Chapter 2
Particles…

How do we classify them?
How do they interact?
How do we detect them?

Outline/Plan

1. Introduction: goal of detectors

2. Particles interaction with matter
    1. Energy loss by atomic collisions
    2. Energy loss of electrons
    3. Multiple scattering
    4. Cerenkov radiation
    5. Photons interactions
    6. Electromagnetic showers
    7. Hadronic showers

3. **The basic detectors**
    1. Ionization detectors
    2. Scintillation detectors
    3. Photodetectors

1. Buts des détecteurs

2. Interaction particules-matière
    1. Perte d’énergie par collisions atomiques
    2. Perte d’énergie des électrons
    3. Diffusion multiple
    4. Radiation Cerenkov
    5. Interactions des photons
    6. Gerbes électromagnétiques
    7. Gerbes hadroniques

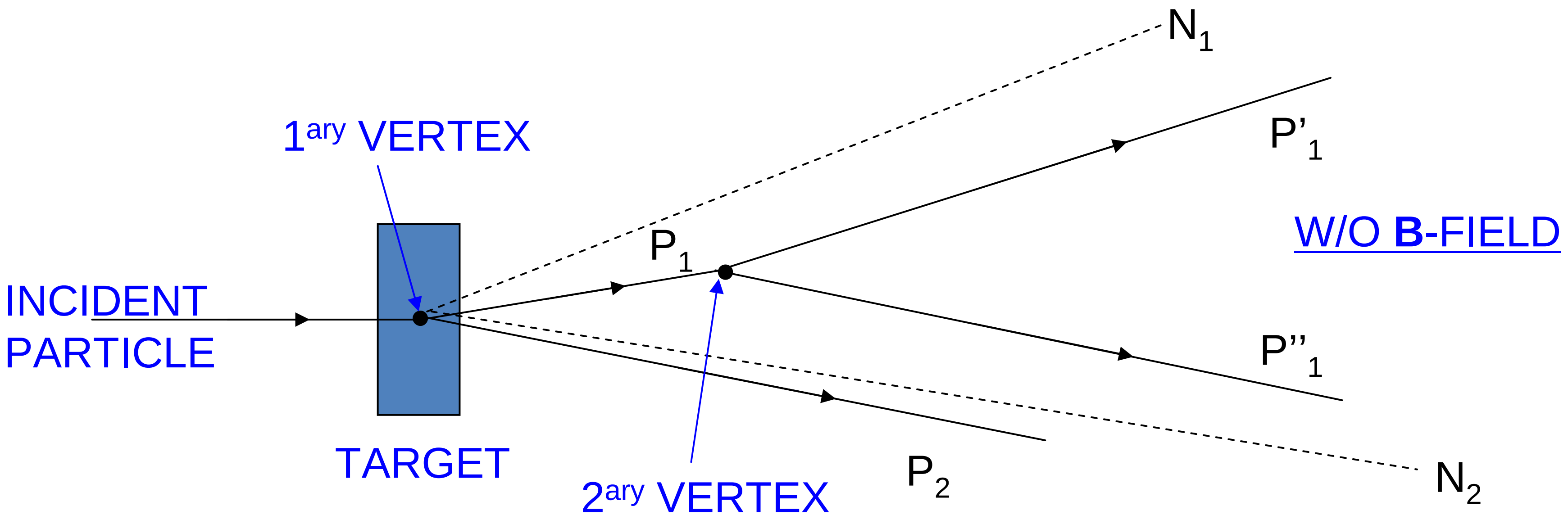
3. **Interactions fondamentales**
    1. Détecteurs à ionisation
    2. Détecteurs à scintillation
    3. Photodétecteurs

1- Introduction

General features:

- The goal of a detector in particle physics is to measure the results of an interaction to study the fundamental processes between elementary particles.

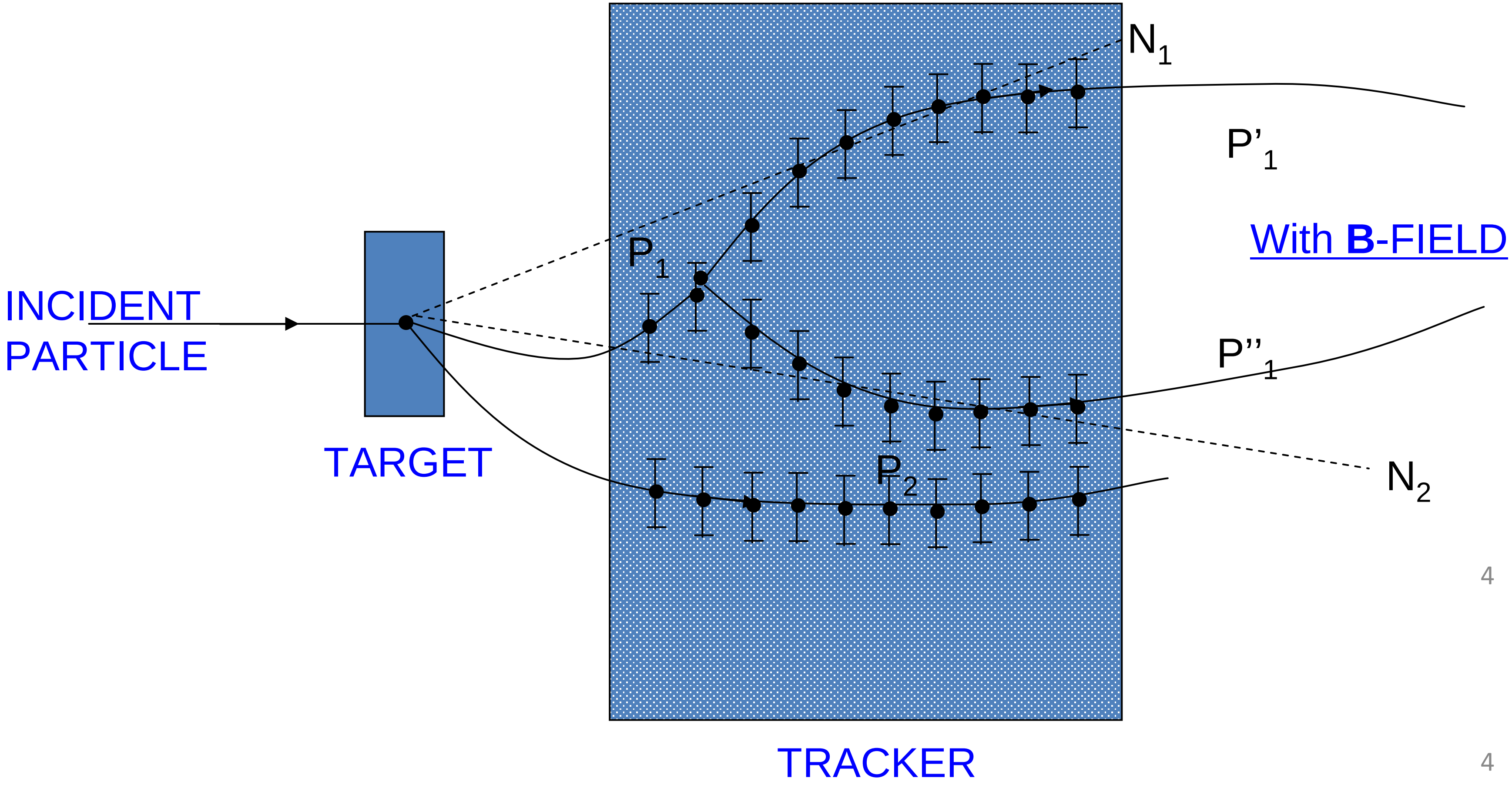
- PROJECTILE + TARGET (fixed/moving) →FINAL STATE PARTICLES



1- Introduction

Measuring particle’s impulsions : effect of **B**-field

- Curvature ➔ P $P_{(\mathrm{MeV/c})} = 300\ B_{(\mathrm{T})}\ R_{(\mathrm{m})}$
- Particle’s tracks



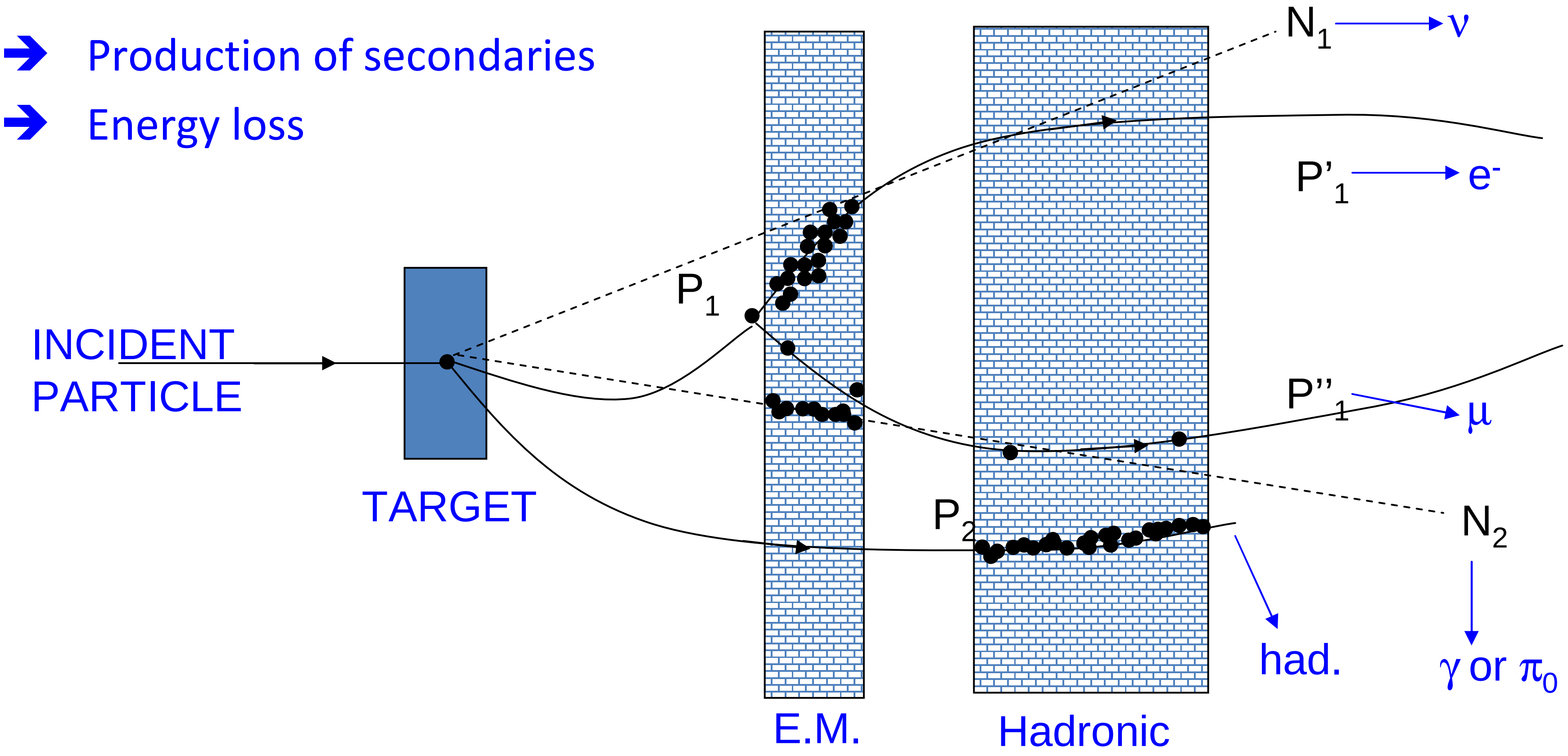
1- Introduction

Measuring particle's energy and interacting neutrals :

- Use of "calorimeters" where the particles are forced to interact with the detector

➔ Production of secondaries

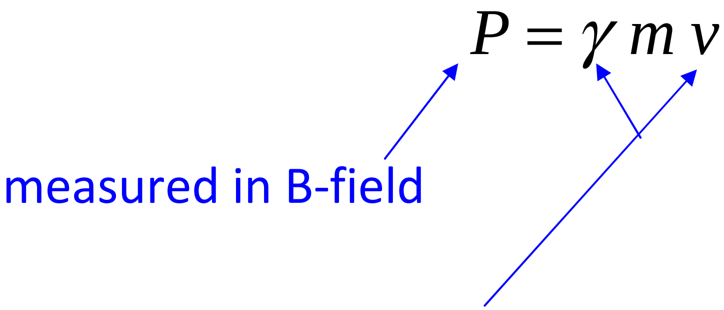
➔ Energy loss



- Depends of the interaction type (E.M. / hadronic)

1- Introduction

Identifying the particles through the measurement of the mass :



$$P = \gamma \, m \, v$$

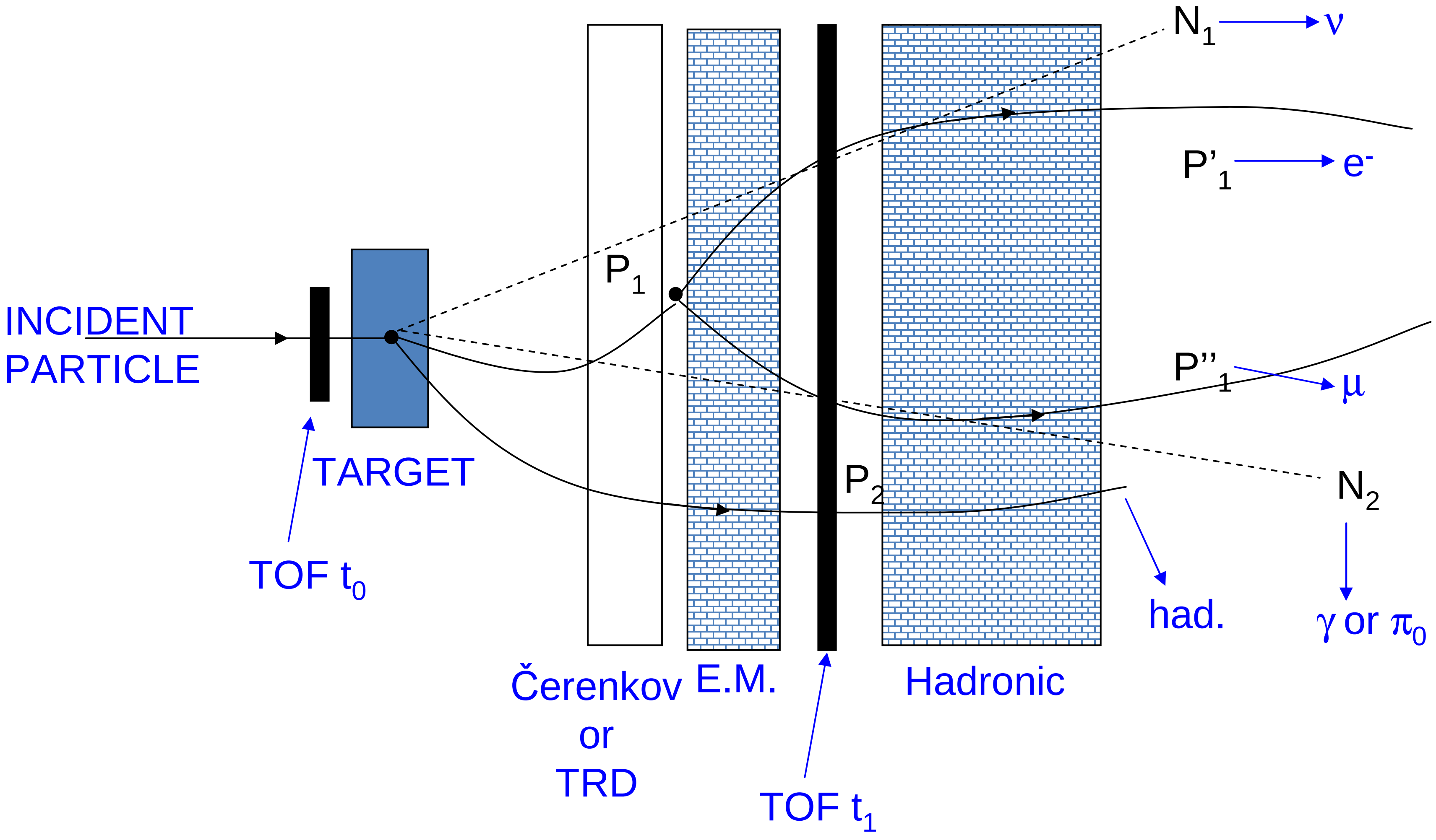
measured in B-field

Velocity measurements techniques :

- Direct measurement through the time of flight (tof) $v = L/(t_1 - t_0)$
- Indirect measurement through a physical process depending on $\beta = v/c$

  - energy loss by ionization (dE/dx)
  - Čerenkov effect (γ emission)
  - transition radiation detector (X emission)

