Accelerators and Detectors

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Particle Physics (2015/2016)

Particle interaction with matter

§ (SUMMARY) §

PHOTONS

- Photoelectric effect
- Compton scattering
- Pair production
- Rayleigh scattering

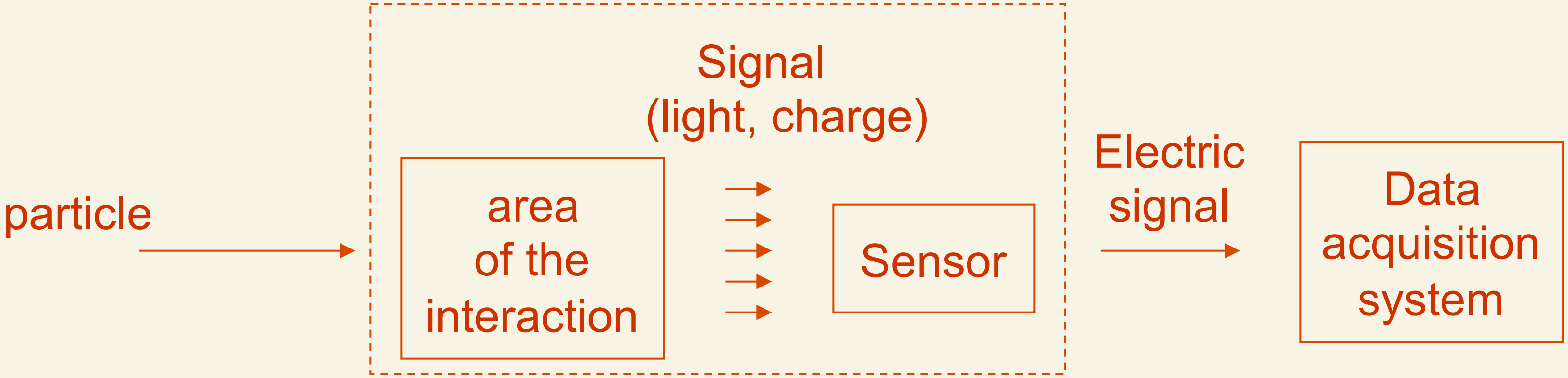
CHARGED PARTICLES

- Inelastic collisions with atomic electrons:
  - Ionization/Excitation
- Interactions with a e.m. field (for instance the one created by a nucleus)
  - Bremsstrahlung
  - Multiple Scattering (Rutherford)
- Cerenkov radiation

Particle detectors

Radiation detectors

- Objective:
  - Measure the properties of the particles (charged or neutral)
    - **Energy, momentum, position, trajectory, time, velocity, mass, charge…**
- Operation mode:
  - A deposition of (total/partial) energy of the particle occurs when the particle interacts with the detector



particle

area of the interaction

Signal (light, charge)

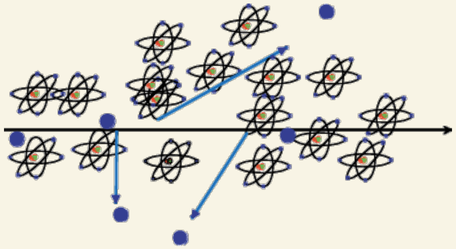
Sensor

Electric signal

Data acquisition system

Detection principle

- The detection of particles is always done through its interaction with matter.
- When traversing a medium, charged particles leave behind a trail of excited atoms, electron-ion pairs (in gases) or pairs of electron-holes (in solids).
- Photons interact with matter producing charged particles that will interact with the medium.



- **Excitation:**
  - The emitted photons by the excited atoms can be recorded with light detectors.

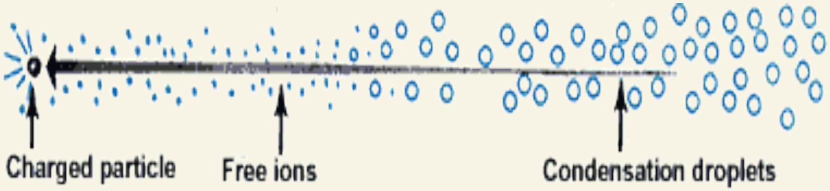
Scintillation Detectors

- **Ionization:**
  - Charged particles produce electron-ion (gases) or electron-holes (solid) pairs. The charges can be collected through the application of an electric field and read using a suitable electronic.

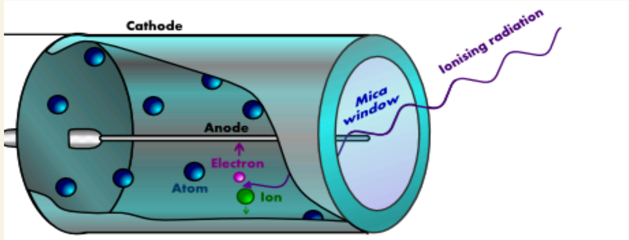
Ionization Detectors

Ionization Detectors

- **Gaseous detectors:**
  - The particles leave a trail of pairs electron-ion in gases or liquids
  - The ionization may induce reactions that enable the visualization of the particle trajectory



