Detection techniques & applications

A short and biaised overview

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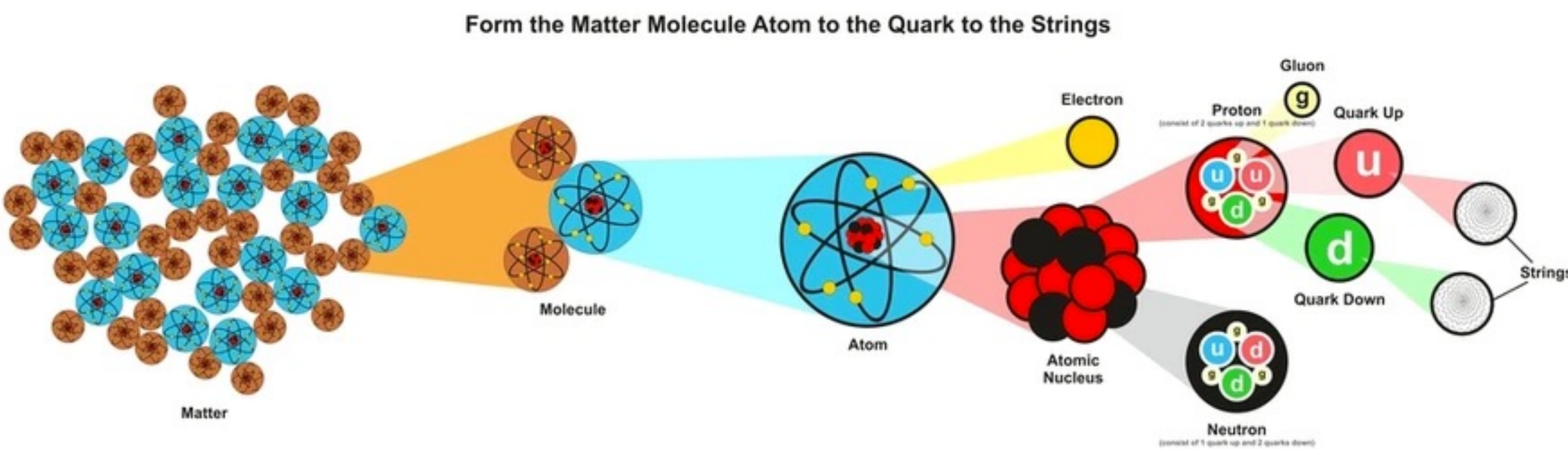
A recent science



How to observe / study particle physics?

1) Watch what arrives on Earth :

-Until the 50's cosmic rays source of most of the discoveries but lack of knowledge of the initial state and detection of long-lived particles (~10-10s)

-➔ Measurable path before disintegration (bubble chamber, emulsion)

- Remains the only way to reach the highest energies (but unknown rate)

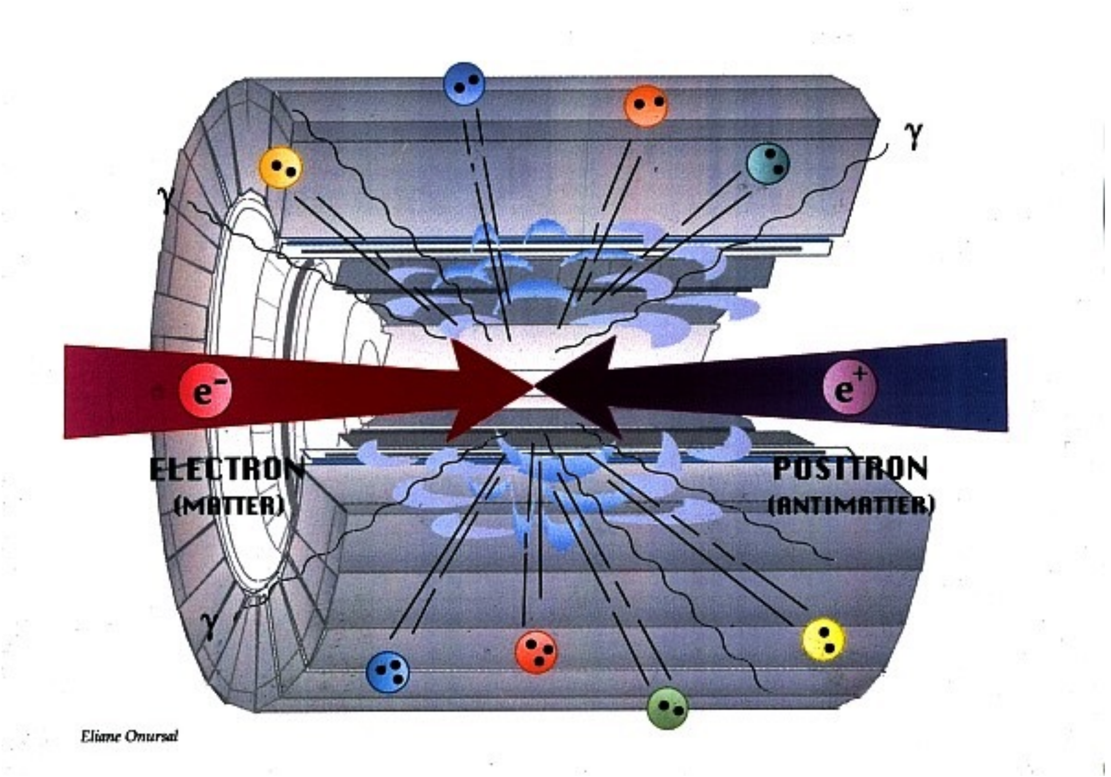
➔ Astroparticules

How to observe / study particle physics?

2) Produce the initial state as close as possible to the big bang: particle collisions

By provoking collisions, we control the initial state (energy, momentum)

➔ We can measure the whole final state and detect very short-lived particles



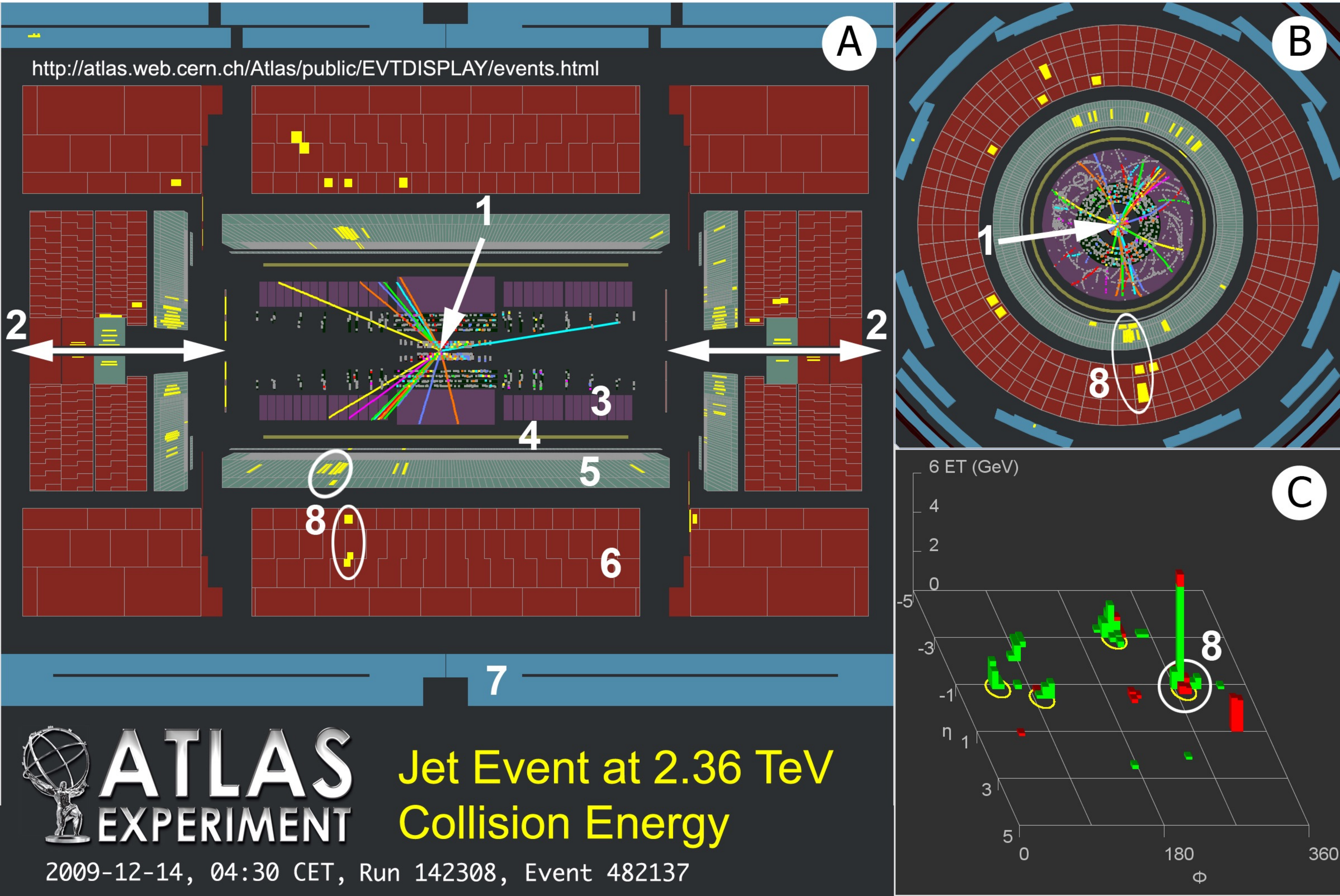
Particle detection

A particle detector does NOT allow to see a particle

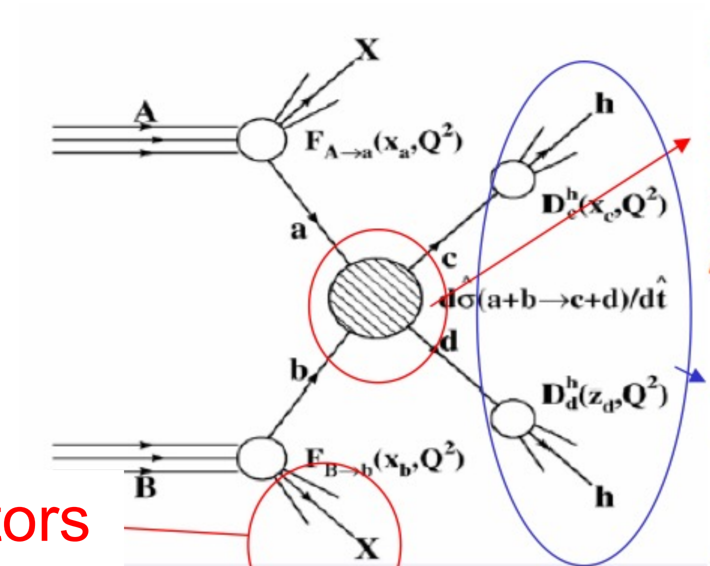
In practice, we only measure the effects of the passage of a particle in matter in the form of excitation or ionization, mainly by electromagnetic interaction

The role of a detector is to transform a microscopic disturbance into a macroscopic phenomenon

Particles recorded in a detector



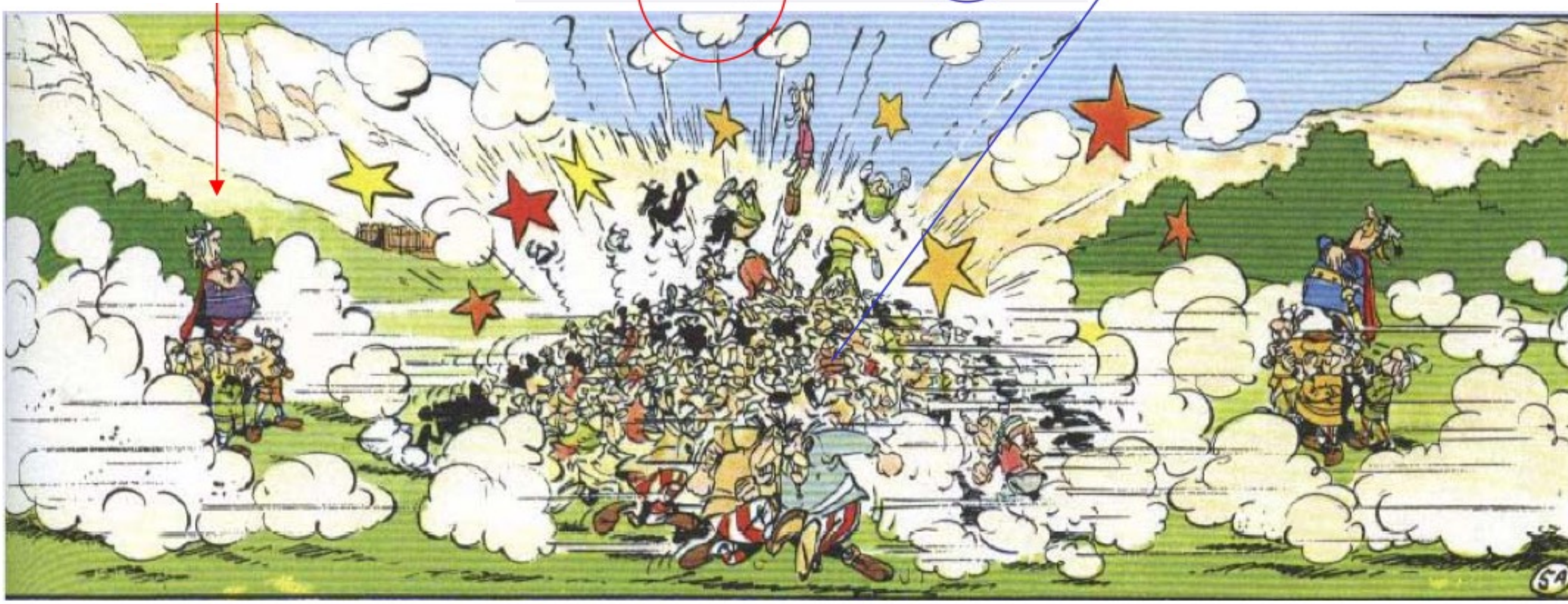
Collision can be see as collision!



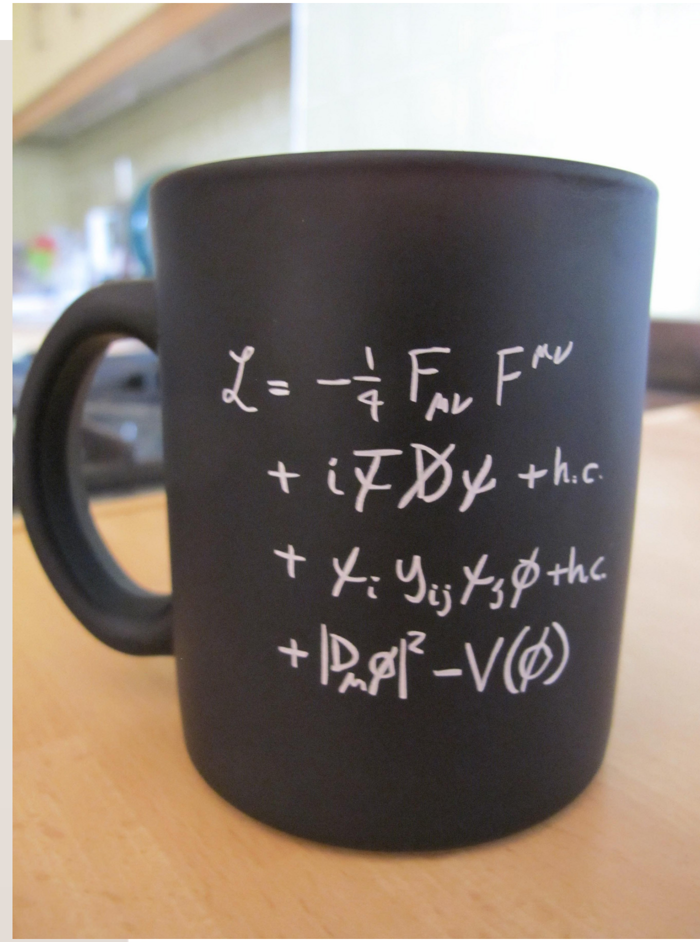
Collision with high transversal momentum

Many particle in final state

Parton quark spectators



Standard Model seen from theorists



How particle are seen from experimentalists

W

$J = 1$

Charge $= \pm 1\ e$
Mass $m = 80.385 \pm 0.015$ GeV
$m_Z - m_W = 10.4 \pm 1.6$ GeV
$m_{W^+} - m_{W^-} = -0.2 \pm 0.6$ GeV
Full width $\Gamma = 2.085 \pm 0.042$ GeV
$\langle N_{\pi^\pm} \rangle = 15.70 \pm 0.35$
$\langle N_{K^\pm} \rangle = 2.20 \pm 0.19$
$\langle N_p \rangle = 0.92 \pm 0.14$
$\langle N_{\text{charged}} \rangle = 19.39 \pm 0.08$

spin ➔ angular distribution

charge ➔ electromagnetic Interaction

Mass

Width Γ (τ = hbar/Γ)

W^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\ell^+\nu$	[b]	(10.80 ± 0.09) %		–
$e^+\nu$		(10.75 ± 0.13) %		40192
$\mu^+\nu$		(10.57 ± 0.15) %		40192
$\tau^+\nu$		(11.25 ± 0.20) %		40173
hadrons		(67.60 ± 0.27) %		–
$\pi^+\gamma$		$< 8 \times 10^{-5}$	95%	40192
$D_s^+\gamma$		$< 1.3 \times 10^{-3}$	95%	40168
cX		(33.4 ± 2.6) %		–
$c\overline{s}$		$(31 {}^{+13}_{-11})$ %		–
invisible	[c]	(1.4 ± 2.9) %		–

Final states
(if not stable)

Overview

I (Long) Introduction
II General Characteristics

II Main detection techinics
1. Ionisation in gas
2. Ionisation in solid
3. Light emission

III Somes detection technics
1. Traces detector and momentum measurement
2. Electromagnetic / Hadronic calorimeter
3. Particle Identification

IV Example of full detectors
1. CMS (LHC)
2. HESS (gamma ray in astroparticle)
3. XENON (Direct Dark matter detection) – liquid xenon application

General Caracteristics

General principle of operation of a detector:
convert the energy radiated by a particle into a signal accessible to our perception

Different types of detectors :

- Detectors based on ionization processes in gases
= ionization chamber, proportional chamber, drift chamber, time projection chamber...
- Detectors based on ionization processes in solids
  = semiconductors
- Detectors based on excitation processes followed by photon emission
  = scintillator, Cerenkov detector, transition radiation

Types of particles

Charged particles

- Interaction modes (heavy particles / e+ and e-)
- Gas and semiconductor based detectors / Plastic scintillators

Photons

- Compton, photoelectric, pair creation
- Semiconductor (Ge) and scintillation detectors

Neutrons

- Capture, induced fission, elastic, inelastic scattering...
- Gas and scintillation detectors

General operation

- General principle of operation of a detector: convert the energy radiated by a particle into a signal accessible to our perception → use of the charge Q released during the passage of the particle by interaction with matter

- Charge Q guided towards an electrode thanks to electric (+ sometimes magnetic) fields then collected

- Collection time of the charge tc : a few nanoseconds (semiconductors, photomultiplicators) to a few microseconds (ionization chambers) ⇒ detector produces a current between t=0 and t=tc, current whose integral is Q

- Several modes of operation of the detectors.
  - Current mode (dose measurement...) - integral
  - Pulse mode (spectroscopy...)