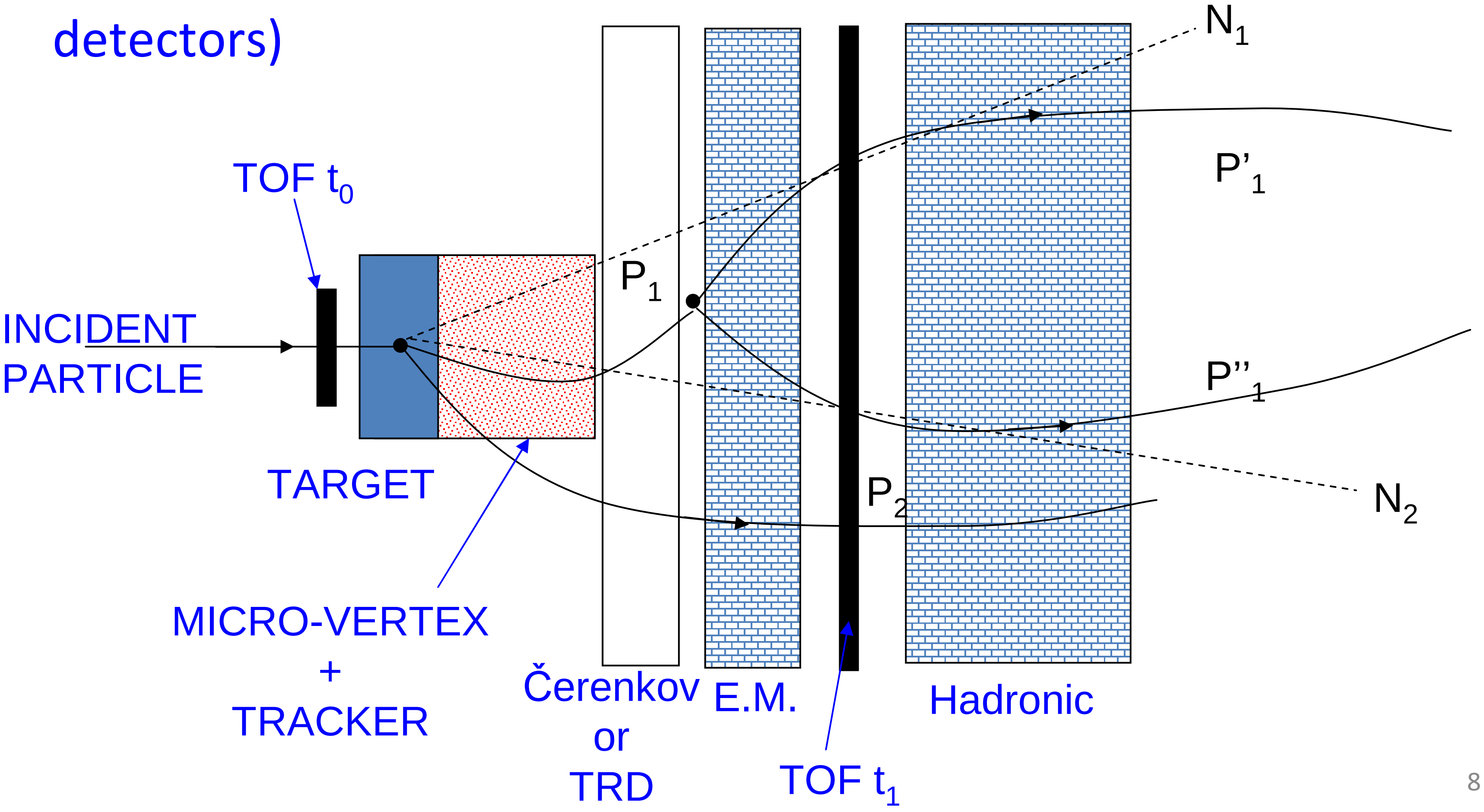
1- Introduction



1- Introduction

Measuring particle’s origin and lifetime :

- Use of micro-vertex detectors to measure 1^{ary} and 2^{ary} vertices (could be the target itself like in “bubble chambers” or pixels detectors)



2- Particles interaction with matter

General features of particle’s interactions with matter :

- It results in a loss of energy by the particle and a deflection from its incident direction

- Two processes dominate:
  - inelastic collisions with the atomic electrons of the material
  - elastic scattering from nuclei

- Other sub-leading processes exist :
  - emission of Cerenkov radiation
  - nuclear reactions
  - bremsstrahlung

2- Particles interaction with matter

A kind of classification of particle's interactions with matter :

- According to the mass : one should disentangle electrons (positrons) from heavier particles (μ, π, p, α, light nuclei…). The small mass of the electrons leads to special treatments and results.
- According to the charge : we treat separately interactions of electrons, heavier charged particles, photons and neutrons
- According to the incident energy : atomic collisions are divided into soft collisions (at low energy) in which only an excitation occurs and hard collisions in which a real ionization occurs. In the hardest collisions freed electrons have enough energy to induce secondary ionization with emission of recoil electrons (δ-rays)

2-1 Energy loss by atomic collisions

Interactions of charged particles with matter

- Interactions with atomic electrons:

  → ionization (ion + free electron)

  → excitation to higher atomic levels (photon de-excitation)

- Scattering on the nucleus (e.g. Rutherford classical scattering)

Ionization + excitation of atomic energy levels ➡ energy loss non destructive allowing to visualize the trajectories

Mean energy loss rate – dE /dx:

- Proportional to (electric charge)^2 of incident particle
- Function of the particle's velocity
- *dx* expressed in g/cm^2 to avoid material dependency

2-1 Energy loss by atomic collisions

Bethe-Bloch formula :

$$\left\langle -\frac{dE}{dx} \right\rangle = -4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\tfrac{1}{2}\ln\frac{2m_e c^2\gamma^2\beta^2}{I^2}T^{\max} - \beta^2 - \frac{\delta}{2}\right]$$

Depends on Z/A:
neutron-rich nuclei
less efficient

Mean excitation potential
~ 16 Z^0.9 eV

Screening of E-field
due to electron
density effect
(Fermi plateau)

2-1 Energy loss by atomic collisions

Bethe-Bloch formula a few numbers :

For $Z \approx 0.5\,A$

$1/\rho\ dE/dx \approx 1.4$ MeV cm ^{2}/g for $\beta\gamma \approx 3$

Example 1:

Scintillator: Thickness = 2 cm; $\rho = 1.05$ g/cm^3

Particle with $\beta\gamma = 3$ and $Z=1$

$1/\rho\ dE/dx \approx 1.4$ MeV

$dE \approx 1.4 * 2 * 1.05 = 2.94$ MeV

Example 2:

Iron: Thickness = 100 cm; $\rho = 7.87$ g/cm^3

$dE \approx 1.4 * 100 * 7.87 = 1102$ MeV

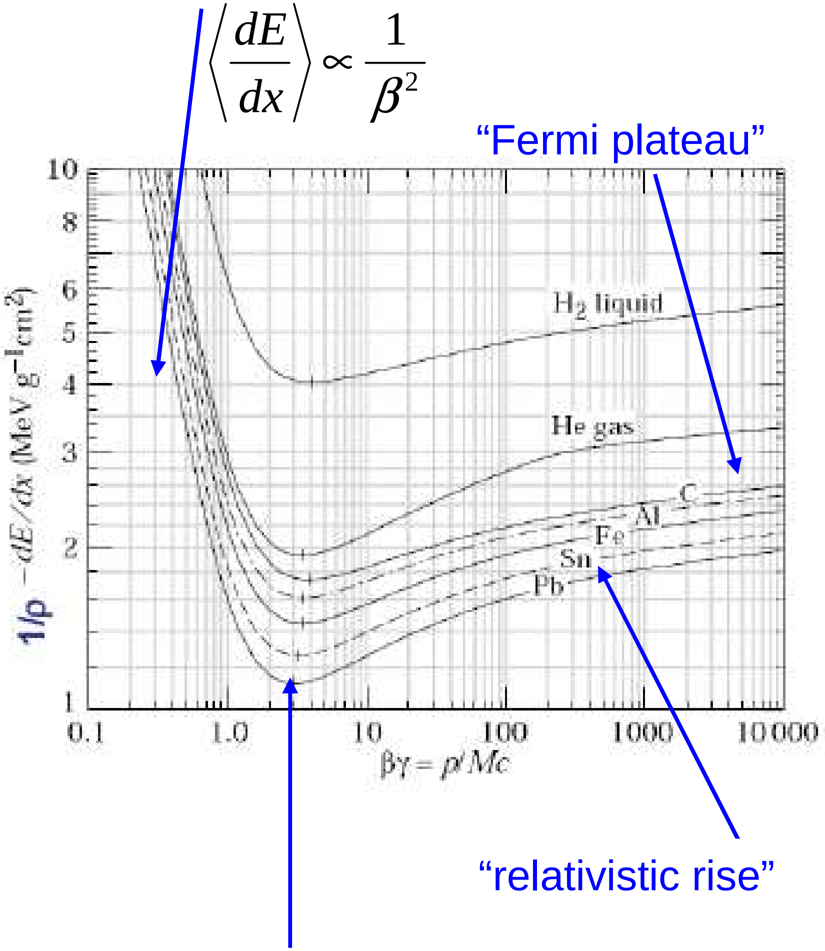
Example 3:

Energy Loss of a Carbon Ion with Z=6 and Momentum of 330 MeV/c/Nukleon in Water, i.e. $\beta\gamma = p/m = 330/940 \approx .35 \rightarrow$

$\beta \approx .33$

$dE/dx \approx 1.4\,Z^2/\beta^2 \approx 460$ MeV/cm →

Cancer Therapy !



"kinematical term"

$$\left\langle \frac{dE}{dx} \right\rangle \propto \frac{1}{\beta^2}$$

"Fermi plateau"

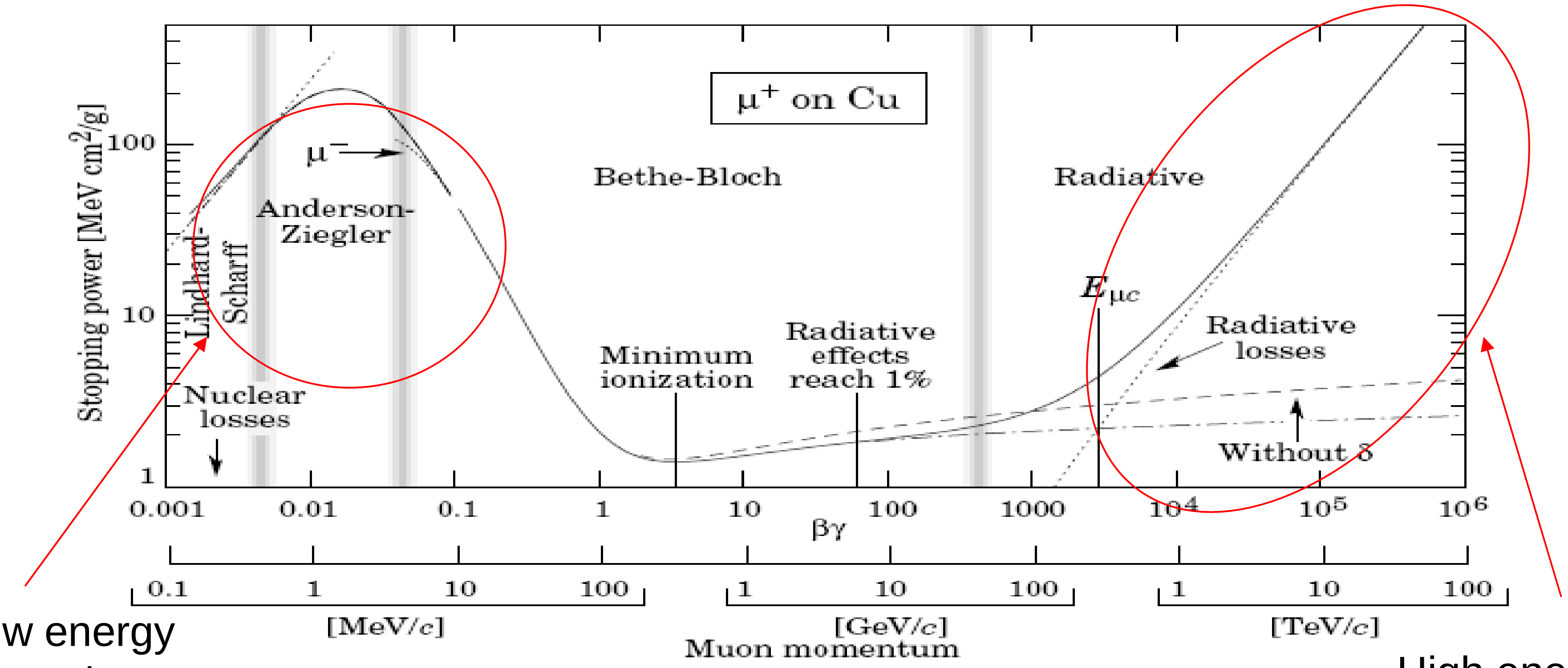
"relativistic rise"

$\beta\gamma \approx$ 3-4

minimum ionizing particles, MIPs

2-1 Energy loss by atomic collisions

Stopping power :



Low energy corrections needed

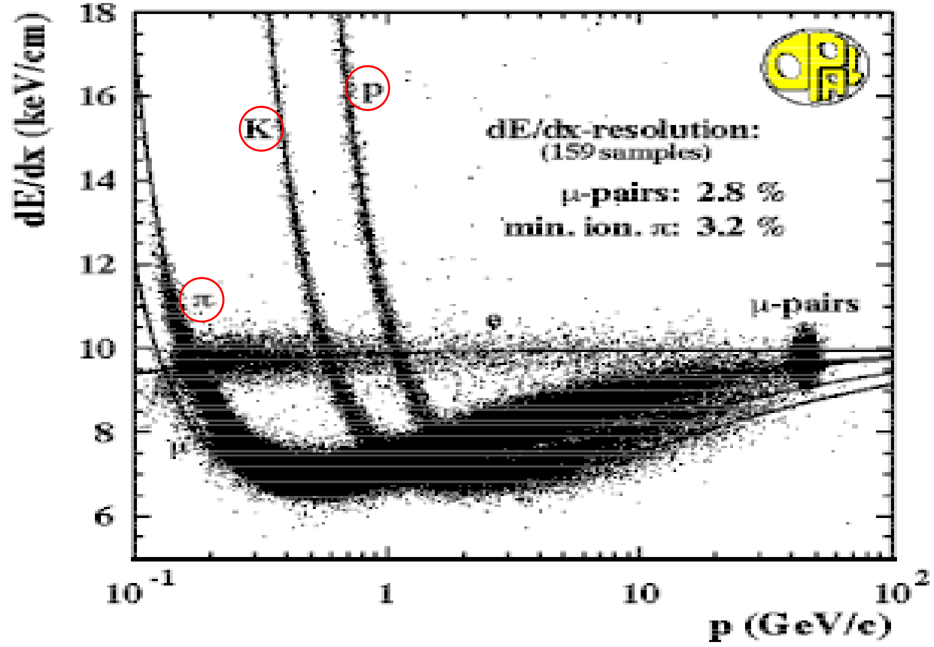
High energy radiative corrections important

Fig. 27.1: Stopping power ($= \langle -dE/dx \rangle$) for positive muons in copper as a function of $\beta\gamma = p/Mc$ over nine orders of magnitude in momentum (12 orders of magnitude in kinetic energy). Solid curves indicate the total stopping power. Data below the break at $\beta\gamma \approx 0.1$ are taken from ICRU 49 [2], and data at higher energies are from Ref. 1. Vertical bands indicate boundaries between different approximations discussed in the text. The short dotted lines labeled "μ^-" illustrate the "Barkas effect," the dependence of stopping power on projectile charge at very low energies [3].

2-1 Energy loss by atomic collisions

Particle id. with stopping power

- By measuring the ionization in many layers and removing the tail the mean ionization loss can be measured at few % accuracy
- Get γ from relativistic rise or β from the low energy part
- If you know *p* from curvature in **B**-field → compute *m*



Ar/CH_4 : (80%/20%) at NTP

2-2 Energy loss of electrons

Electrons (positrons) lose energy through collisions but their small mass leads to specific computations :

- The Bethe-Bloch formula must be adapted to account for the smallness of the mass. In particular the incident particle does not remain undeflected in that case. One has also to account for the indistinguishability in identical particles collisions.
- Additional processes occur with comparable orders of magnitude : emission of e.m. radiation from the scattering in the E-field of the nucleus (bremsstrahlung) due to the acceleration felt during the deviation from incident direction.

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

2-2 Energy loss of electrons

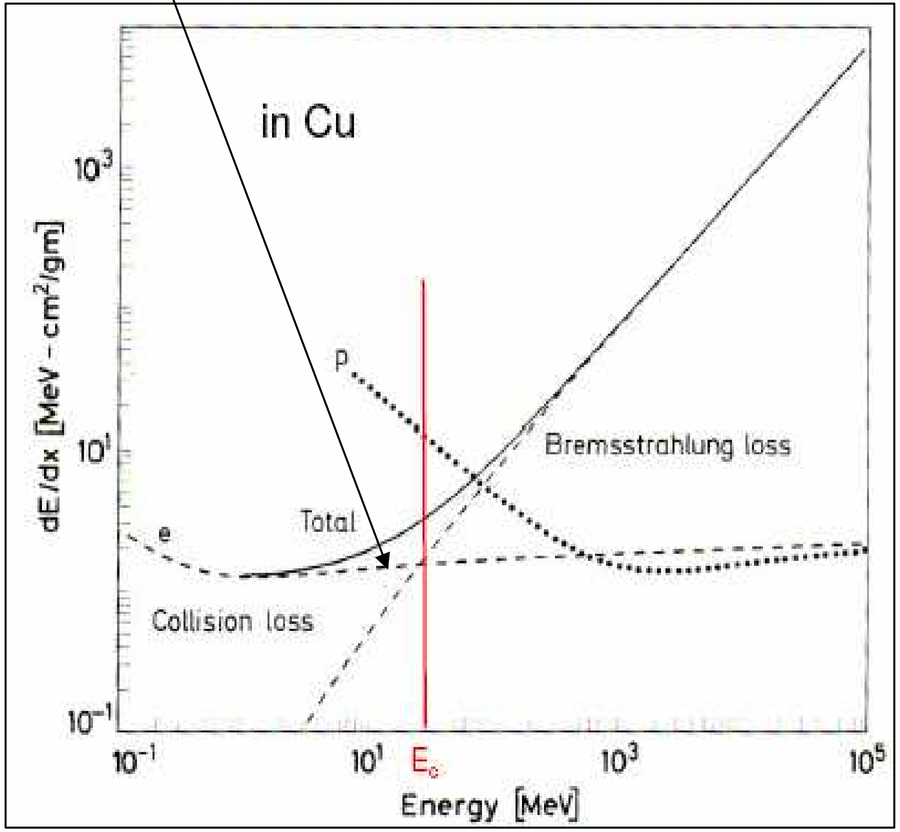
Modified Bethe-Bloch formula:

$$\left\langle -\frac{dE}{dx}\right\rangle = -2\pi N_A r_e^2 m_e c^2 \rho \frac{Z}{A}\frac{1}{\beta^2}\left[\ln\frac{\tau^2(\tau+2)}{2(I^2/m_e c^2)} + F(\tau) - \delta - 2\frac{C}{Z}\right]$$

τ : kinetic energy of particle in units of $m_e c^2$

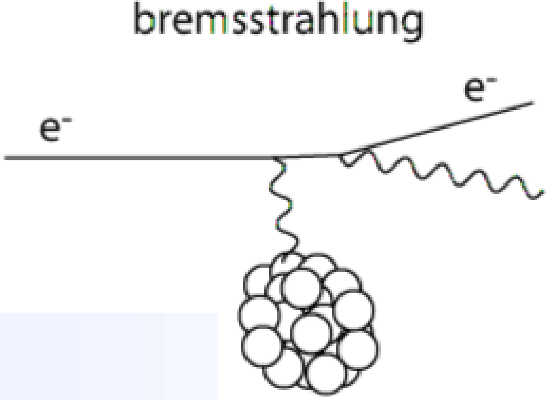
$F(\tau)$ differs for e^+ and e^-

After a specific energy, called critical energy, radiation losses are more important than collision losses.