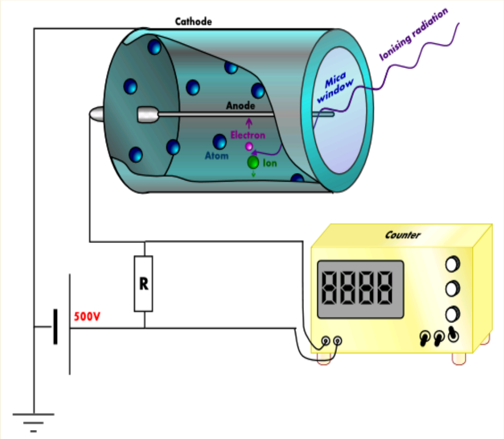
- The produced particles may be collected by applying an electric field. The collected charge can be amplified in the chamber to induce a measurable signal



Ionization detectors regime

- There are different types of ionization detectors:
  - Ionization chamber
  - Proportional counter
  - Geiger-Müller counter
- However these are basically the same device working in distinct tension regime and with different geometric configurations, exploring particular aspects of the involved phenomena
- Example of a typical configuration:
  - Cathode: cylinder of conducting walls filled with a noble gas
  - Anode: conductor wire along the cylinder axis (+V_0)
  - Electric radial field:
  - Depends on the tension, V_0

$$E(r) = \frac{1}{r}\frac{V_0}{\ln\left(\frac{r_{ext}}{r_{int}}\right)}$$



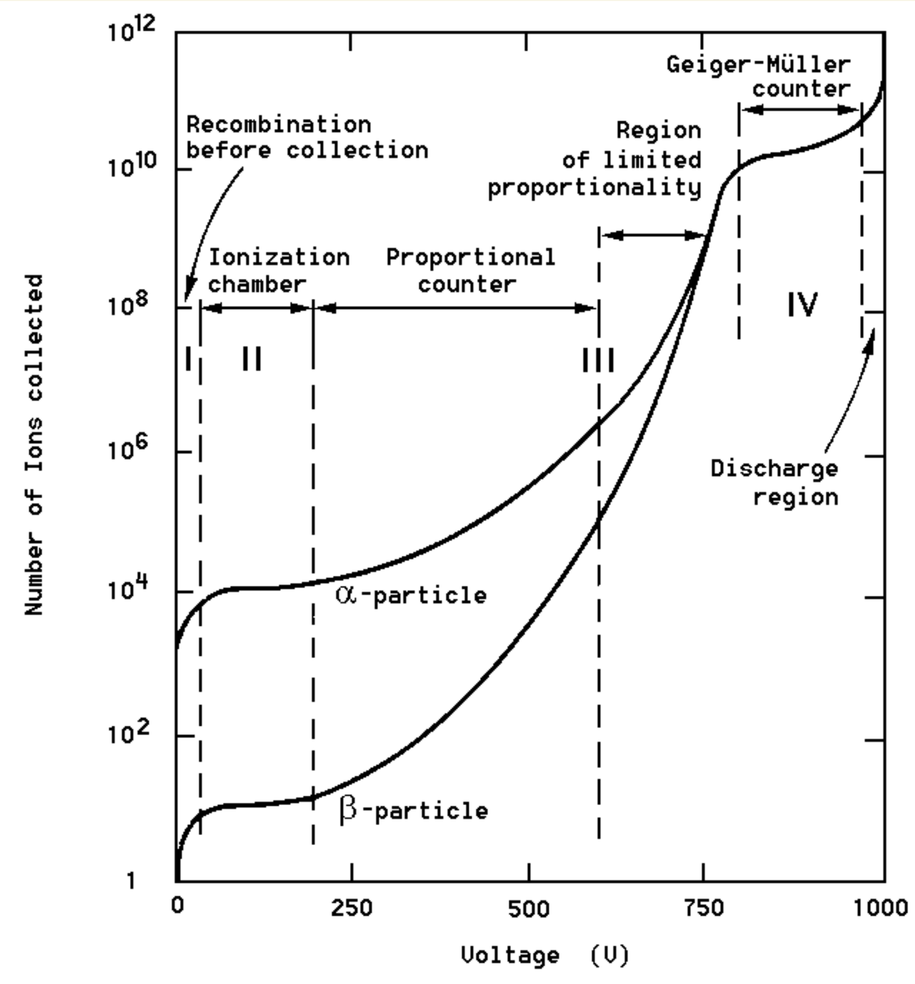
Incident radiation

Gas ionization

Movement of the electric charges towards the electrodes due to the electric field

Collecting of the electric signal

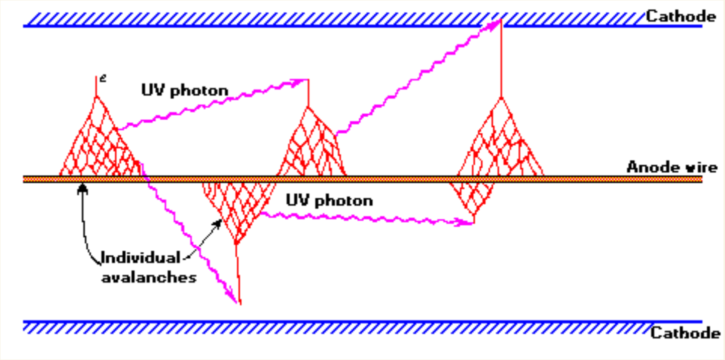
Ionization detectors regime



- **Region I** – recombination of electron–ion pairs
  - **There is no charge collection.**
- **Region II – Ionization chamber**
  - From a given tension, $V_{0,}$ all the produced pairs are collected independently of this tension: **first plateau**.
- **Region III – Proportional counter**
  - The increase of the tension leads to a new regime where the released electrons have enough energy to produce **secondary ionizations**
    - **Avalanche ionization** (near the anode)
- **Region IV – Geiger-Müller counter**
  - **Multiple avalanches**: created by photons from the molecular de-excitations. Again, doesn't depend on the tension - **plateau**