General Characteristics

Sensitivity: Capacity of a detector to produce a signal

Detectors are not sensitive to all particles, to all energies

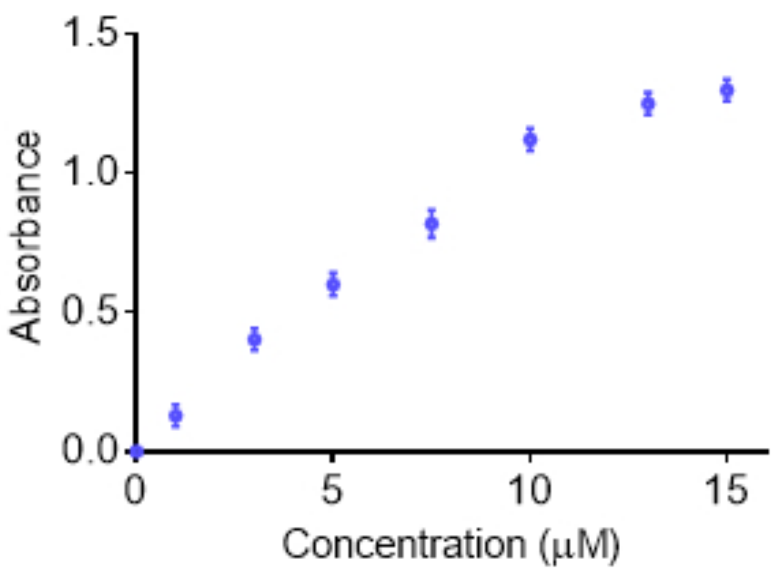
⇒ Notion of detector response function: in energy (total or partial) / in time (time to form the signal in the detector, response time of the electronic chain)
→ dead time, stacking

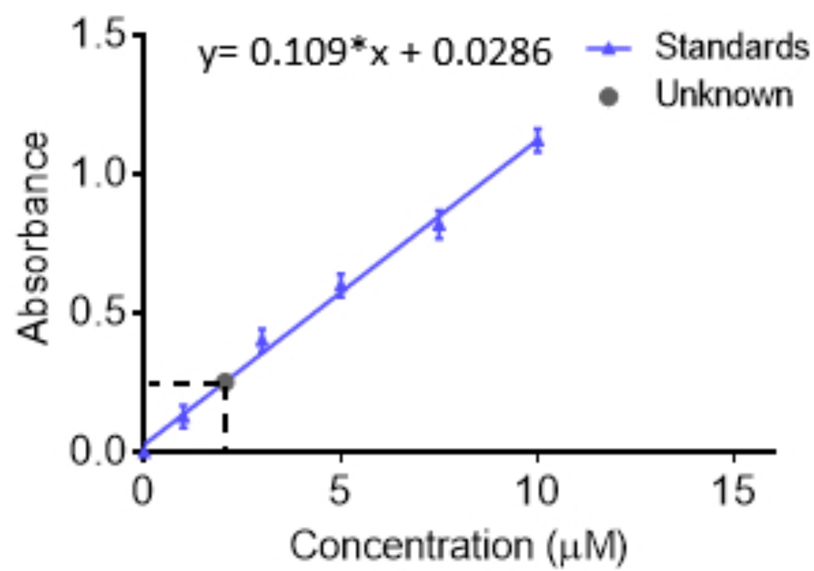
General Characteristics

Linearity

The relationship between the measured quantity z and the original value of the quantity Z is established by the calibration of the detector via monochromatic beams of particles

The relationship is of the type <z> = c.Z





General Characteristics

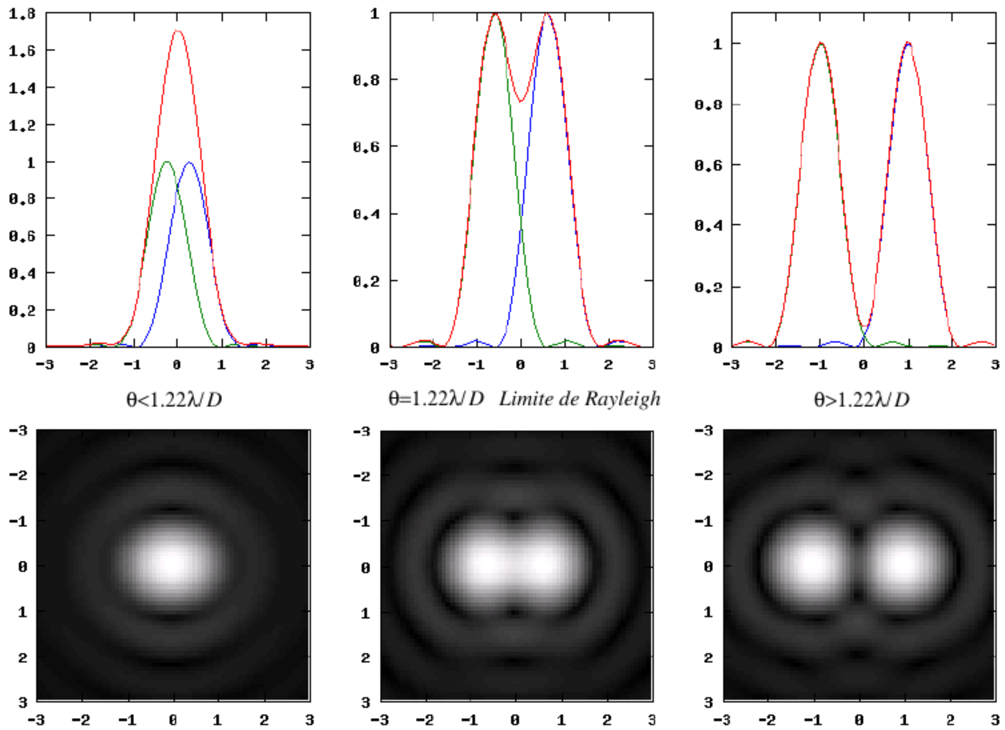
Power of resolution: Capacity of a detector to produce a signal

Let z be the response of a detector during a measurement
$\Rightarrow$ the resolution is defined as the standard deviation σ_z or the width at half maximum Δz of the distribution D(z) of the measured quantity

Relative resolution: σ_z / $<z>>$

General Characteristics

Spacial resolution:
Let 2 distinct particles of trajectories in x and x+dx
⇒ the spatial resolution is the smallest value of dx that allows to separate the 2 particles (visually or electronically)



General Characteristics

In addition to statistical fluctuations, other factors affect the resolution of the measurement (calibration of the detector, electronic noise, drift ...)

These fluctuations are independent of each other and the final response is always fitted by a Gaussian shape

The total width of the energy distribution is obtained by making a quadratic sum of the different contributions to the fluctuations:

$$(\Delta E)^2_{total} = (\Delta E)^2_{statistics} + (\Delta E)^2_{noise} + (\Delta E)^2_{detector} \dots$$

General Characteristics

Efficiency:
The absolute efficiency of the detector is the fraction of events that are detected among all events that take place:

$$\epsilon_{tot} = \frac{\text{stored events}}{\text{events emitted by the source}}$$

This efficiency comes from two sources: $\epsilon_{tot} = \epsilon_{int} \times \epsilon_{geo}$

General Characteristics

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This efficiency comes from two sources: $\epsilon_{tot} = \epsilon_{int} \times \epsilon_{geo}$

The geometric efficiency is the fraction of events that occurred that are geometrically intercepted by the detector:

$$\epsilon_{geo} = \frac{\text{events entering the detector}}{\text{events emitted by the source}}$$

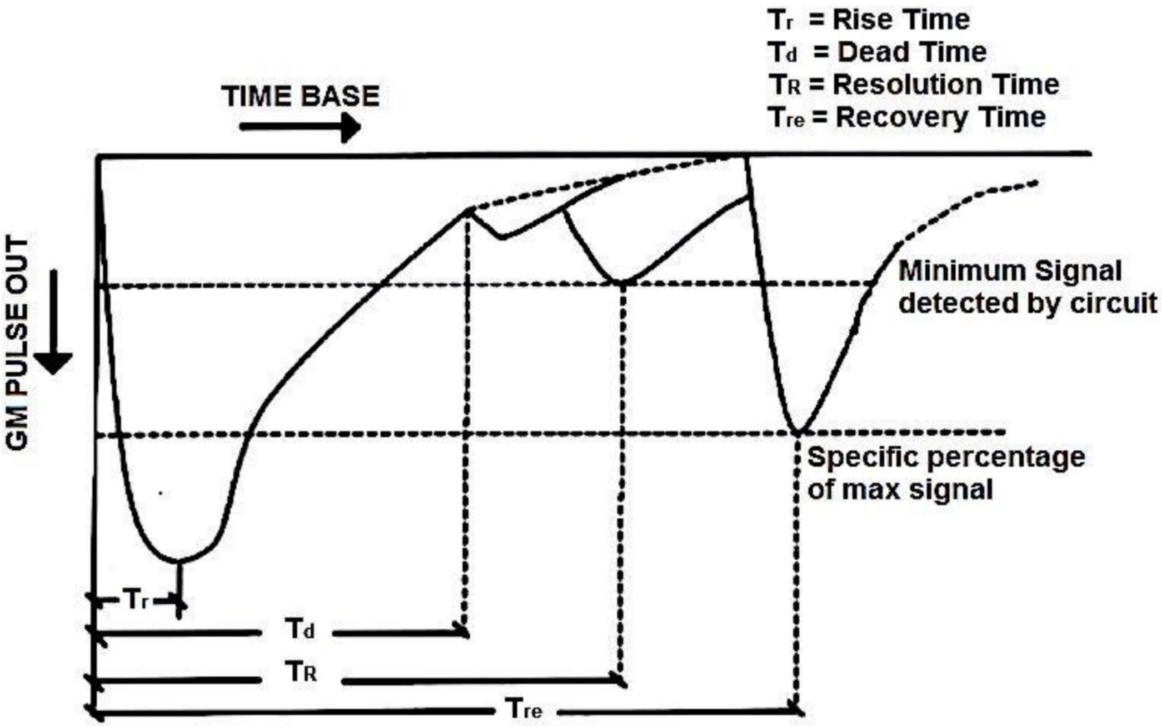
The intrinsic efficiency comes from the type of event, the effective cross section of interaction with the materials composing the detector, the energy of the particle... :

$$\epsilon_{int} = \frac{\text{stored events}}{\text{event entering the detector}}$$

General Characteristics

<u>Dead time</u>:

The intrinsic effciency may be reduced if the detection system, busy processing the current event, cannot take into account the following event(s)



Phenomenon occurring in case of high count rates or for slow detection systems and named dead time

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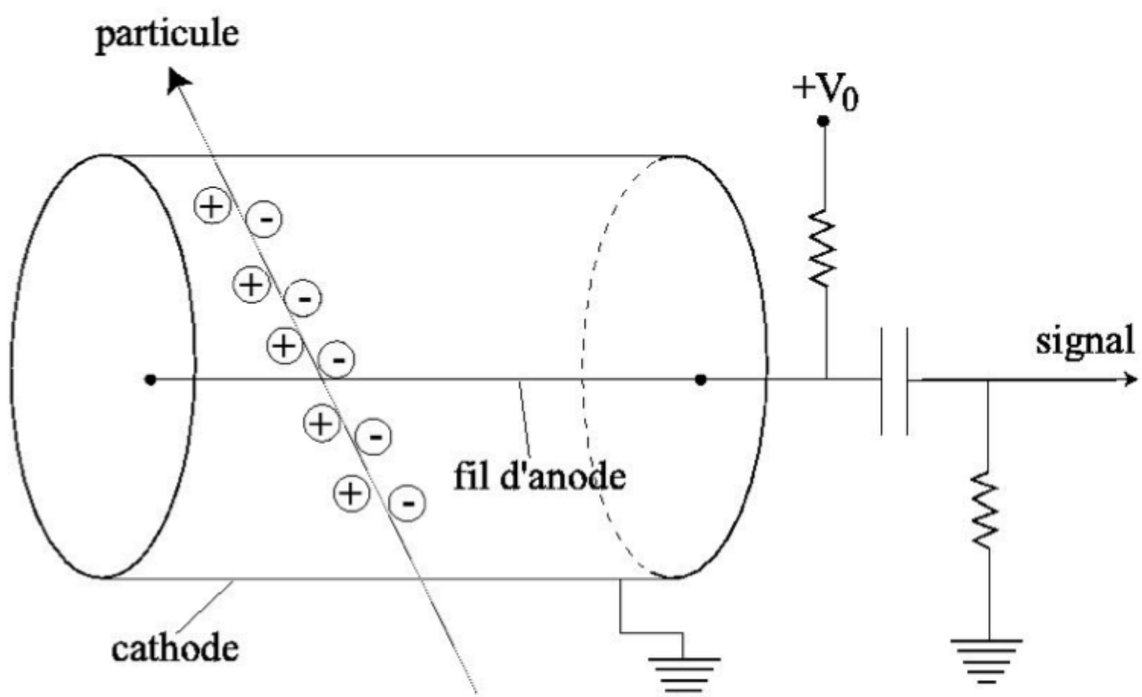
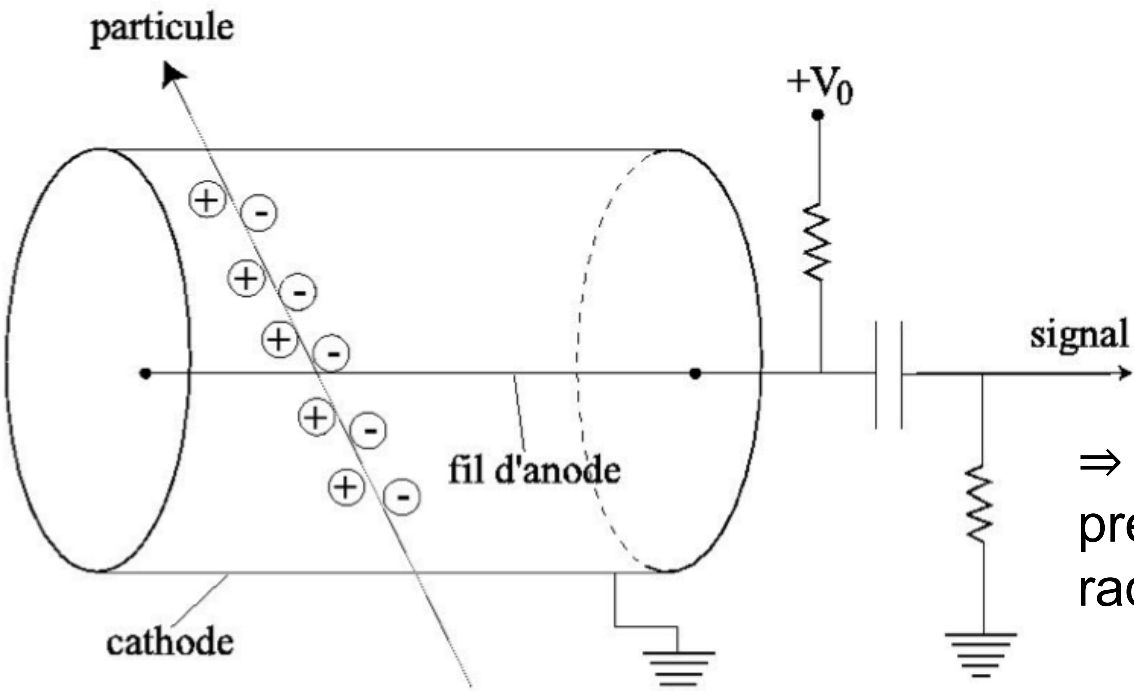
Ionisation in gas

Basic principle of these detectors = collect electrons and ions created by ionization of the gas when a charged incident particle passes by ⇒ electric pulse

Simplest form of these detectors = cylindrical geometry: anode (+) ≡ small diameter wire, stretched along the axis of a cylindrical cathode



Ionisation in gas



Vo = potential difference between the anode (wire of radius a) and the cathode

⇒ Electric field at a distance r prevailing in the cylinder of radius b :

$$E(r) = \frac{1}{r}\frac{V_0}{\ln(b/a)}$$

The number of pairs (electron-ion) created is proportional to the energy deposited by the particle in the detector

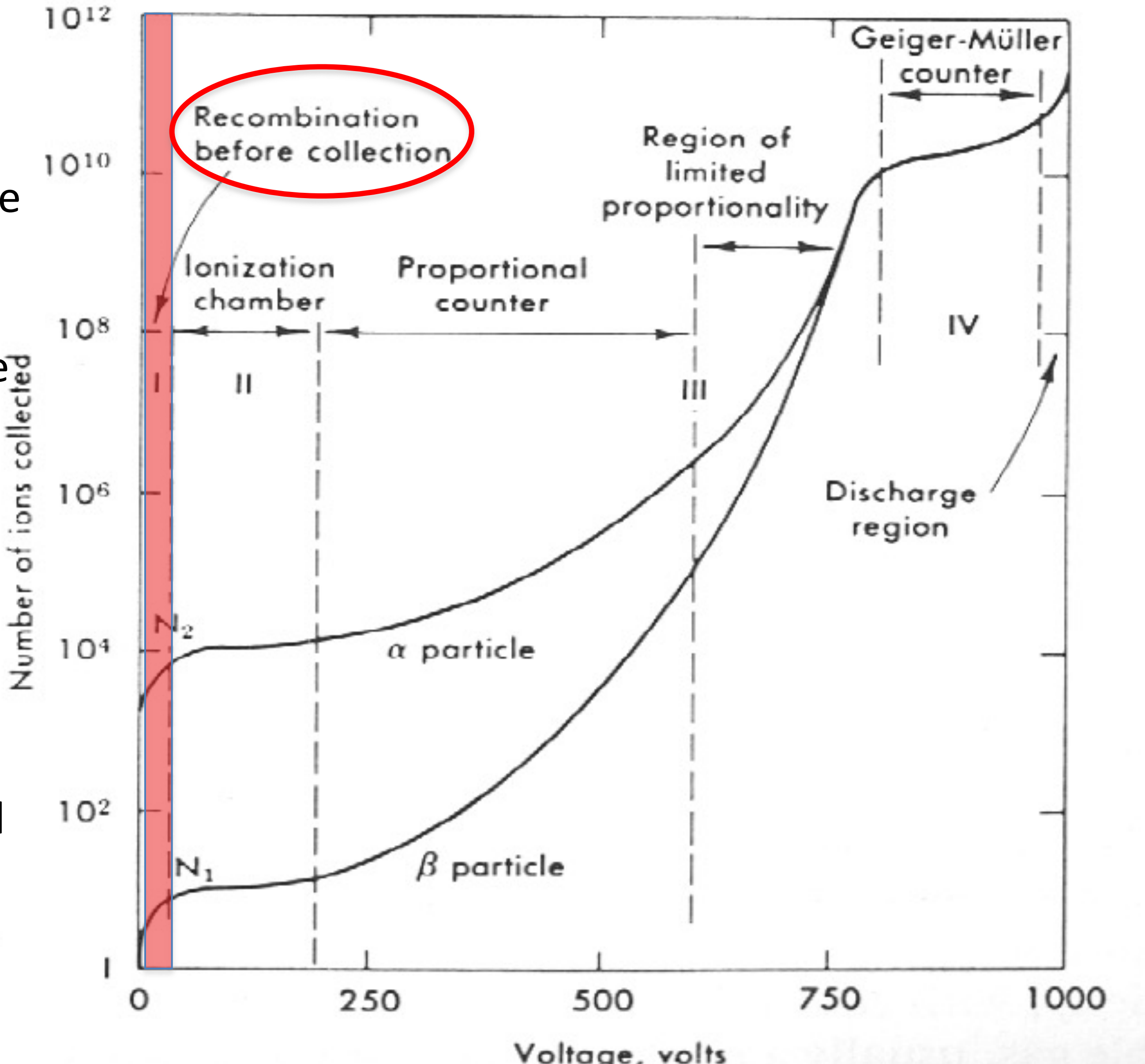
The signal collected is not always proportional to the energy deposited: it depends on the potential difference Vo

Working Mode

<u>Zone I: recombination</u>

Vo is too low
→ electrons ions cannot be brought (therefore collected) on the anode/cathode before recombining with the ions