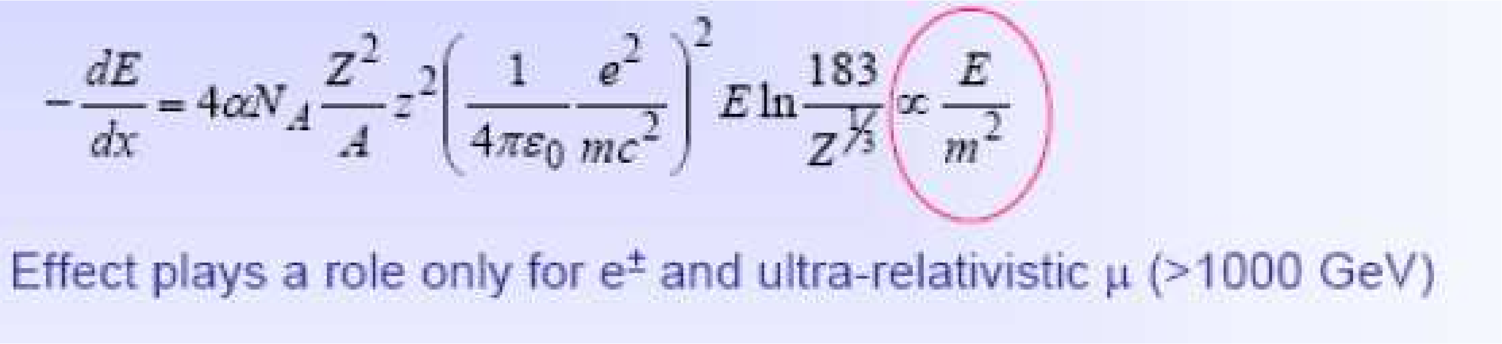


2-2 Energy loss of electrons

Bremsstrahlung (braking radiation) : a sketch



…and a formula :



$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} z^2 \left(\frac{1}{4\pi\varepsilon_0}\frac{e^2}{mc^2}\right)^2 E \ln\frac{183}{Z^{1/3}} \boxed{\propto \frac{E}{m^2}}$$

Effect plays a role only for e± and ultra-relativistic μ (>1000 GeV)

O.M. given the mass of the muon (106 MeV ie ~200 times m_e) the radiation loss for muons is 40000 lower than for electrons. Therefore the ability to cross thick layers of matter can be used to identify muons in a beam.

N.B. radial acceleration induces synchrotron radiation prop. to a^2

2-2 Energy loss of electrons

Radiation length. This parameter is defined as the distance over which the electron energy is reduced by a factor *1/e* due to radiation loss only.

$$\left\langle -\frac{dE}{E} \right\rangle = N\Phi_{rad}dx \Rightarrow E = E_0 \exp\left(\frac{-x}{X_0}\right)$$

where X_0 is the radiation length

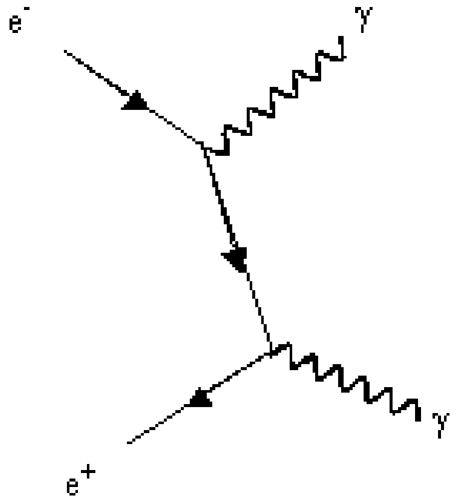
$$X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln\frac{183}{Z^{1/3}}}$$

radiation length [g/cm^2]

(divide by specific density to get X_0 in cm)

2-2 Energy loss of electrons

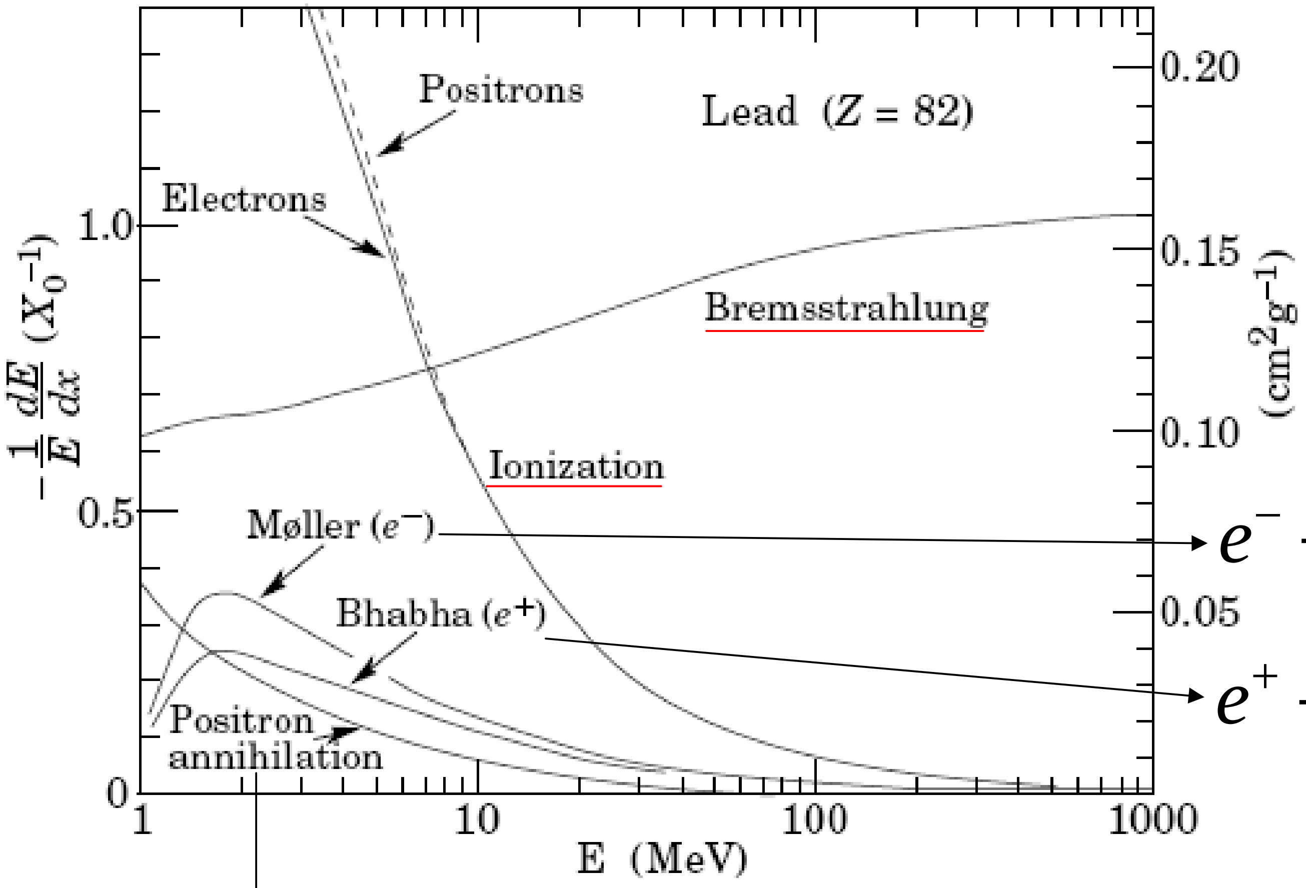
Positron annihilation



- In almost all cases, positrons that pass through matter annihilate with an electron, to create photons: $e^{+}+e^{-}\rightarrow\gamma+\gamma$
- Single photons are possible if the electron is bound to a nucleus… this occurs at only 20% the rate for two photons.
- A high energy positron will lose energy by collision and radiation, until it has a low enough energy to annihilate.
- Positronium: e^{+} and e^{-} can form a temporary bound state, similar to the hydrogen atom.

2-2 Energy loss of electrons

Energy loss of electrons and positrons : summary



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

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

$$e^+ + e^- \rightarrow \gamma + \gamma$$

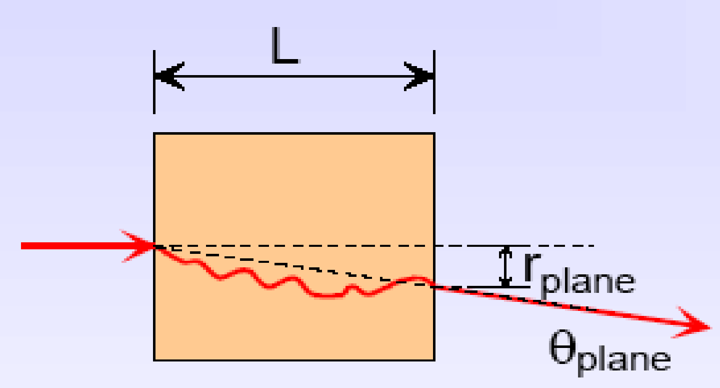
2-3 Multiple scattering

In addition to inelastic collisions with atomic electrons charged particles passing through matter suffer repeated elastic Coulomb scatterings from nuclei:

- Rutherford scattering formula (T.D.) $$\frac{d\sigma}{d\Omega} = 4z^2Z^2r_e^2\left[\frac{m_ec}{\beta p}\right]^2 \frac{1}{\sin^4 \theta/2}$$

  Main features :

  - small angular deflection of the particle
  - quasi negligible energy transfer to the heavy nucleus
- The cumulative effect of these small angle scatterings is a net deflection from the original incident direction in a zigzag path.



2-3 Multiple scattering

If the number of independent scatterings is large enough the problem can be treated statistically to obtain a probability distribution as a function of the thickness of material crossed.

- If one ignores small probability for large-angle scattering single scattering then the probability distribution can be approximated by a Gaussian

$$P(\theta) \approx \frac{2\theta}{\langle \theta^2 \rangle} \exp\left(\frac{-\theta^2}{\langle \theta^2 \rangle} \right) d\theta \text{ with}$$

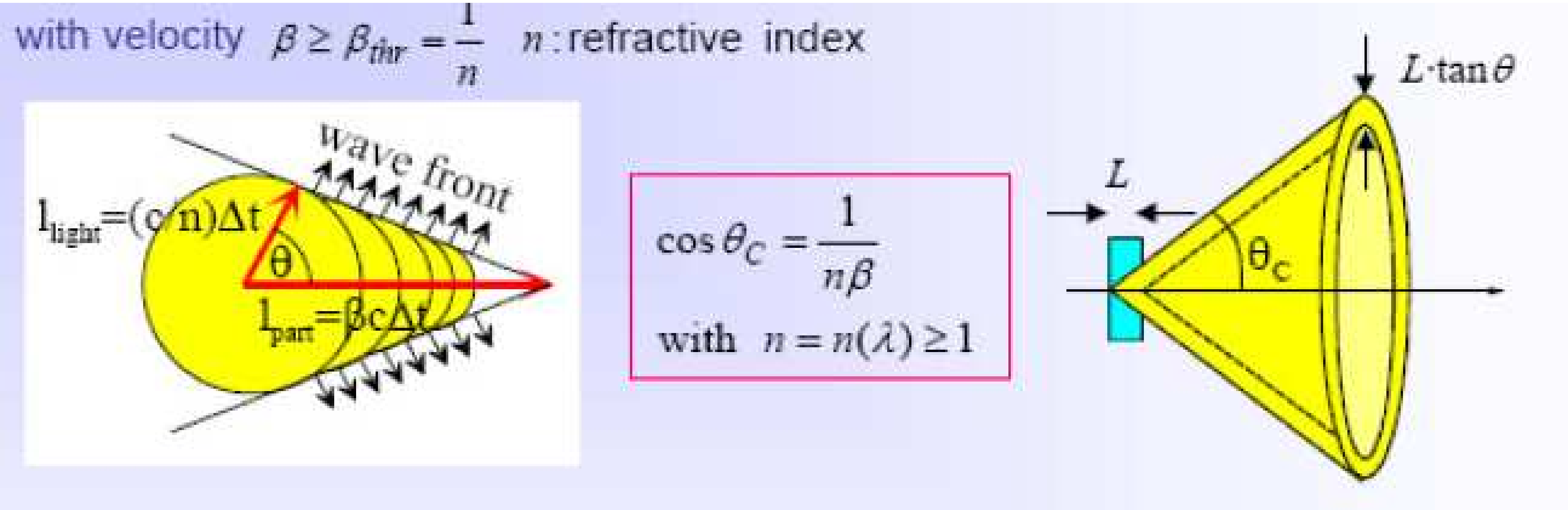
$$\theta_{rms} = \theta_0 = \sqrt{\langle \theta^2 \rangle} = \frac{13.6(\text{MeV})}{\beta c p} Z_i \sqrt{\frac{x}{X_0}} \left(1 + 0.038 \ln \frac{x}{X_0} \right)$$

N.B. the introduction of the radiation length is just for commodity

2-4 Cerenkov radiation

Cerenkov effect occurs when a charged particle crosses a dielectric material with speed greater than the one of light in matter $v \geq \frac{c}{n}$

- The phenomenon results in photon emission in a specific direction



with velocity $\beta \geq \beta_{thr} = \frac{1}{n}$ n : refractive index

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

with $n = n(\lambda) \geq 1$

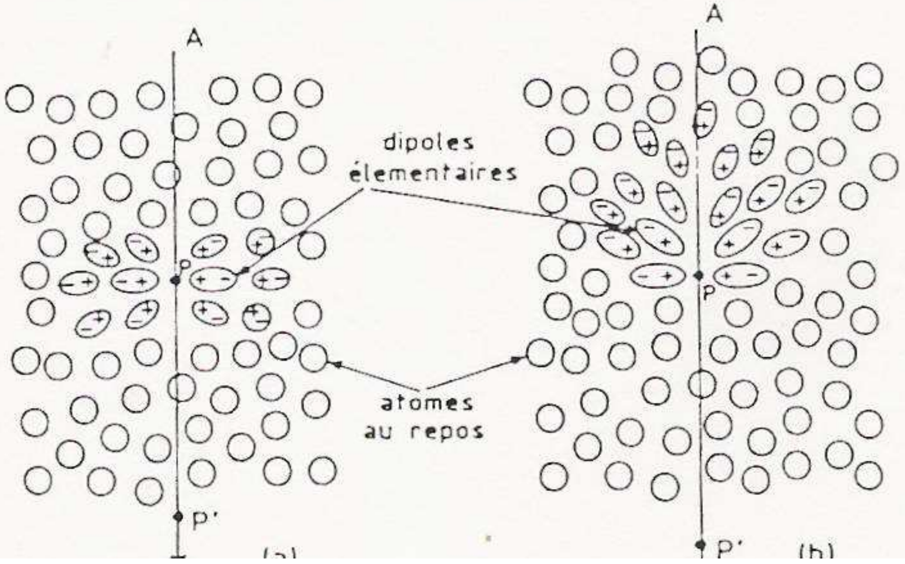
2-4 Cerenkov radiation

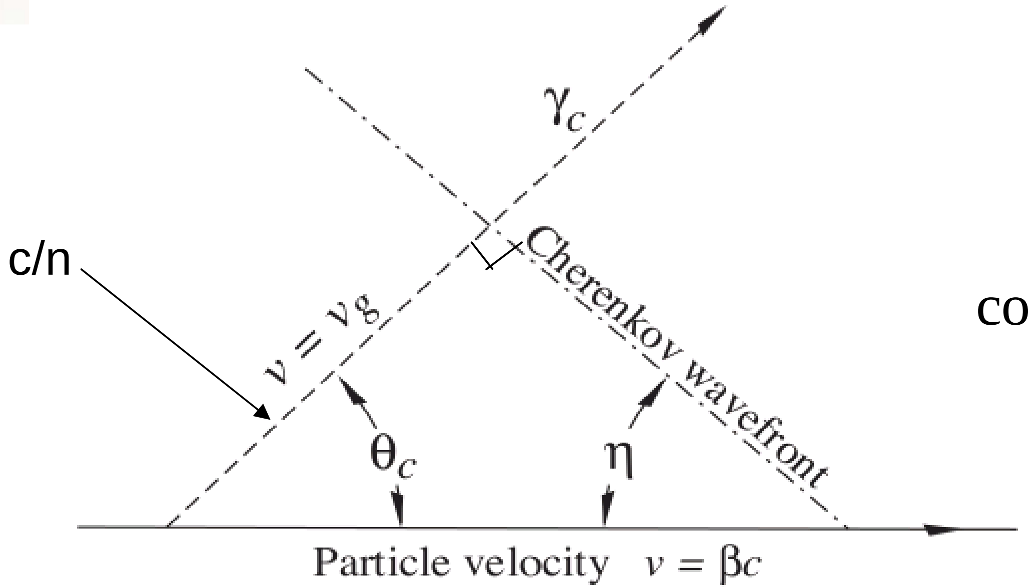
Physically this effect can be seen as a polarization effect which symmetry depends on the speed of the incoming particle

- If the particle travels at low speed the medium is polarized with a total azimutal and longitudinal symmetry → no field at long distance → no radiation emitted

- If the particle travels at large speed the polarization field loses its longitudinal symmetry → non-vanishing dipolar field → radiation emitted. Constructive interference of spherical waves on the light front.

