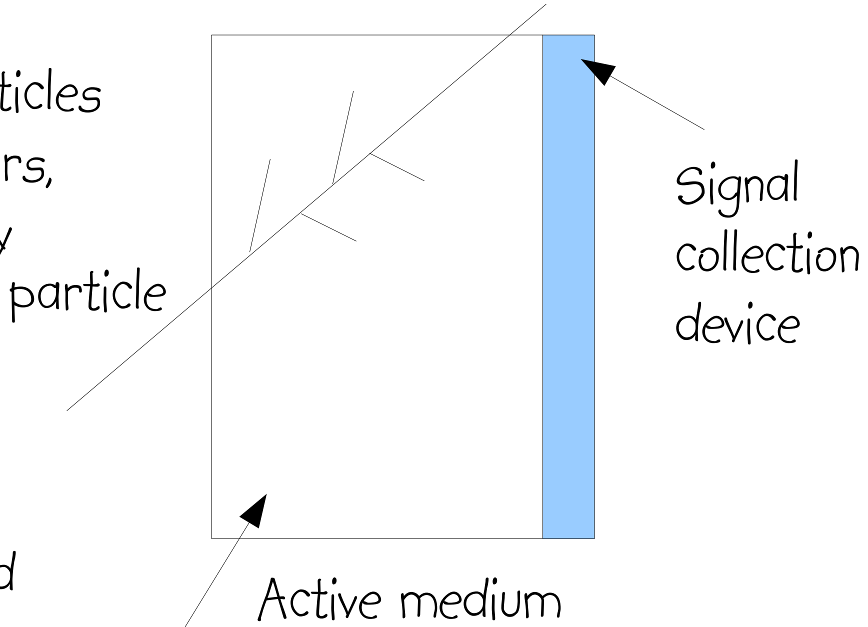
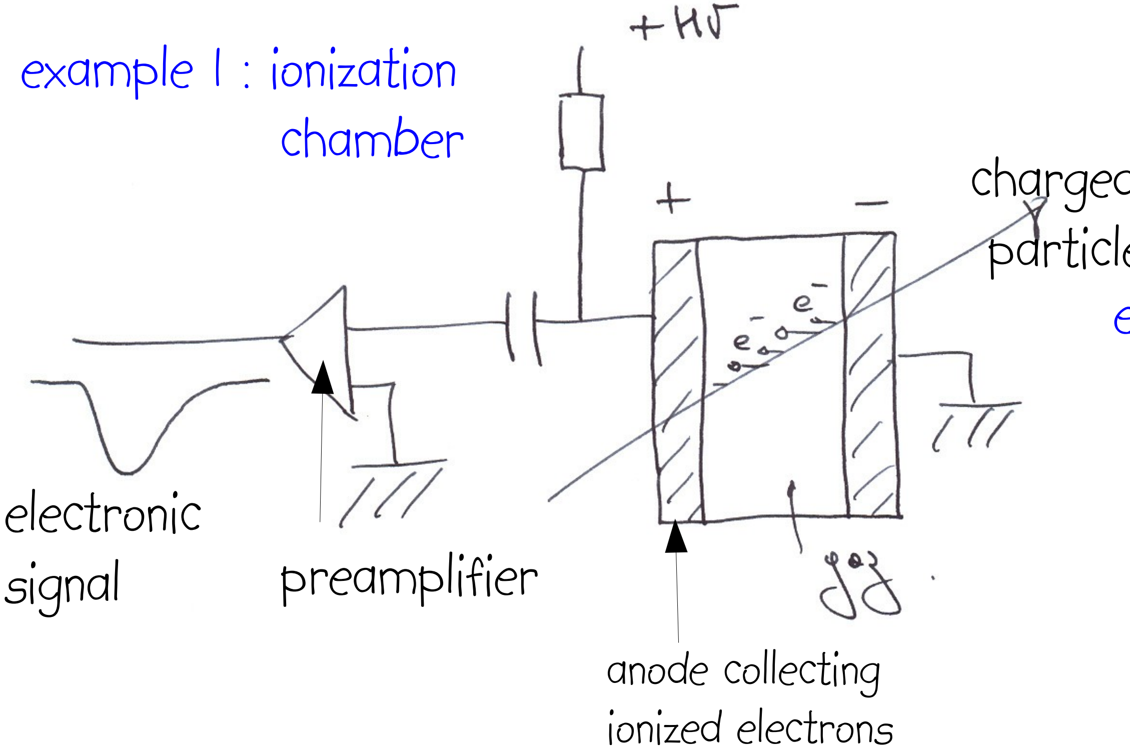
Subatomic particle detectors

