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
    4. Altogether: example of a LAr TPC

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
    4. Utiliser l'ensemble de ces techniques: exemple d'une chambre à projection temporelle à Argon liquide

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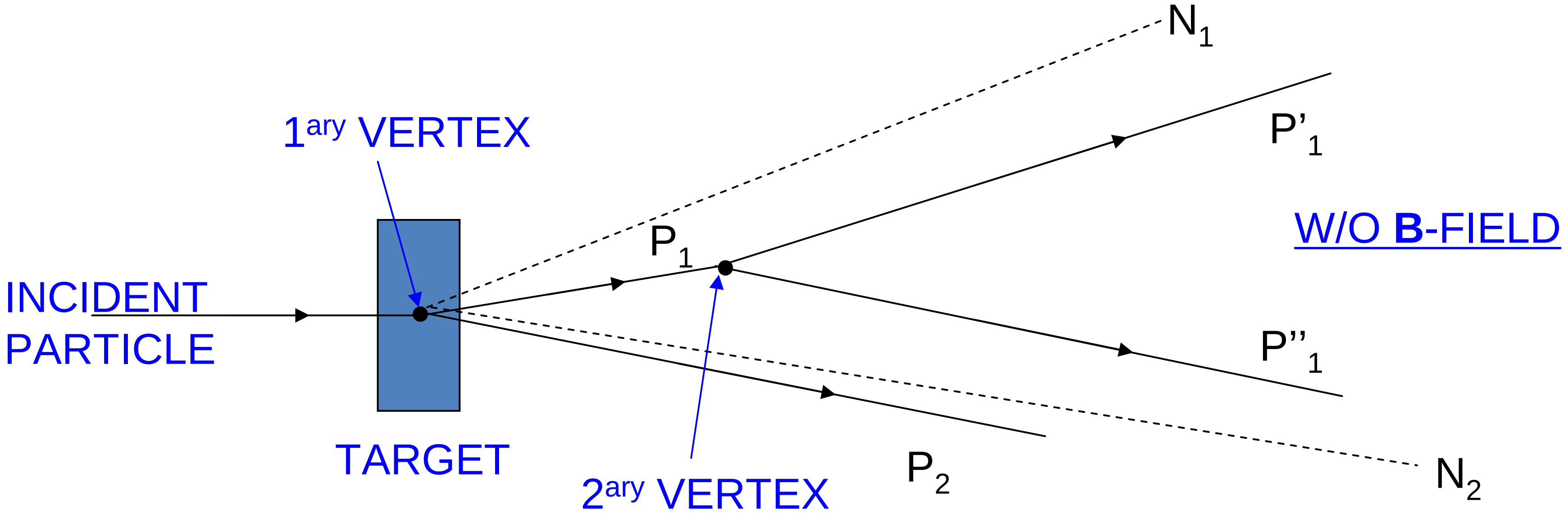
- Lectures given by D.Autiero (IPNL, CNRS) in M2 (UCBL) Detection techniques in experimental Particle Physics

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.

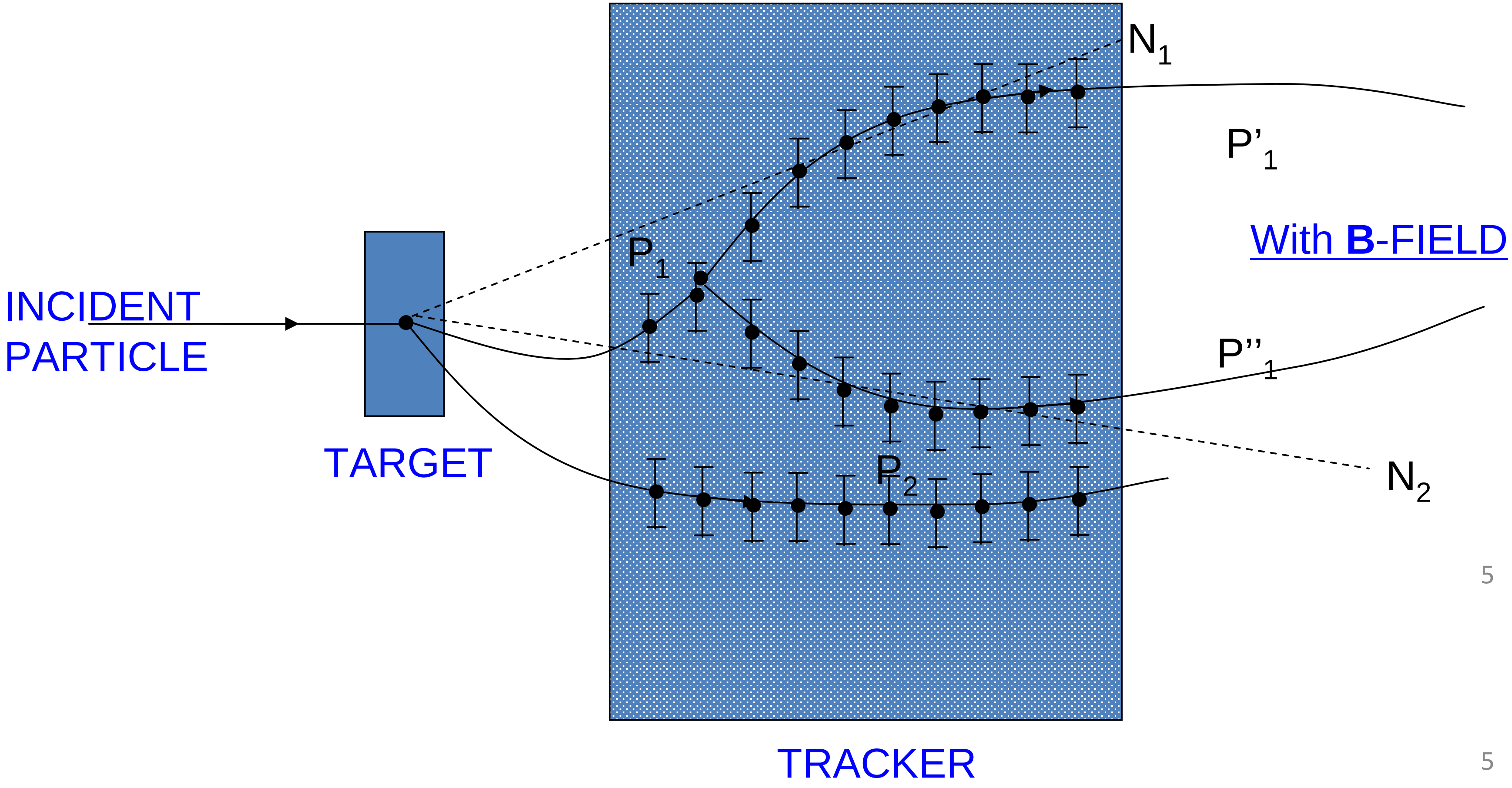
- PROJECTILE + TARGET (fixed/moving) →FINAL STATE PARTICLES



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



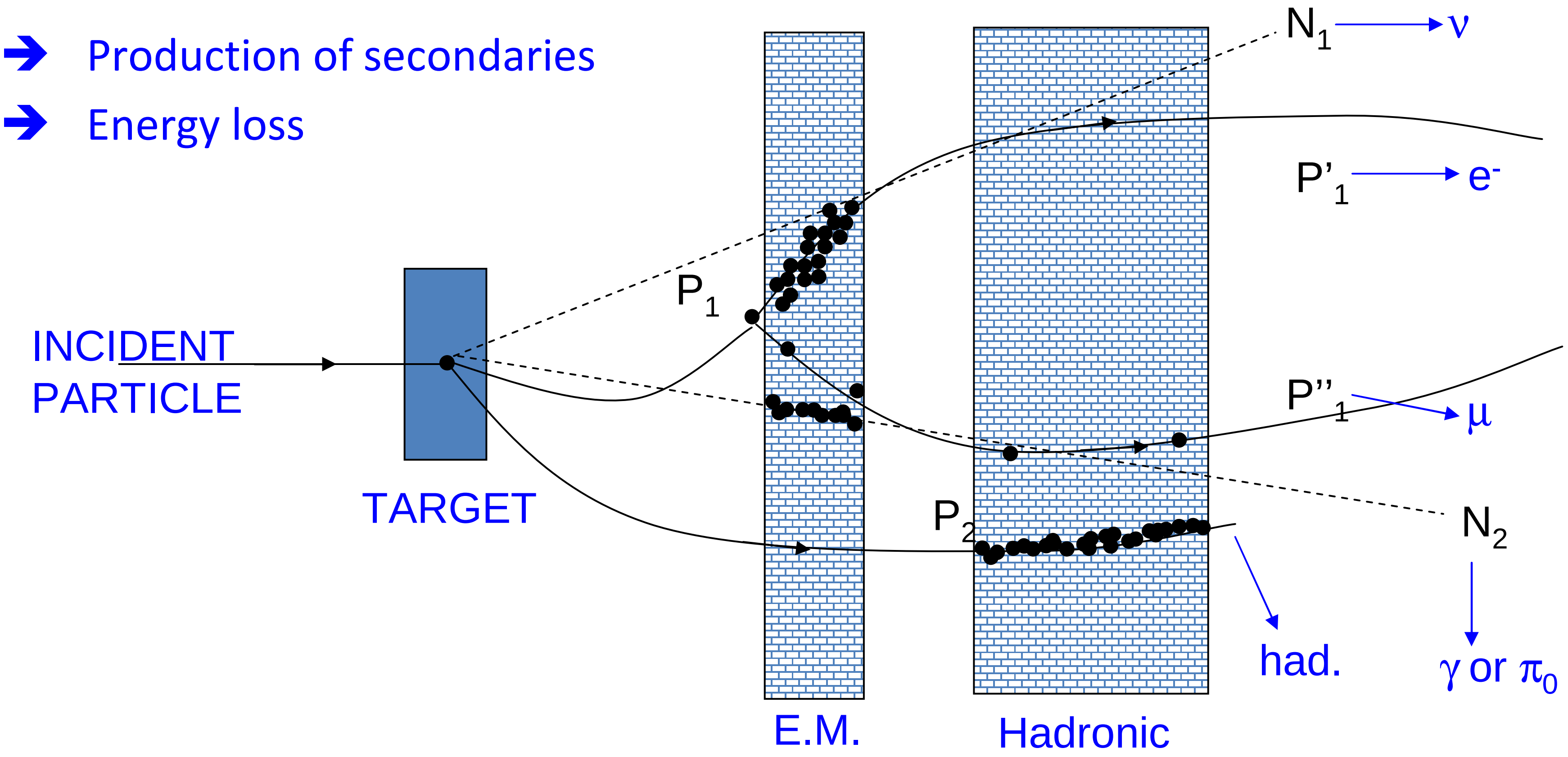
1- Introduction

Measuring particle's energy and interacting neutrals :

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

➔ Production of secondaries

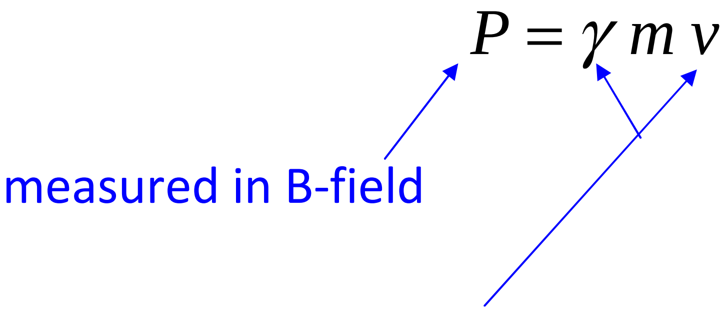
➔ Energy loss



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

1- Introduction

Identifying the particles through the measurement of the mass :



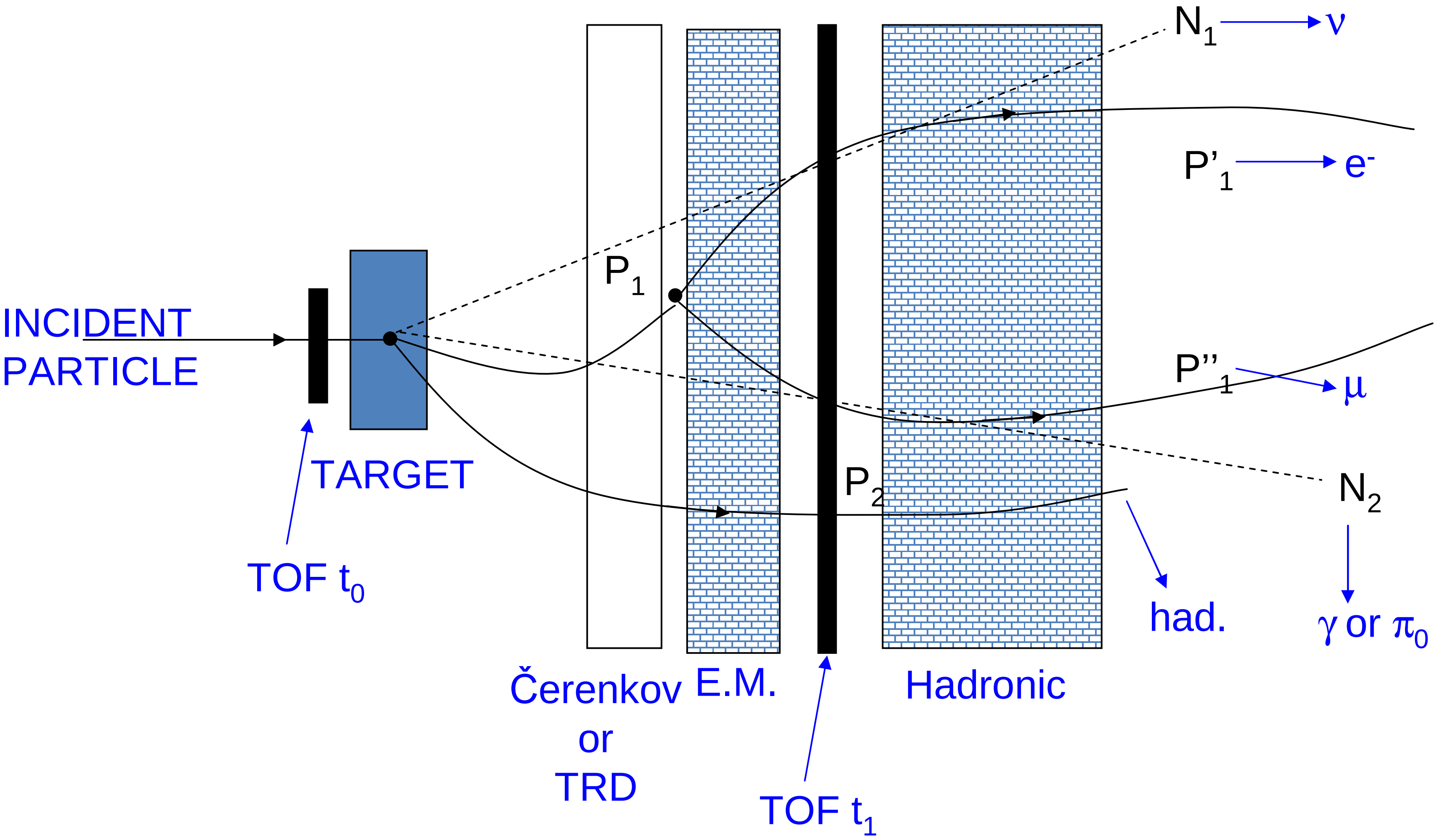
$$P = \gamma \, m \, v$$

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



INCIDENT PARTICLE

TARGET

TOF t_0

Čerenkov or TRD

E.M.

TOF t_1

Hadronic

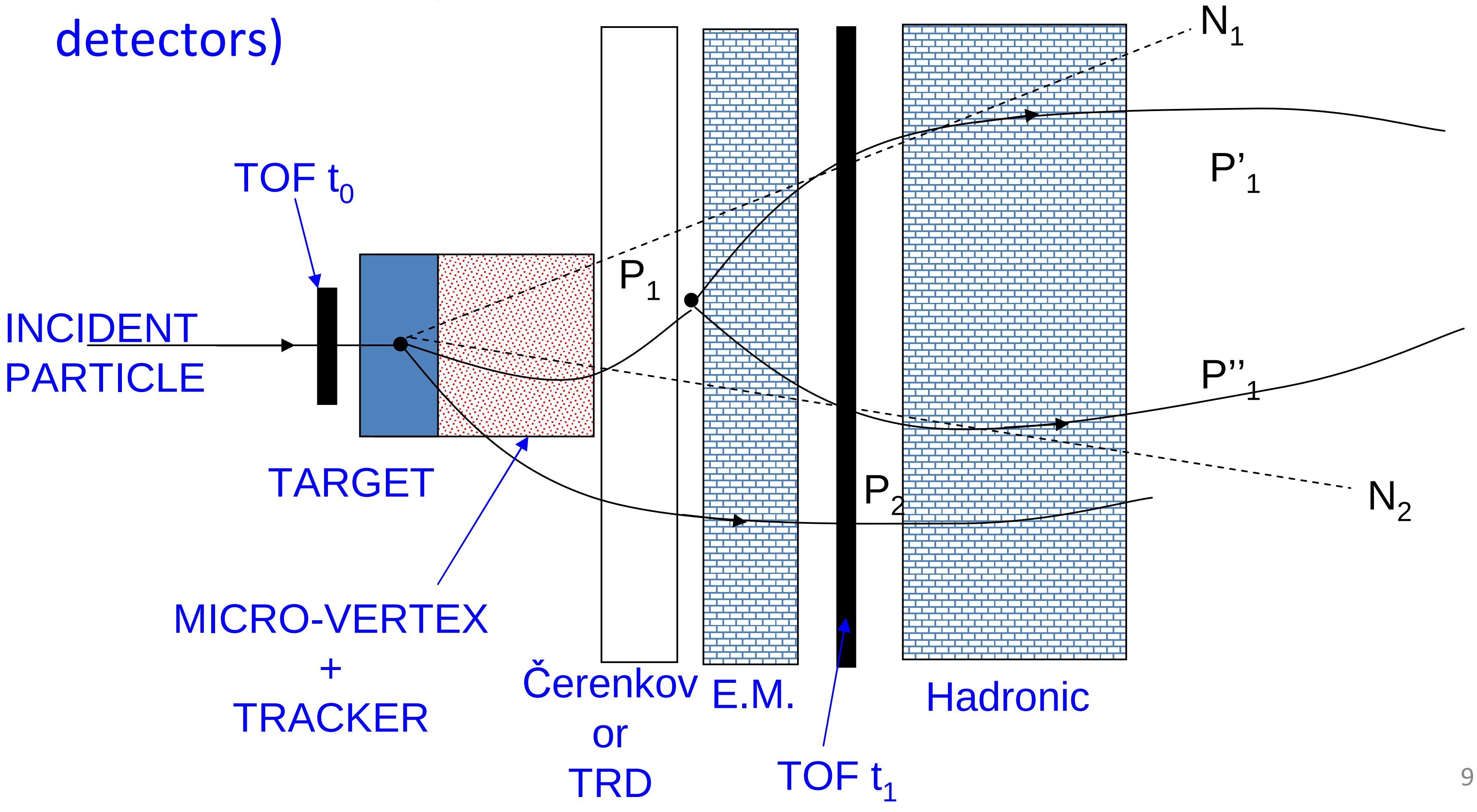
had.

γ or π_0

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)

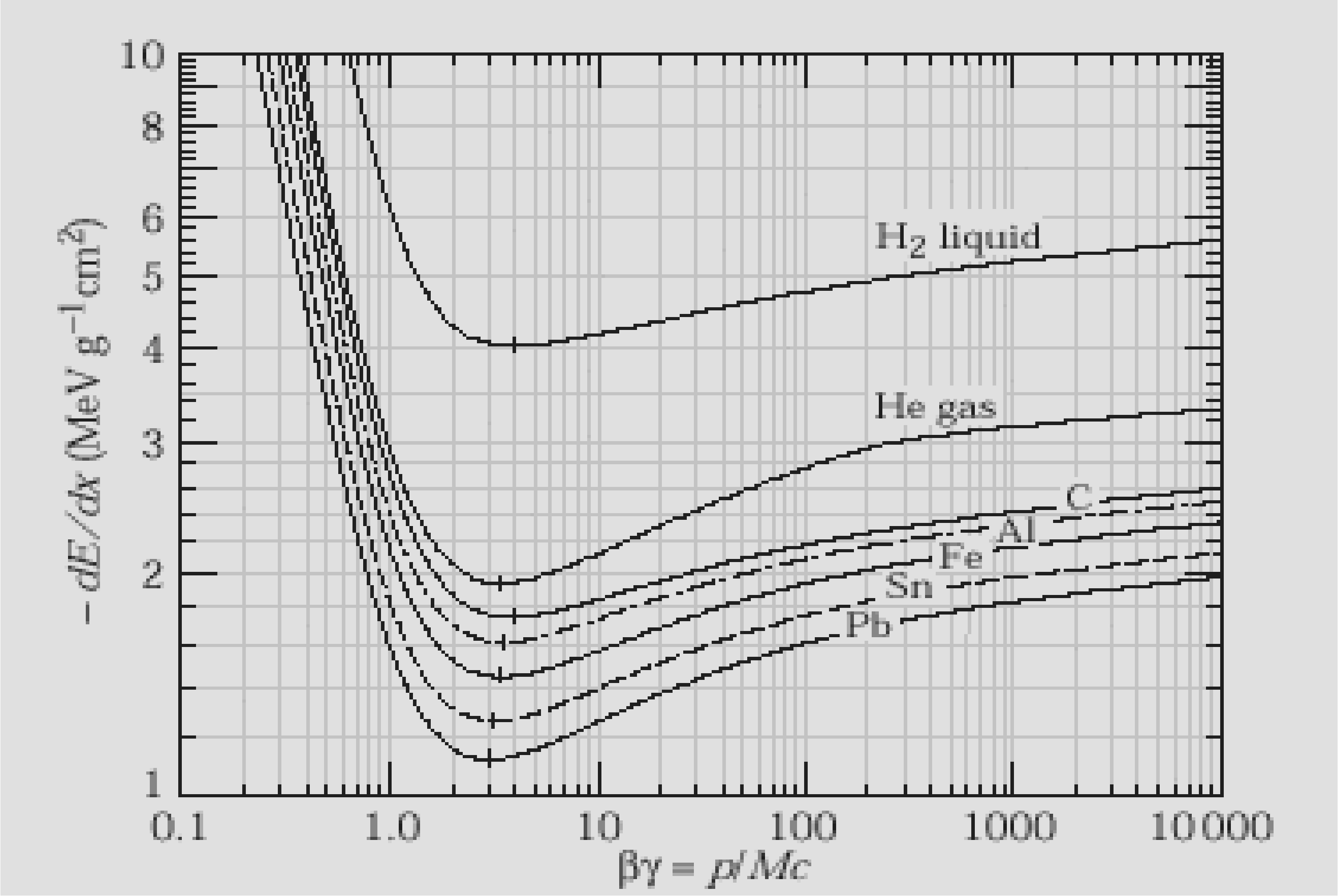
Ionization + excitation of atomic energy levels ➡ energy loss non destructive allowing to visualize the trajectories

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

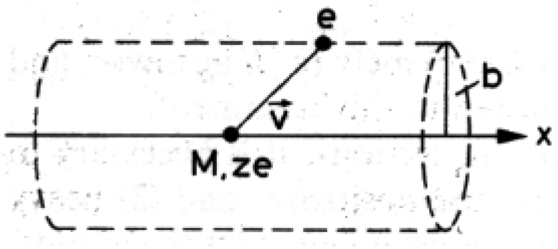
2-1 Energy loss by atomic collisions

Typical value at minimum: -dE /dx = 1 – 2 MeV /(g cm^{-2})



2-1 Energy loss by atomic collisions

Classical computation (Bohr)



- Assumptions : particle of mass *M*, velocity *v*, charge *ze*, passing at a distance *b* from an electron in the absorber medium.

- Since *M* >> *Me* the path of the particle is NOT affected by the collisions with electrons. Electron free and at rest !
- Electron only moving very little during interaction, electric field taken at its initial position.
- Momentum gained by the electrons

$$I = \int F\,dt = e\int E_{\perp}\,dt = e\int E_{\perp}\frac{dt}{dx}\,dx = e\int E_{\perp}\frac{dx}{v}$$

- E-field computation using Gauss'law.

2-1 Energy loss by atomic collisions

Classical computation (developed in T.D.)

- Electron energy gain : $\Delta E(b) = \frac{I^2}{2m_e} = \frac{2z^2e^4}{m_e v^2 b^2}$.

- Integrating over the medium one gets : $-\frac{dE}{dx} = \frac{4\pi z^2 e^4}{m_e v^2} N_e \ln \frac{b_{\max}}{b_{\min}}$
  where the limits of integration have
  to be evaluated on reasonable assumptions

  b_{min}: max. energy transfer is for head-on collision

  $$\frac{2z^2e^4}{m_e v^2 b_{\min}^2} = 2\gamma^2 m v^2, \qquad b_{\min} = \frac{ze^2}{\gamma m_e v^2}$$

  b_{max}: electrons are bound to atoms. Energy transfer only for a process shorter than the revolution period of the electron (adiabatic invariance)

  $$\frac{b}{\gamma v} \leq \tau = \frac{1}{\bar{\nu}}. \quad \text{ie} \quad b_{\max} = \frac{\gamma v}{\bar{\nu}}$$

2-1 Energy loss by atomic collisions

First order approximation :

$$-\frac{dE}{dx}=\frac{4\pi z^2 e^4}{m_e v^2} N_e \ln \frac{\gamma^2 m v^3}{z e^2 \bar{\nu}} .$$

- This formula works reasonably for heavy particles, like alpha particles, already for protons gets in troubles due to quantum effects.

- The correct quantum-mechanical calculation was performed by Bethe and Bloch (momentum transfer vs impact parameter)

2-1 Energy loss by atomic collisions

Bethe-Bloch formula :

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

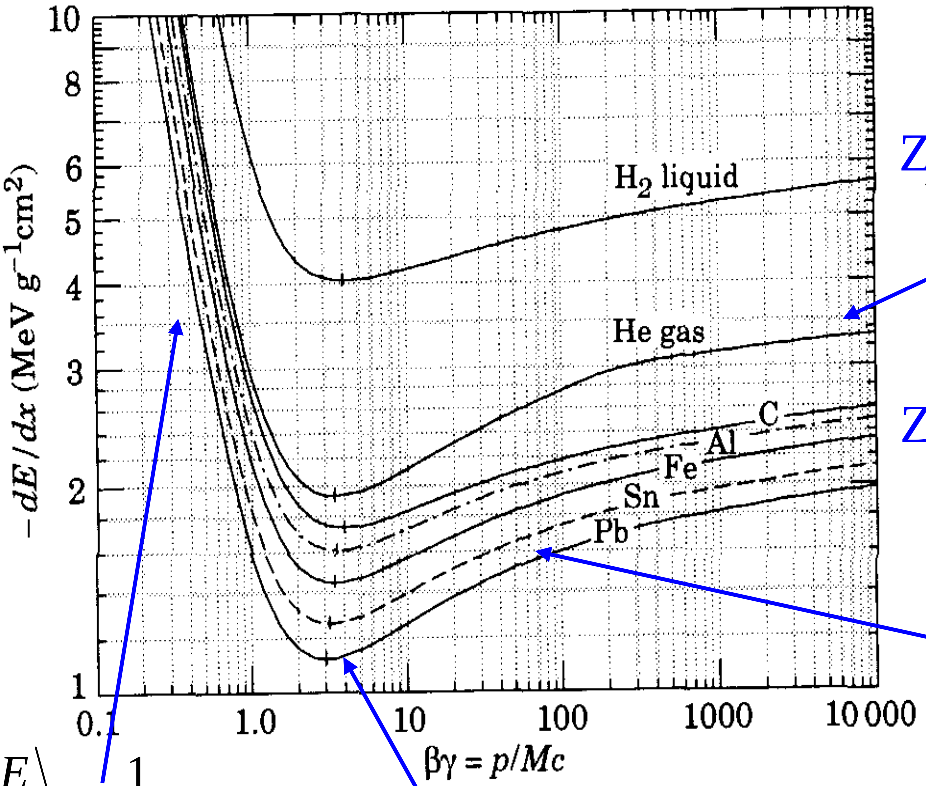
Depends on Z/A:
neutron-rich nuclei
less efficient

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 :



Z/A = 1

“Fermi plateau”

Z/A~0.5

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

“relativistic rise”

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

“kinematical term”

$\beta\gamma \approx 3\text{-}4$

minimum ionizing particles, MIPs

2-1 Energy loss by atomic collisions

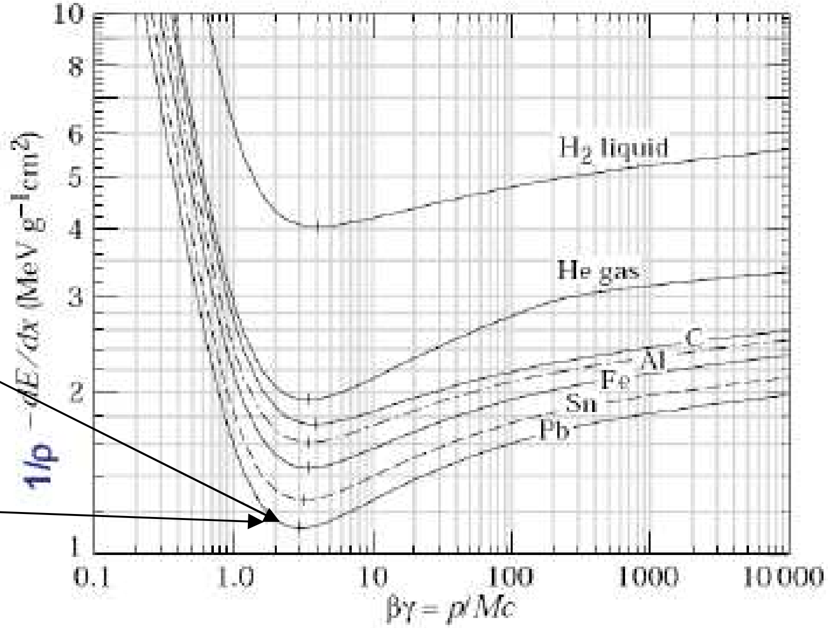
Bethe-Bloch formula a few numbers :

For $Z \approx 0.5\,A$
$1/\rho\ dE/dx \approx 1.4$ MeV cm^2/g for $ß\gamma \approx 3$

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

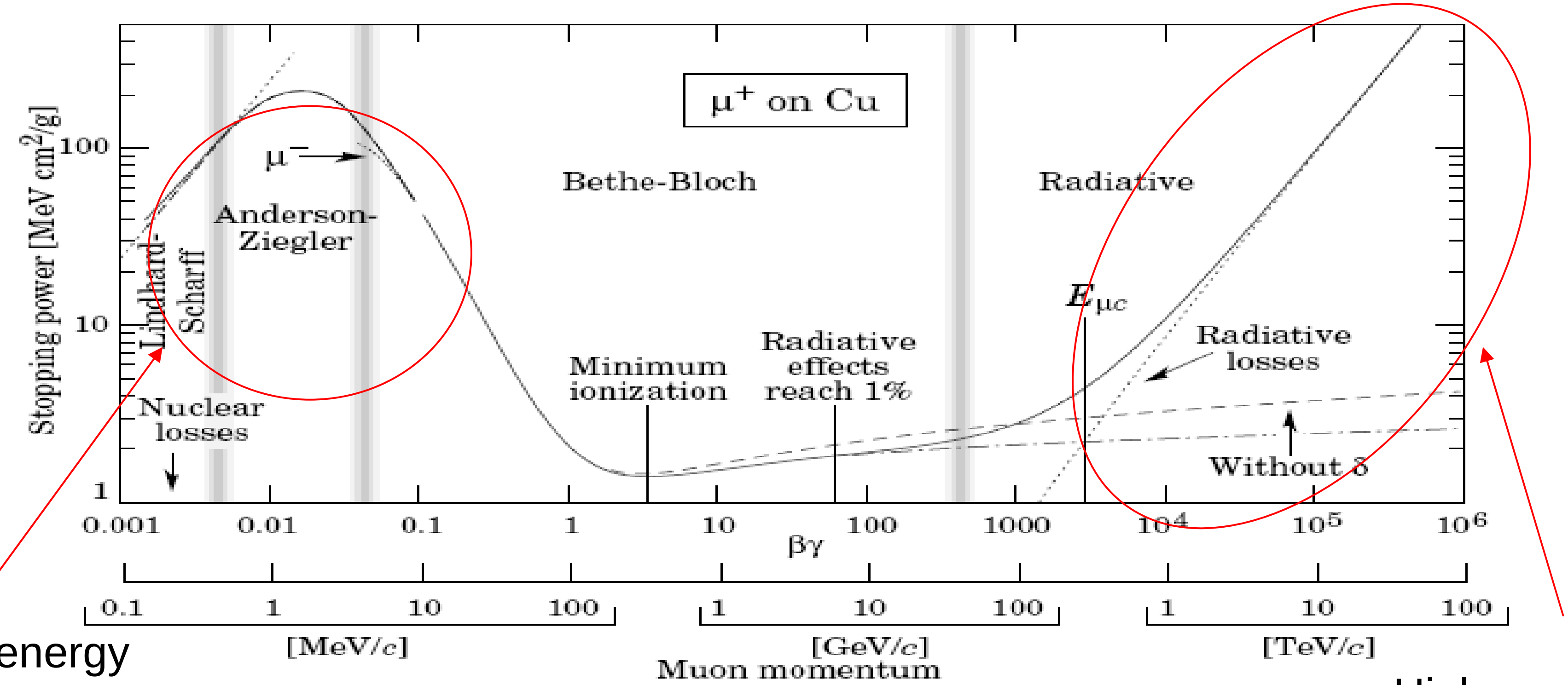
Example 3:
Energy Loss of a Carbon Ion with $Z=6$ and Momentum of 330 MeV/c/Nukleon
in Water, i.e. $\beta\gamma = p/m = 330/940 \approx .35 \rightarrow$
$\beta \approx .33$
$dE/dx \approx 1.4\ Z^2/\beta^2 \approx 460$ MeV/cm →
Cancer Therapy !