2-4 Cerenkov radiation





$$\cos\theta = \frac{c/n}{v} = \frac{1}{n\beta}$$

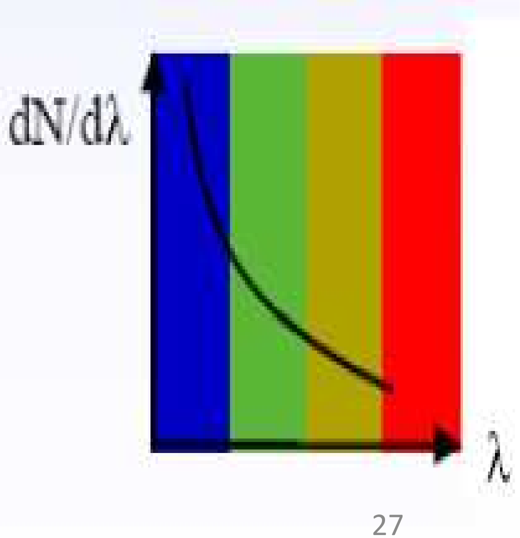
2-4 Cerenkov radiation

Cerenkov effect general features:

- ∃ threshold value for the particle speed : $\cos\theta = 1 \Rightarrow \beta_{threshold} = \frac{1}{n}$
- If $\beta \to 1$ then the angle goes to a maximum $\theta_{\max} = \arccos\left(\frac{1}{n}\right)$
- The radiation intensity can be computed (Frank and Tamm, 1937): the number of photons emitted per $d\lambda$ interval for an element of trajectory dx is given by

$$\frac{d^2N_{ph}}{d\lambda dx} = 2\pi\alpha\frac{Z_i^2\sin^2\theta}{\lambda^2} = 2\pi\alpha\frac{Z_i^2}{\lambda^2}\left(1-\frac{1}{\beta^2n^2}\right) \text{ with } \alpha = 1/137$$

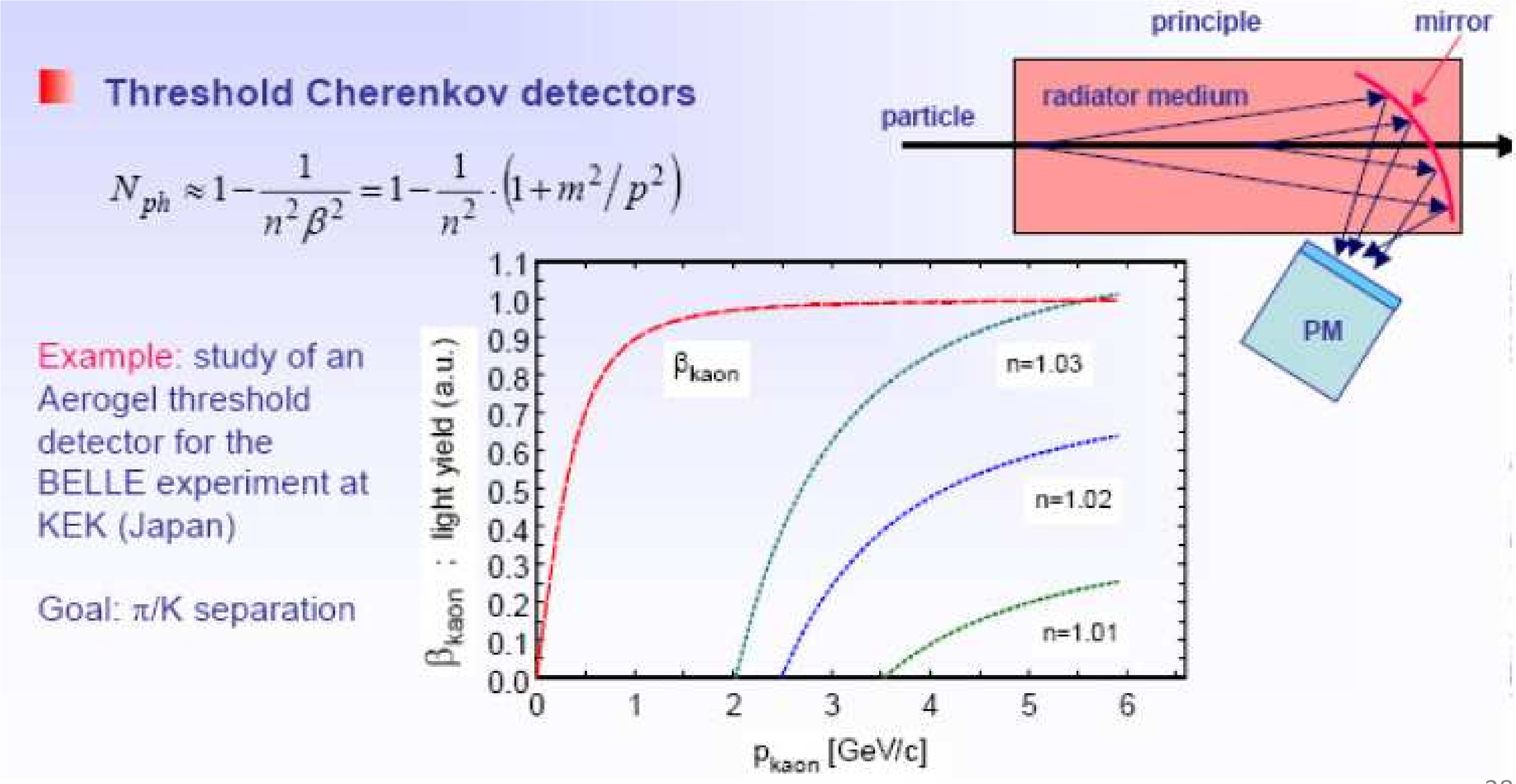
$$\frac{dN_{ph}(\text{visible})}{dx} \simeq 500\sin^2\theta$$



2-4 Cerenkov radiation

Applications to Cerenkov detectors:

- Threshold detectors exploiting $N_{ph}(\beta)$
- Ring Imaging Cerenkov Detector (RICH) exploiting $\theta(\beta)$



Threshold Cherenkov detectors

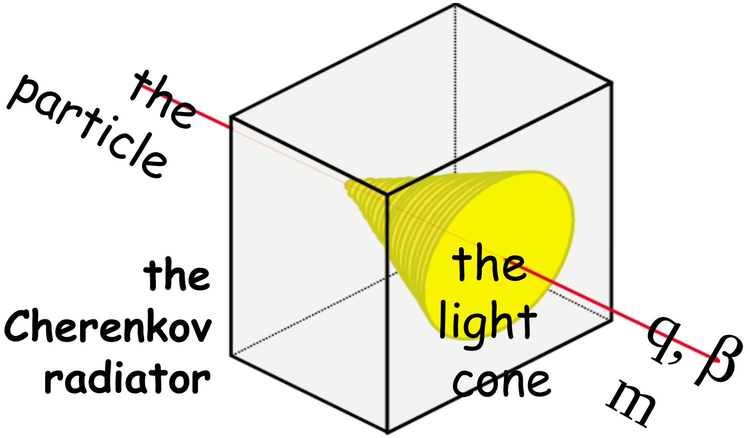
$$N_{ph} \approx 1-\frac{1}{n^2\beta^2}=1-\frac{1}{n^2}\cdot\left(1+m^2/p^2\right)$$

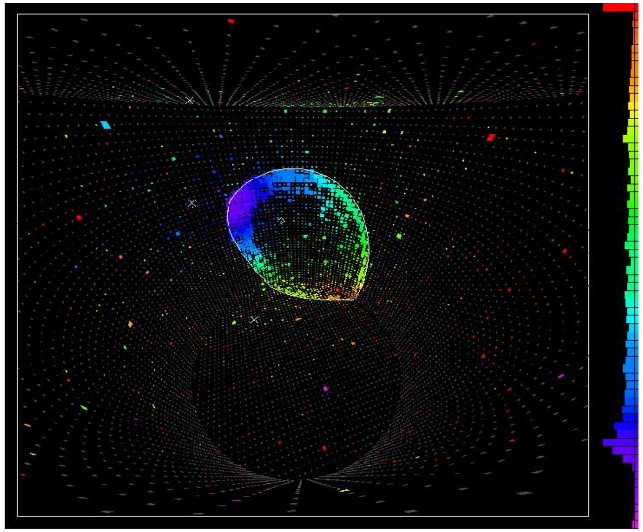
Example: study of an Aerogel threshold detector for the BELLE experiment at KEK (Japan)

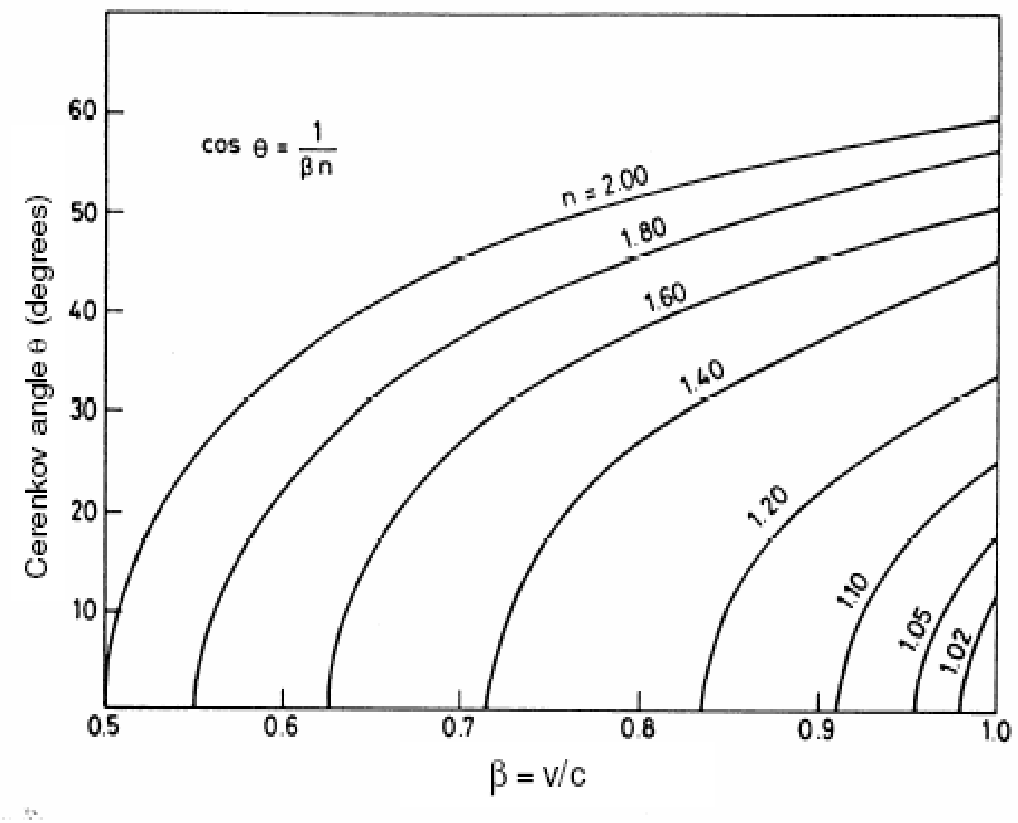
Goal: π/K separation

2-4 Cerenkov radiation

RICH : at fixed n, measuring θ defines β







2-5 Photons interaction

General features:

- Charged particles crossing matter lose energy and have a modified trajectory but most of the times the incident particle keeps its identity
- For photons the probability to disappear is quite large and is characterized by a linear absorption coefficient μ

$$dN = -\mu N dx \Rightarrow N = N_0 e^{-\mu x}$$

which can be expressed in terms of the absorption cross-section

$$\mu = \rho \, {N_A}/{A} \, \sigma_{abs}$$

- A γ beam is not degraded in energy but in intensity
- γ (X- and γ-rays) are many times more penetrating particles in matter than charged particles

2-5 Photons interaction

The (total) absorption cross-section corresponds to 3 main electromagnetic processes:

- photo-electric effect

$$\boxed{\gamma + \text{atom} \rightarrow \text{ion} + e^-}$$

- Compton effect

$$\boxed{\gamma + e^- \rightarrow \gamma + e^-}$$

- Pair creation

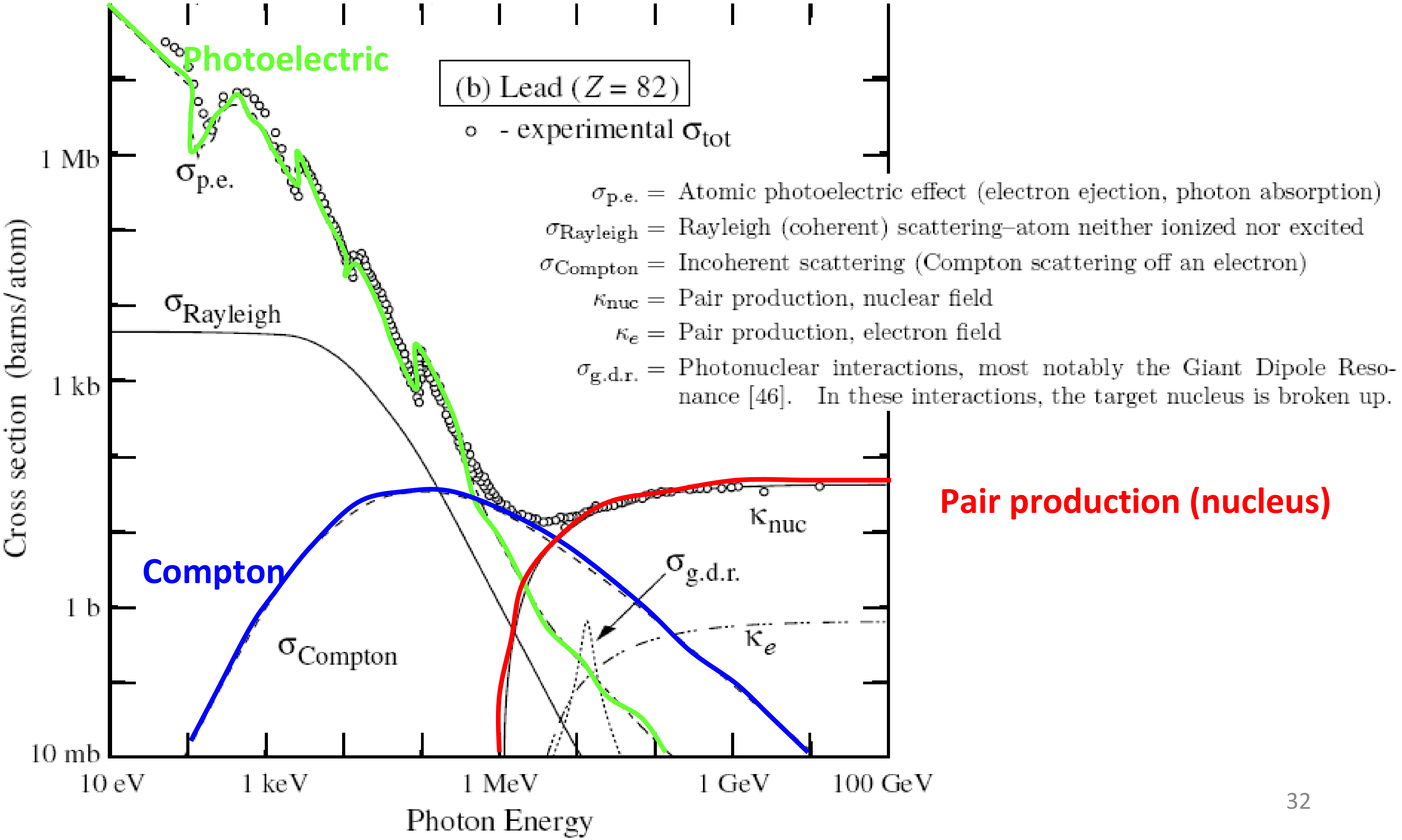
$$\boxed{\gamma + \text{nucleus} \rightarrow e^+ + e^- + \text{nucleus}}$$

To those processes could be added at certain energies other processes such as

- coherent Rayleigh scattering $E_\gamma < 100\ \text{keV}$
- photonuclear absorption $10\ \text{MeV} < E_\gamma < 25\ \text{MeV}$

2-5 Photons interaction

The (total) absorption cross-section vs γ energy



$\sigma_{p.e.}$ = Atomic photoelectric effect (electron ejection, photon absorption)

$\sigma_{Rayleigh}$ = Rayleigh (coherent) scattering–atom neither ionized nor excited

$\sigma_{Compton}$ = Incoherent scattering (Compton scattering off an electron)

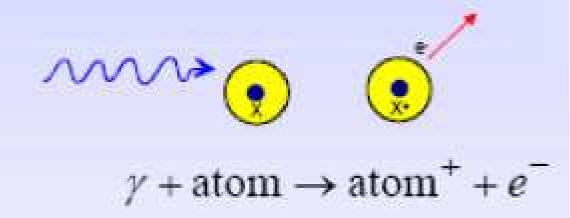
κ_{nuc} = Pair production, nuclear field

κ_e = Pair production, electron field

$\sigma_{g.d.r.}$ = Photonuclear interactions, most notably the Giant Dipole Resonance [46]. In these interactions, the target nucleus is broken up.