General properties of detectors

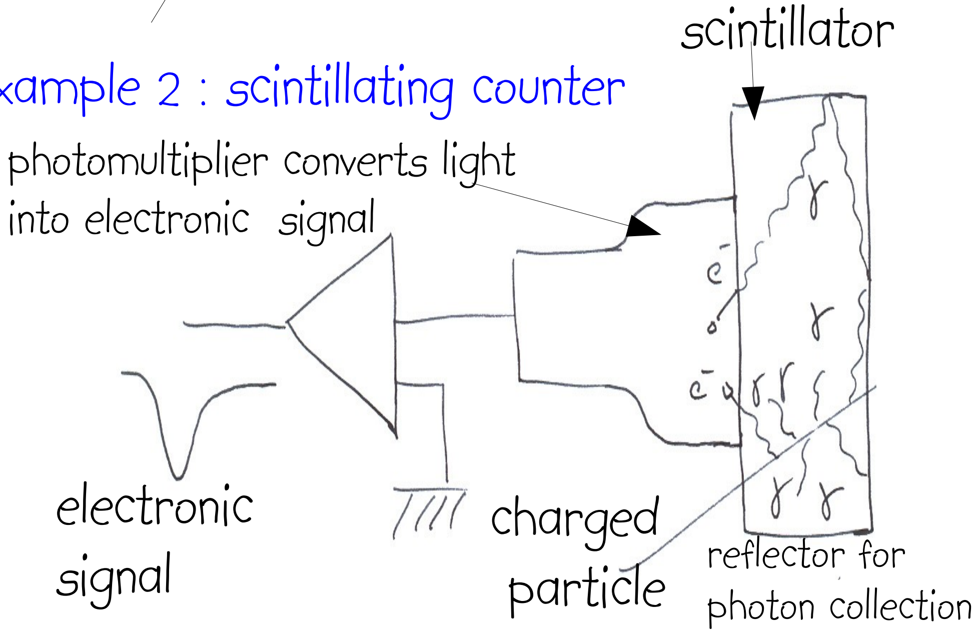
A detector always has an active medium in which particles interact and generate signal carriers (ion-electron pairs, photons, electron-hole pairs..) which are *subsequently* collected to form an electronic signal.



example 1 : ionization chamber

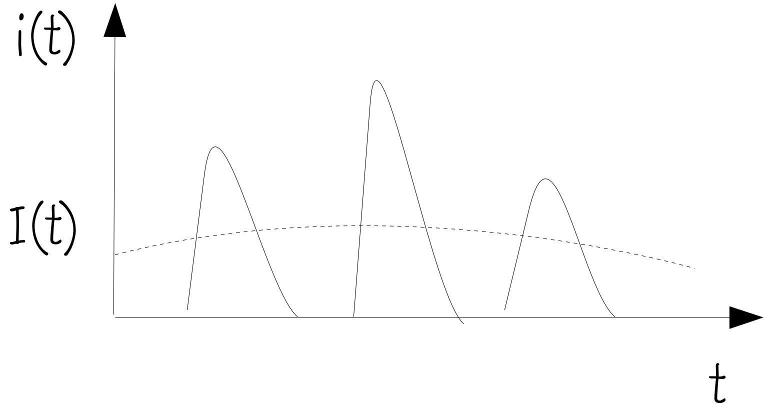


example 2 : scintillating counter



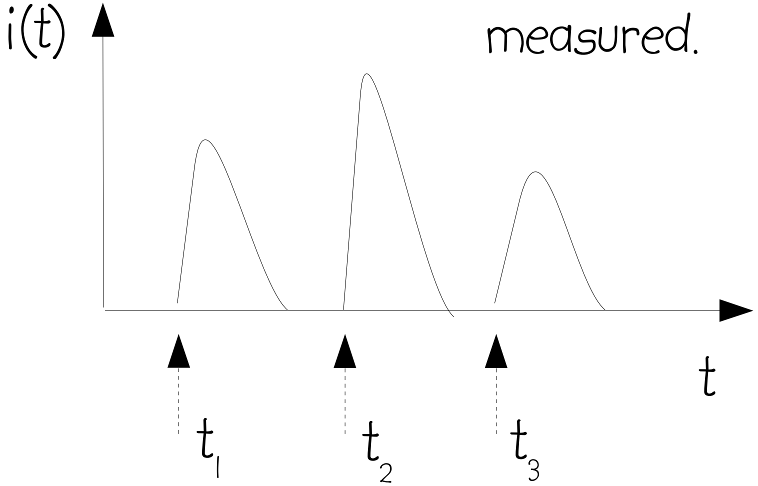
modes of detector operation

Current mode : Measures current averaged over time interval T : $I(t)=\frac{1}{T}\int_{t-T}^{t} i(t')dt'$



This mode is used when only the average current induced by particle interactions is of interest or when the interaction rate is much too high.
Examples : neutron flux detectors in nuclear reactors. Active dosimeters. Beam diagnostics.