This number must be multiplied with $\rho\ [g/cm^3]$ of the Material → dE/dx [MeV/cm]

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

Minimum ionization particles : material dependence

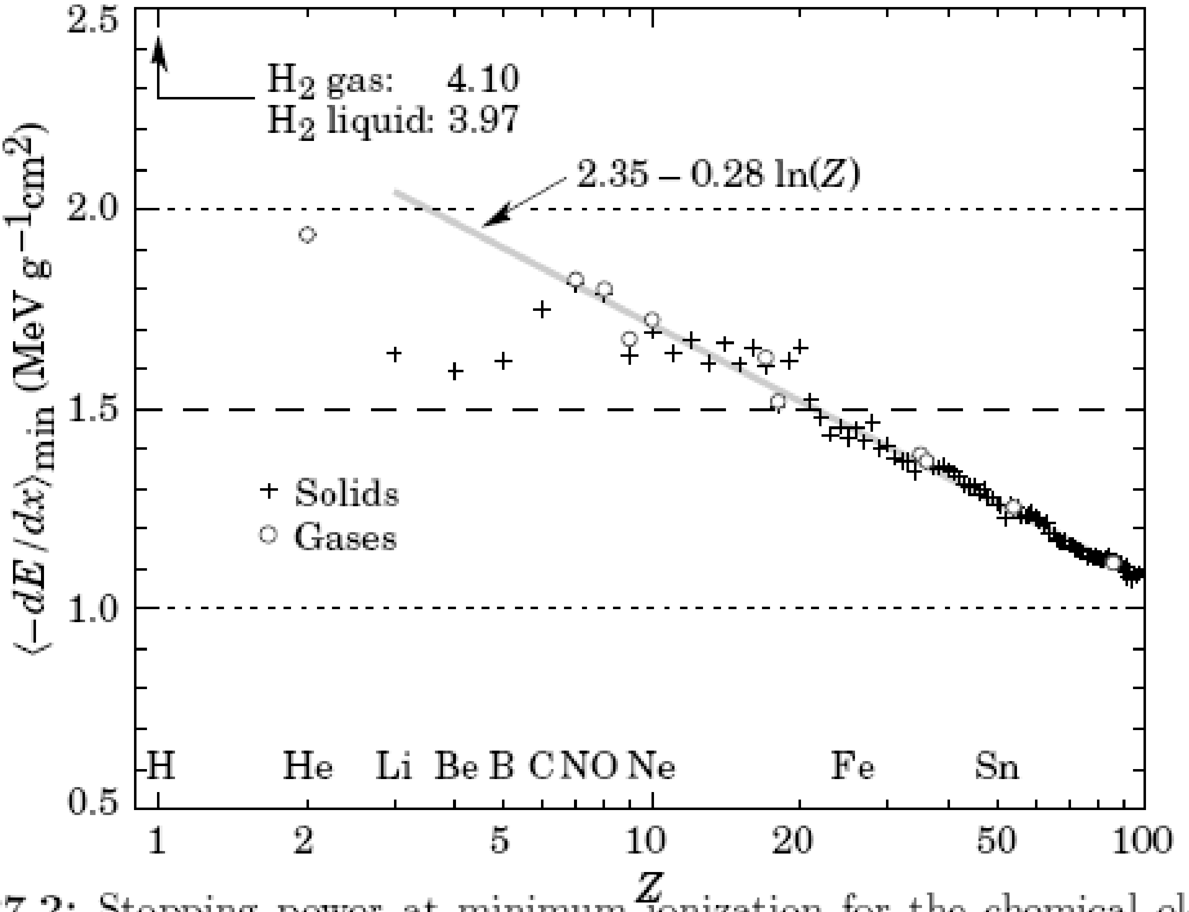


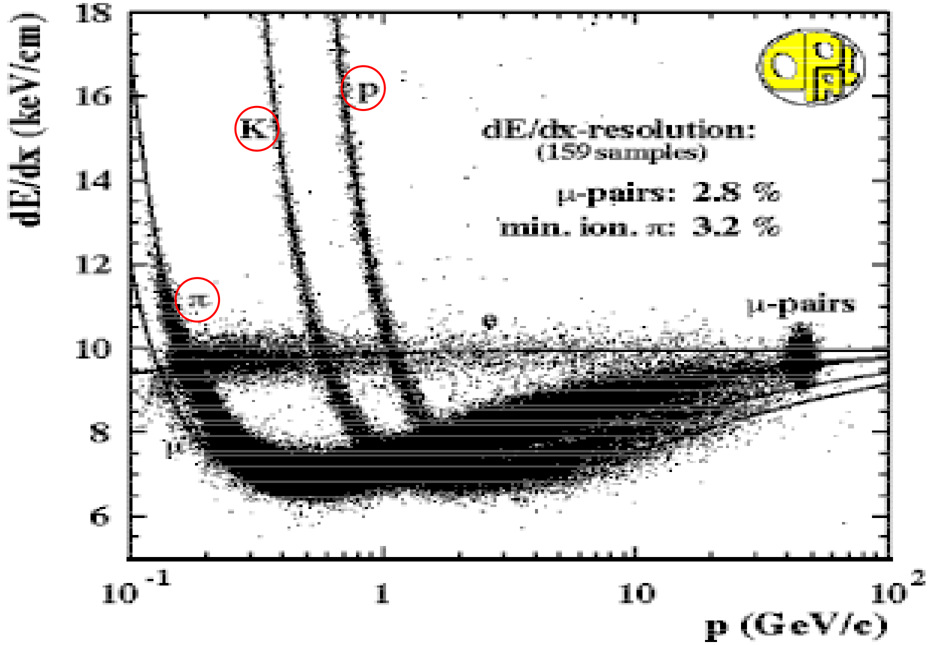
Figure 27.2: Stopping power at minimum ionization for the chemical elements. The straight line is fitted for $Z > 6$. A simple functional dependence on Z is not to be expected, since $\langle -dE/dx \rangle$ also depends on other variables.

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



2-1 Energy loss by atomic collisions

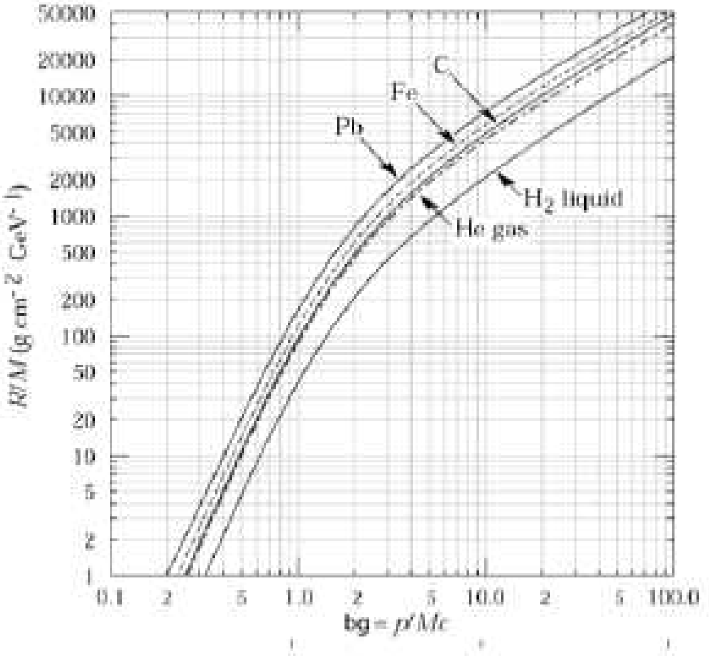
Range : the particle interacts, loses energy until it stops at distance R.

$$R(E_0) = \int_{E_0}^{0} \frac{-1}{dE/dx} dE$$

$$R(\beta_0\gamma_0) = \frac{Mc^2}{\rho} \frac{1}{Z_1^2} \frac{A}{Z} f(\beta_0\gamma_0)$$

$$\frac{\rho}{Mc^2} R(\beta_0\gamma_0) = \frac{1}{Z_1^2} \frac{A}{Z} f(\beta_0\gamma_0)$$

≈Independent of the material



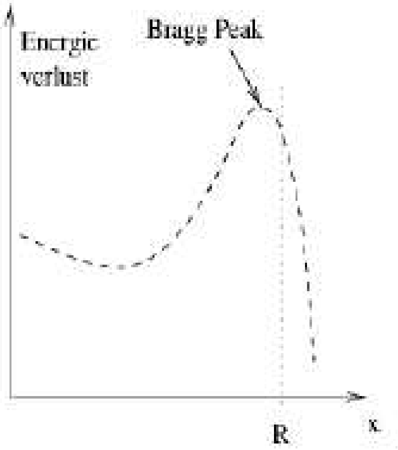
2-1 Energy loss by atomic collisions

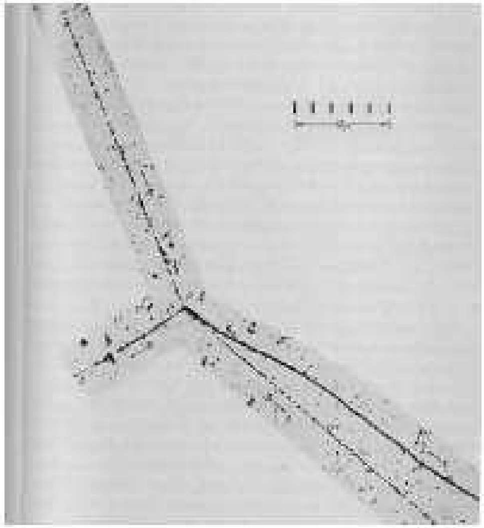
Some applications of the stopping tracks:

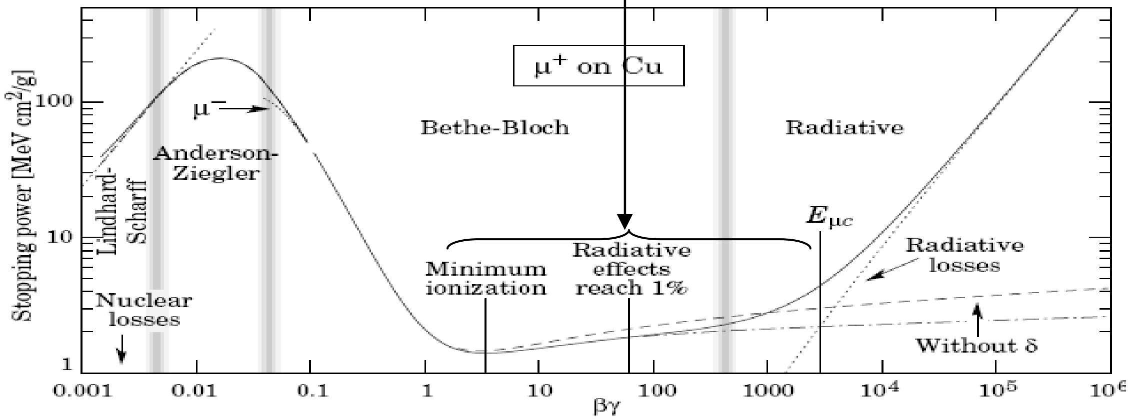
Bragg Peak: For βγ>3 the energy loss is ≈ constant (Fermi Plateau)

If the energy of the particle falls below βγ=3 the energy loss rises as $1/\beta^2$

Towards the end of the track the energy loss is largest → Cancer Therapy.







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

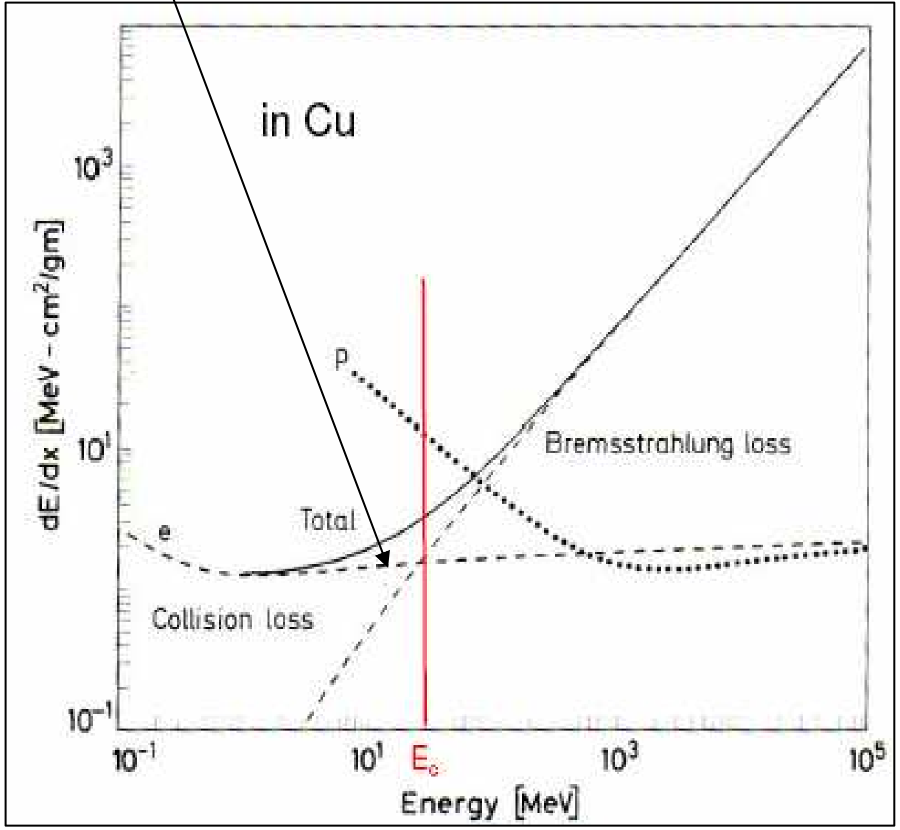
Modified Bethe-Bloch formula:

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

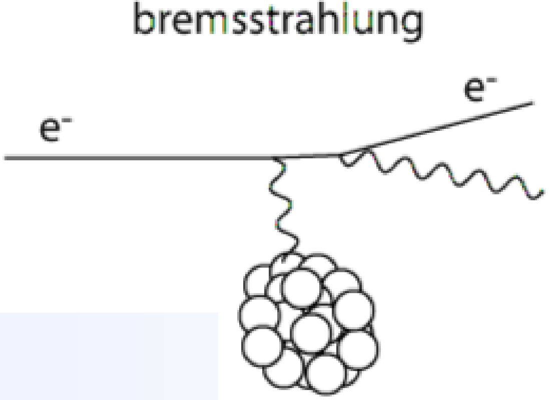
τ : kinetic energy of particle in units of $m_e c^2$

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

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

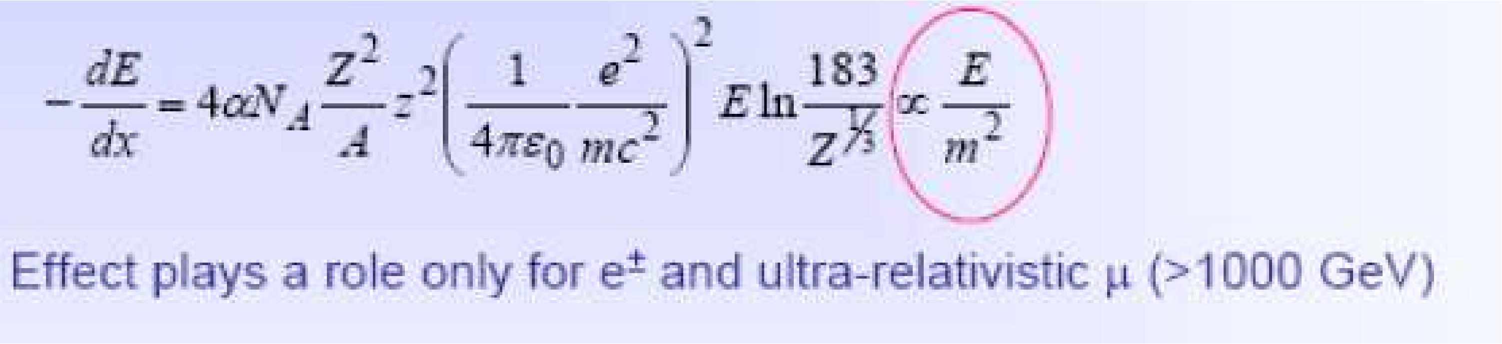


2-2 Energy loss of electrons



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

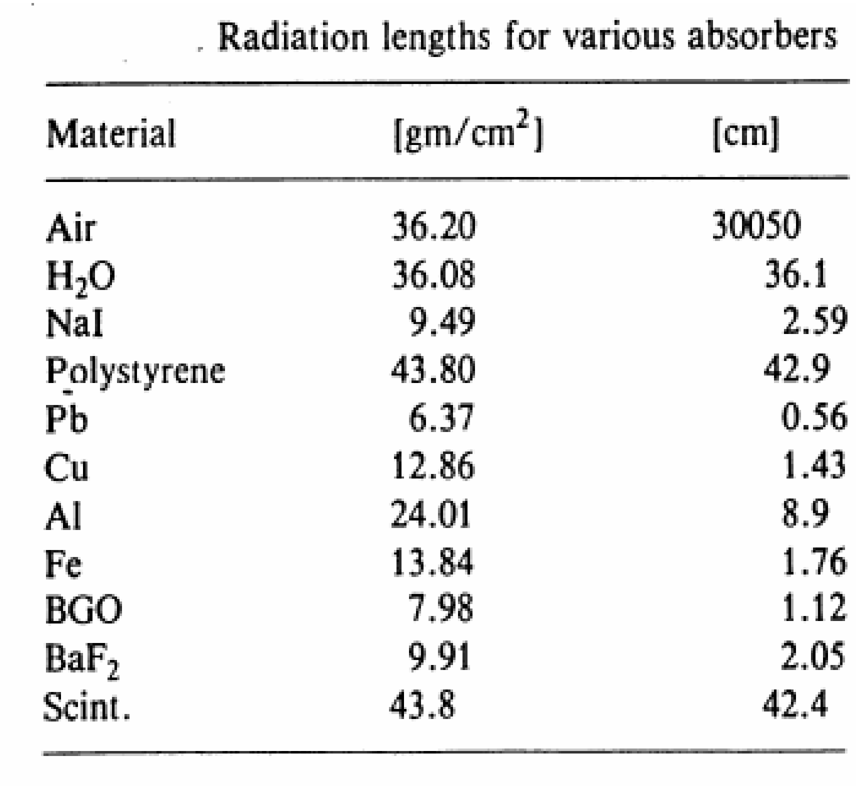
$$X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln\frac{183}{Z^{1/3}}}$$

radiation length [g/cm^2]

(divide by specific density to get X_0 in cm)

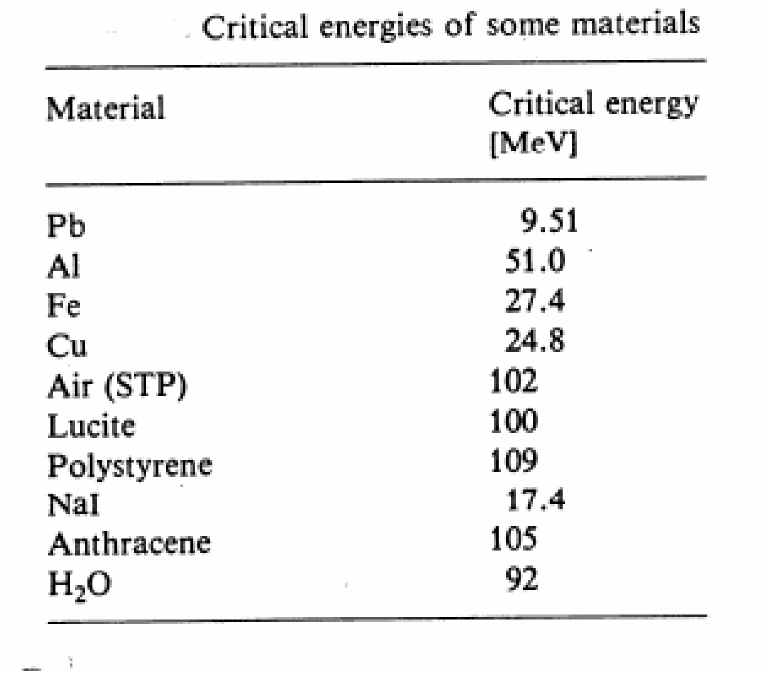
2-2 Energy loss of electrons

Radiation length and critical energy for current materials



Radiation lengths for various absorbers

Material	[gm/cm^2]	[cm]
Air	36.20	30050
H_2O	36.08	36.1
NaI	9.49	2.59
Polystyrene	43.80	42.9
Pb	6.37	0.56
Cu	12.86	1.43
Al	24.01	8.9
Fe	13.84	1.76
BGO	7.98	1.12
BaF_2	9.91	2.05
Scint.	43.8	42.4



Critical energies of some materials

Material	Critical energy [MeV]
Pb	9.51
Al	51.0
Fe	27.4
Cu	24.8
Air (STP)	102
Lucite	100
Polystyrene	109
NaI	17.4
Anthracene	105
H_2O	92

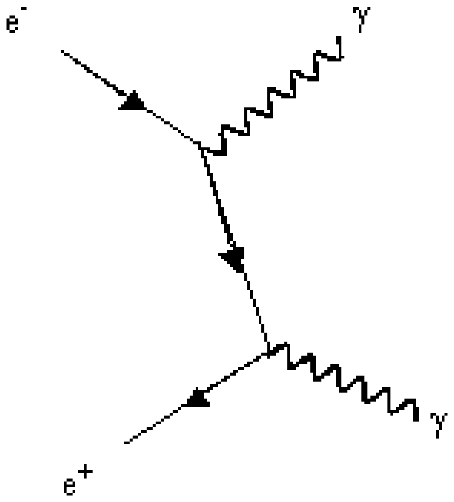
x_0 : radiation length
is the length scale for
Bremsstrahlung:
$E(x) = E_0 e^{-x/x_0}$

at $e^{\pm}$ energies above
~ 10 - 20 MeV
in a heavy material like Pb
Bremsstrahlung
dominates the energy loss

2-2 Energy loss of electrons

Positron annihilation

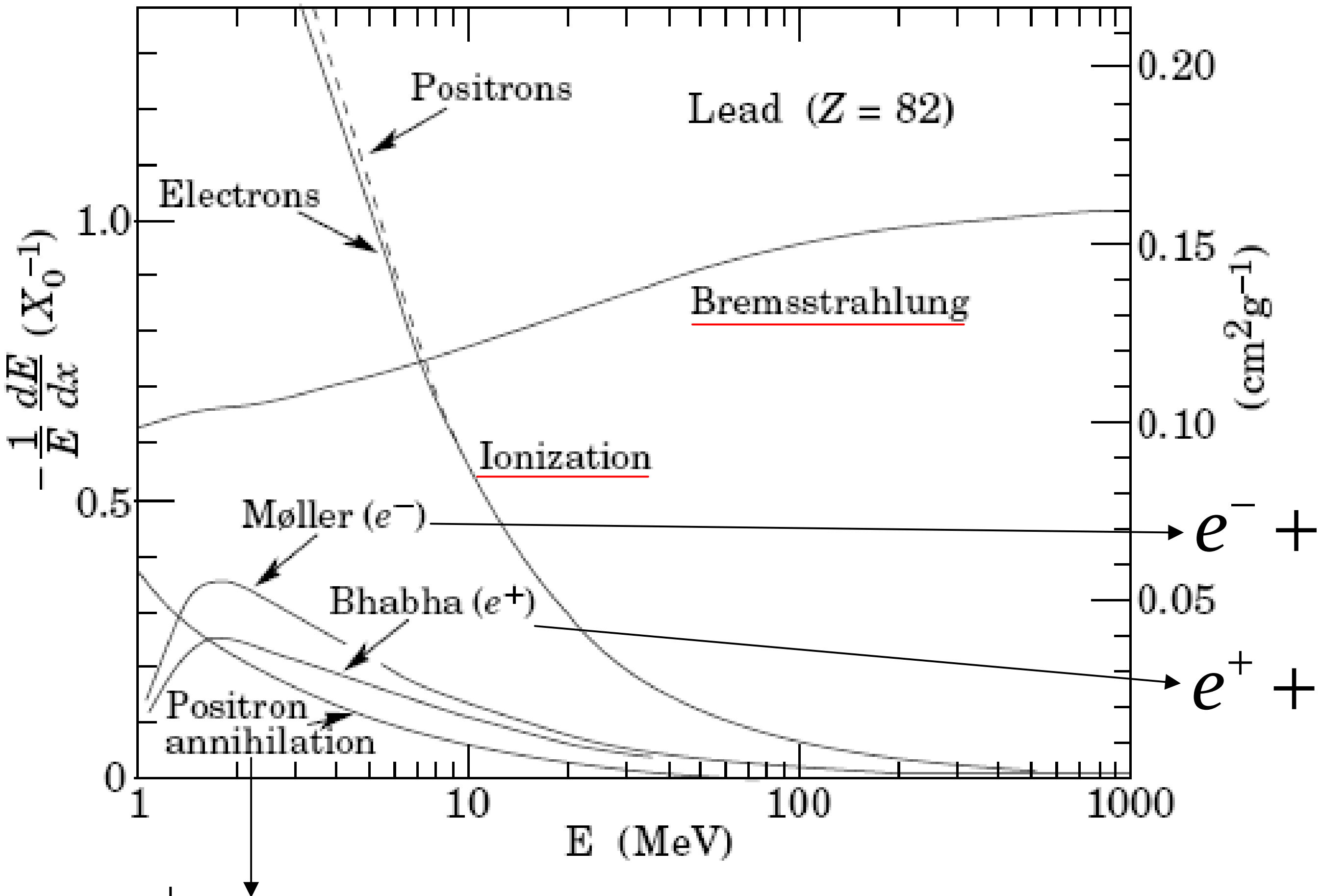
- In almost all cases, positrons that pass through matter annihilate with an electron, to create photons: $e^{+} + e^{-} \rightarrow \gamma + \gamma$



- 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



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

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

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

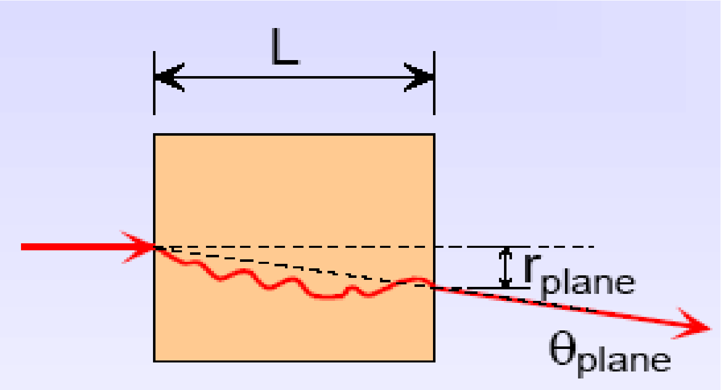
2-3 Multiple scattering

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

  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

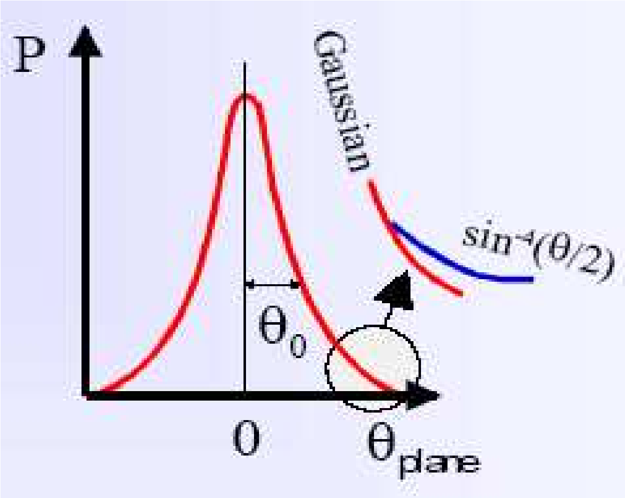
$$P(\theta) \approx \frac{2\theta}{\langle \theta^2 \rangle} \exp\left(\frac{-\theta^2}{\langle \theta^2 \rangle} \right) d\theta \text{ with}$$

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

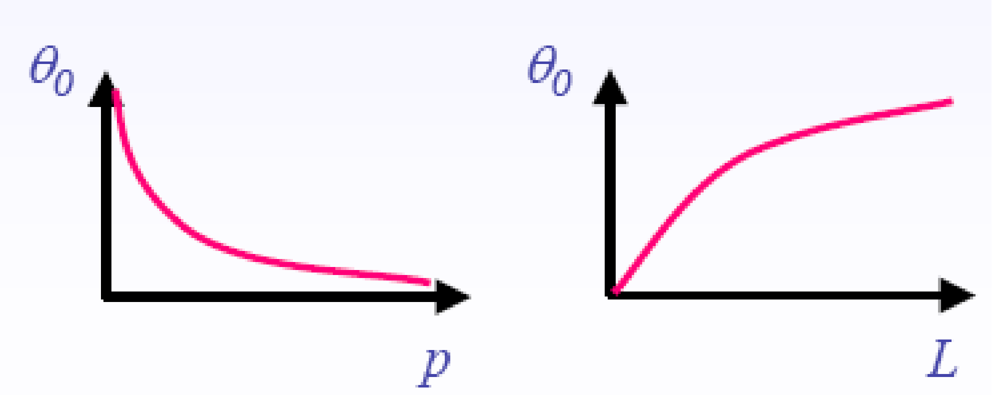
N.B. the introduction of the radiation length is just for commodity

2-3 Multiple scattering

Some remarks on the multiple scattering distribution :



- Tails described by single scatters with the Rutherford formula



- Expectation value as a function of momentum and path length
- Multiple Coulomb scattering limits the precision with which the direction of a particle can be determined
- We have considered the projection on 1 plane : $\theta_0^{space} = \sqrt{2}\theta_0$