2-5 Photons interaction

Photoelectric effect:


$$\gamma + \text{atom} \rightarrow \text{atom}^{+} + e^{-}$$

- Interactions with atoms: absorption of a γ from an atomic e^{-} $\Rightarrow$ ejection of an electron
- A free electron cannot absorb the photon and conserve momentum $\Rightarrow$ effect always on bound electrons with nucleus absorbing recoil momentum)
- Energy of outgoing electron: $E = h\nu - B.E.$ (Binding Energy) where

$$B.E. = hcR_{\infty}\frac{(Z-\xi)^2}{n^2}$$

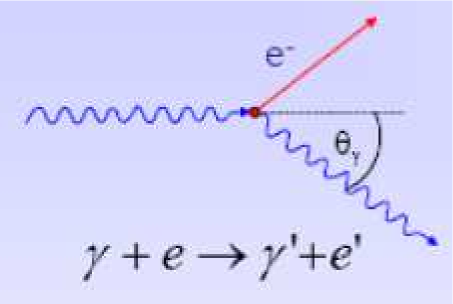
Screening effect

involving the Rydberg energy $hcR_{\infty} = 13.6056923(12)\,\mathrm{eV} \equiv 1\,\mathrm{Ry} = \frac{1}{2}\frac{m_e e^4}{\hbar^2}$

and the shell main quantum number n

2-5 Photons interaction

Compton scattering:



- Standard computation of the emitted γ energy using energy-momentum conservation

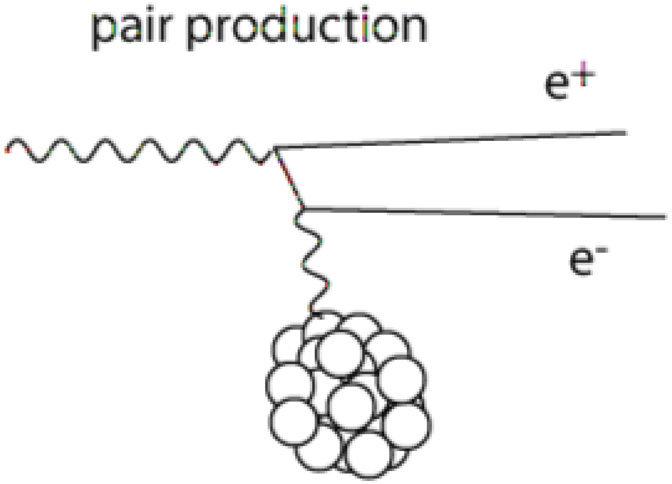
$$E_\gamma^{'} = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_e c^2}(1 - \cos\theta)}$$

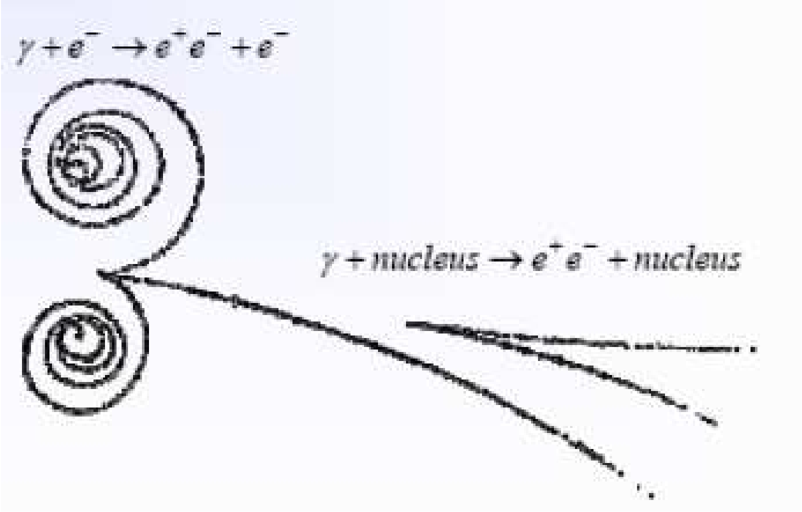
- Resulting in the wavelength shifting:

$$\lambda - \lambda_0 = h / mc(1 - \cos\theta)$$

2-5 Photons interaction

Pair production:





- Conversion of a high energy photon to an electron-positron pair in the field of a nucleus (related to the electron bremsstrahlung by a simple correspondence)
- To conserve momentum $\gamma \rightarrow e^+ e^-$ can only occur in presence of another body usually a nucleus.
- The screening of atomic electrons plays an important role.

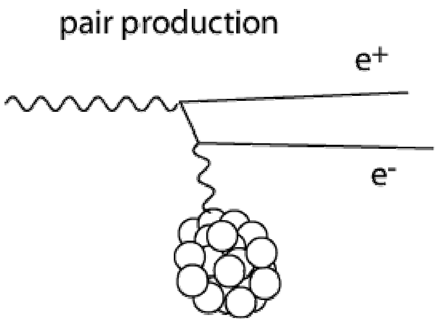
2-6 Electromagnetic showers

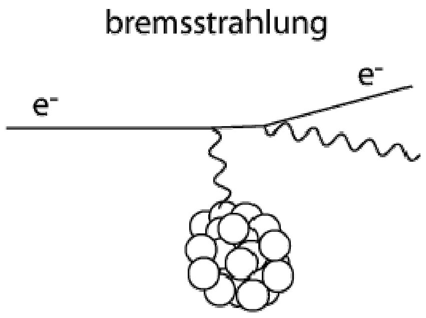
Above energies ~10 MeV the dominant processes for electrons and photons are bremsstrahlung and pair production resp.

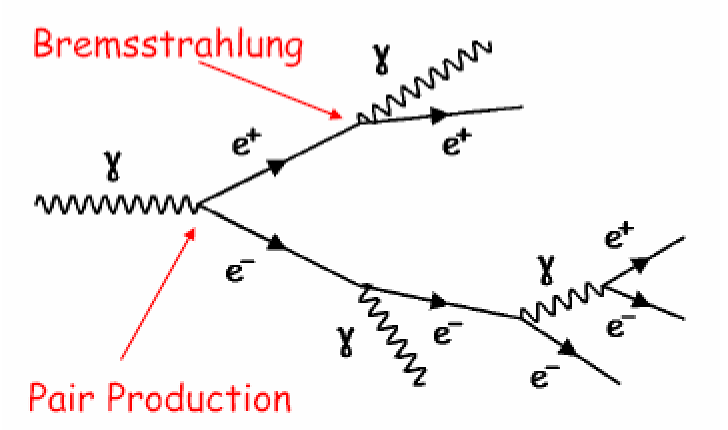
- The radiated photons have enough energy to produce extra pairs
- The emitted e^+ and e^- have enough energy to emit radiation γ etc

➔ The number of photons and electrons per unit length increase

➔ Development of an electromagnetic shower

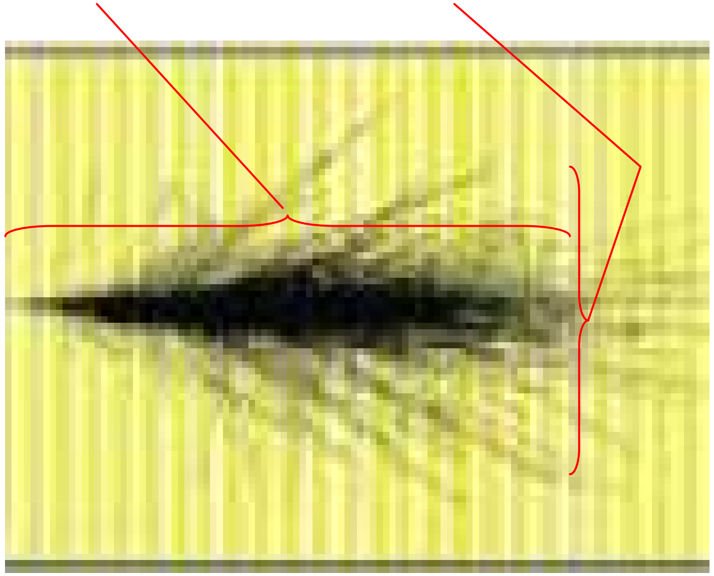


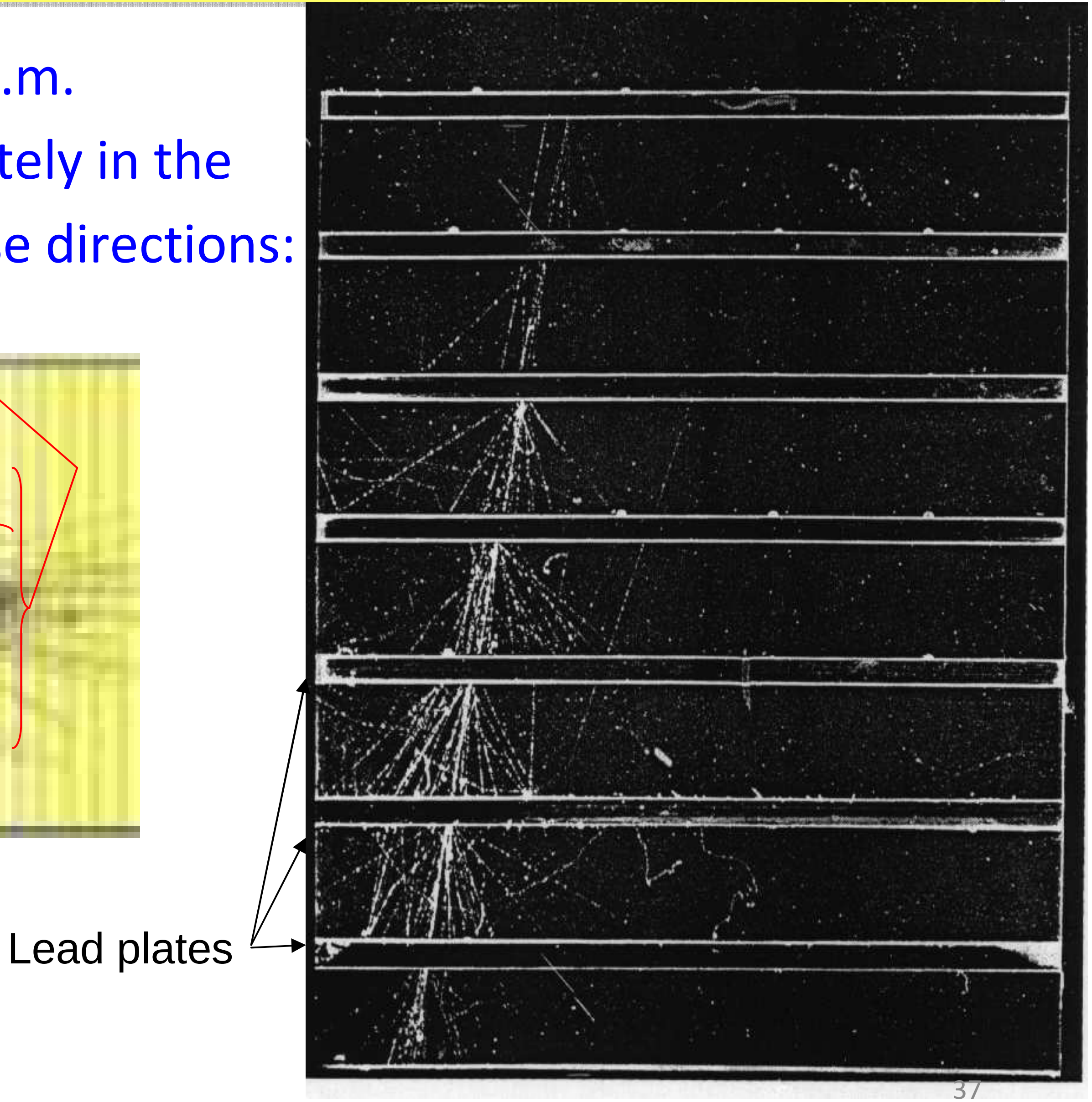




2-6 Electromagnetic showers

The development of the e.m. showers is treated separately in the longitudinal and transverse directions:





2-6 Electromagnetic showers

E.M. shower properties:

- Longitudinal energy deposition:

  $$\frac{dE}{dt} = E_0 c t^{\alpha} \exp(-\beta t), \text{ where } t = X / X_0 \text{ and}$$

  $$\beta \approx 0.5,\ \alpha \approx \beta t_{\max},\ \text{and c} = \beta^{\alpha+1} / \Gamma(\alpha+1)$$

  vary logarithmically with energy

- Transverse energy deposition:

  - Proportional to the Moliere Radius: $R_M = 21\ (\mathrm{MeV}) \times \dfrac{X_0}{E_c}$

  - Radial distribution in R_M independent of material used!

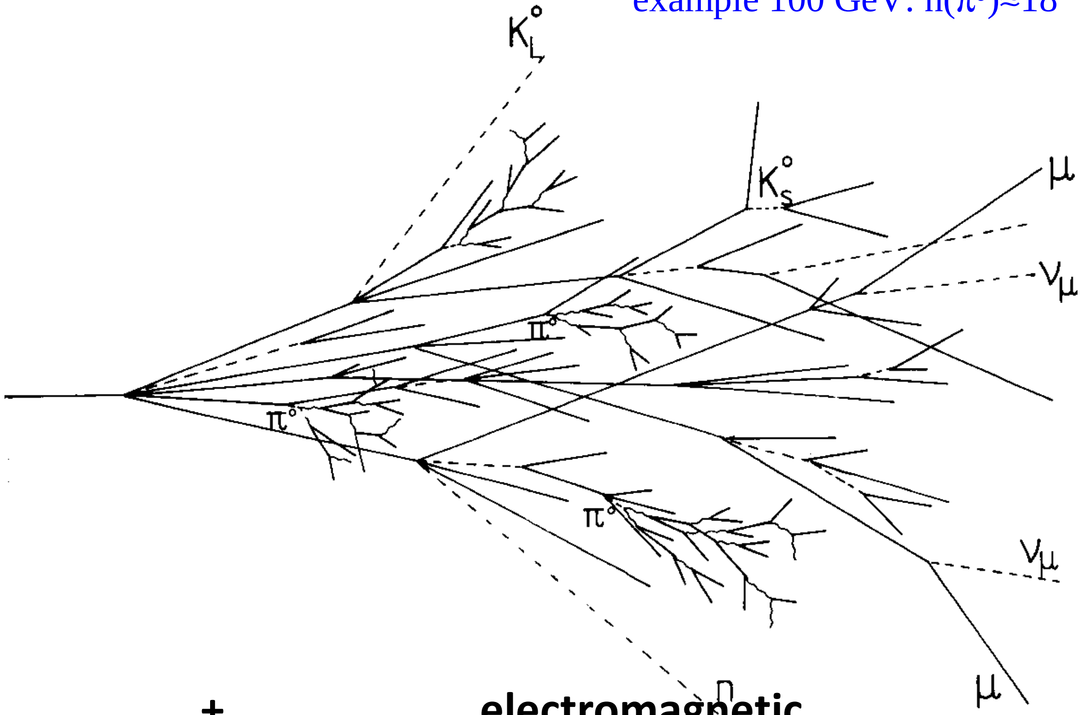
  - 99% of energy is inside a radius of 3.5 R_M.

  - 10% of energy is outside a radius of 1 R_M.

2-7 Hadronic showers

Complicated processes involving many interaction types!!!

example 100 GeV: n(π^0)≈18



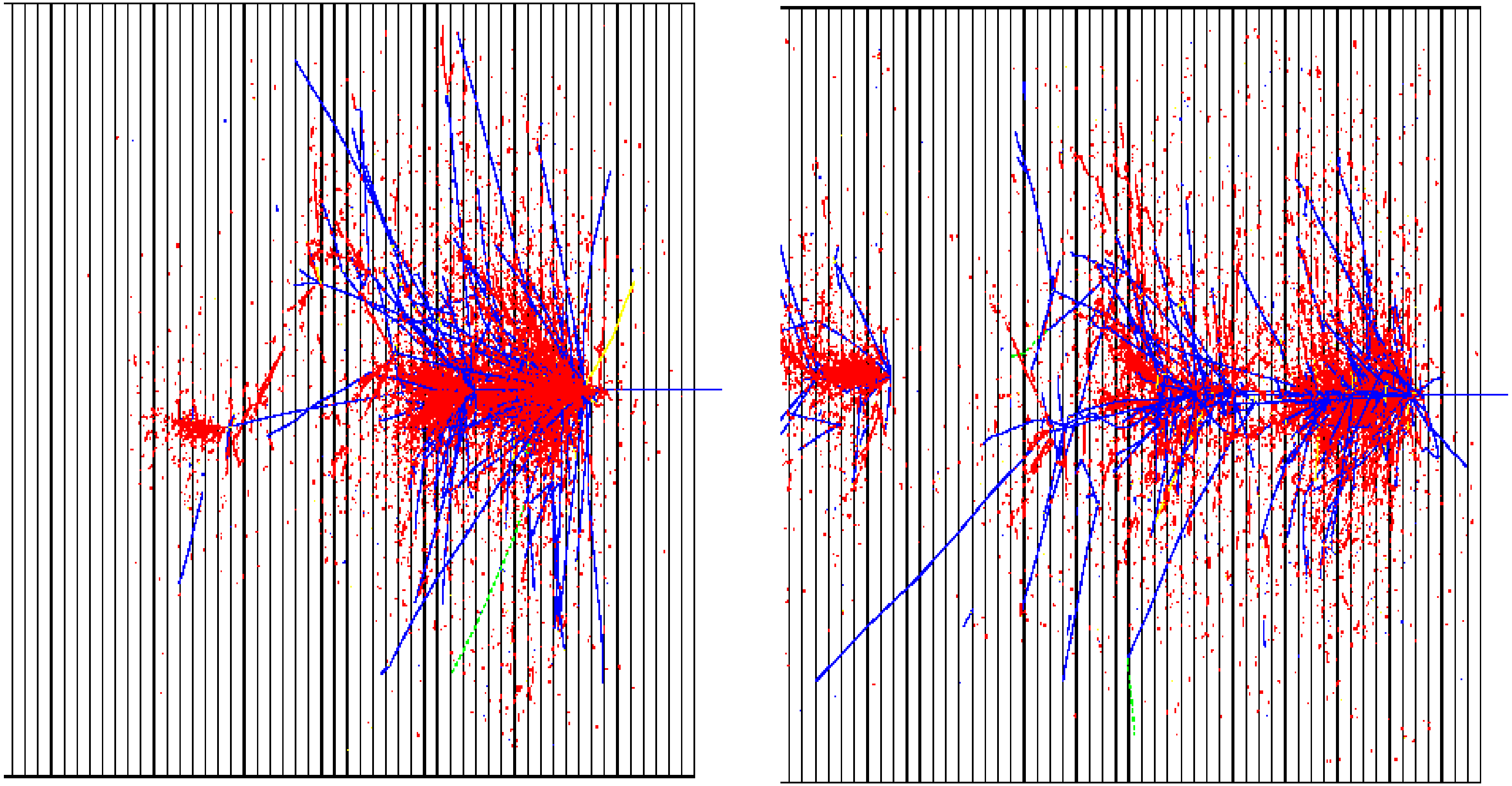
Hadronic + **electromagnetic**

charged pions, protons, kaons ….
Breaking up of nuclei
(binding energy), neutrons,
neutrinos, soft γ's
muons …. → invisible energy

neutral pions → 2γ →
electromagnetic cascade

2.7 Hadronic showers

150 GeV Pion Showers in Cu



red - e.m. component
blue - charged hadrons

3- The basic detectors

Passage of particles through matter (summary):

- When particles pass through matter many interaction processes are involved which may result in energy loss, particle deflection, shower development, various types of radiation emission etc.
- Some of those processes are destructive (absorption or conversion of the incident particle, complete energy absorption) while others just result in attenuation:

  - calorimeters are used to measure the energy by absorbing possibly all the incident energy

  - tracking detectors exploit small energy deposit to locate the particles in time and space

Key parameters of detectors are sensitivity, response, resolution (energy, time, space), efficiency, dead time