Pulse mode : The characteristics (time, amplitude...) of each pulse are individually measured.

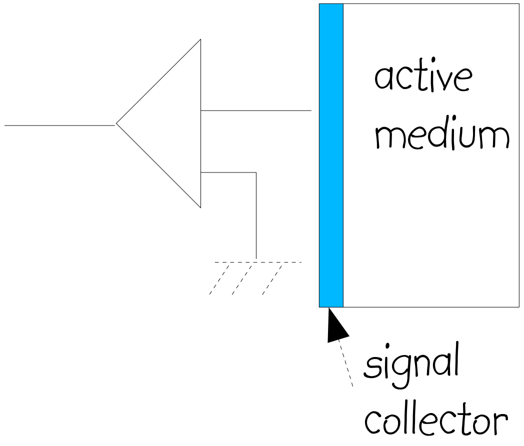


This mode is used when detecting individual particles is of interest. It requires fast electronics.
Examples : all kinds of particle detectors used in high energy physics.

Detector types

Mono-channel detectors :

channel means electronic channel



Counters :

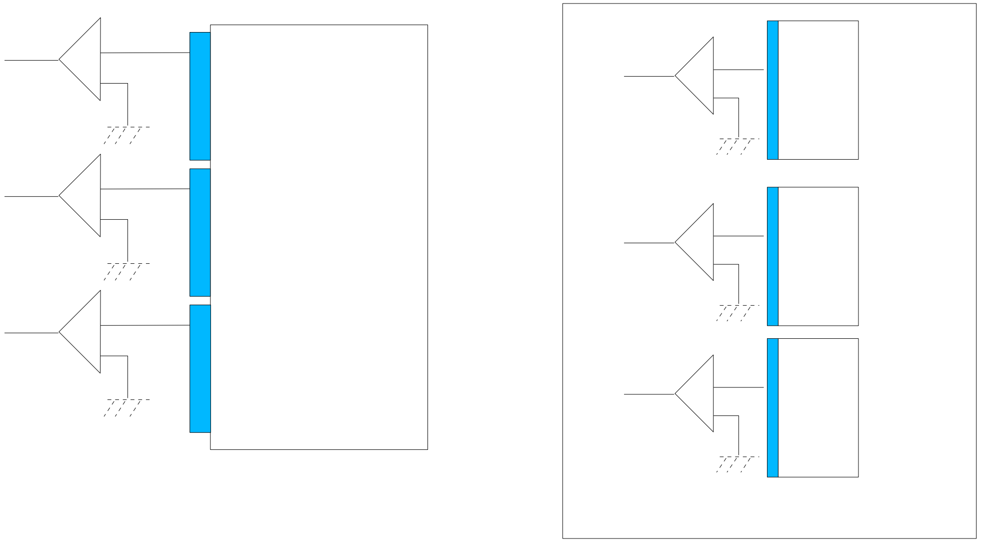
Usually a detector which selectively measures one type of particles over a certain parameter range.

Multi-detectors :

A multi-detector is made of several sub-detectors, each sub-detector being a multi-channel detector.

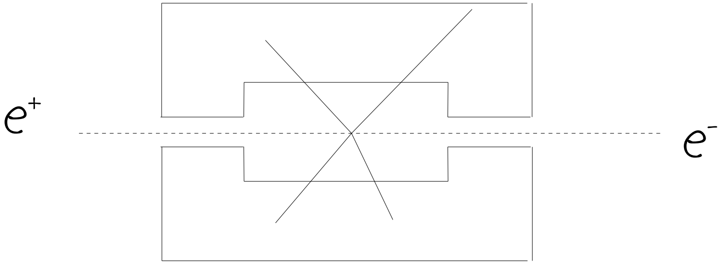
Nowadays, particle colliders are equipped with 4π multi-detectors.

Multi-channel detectors :



4π detectors :

Detectors which measure particles over full solid angle.



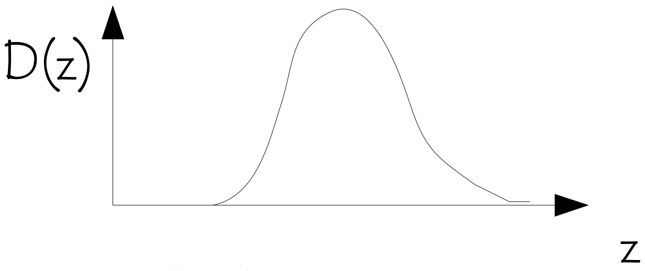
example : detector on e^+e^- collider

Detector response function

Each measurement comes with a measurement error which - in subatomic physics - is always stochastic. Suppose a detector measures the physics observable z. Then z is a random variable with D(z) its measurement probability density. D(z) is called the detector response function of z.