2-3 Multiple scattering

O.M. compute the spatial angular dispersion of a 5 GeV/c momentum electrons beam after 2 cm of plastic scintillator

$$\beta = \frac{p}{E} \approx 1$$

$$X_0 = 42.4 \text{ cm}$$

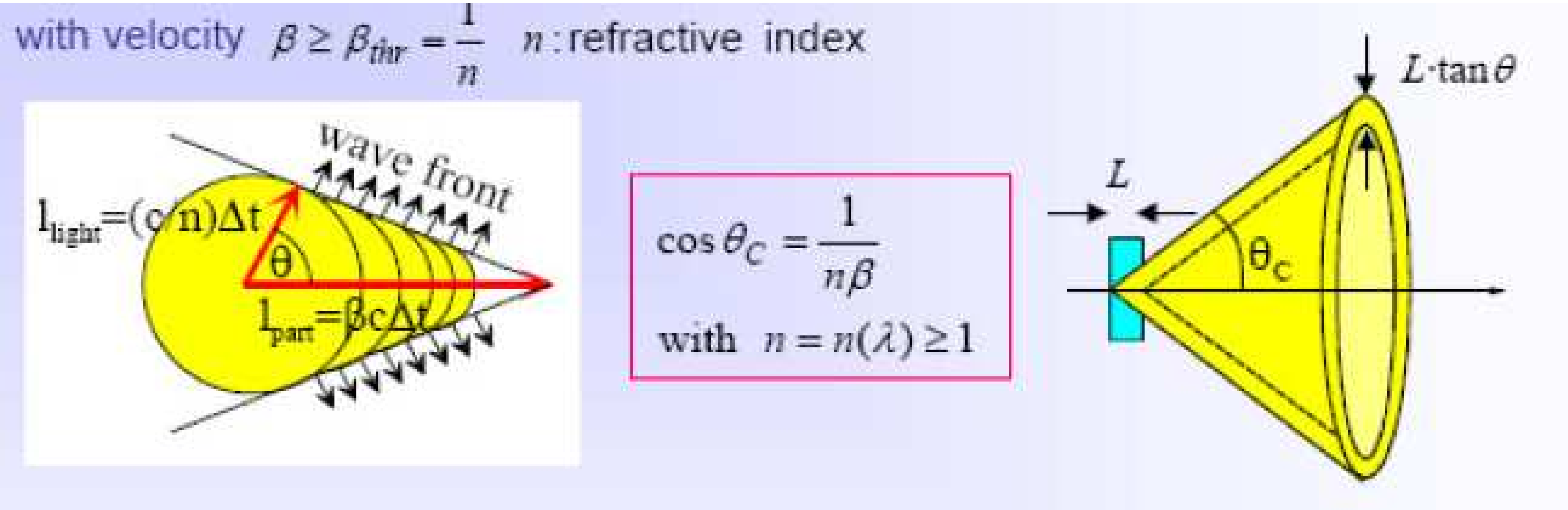
$$\theta_0^{space} = \sqrt{2} \times \frac{13.6}{1 \times 5.10^3} \times 1 \sqrt{\frac{2}{42.4}} \left(1 + 0.038 \ln \frac{2}{42.4} \right)$$

$$\theta_0^{space} \approx 0.738\, 10^{-3} \text{ rad} = 0.04°$$

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

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

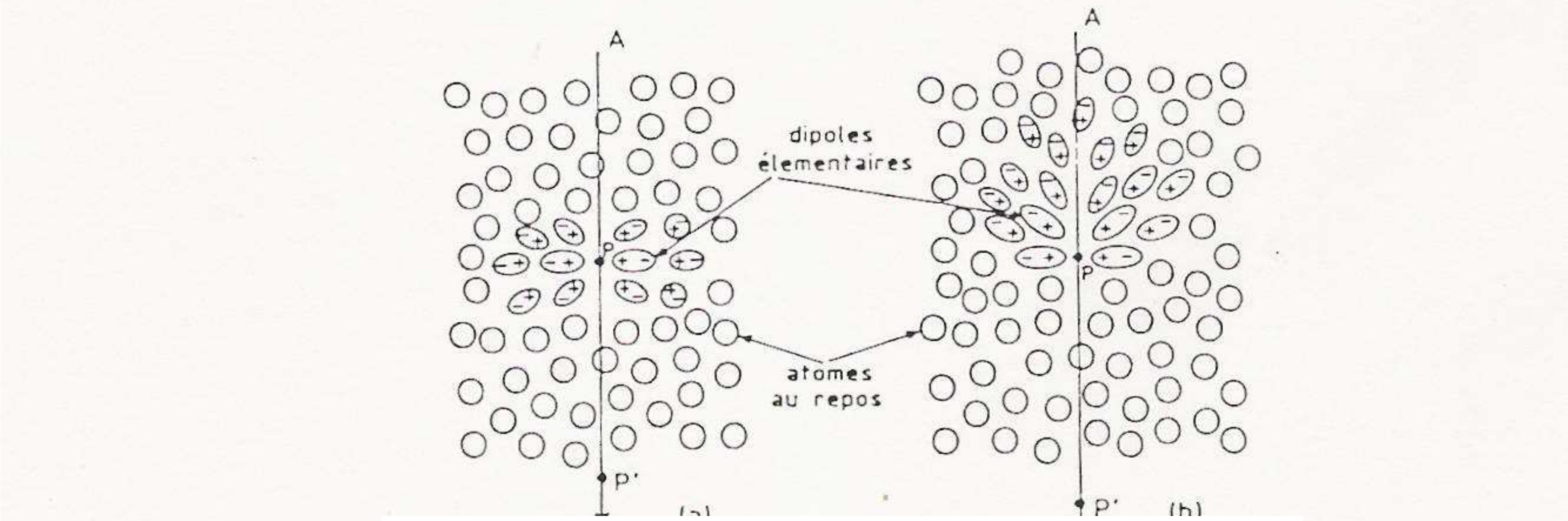
with $n = n(\lambda) \geq 1$

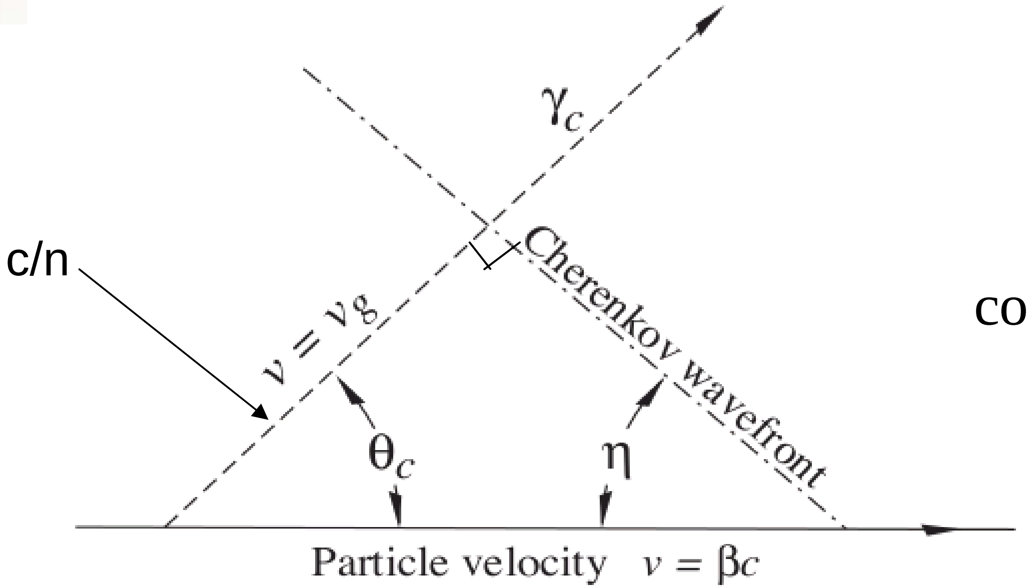
2-4 Cerenkov radiation

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





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

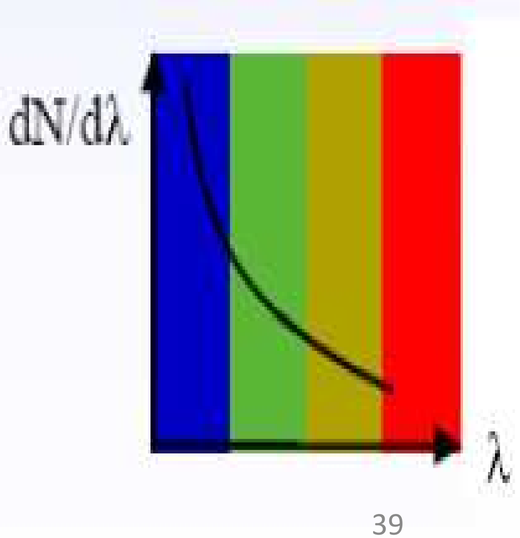
2-4 Cerenkov radiation

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

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

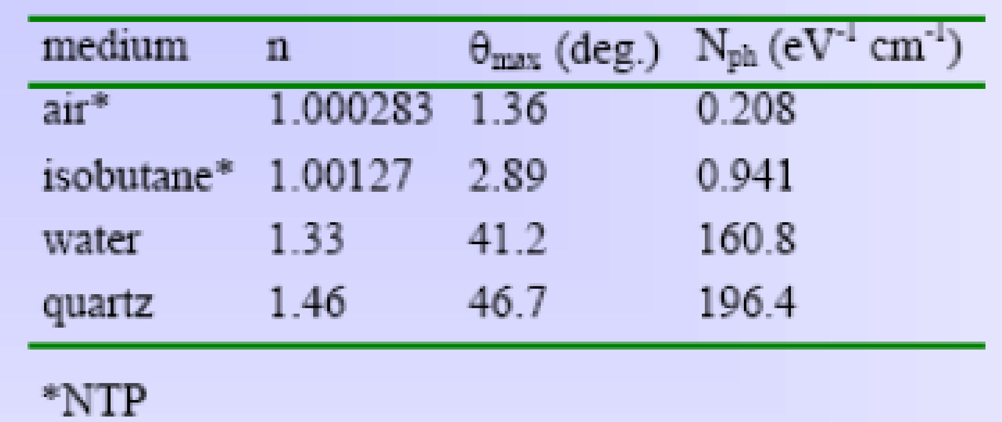
$$\frac{dN_{ph}(\text{visible})}{dx} \simeq 500\sin^2\theta$$



2-4 Cerenkov radiation

Cerenkov effect general features (cont’d):

- The energy loss is very small compared to the ionization one



medium	n	θ_{max} (deg.)	N_{ph} (eV^{-1} cm^{-1})
air*	1.000283	1.36	0.208
isobutane*	1.00127	2.89	0.941
water	1.33	41.2	160.8
quartz	1.46	46.7	196.4

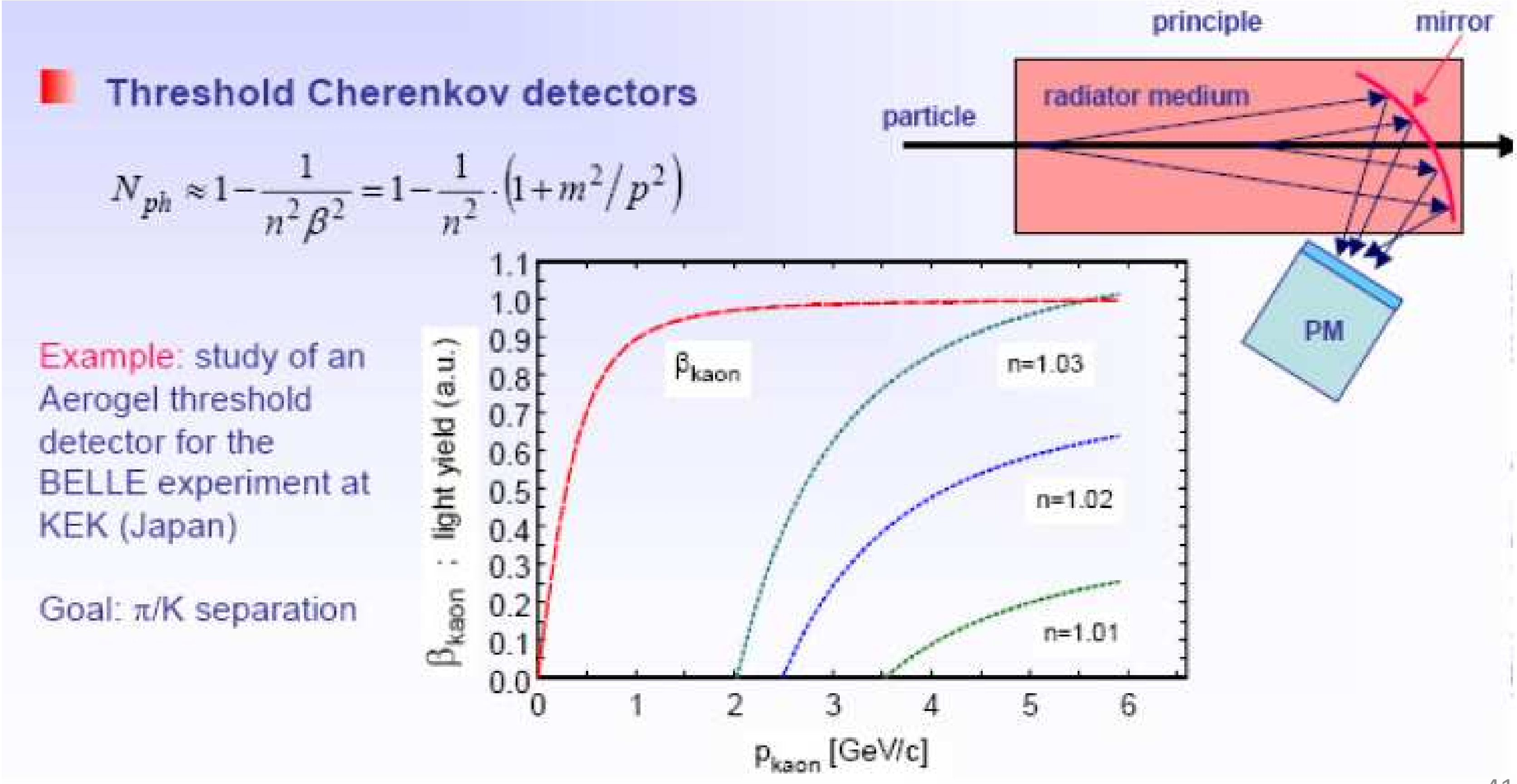
*NTP

- O.M. in water ~200 photons emitted in the visible spectrum → ~500 eV/cm energy loss (~0.1% of ionization energy loss)

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

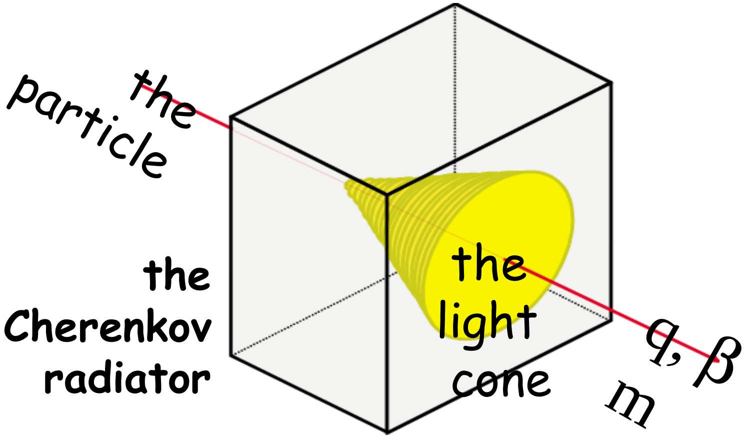
$$N_{ph} \approx 1-\frac{1}{n^2\beta^2} = 1-\frac{1}{n^2}\cdot\left(1+m^2/p^2\right)$$

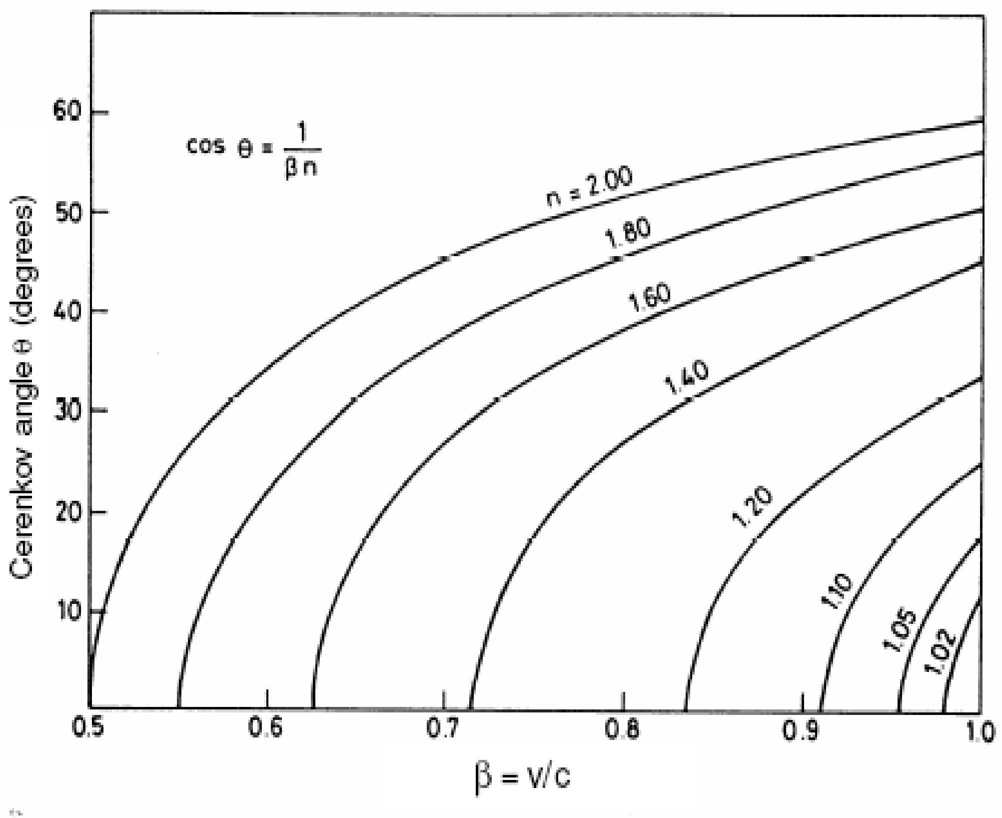
Example: study of an Aerogel threshold detector for the BELLE experiment at KEK (Japan)

Goal: π/K separation

2-4 Cerenkov radiation

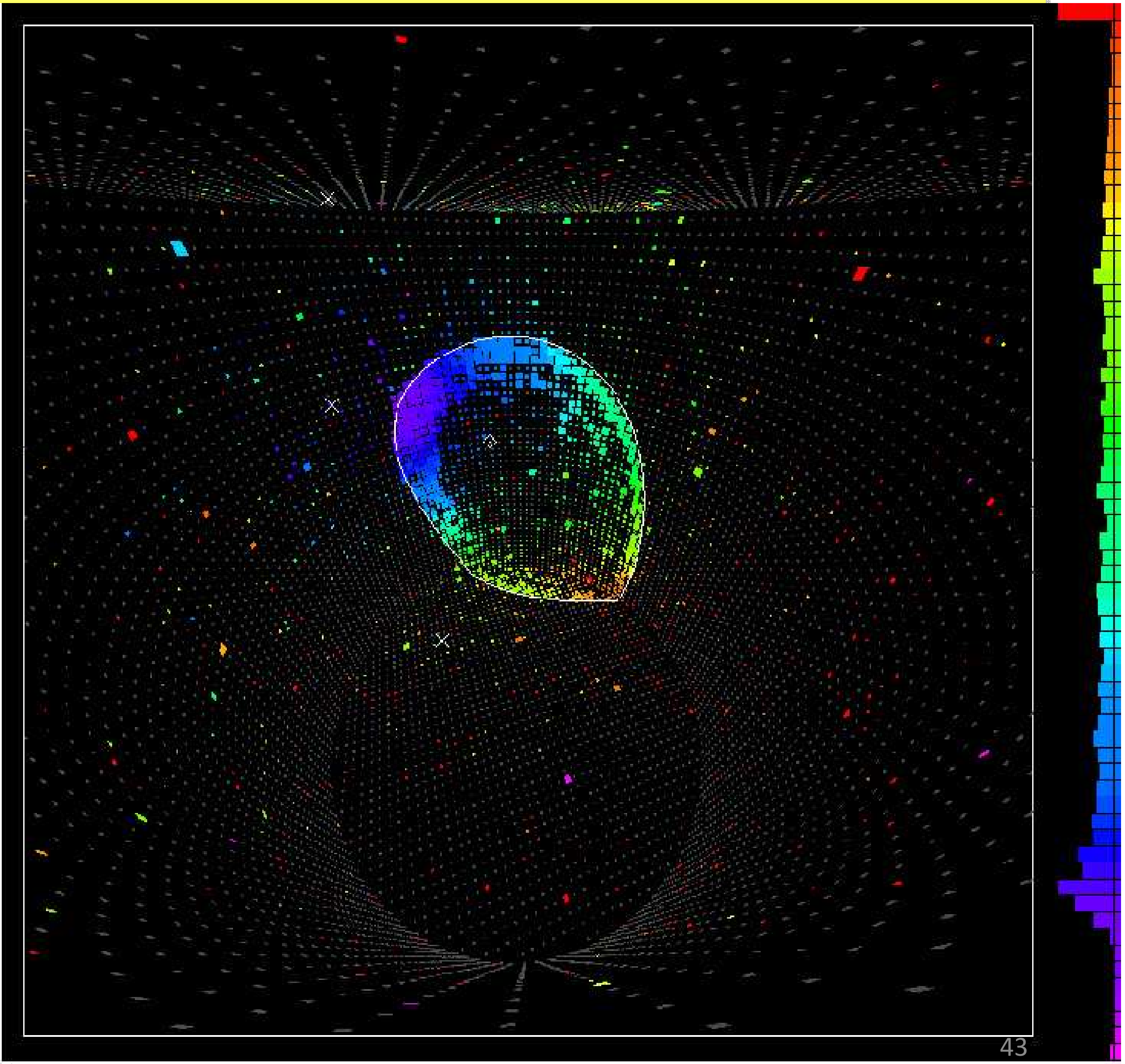
RICH : at fixed n, measuring θ defines β





2-4 Cerenkov radiation

Example of Cerenkov light cone:



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

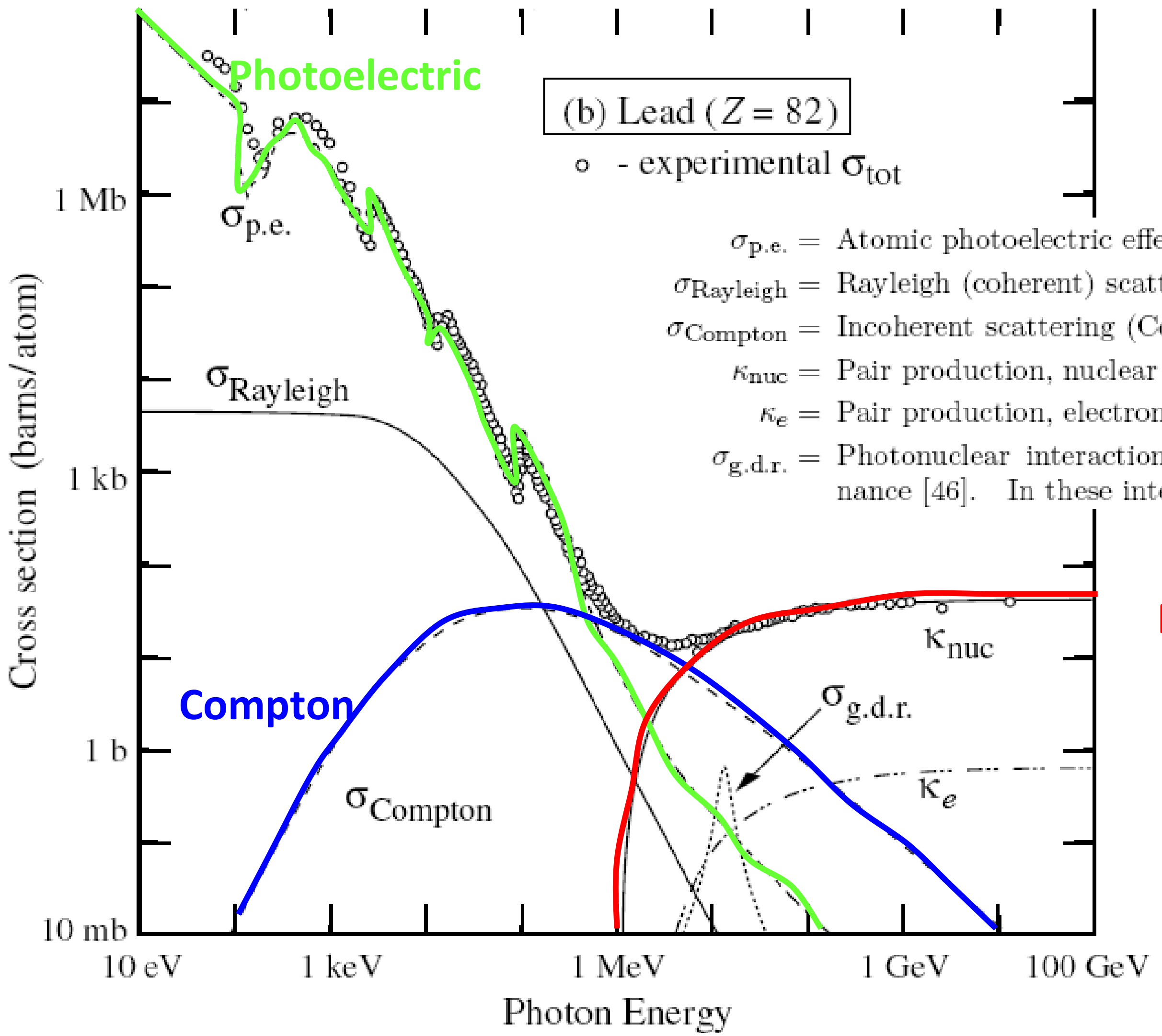
$$\boxed{\gamma + \text{nucleus} \rightarrow e^+ + e^- + \text{nucleus}}$$

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



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

σ_{Rayleigh} = Rayleigh (coherent) scattering–atom neither ionized nor excited

σ_{Compton} = Incoherent scattering (Compton scattering off an electron)

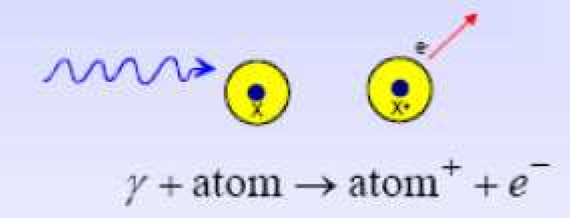
κ_{nuc} = Pair production, nuclear field

κ_e = Pair production, electron field

$\sigma_{\text{g.d.r.}}$ = 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^- ⇒ ejection of an electron
- A free electron cannot absorb the photon and conserve momentum ⇒ 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

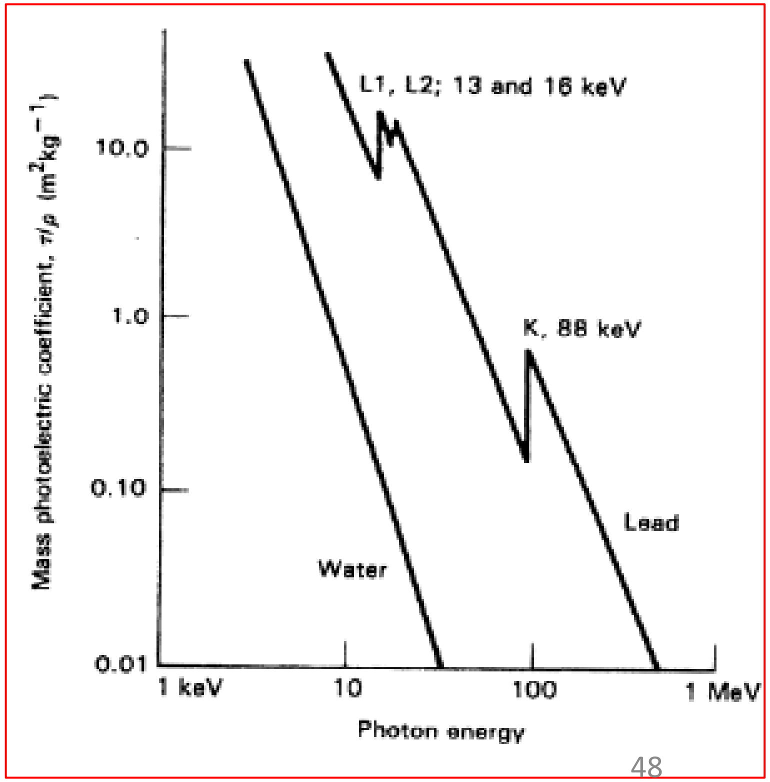
involving the Rydberg energy $hcR_{\infty} = 13.6056923(12)\,\text{eV} \equiv 1\,\text{Ry} = \frac{1}{2}\frac{m_e e^4}{\hbar^2}$ and the shell main quantum number *n*

2-5 Photons interaction

Photoelectric cross-section

- After the electron emission different processes may occur:
  - fluorescence (external shell-electron occupies the hole after radiation emission)
  - Auger electrons emission: a K-electron is replaced by a L-electron and the energy is sufficient to emit a M-electron with energy $E_K - E_L - E_M$

- Energy modulation for $E\gamma$~E orbital shells (M,L,K)



2-5 Photons interaction

Photoelectric cross-section

- Highest binding energy K-shell: σ increases in correspondence to the shell energy and then drops since K electrons are no more available. For energies above the K shell and in non relativistic approximation ($h\nu \ll m_e c^2$) the cross section per atom can be computed using the Born approximation

$$\sigma_{photo}^{K} = \left(\frac{32}{\varepsilon^{7}}\right)^{\frac{1}{2}} \alpha^{4} \boxed{Z^{5}} \sigma_{Th}^{e} \qquad \varepsilon = \frac{E_{\gamma}}{m_e c^{2}} \qquad \sigma_{Th}^{e} = \frac{8}{3}\pi r_e^{2} \quad \text{(Thomson)}$$

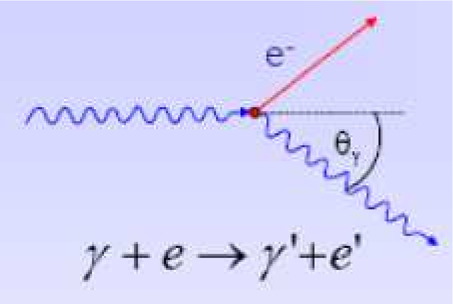
Depends on Z^5 → use of high Z materials for γ ray shielding

$$\sigma_{\text{Thomson}} = \frac{8\pi}{3} r_e^{2} = 6.65\,10^{-25}\ \text{cm}^{2} = 0.665\ \text{barn}$$

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

2-5 Photons interaction

Compton scattering:



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

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

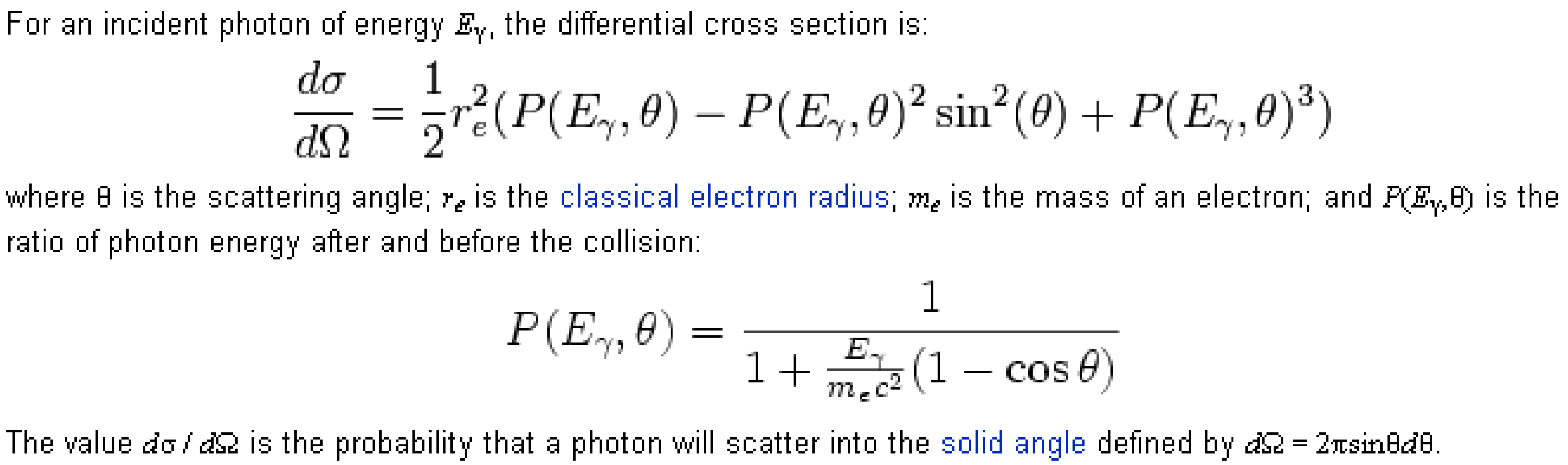
- Resulting in the wavelength shifting:

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

2-5 Photons interaction

Compton scattering:

- Computation performed in the scope of QED (Klein, Nishima 1929)



For an incident photon of energy E_γ, the differential cross section is:

$$\frac{d\sigma}{d\Omega} = \frac{1}{2} r_e^2 \left(P(E_\gamma,\theta) - P(E_\gamma,\theta)^2 \sin^2(\theta) + P(E_\gamma,\theta)^3\right)$$

where θ is the scattering angle; r_e is the classical electron radius; m_e is the mass of an electron; and $P(E_\gamma,\theta)$ is the ratio of photon energy after and before the collision:

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

The value $d\sigma / d\Omega$ is the probability that a photon will scatter into the solid angle defined by $d\Omega = 2\pi \sin\theta d\theta$.