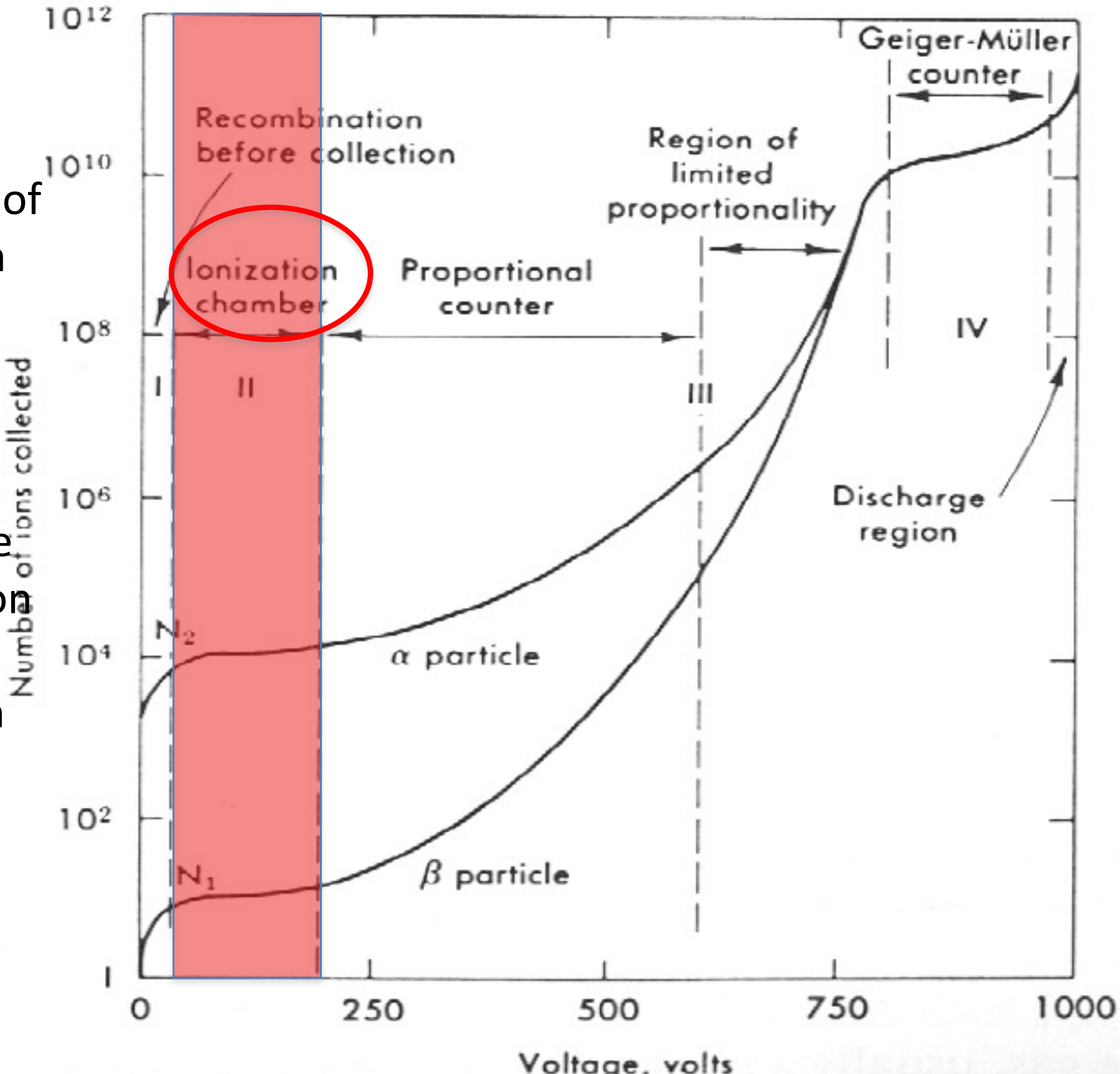
When Vo increases :
less pairs (e-/ion) recombine number of e-/ions collected increases ⇒ the signal increases



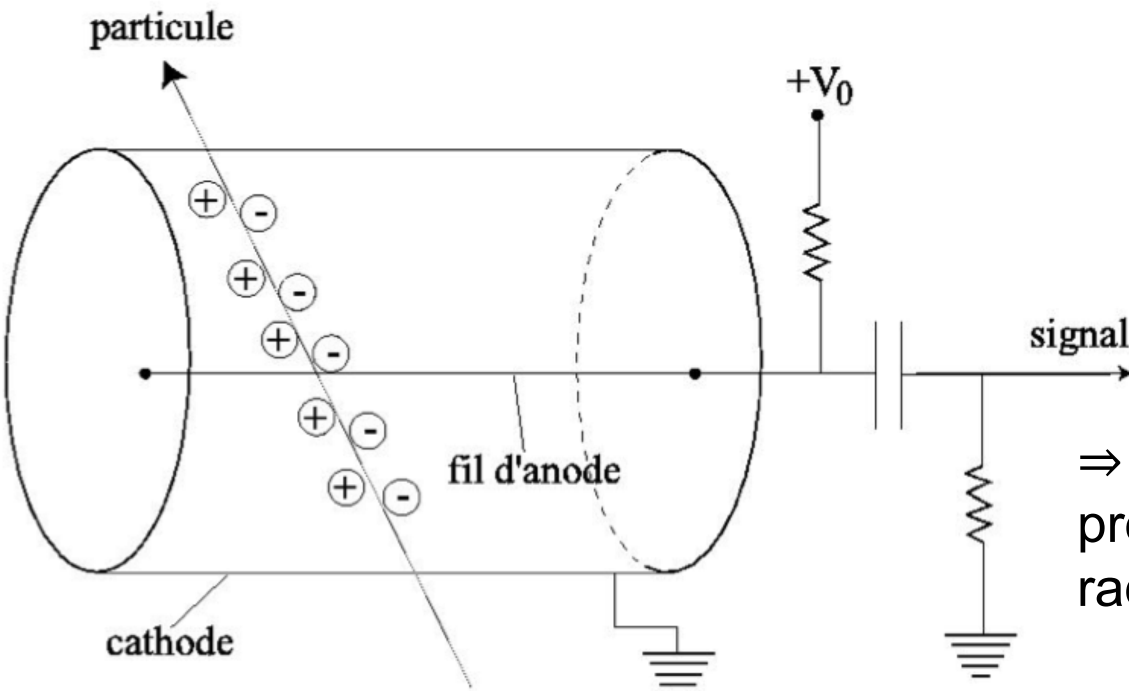
Working Mode

Zone II: saturation ionization chamber

- Above a certain value of Vo, the recombination becomes negligible
- all electrons/ions produced by the passage of the particle are collected saturation
- value of the ionization current



Ionisation in gas



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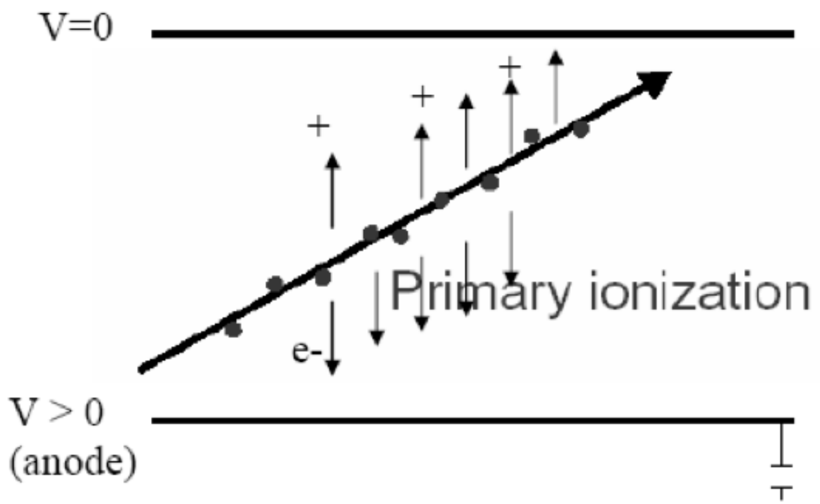
Working Mode

What signal produced in an ionization chamber ?



Let us consider an ionization chamber of thickness 1 cm (gas = Ar). A particle at minimum ionization deposits 3.5 keV/cm.

It takes ~30 eV to create an e-/ion pair ⇒ ~120 pairs created

Let the collected charge Q = C.V with C = 10pF typically

If we collect all the charge created, we measure: V = Q/C = n.e/C = 2 μV (small)

Working Mode

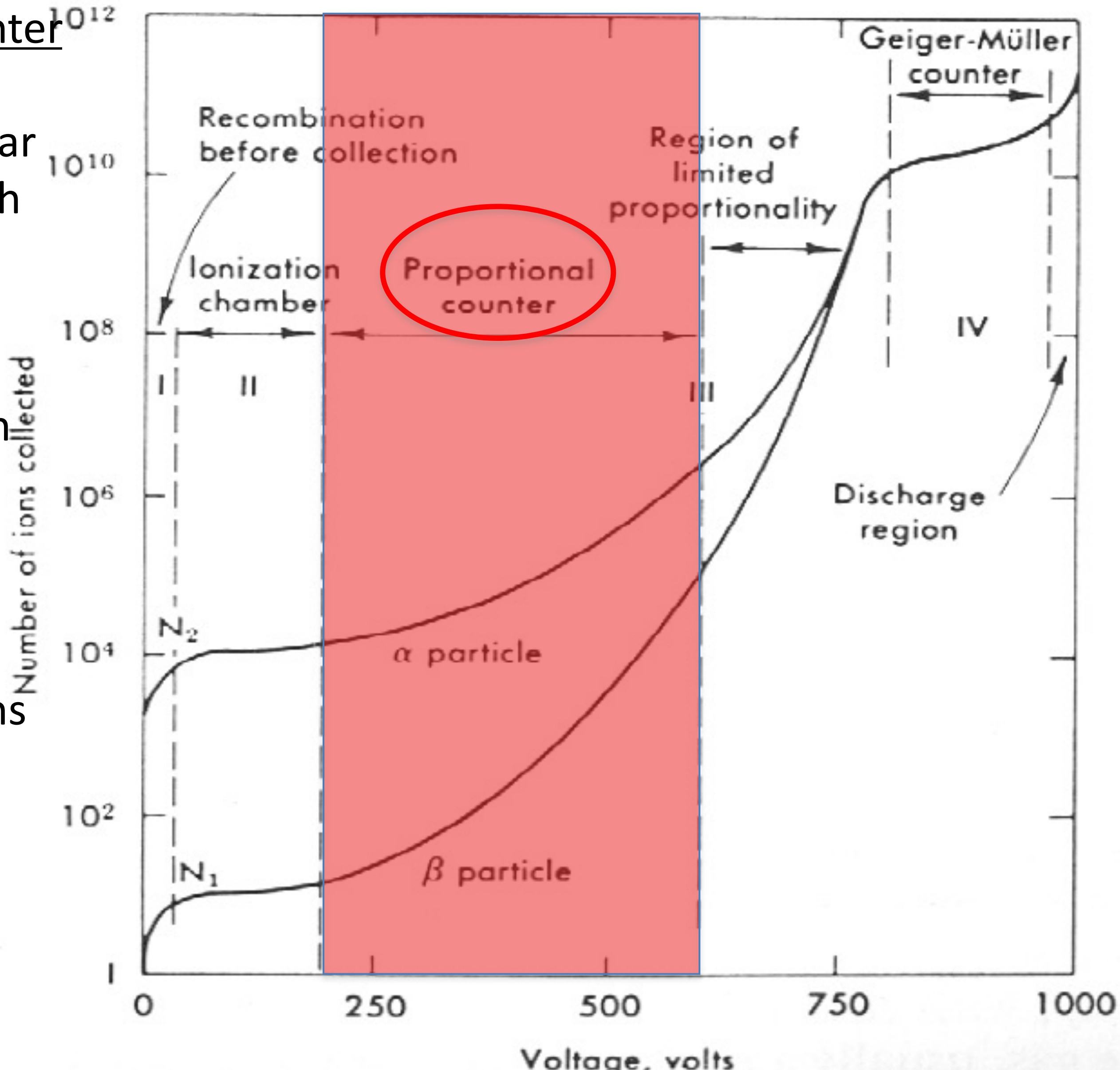
Zone III: proportional counter

- Here the electric field near the anode is strong enough

- the electrons created (primary) are accelerated enough to ionize the gas in their path

- secondary electrons

- multiplication of electrons around the anode (called Townsend avalanche)



Amplification

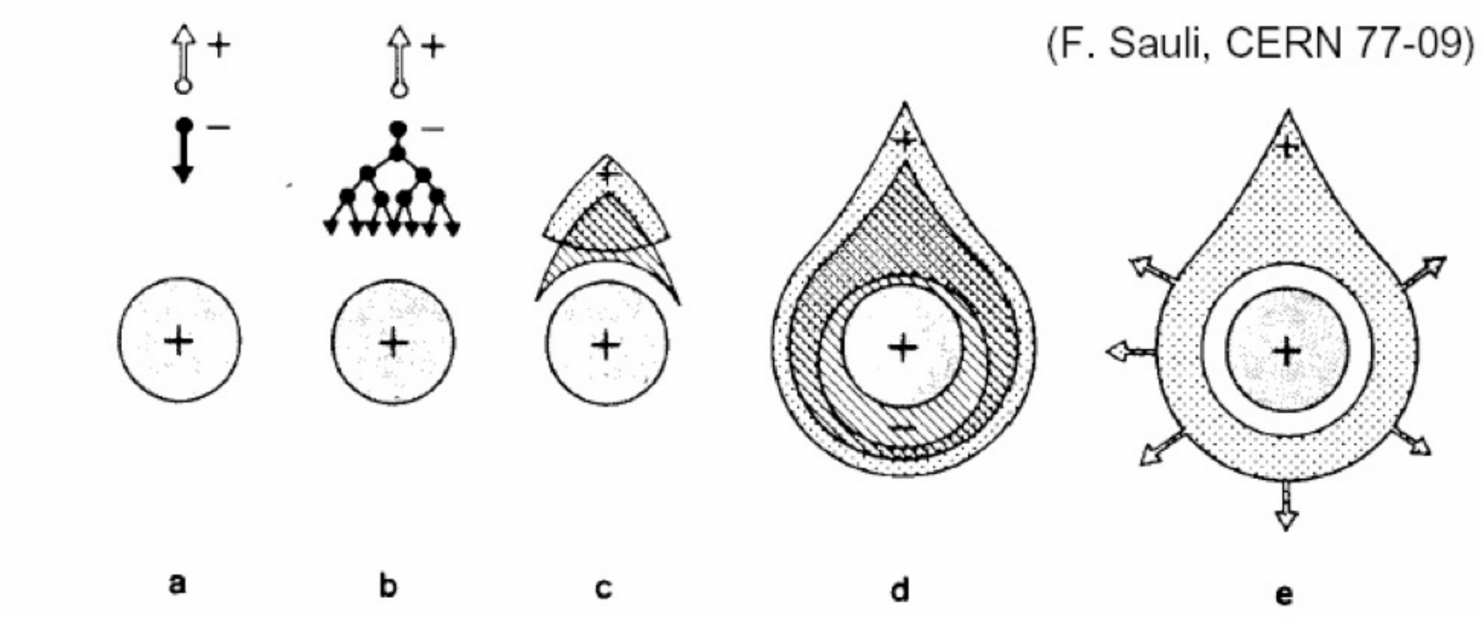
Amplification

- It is essential to amplify the q tens to q hundreds of electrons thus obtained

- The electrons drift towards the central wire under the effect of the electric field

- Near the wire (a few radii from the wire), important acceleration⇒ionization by shock, and the process is self-sustaining

- Time scale of the amplification: a few ns



Simulated avalanches

Fig. 5 Two dimensional display of a simulated drift process of one electron from starting point to anode wire surface.

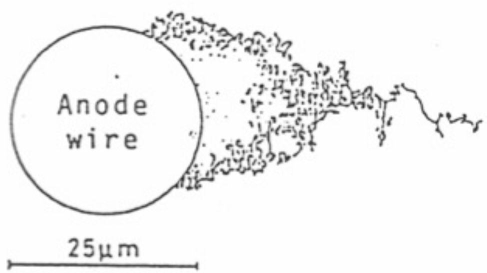


Fig. 6 Two dimensional display of a simulated electron avalanche.

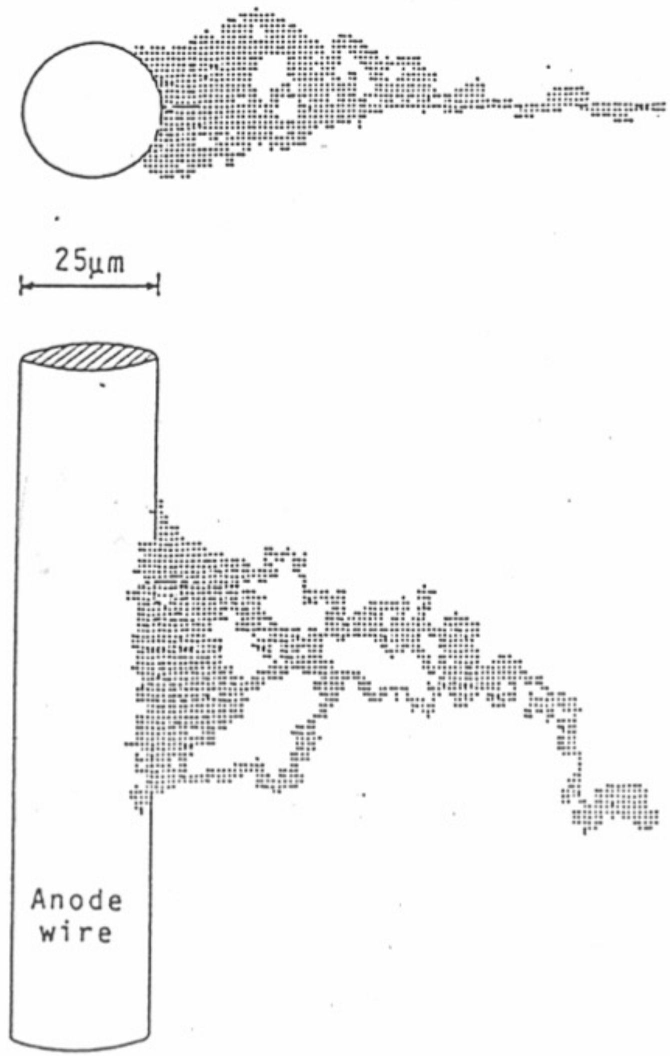


Fig. 7 Two dimensional displays of a simulated electron avalanche. Shading shows the density of electrons in the avalanche.

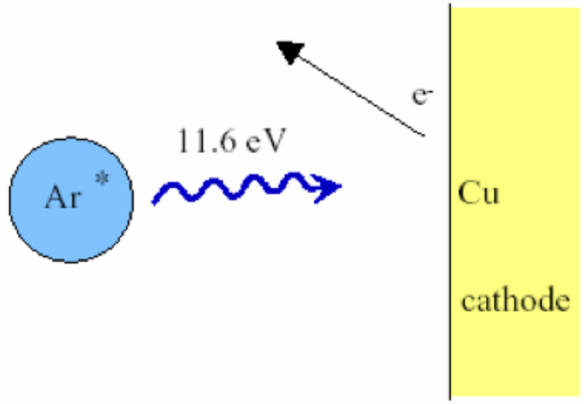
Choice of the gas

- We need gases in which the energy will be dissipated mainly by ionization
⇒ rare gases, which do not have vibrational or rotational states

- Counterpart: an excited atom has a high probability to de-excite by emission of UV photons (11.6 eV for Argon)

- These photons have a high probability of tearing off an electron in the surrounding medium (walls of the detector)

- The detector risks being in permanent avalanche.



Gas : quenching

<u>Addition of a 'quencher' gas:</u>

- Polyatomic gas, having vibrational and rotational states, on which the energy of the UV photons can be distributed, by collision and dissociation.

- Examples of quenchers often used: methane, isobutane, ethanol.

- « Magic gas »: 70% Ar, isobutane 29.6%, Freon 0.4% . Allows high gains.