Geiger-Müller counter

- **No measurement of incident particle energy**– operates in a discharge mode, where all the signal have the same amplitude independently of the deposited energy (number of initial pairs electron-ion)



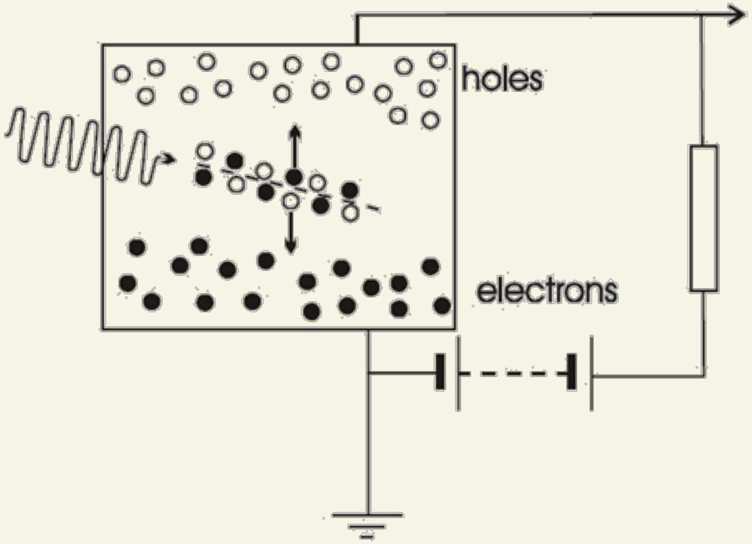
- **Relatively high recovery time**

- **Induces very high signals**, due to the large collected charge

- **Simple system** (electronics) and cheap

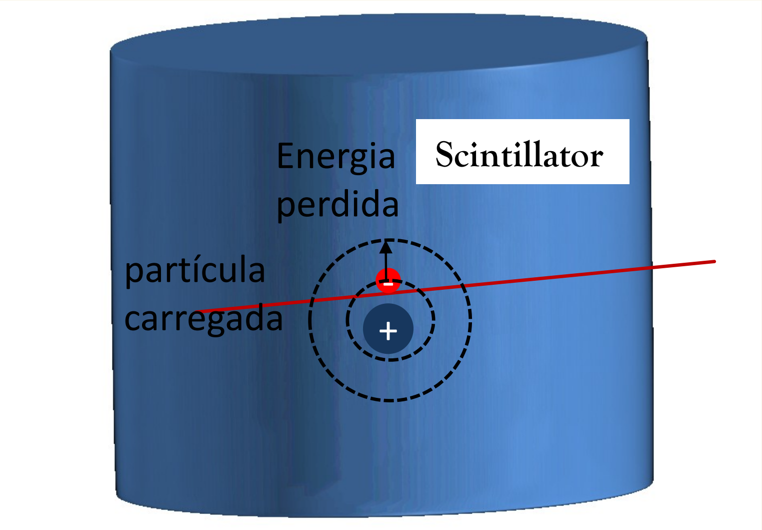
Ionization detectors

- **Solid state detectors:**
  - Charged particles leave a trail of electron-holes pairs. The charges in motion can be collected and recorded by a suitable electronic system. In these kind of detectors the produced signal by the initial charge is generally sufficient, i.e. **there is no need for amplification**.

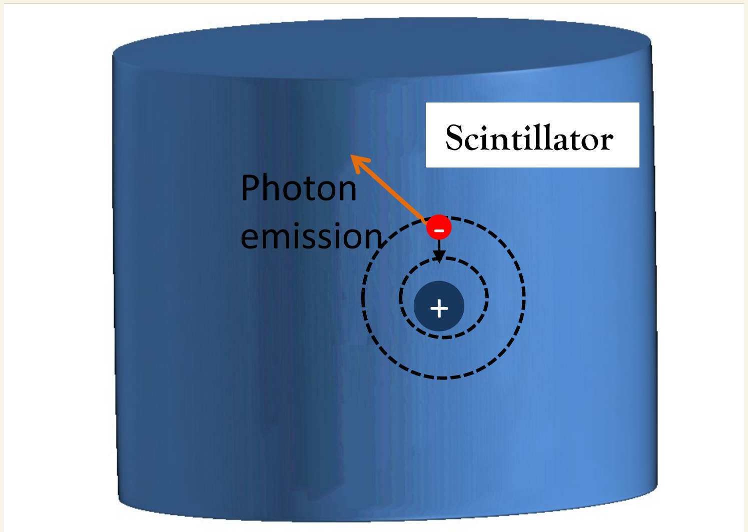


Scintillators

- Operation principle:
  - The incident particle **excites the atoms** from the material. The consequent de-excitation produces **light emission** that has a wavelength in the visible region or in the ultraviolet (UV) region