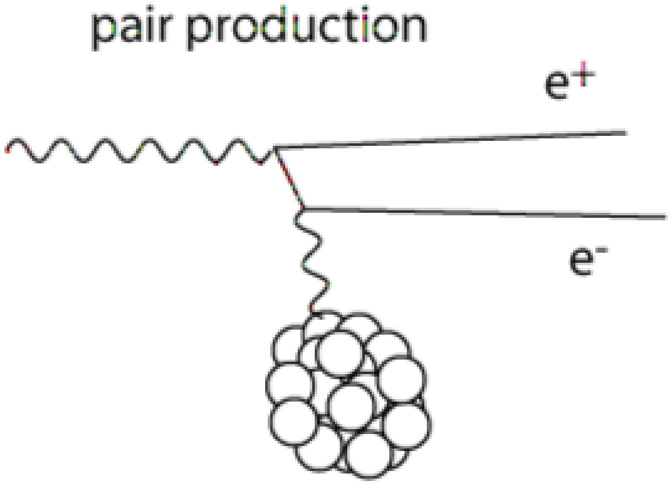
- Asymptotic behaviors:

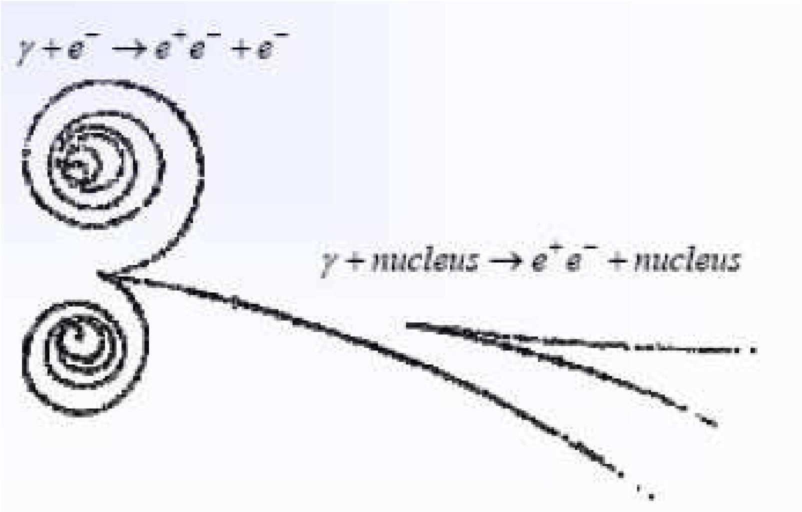
- At low energies $\sigma_{\text{Compton}} \to \sigma_{\text{Thomson}} (1-2\varepsilon)$ for $\varepsilon = \dfrac{E_\gamma}{m_e c^2} \ll 1$

- at high energies $\sigma_{\text{Compton}} \to \dfrac{3}{8} \sigma_{\text{Thomson}} \dfrac{1}{\varepsilon}\left(\dfrac{1}{2} + \ln\varepsilon\right)$ for $\varepsilon \gg 1$

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.

2-5 Photons interaction

Pair production:

- At high energies

$$\sigma_{\text{pair}} = \frac{4}{137} Z_t^2 r_e^2 \left[\frac{7}{9} \ln\left(\frac{183}{Z_t^{1/3}} \right) - \frac{1}{54} \right] \text{ i.e. } \sigma_{\text{pair}} \simeq \frac{7}{9} \sigma_{\text{rad.}}$$

- Which leads to the definition of the pair-creation length

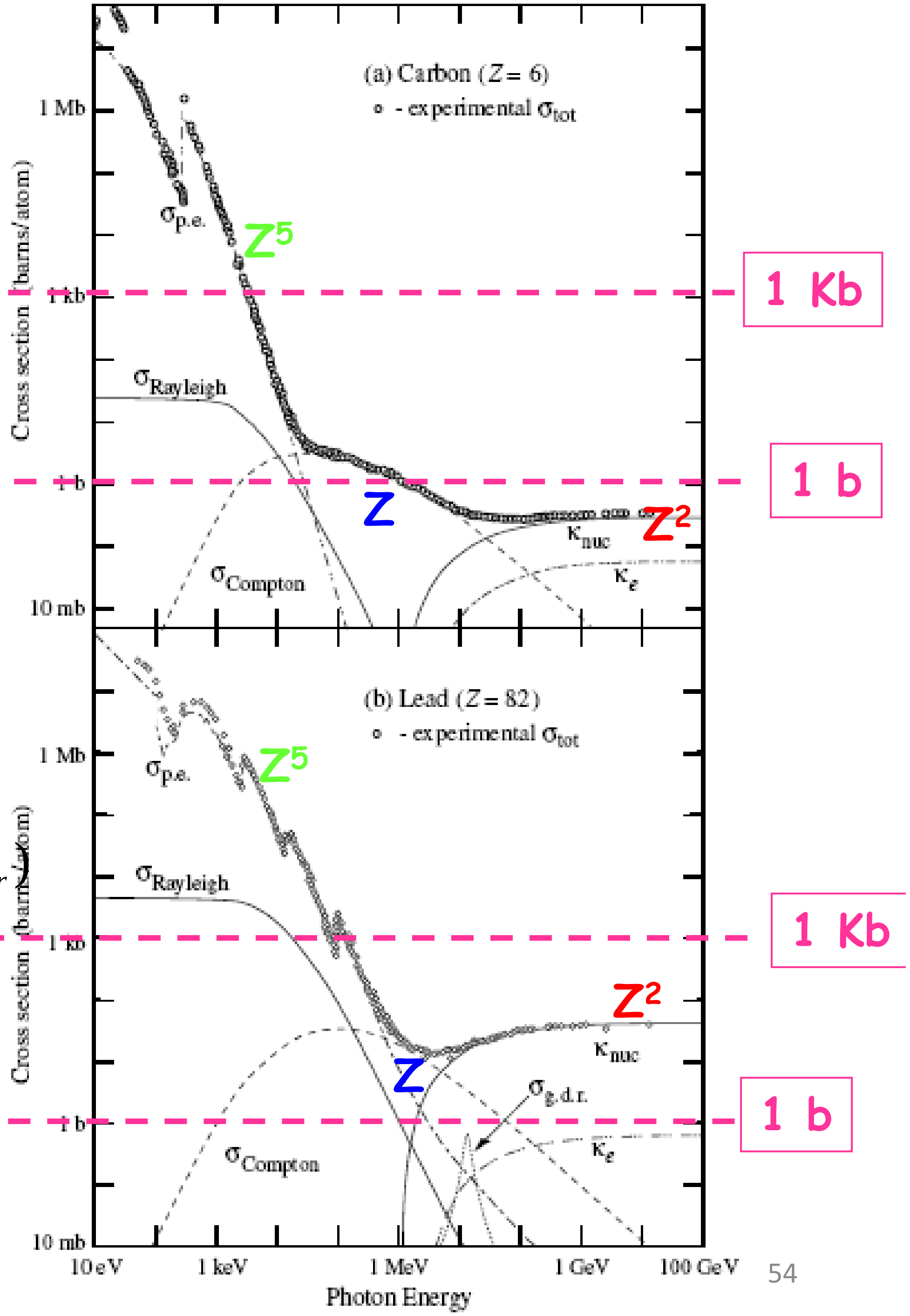
$$\lambda_{\text{pair}} = \frac{A}{\rho N_A \sigma_{\text{pair}}} \text{ i.e. } \lambda_{\text{pair}} \simeq \frac{9}{7} X_0$$

2-5 Photons interaction

Summary:

- Comparison between 2 different nuclei (carbon and lead)
- Total attenuation length λ

$$\frac{1}{\lambda}=\frac{\mu}{\rho}=\frac{N_A}{A}\sigma_{tot}\cong\frac{N_A}{A}(\sigma_{pE}+Z\sigma_{comp}+\sigma_{pair})$$



2-5 Photons interaction

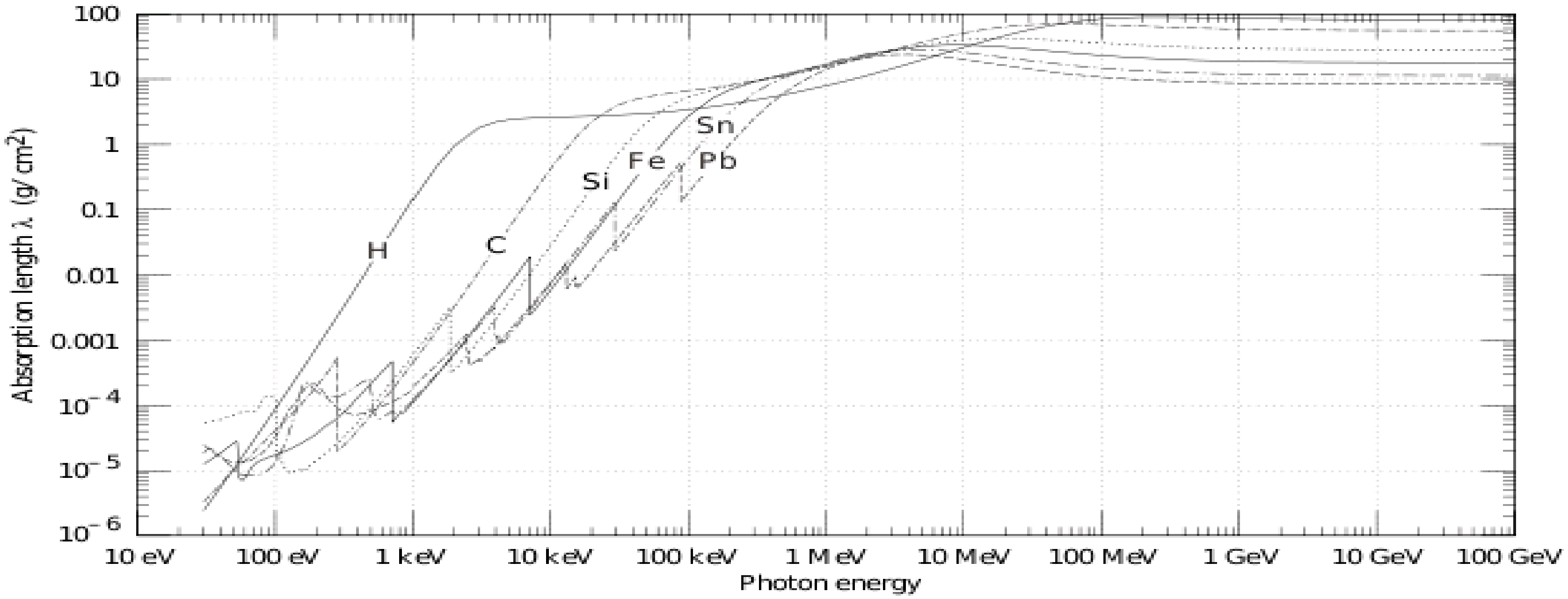


Figure 27.16: The photon mass attenuation length (or mean free path) $\lambda = 1/(\mu/\rho)$ for various elemental absorbers as a function of photon energy. The mass attenuation coefficient is μ/ρ, where ρ is the density. The intensity I remaining after traversal of thickness t (in mass/unit area) is given by $I = I_0 \exp(-t/\lambda)$. The accuracy is a few percent. For a chemical compound or mixture, $1/\lambda_{\rm eff} \approx \sum_{\rm elements} w_Z/\lambda_Z$, where w_Z is the proportion by weight of the element with atomic number Z. The processes responsible for attenuation are given in Fig. 27.10. Since coherent processes are included, not all these processes result in energy deposition. The data for 30 eV $< E <$ 1 keV are obtained from `http://www-cxro.lbl.gov/optical_constants` (courtesy of Eric M. Gullikson, LBNL). The data for 1 keV $< E <$ 100 GeV are from `http://physics.nist.gov/PhysRefData`, through the courtesy of John H. Hubbell (NIST).

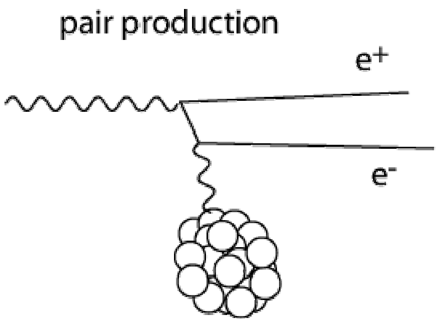
2-6 Electromagnetic showers

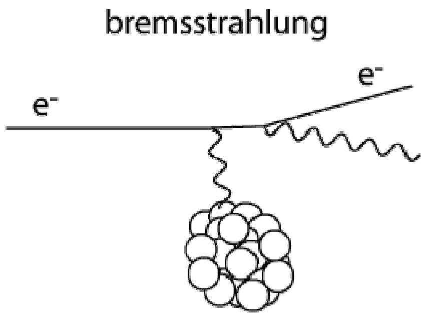
Above energies ~10 MeV the dominant processes for electrons and photons are bremsstrahlung and pair production resp.

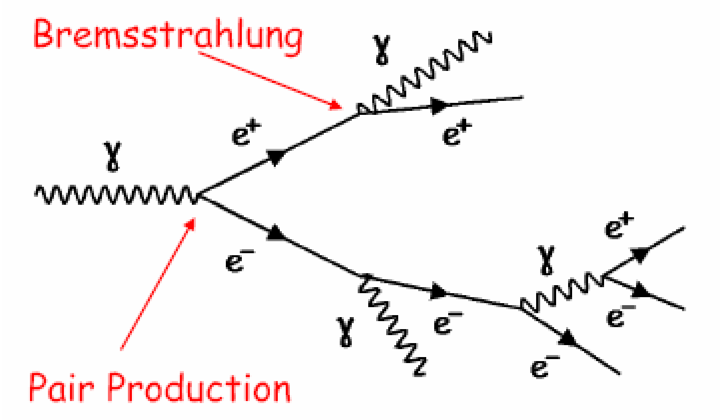
- The radiated photons have enough energy to produce extra pairs
- The emitted e^+ and e^- have enough energy to emit radiation γ etc

→ The number of photons and electrons per unit length increase

→ Development of an electromagnetic shower

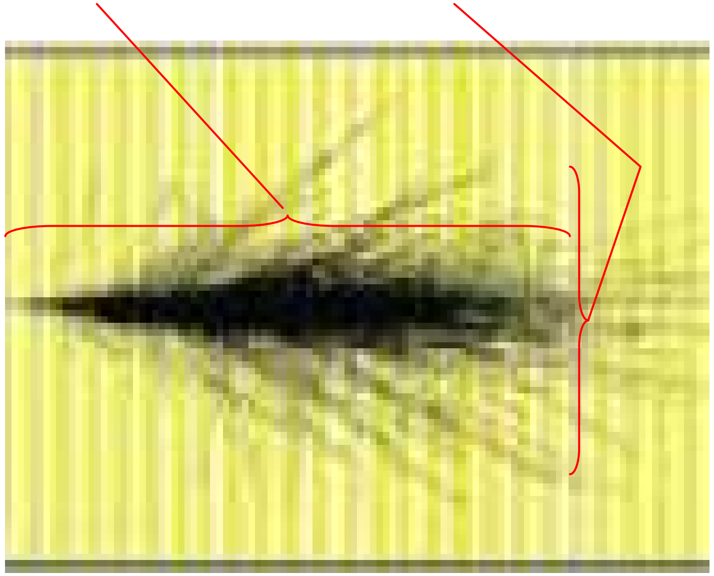


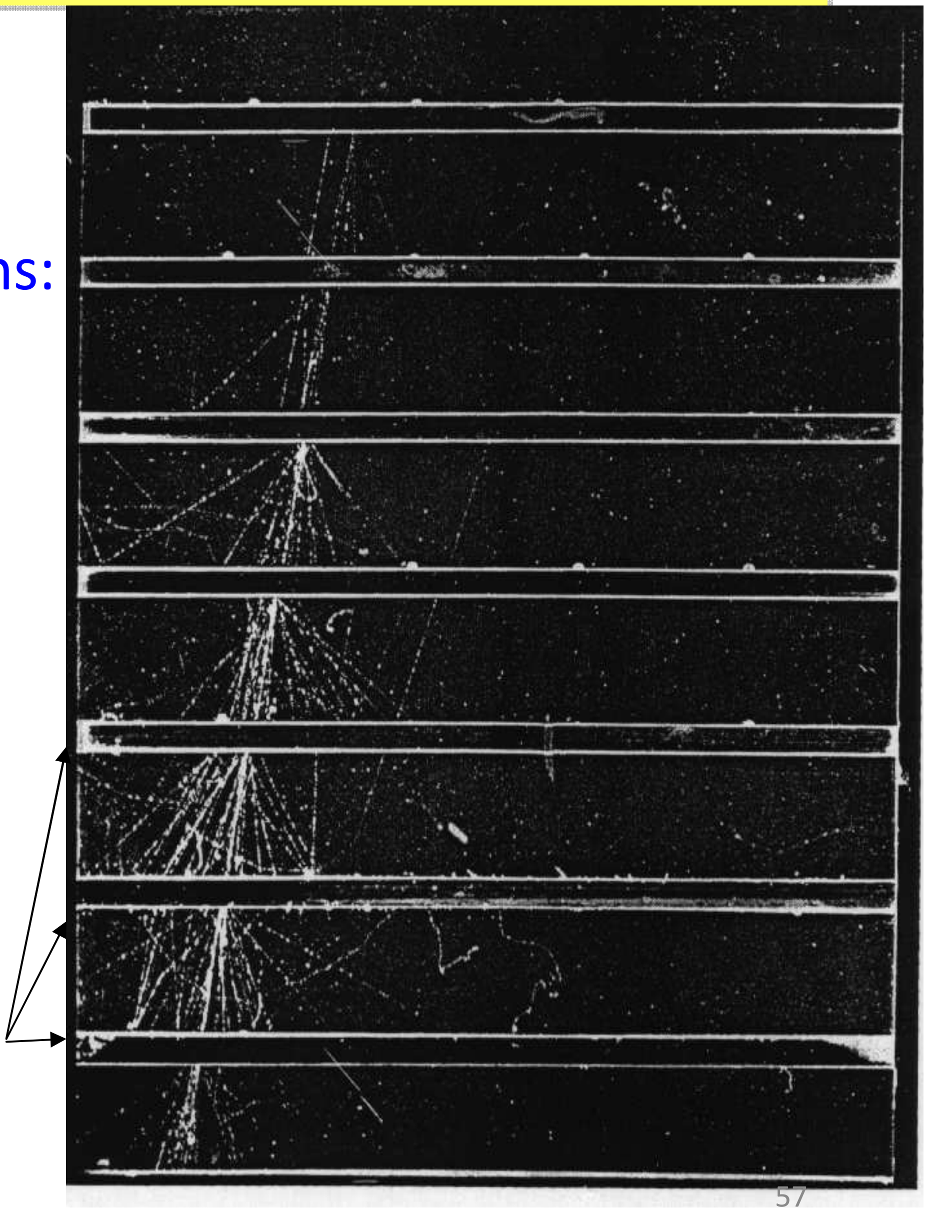




2-6 Electromagnetic showers

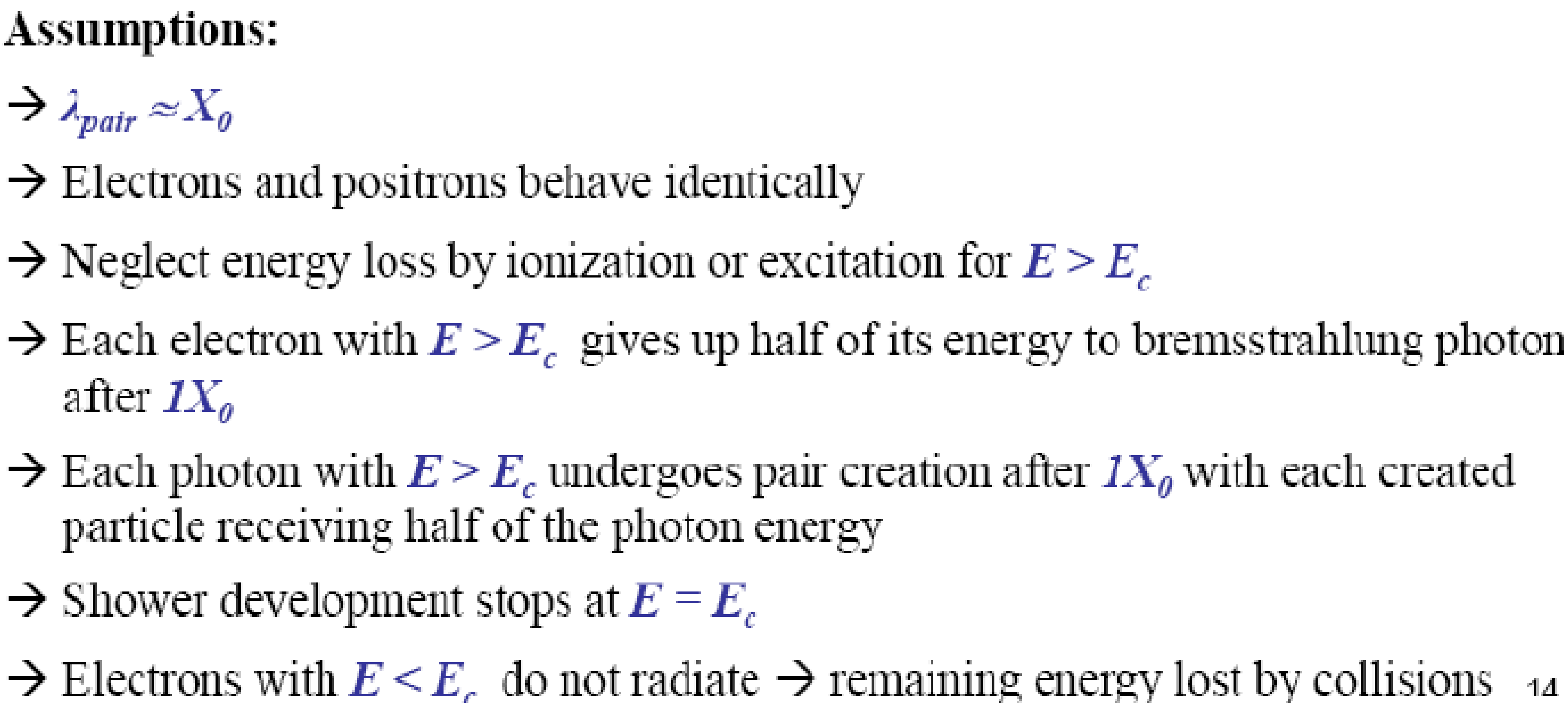
The development of the e.m. showers is treated separately in the longitudinal and transverse directions:





2-6 Electromagnetic showers

Simple model



Assumptions:

→ $\lambda_{pair} \approx X_0$

→ Electrons and positrons behave identically

→ Neglect energy loss by ionization or excitation for $E > E_c$

→ Each electron with $E > E_c$ gives up half of its energy to bremsstrahlung photon after $1X_0$

→ Each photon with $E > E_c$ undergoes pair creation after $1X_0$ with each created particle receiving half of the photon energy

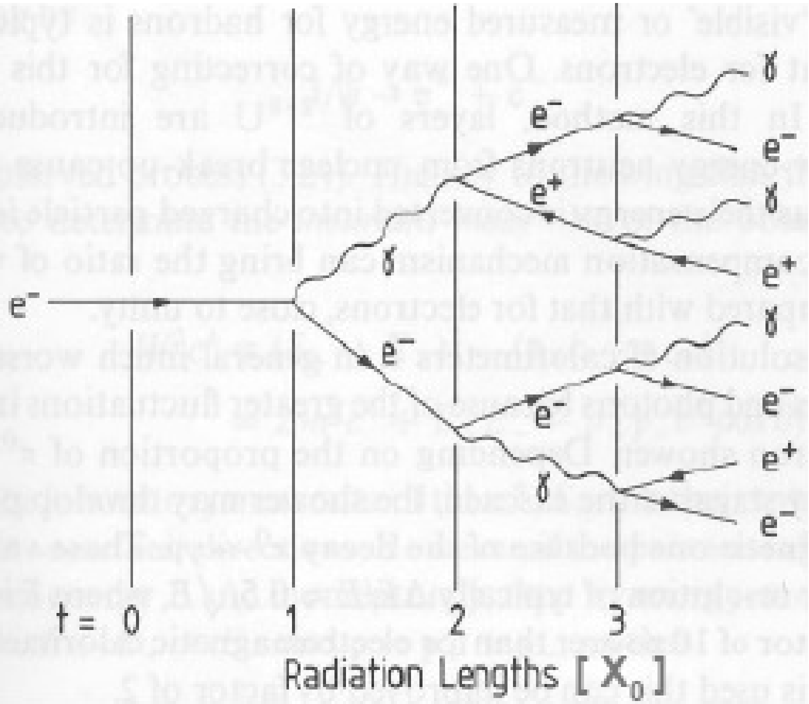
→ Shower development stops at $E = E_c$

→ Electrons with $E < E_c$ do not radiate → remaining energy lost by collisions

2-6 Electromagnetic showers

Simple model : an alternating sequence of interactions leads to a cascade:

- Primary γ with E_0 energy pair-produces with 54% probability in X_0
- On average, each e has $E_0/2$ energy. If $E_0/2 > E_c$, they lose energy by Brems.
- Next layer X_0, charged particle energy decreases to $E_0/(2e)$
- Brems. of average energy between $E_0/(2e)$ and $E_0/2$ is radiated. Mean # particles after layer $2X_0$ is ~4.



- After n generations ($dx = nX_0$), 2^n particles each of energy $E_0/2^n$.
- Cascade stops when e^- energy → critical energy $E_c = E_0/2^n$.
- Number of generations: $n = \ln(E_0/E_c)/\ln 2$.
- Number of particles at shower maximum: $N_p = 2^n = E_0/E_c$.

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: $R_M = 21\ (\text{MeV}) \times \frac{X_0}{E_c}$
  - 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.

2-6 Electromagnetic showers

E.M. shower properties:

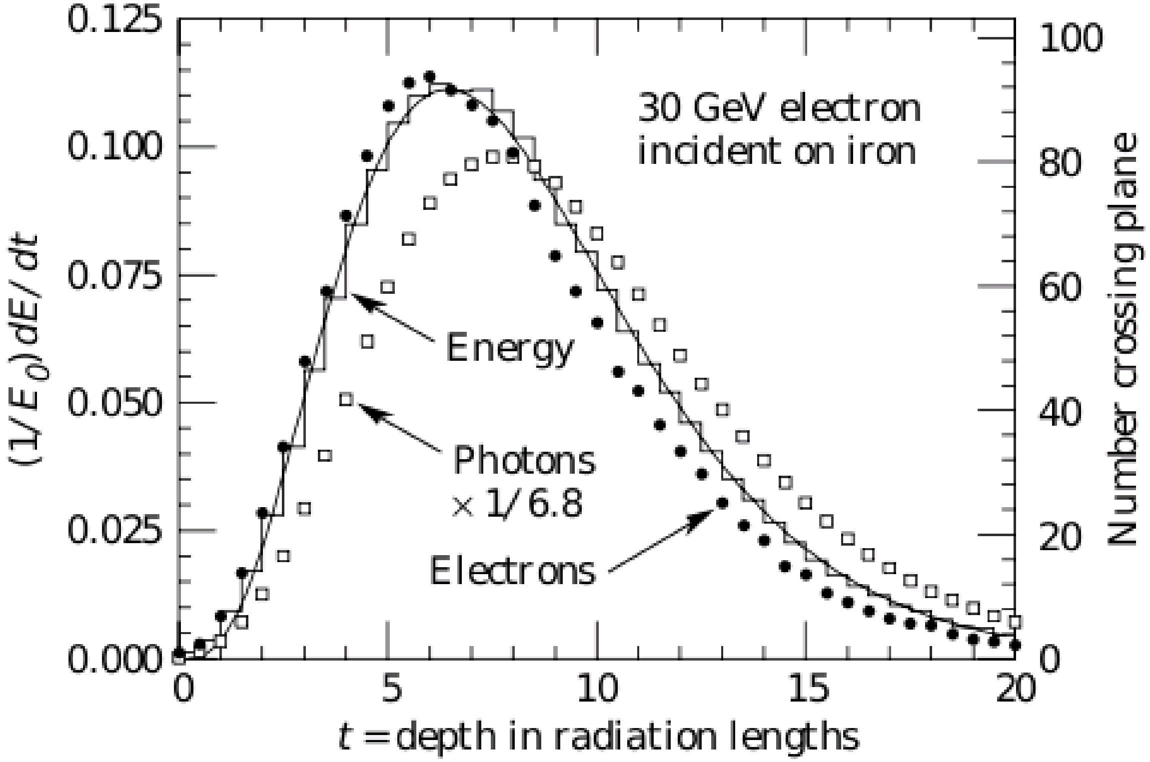
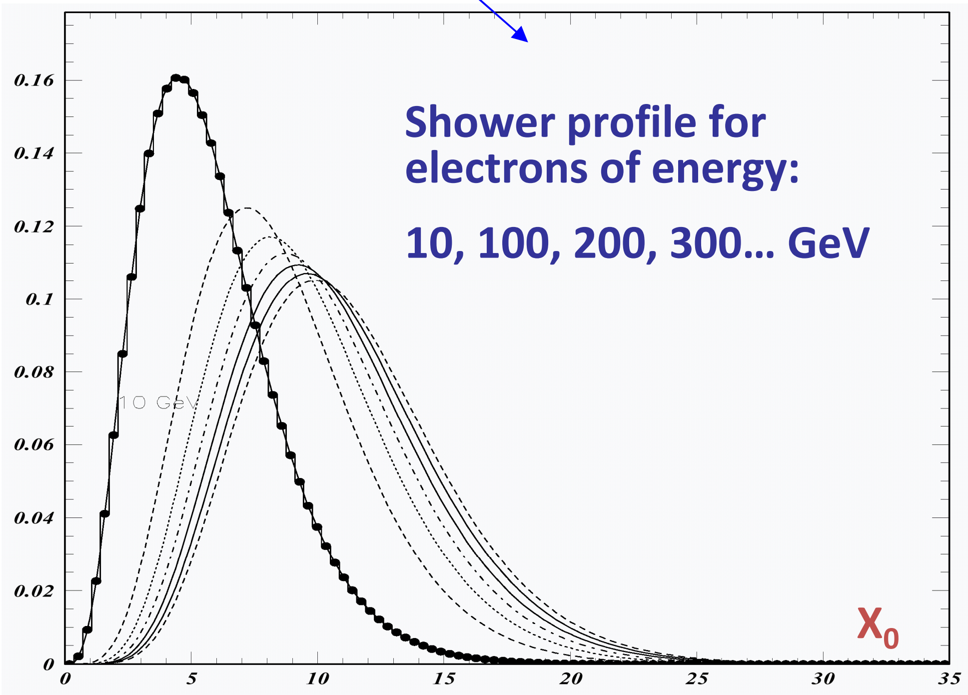


Figure 27.18: An EGS4 simulation of a 30 GeV electron-induced cascade in iron. The histogram shows fractional energy deposition per radiation length, and the curve is a gamma-function fit to the distribution. Circles indicate the number of electrons with total energy greater than 1.5 MeV crossing planes at $X_0/2$ intervals (scale on right) and the squares the number of photons with $E \geq 1.5$ MeV crossing the planes (scaled down to have same area as the electron distribution).