- Many mixtures have been tested... See for example F. Sauli, "Principles of operation of multiwire proportional chambers", internal note CERN 77-09

Slow down

Migration and collection of charges

Displacement of charges (electrons and ions) by EM forces

Recombination

$$Ne^+ + e^- \rightarrow Ne + \gamma(h\nu)$$

Frequency of collisions depends on the concentration of charges along the trajectory

Charge transfer

- Between ions and molecules in the medium :

$$A^+ + C2H5OH \rightarrow A + C2H5OH^+$$

- Attachment of an electron to atoms or molecules:

$$e^- + O_2 \rightarrow O + O^-$$

(Electrophilic gases: O_2, H_2O, CCl_4)

Quencher

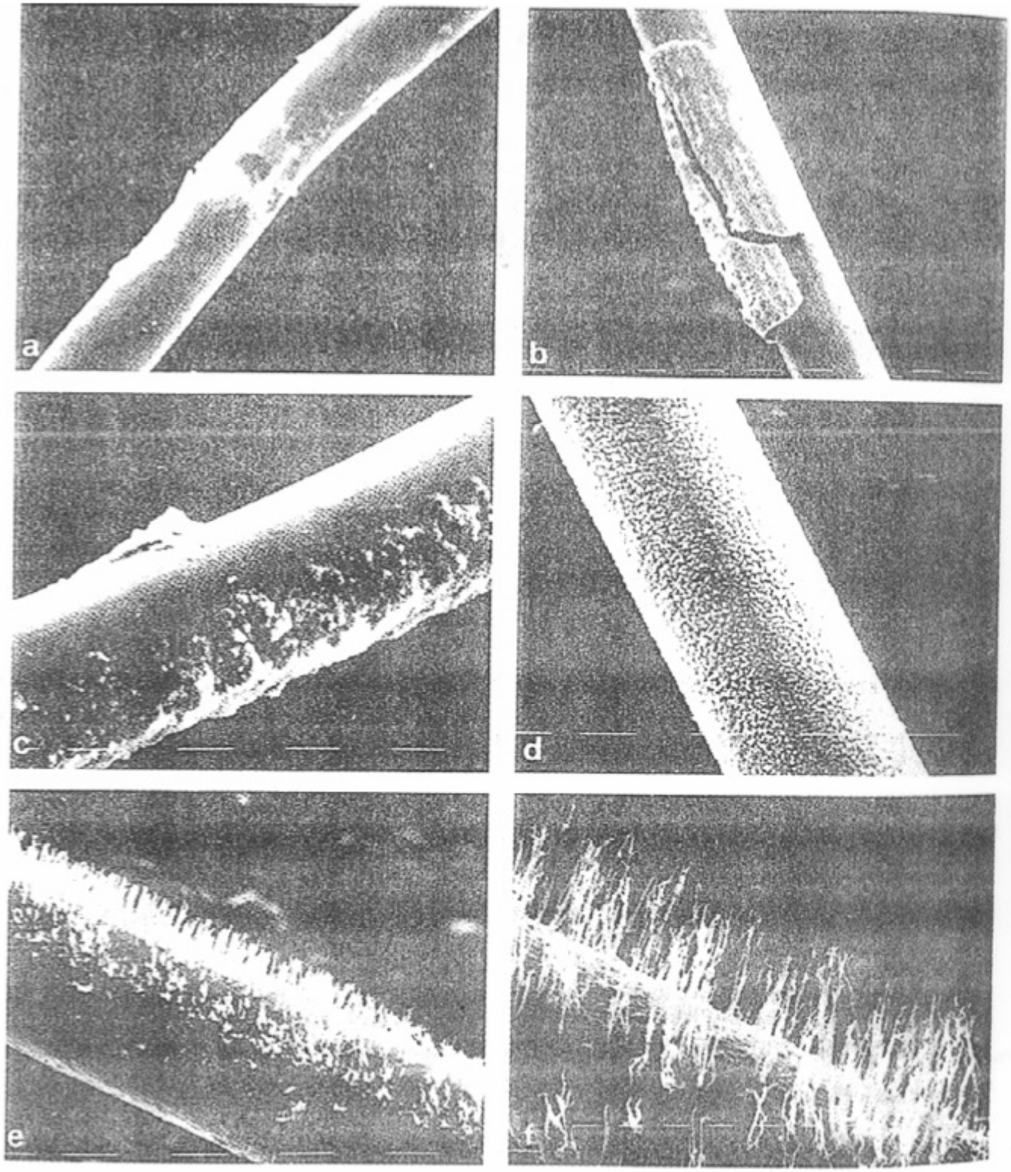


Fig. 4.31. Deposits on anode wires: (a) – $Ar + C_2H_6$; (b) – $Ar + C_2H_6$ + methylal; (c) – $Ar + CO_2$; (d) – perspex chamber; (e, f) – chambers with G10 fiber-glass and a cold trap (Adam 1983)

<u>Disadvantage of 'quencher':</u>

Quencher "debris" settles and polymerizes on the wire.

The deposits are generally very insulating. They end up disturbing the normal operation of the detector.

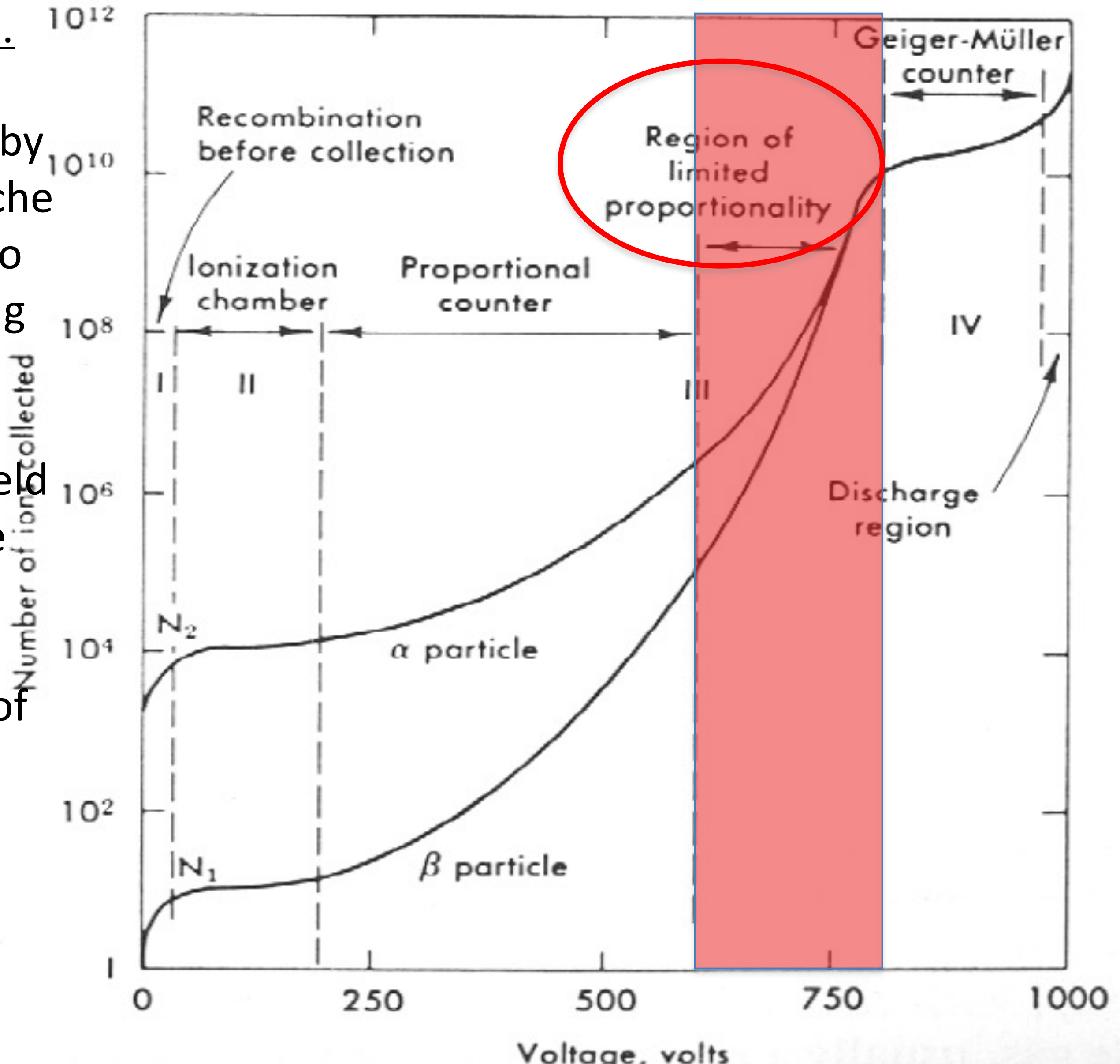
Working Mode

Zone IV: proportional limit.

- The charge produced by the Townsend avalanche is important enough to propagate a little along the anode wire

- In addition, electric field modified by the space charge created

→ end of proportionality of the signal with the energy deposited by the particle



Working Mode

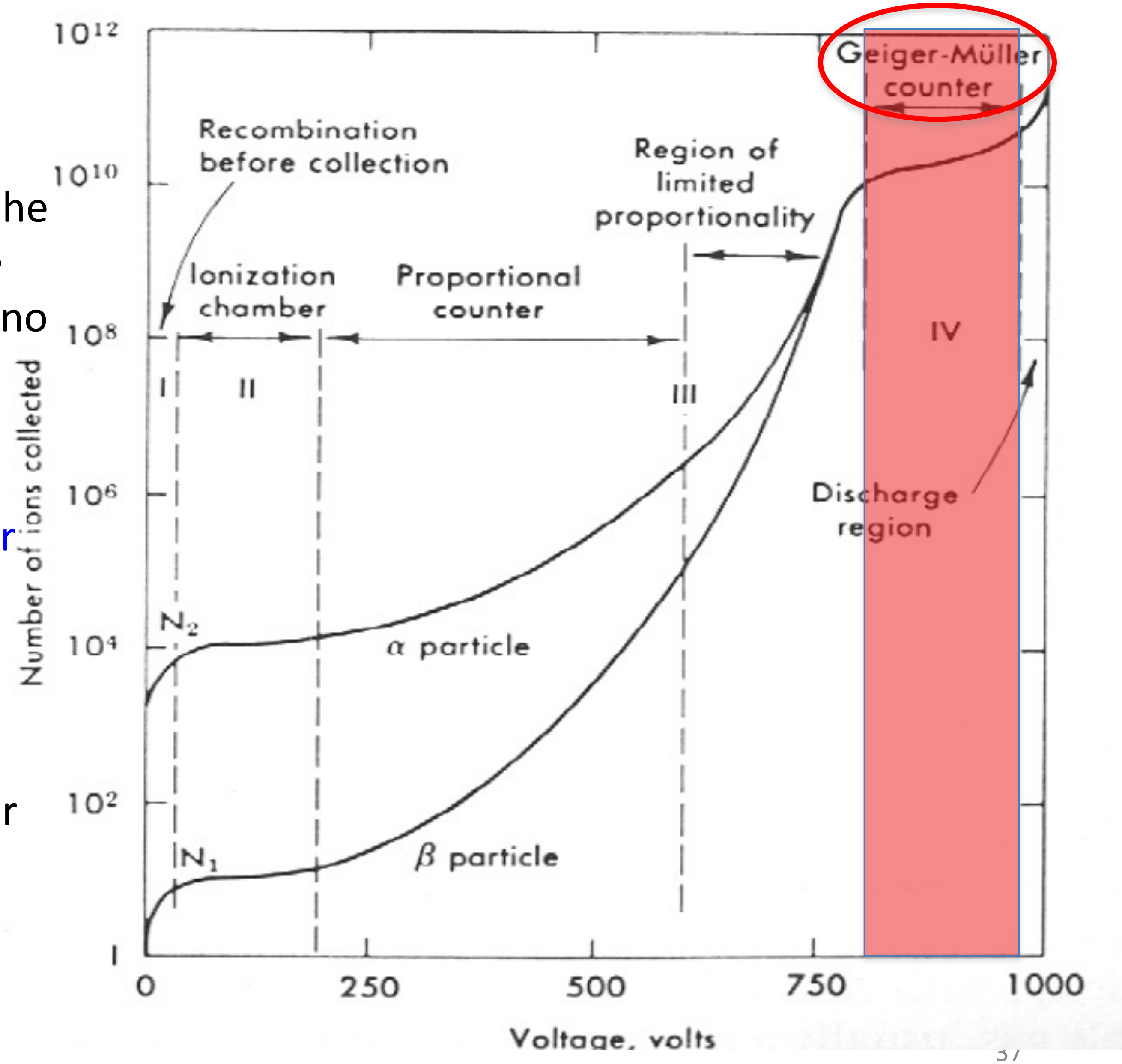
<u>Zone V: Geiger-Müller counter</u>

-The electric discharge propagates all along the anode wire, up to the ends of the detector, no proportionality at all

-Functioning of the Geiger-Müller counter

- The dead time is quite important, about 200 microseconds

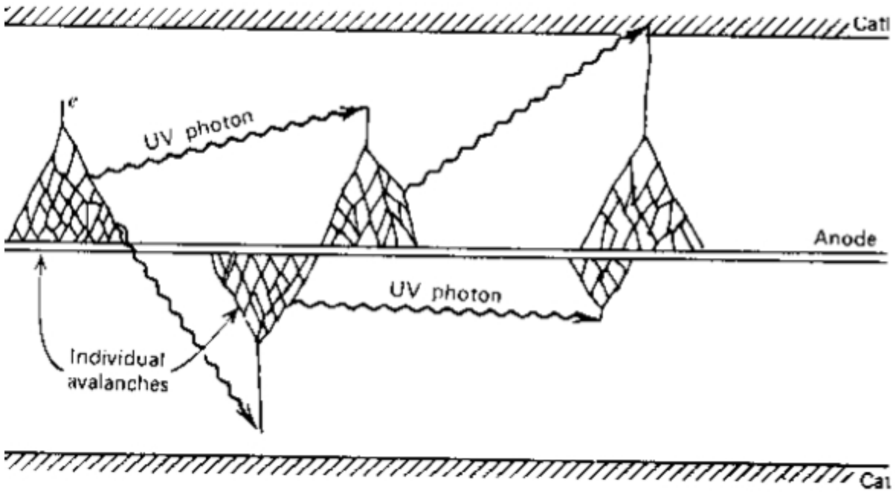
-Saturation of the detector from a few hundred counts per second

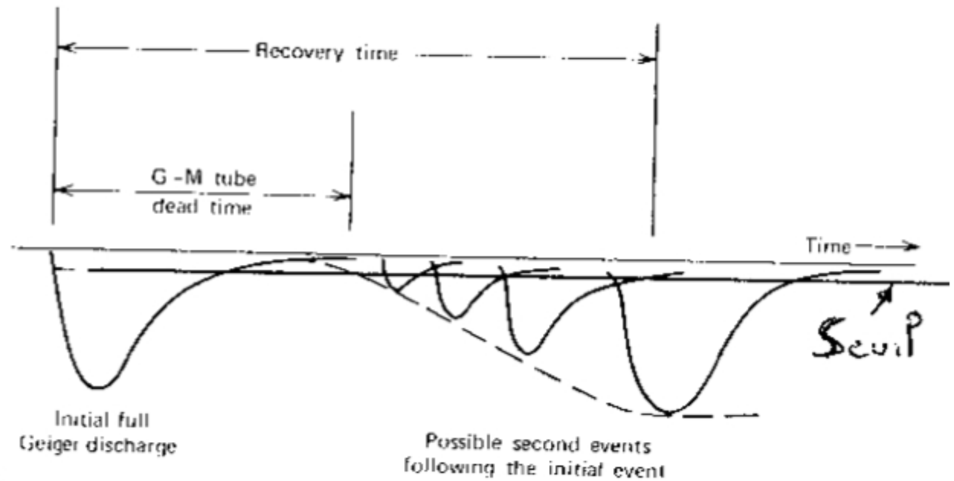


Geiger Muller

An Electrical Method of Counting the Number of Alpha Particles from Radioactive Substances

(Geiger Muller) 1908





development of the avalanche *recovery time of the dead time*

The problem is no longer to cause the avalanche, but to stop it!

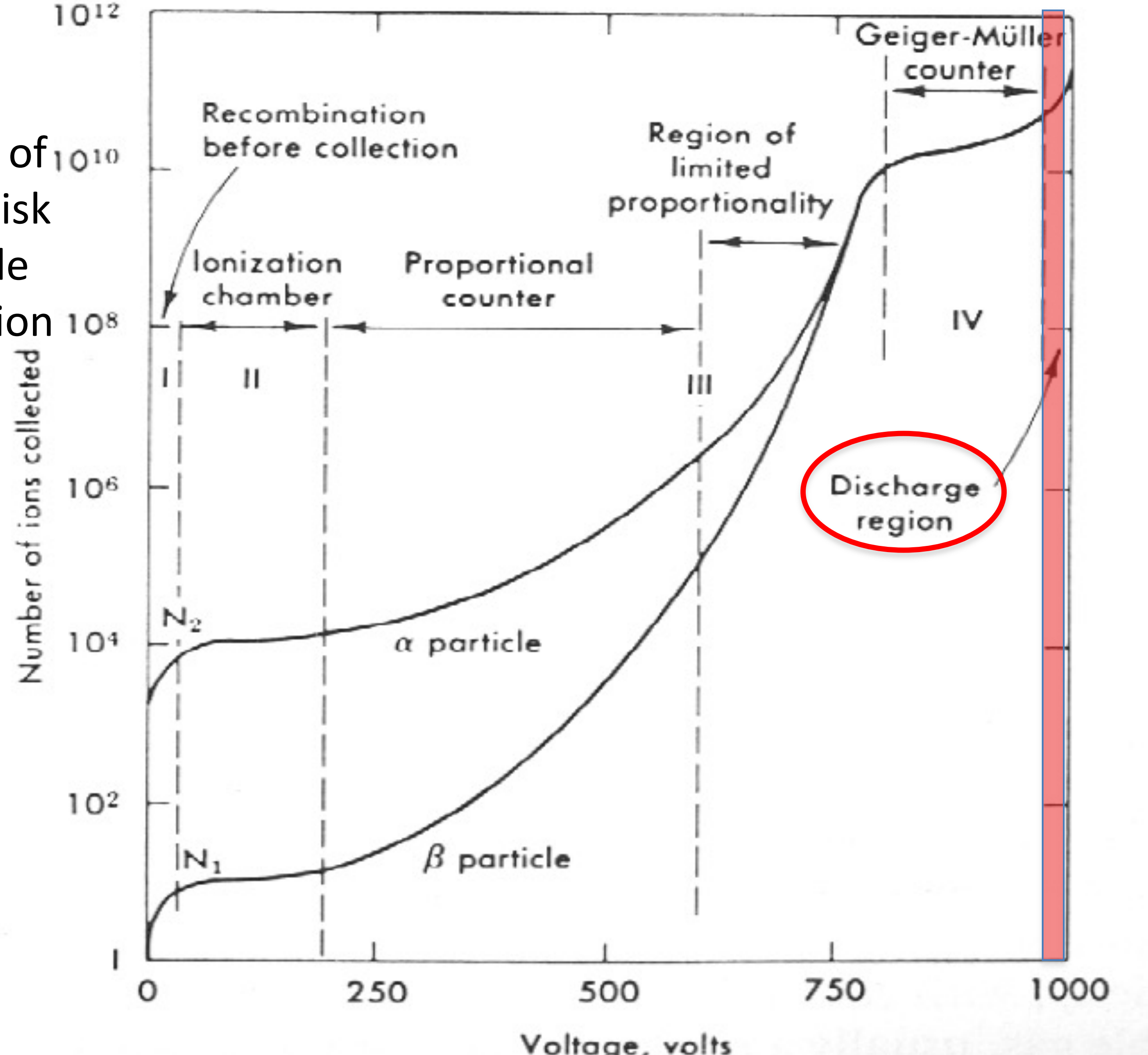
⇒ Addition of a quencher gas is essential (a few % of the main filling gas)

