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

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1. **Buts des détecteurs**

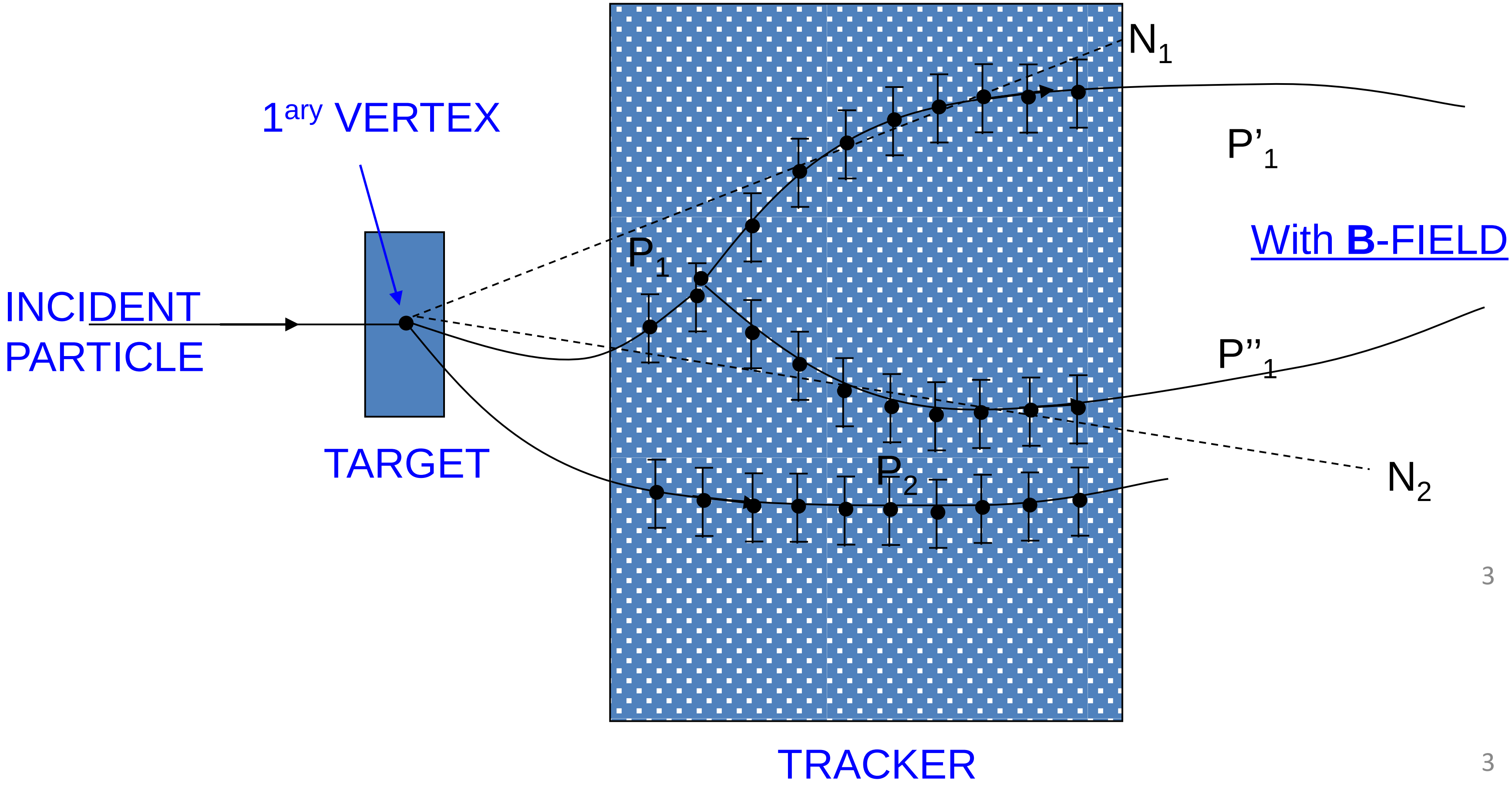
2. **Interaction particules-matière**
    1. Perte d’énergie par collisions atomiques
    2. Perte d’énergie des électrons
    3. Diffusion multiple
    4. Radiation Cerenkov
    5. Interactions des photons
    6. Gerbes électromagnétiques
    7. Gerbes hadroniques

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

1- Introduction

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

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



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With **B**-FIELD

3

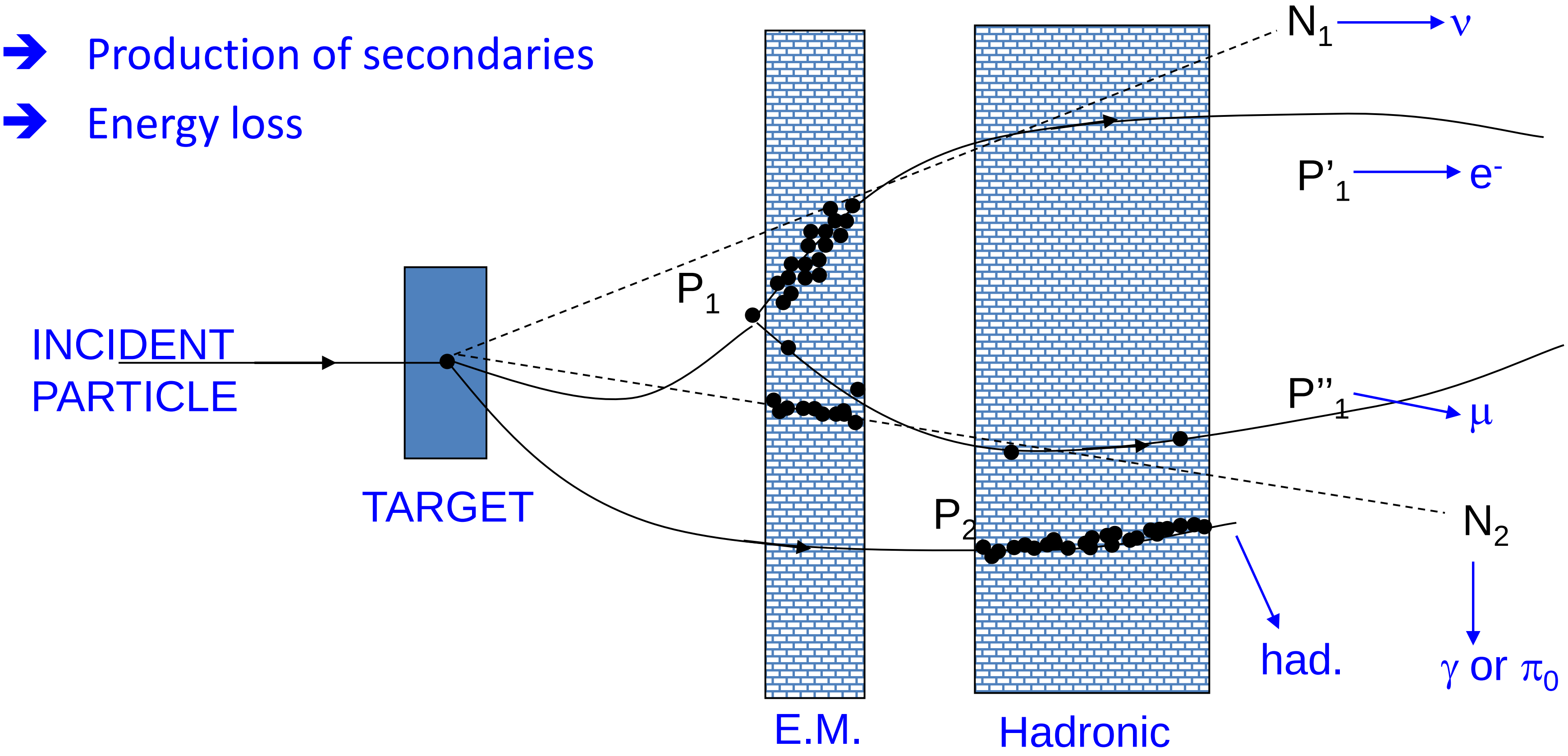
1- Introduction

Measuring particle's energy and interacting neutrals :