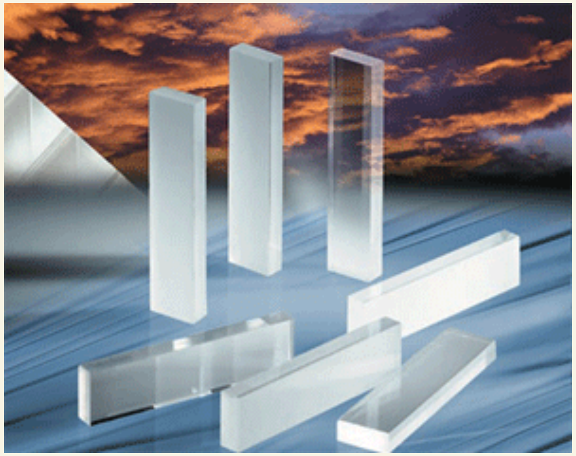


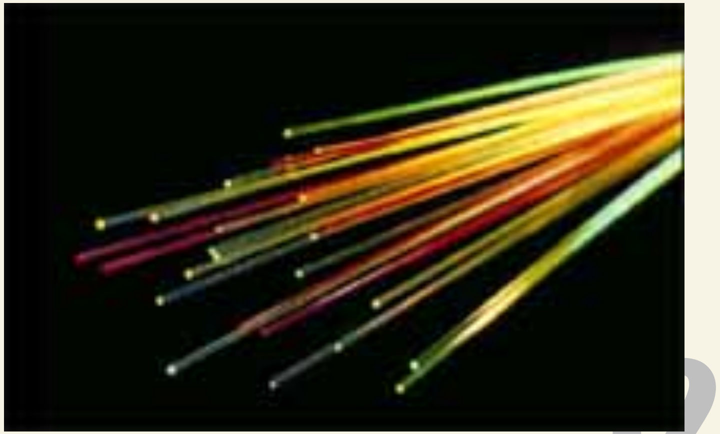
$$\xrightarrow{+\Delta t}$$



Scintillators

- **Classification accordingly to the de-excitation time:**
  - Fluorescence: rapid reemission of light (can have a fast component and another one slower)
  - Phosphorescence: slow light reemission
- **Characterization:**
  - Efficiency of the conversion from energy deposited by the particle into light (Light yield)
  - Emission time (fast component)
  - Emission spectrum
  - Transparency





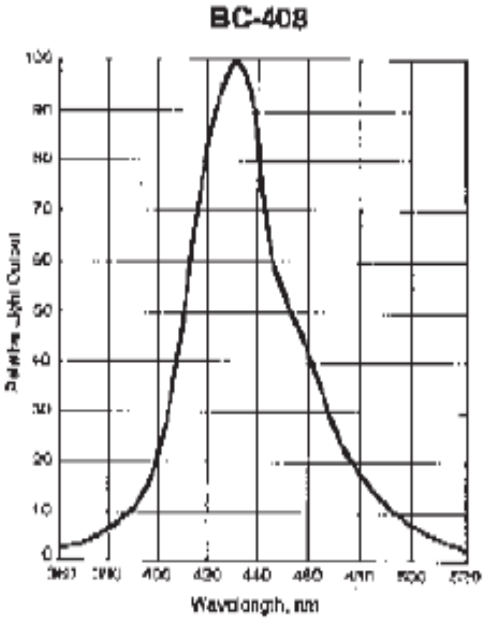
Scintillators

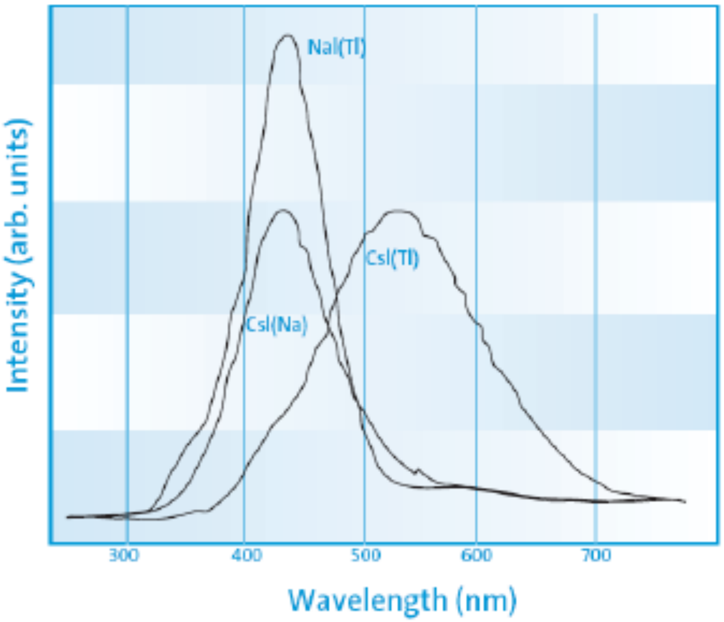
ORGANIC	INORGANIC
Material of low Z: plastics (e.g. polystyrene) doped with fluorescent molecules	High density and Z: Crystals of NaI, CsI, BGO, … doped with activator impurities: NaI(Tl)
Scintillation of molecular nature	Scintillation occurs due to the due to the electronic band structure of the crystal
Low Light Yield	High Light Yield
Fast light emission (1–3 ns)	Slow light emission (≈100 ns)
Good to detect electrons	Good to detect photons Used in nuclear medicine