2-6 Electromagnetic showers

E.M. shower properties:

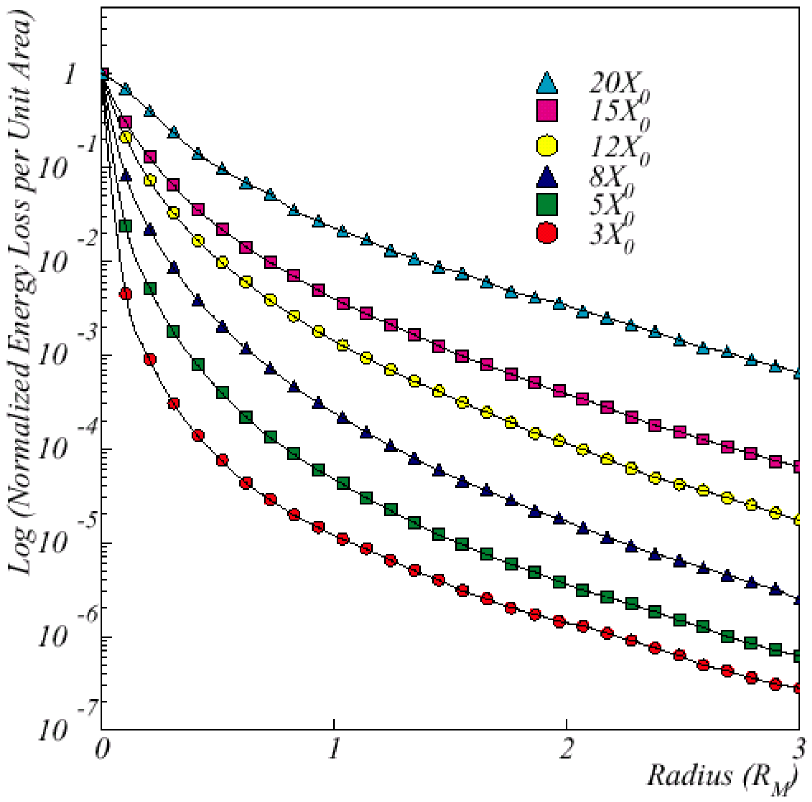
- Longitudinal profiles and transverse profiles



Shower profile for electrons of energy:

10, 100, 200, 300… GeV

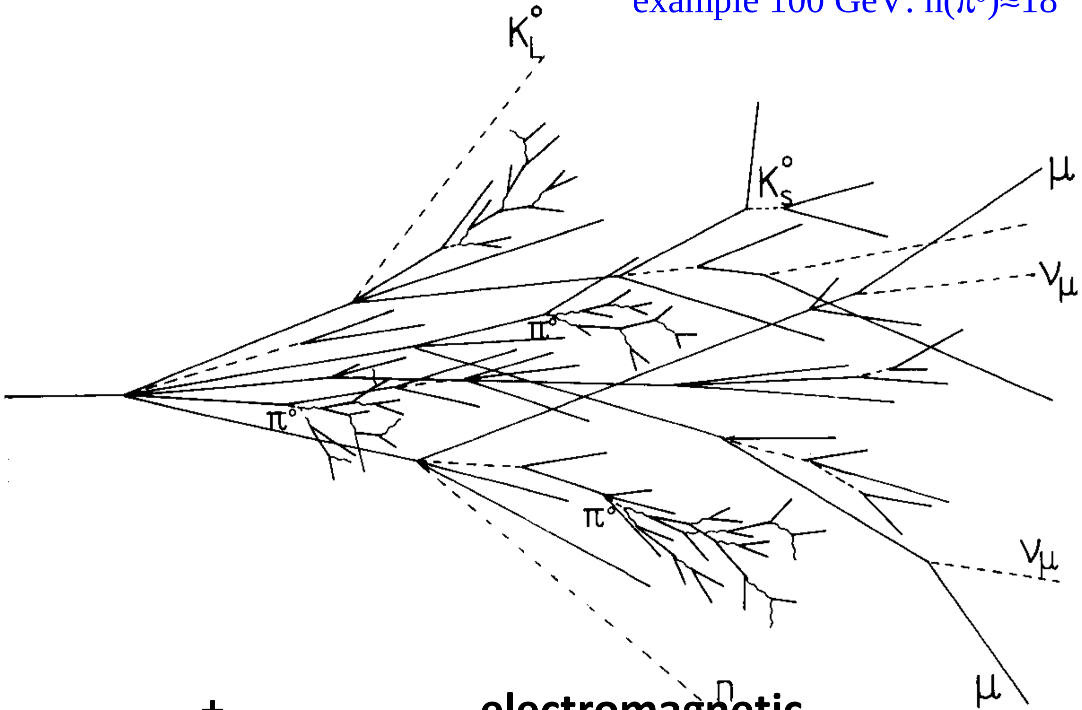
50 GeV electrons in $PbWO_4$



2-7 Hadronic showers

Complicated processes involving many interaction types!!!

example 100 GeV: n(π^0)≈18



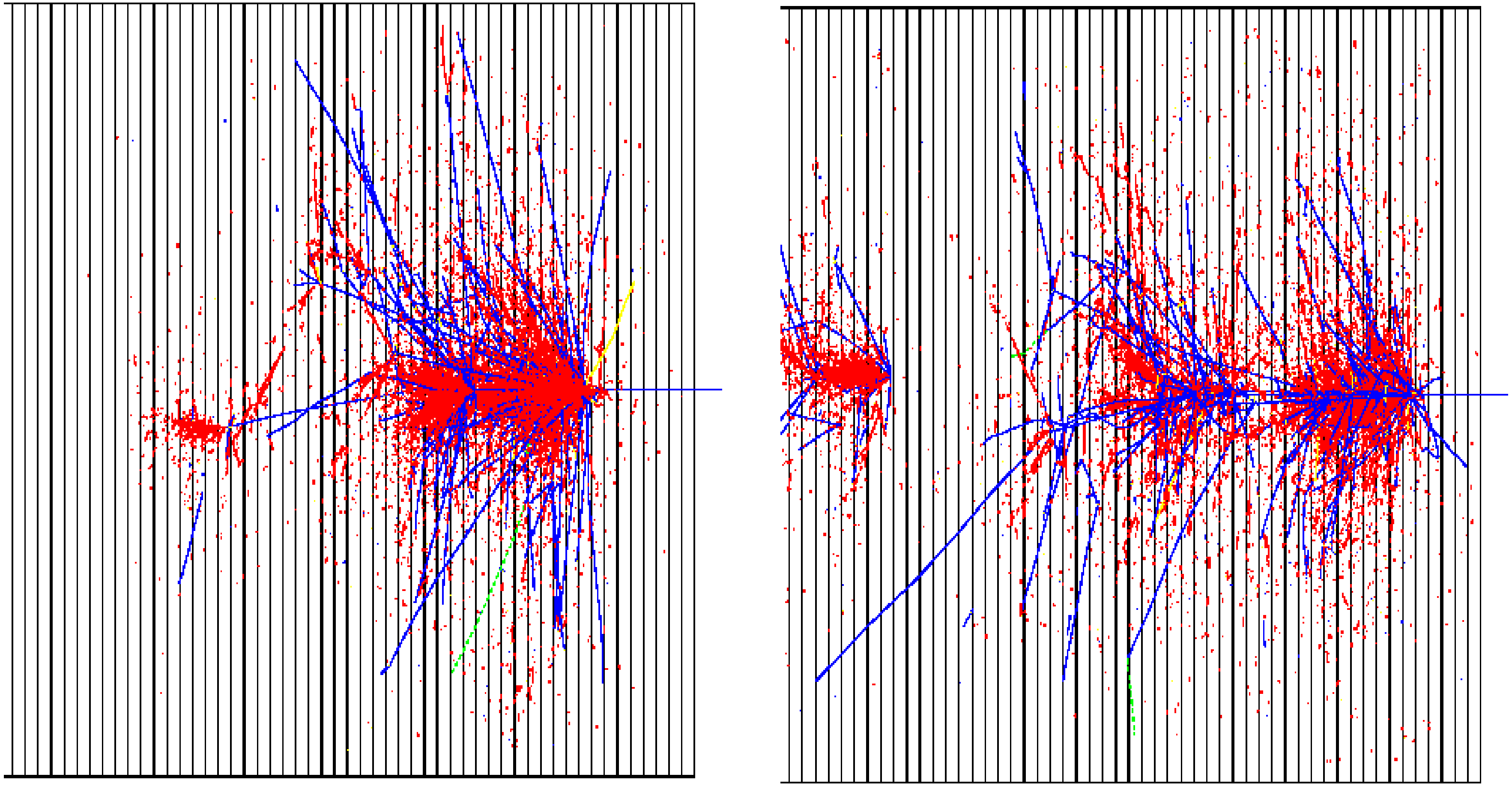
Hadronic + **electromagnetic**

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

3-1 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: $X+p \rightarrow X^{*} + p$

   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

General features:

- Electrons and ions created by incident radiation are called primary ionization.
- If these ionizations have enough energy they can also create electron-ion pairs (secondary ionization).
- Penning effect: metastable states are created which cannot de-excite to the fundamental state with a photon emission ➔ de-excitation through the collision with a second atom

  ($Ne^* + Ar \rightarrow Ne + Ar^+ + e^-$). Adding a little bit of Ar (0.1%) can double the ionization !
- Formation of molecular ions may happen in noble gases ($He^+ + He \rightarrow He^{2+}$)

3-1 Ionization detectors

Mean number of electron-ion pairs created:

- In gases usually one considers 1 electron-ion pair per 30eV energy loss (w_i).
- The total number of electron-ion papers produced in Δx will be:

$$\boxed{n_{total} = \frac{\Delta E}{w_i}}$$

where ΔE is the energy lost (Bethe-Block) in the path Δx and w_i is the average energy to be spent to create a ion electron pair.

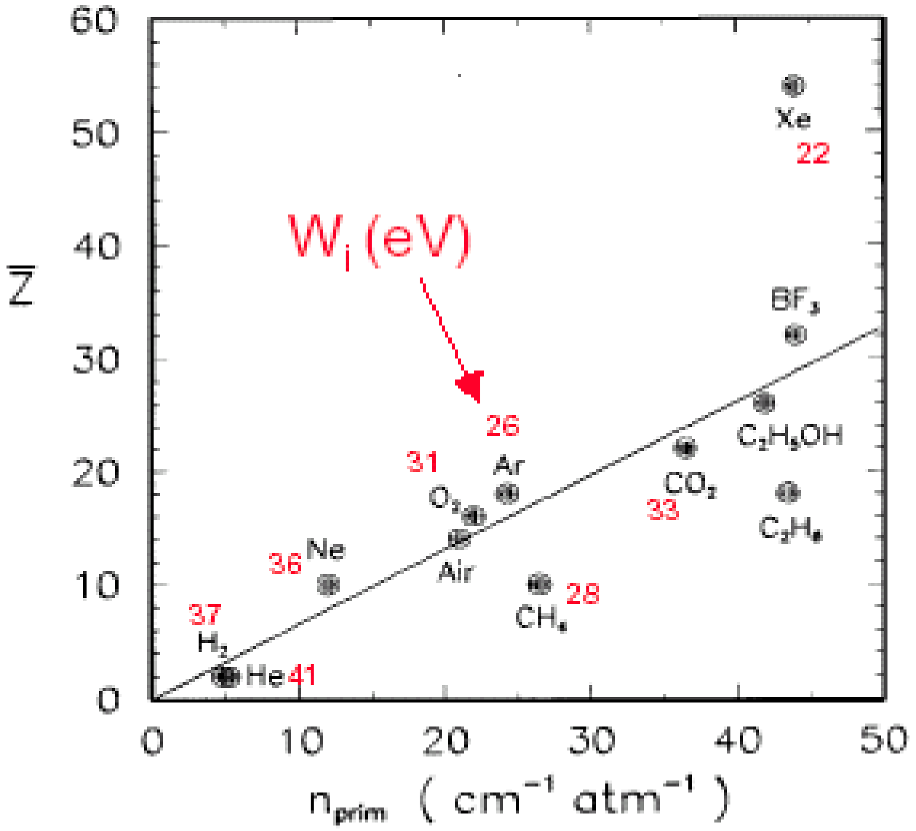
- N.B. detection issue: ≈ 100 electron-ion pairs are not easy to detect! Noise of amplifier ≈1000 e- (ENC) ! We need to increase the number of e-ion pairs.

3-1 Ionization detectors

Weak dependence of w_i with Z

Number of primary electron/ion pairs in frequently used (detector) gases.

(Lohse and Witzeling, Instrumentation In High Energy Physics, World Scientific, 1992)



Resolution for an energy E : $\sigma_E = 2.35\sqrt{Fw_i / E}$ (F is the Fano factor (<<1) taking into account that ionization events are not all statistically independent)

3-1 Ionization detectors

Gas	Z	A	E_{ex} eV	E_i eV	W_i eV	dE/dx MeV/g cm^{-2}	dE/dx KeV/cm	n_p i.p/cm	n_T i.p/cm
Ar	18	39.9	11.6	15.8	26	1.47	2.44	29.4	94
Kr	36	83.8	10.0	13.9	24	1.32	4.60	22	192
Xe	54	131.3	8.4	12.1	22	1.23	6.76	44	307
CO_2	22	44	5.2	13.7	33	1.62	3.01	34	91
CH_4	10	16		15.2	28	2.21	1.48	16	53
C_4H_{10}	34	58		10.6	23	1.86	4.50	46	195

Where: E_{ex} = excitation potential; E_i = ionization potential;
W_i = average energy loss to create a ion-electron pair;
dE/dx = energy losses at the minimum (MIP);
n_p = number of primary pairs; n_T = total number of pairs.

3-1 Ionization detectors

After Ionization, what's next?

- Once ion pairs are created, many processes can occur: recombination, charge exchange, attachment, absorption.
- Since we have already very few ion-electron pairs it is very important that they do not get lost before being collected ….

1. Recombination of the electron-ion and emission of a photon: $X^+ + e^- \rightarrow X + \gamma$
2. Recombination of positive/negative ions to neutrals:

   $X^+ + Y^- \rightarrow X + Y + \gamma$

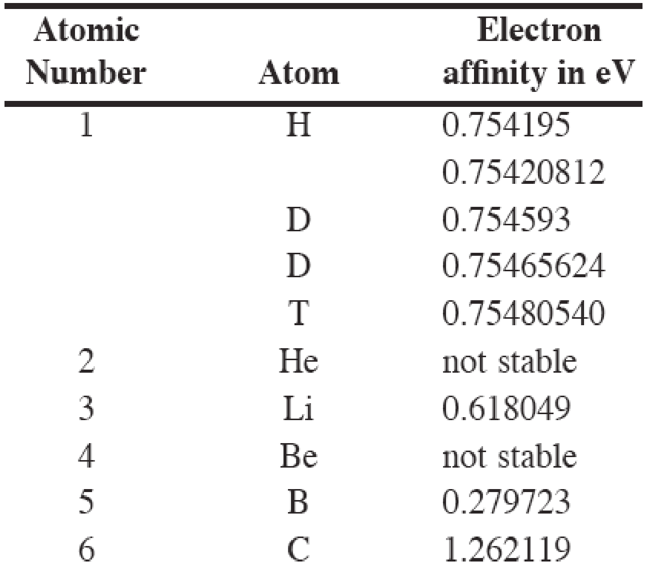
- In general the recombination speeds depends on the concentration of ions: $dn = bn_+ n_- dt$ where *b* is a constant depending on the gas and *n+*, *n-* are the concentrations of negative and positive ions.

3-1 Ionization detectors

After Ionization, what's next?

3. Electron attachment is the capture of free electrons by electronegative atoms to form negative ions: $X + e^- \rightarrow X^- + \gamma$

- It is therefore important to avoid the use (or the contamination) of gases with large electron affinity (water vapor, O2, ethanol, CO_2 SF_6, CCl_4, freon).
- Noble gases on the contrary have negative electron affinities !!!



Atomic Number	Atom	Electron affinity in eV
1	H	0.754195
		0.75420812
	D	0.754593
	D	0.75465624
	T	0.75480540
2	He	not stable
3	Li	0.618049
4	Be	not stable
5	B	0.279723
6	C	1.262119

3-1 Ionization detectors

After Ionization, what's next?

4. Charge exchange : ionization potential of the ion is greater than some molecule mixed with the gas, usually polyatomic gas like ethanol or methylal. Gas quenches the ion multiplication by neutralizing ions of the main chamber gas: dissipates ionization energy by dissociating into smaller fragments and absorbs γ's emitted in radiative de-excitation process. This is called a quenching gas.

3-1 Ionization detectors

Transports of electrons and ions in gases:

- The motion of electrons and ions can be features from classical kinetic theory of gases.
- Diffusion:

  - in absence of E-field liberated particles diffuse with a typical distribution $$\frac{dN}{N} = \frac{1}{\sqrt{4\pi Dt}} e^{-(x^2/4Dt)}\, dx$$ D: diffusion coefficient

  - the r.m.s. spread is given by $\sigma_x(t) = \sqrt{2Dt}$
- Drift in E-field

  - mobility : $\mu = v / E$

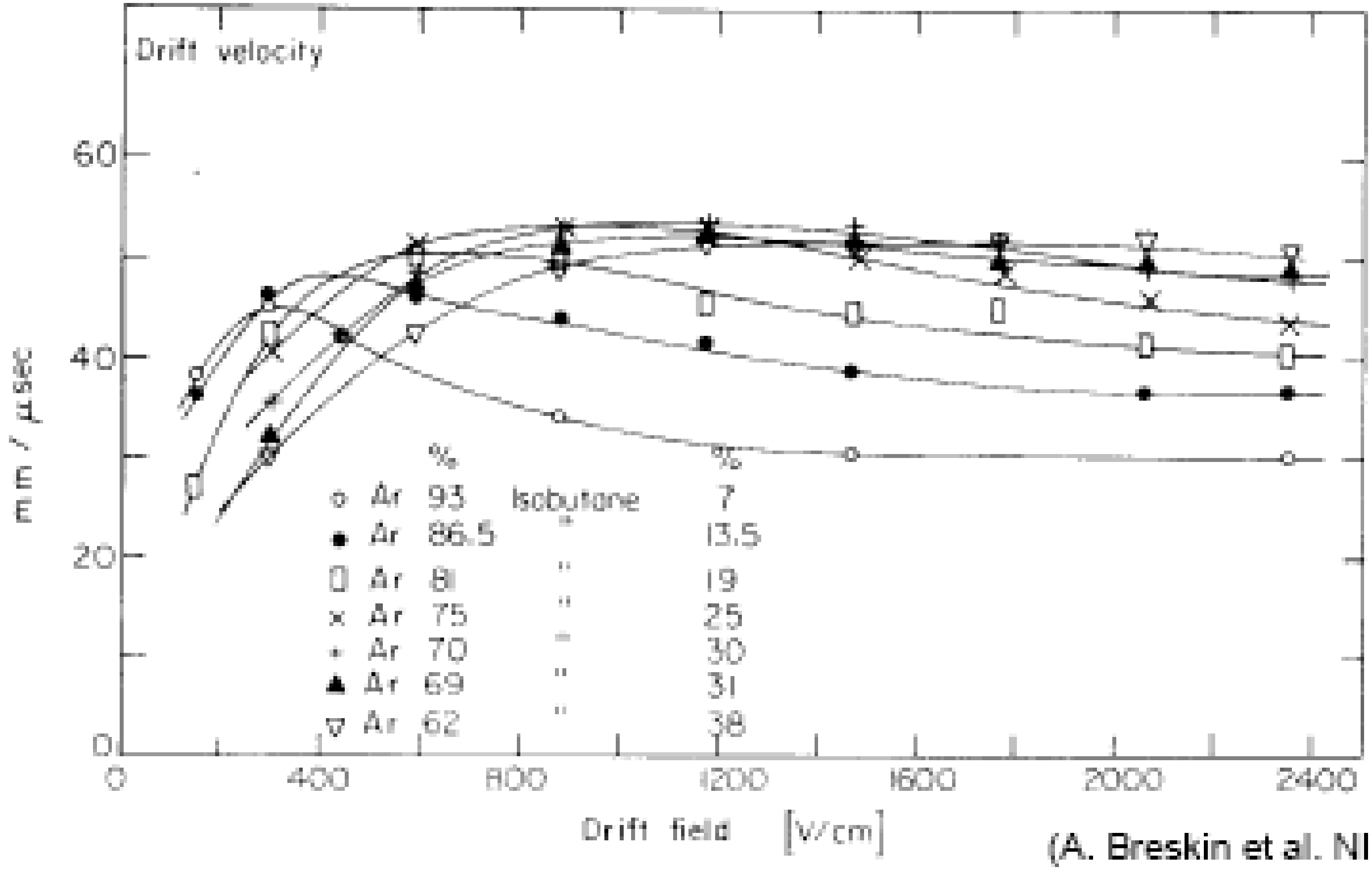
  - drift speed : proportional to *E* and inversely proportional to the collision cross section and to the thermal velocity

$$\langle v_D \rangle \sim \left(\frac{eE}{m}\right) \frac{A / N_o \rho\sigma}{v_t} = \frac{eEA}{N_o \rho\sigma \sqrt{3KTm}}$$

3-1 Ionization detectors

Some typical values as function of the E-field:

- With 75% argon and 25% isobutane and field of 800-1000 V/ cm one has a drift velocity ~ 50 mm/ms

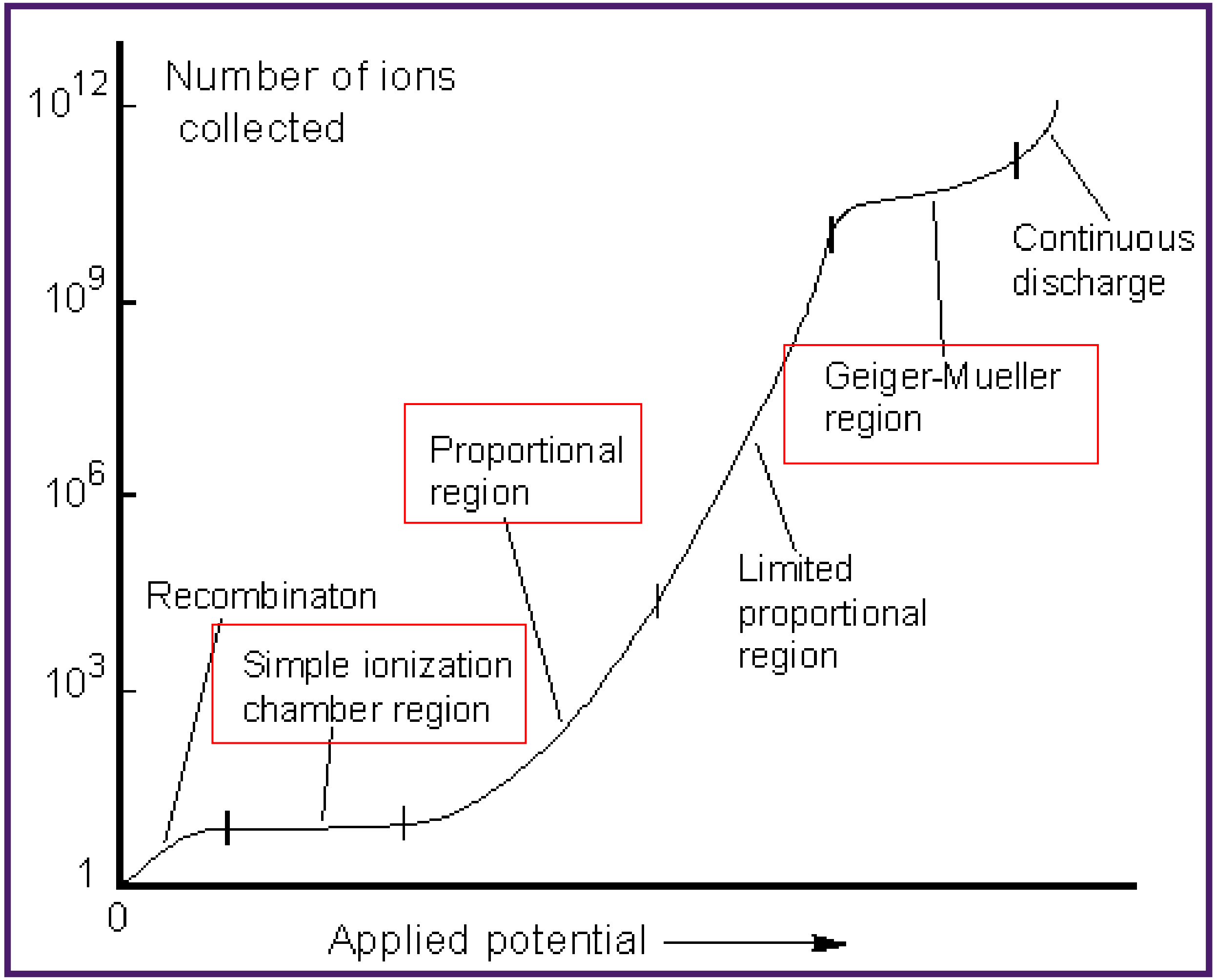


Argon-Isobutane

(A. Breskin et al. NIM 124 (1975) 189)

3-1 Ionization detectors

Collection versus applied E-field :



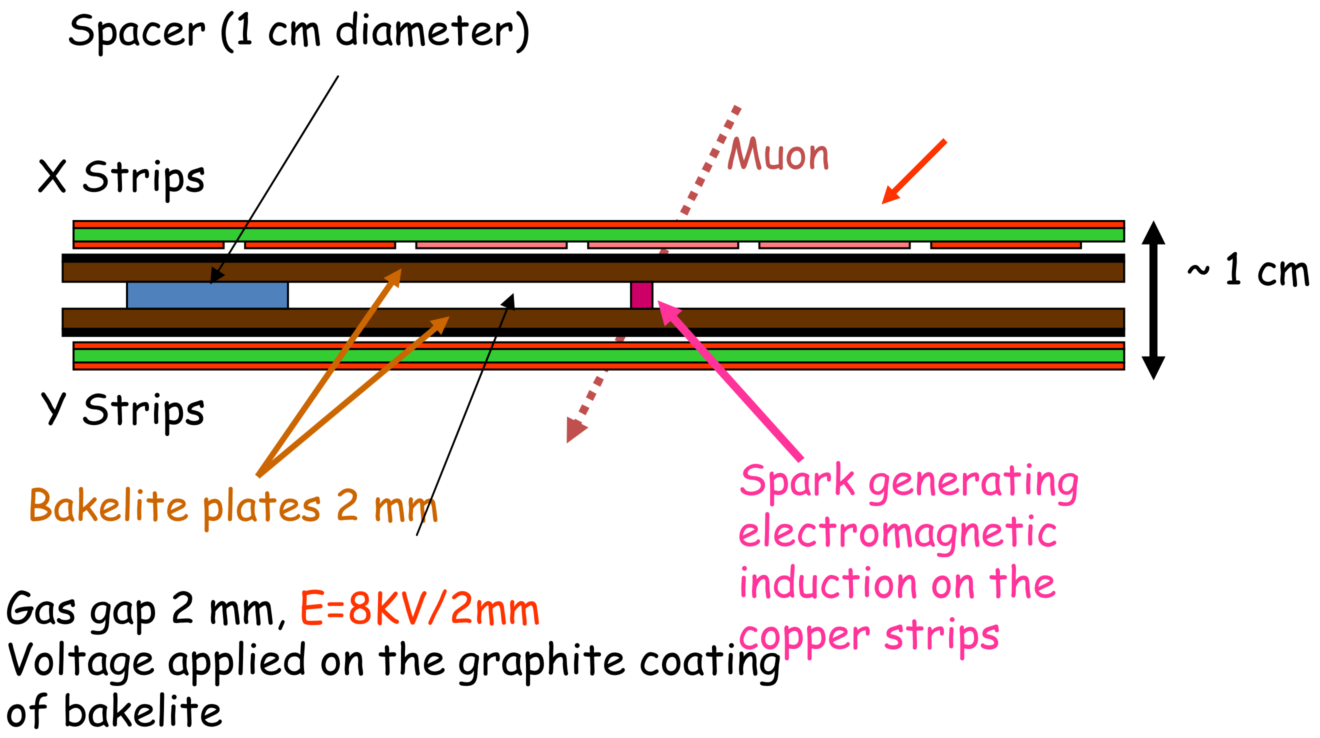
3-1 Ionization detectors

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)



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

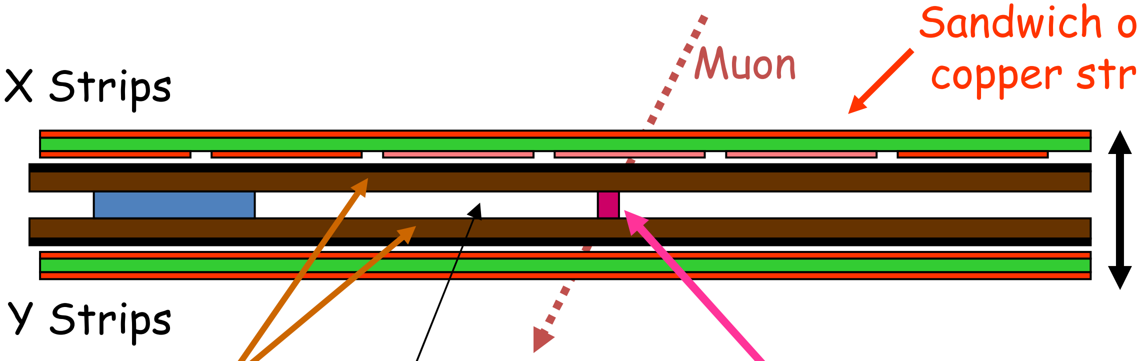
The streamer is confined in about 2 mm around the point where the particle passed. It creates a short circuit which discharges the bakelite. The bakelite will take few ms to recharge but only the hit region a few mm^2 will be dead.

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



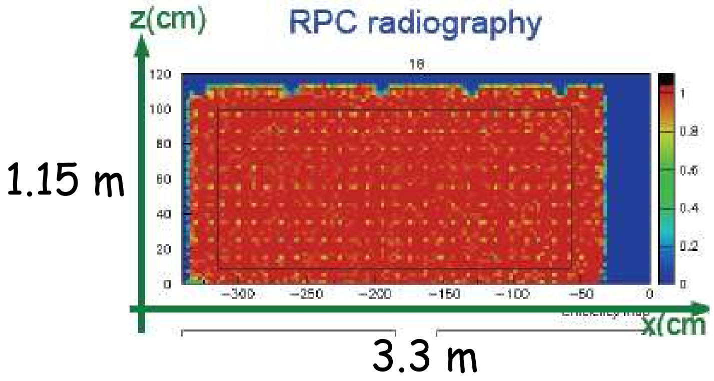
X Strips

Y Strips

Bakelite plates 2 mm

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

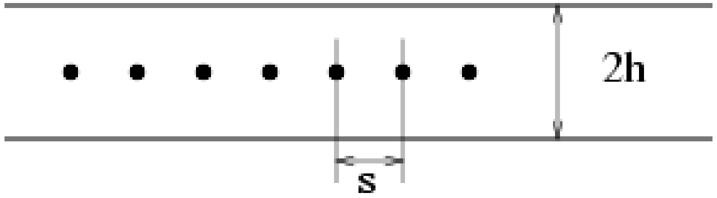
Spark generating electromagnetic induction on the copper strips



3-1 Ionization detectors

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

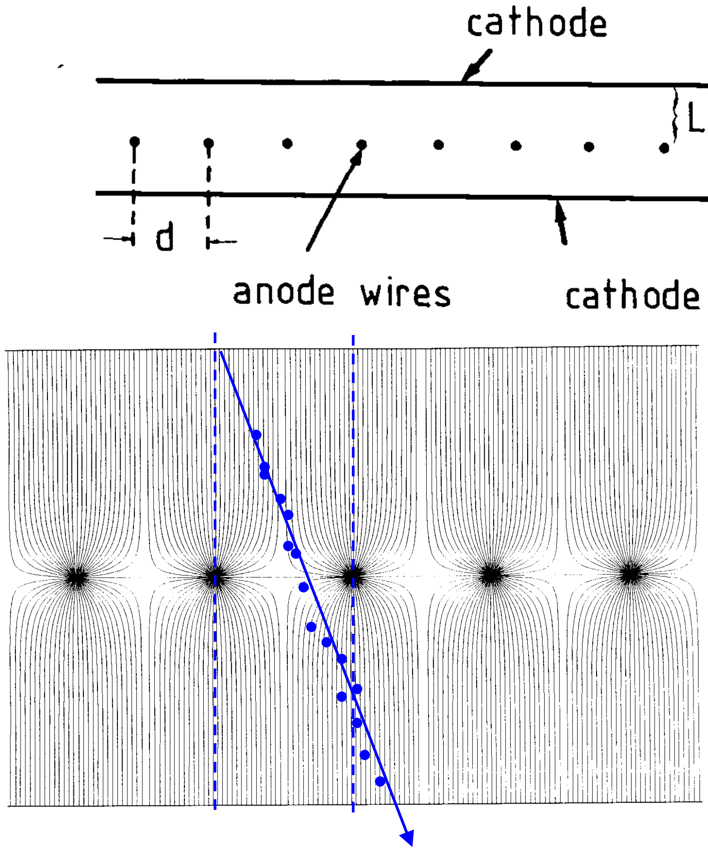
- G. Charpak 1968, readout of individual wires and proportional mode working point.

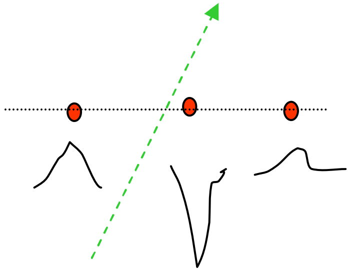


- In 1968 Charpak demonstrated that the MWPC works as many independent proportional tubes very close to each other. This opened the way to the world of completely electronic experiments with fine tracking and data acquired by computers.

3-1 Ionization detectors

MWPC (Multi-Wire Proportional Chambers)





Typical parameters:

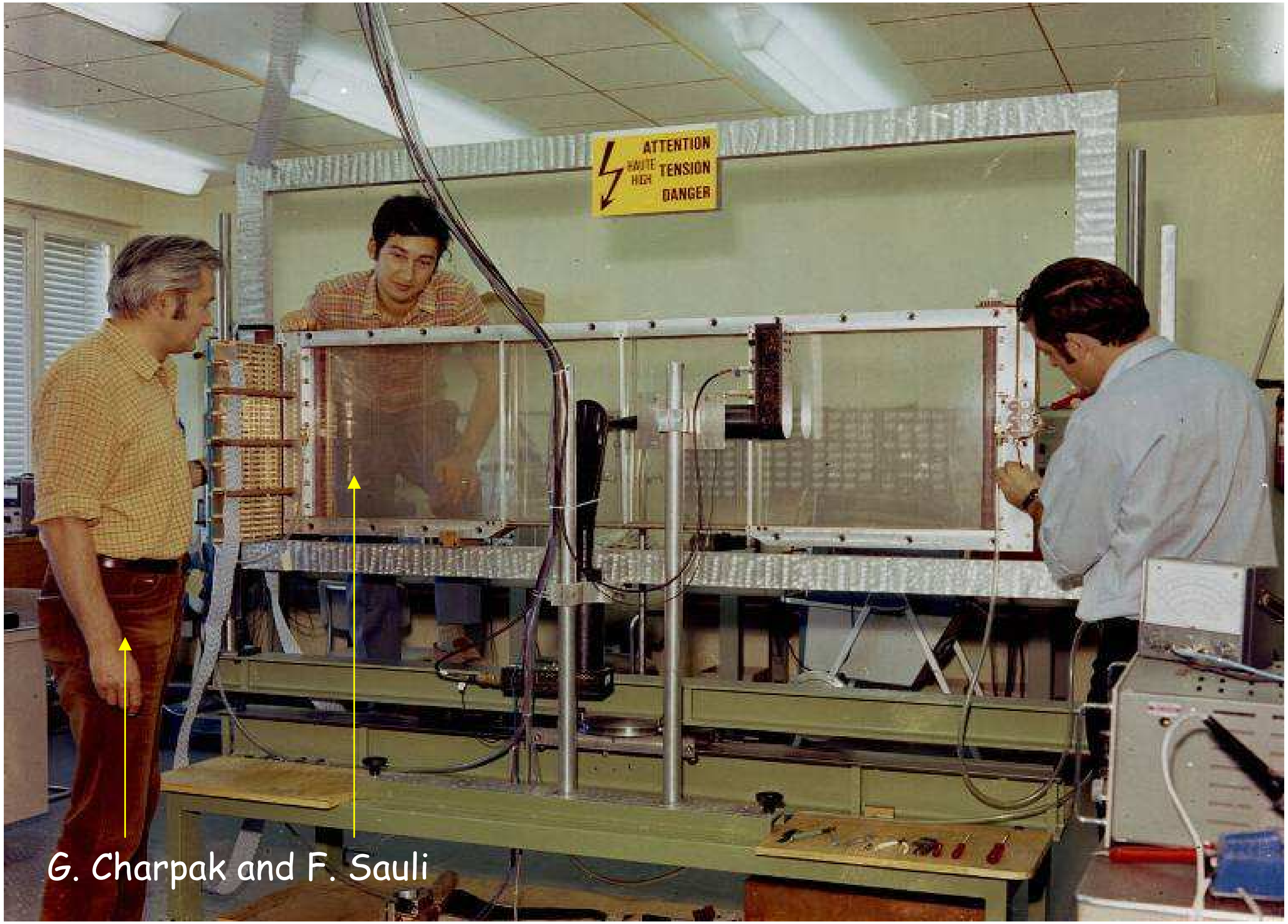
L=5mm, d=1mm,

a_{wire}=20µm.