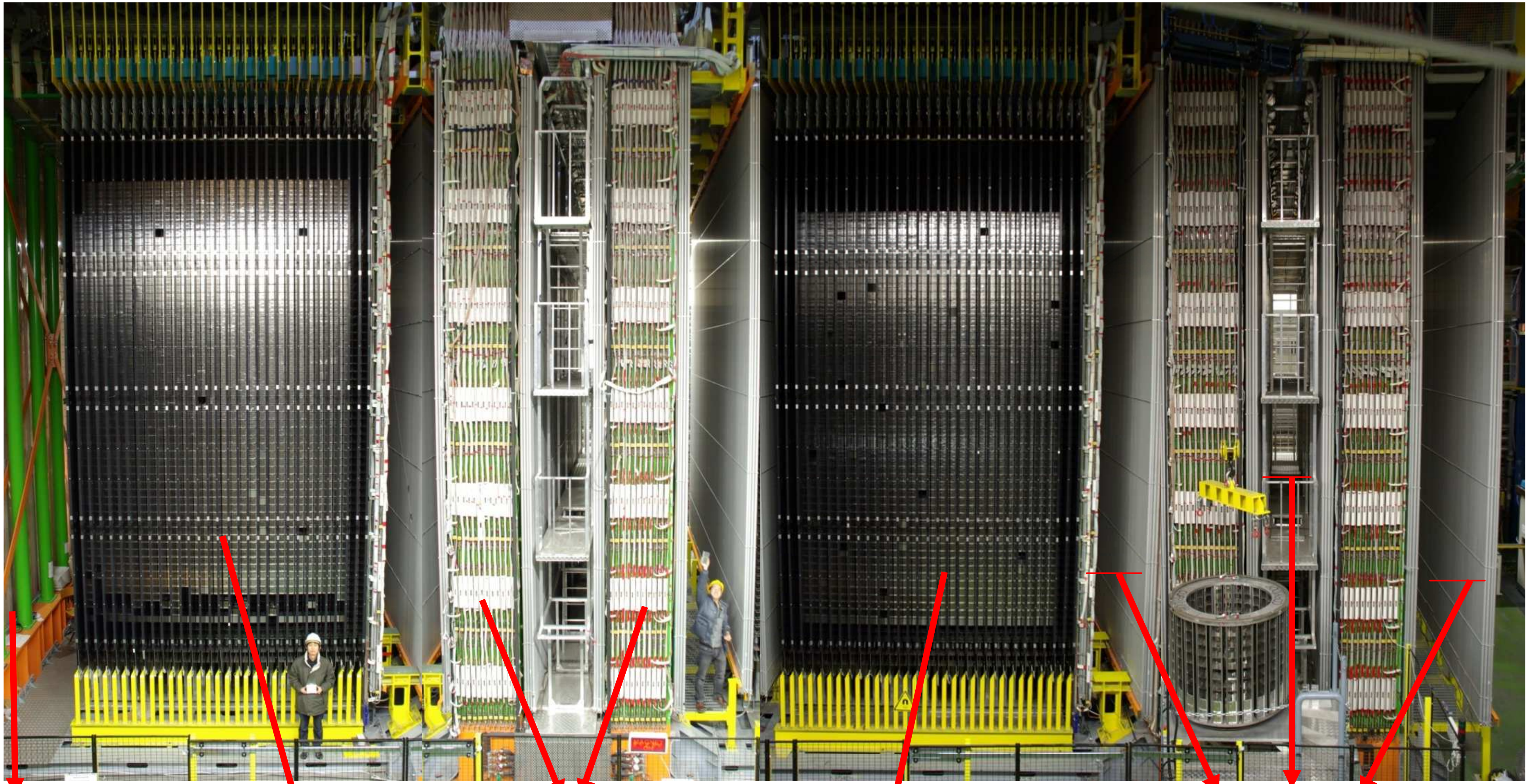
3- The basic detectors

Basic detectors currently used in High Energy Physics (HEP):

- Ionization detectors (gaseous and liquid)
  - proportional counters
  - Multi Wire Proportional Chamber (MWPC)
  - Drift and Time Projection Chamber (TPC)
- Scintillation detectors
  - organic scintillators
  - inorganic scintillators
  - gaseous scintillators
- Photosensors
  - photomultipliers
  - hybrid photodetectors
- Semi-conductor detectors

3- The basic detectors

SM1 SM2



VETO : RPCs

Magnet & Resistive Plate Chambers

Precision Tracker : drift tubes

Target Tracker : plastic scintillators + photodetectors

3-1 Ionization detectors

General features:

- Direct measurement of ionization losses
- Transparent detectors (not too much material on the path of the particles)
- Possibility of fine readout segmentation

  ➔ tracking, spectrometry (+ B-field)

Energy losses mechanisms of a charged particle p:

1. Excitation of an atom X: X+p -> X* + p

   It is a resonant reaction which happens only when the correct amount of energy is transferred. Typical cross sections for noble gases at the resonance 10^{-17} cm2

   No ions are created but the excited atom can participate later in further reactions with other atoms resulting in ionization. De-excitation in general with a photon emission

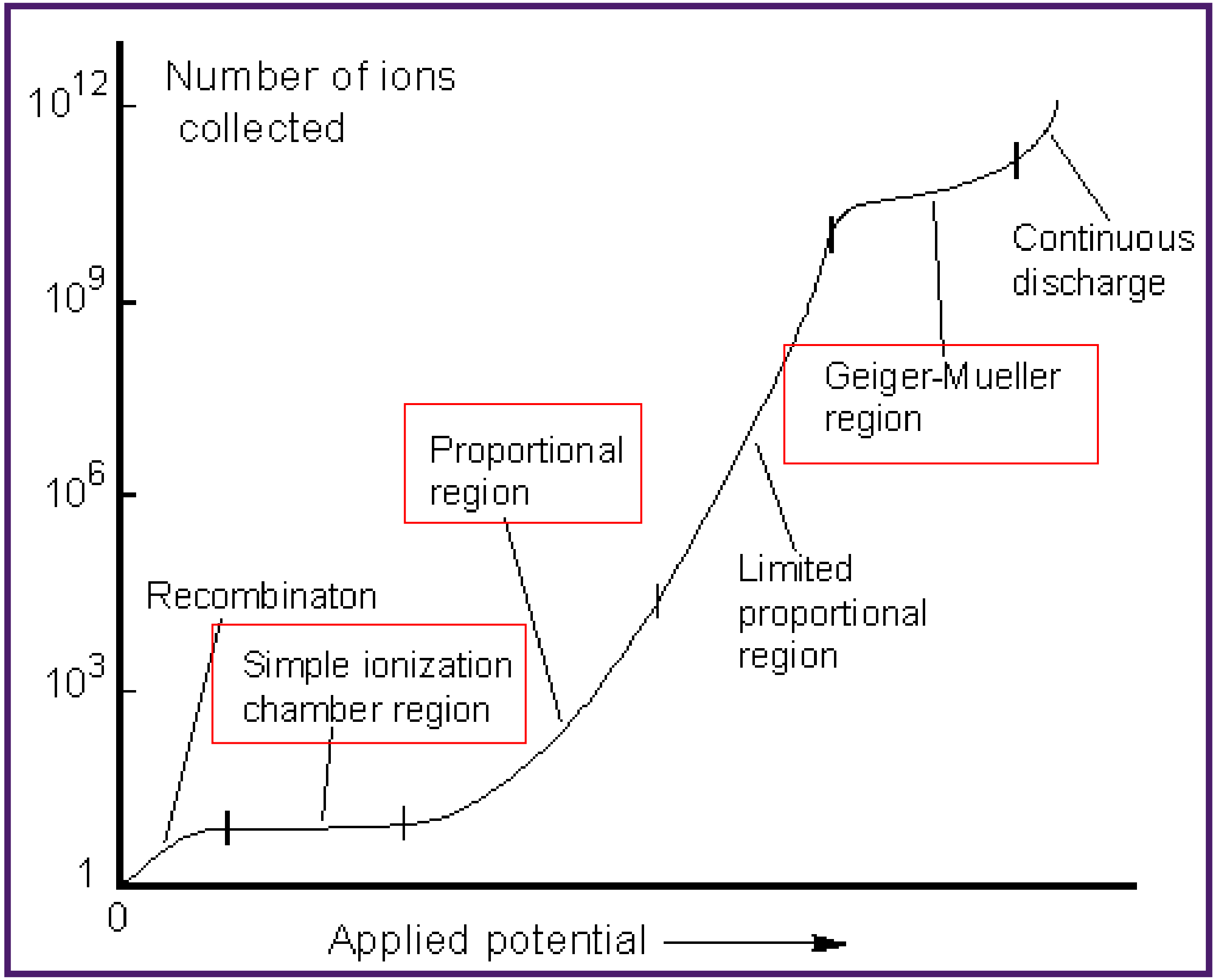
2. Ionization: $X+p \rightarrow X^{+} + p + e^{-}$

   No exact energy requirement (larger cross section 10^{-16} cm2), but there is an energy threshold which is relatively high (energy transferred > ionization potential).

   Since low energy transfers are the most probable the excitation reactions generally dominate

3-1 Ionization detectors

Collection versus applied E-field :



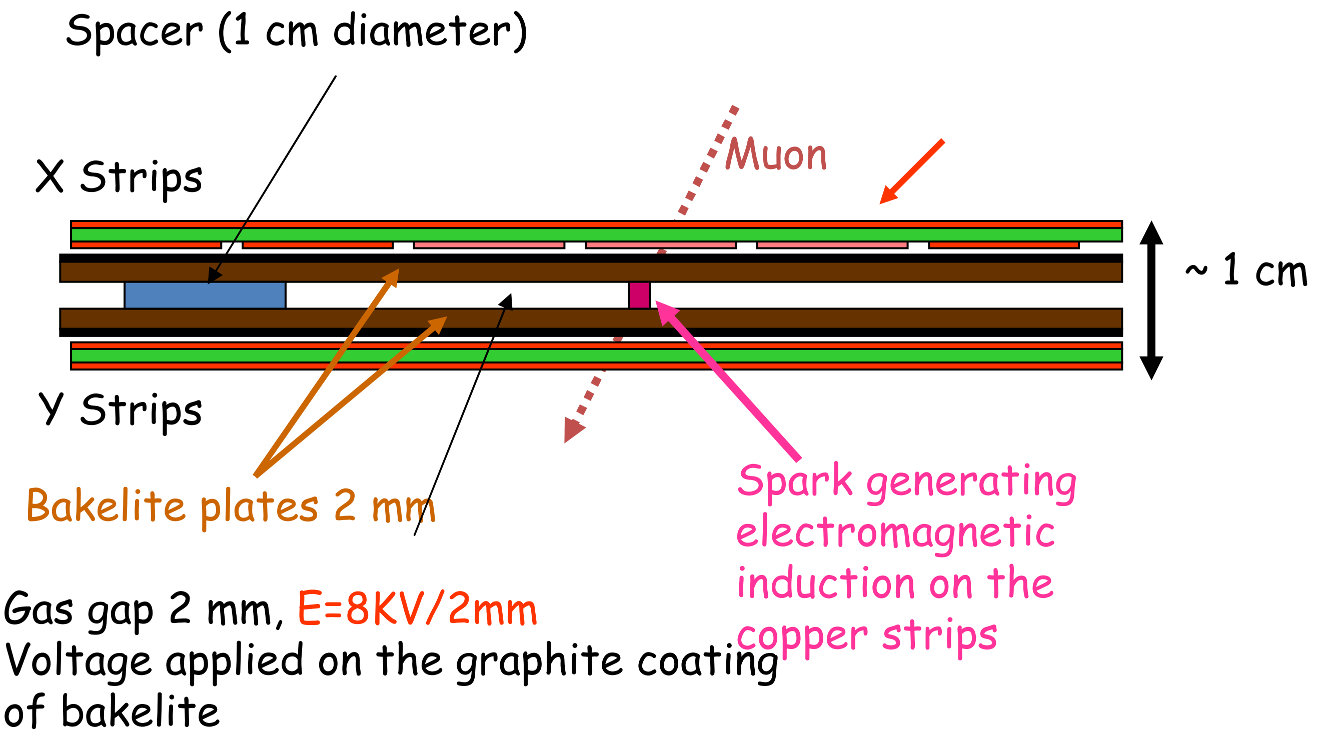
3-1 Ionization detectors

Collection versus applied E-field :

1. Ionization chamber region : electron-ion pairs may be collected before they recombine. All pairs are collected but the signal is small (application: measuring gamma ray exposure, radiation flux monitoring)
2. Proportional region: freed electrons induce further ionizations and generate a cascade or avalanche. The number of electron-ions created is proportional to the primary electrons.
3. If the voltage increases further charge space effect distorts the shape of the E-field and proportionality starts to be lost. At some point discharges (chain reaction of avalanches induced by emitted photons) occur which should be quenched! A plateau is observed where counting rates vary only slowly : Geiger-Müller region.

3-1 Ionization detectors

Some practical applications: RPC (Resistive plate counters)



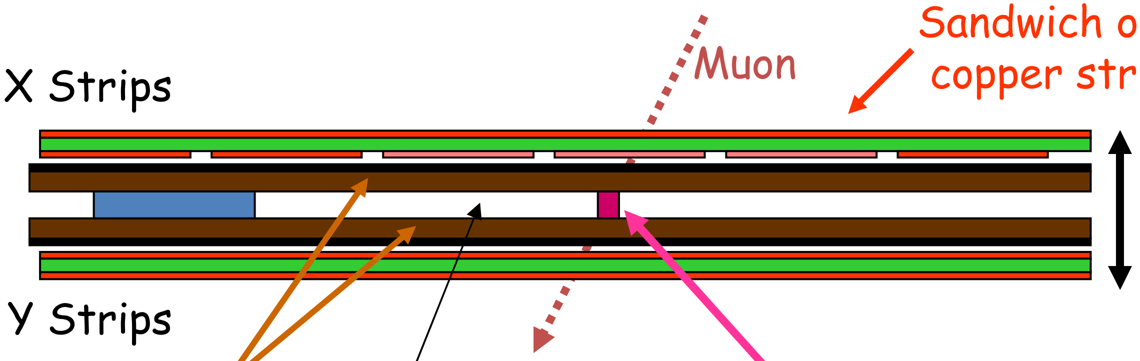
The streamer is confined in about 2 mm around the point where the particle passed. It creates a short circuit which discharges the bakelite. The bakelite will take few ms to recharge but only the hit region a few mm^2 will be dead.

Bakelite RPC

OPERA:
21 chambers
x 22 gaps =
1540 m^2 active
surface
per magnet

Each layer of RPC provides X and Y coordinates with ~ 1 cm accuracy

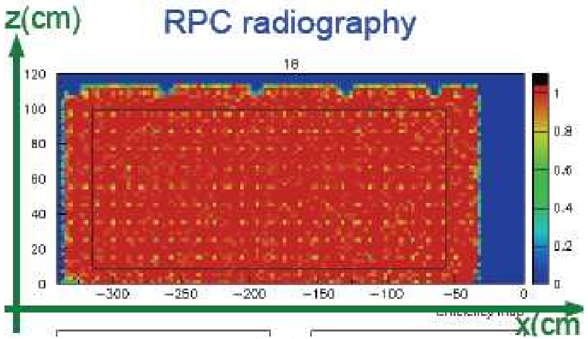
Sandwich of:
copper strips/insulator/copper plane



Bakelite plates 2 mm

Gas gap 2 mm, E=8KV/2mm

Spark generating electromagnetic induction on the copper strips



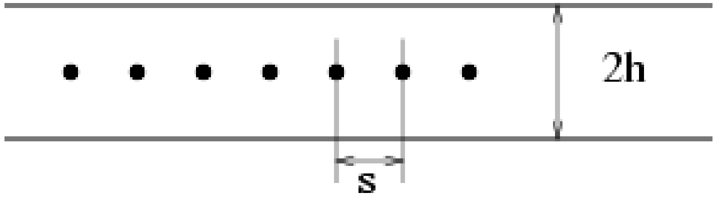
1.15 m

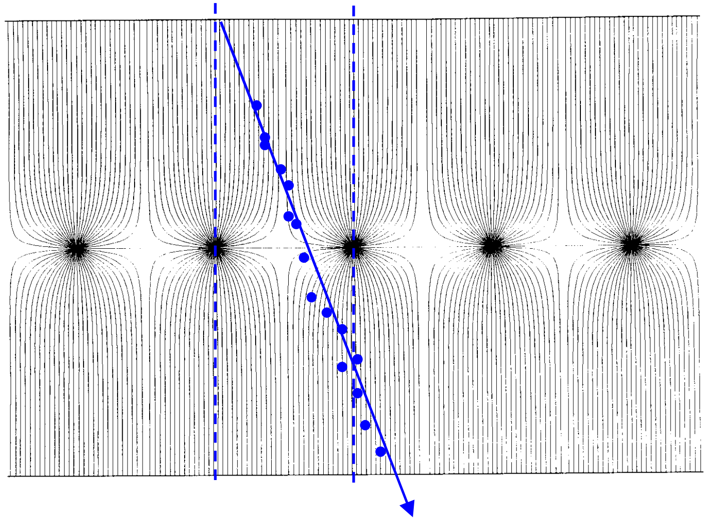
3.3 m

3-1 Ionization detectors

Some practical applications: MWPC (Multi-Wire Proportional Chambers)

- G. Charpak 1968, readout of individual wires and proportional mode working point.