Another types: gases (noble!), glass,…

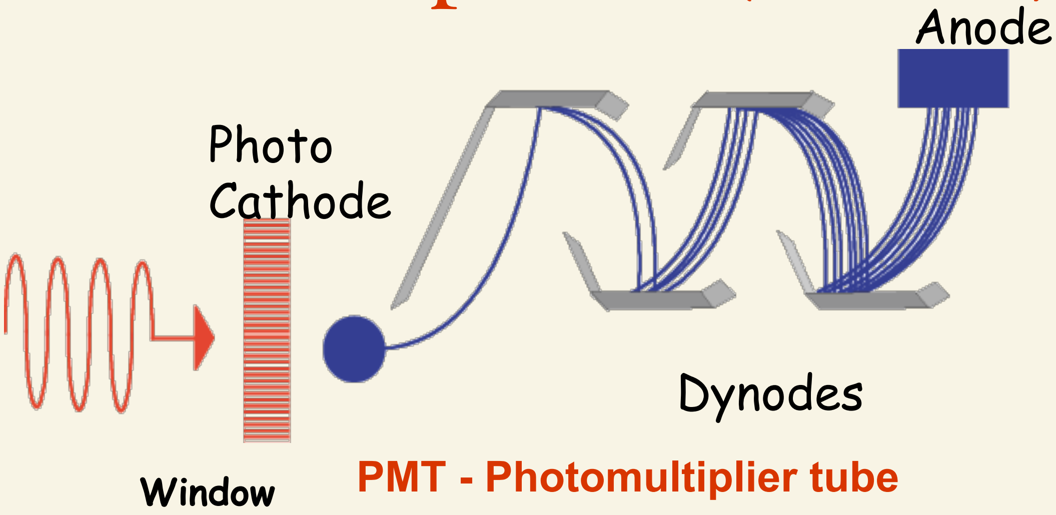
Scintillators properties

Material	eV/fotão	Tempo (nsec)	λ_{max} (nm)	ρ (g/cm^3)	$\frac{dE}{dx}$ (mip) (MeV/cm)	n
Anthracene	60 (100%)	30	447	1.25		1.62
Plástico NE104	88 (68%)	1.9	406	1.032		1.58
NaI	26 (230%)	230	413	3.67	4.8	1.85
BGO	173	300	480	7.13	9.2	2.20





Photomultipliers (PMTs)



PMT - Photomultiplier tube

- **Photon detectors**
- Morphology:
  - Transparent entry window (glass or quartz)
- Photocathode:
  - Incident photons are converted into electrons (photoelectrons) by photoelectric effect
  - Quantum efficiency =$N_{pe}/N_{\gamma} \sim 20\%$
  - Low noise = Dark current (spontaneous emission) + static noise
- Dynodes: Amplification
  - Tension applied
  - Emission of secondary electrons
- Gain ≈ 10^6
- Response ≈ 200 ps (very fast)

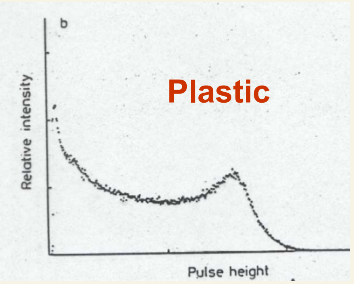
General detector characteristics

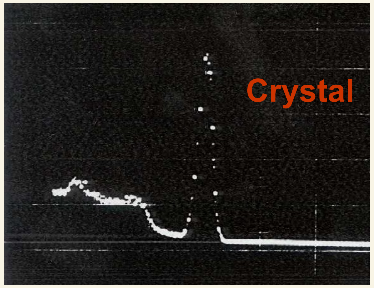
Sensitivity

... to a given type of particle and range of energies. Depends on the involved cross-sections, detector volume, electronic noise, ...

Example: Detection of photons by plastic and crystal scintillators

$\sigma_{Compton} \sim Z \; ; \; \sigma_{phot} \sim Z^5$



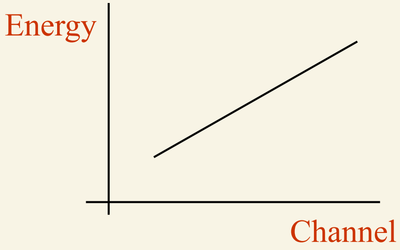


Response/Linearity

If the incident radiation is completely absorbed, the recorded signal in the detector, converted into an electric impulse and integrated in time give us a charge which is proportional to the incident energy

In many cases the response of the detector is linear:

Measured value = k × Initial value
k = calibration constant



Efficiency

ε_{total} = detected events / events emitted by the source

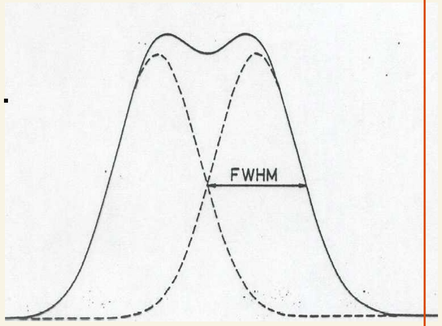
$\varepsilon_{total} = \varepsilon_{intrínsic} \times \varepsilon_{geometric}$

$\varepsilon_{intrinsic}$ = detected events / events hitting the detector
Depends on the type and energy of the radiation and on the material and volume of the detector

$\varepsilon_{geometric}$ = events hitting the detector / events emitted by the source
Depends on the angular distribution of the emitted radiation as well as on the fraction of solid angle covered by the detector

General detectors characteristics

Energy resolution



It is the detector capability to distinguish two close energy values.
Note that the individual measurements fluctuate statistically around the average value.