Normally digital readout:
spatial resolution limited to $\sigma_x \approx \frac{d}{\sqrt{12}}$ (d=1mm, σ_x=300 µm)

3-1 Ionization detectors

MWPC (Multi-Wire Proportional Chambers)



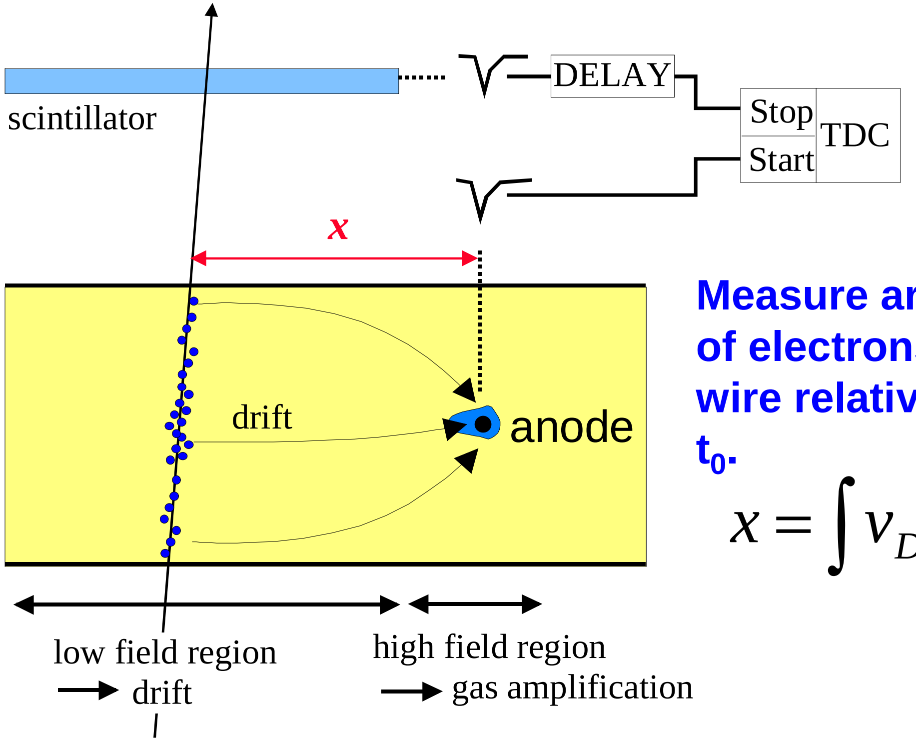
G. Charpak and F. Sauli

3-1 Ionization detectors

Some practical applications: drift chambers

Drift Chambers :

- **Reduced numbers of readout channels**
- **Distance between wires typically 5-10cm giving around 1-2 µs drift-time**
- **Resolution of 50-100µm achieved limited by field uniformity and diffusion**
- **Perhaps problems with occupancy of tracks in one cell.**



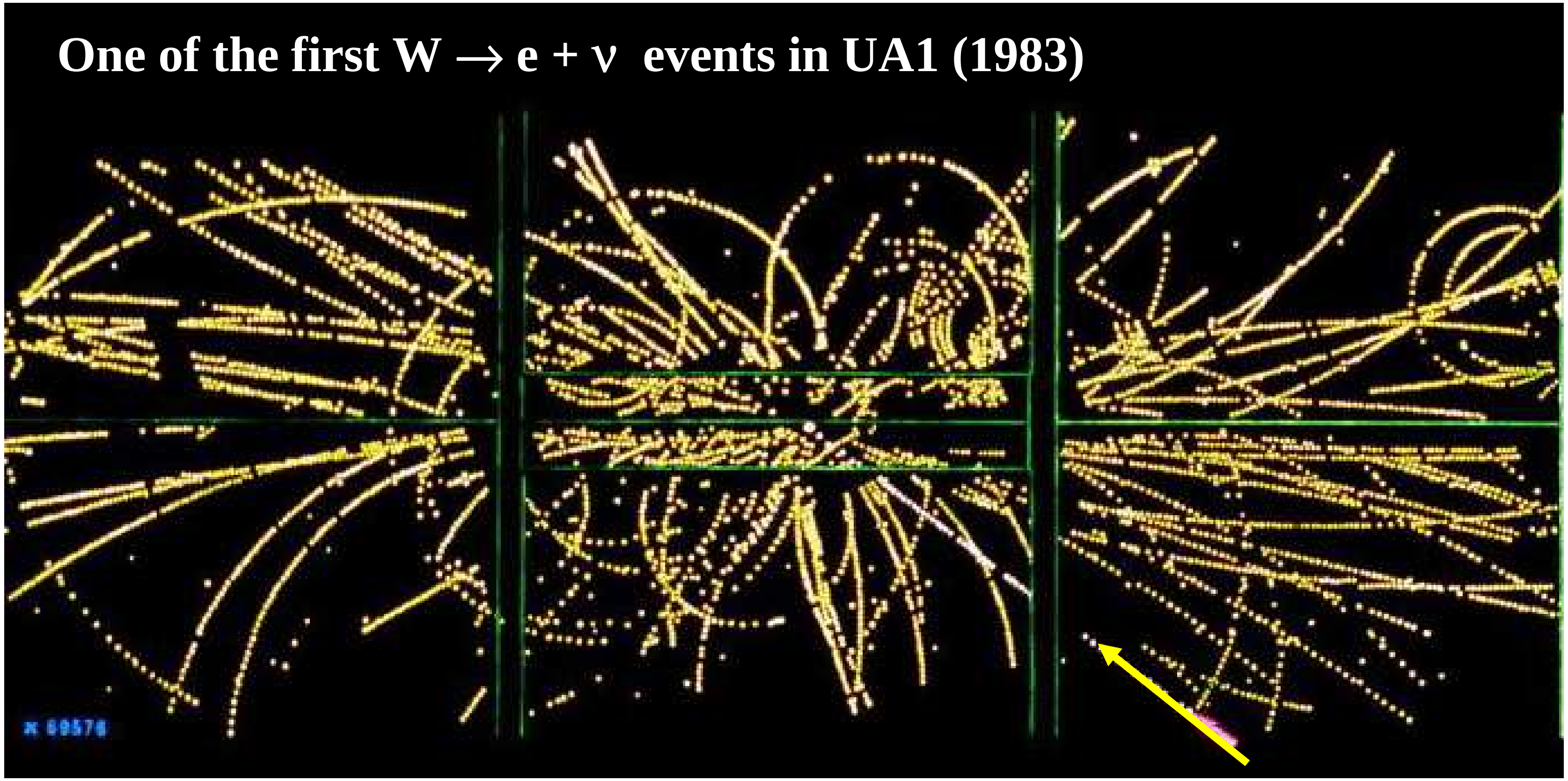
Measure arrival time of electrons at sense wire relative to a time t_0.

$$x = \int v_D(t)dt$$

(First studies: T. Bressani, G. Charpak, D. Rahm, C. Zupancic, 1969
First operation drift chamber: A.H. Walenta, J. Heintze, B. Schürlein, NIM 92 (1971) 373)

3-1 Ionization detectors

Some practical applications: drift chambers



One of the first W → e + ν events in UA1 (1983)

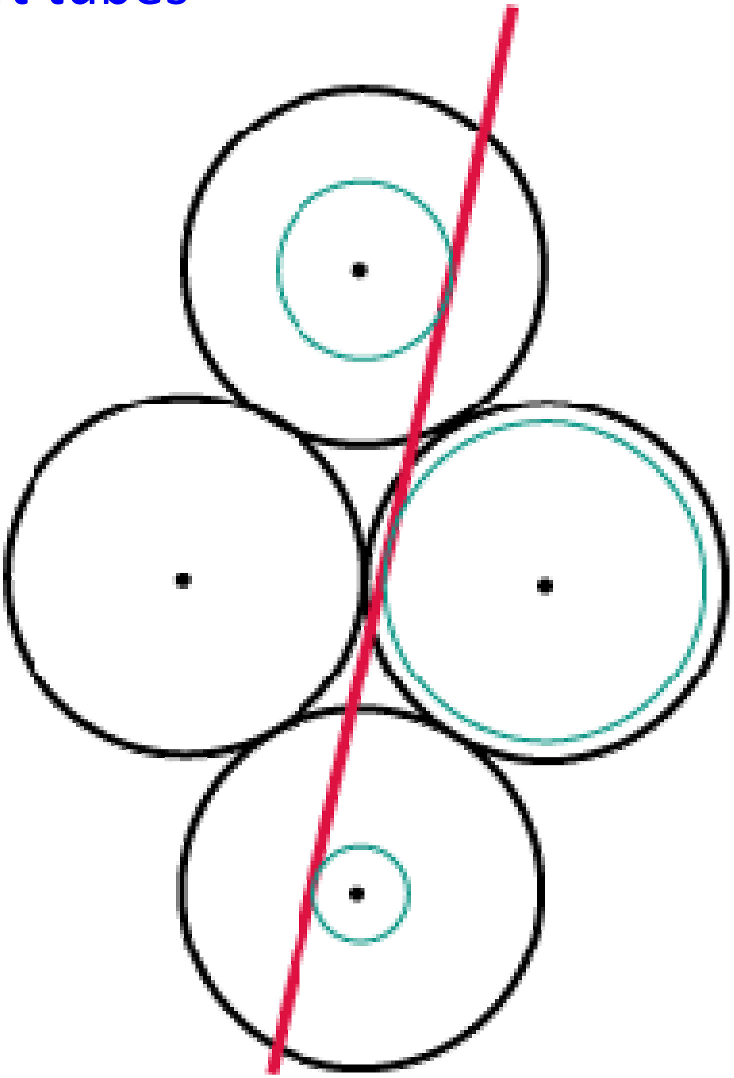
Neutrino detected indirectly by momentum unbalance on plane perpendicular to the beam (almost hermetic detector)

48 GeV electron identified by surrounding calorimeters

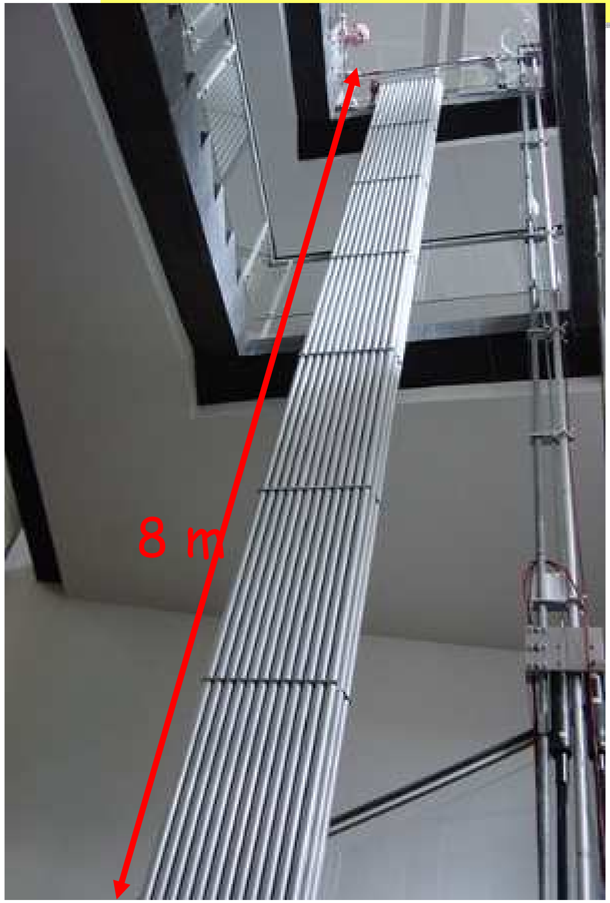
3-1 Ionization detectors

Some practical applications: precision drift tubes

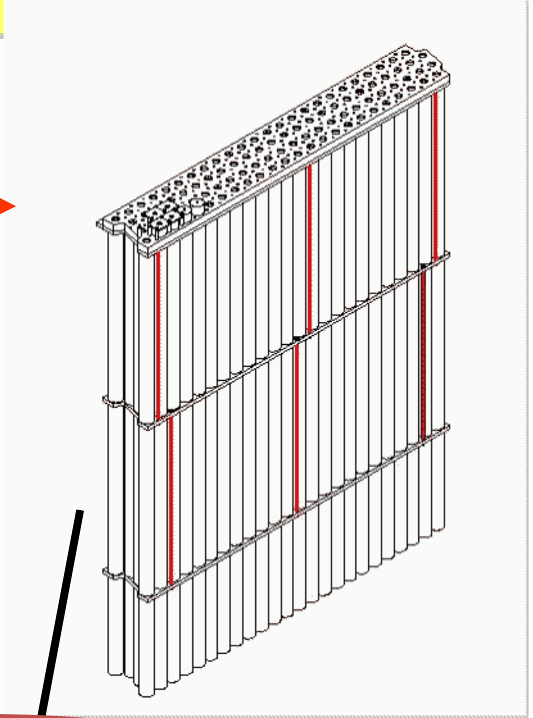
- Next idea: stack up proportional wire drift tubes, measure time of arrival of the ionization pulse
- Find track from tangents to circles
- Can get about 150 μm position resolution
- But: too much material!

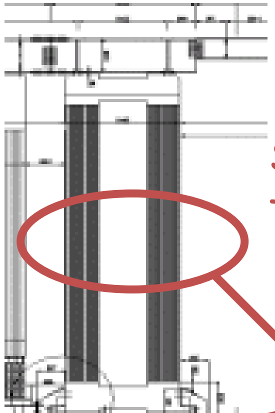


3-1 Ionization detectors

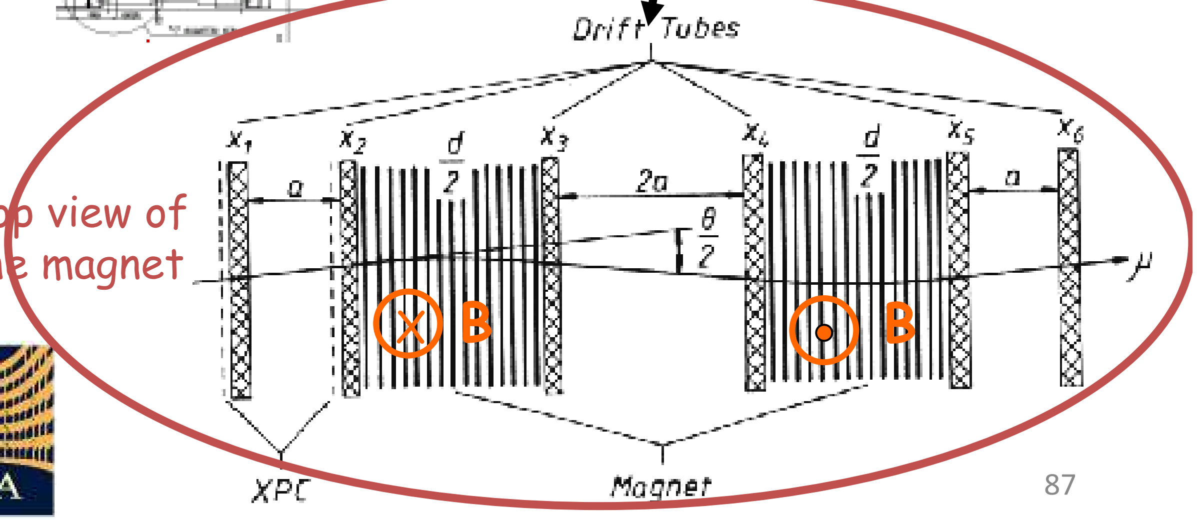


- **Tube :** vertical , ϕ = 38 mm, length 8 m , wire ϕ = 50 μm
- **Plane:** 4 staggered layers, each with 168 tubes





Side view of the magnet



Top view of the magnet

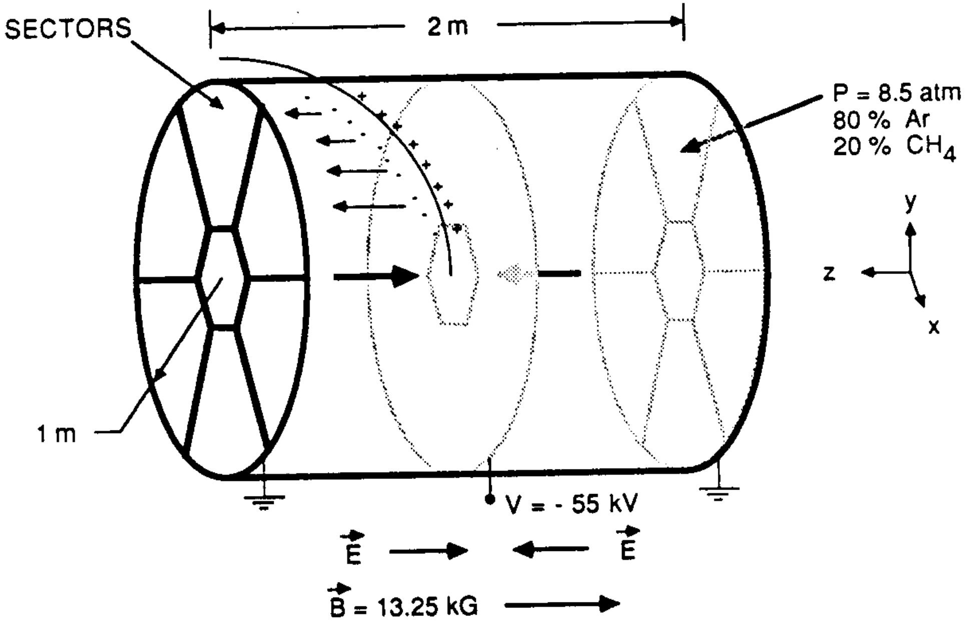
Performance:

- resolution: < 300 μm

3-1 Ionization detectors

Some practical applications: TPC (Time Projection Chambers)

- Full 3D reconstruction



- *x-y* from wires and segmented cathode of MWPC
- *z* from drift time
- in addition *dE/dx* information

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:

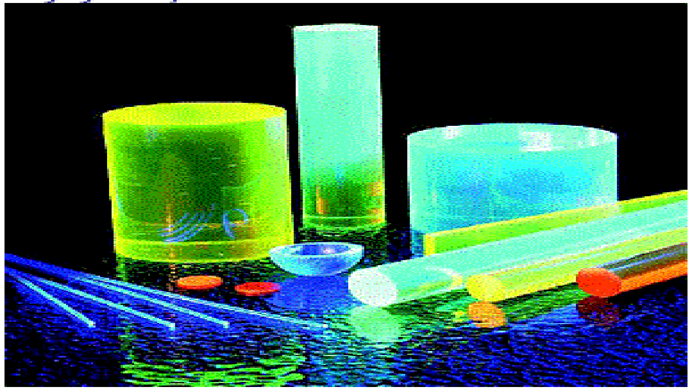
  - Inorganic, work at crystal level : large light yield but in general slow signals

  - 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 High Z Large variety of Z and ρ Undoped and doped ns to μs decay times Expensive	Up to 10000 photons per MeV Low Z $\rho \sim 1 \mathrm{gr/cm^3}$ Doped, large choice of emission wavelength ns decay times Relatively inexpensive
E.m. calorimetry (e, γ) Medical imaging Fairly Rad. Hard (100 kGy/year)	Tracking, TOF, trigger, veto counters, sampling calorimeters. 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

General features:

- Luminescence: materials property consisting in absorbing energy (heat, light, radiation) and re-emitting it in visible light

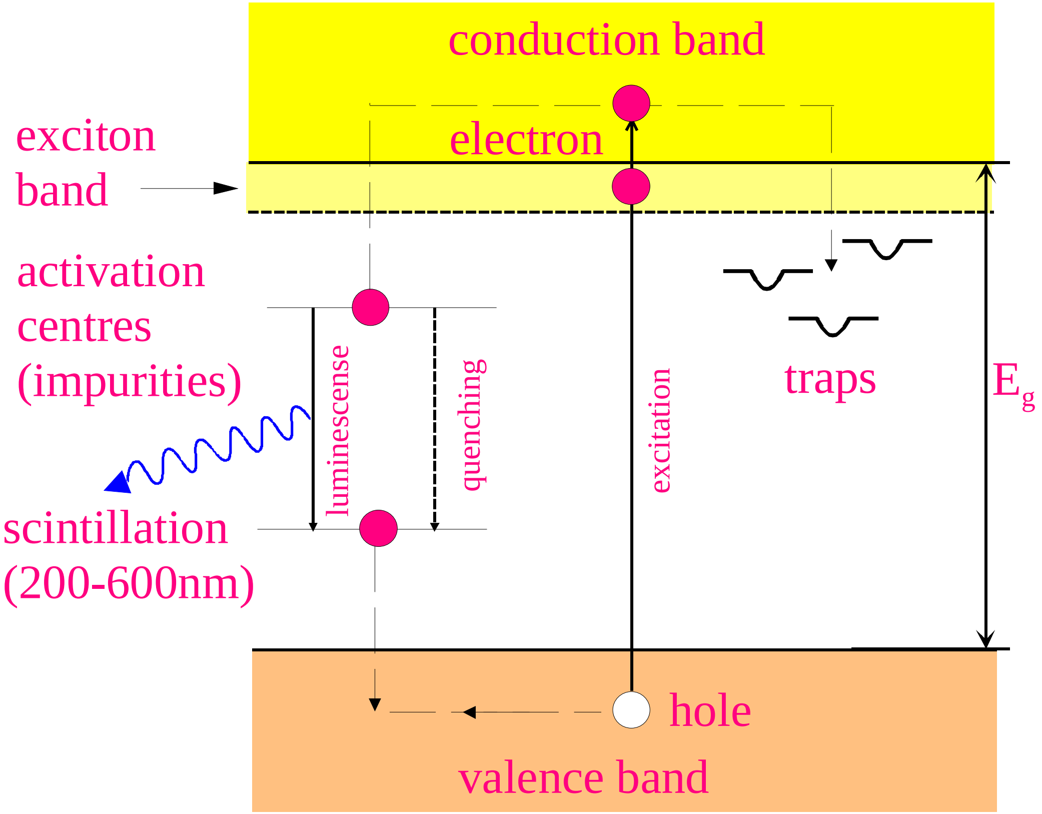
- Re-emission immediately after absorption (within 10^{-8} s time taken by atomic transitions) ➔ fluorescence
- Delayed re-emission due to meta-stable excited state ➔ phosphorescence or afterglow (delays from ms to hours depending on the material).

- At first approximation the re-emission is described as a simple exponential decay process (N=number of photons emitted at the time t, N_0= total number of emitted photons):

$$\boxed{N = \frac{N_0}{\tau_d} \cdot e^{-t/\tau_d}}$$

3-2 Scintillation detectors

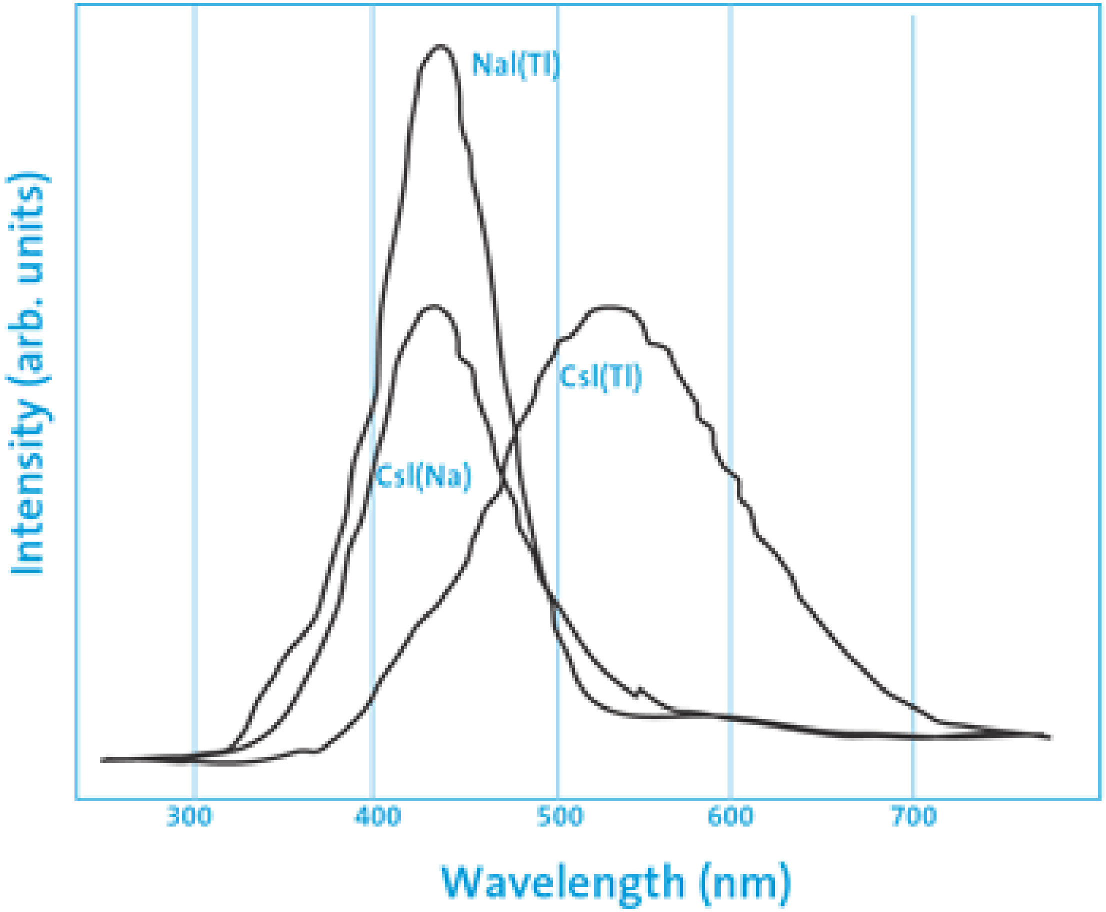
Light emission mechanisms (I) : inorganic scintillators (NaI, CsI, BGO, $PbWO_4$, BaF_2…)



- Depend on properties of crystal.
- Interaction of atoms in lattice broaden energy levels of individual atoms into bands.
- In an insulator, valence band is full , conduction band is empty.
  - Electrons “locked into position”, (no available energy states)
  - If promoted to conduction band, electrons are free to move
- If promoted to conduction band electrons will move through lattice until trapped by an impurity/defect in the lattice or a deliberately introduced dopant
- For some traps, the electron decays by emitting a photon (scintillation)
- Electron decays from some traps without emitting light (quenching)

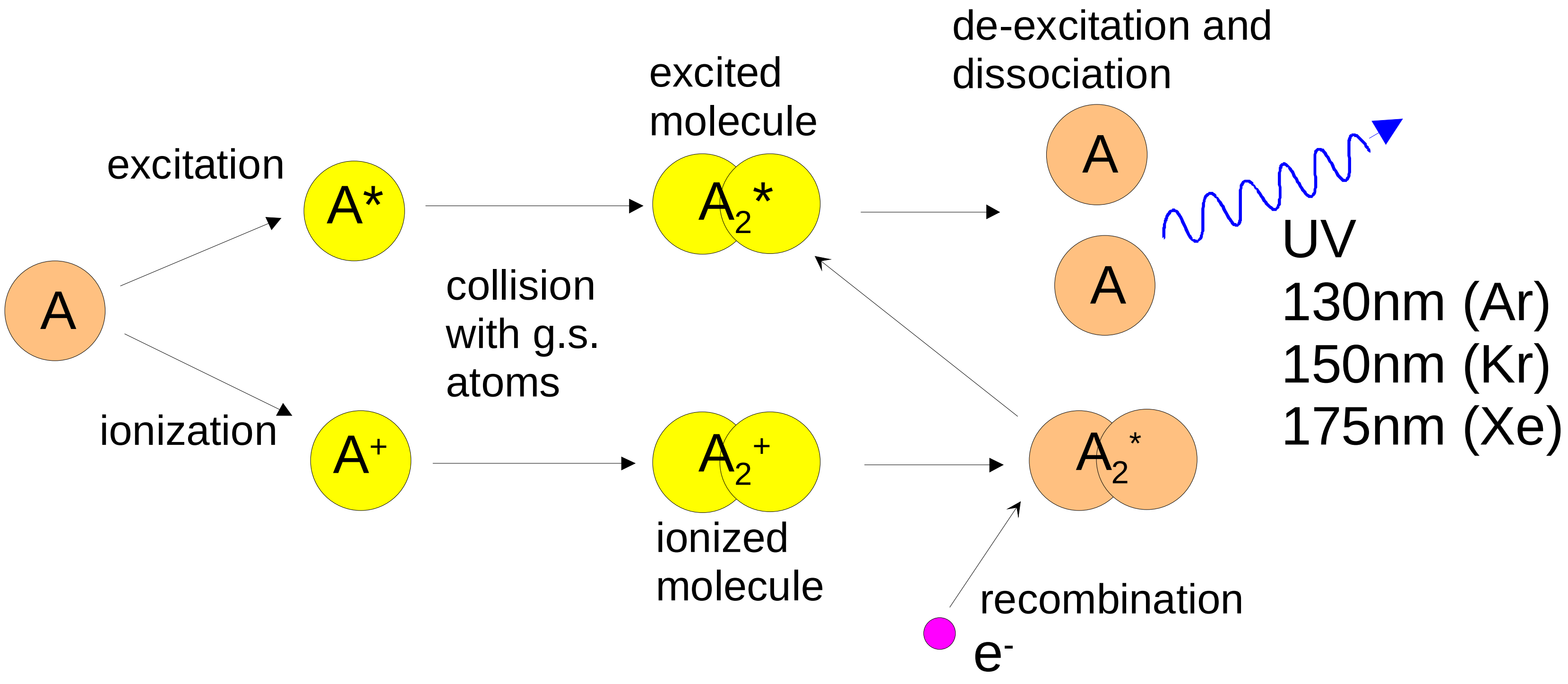
3-2 Scintillation detectors

Light emission mechanisms (I) : typical spectra



3-2 Scintillation detectors

Light emission mechanisms (II) : noble liquids (LAr, LXe, LKr…)



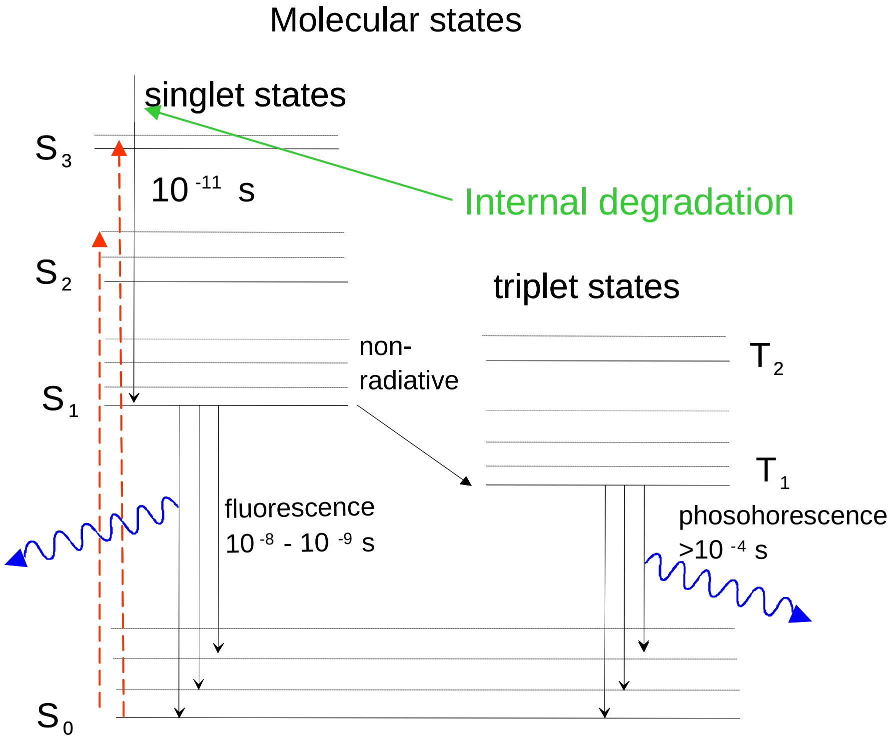
Light emitted in the UV and difficult to be detected:

Ar 130 nm, Kr 150 nm, Xe 175 nm

Also the noble gas (at high pressure) can emit scintillation light.