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

➔ Production of secondaries

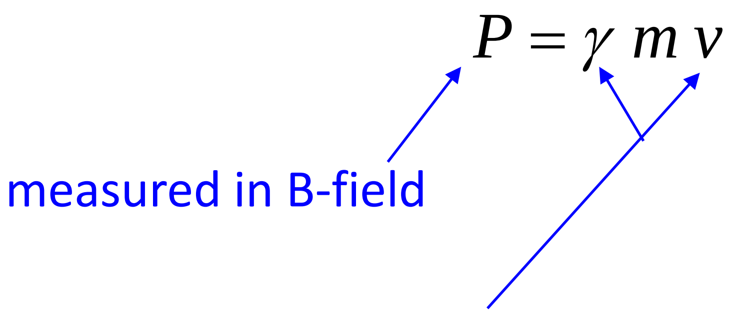
➔ Energy loss



- 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

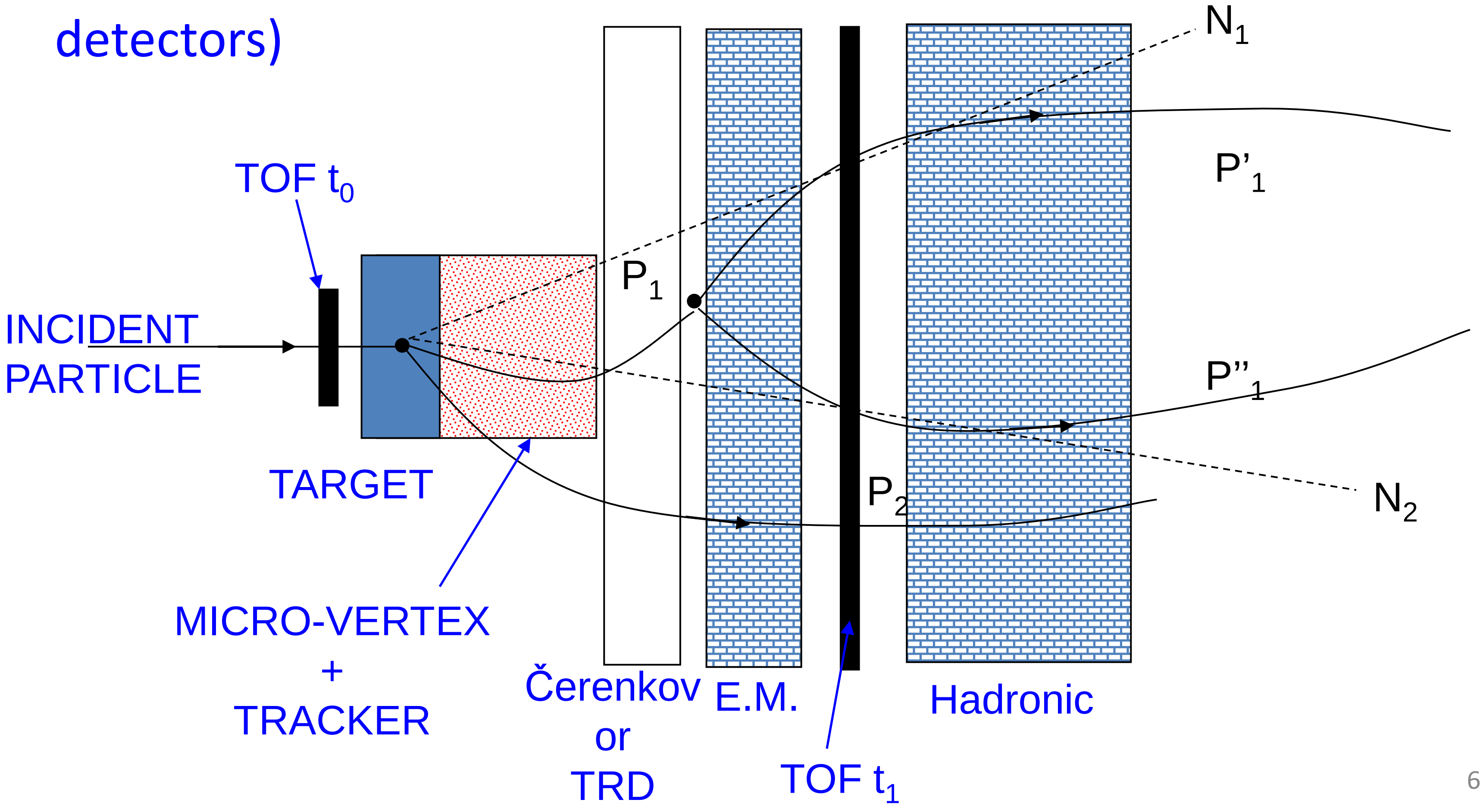
Velocity measurements techniques :

- 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

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 :

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

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 ≈ 0.5 A
1/ρ dE/dx ≈ 1.4 MeV cm ^{2}/g for ßγ ≈ 3

Example 1:
Scintillator: Thickness = 2 cm; ρ = 1.05 g/cm^3
Particle with βγ = 3 and Z=1
1/ρ dE / dx ≈ 1.4 MeV
dE ≈ 1.4 * 2 * 1.05 = 2.94 MeV

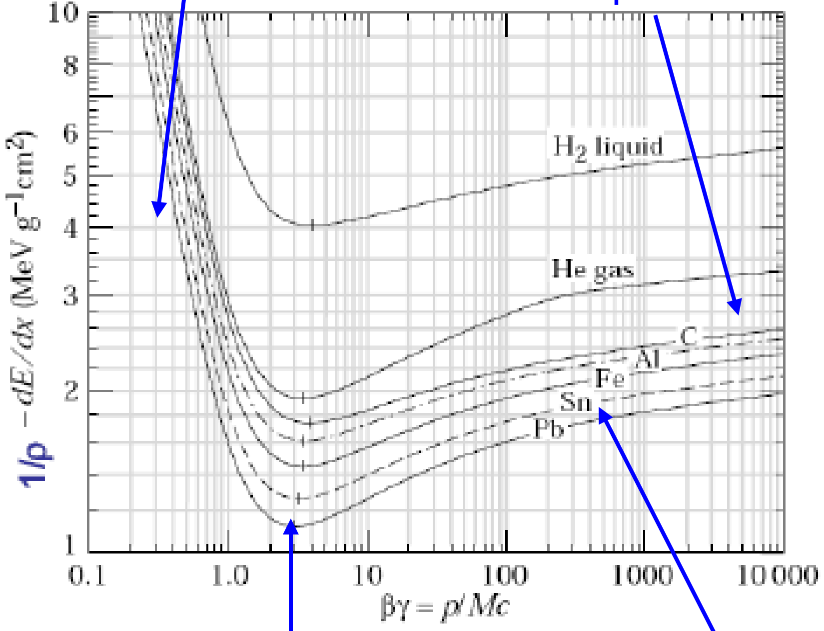
Example 2:
Iron: Thickness = 100 cm; ρ = 7.87 g/cm^3
dE ≈ 1.4 * 100* 7.87 = 1102 MeV

Example 3:
Energy Loss of a Carbon Ion with Z=6 and
Momentum of 330 MeV/c/Nukleon
in Water, i.e. βγ = p/m = 330/940 ≈ .35→
β ≈ .33
dE/dx ≈ 1.4 Z^2 /β^2 ≈ 460 MeV/cm→
Cancer Therapy !

"kinematical term"

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

"Fermi plateau"



"relativistic rise"

βγ ≈ 3-4
minimum ionizing particles, MIPs

2-1 Energy loss by atomic collisions

Stopping power :

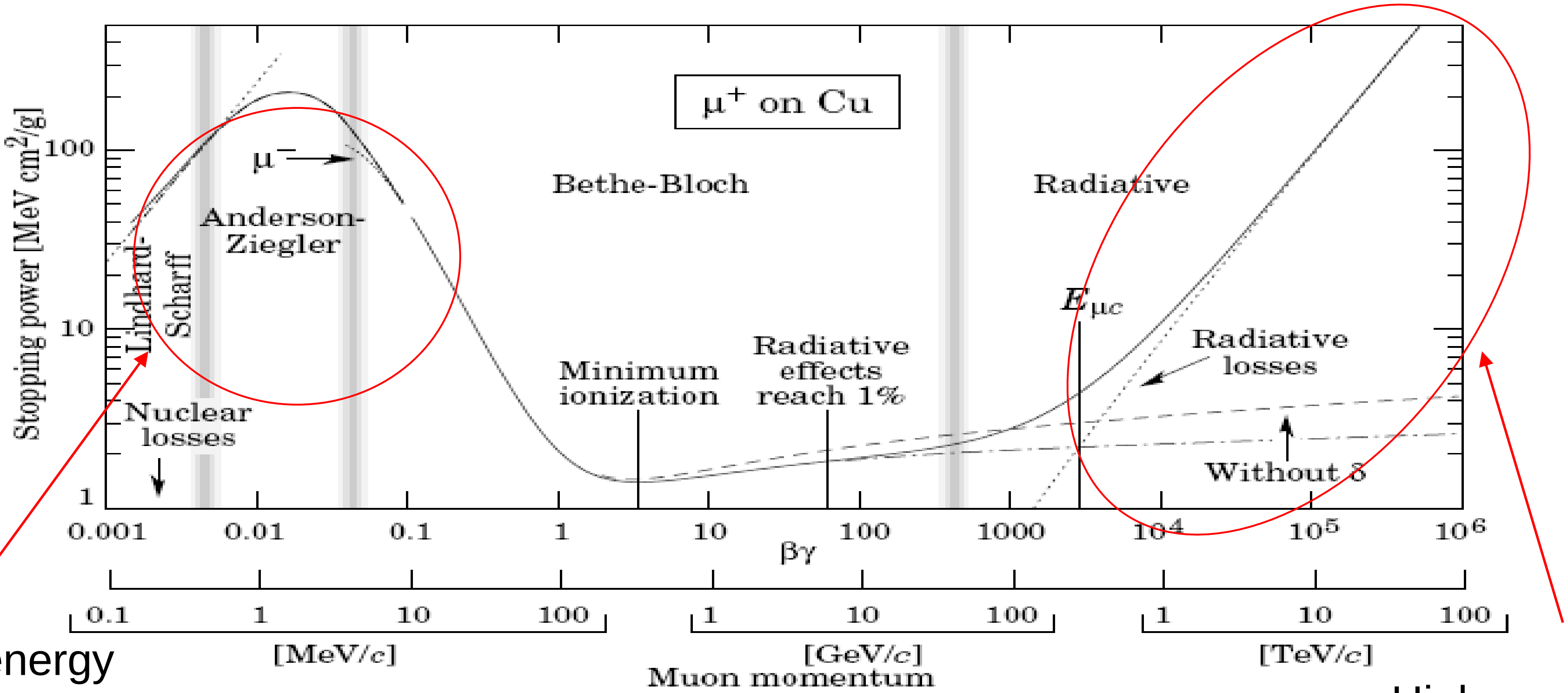


Fig. 27.1: Stopping power ($= \langle -dE/dx \rangle$) for positive muons in copper as a function of $\beta\gamma = p/Mc$ over nine orders of magnitude in momentum (12 orders of magnitude in kinetic energy). Solid curves indicate the total stopping power. Data below the break at $\beta\gamma \approx 0.1$ 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].