Working Mode

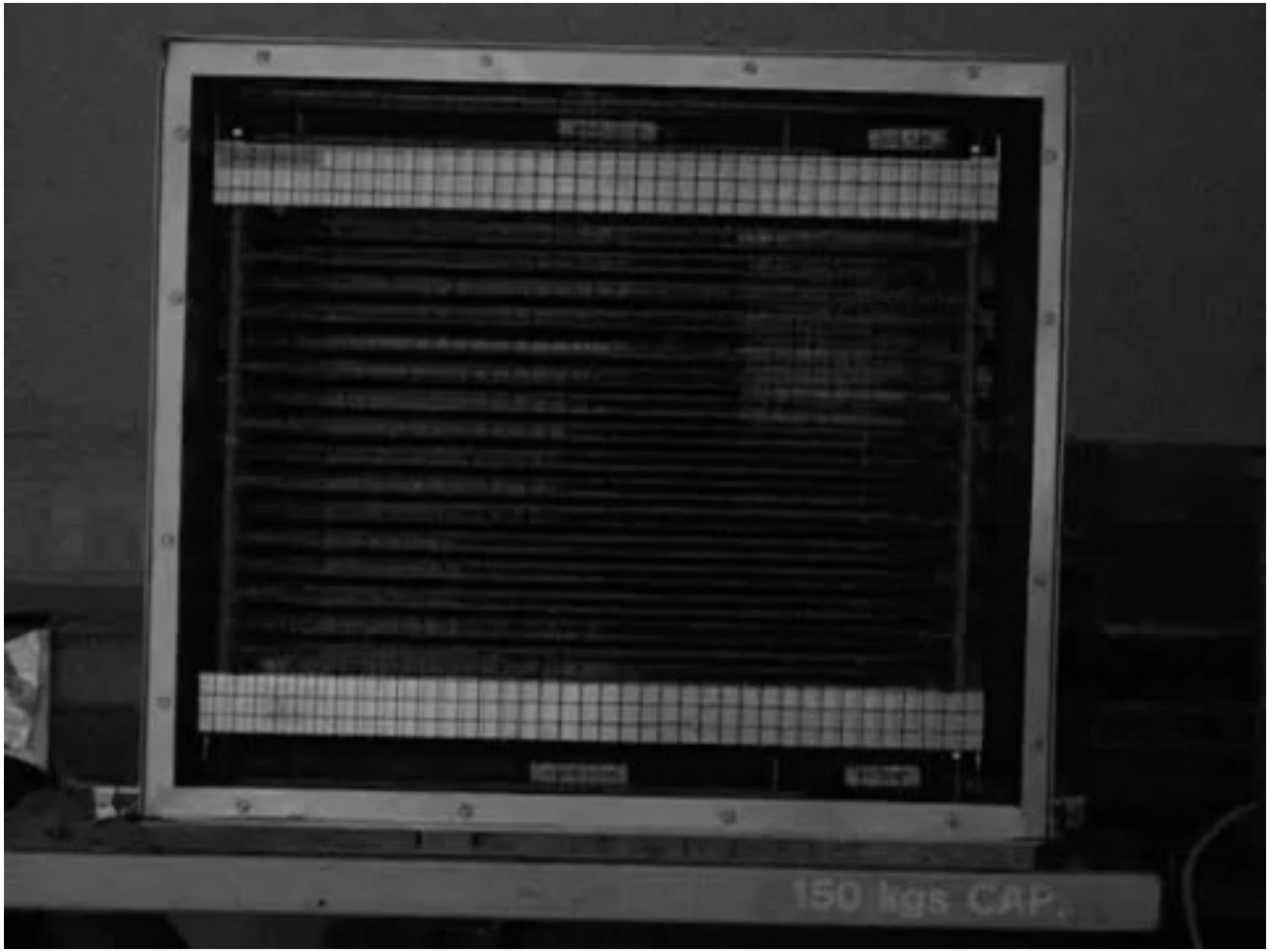
Beyond that, a succession of autonomous discharges (risk of destruction of the anode wire) and possible formation of discharge sparks

operation of the spark chamber

It is then necessary to use large diameter anodes or parallel flat electrodes



Sparkling Chamber



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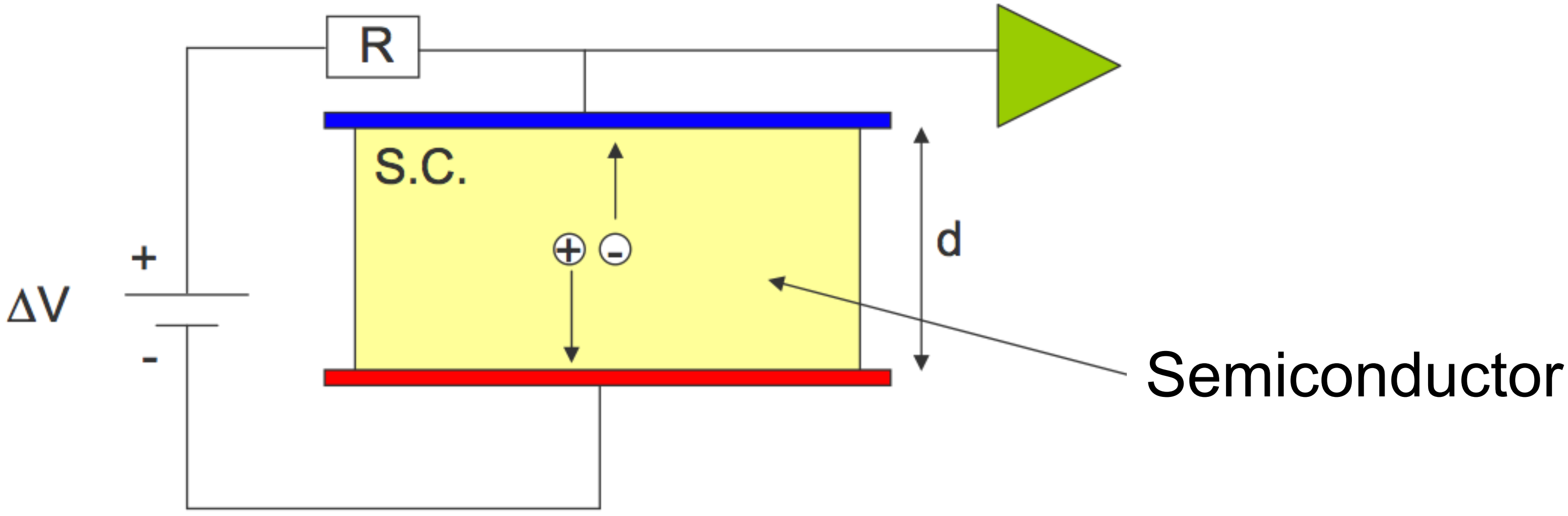
Ionisation in solid

Appeared in the 60's
High evolution potential but manufacturing and associated elements are expensive

<u>Semiconductors are solid ionization chambers</u>

The passage of an ionizing particle induces the creation of an e- / hole pair

The charges are collected by an electric field



Ionisation in solid

The principle is identical to that of detectors based on ionization in gases but here creation of electron-hole pair instead of electron-ion pair

Advantages:
1/ Energy required to create a pair 10 times smaller than in a gas ⇒ 10 times more pairs created for the same energy deposit
⇒ lower relative statistical fluctuation
⇒ much better energy resolution
2/ Denser solids than gases
⇒ much greater stopping power
⇒ compact detectors
3/ Fast detectors

Disadvantages:
1/ Semi-conductors = crystalline nature ⇒ sensitive to radiation
2/ Expensive

Main characteristics Si and Ge

	Si	Ge
Z	14	32
A	28,1	72,6
ρ [g/cm^3]	2,33	5,32
Gap (300 K) [eV]	1,1	0,7
Gap (0 K) [eV]	1,21	0,785
Mobility e$^-$ [cm^2/Vs]	1350	3900
Mobility hole [cm^2/Vs]	480	1900
E_{moy}(Pair creation)	3,62 eV	2,96 eV

Silicon junction: advantage = no cooling required
⇒ very used for the detection of charged particles in particle physics (cf. vertex detector)
Germanium junction : Advantage = high Z ⇒ important photoelectric effect ⇒ spectroscopy γ
Disadvantage = requires cooling

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Light emission

Principle:

- Based on excitation processes
- Interaction of the incident particle

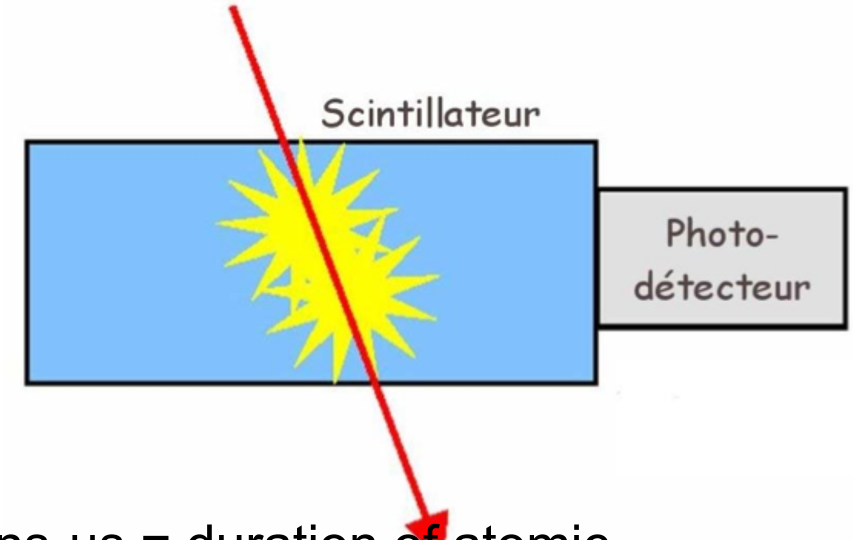
→ Creation of phonons, e-holes, excitons (bound e-hole pairs)

- Followed by scintillation (emission of photons or radiation) by indirect recombination of charges or excitons

Detection systems composed of :

- Recovery of the energy of the incident particle in the form of light: scintillator, Cerenkov detector, transition radiation detector
- Particle detector reading :
  - geometrical adaptation = light guide
  - production of an electronic signal = transformation of the light into an electronic signal : photo-multiplier, photo-diode

Light emission



Scintillators

Convert ionization into visible photons

Sensor = radio-luminescent material, i.e. that produces photons along the path of a charged particle

Distinguish, in the luminescence :

- fluorescence or immediate emission (ns-μs = duration of atomic transitions), independent of temperature
- the phosphorescence or delayed emission (μs-mn = metastable excited state), dependent on temperature

Origin of photon emission:

- the crystal lattice ⇒ inorganic scintillator
- molecules (delocalized electrons) ⇒ organic scintillator
- atoms (atomic electrons) ⇒ gas scintillator

Charactéristics

- scintillation efficiency = $h\nu/W_{lumi}$
with $h\nu$ the average energy of the detector spectrum and W_{lumi} the amount of energy needed to create a photon:
25 eV for NaI, 100 eV for plastic, 300 eV for BGO

- the transparency to its own fluorescence
The absorption spectrum must be as little different as possible from the emission spectrum (Stockes shift)

- the scintillation efficiency = ratio between the absorbed energy and the emitted photon energy
~12% for NaI (40000 photons of 3 eV emitted per MeV absorbed)

Organic scitillators

Aromatic compounds (benzene cycle) solid or liquid, plastic

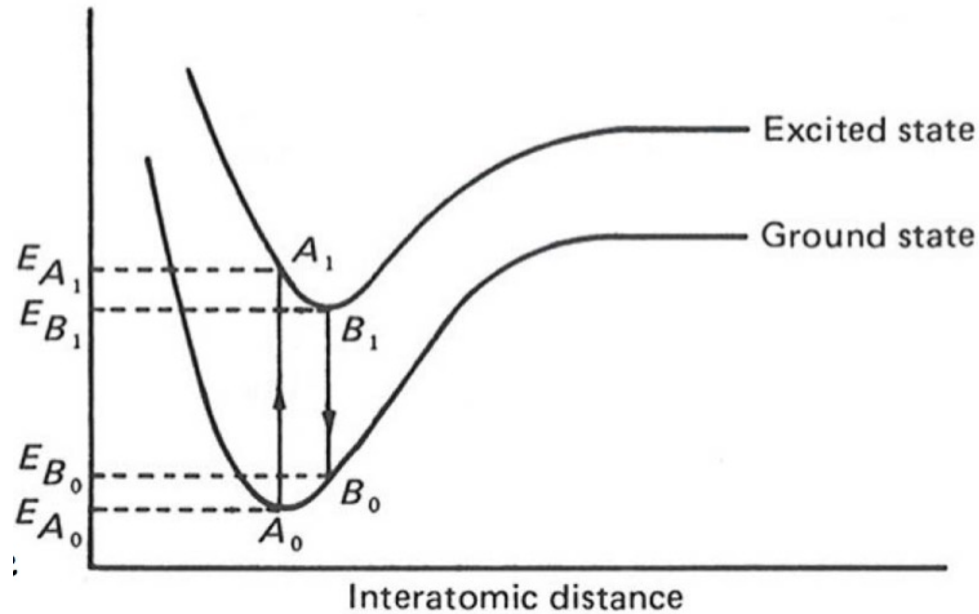
<u>Characteristics :</u>

- Light emission by molecular excitations (delocalized electrons)

- Fast scintillators (< 10 ns)

- Response to electrons linear as a function of the energy
→good electron spectrometer

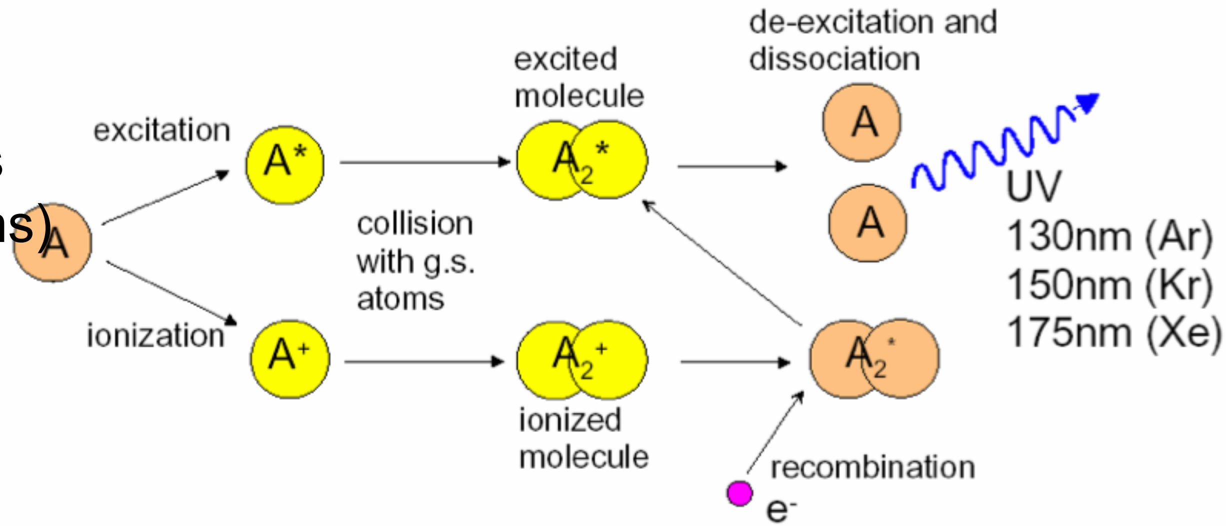
- For photons: Compton effect only
⇒ no accurate energy measurement possible



Noble liquid (Inorganic scitillators)

1b. Liquid noble gases (LAr, LXe, LKr)

<u>Characteristics:</u>
- Individually excited atoms and fast de-excitation (< 1ns)
⇒ very fast response



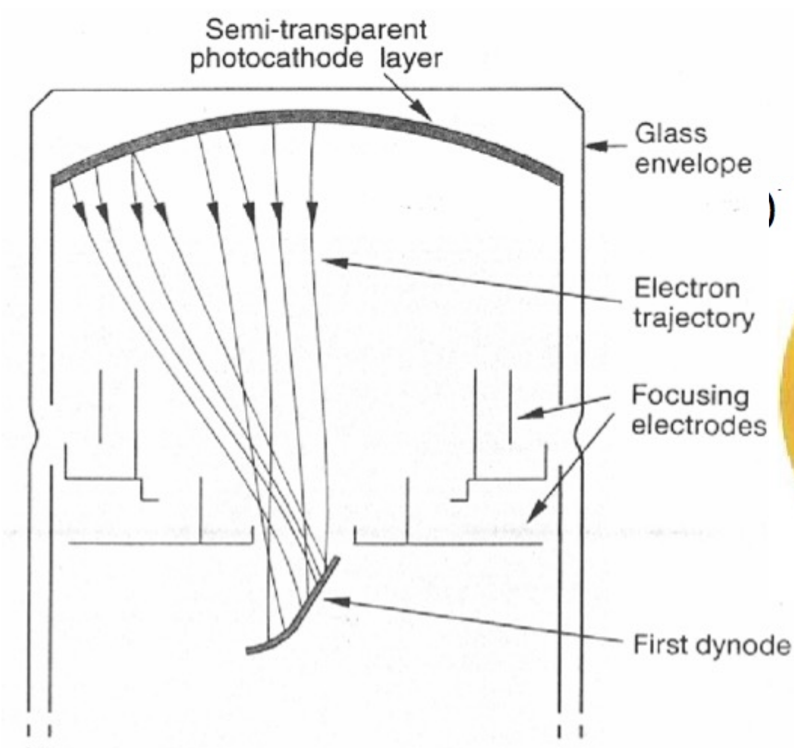
- Light emission in the ultraviolet and photo-multipliers ineffective in this region ⇒ need to shift this light to the visible with a converter (UV absorbing product emitting in the blue-green)

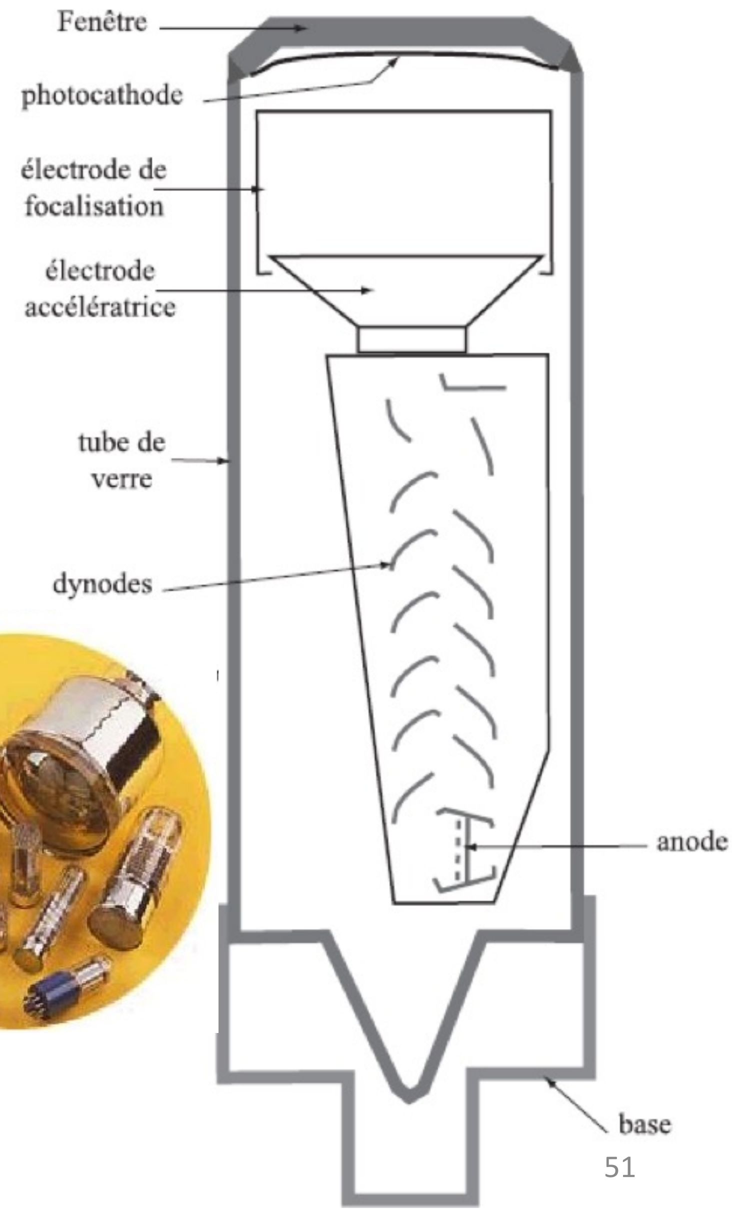
- Amount of light still ∝ energy absorbed by the gas: no saturation effect (≠ liquid or solid scintillators) ⇒ useful for spectrometry of highly ionizing particles (α, PF)

Photomultipliers

Vacuum tube :

- an input photocathode, which converts photons into electrons by photoelectric effect (photoelectrons) - Energy of photoelectrons: E = hv - Φ where Φ is the output work
- A system (ddp of ~ 200 V) to direct the photoelectrons



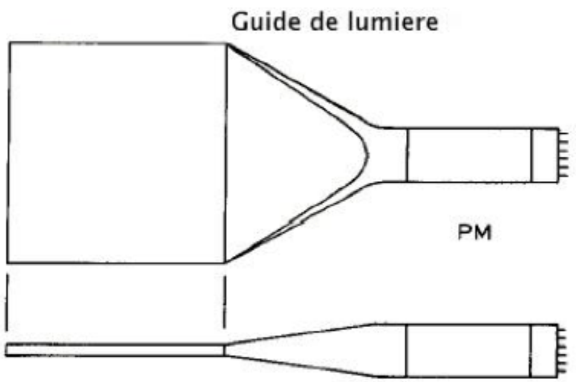


Waveguide

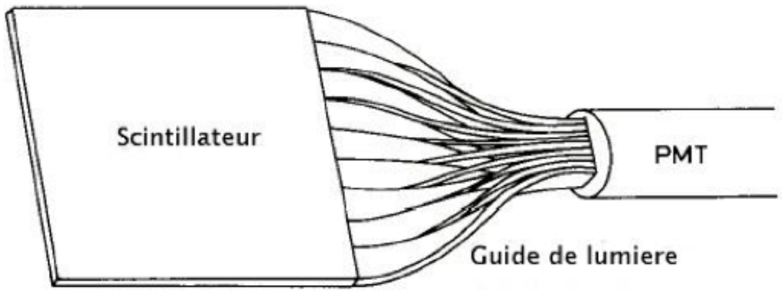
Used to couple the particle detector (scintillator, Cerenkov...) and the light detector (PM, photodiode)

Often necessary when the light emitting detector cannot be glued directly to the photodetector: incompatible geometries, too much space around the detector to install the photodetector...