$R = \Delta E / E = FWHM / E$

Example NaI: Resolution variation with energy: R goes with $1/\sqrt{E}$

Poisson => **$\sigma^2 = N$** **($\Delta N = FWHM = 2.35\ \sigma$)**

$R = \Delta E / E = \Delta N / N = 2.35/\sqrt{N}$

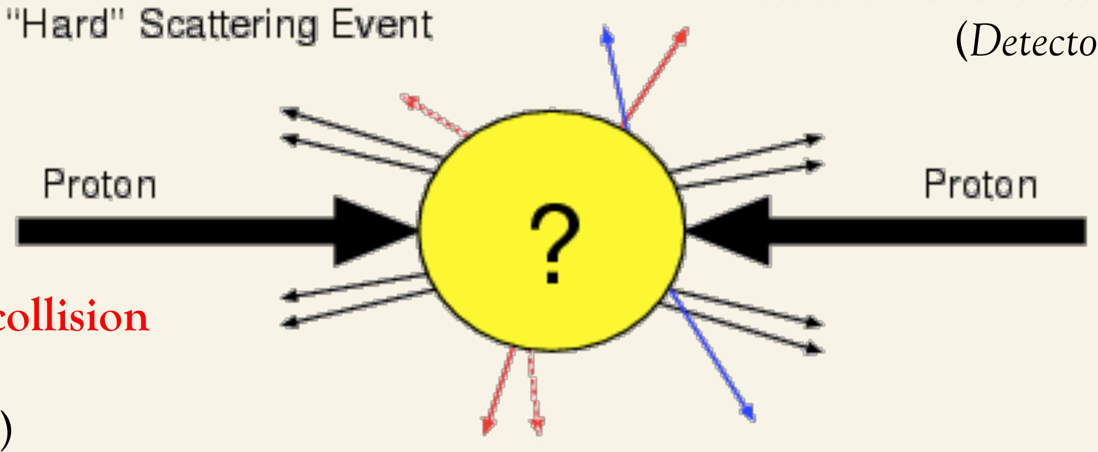
Dead time

It is the time τ necessary by the detection system to process one event.
Might be related with the electronics or it might be a byproduct of the physical detection mechanism.
If the detector is active during this time there is a pile up of events, otherwise all the events are lost during this time.

Particle accelerators

Investigate the structure of matter

- **Objective:** determine the properties of matter and their structure evolution with energy



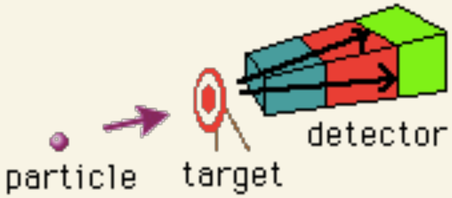
Detection of the reaction products
(*Detectors*)

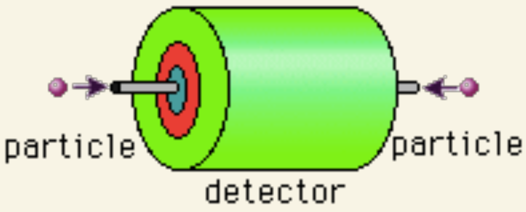
Acceleration and collision
of particles
(*Accelerators*)

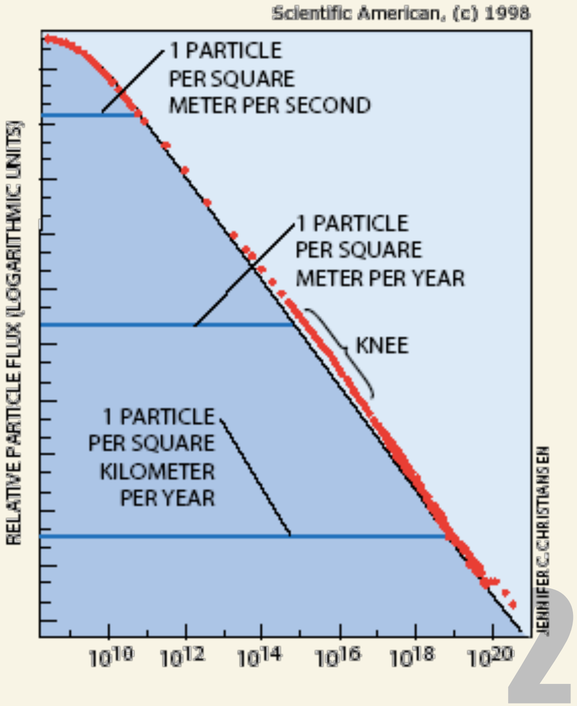
Test the comprehension on observables
(*Theory/Models*)

