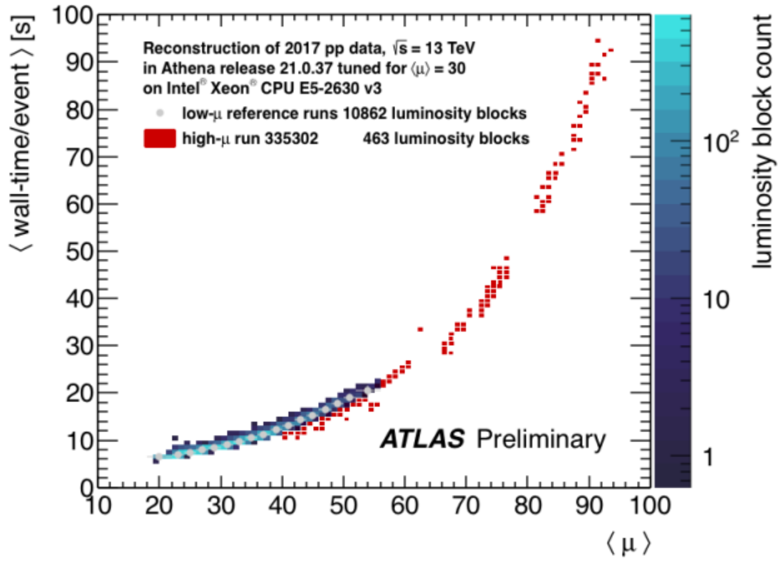
Track and Charge reconstruction: challenges







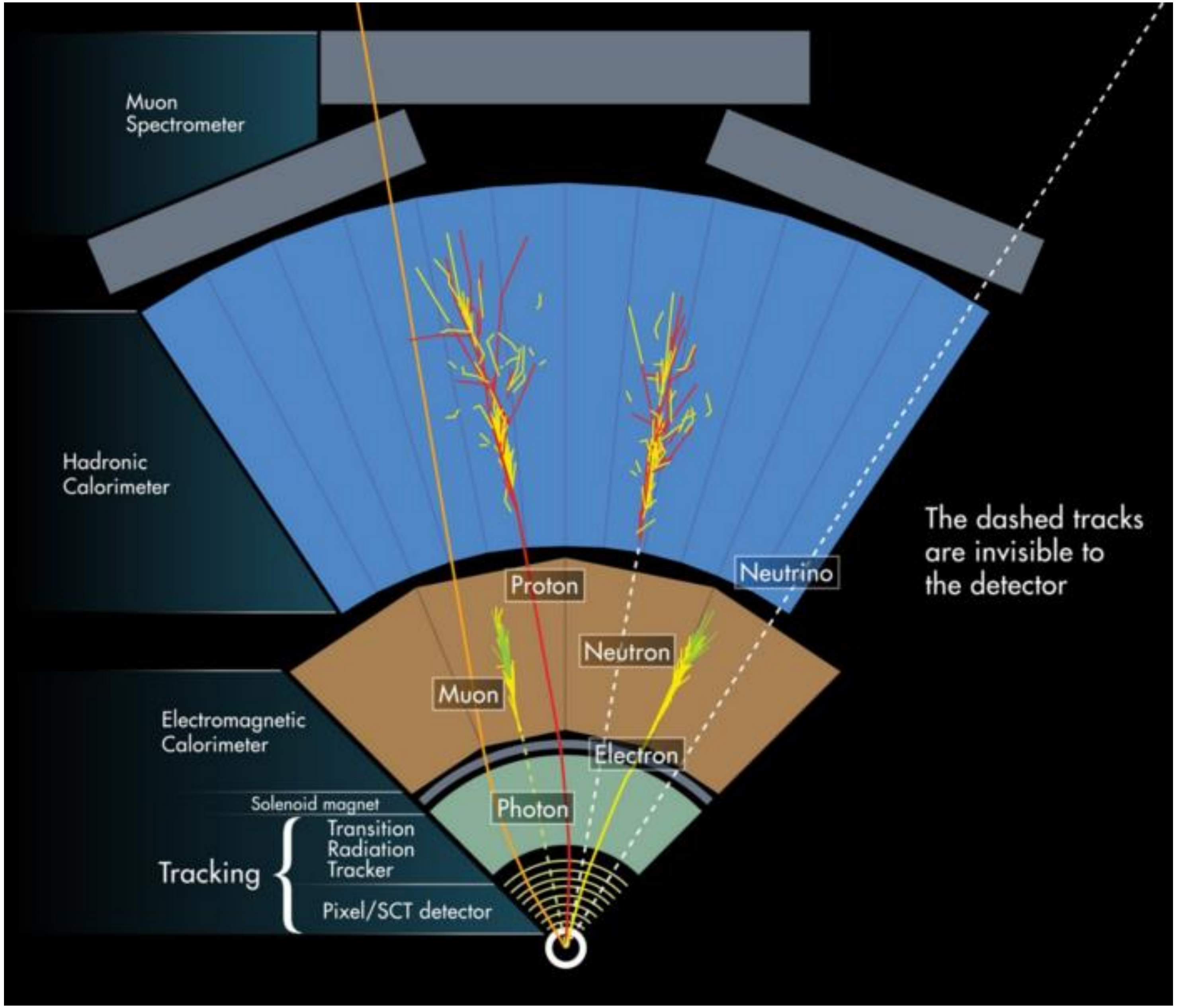




Part 4 – Measurement of particle properties

Particle identification

A general multidetector allows identification of high energy particles



Part 5 – Quantum sensors

Quantum Sensors for High Energy Physics

arXiv:2311.01930 [hep-ex]

A new era is opening

Merci !