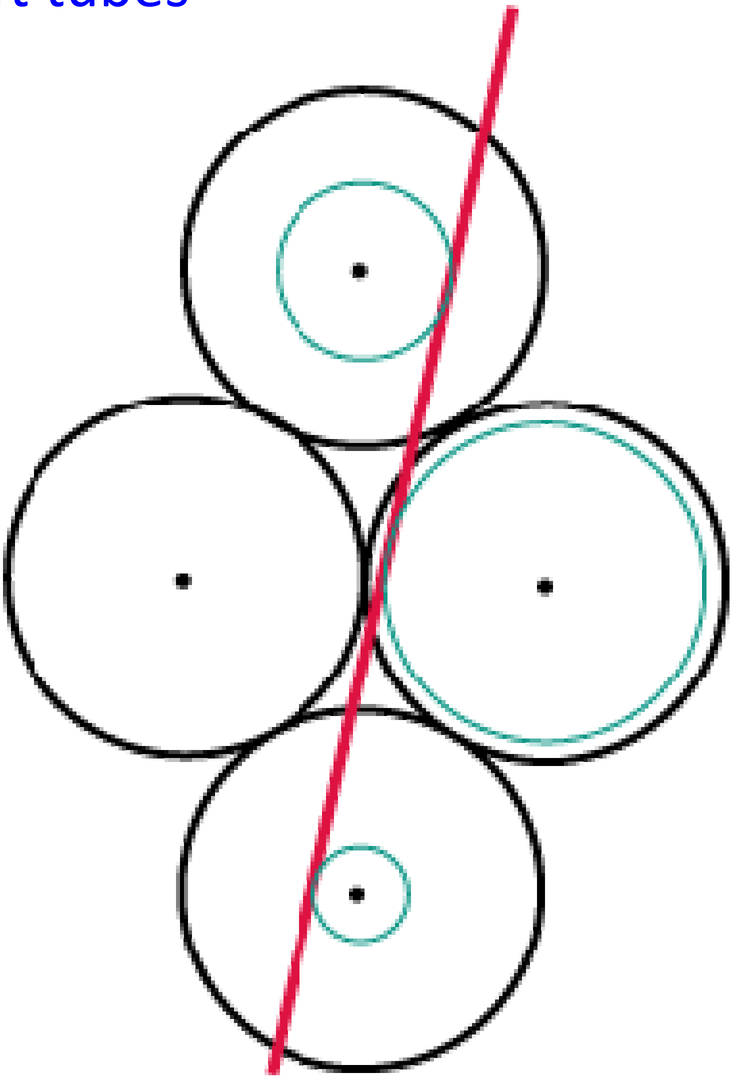


- In 1968 Charpak demonstrated that the MWPC works as many independent proportional tubes very close to each other.
  This opened the way to the world of completely electronic experiments with fine tracking and data acquired by computers.

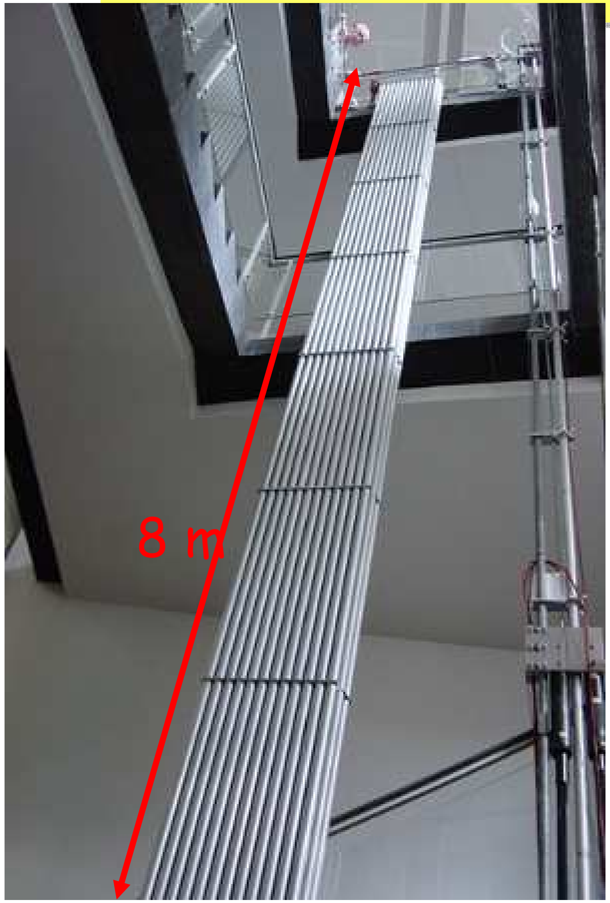
3-1 Ionization detectors

Some practical applications: precision drift tubes

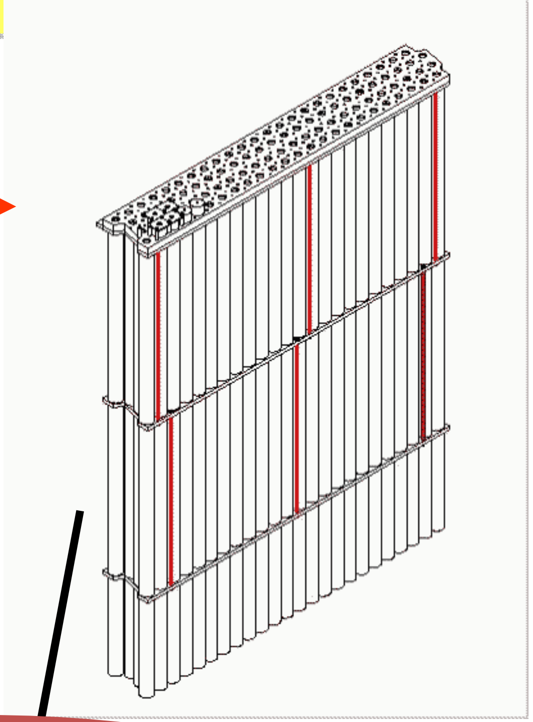
- Next idea: stack up proportional wire drift tubes, measure time of arrival of the ionization pulse
- Find track from tangents to circles
- Can get about 150 μm position resolution
- But: too much material!

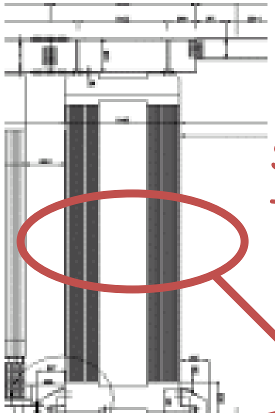


3-1 Ionization detectors

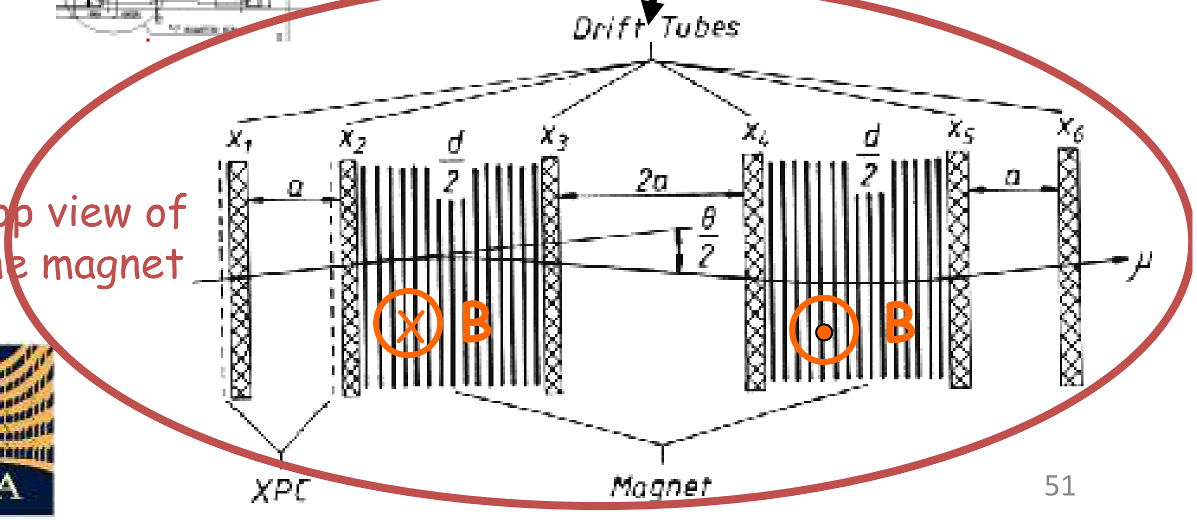


- **Tube :** vertical , ϕ = 38 mm, length 8 m , wire ϕ = 50 µm
- **Plane:** 4 staggered layers, each with 168 tubes





Side view of the magnet



Top view of the magnet

Performance:
- resolution: < 300 µm

3-2 Scintillation detectors

General features:

- Ionization energy losses ➔ scintillating materials produce light when traversed by charged particles (by luminescence).
- The light can be collected and transmitted to a photodetector with a light guide (e.g. optical fibres) or other means.
- In the photodetector the light is converted into an electrical pulse, first via the photoelectric effect and then with an amplification mechanism. The output signal can be easily readout.
- Typical materials:

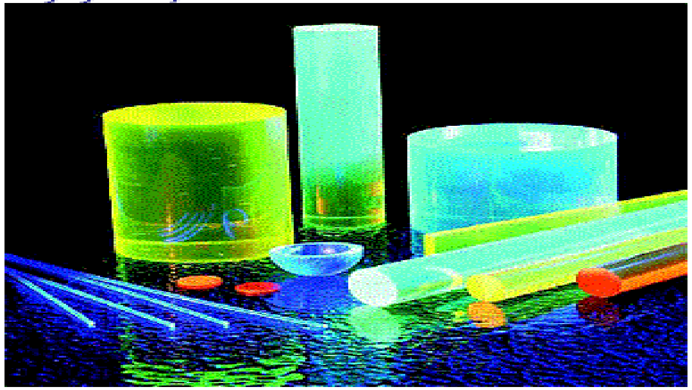
  - Inorganic, work at crystal level : large light yield but in general slow signals

  - Organic, work at molecular level plastic : smaller light yield but fast response (counters, TOF etc …)

3-2 Scintillation detectors

General features:

Inorganic (crystalline structure)	Organic (plastics or liquid solutions)
Up to 40000 photons per MeV	Up to 10000 photons per MeV
High Z	Low Z
Large variety of Z and ρ	ρ~1gr/cm^3
Undoped and doped	Doped, large choice of emission wavelength
ns to μs decay times	ns decay times
Expensive	Relatively inexpensive
E.m. calorimetry (e, γ) Medical imaging	Tracking, TOF, trigger, veto counters, sampling calorimeters.
Fairly Rad. Hard (100 kGy/year)	Medium Rad. Hard (10 kGy/year)



3-2 Scintillation detectors

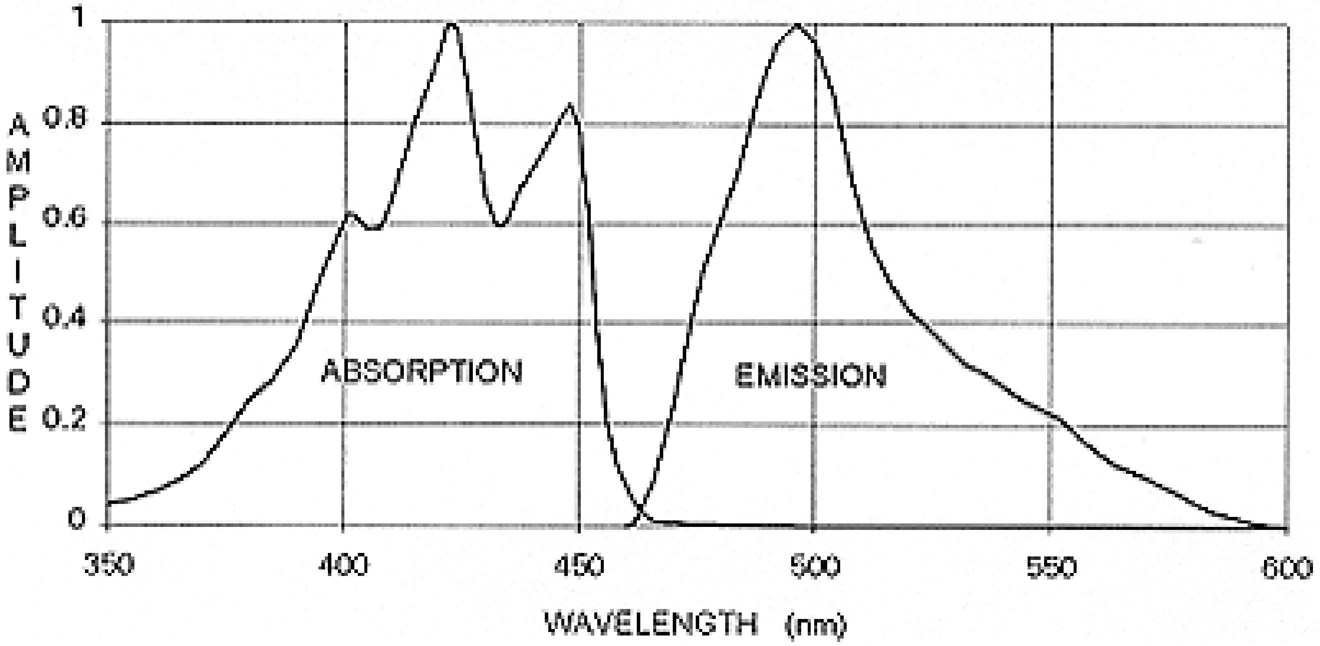
General features: in general the scintillator signal can provide many informations among which:

- Sensitivity to energy: Scintillators behave linearly with respect to the deposited energy ➔ light output proportional to ionization. In general also the photodetector is linear so the amplitude of the electrical signal will be proportional to the deposited energy
- Fast response: (response and recovery time short compared to other detectors), timing informations can be obtained with high precision (Time Of Flight, high counting rates)
- Pulse shape discrimination: distinguish particles types by looking at the pulse shape (excitation of different fluorescence mechanisms depending on the different ionization power: alpha,p, e-)

3-2 Scintillation detectors

Light emission mechanisms : organic scintillators

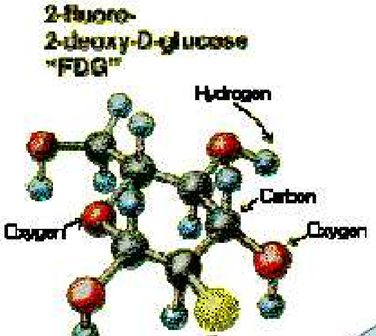
- Absorption and emission spectra may differ



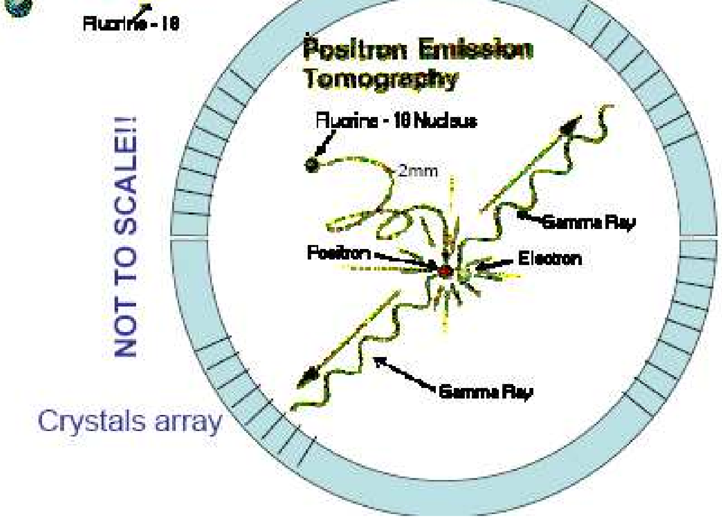
- Fluors are usually used dopants for wavelength shifting applications (they absorb UV-light and re-emit it as visible light)

3-2 Scintillation detectors

Applications : Positron Emission Tomography (PET)



http://www.medical.philips.com/main/products/pet/products/gemini/clinicalimages/10/index.as



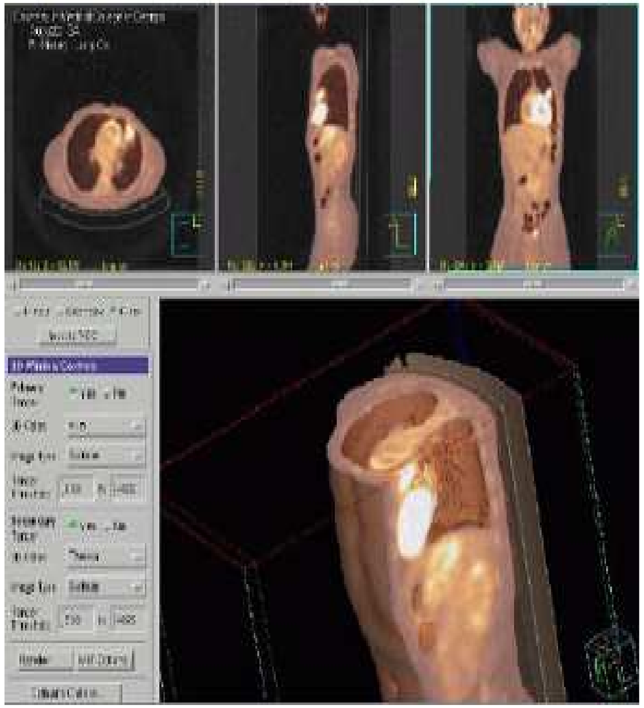
2 x 511 keV energy

γ-γ co-linearity

time coincidence

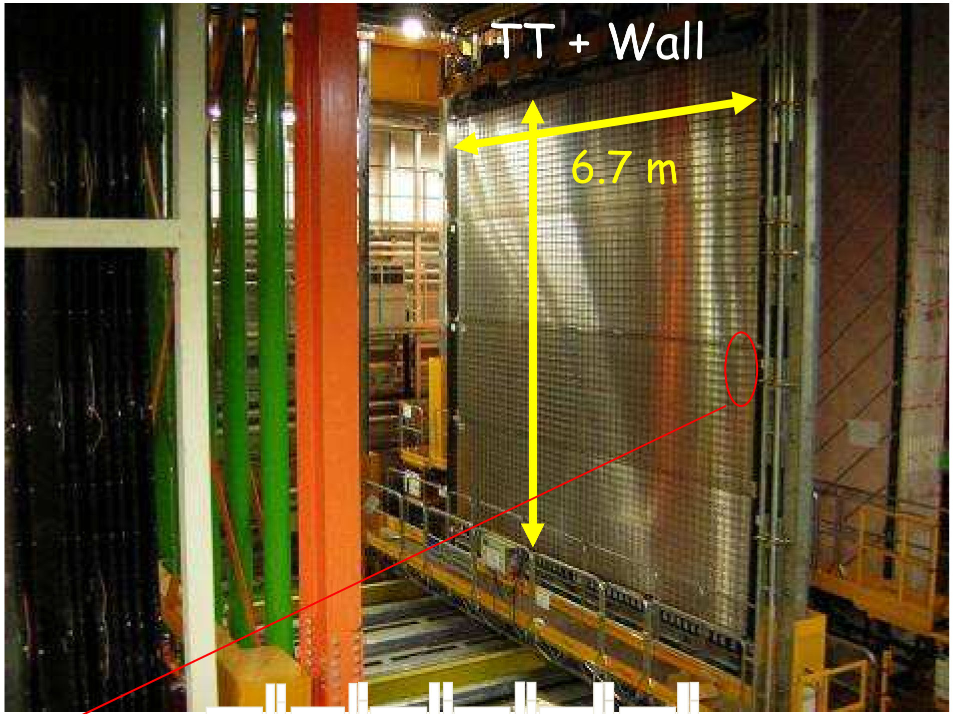
reconstruct functional image

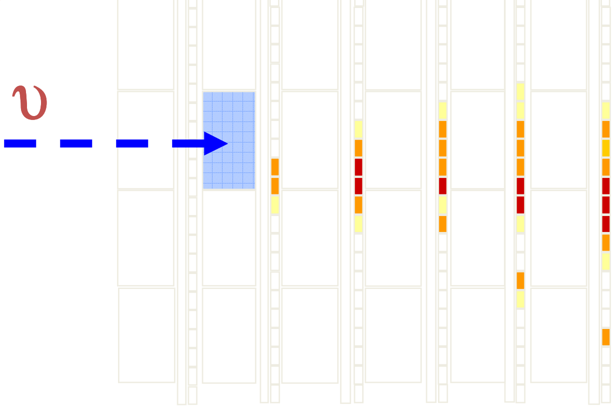
http://www.medical.philips.com/main/products/pet/products/gemini/clinicalimages