3-2 Scintillation detectors

Light emission mechanisms (III) : organic scintillators (hydrocarbon compounds with Benzene cycles).

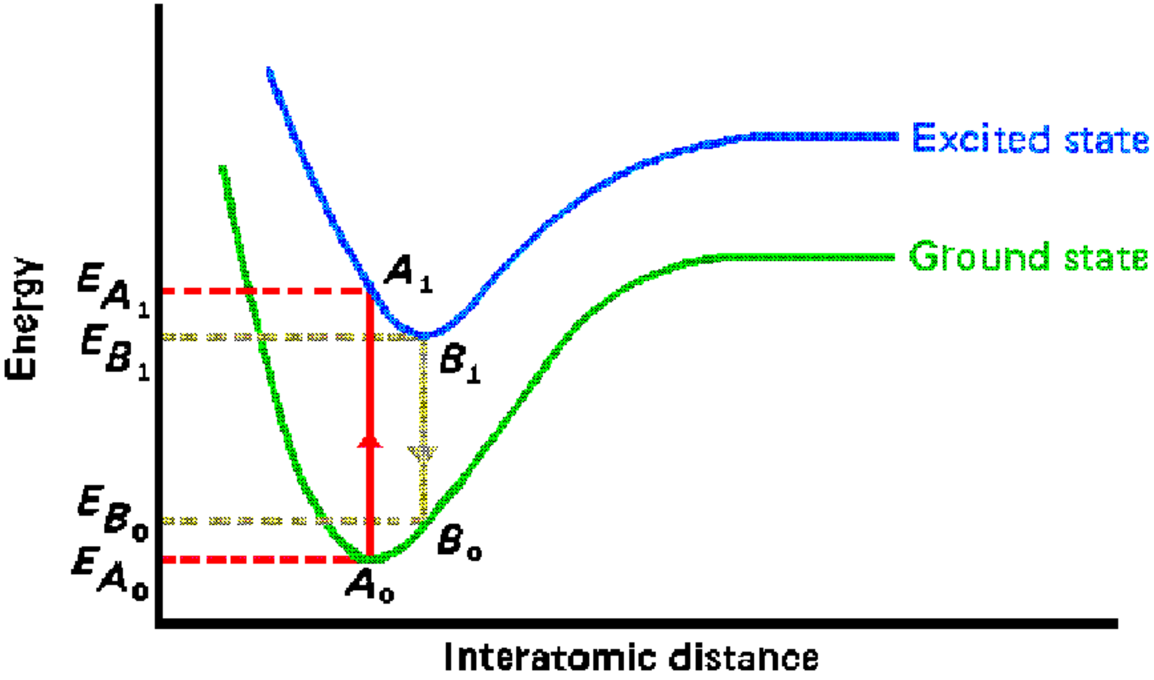


Luminescence coming from transitions of free valence electrons of the molecules. These electrons are not associated to a particular atom in the molecule but they occupy the molecular orbitals π

3-2 Scintillation detectors

Light emission mechanisms (III) : organic scintillators

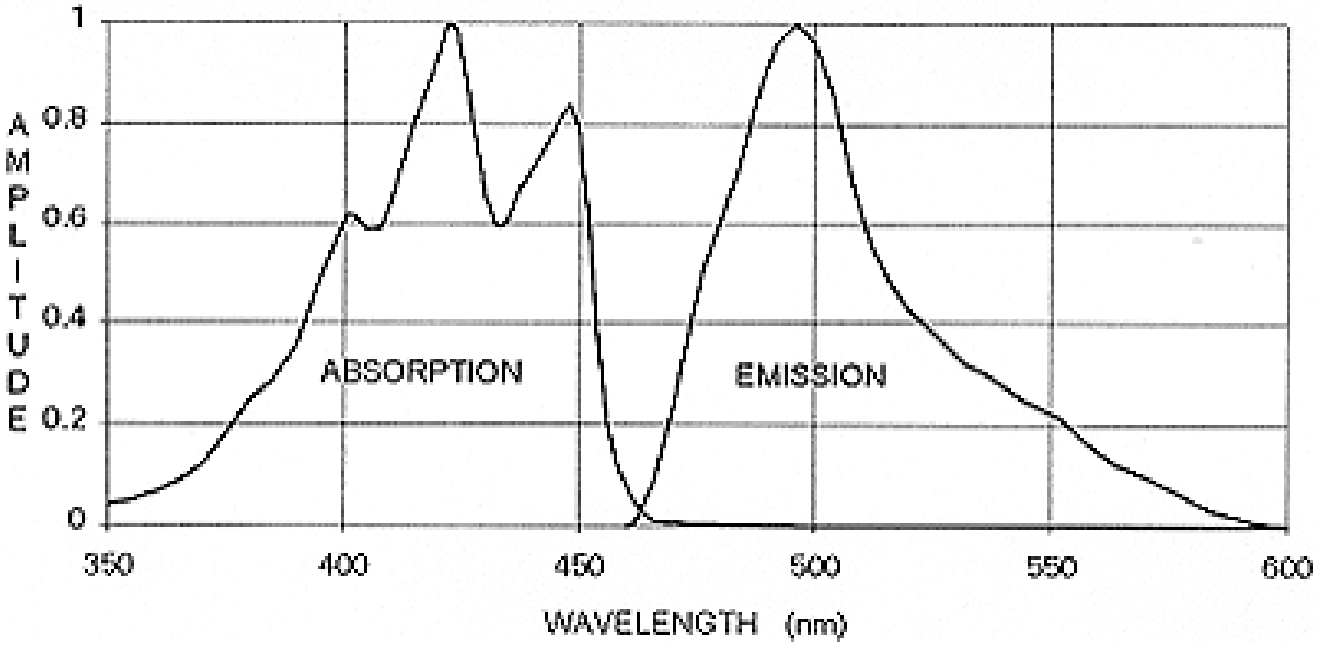
- Passage of charged particle excites molecule.
- Can decay radiatively with photon energy , $E_{emission} = E_{B1} - E_{B0}$
- B_0 rapidly decays to A_0 by exchanging vibrational quanta with surroundings



3-2 Scintillation detectors

Light emission mechanisms (III) : 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

Summary tables (inorganic and nobles liquid):

scintillator	density (g/cm3)	Rifraction index	Wave length (nm)	Fast decay constant (μs)	yield. (relative to NaI(Tl)	note	photons/MeV
NaI	3.67	1.78	303	0.06	190		
NaI(Tl)	3.67	1.85	410	0.25	100	at 80 K	$4x10^4$
CsI	4.51	1.80	310	0.01	6	at 80 K	
CsI(Tl)	4.51	1.80	565	1.0	45	at 80 K	$1.1x10^4$
^{6}LiI(Eu)	4.06	1.96	470-485	1.4	35	at 80 K	$1.4x10^4$
BaF_2	4.88	1.49	190/220 310	0.0006 0.63	5 15		$6.5x10^3$ $2x10^3$
$Bi_4Ge_3O_{12}$	7.13	2.15	480	0.30	10		$2.8x10^3$
$PbWO_4$	8.28	1.82	440,530	0.02	0.1		100
LAr	1.4	1.29	120-170	0.005/0.860		at 170 nm	
LKr	2.41	1.40	120-170	0.002/0.085		at 170 nm	
LXe	3.06	1.60	120-170	0.003/0.022		at 170 nm	$4x10^4$

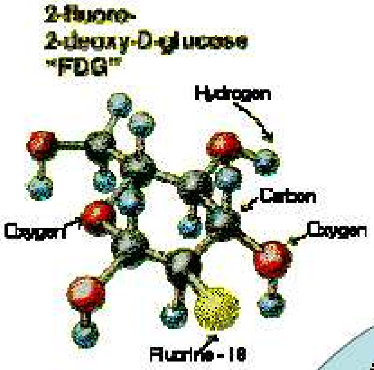
3-2 Scintillation detectors

Summary tables (organic):

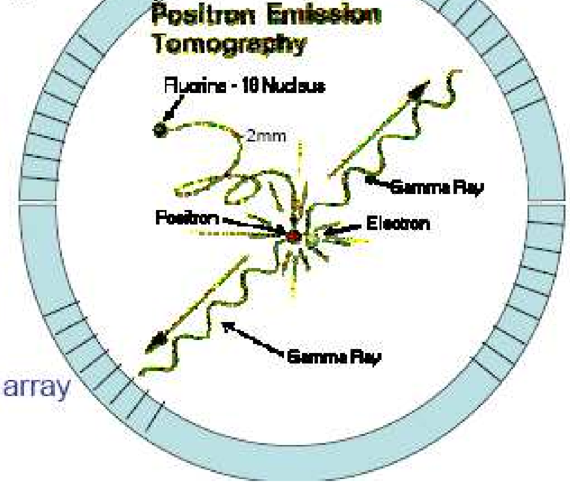
material	density (g/cm³)	n	λ (nm)	τ (ns)	scint. Yield rel antr	H/C	note	yeild/ NaI
naphthalene	1.15	1.58	348	11	11	0.800	monocrist.	
anthracene	1.25	1.59	448	30-32	100	0.714	monocrist.	0.5
NE 102 A	1.032	1.58	425	2.5	65	1.105	Nucl. Ent.	
NE 104	1.032	1.58	405	1.8	68	1.100	Nucl. Ent.	
NE 110	1.032	1.58	437	3.3	60	1.105	Nucl. Ent.	
BC 412	1.032	1.58	434	3.3	60	1.104	Bicron	
BC 414	1.032	1.58	392	1.8	68	1.110	Bicron	
BC 416	1.032	1.58	434	4.0	50	1.110	Bicron	

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

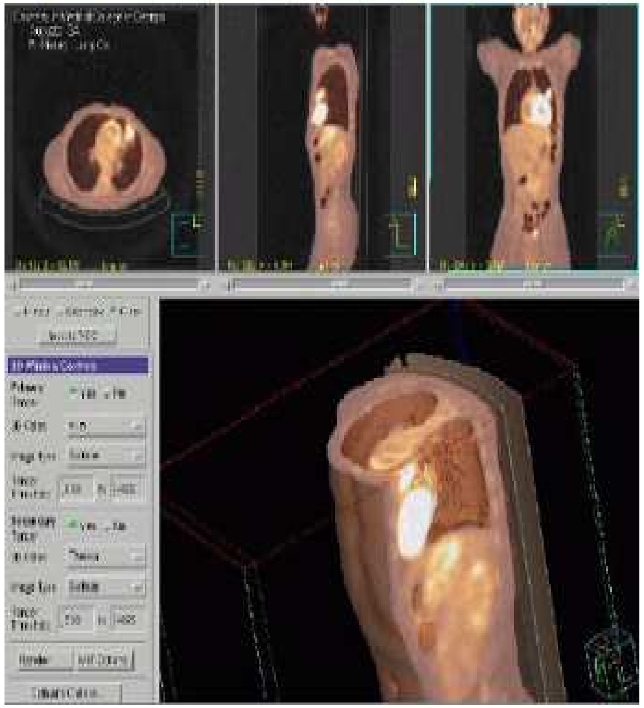
2 x 511 keV energy

γ-γ co-linearity

time coincidence

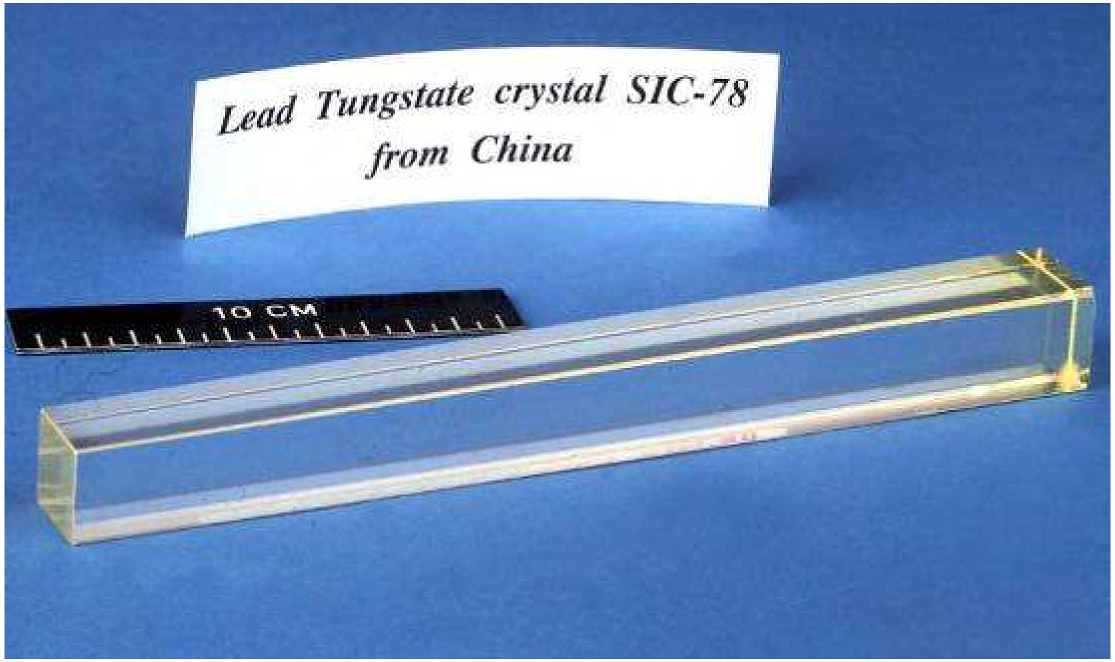
reconstruct functional image

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



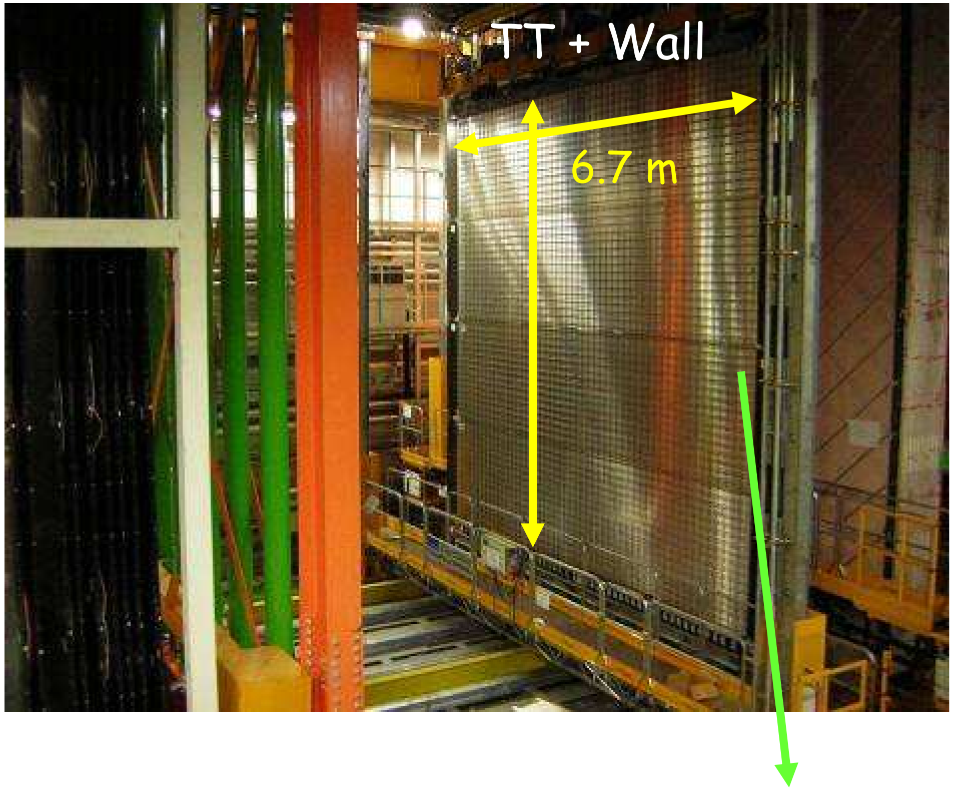
3-2 Scintillation detectors

Applications : calorimetry in HEP (scintillator crystals from CMS)



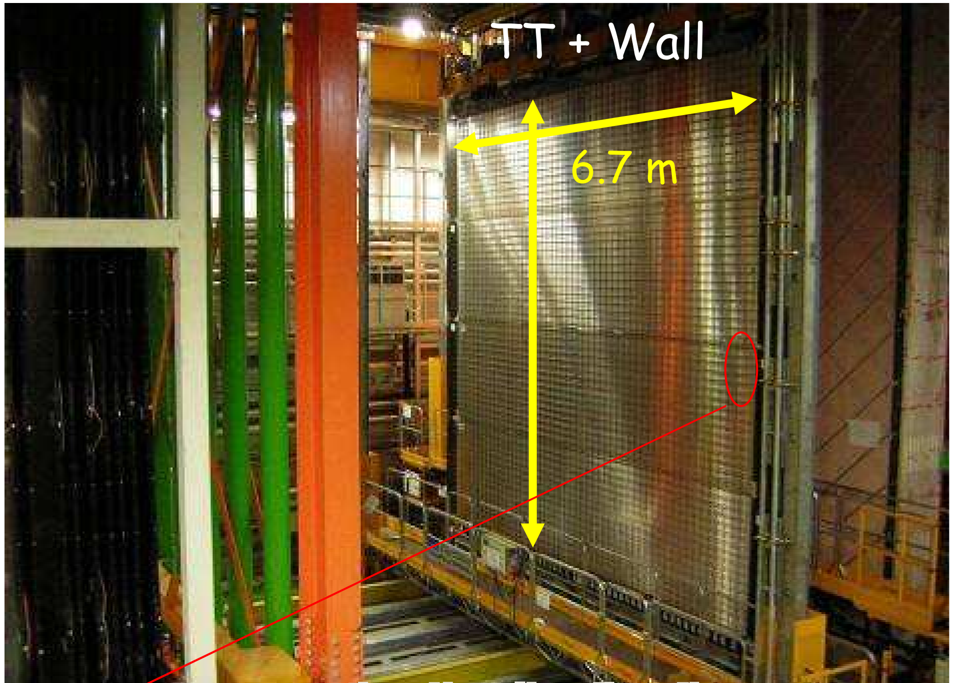
3-2 Scintillation detectors

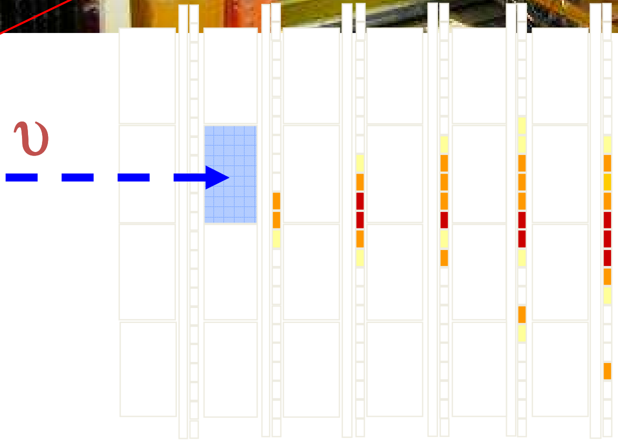
Applications : tracking in HEP (OPERA target tracker)



3-2 Scintillation detectors

Applications : tracking in HEP (OPERA target tracker)

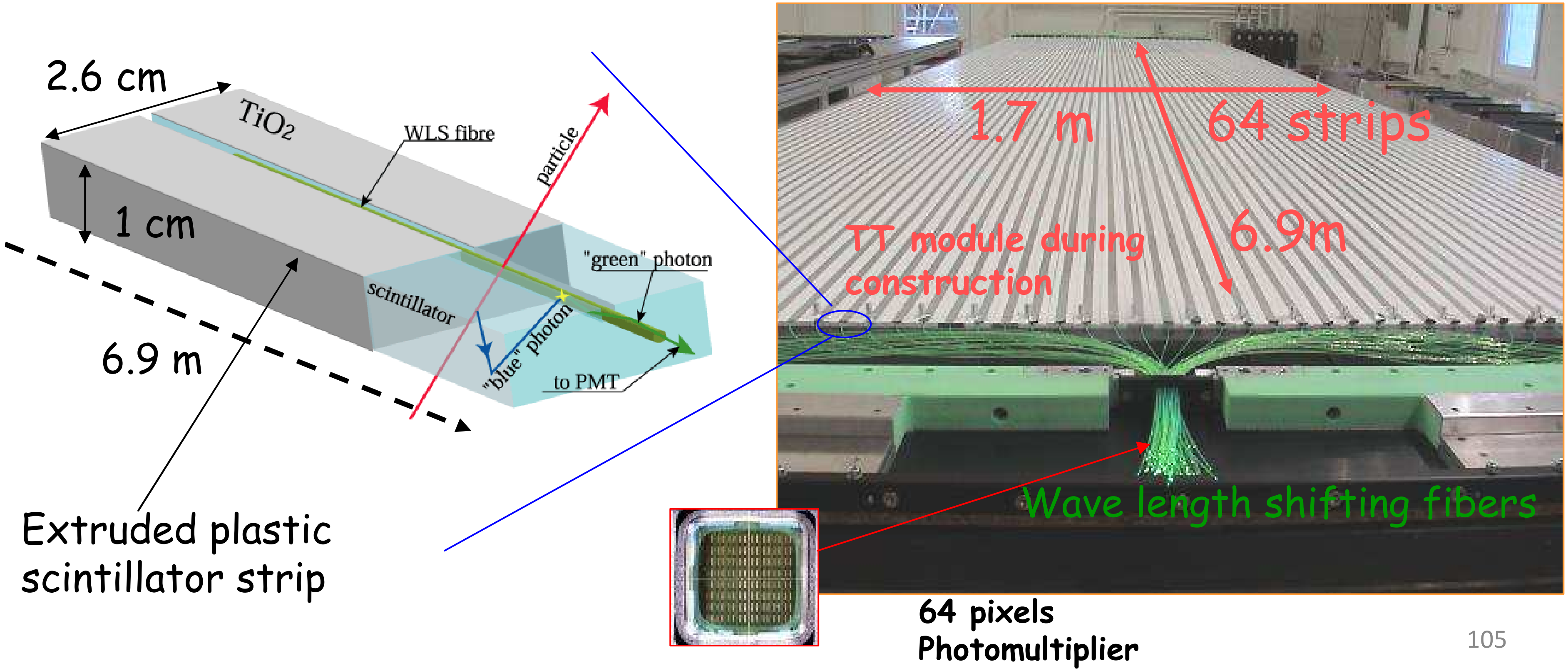




3-2 Scintillation detectors

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)

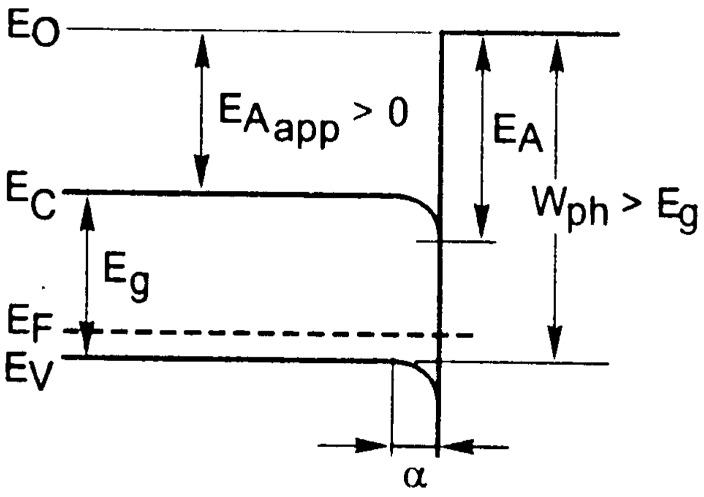
2. Photo-electrons amplification : from few p.e.'s to detectable charge or current signal (different stage)

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

3-3 Photodetectors

1/ Photocathode:

- 3 step processes:
  - Photoelectric effect
  - Electron propagation in the cathode
  - Electron escape in the vacuum
- Most photocathodes are semiconductors: photon energy has to be sufficient to bridge the band gap Eg, but also to overcome the electron affinity EA, so that the electron can be released into the vacuum.



3-3 Photodetectors

1/ Photocathode:

- Photoelectrons kinetic energy :

$$T=h\nu-\phi$$

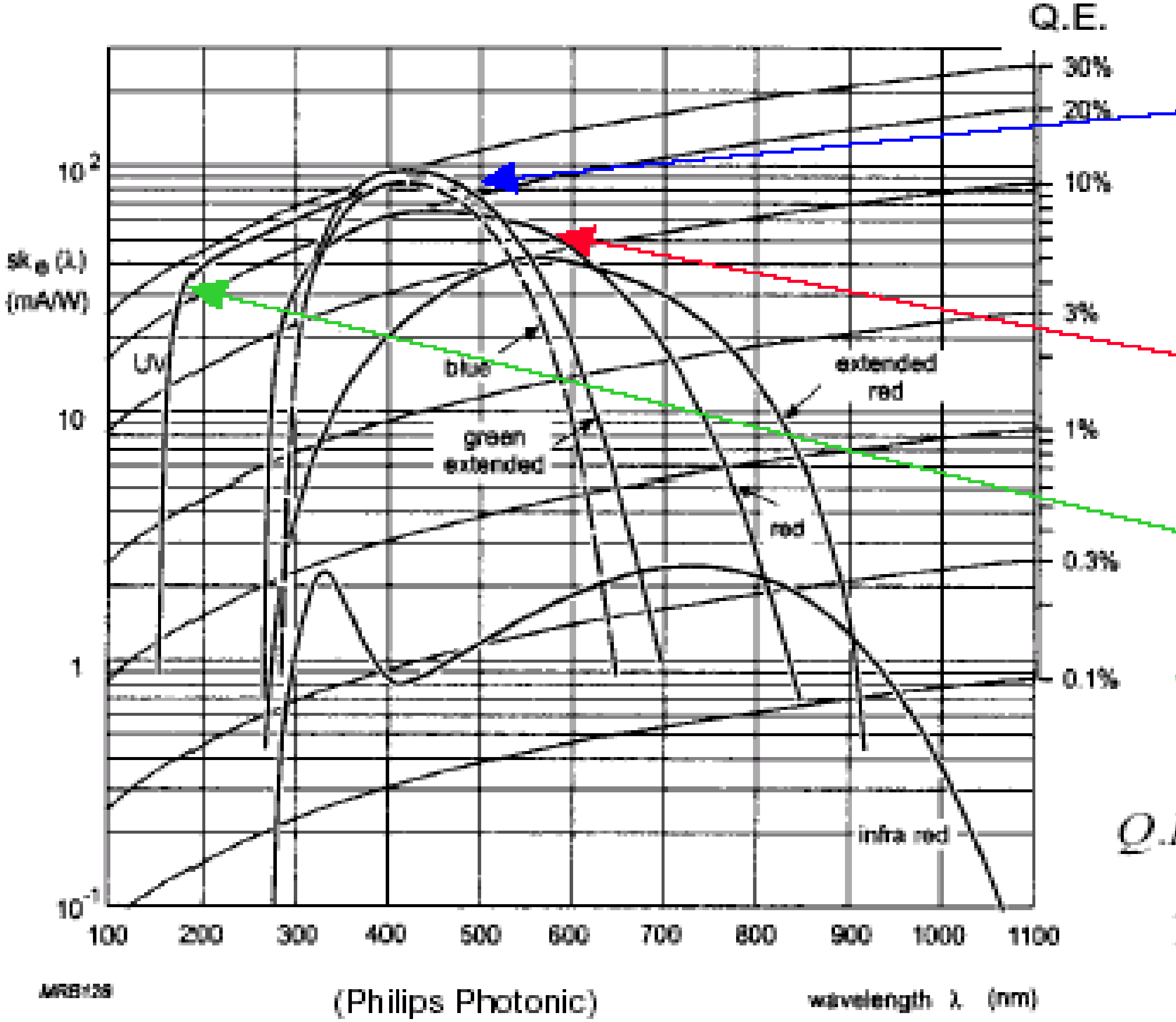
ϕ work function, ν frequency of incident light.