Low energy corrections needed

High energy radiative corrections important

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

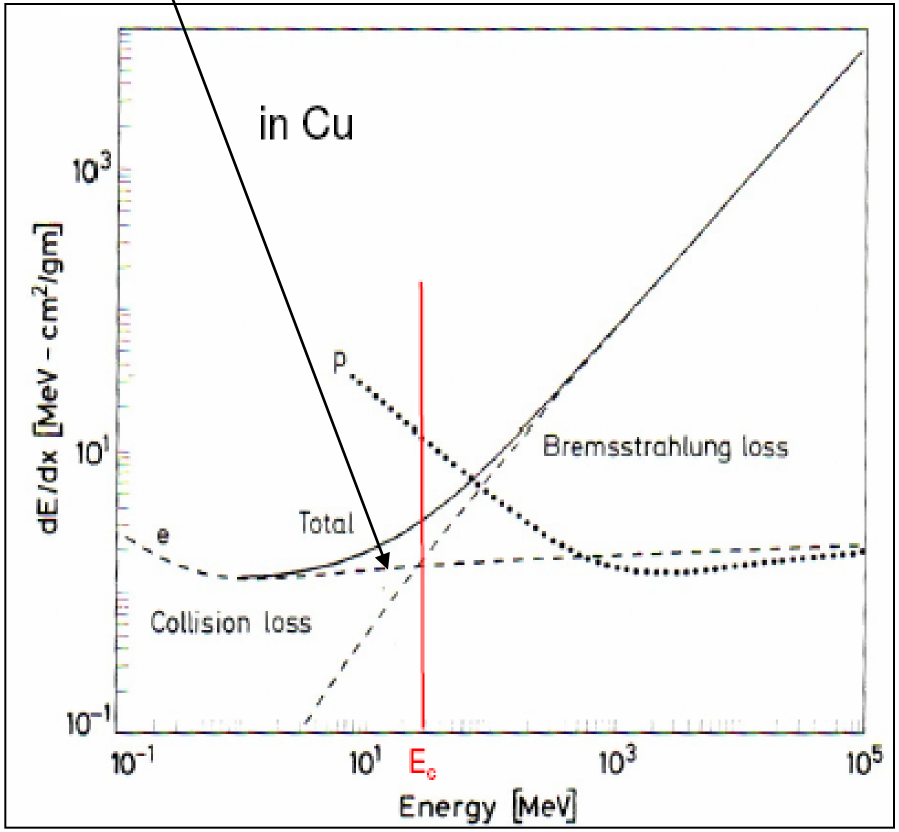
Modified Bethe-Bloch formula:

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

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

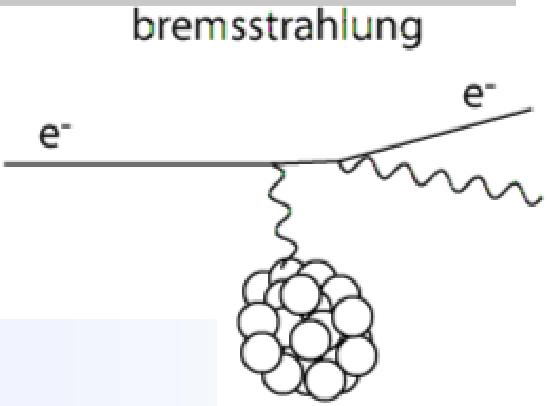
$F(\tau)$ differs for e^+ and e^-

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

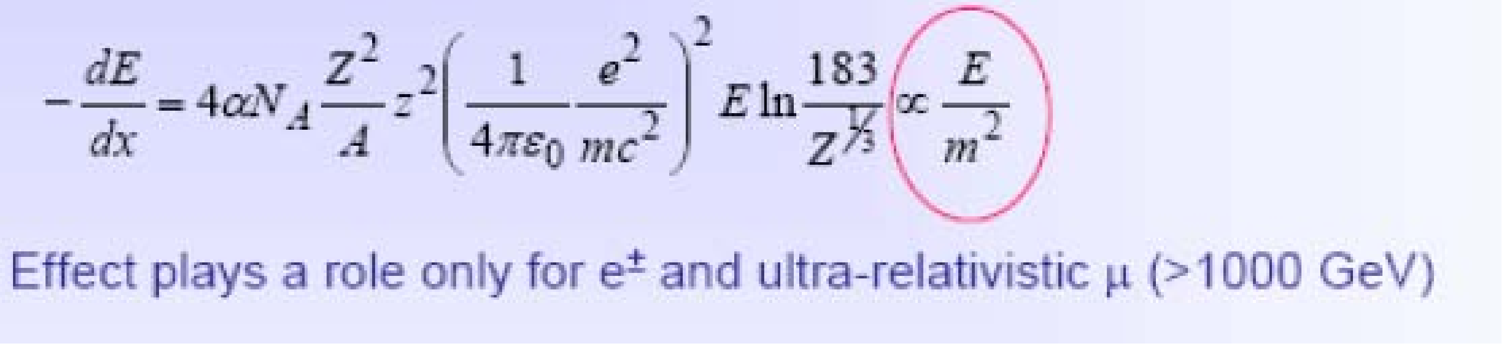


2-2 Energy loss of electrons

Bremsstrahlung (braking radiation) : a sketch



…and a formula :



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

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.

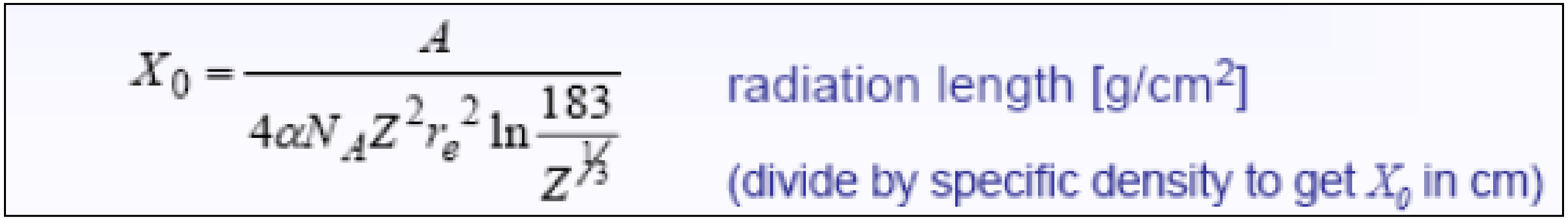
N.B. radial acceleration induces synchrotron radiation prop. to a^2

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



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

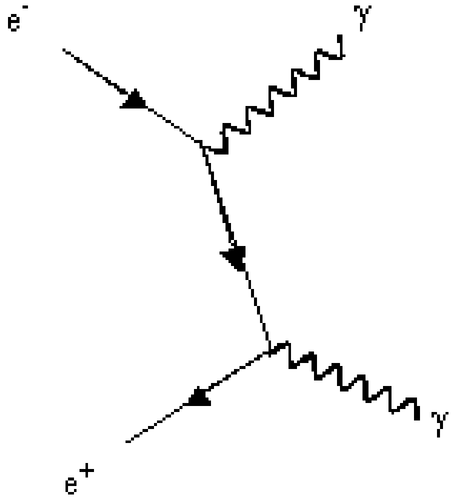
radiation length [g/cm^2]

(divide by specific density to get X_0 in cm)

2-2 Energy loss of electrons

Positron annihilation

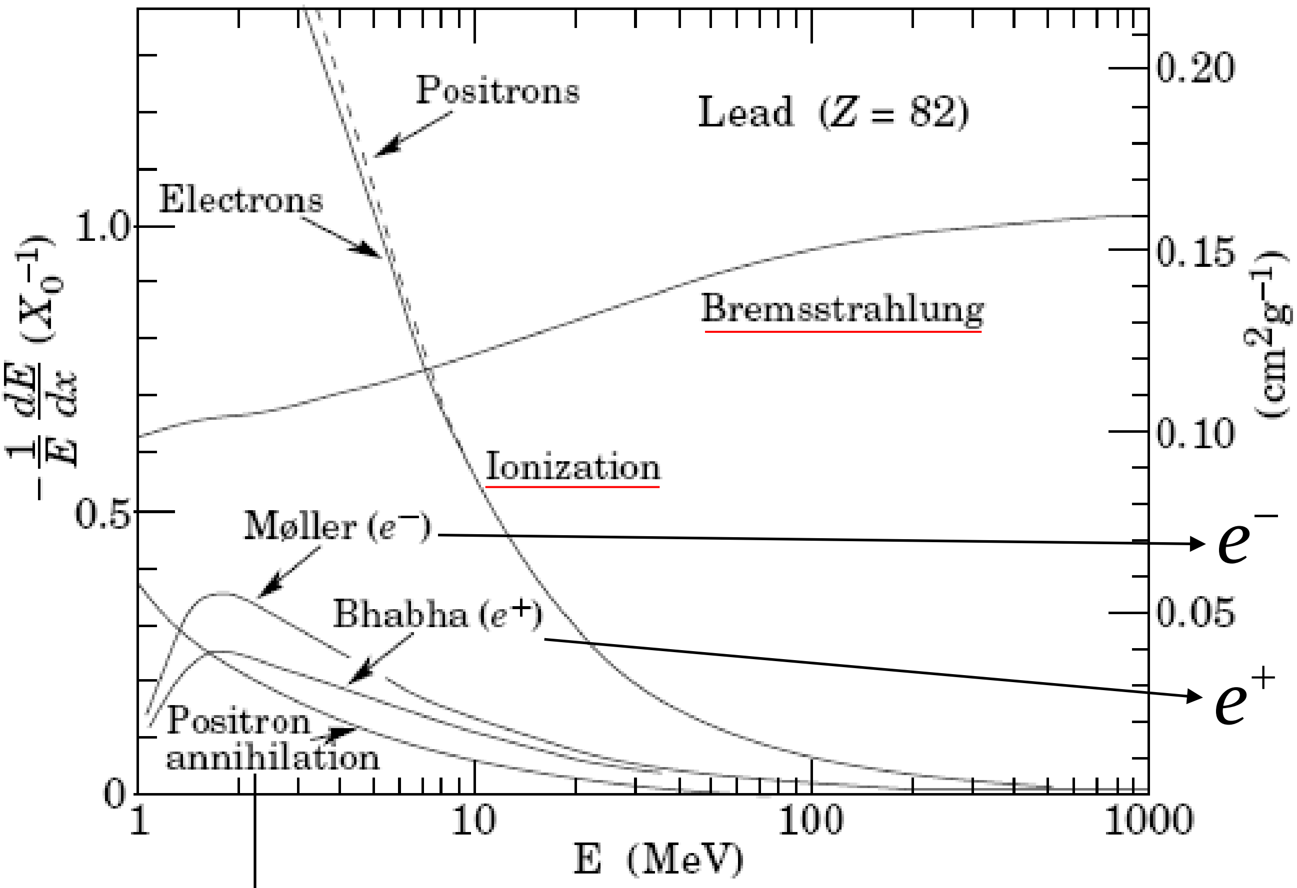
- In almost all cases, positrons that pass through matter annihilate with an electron,
  to create photons: $e^{+} + e^{-} \rightarrow \gamma + \gamma$