3-2 Scintillation detectors

Applications : tracking in HEP (OPERA target tracker)

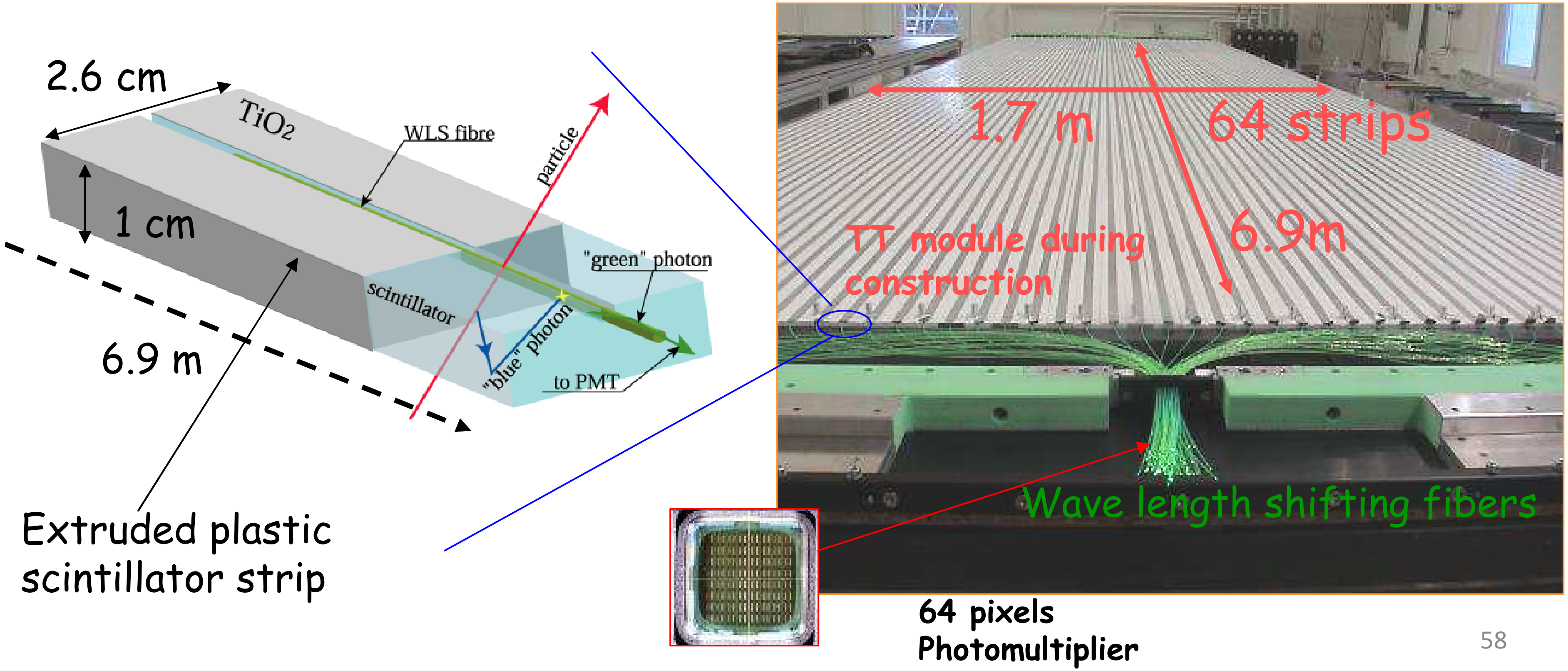




3-2 Scintillation detectors

Applications : tracking in HEP (OPERA target tracker)

It is the active part of the target which allows immediately to «see» the neutrino interaction and to find the brick. Scintillator strips emit light when crossed by particles. Light is collected by fibers. Fibers are read out by a photomultiplier which converts the light in electric signals



3-3 Photodetectors

General features:

- Typically only get a few photons at light detector due to passage of particle : requires single-photon sensitivity.
- Convert the light by photoelectric effect in electric pulses. The spectrum of applications goes from visible to UV.
- High sensitivity ➔ quantum efficiency: $Q.E.=N_{p.e.}/N_{photons}$

- Main photodetectors types :
  - Photomultiplier tube (under vacuum)
  - Avalanche photo-diode (solid state)
  - Hybrid photodiode

3-3 Photodetectors

General features: three main steps of the photodetection

1. Photoelectric conversion at the level of the photocathode deposited on the entrance window :

   photons ➔ photo-electrons

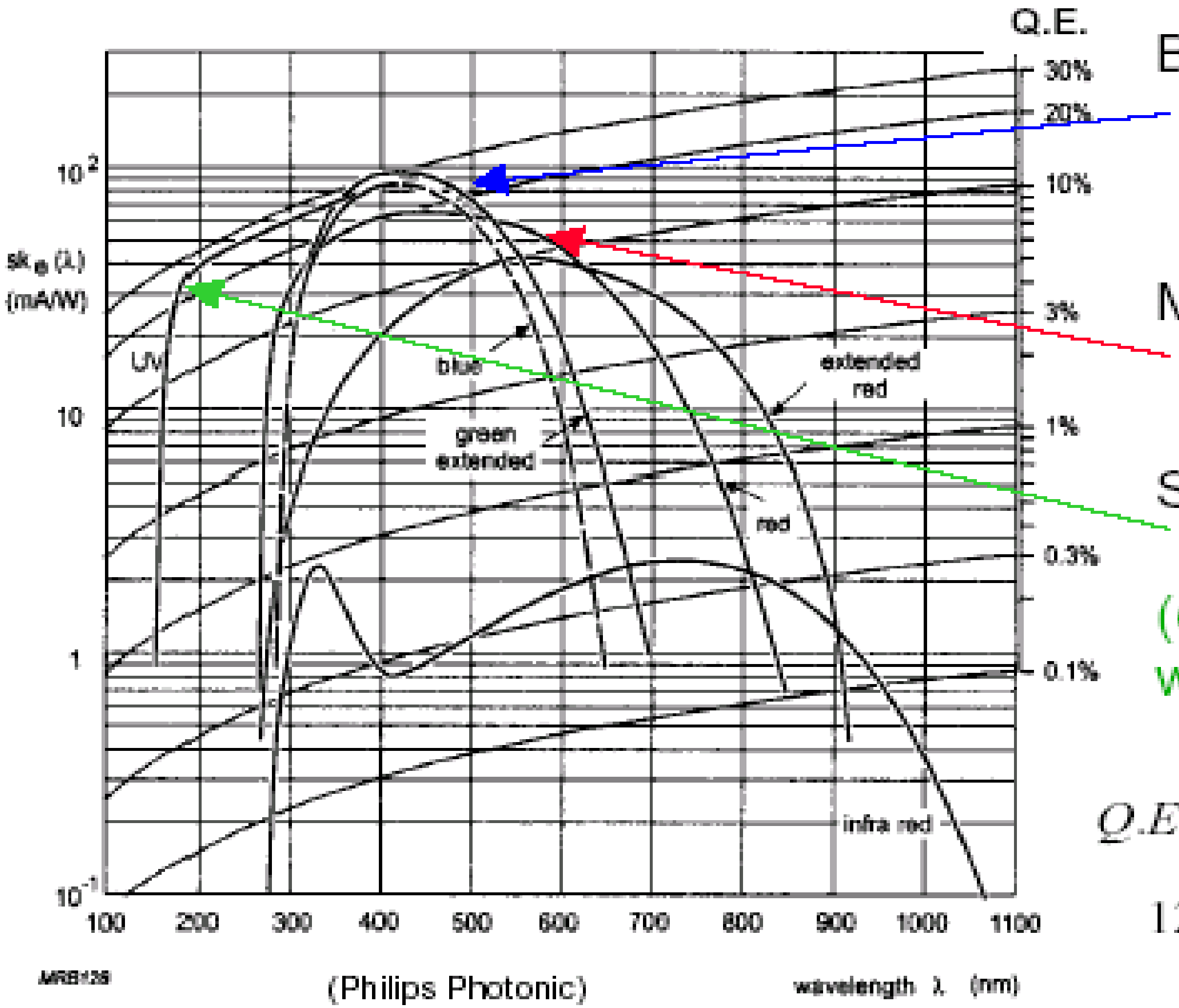
   (this stage is common to many photosensors)

2. Photo-electrons amplification : from few p.e.'s to detectable charge or current signal (different stage)

3. Electrical signal readout (preamplification/amplification/shaping and buffering/digitization) : 1st stage specific to each type

3-3 Photodetectors

1/ Photocathode emission spectrum :



(Philips Photonic)

Bialkali

SbK$_2$Cs

SbRbCs

Multialkali

SbNa$_2$KCs

Solar blind

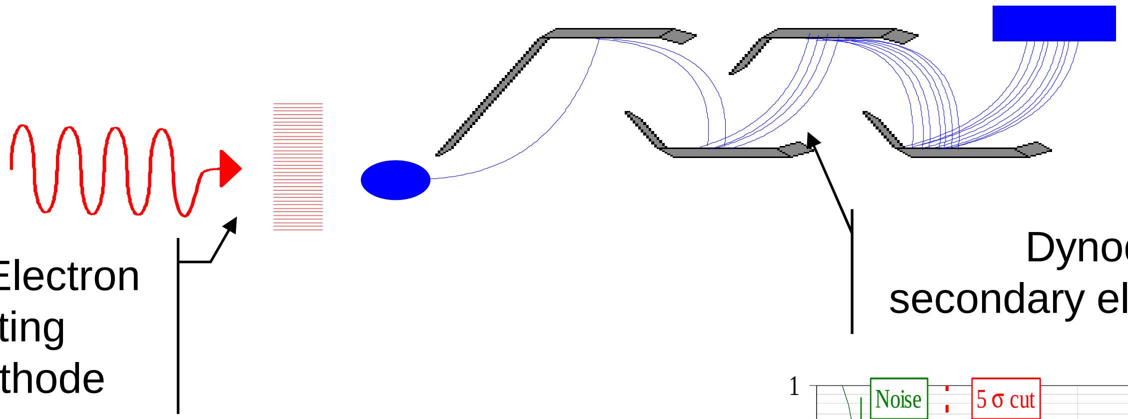
CsTe

(cut by quartz window)

$$Q.E.(\%) \approx 124 \cdot \frac{sk_e(mA/W)}{\lambda(nm)}$$

3-3 Photodetectors

2/ Multiplication in PhotoMultiplier Tubes (PMTs)



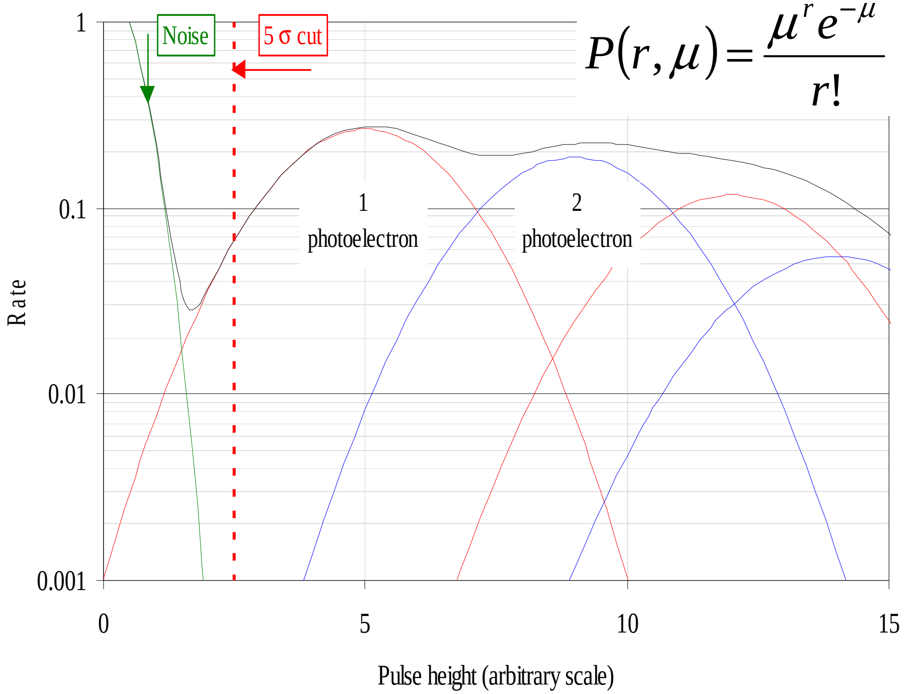
Anode

Photon-to-Electron
Converting
Photo-Cathode

Dynodes with
secondary electron emission

- When a photoelectron strikes dynode several electrons emitted (on average) n~5 ➔ Several dynodes (~10) give high gain (10^6 to 10^7)
- The final signal is collected at the anode level
- Transient time spread ≈ 200 ps

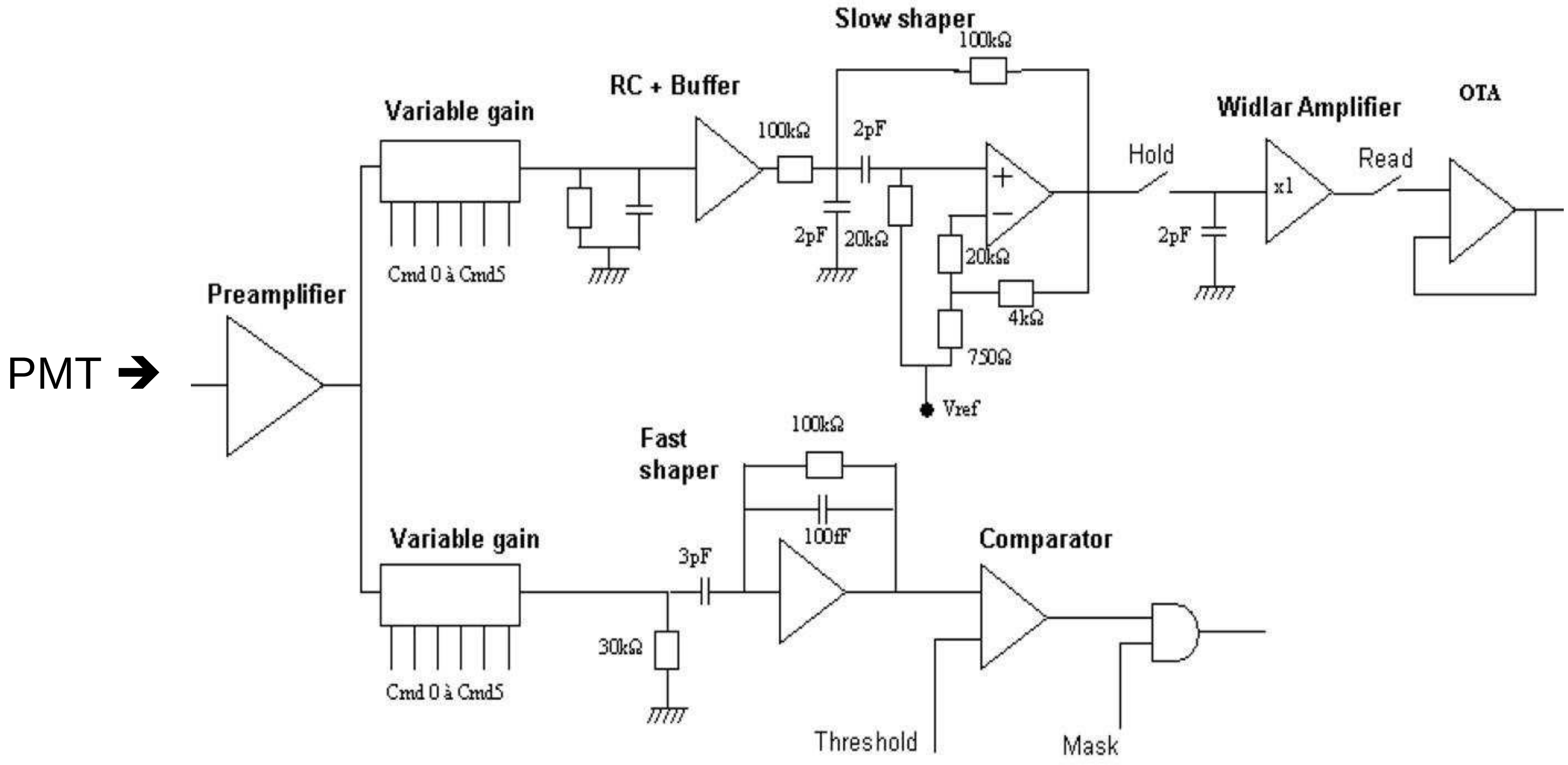
$$P(r,\mu)=\frac{\mu^r e^{-\mu}}{r!}$$



3-3 Photodetectors

3/ Electronic readout : auti-triggered chain

- 1st stage: preamplifier (gain compensation if required)
- 2nd stage: fast (trigger generation) and slow shaping (Q readout)
- Towards digitization : MUX + ADC



3-4 Conclusions

- Passage of particles through matter involves many basic physics processes
- Particles detection (almost)* always requires an action on the particle (energy absorption, modified trajectory, particle annihilation etc)
- * non interacting particles (neutrinos) may be identified and measured through missing quantities (energy, momentum, transverse energy etc)
- HEP involves large apparatus but requires a lot of expertise in laboratory-scale detectors…