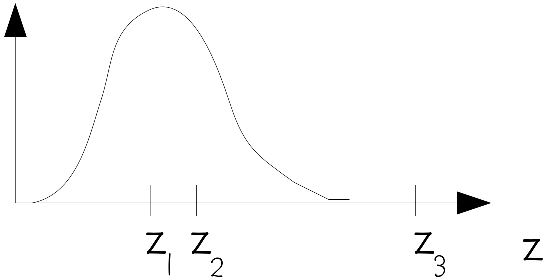
$$\int D(z)dz=1$$

By definition of a probability density.



If the number of error sources on z is big, the central value theorem states that z is normally (Gaussionnally) distributed. This explains why very often, repeated measurements of the same physics observable are normally distributed (but not always) .

The absolute resolution of z is the standard deviation of D(z).



if $z_2 - z_1 < \sigma$ z_2 and z_1 are confused

if $z_3 - z_1 \gg \sigma$ z_3 and z_1 are separated

Energy resolution

The standard deviation of the energy response function is the absolute energy resolution of the detector.

To measure the energy of a particle, one collects the signal carriers created in the active medium. In a linear medium (immense majority of detectors), the energy deposited by a particle is proportionnal to the number of charge carriers : $E = k\,N$

If N follows a Poisson probability density law, $\sigma(N) = \sqrt{N}$

and therefore the absolute energy resolution is given by : $\sigma(E) = k\,\sigma(N)$

The relative energy resolution is then : $\dfrac{\sigma(E)}{E} = \dfrac{1}{\sqrt{N}}$

The relative energy resolution improves when number of signal carriers gets bigger !

This is why semiconductor and cryogenic detectors are becoming more and more popular.

Fano factor

But for a given deposited energy, N cannot be arbitrarily big ! So N does not strictly follow a Poisson distribution and in general its fluctuations from the average value are less than predicted by a Poisson distribution. F , the Fano factor , is then defined by :

$$F = \frac{\text{observed variance of N}}{N} \quad \text{or} \quad \left.\frac{\sigma(E)}{E}\right._{\text{observed}} = \sqrt{\frac{F}{N}}$$

F is always less or equal to 1 . Example : low energy protons in Si , F = 0.16

F depends on the energy and the type of the particle as well as on the medium.

$$\left.\frac{\sigma(E)}{E}\right._{\text{observed}} = \sqrt{\frac{F}{N}} = \sqrt{\frac{F\,k}{E}} = \frac{S}{\sqrt{E}}$$

where : $S = \sqrt{F\,k}$ is a constant.

S is sometimes called the stochastic term of the energy resolution.

Noise and inhomogeneity contributions to energy resolution

To obtain the complete formula of the energy resolution, one needs to add the contributions of the electronic noise and the detector inhomogeneity.

The variance B of the electronic noise contribution to the energy measurement is by definition independant on the signal, then its energy.

If in the formula E = k N, k is not constant (homogeneous) over the detector, then :

$$\sigma(E)^{\text{inho.}} = \sigma(k)\,N \quad\Rightarrow\quad \frac{\sigma(E)^{\text{inho.}}}{E} = \frac{\sigma(E)^{\text{inho.}}}{k\,N} = \frac{\sigma(k)}{k} = D$$

And finally when all terms are quadratically summed :

$$\left(\frac{\sigma(E)}{E}\right)^2 = \left(\frac{S}{\sqrt{E}}\right)^2 + \left(\frac{B}{E}\right)^2 + D^2$$

constant term

Stochastic term

noise term

Detection efficiency

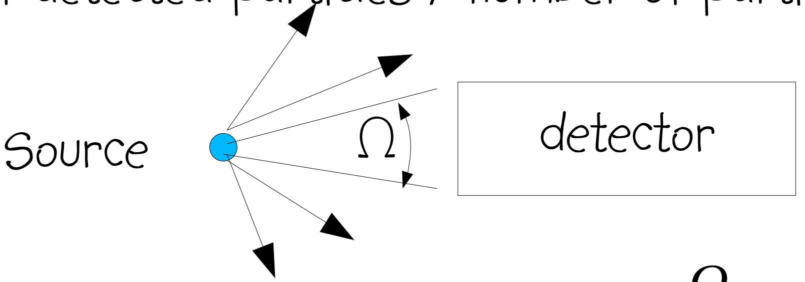
This is the probability to detect a particle.