Can take different forms :



fish tail



adiabatic

Overview

I (Long) Introduction

II General Characteristics

II Main detection techinics

1. Ionisation in gas
2. Ionisation in solid
3. Light emission

III Somes detection technics

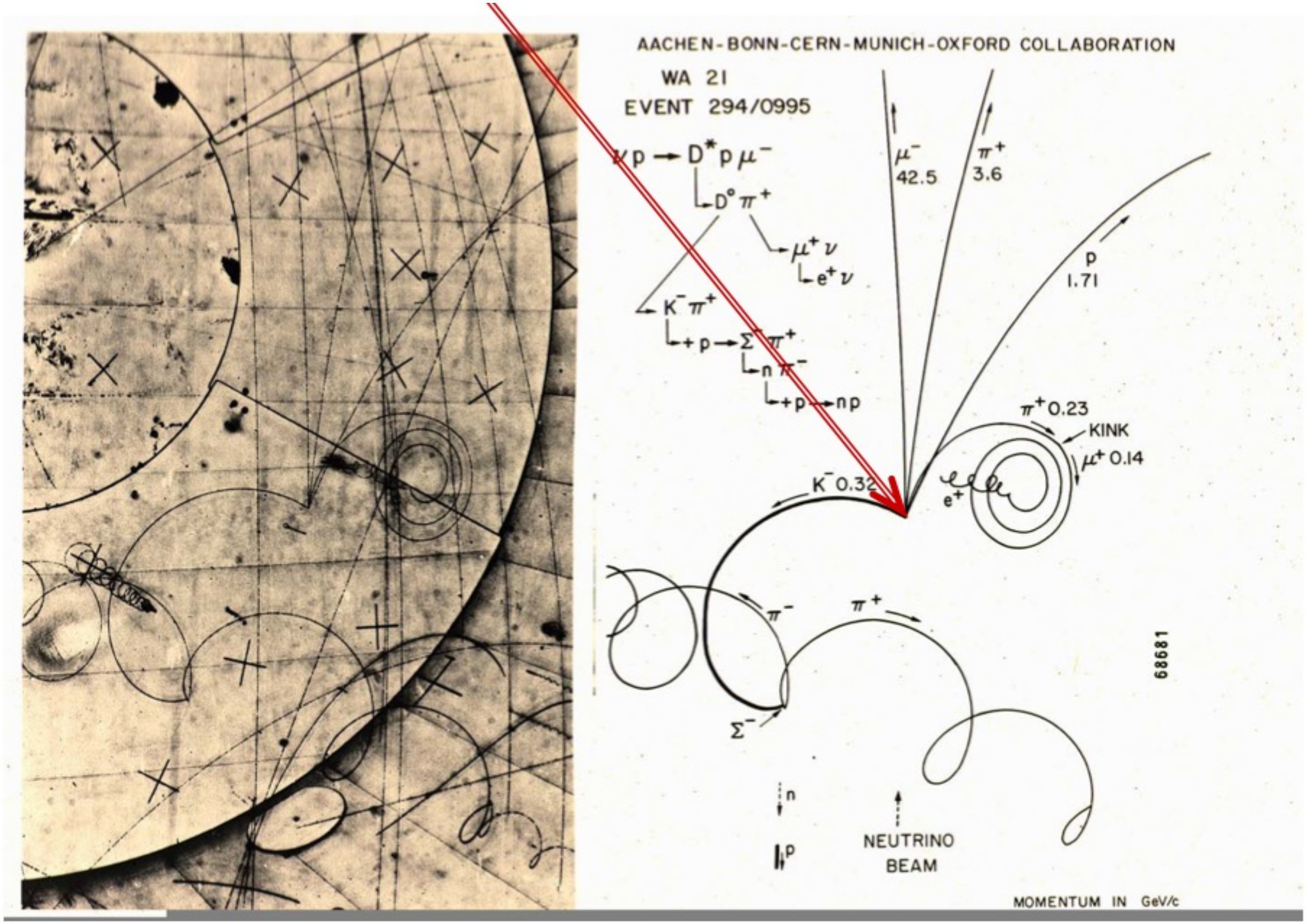
1. Traces detector and momentum measurement
2. Electromagnetic / Hadronic calorimeter
3. Particle Identification

IV Example of full detectors

1. CMS (LHC)
2. HESS (gamma ray in astroparticle)
3. XENON (Direct Dark matter detection) – liquid xenon application

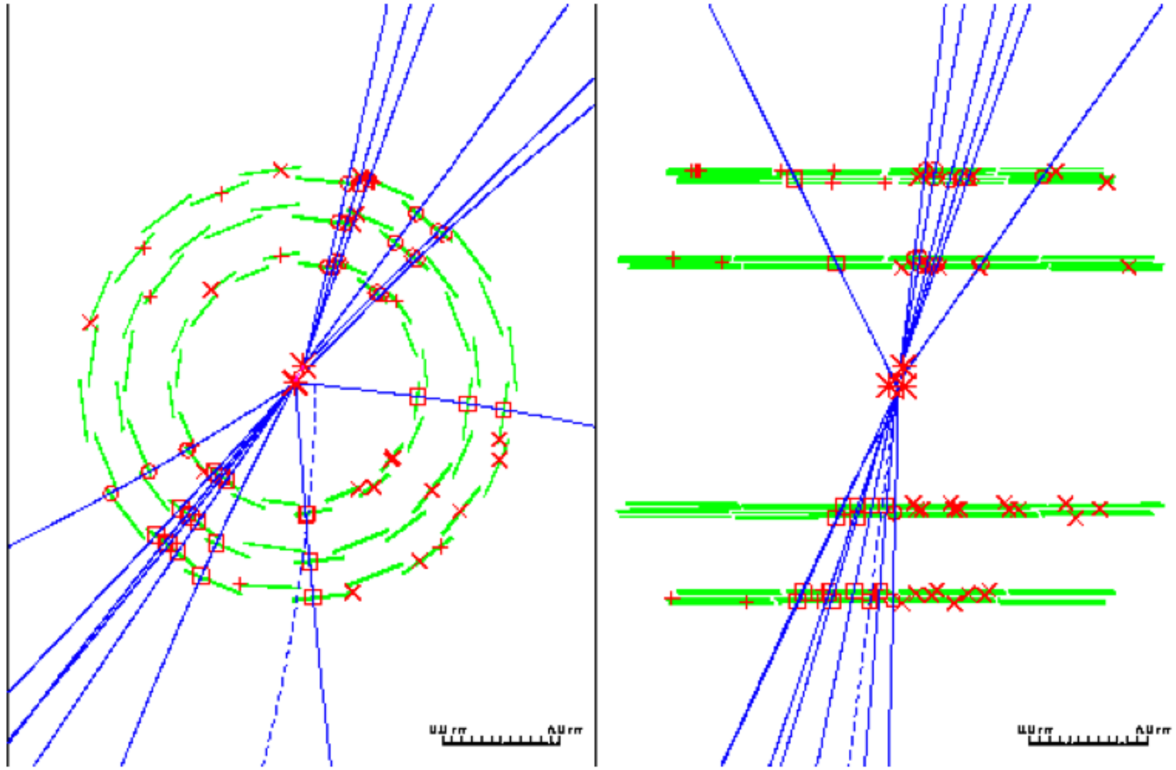
Tracks & Vertex

These silicon detectors are used close to the point of interaction, in order to know very precisely the origin of the particles: point of the collision (primary vertex) or further away (secondary vertex) ⇒ vertex detectors



Silicons

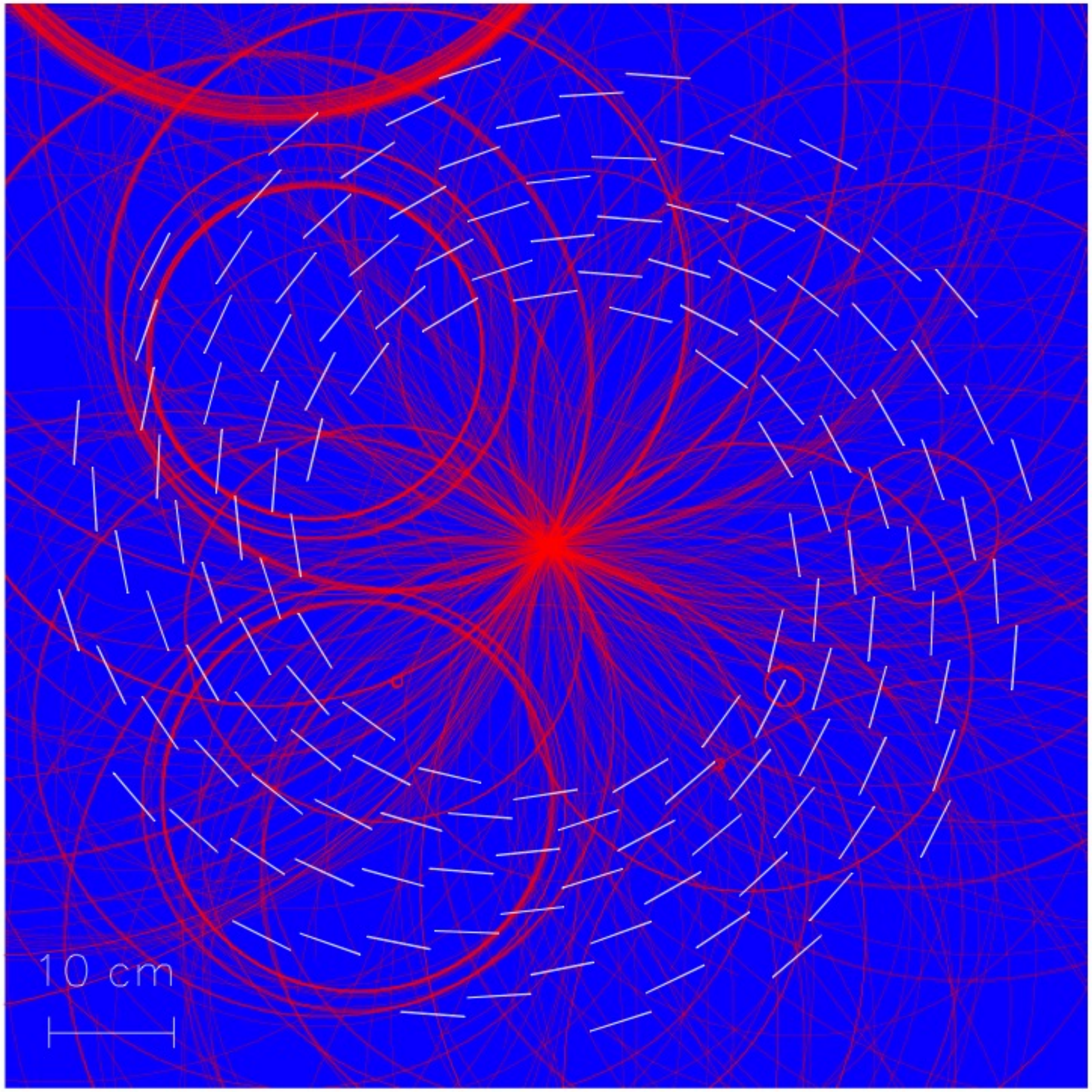
One observes after reading such a detector :



Disadvantage of these detectors: undergoes great damage due to the radiations

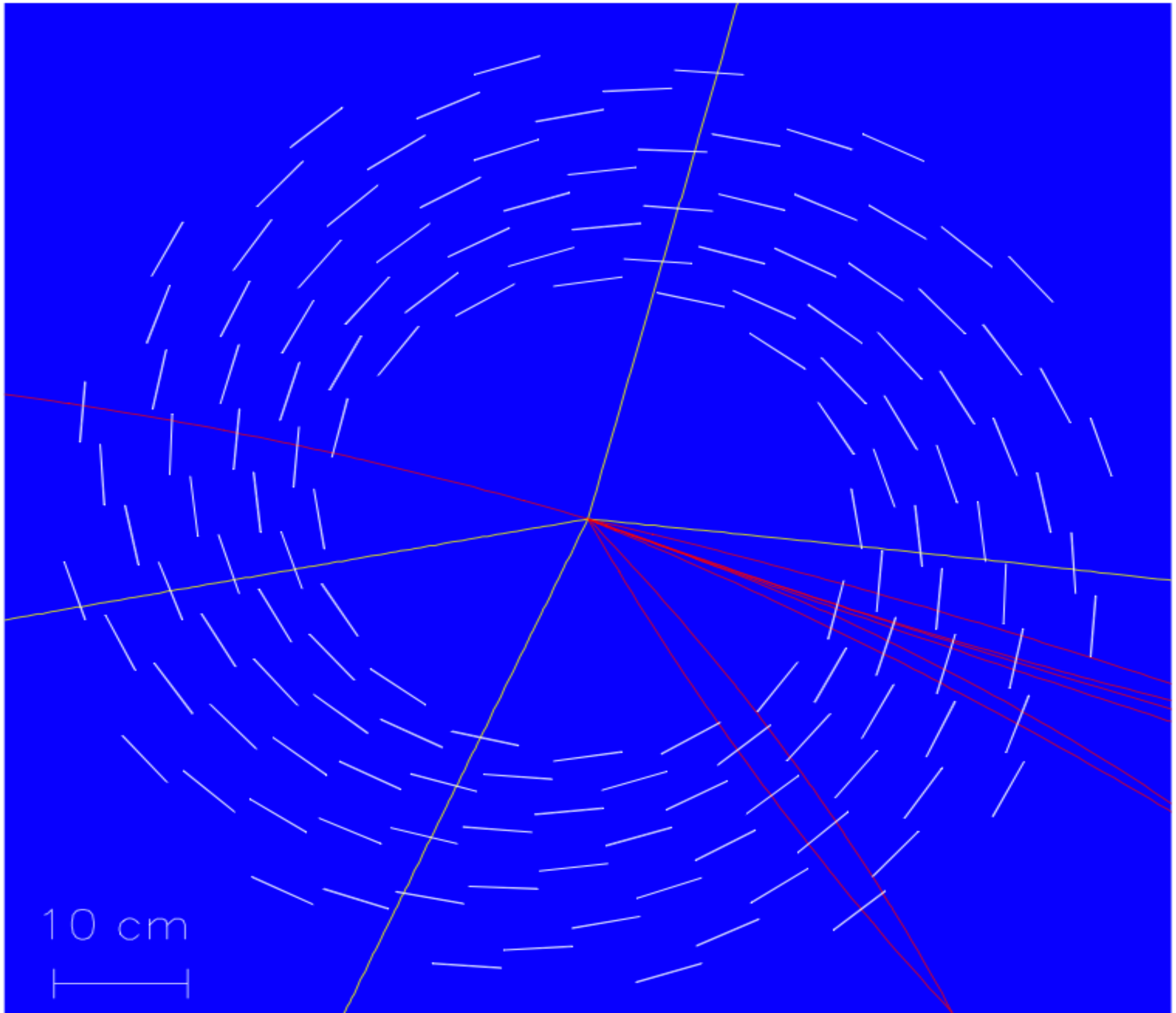
However, detectors close to the vacuum tube containing the beams of accelerated particles
⇒ Big risks for these detectors when the beams are lost
⇒ Detectors changed every 2-3 years in hadronic colliders

Momentum measurement

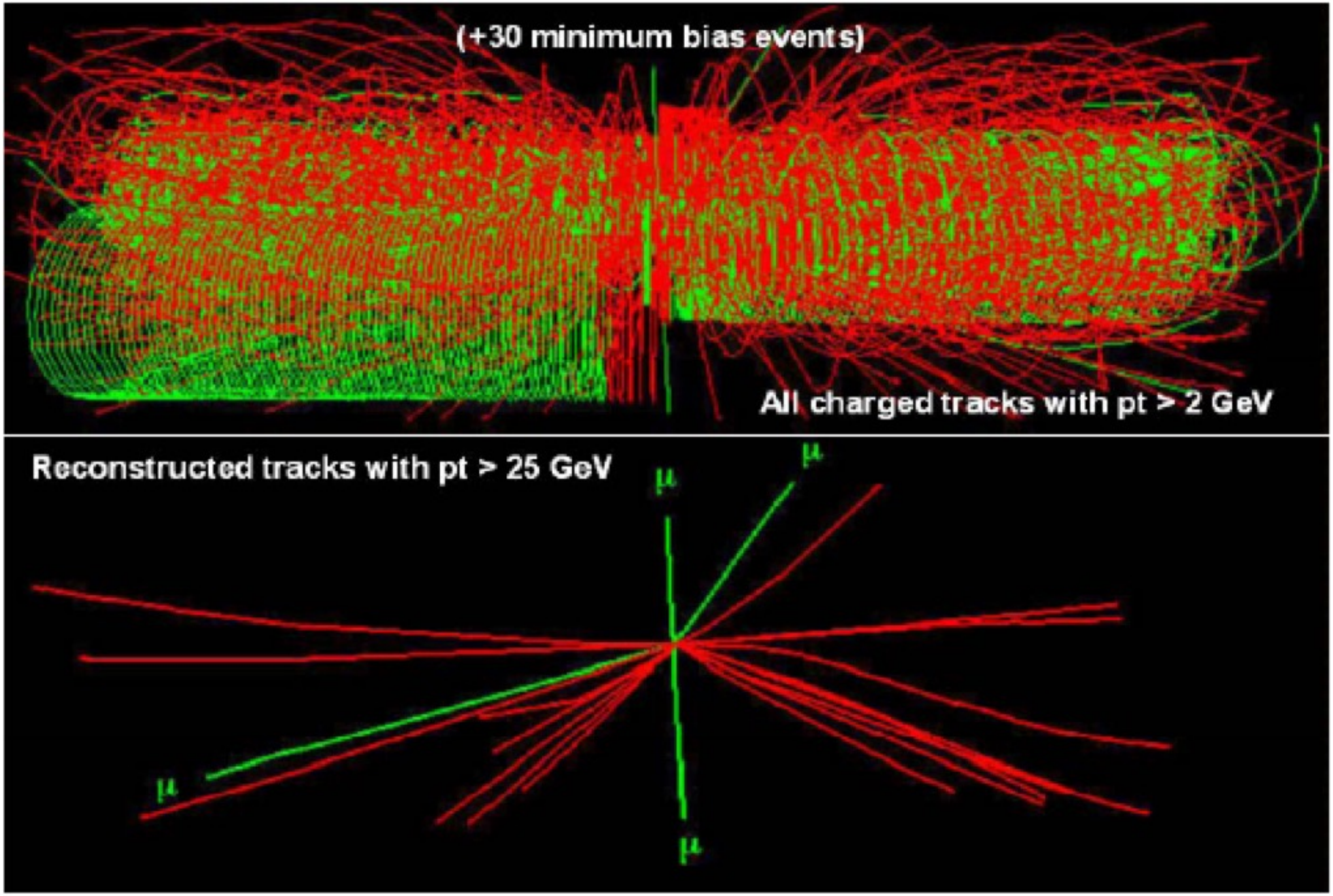


Momentum measurement

For $p_T > 2$ GeV



CMS Tracker



(+30 minimum bias events)
All charged tracks with pt > 2 GeV
Reconstructed tracks with pt > 25 GeV
μ
μ
μ
μ