- 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:

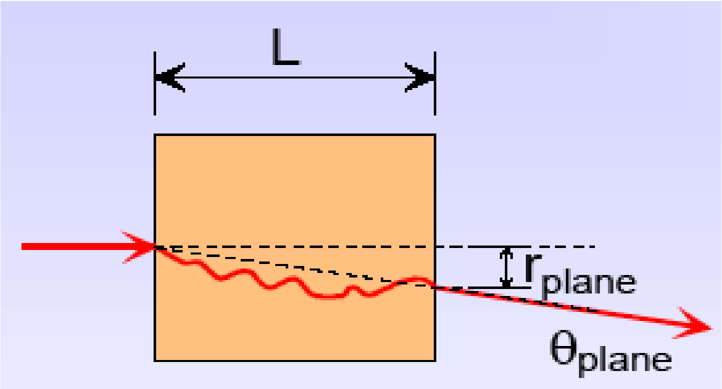
- Rutherford scattering formula (T.D.)

$$\frac{d\sigma}{d\Omega} = 4z^2Z^2r_e^2\left[\frac{m_ec}{\beta p}\right]^2 \frac{1}{\sin^4\theta/2}$$

  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

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

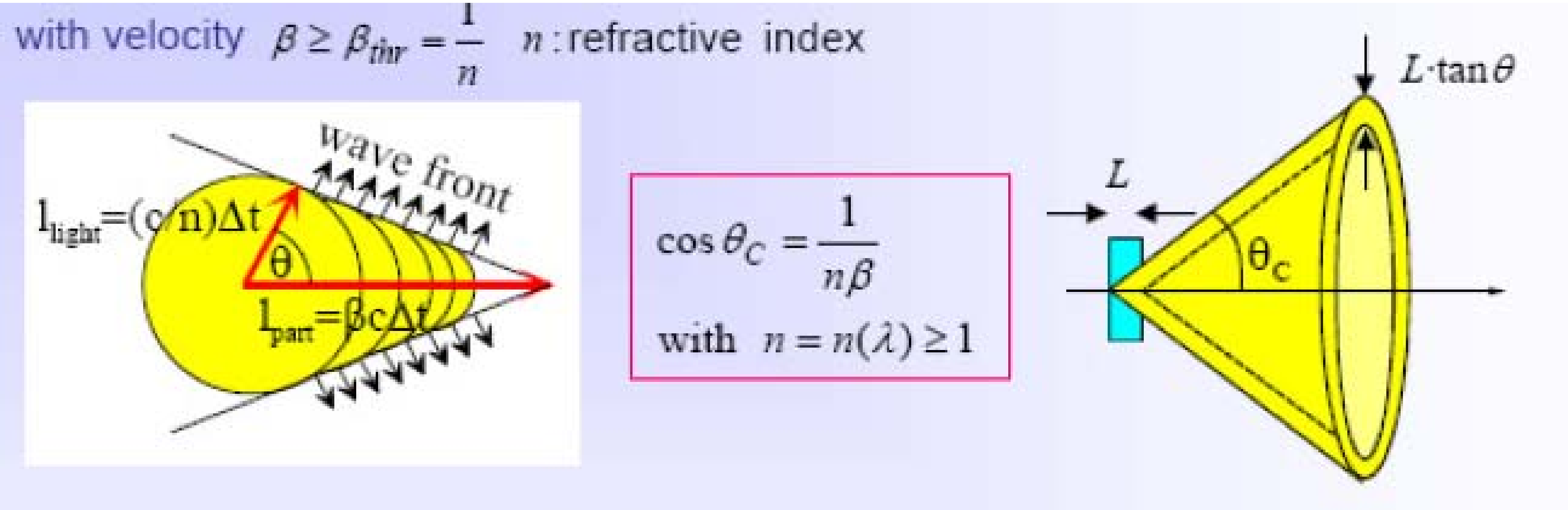
$$\theta_{rms} = \theta_0 = \sqrt{\langle\theta^2\rangle} = \frac{13.6(\mathrm{MeV})}{\beta cp} Z_i \sqrt{\frac{x}{X_0}}\left(1 + 0.038\ln\frac{x}{X_0}\right)$$

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

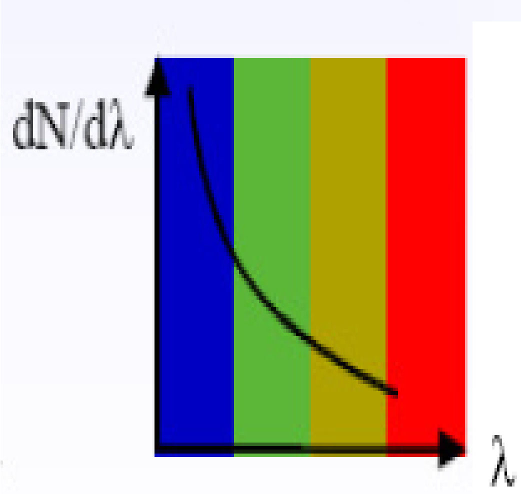
2-4 Cerenkov radiation

Cerenkov effect general features:

- ∃ threshold value for the particle speed : $\cos\theta = 1 \Rightarrow \beta_{threshold} = \frac{1}{n}$
- If $\beta \rightarrow 1$ 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

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

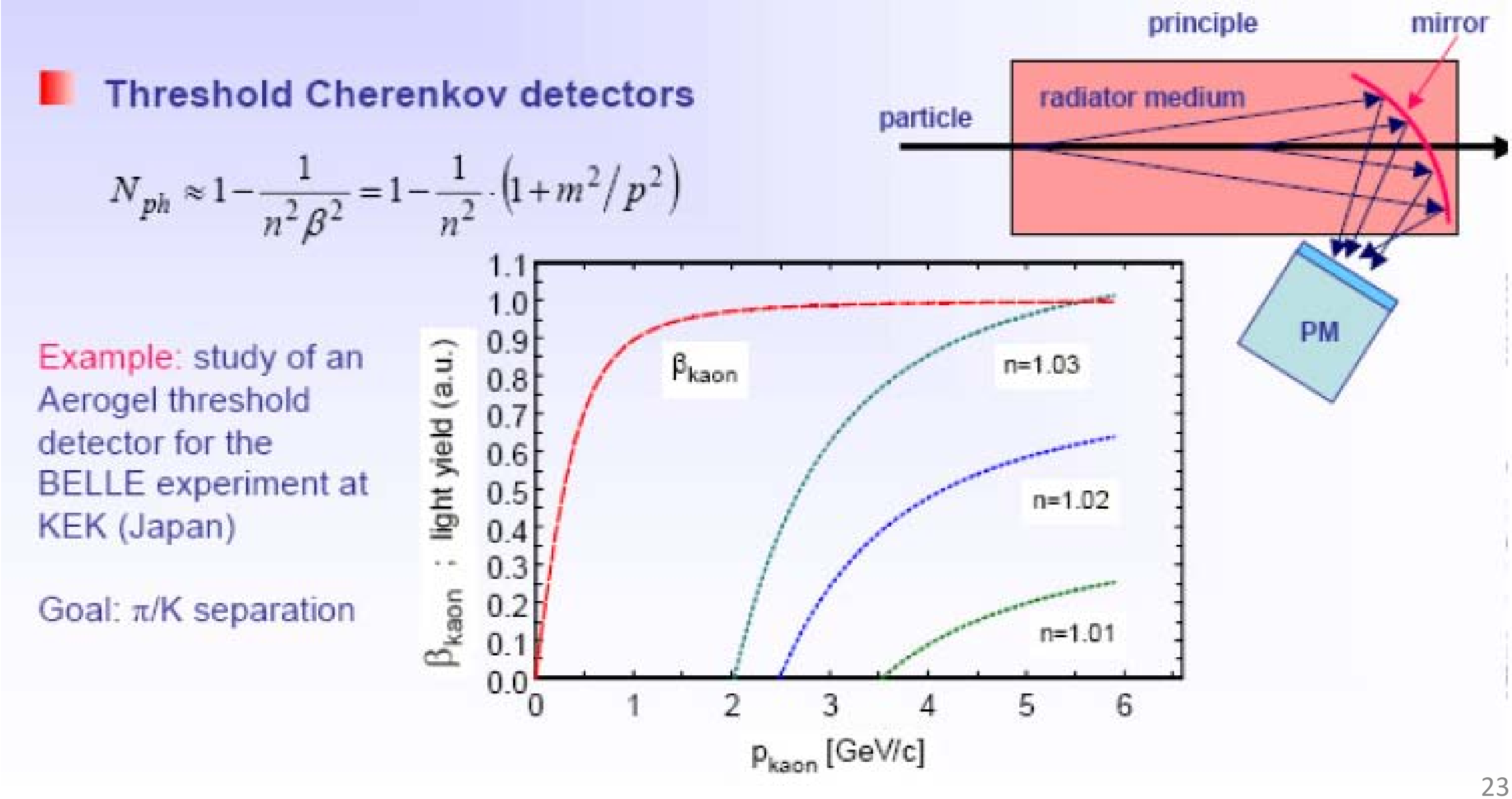
$$\frac{dN_{ph}(\text{visible})}{dx} \square\, 500\sin^2\theta$$