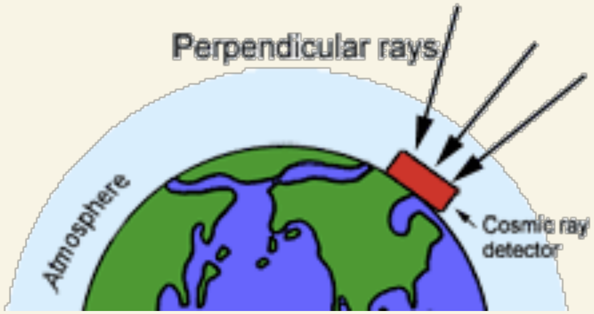
Particle accelerators

- **Experiment types:**
  - Fixed target:
    - $E_{CM} \propto \sqrt{E_{beam}}$
  - Colliders:
    - $E_{CM} \propto E_{beam}$
  - Cosmic rays:
    - Several orders of magnitude in energy;
    - Several orders of magnitude in flux





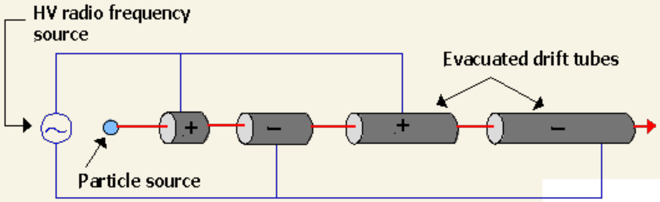




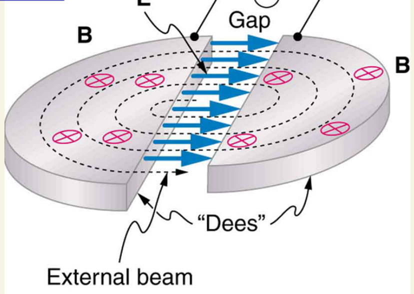
Accelerator types

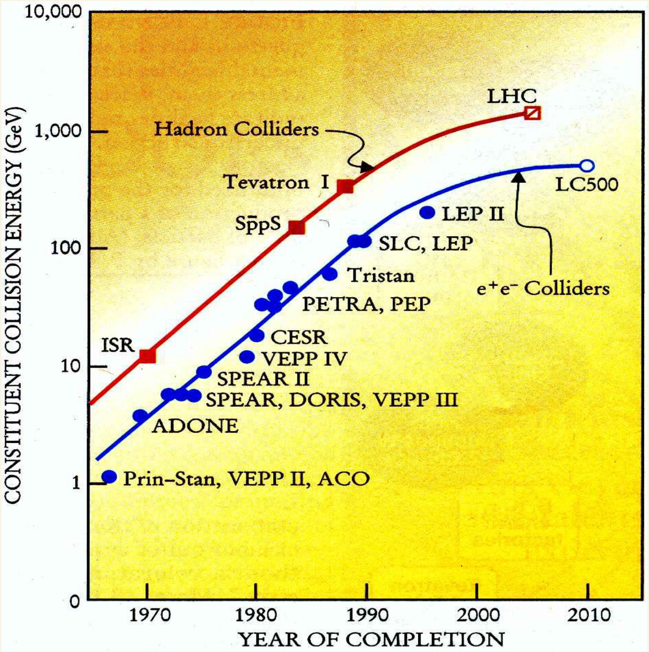
- Accelerators
  - Linear
    - Less sensitive to radiative losses
  - Circular
    - Use the same path to continuously accelerate the same particle
    - Use a magnetic field to confine the particle
      - Ex: cyclotron, LHC