Absolute efficiency :

ε_{abs} = number of detected particles / number of particles emitted by the source

Intrinsic efficiency :

ε_{int} = number of detected particles / number of particles passing through the detector

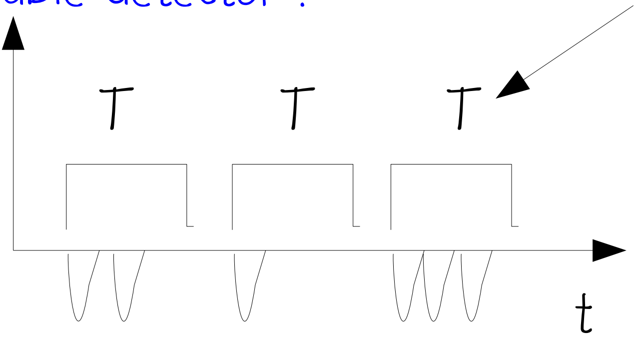


$$\epsilon_{abs} \simeq \epsilon_{int} \frac{\Omega}{4\pi}$$

Dead time of a detector

This is the minimal time interval that separates two consecutive event (particle) measurements. If two particles pass through a detector with a time separation less than the dead time, the second particle is not recorded. The dead time may be due to the detector, its electronics or the acquisition system (PC and software).

Non-paralysable detector :



fixed dead time T generated when a particle is detected

n : particle interaction rate in the detector (Hz)
m : detected particle rate in the detector (Hz)
T : dead time (s)

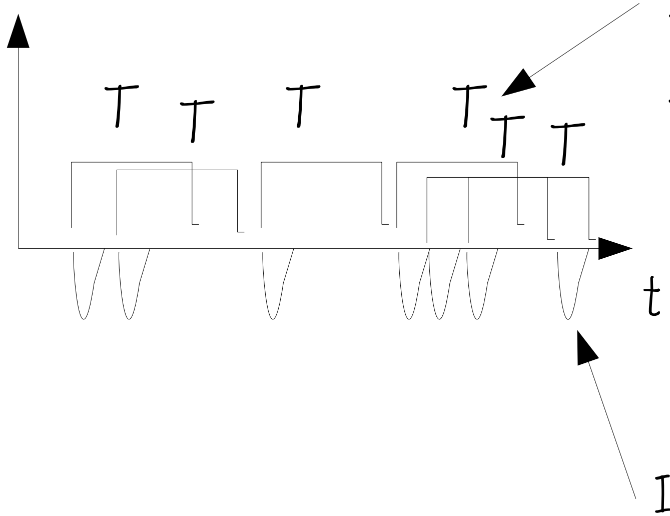
$$n = \frac{m}{(1 - m\,T)} \quad \text{and} \quad m = \frac{n}{(1 + n\,T)}$$

$$\lim_{n -> \infty} m = \frac{1}{T}$$

This detector type will never get paralysed .

Dead time of a detector

Paralysable detector :



Dead time T generated every time a particle pass through the detector.

n : particle interaction rate in the detector (Hz)
m : detected particle rate in the detector (Hz)
T : dead time (s)

If paralysable, this particle is lost !

$$m = n \exp(-nT)$$

$$\lim_{n \to \infty} m = 0$$

This detector type may get paralysed.

$$\lim_{nT \to 0} m = n(1 - nT)$$

Same as non-paralysable case .

Detector calibration

This operation consists of determining the efficiency and the response function(s) of a detector, through measurements by also very often by using Monté-Carlo calculations.

If the physical observable is not the measured variable (example E (MeV) = a V (Volt) + b).

physical observable

$$z_{phys} = f(z, \vec{\alpha})$$

calibration function constant parameters

Calibration function

Response function of Z_{phys}

$$D'(z_{phys}) = \left| \frac{dz}{dz_{phys}} \right| D(z)$$

Response function of z

example : energy calibration of a linear detector : E (MeV) = a V (Volt) + b

Physical observable

measured variable

For a multi-detector (like ATLAS) operated over a long time period, calibration becomes a fastidious task that employs lots of people and computers !

To learn more :

- Particle detectors, Claus Grupen, Cambridge monographs on particle physics
- Detectors for Particle radiation, Konrad Kleinknecht, Cambridge University Press
- Radiation detection and measurement, G.F. Knoll, J. Wiley & Sons
- Single Particle Detection and Measurement, R. Gilmore, Taylor & Francis
- Radiation detectors, C.F.G. Delaney and E.C. Finch , Oxford Science Publications