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

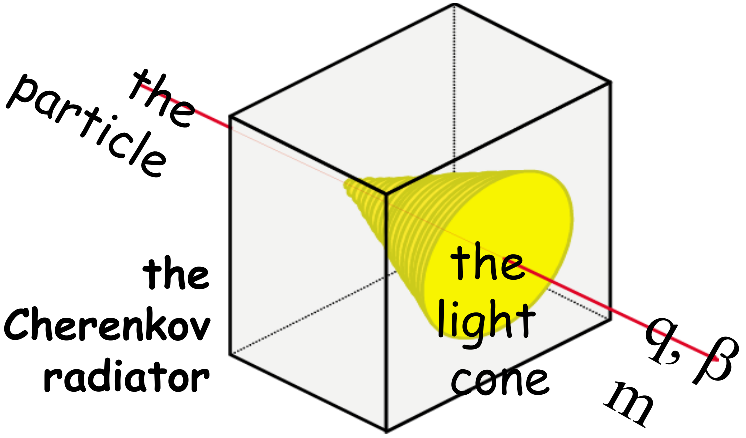
$$N_{ph} \approx 1 - \frac{1}{n^2\beta^2} = 1 - \frac{1}{n^2}\cdot\left(1 + m^2/p^2\right)$$

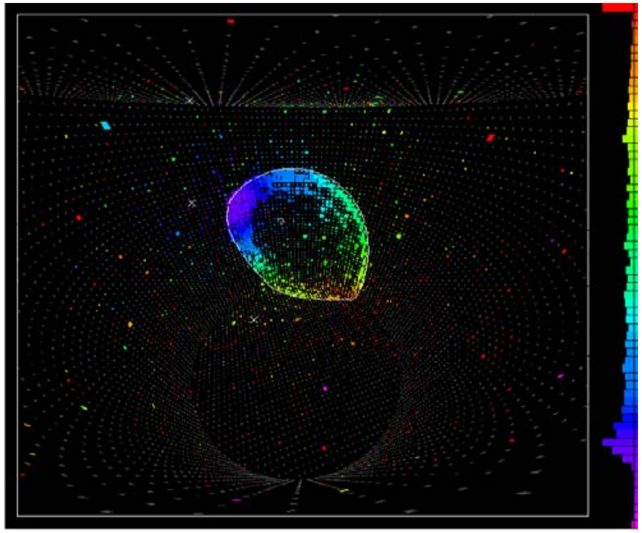
Example: study of an Aerogel threshold detector for the BELLE experiment at KEK (Japan)

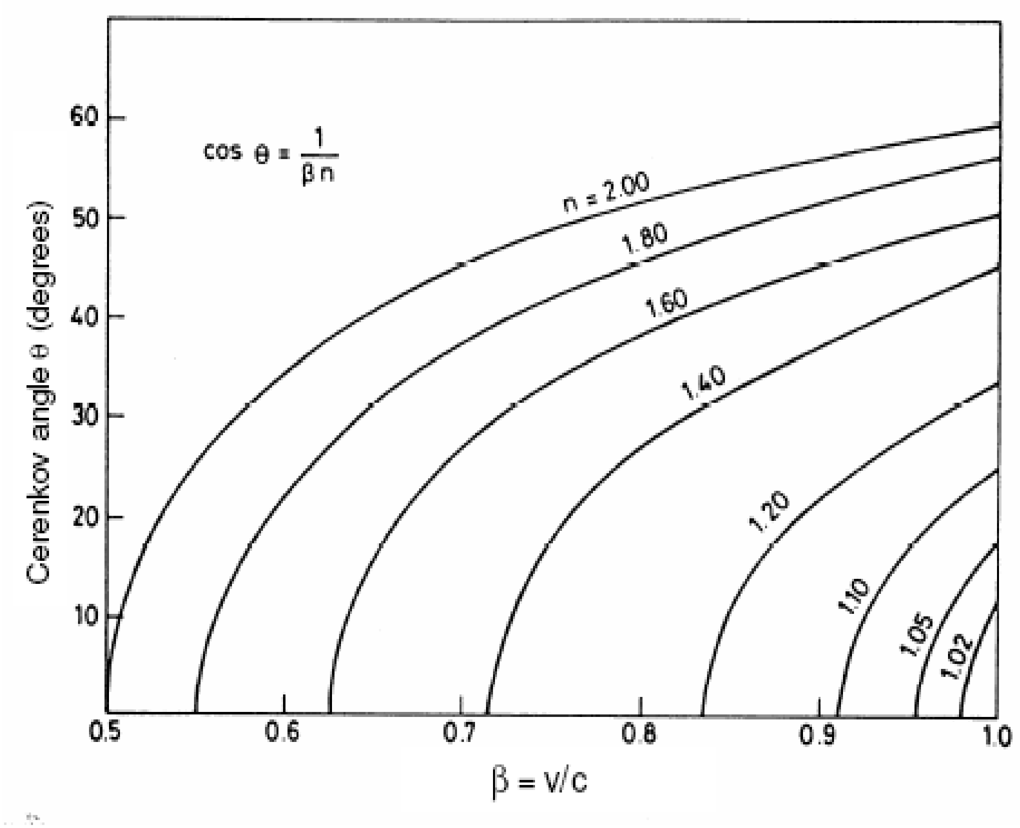
Goal: π/K separation

2-4 Cerenkov radiation

RICH : at fixed n, measuring θ defines β

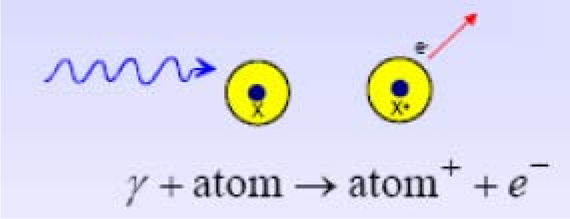






2-5 Photons interaction

Photoelectric effect:



- 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

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

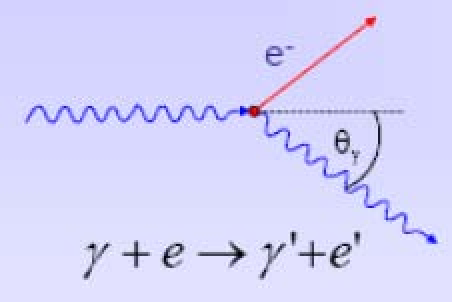
Screening effect

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

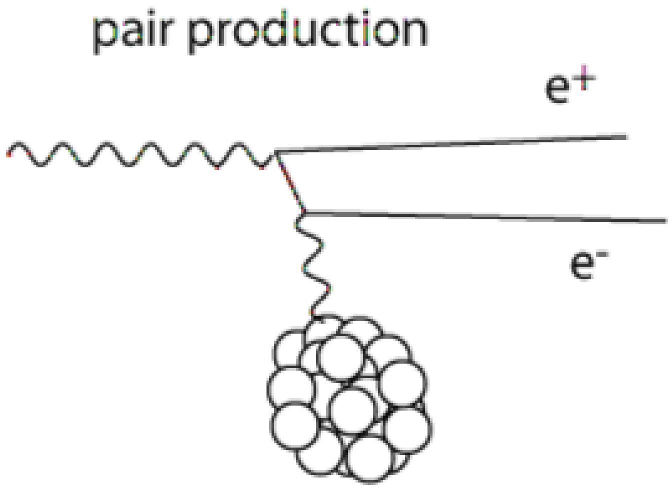
$$E_{\gamma}^{'} = \frac{E_{\gamma}}{1+\frac{E_{\gamma}}{m_{e}c^{2}}(1-\cos\theta)}$$

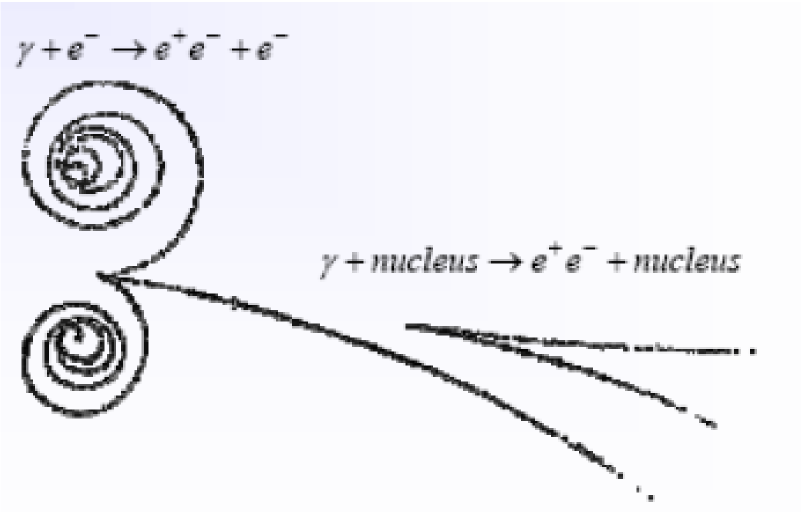
- Resulting in the wavelength shifting:

$$\lambda - \lambda_{0} = h/mc(1-\cos\theta)$$

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.