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Electromagnetic calorimeter

The development of a shower when an e± or a γ enters an electromagnetic calorimeter comes from :

for Ee > 10 MeV

→ photon emission by bremsstrahlung of e±

→ some photons carry away an important part of the incident energy

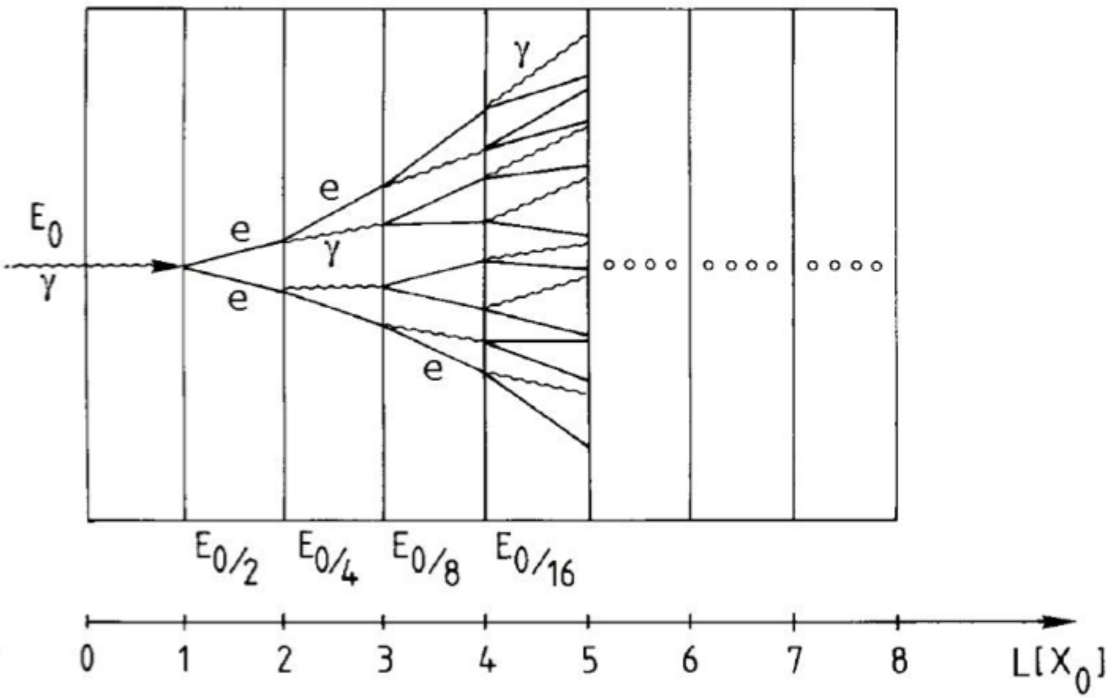
For Eγ > 10 MeV

→ conversion of photon into e+e- pair

The process continues as long as E≥Ecri :

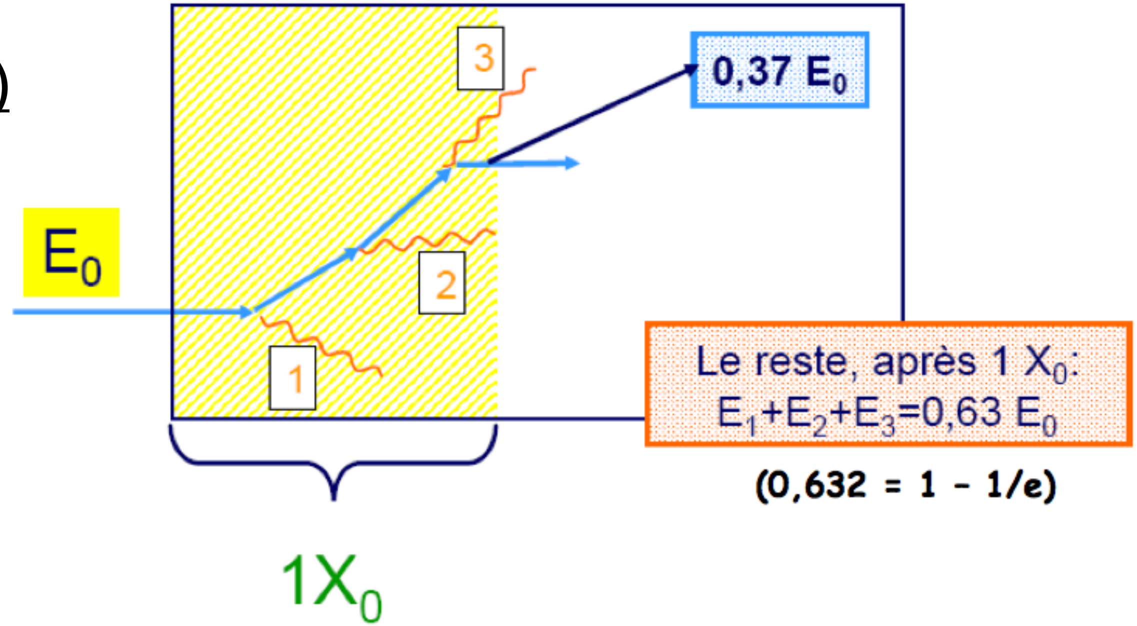
When E < Ecri

⇒ ionization, Compton and photoelectric effect



Electromagnetic calorimeter

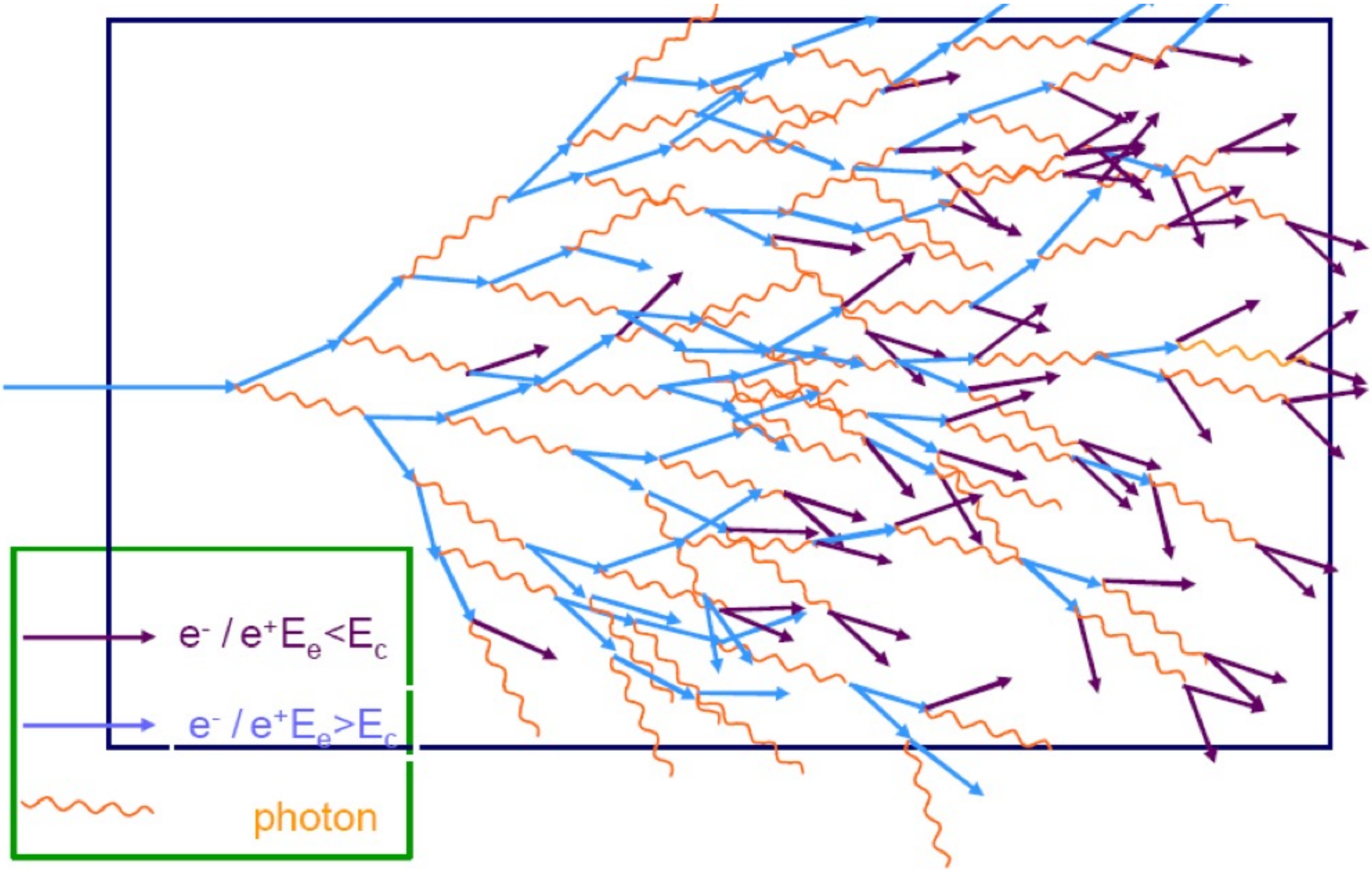
Radiation length (X_0)



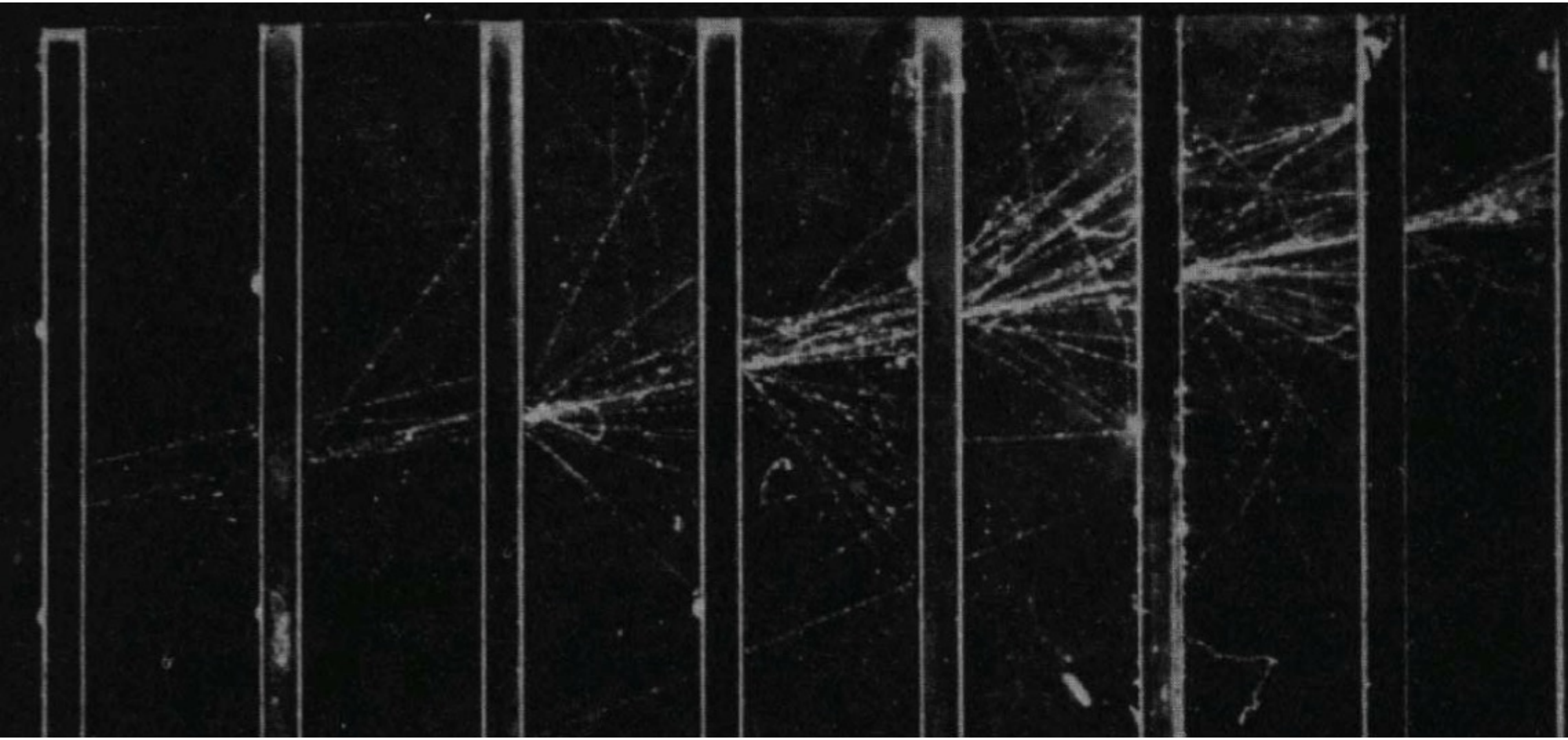
	Air	Eau	Al	LAr	Fe	Pb	$PbWO_4$
Z	-	-	13	18	26	82	-
X_0 (cm)	30420	36	8,9	14	1,76	0.56	0.89

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

EM shower



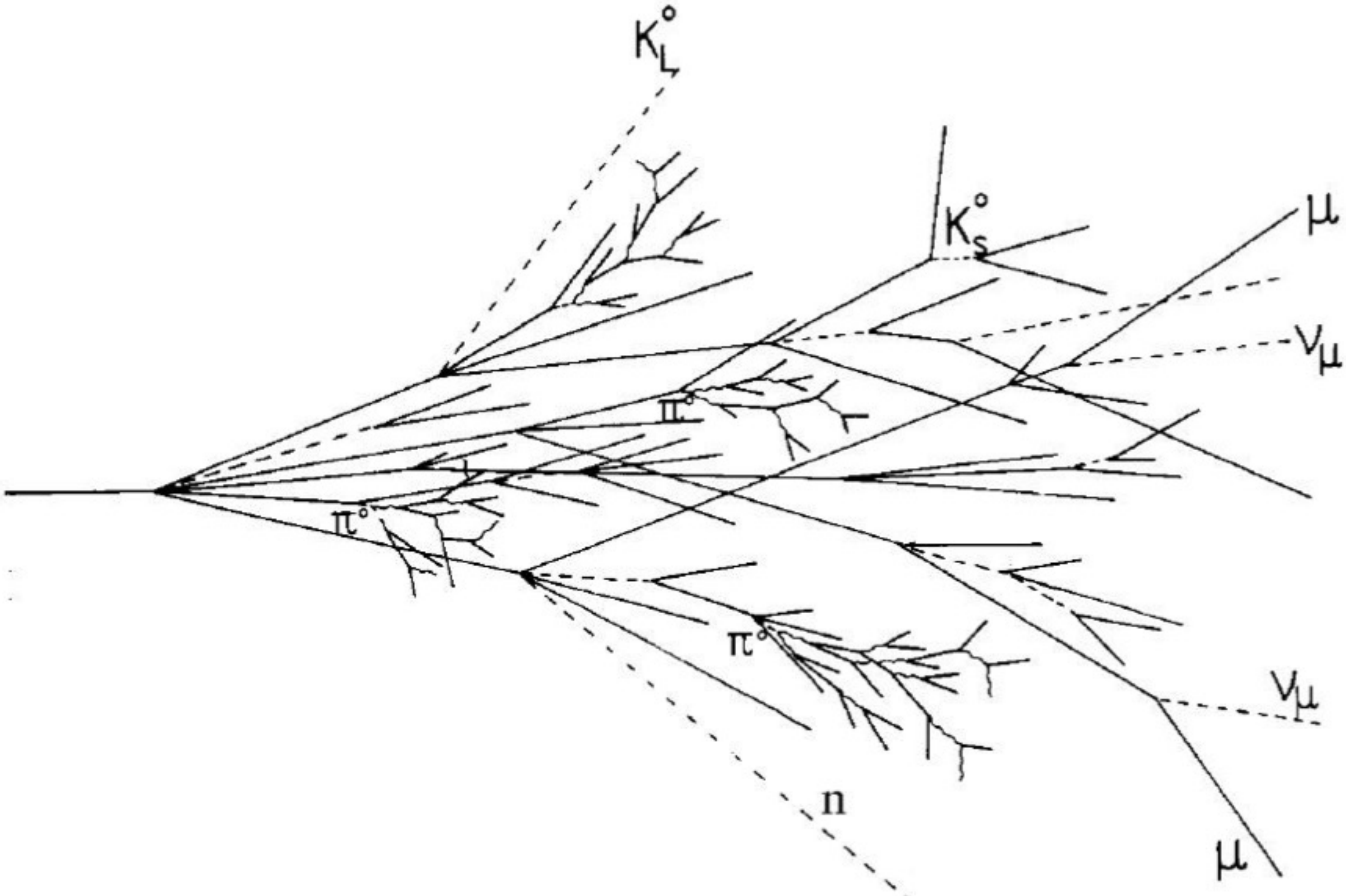
EM shower



Hadronic shower

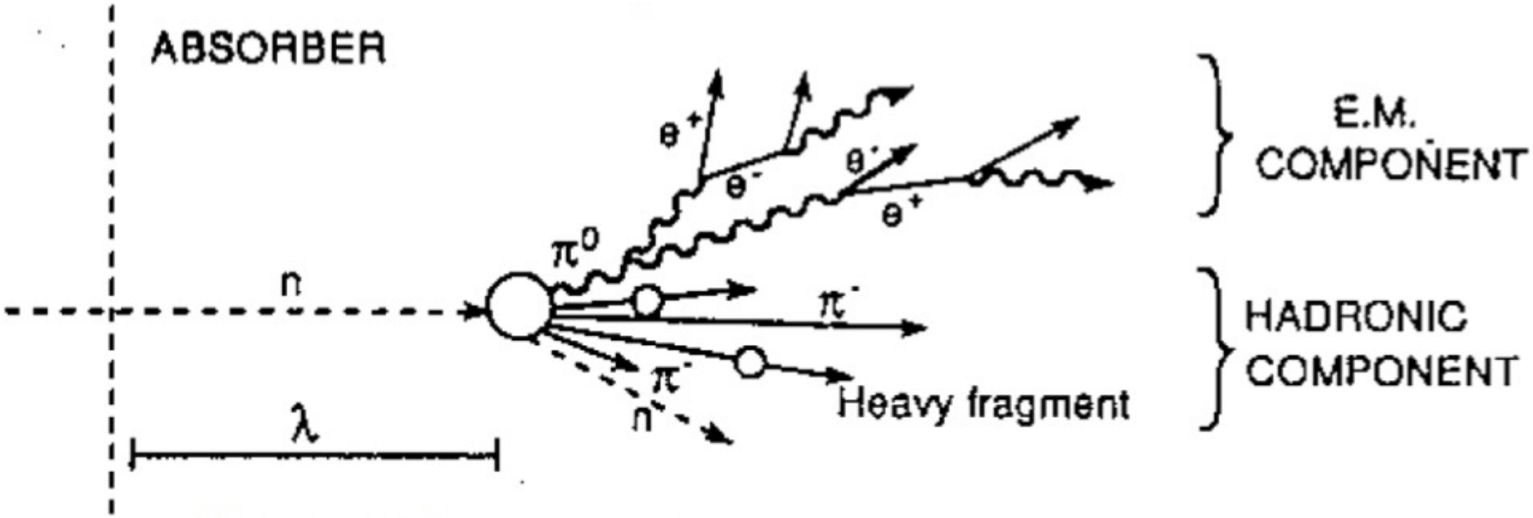
Hadrons made of quarks, which interact by strong and electromagnetic interactions.