- The photoelectric effect has a threshold frequency corresponding to a minimal photon energy. Above threshold the probability to have the photoelectric effect is not 100% but is depending strongly on the frequency of the incident light and on the photocathode material; This probability is called Quantum efficiency: (Q.E.)

$$Q.E.=\#\ photoelectrons/\#\ incident\ photons\ (\lambda)$$

3-3 Photodetectors

1/ Photocathode emission spectrum :



(Philips Photonic)

Bialkali
SbK_2Cs
SbRbCs

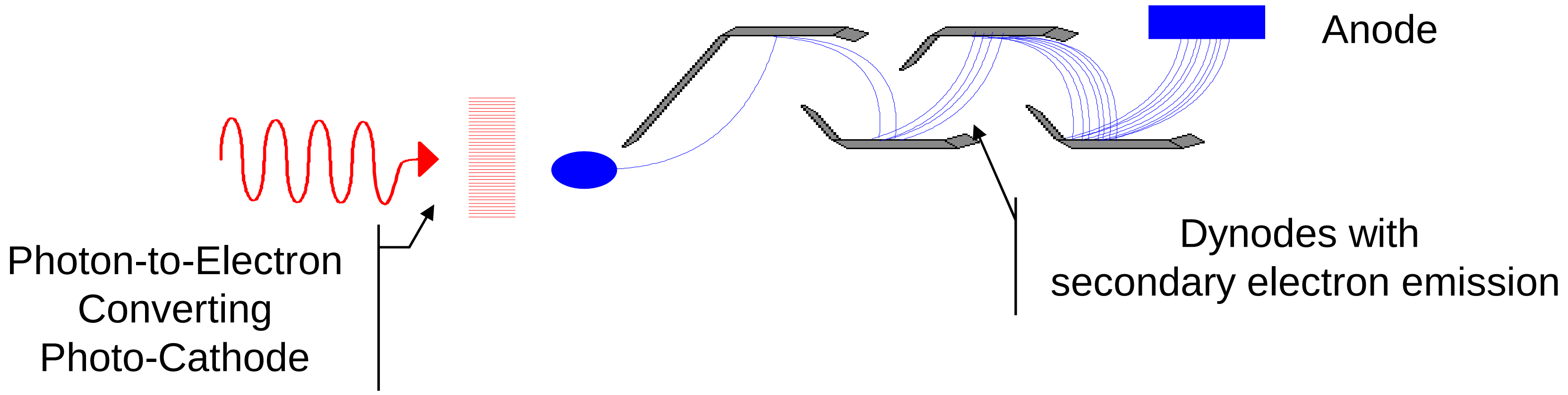
Multialkali
$SbNa_2KCs$

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)

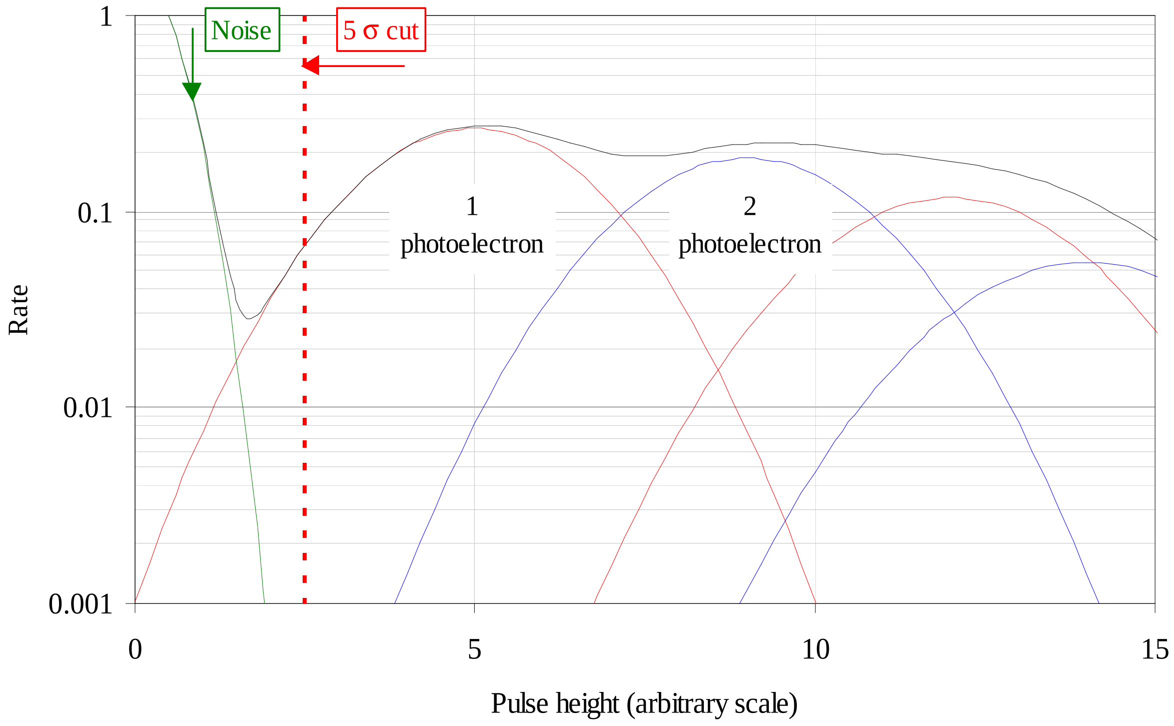


- When a photoelectron strikes dynode several electrons emitted (on average) n~5 ➔ Several dynodes (~10) give high gain (10^6 to 10^7)
- The final signal is collected at the anode level
- Transient time spread ≈ 200 ps

3-3 Photodetectors

2/ Multiplication in PhotoMultiplier Tubes (PMTs) :

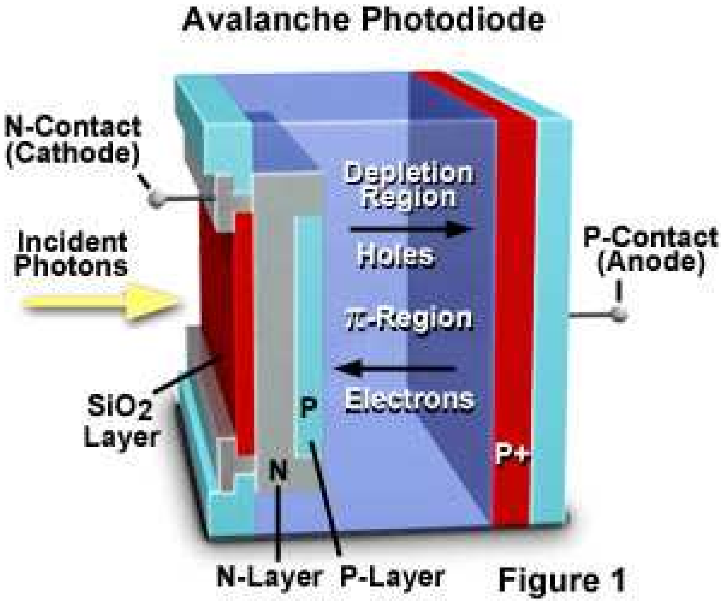
- The energy resolution is determined mainly by the fluctuation of the number of secondary electrons emitted at each dynode.
- Poisson distribution : $P(r,\mu)=\dfrac{\mu^r e^{-\mu}}{r!}$
- Fluctuations mainly induced at the first dynode where the number of primary electrons is small
- PMT structure can be segmented (MultiAnode PMT's)



3-3 Photodetectors

2/ Multiplication in Avalanche PhotoDiodes (APDs) :

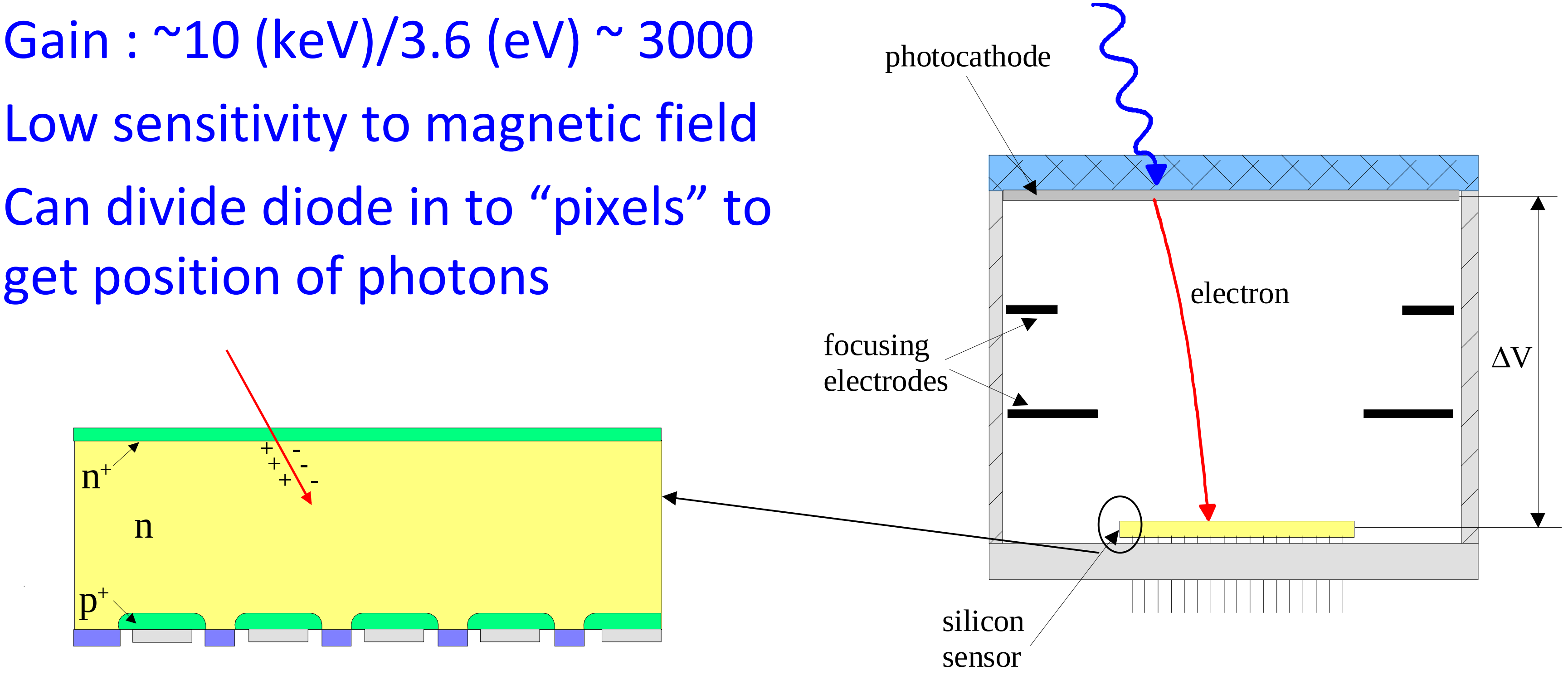
- If a photon falls on a semiconductor an electron/hole pair can be created if the photon energy is greater than the band-gap.
- Increase bias to a point where electrons/holes collide with lattice with sufficient energy to generate new electron/hole pairs ➔ avalanche generation.
- Gain ~ 100 in linear mode (can be operated in “Geiger Muller” mode)
- High QE ~70%



3-3 Photodetectors

2/ Multiplication in Hybrid PhotoDiodes (HPDs) :

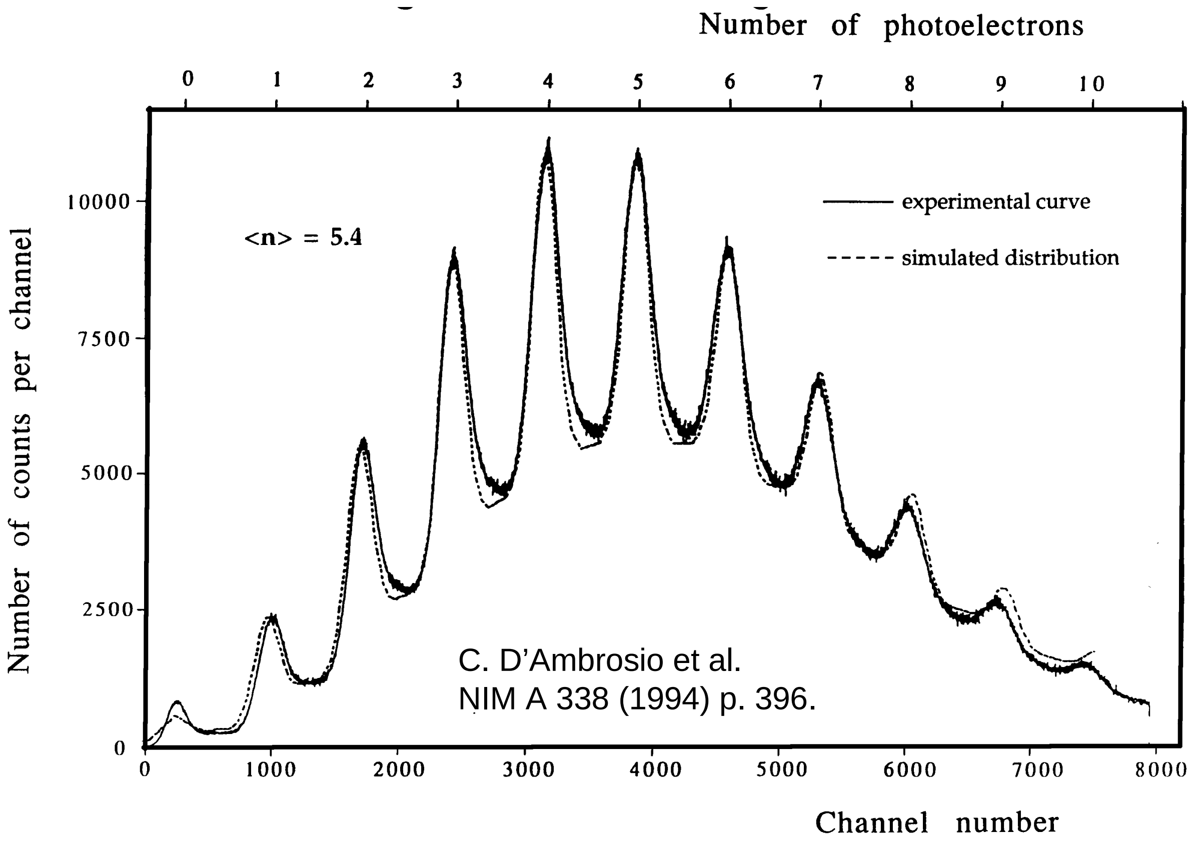
- Principle: couple a “dynode” stage with large HV (~10kV) with a silicon sensor
- The accelerated photoelectron hits diode and liberates several electron-hole pairs. Energy for one electron-hole pair in Si ~ 3.6eV
- Gain : ~10 (keV)/3.6 (eV) ~ 3000
- Low sensitivity to magnetic field
- Can divide diode in to “pixels” to get position of photons



3-3 Photodetectors

2/ Multiplication in Hybrid PhotoDiodes (HPDs) :

- Excellent single p.e. resolution (low fluctuation in 1st stage)
- Limitation due to backscattering of impinging electrons



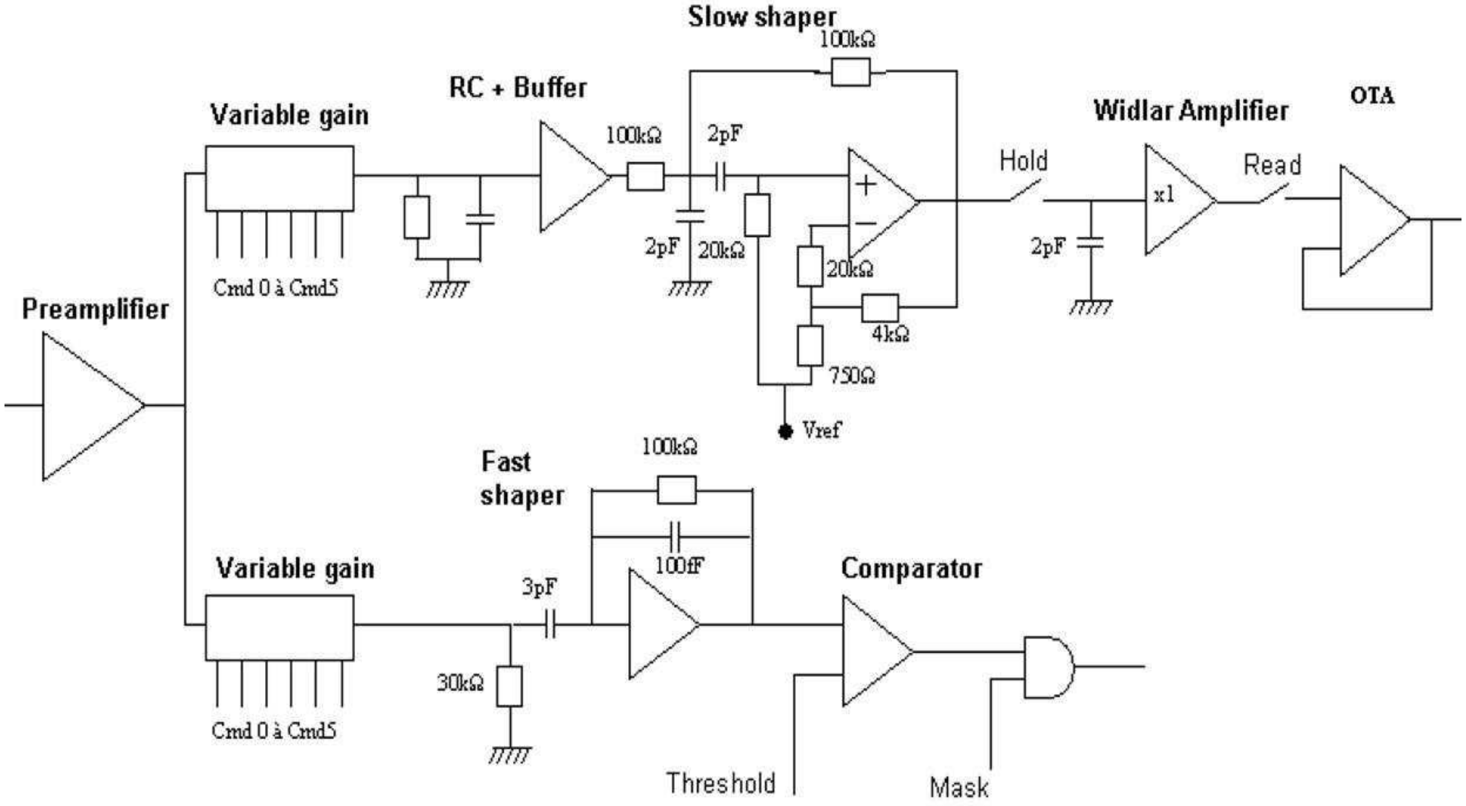
C. D'Ambrosio et al.
NIM A 338 (1994) p. 396.

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

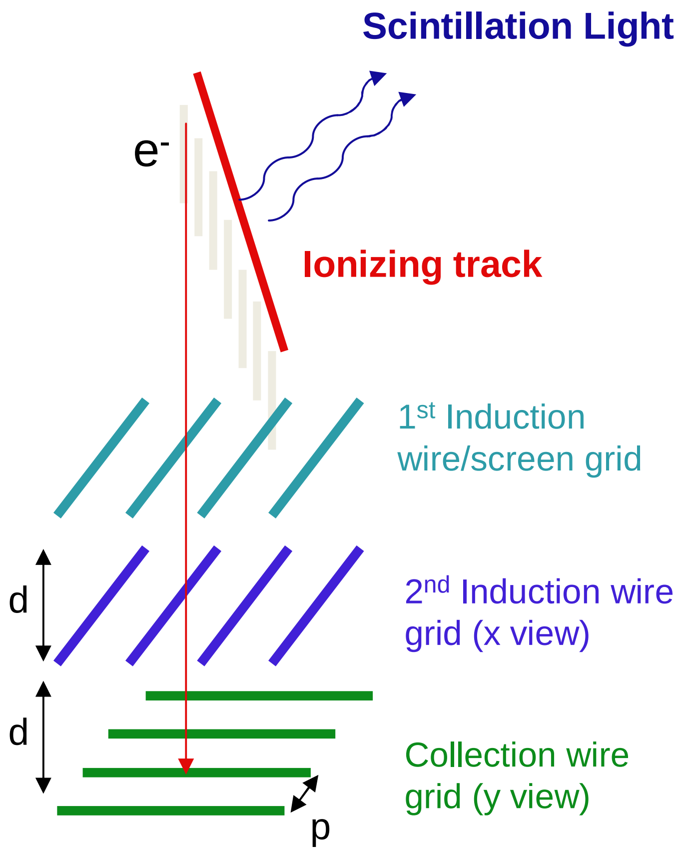
PMT →



3-4 LAr readout

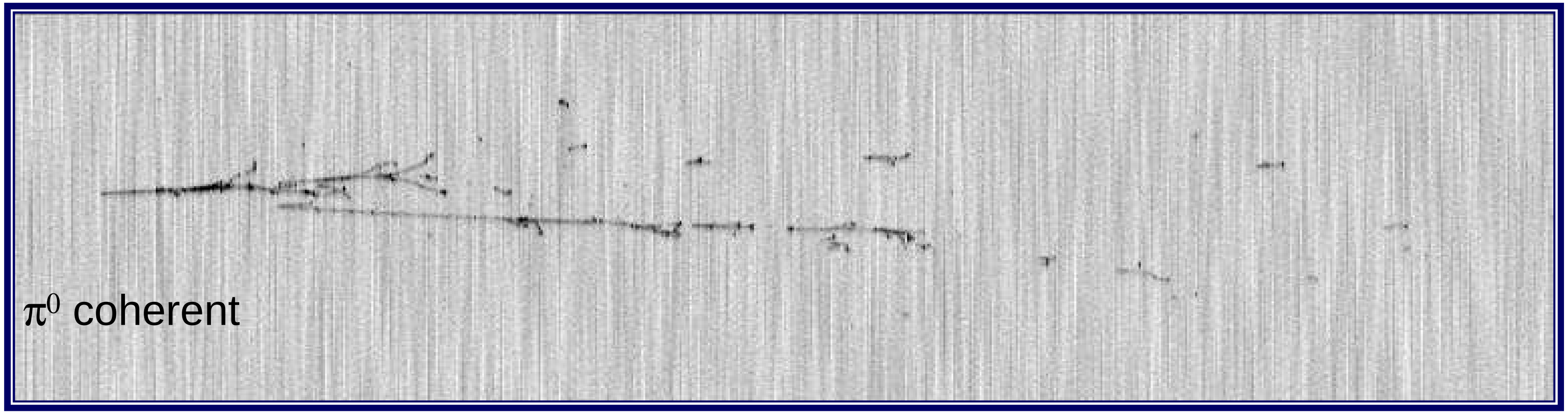
Noble liquids TPC's are used in astroparticles physics for their excellent imaging properties ("electronic" bubble chambers), spatial resolution (tracking), identification capabilities (through *dE/dx*).

- They provide also full calorimetric measurements with a high granularity (0.02 X_0).
- Good electron identification.
- Homogeneous detectors (active volume, readout on surface)
- Ionizing track induces charge signals on different (3) wire planes
- Scintillation light used to provide fast t_0 signal

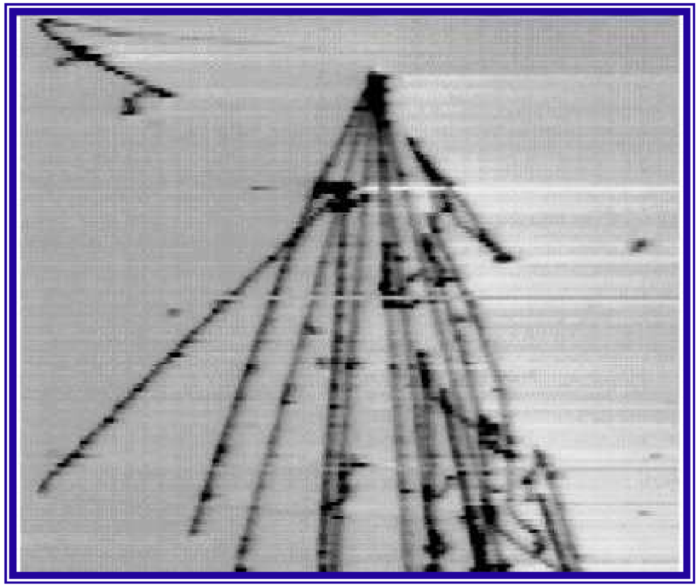


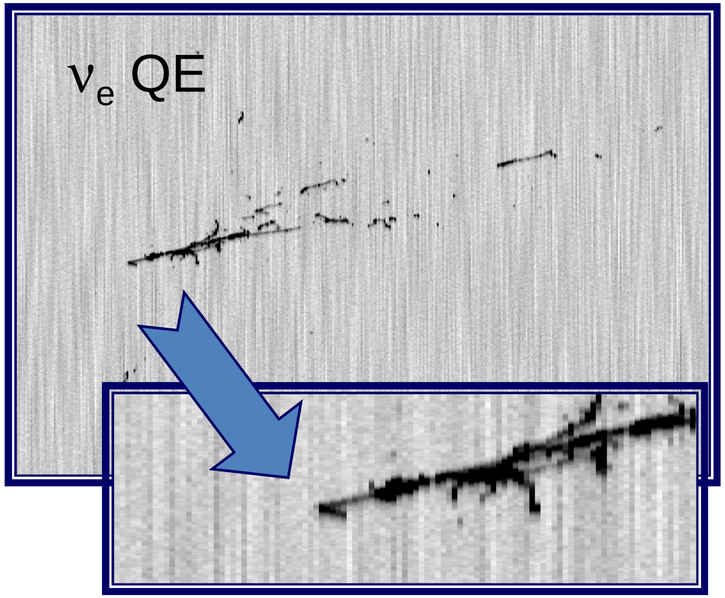
3-4 LAr readout

Illustrating imaging capabilities



π^0 coherent

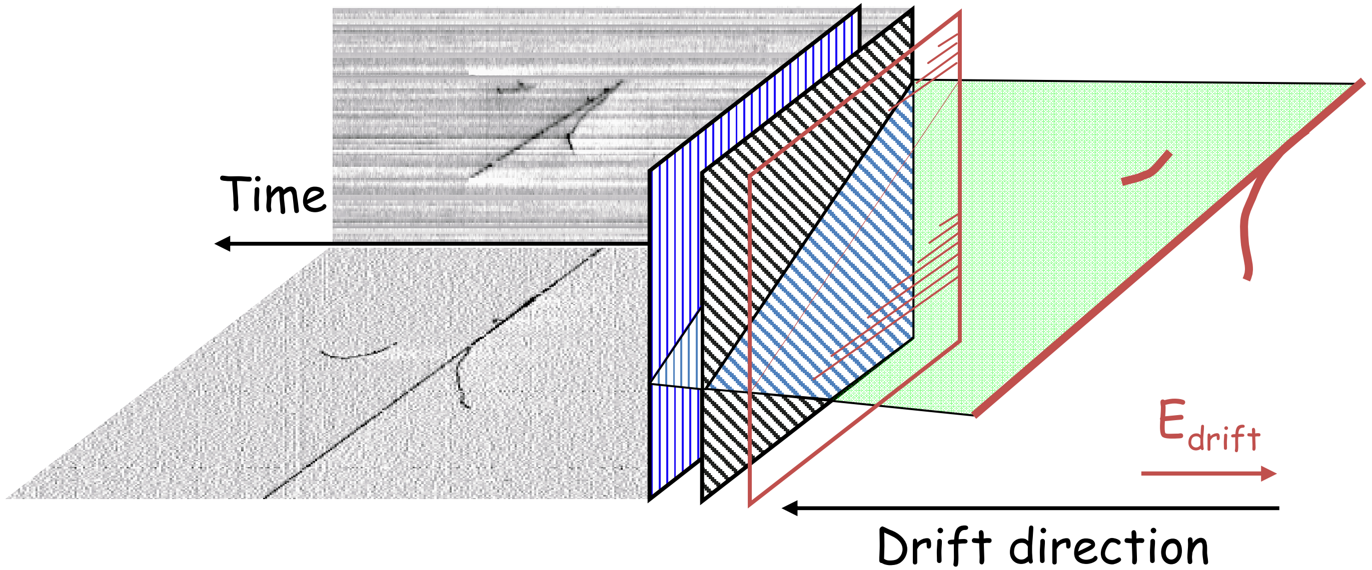


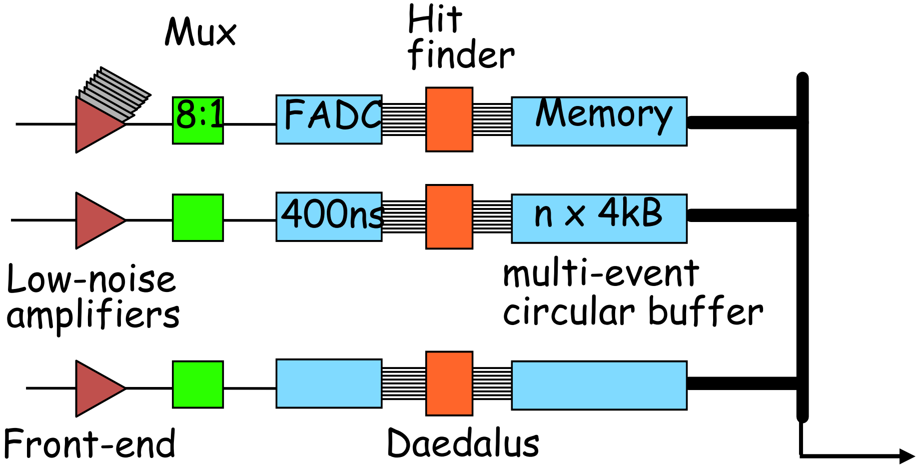


ν_e QE

3-4 LAr readout

Readout principle: from ionizing track to electronic signal





- Continously sensitive
- Self-triggering (Icarus)
- Zero suppression

3-4 LAr readout

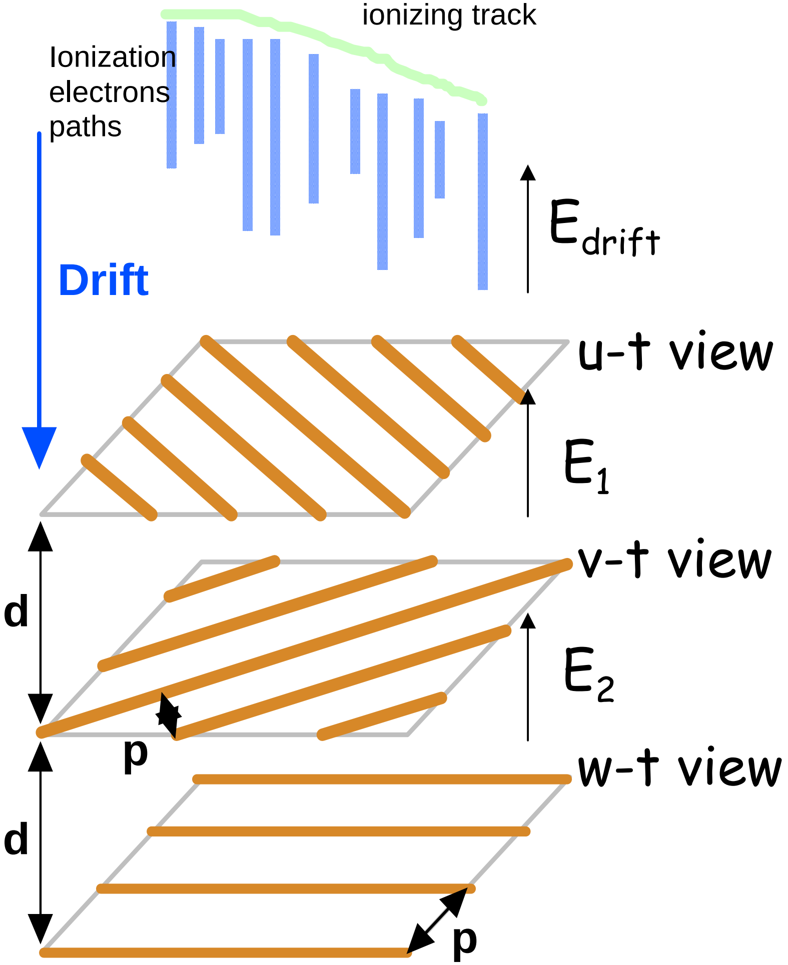
ICARUS TPC:

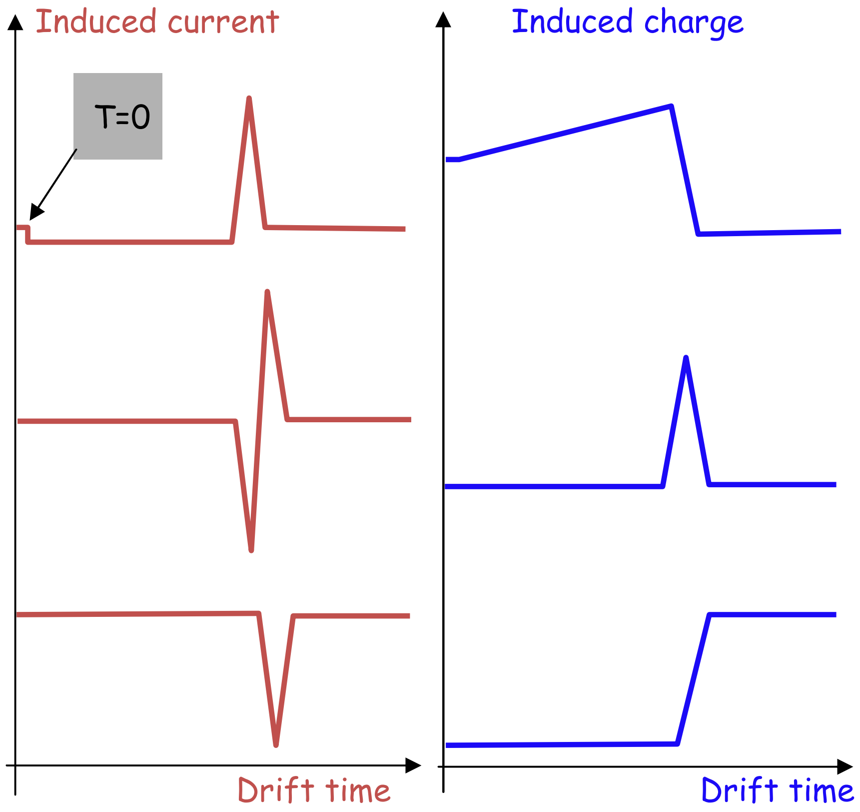
- Detection of primary ionization in LAr : 1 m.i.p ~ 20000 electrons on 3mm.
- 3D event reconstruction with ~1 mm space resolution.
- High resolution calorimetric measurement of e.m. and hadronic showers.
- PMs detecting UV scintillation light in Argon used to provide the t0 of the event ➔ requires WLS treatment
- Electron drift velocity ~ 1.5mm/µs
- Typical grid transit time ~ 2-3 µs

3-4 LAr readout

ICARUS TPC:

E_{drift} = 500 V/cm
p = 3mm
d = 3mm
r = 0.1mm

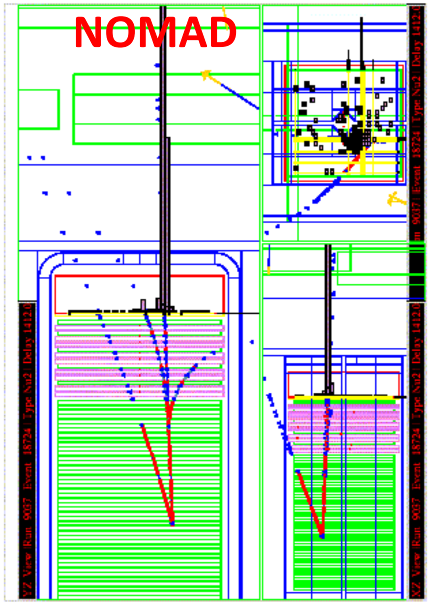


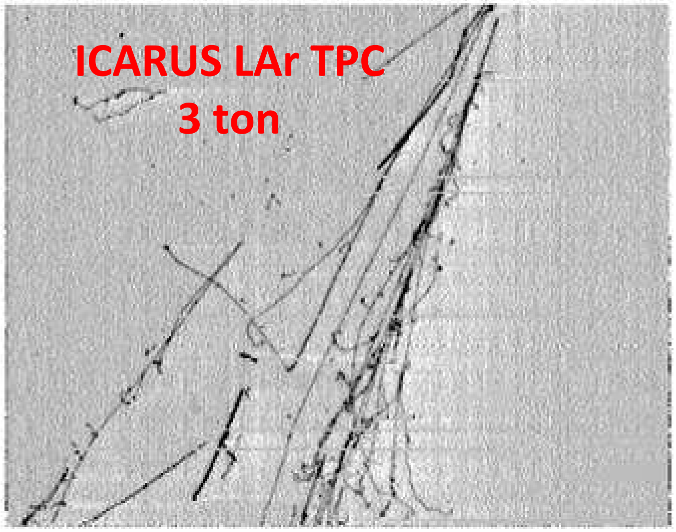


3-4 LAr readout

In conclusion : some evolution on the detection techniques…


Gargamelle Bubble Chamber


NOMAD


ICARUS LAr TPC 3 ton

… for real large scale applications


LNG tank