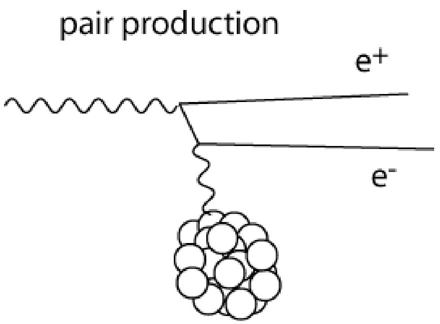
2-6 Electromagnetic showers

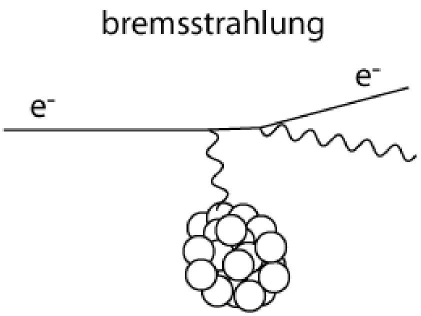
Above energies ~10 MeV the dominant processes for electrons and photons are bremsstrahlung and pair production resp.

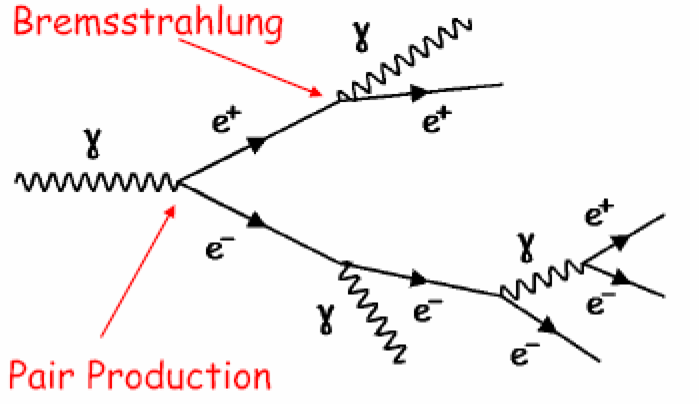
- The radiated photons have enough energy to produce extra pairs
- The emitted e^+ and e^- have enough energy to emit radiation γ etc