Involves many processes
➔ More complex than the electromagnetic cascade



Hadronic shower

The incident hadron (here a neutron n) produces a cascade of secondary particles by strong and EM interactions:



hadronic component

Charged pion, protons, kaons,…
nucleus fragment
(binding energy)

Neutrons, neutrinos, γ, muons
→ Invisible energy

electromagnetic component (~30%)

Neutral pion -> 2γ
-> electromagnetic cascade

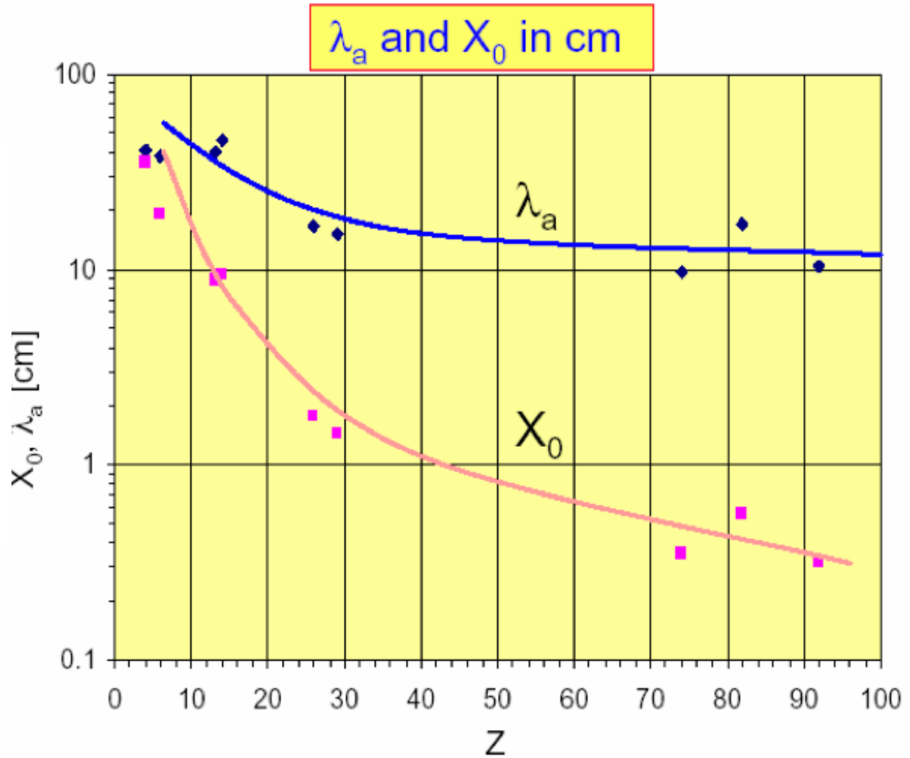
N(π) ~ ln(E-GeV) – 4,6
@100GeV N(π) = 18

Large energy fluctuations
→ Limited energy resolution

Nuclear interaction length (λ_a or λ_{int})

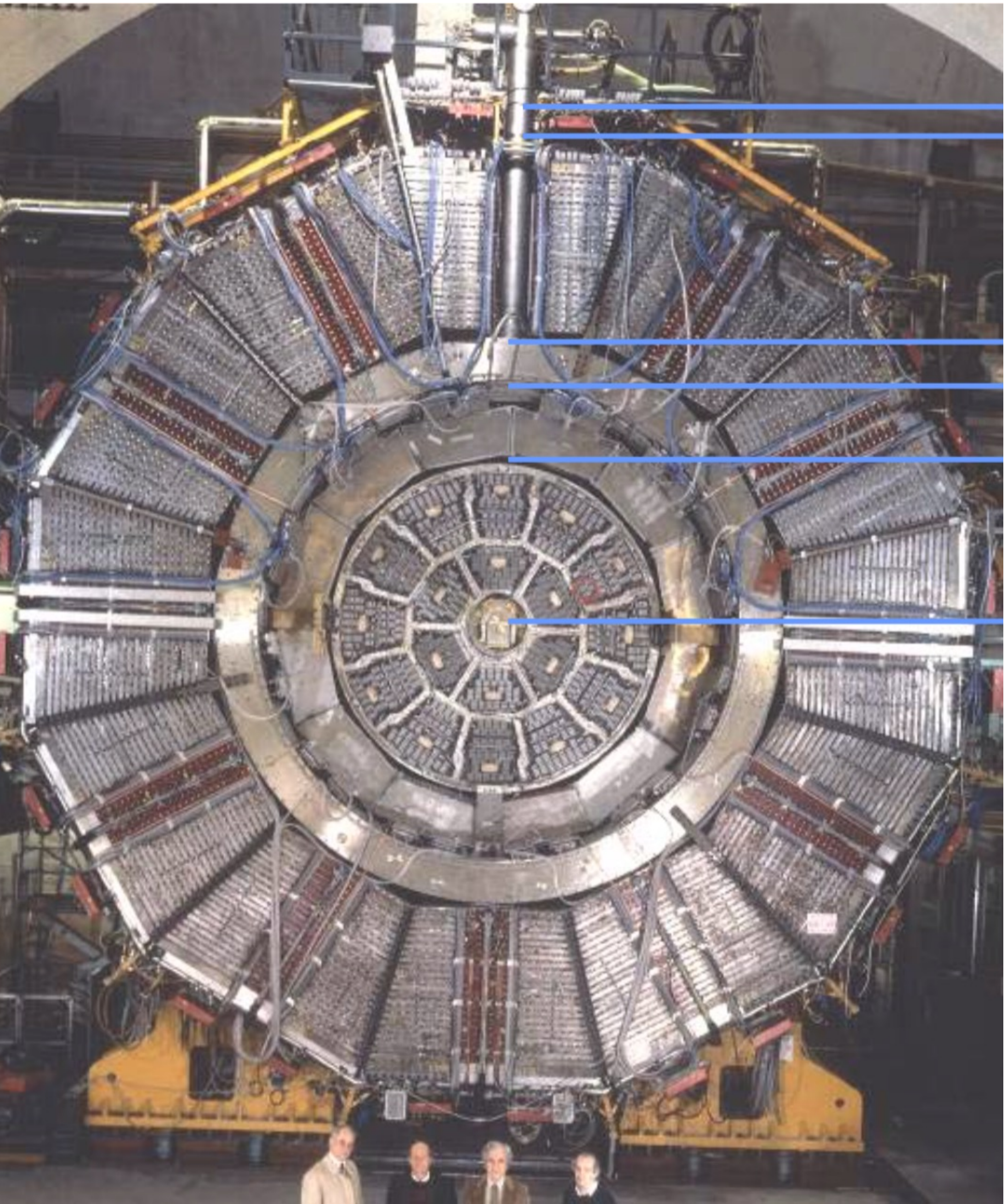
Variable used in calorimetry because it allows to describe the behavior of hadron beams for all (~) materials

For $Z > 6 \Rightarrow \lambda_a > X_0$



	Air	H_20	Al	LAr	Fe	Pb	$PbWO_4$
Z	-	-	13	18	26	82	-
λ_{int} (g/cm^2)	~70000	84	85	66	16.8	17	22.4
X_0 (cm)	30420	36	8,9	14	1,76	0.56	0.89

EM & Hadronic Calorimeter



Muon chamber

Hadronic calorimeter

Supraconductor magnet
EM calorimeter

Traking

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Particle indentification

The processes described here all have in common to have a very low energy loss because we do not want to alter the energy of the particles during this phase

5 main methods :

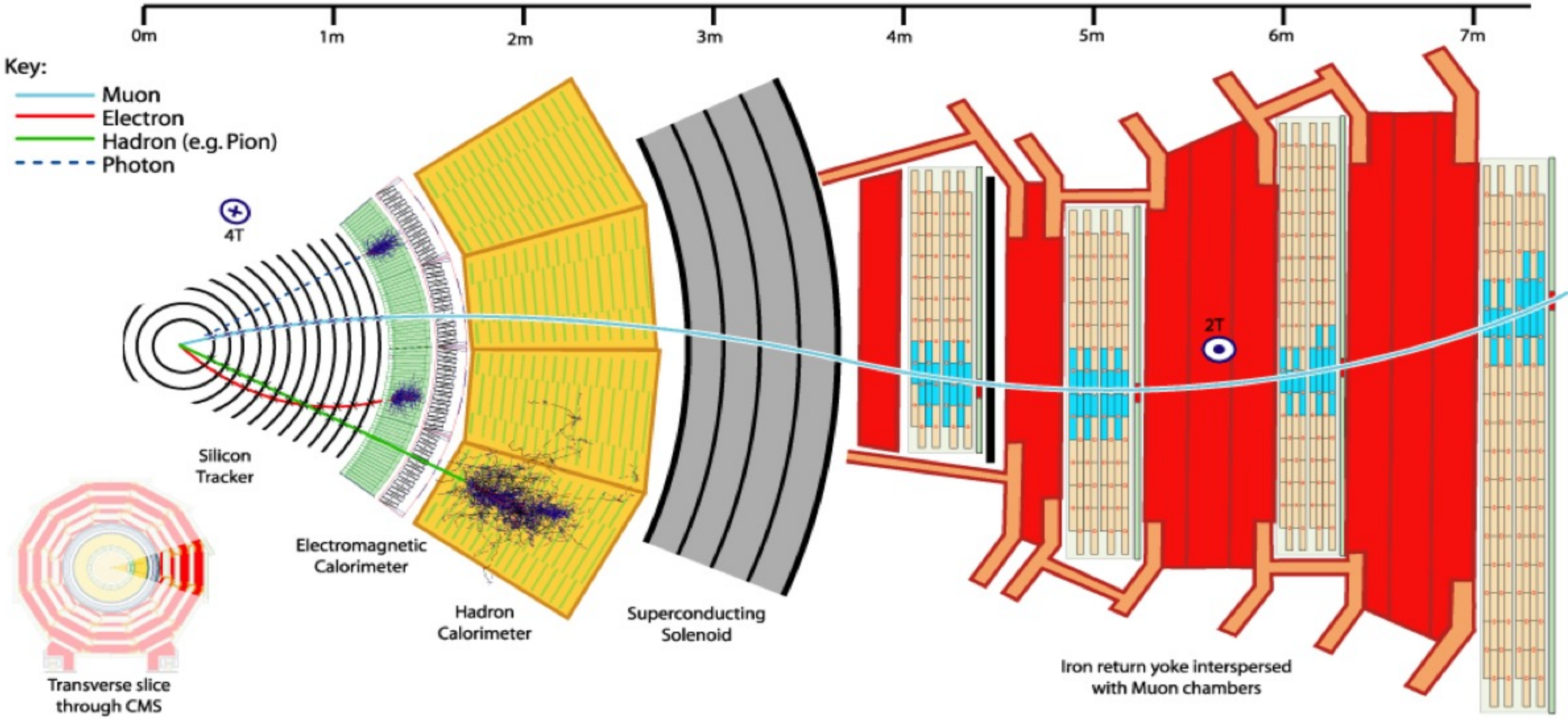
- Measurement of the impulse by curvature in a B field
- Measurement of dE/dx
- Measurement of the time of flight
- Cherenkov radiation
- *Transition radiation*

Identification also requires knowledge of the momentum

Particle indentification

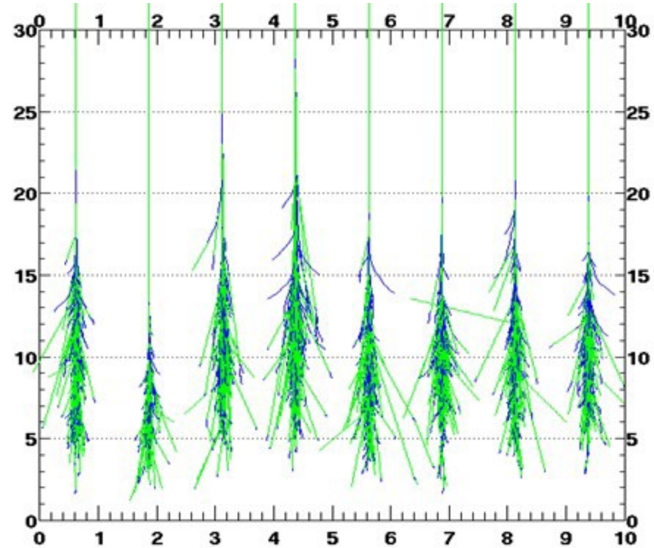
- Short-lived particles are generally identified by their decay products → traces, secondary vertexes, vertex detector
- Neutrinos : deficit in the energy or momentum balance of the reaction = missing energy
- Electrions, photon and Pi0 : electromagnetic jets in calorimeters
- Muons : path and specific penetration power
- Charged Hadrons (Pi, K, p) : these are the most difficult particles to distinguish. *It is mainly to this group that the notions of identification are related.*

CMS : Compact Muon Solenoid



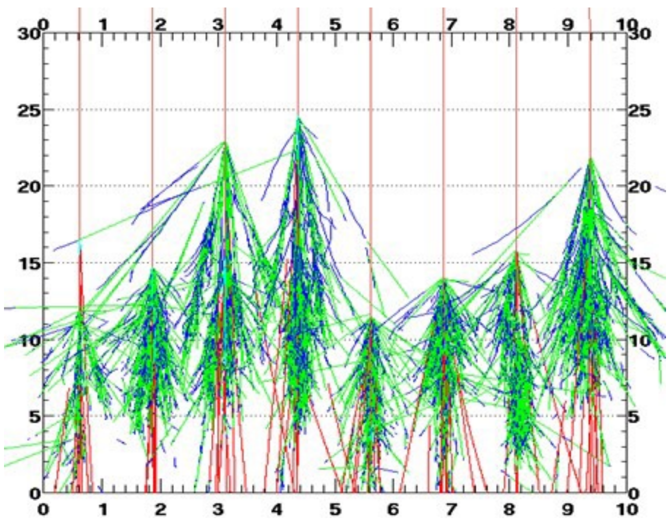
Shower & Cherenkov emission

Gamma 100GeV



EM Interaction
→ Revolution symmetry

Protons 500 GeV

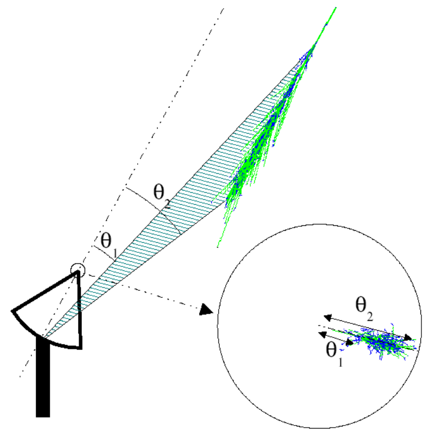


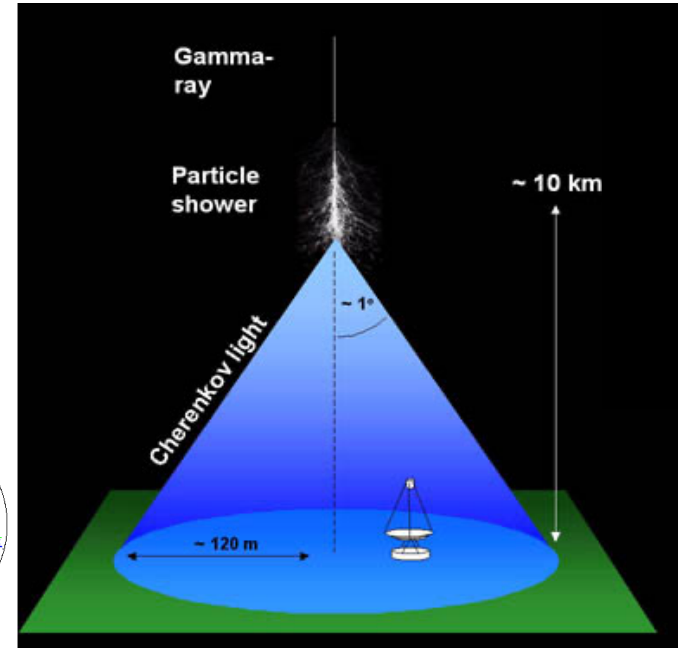
Hadronic Interaction hadronique
→ Large Transverse Momentum
→ Large fluctuations

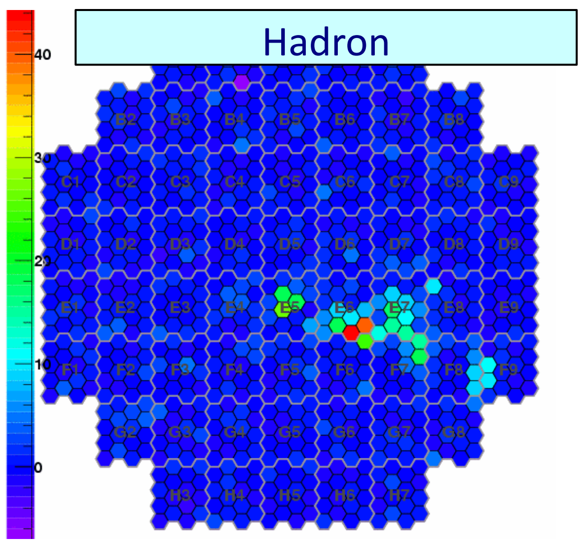
Cherenkov Imaging Telescope

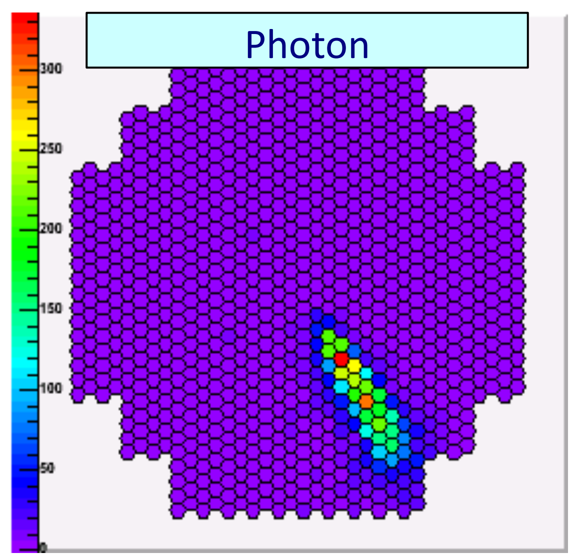
- Analyse the shape of the image :
  - Identification of the primary
  - Energy
  - Direction

- Need an important rejection :
  1 γ for1000 hadrons









H.E.S.S. experiment

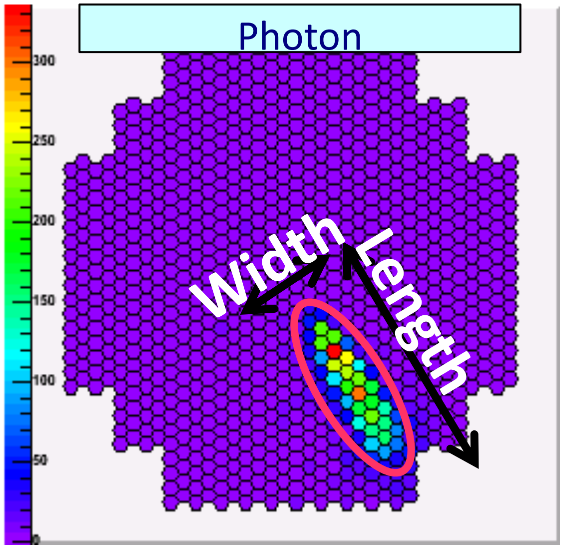
- 4 telescopes arranged to form a square with 120 m side length
- Mirrors of 12 m of diameter
- Field of view: 5°
- Location: Namibia (1800m altitude)
- Observation time : 1 000h/year

- Resolution : $E \in [100 GeV ; 100 TeV]$

  Energy : 15% at 150GeV

  Angular : < 0,1°

Photon / Hadron discrimination



- Hypothesis of a 2D distribution of the p.e. in the camera according to a gaussian (ellipse)
- Parameters used :
  - Length and Width of the main axis through a renormalization (scaled parameters: independent of the energy and the direction,…)
  - Utilization of mean values with the four telescopes.

No energy dependence