➔ The number of photons and electrons per unit length increase

➔ Development of an electromagnetic shower

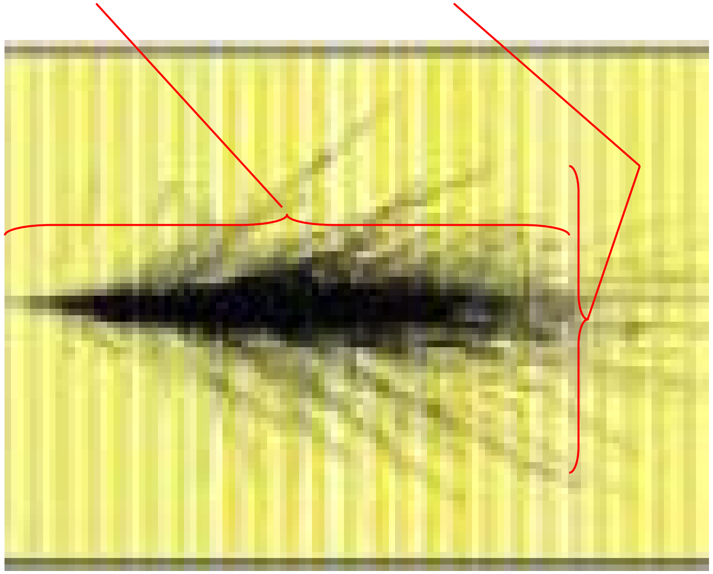


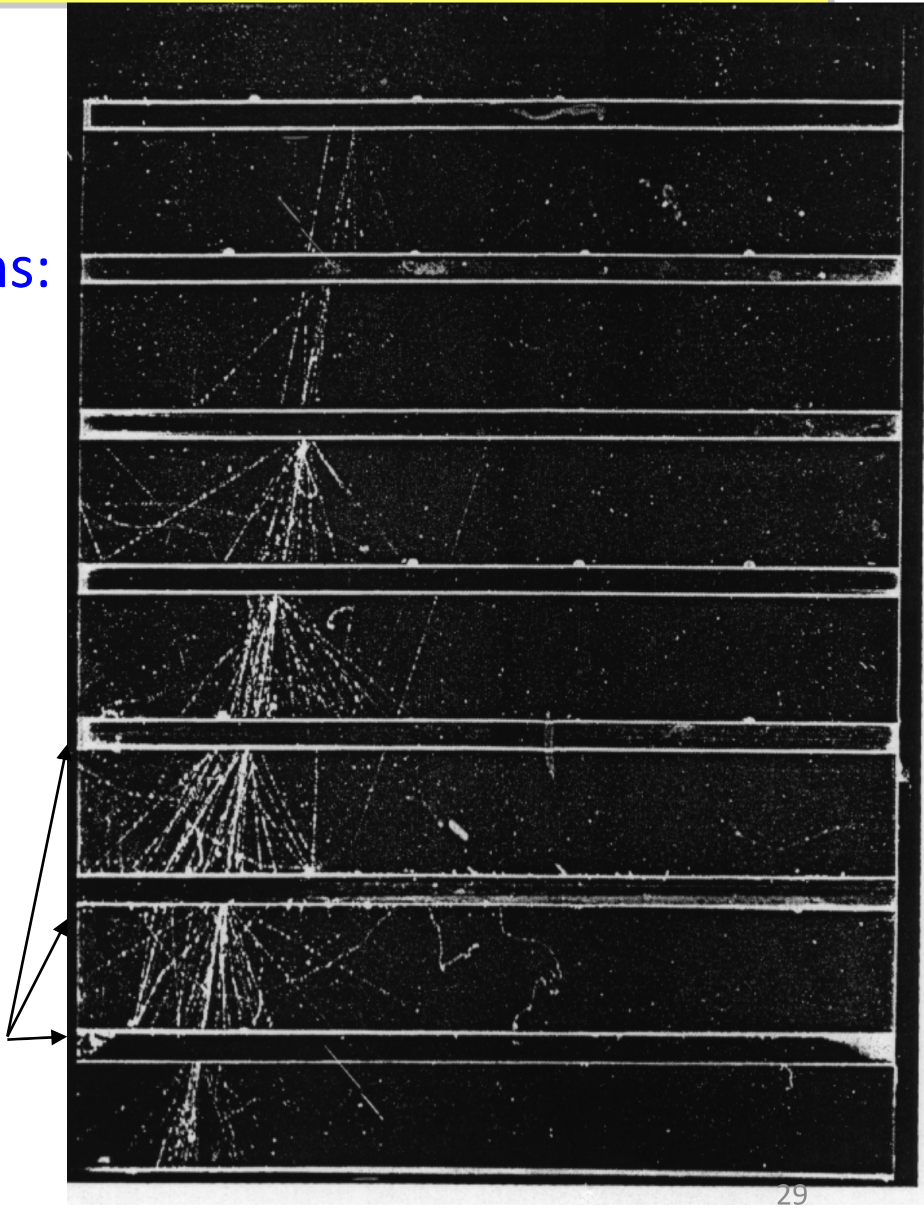




2-6 Electromagnetic showers

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

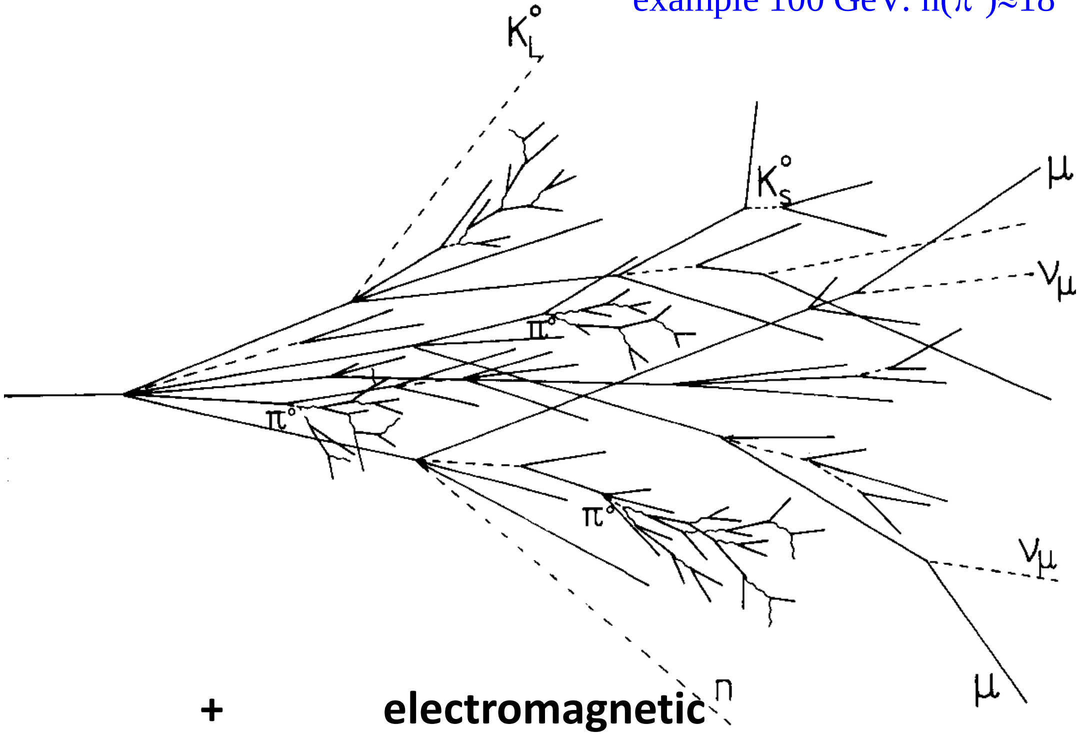




2-7 Hadronic showers

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

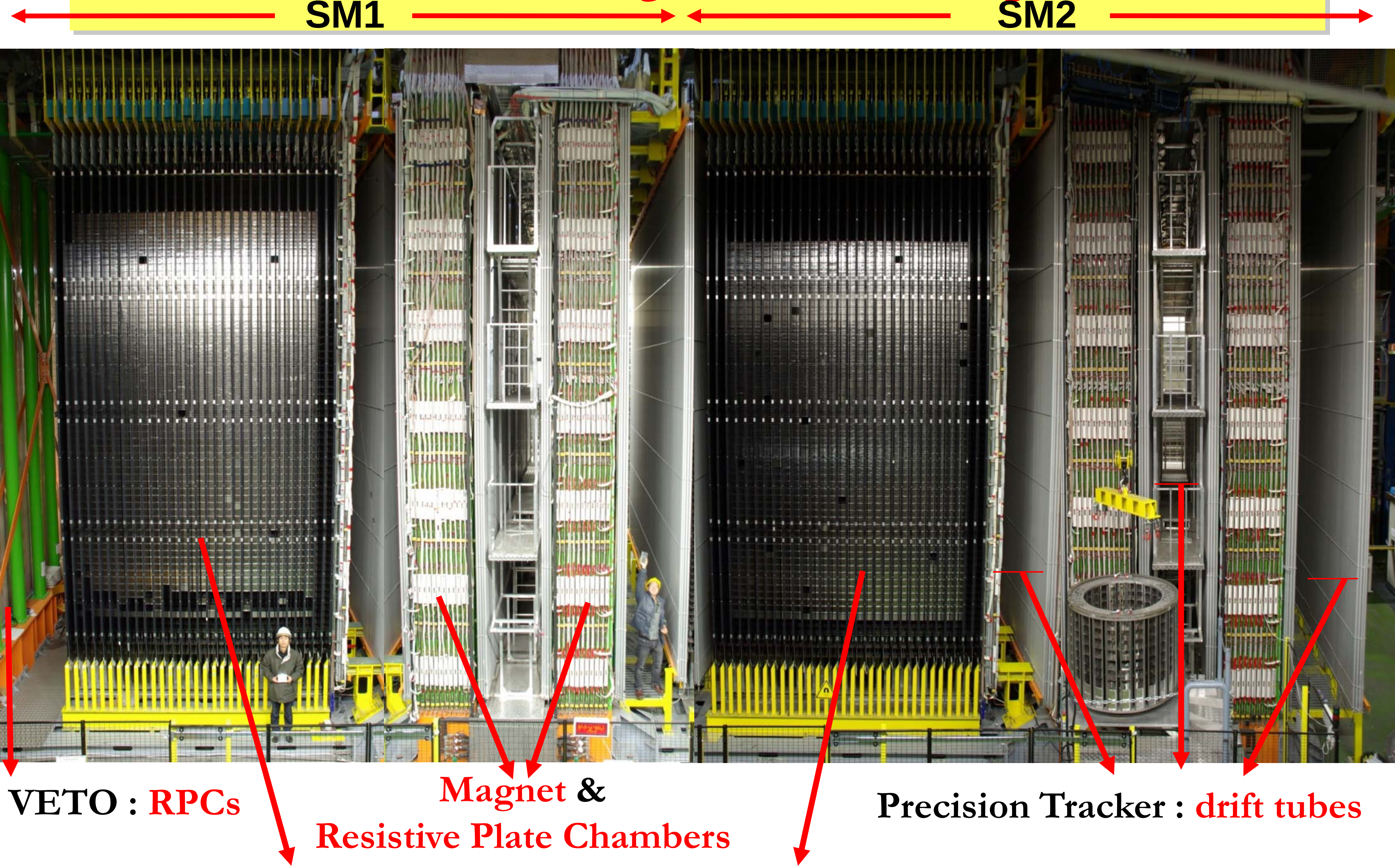
neutral pions → 2γ →
electromagnetic cascade

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



VETO : RPCs

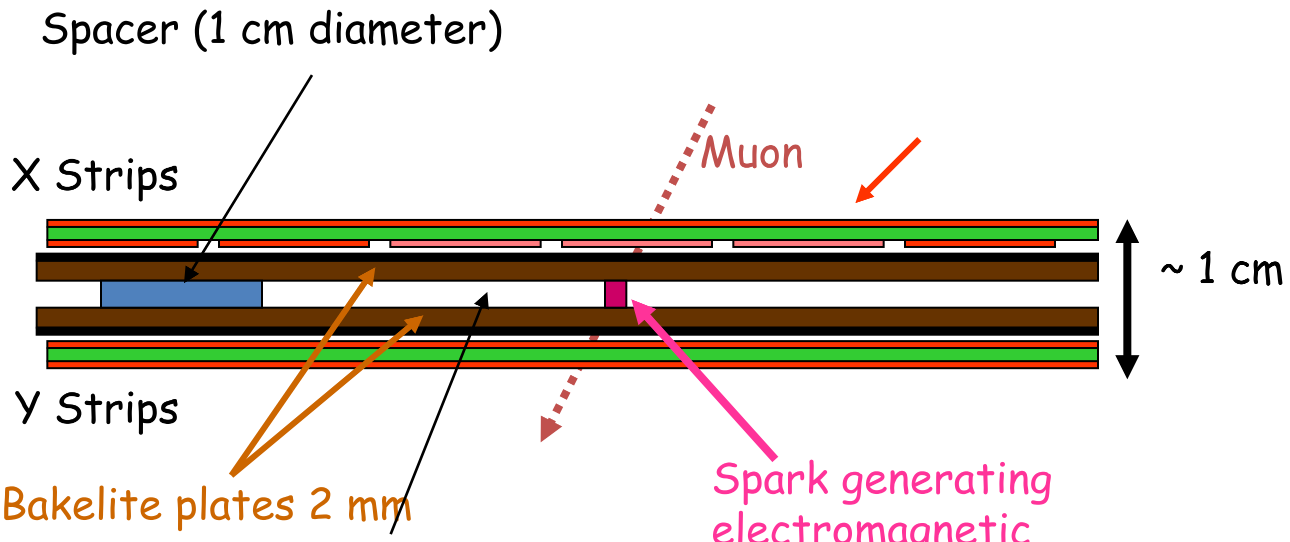
Magnet &
Resistive Plate Chambers

Precision Tracker : drift tubes

Target Tracker : plastic scintillators + photodetectors

3-1 Ionization detectors

Some practical applications: RPC (Resistive plate counters)



Spacer (1 cm diameter)

X Strips

Muon

~ 1 cm

Y Strips

Bakelite plates 2 mm

Spark generating electromagnetic induction on the copper strips

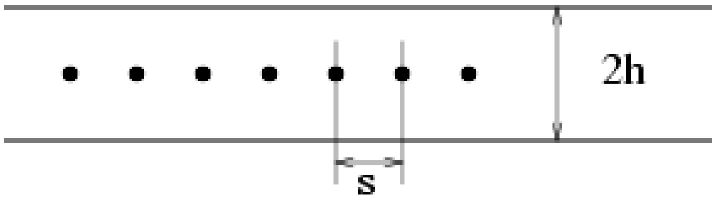
Gas gap 2 mm, E=8KV/2mm
Voltage applied on the graphite coating of bakelite

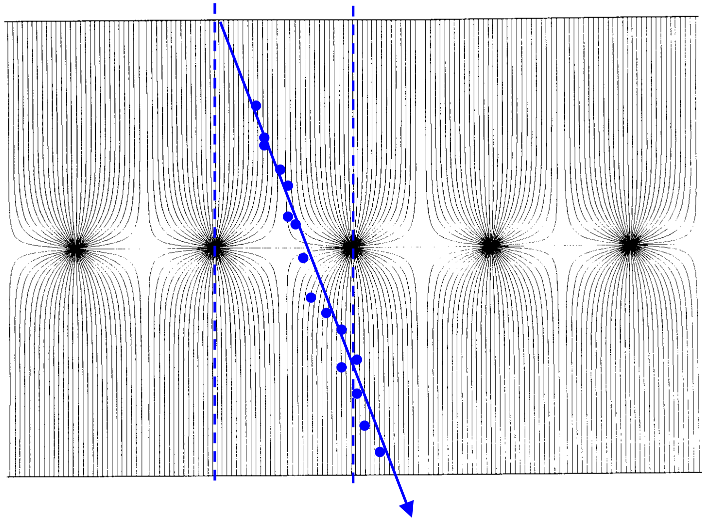
The streamer is confined in about 2 mm around the point where the particle passed. It creates a short circuit which discharges the bakelite. The bakelite will take few ms to recharge but only the hit region a few mm^2 will be dead.

3-1 Ionization detectors

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

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



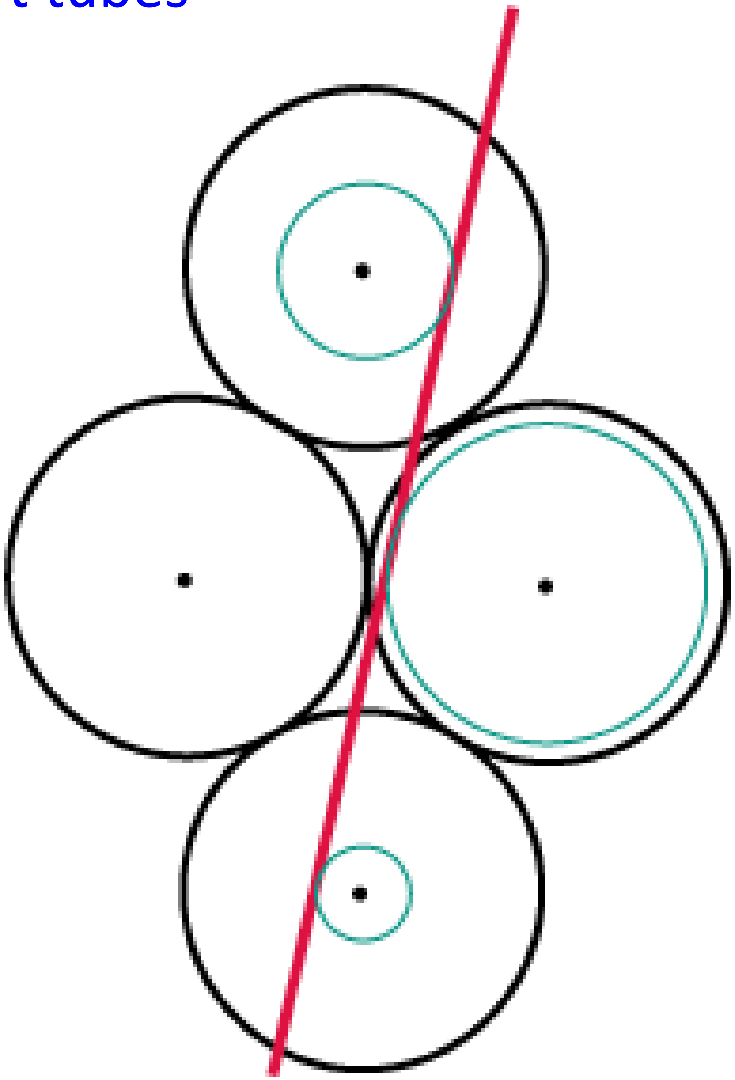


- In 1968 Charpak demonstrated that the MWPC works as many independent proportional tubes very close to each other.
  This opened the way to the world of completely electronic experiments with fine tracking and data acquired by computers.

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!



3-2 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:

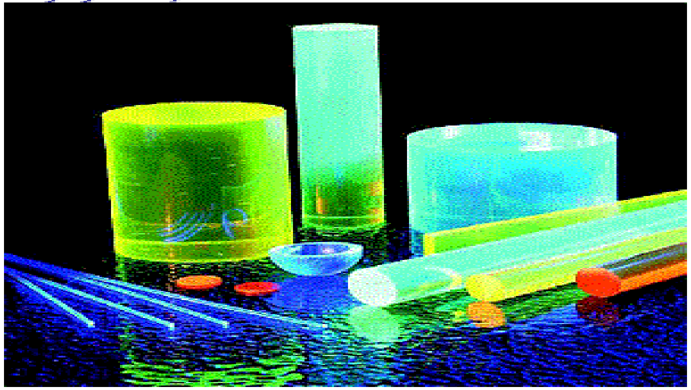
  - Inorganic, work at crystal level : large light yield but in general slow signals

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

3-2 Scintillation detectors

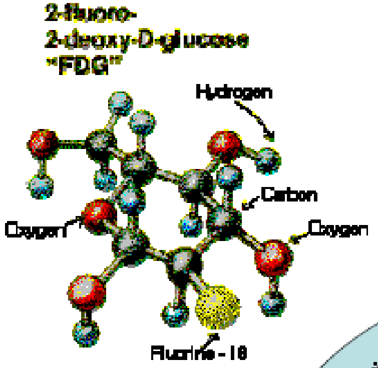
General features:

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	$\rho \sim 1$gr/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)	Tracking, TOF, trigger, veto counters, sampling calorimeters.
Medical imaging	
Fairly Rad. Hard (100 kGy/year)	Medium Rad. Hard (10 kGy/year)

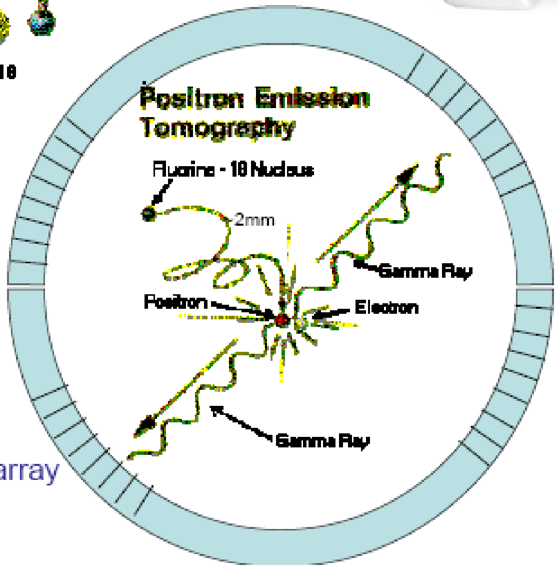


3-2 Scintillation detectors

Applications : Positron Emission Tomography (PET)



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



NOT TO SCALE!!

Crystals array

2 x 511 keV energy

γ-γ co-linearity

time coincidence

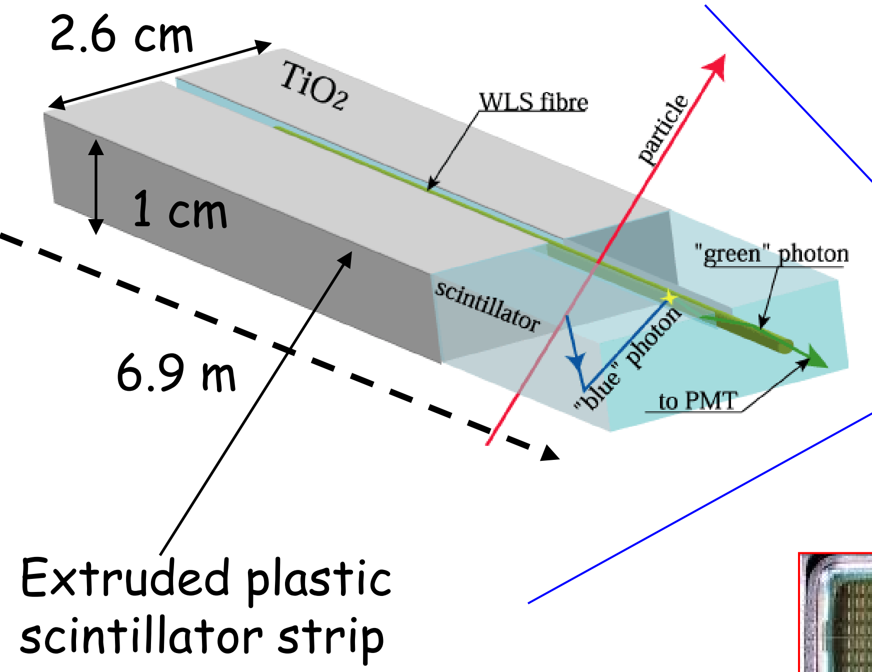
reconstruct functional image

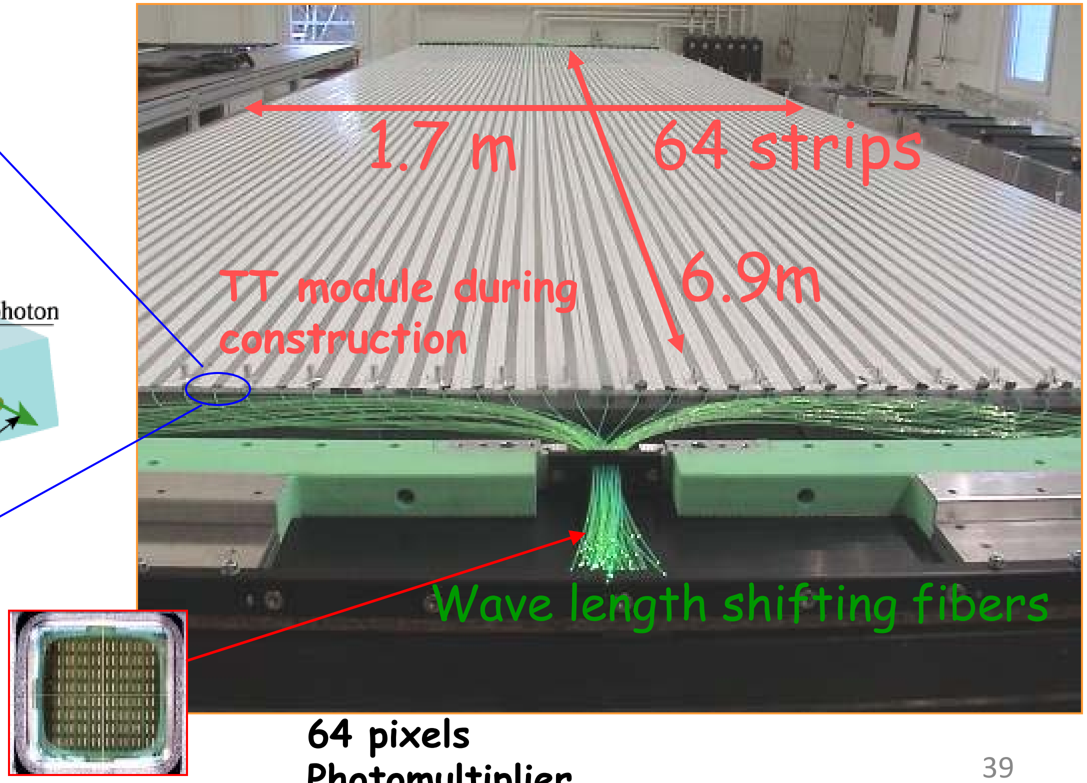
http://www.medical.philips.com/main/products/pet/products/gemini/clinicalimages

3-2 Scintillation detectors

Applications : tracking in HEP (OPERA target tracker)

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





3-4 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…