- Evolution of the accelerators energy through time
  - Livingston plot



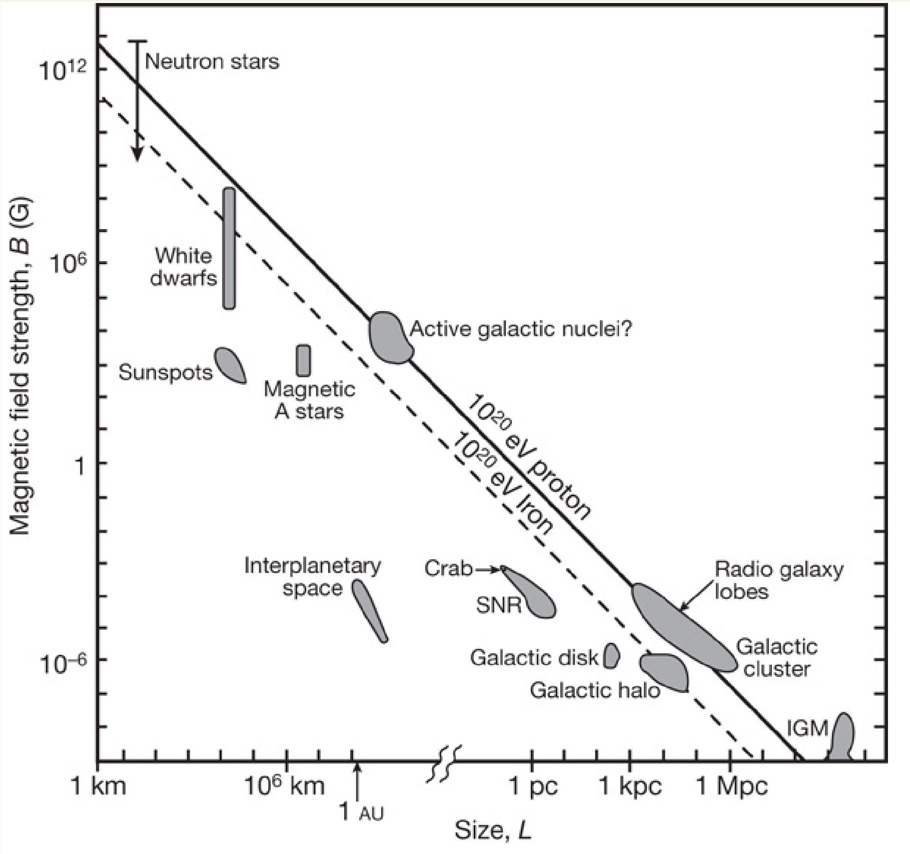
Linear Accelerator

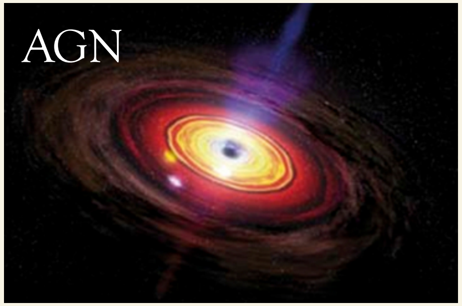




Other accelerators (Nature)

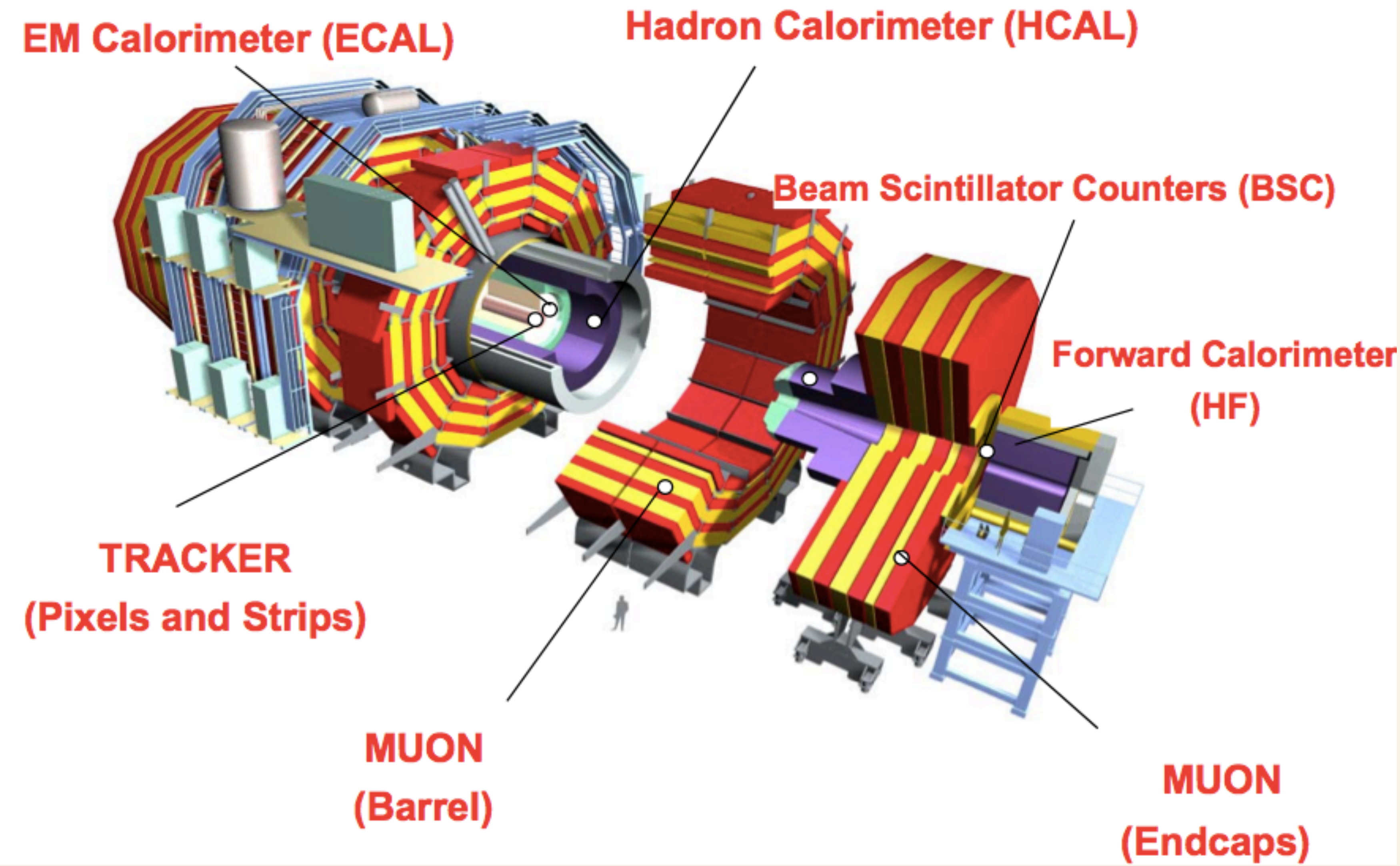
- **Acceleratorss**
  - Particles can be accelerated in the Universe
    - Violent phenomena like supernovas or pulsars
    - Strong magnetic fields like supernova remnants (SNR) or active galactic nuclei (AGN)
  - Interplay between strength of the magnetic field and the size of the "accelerator"





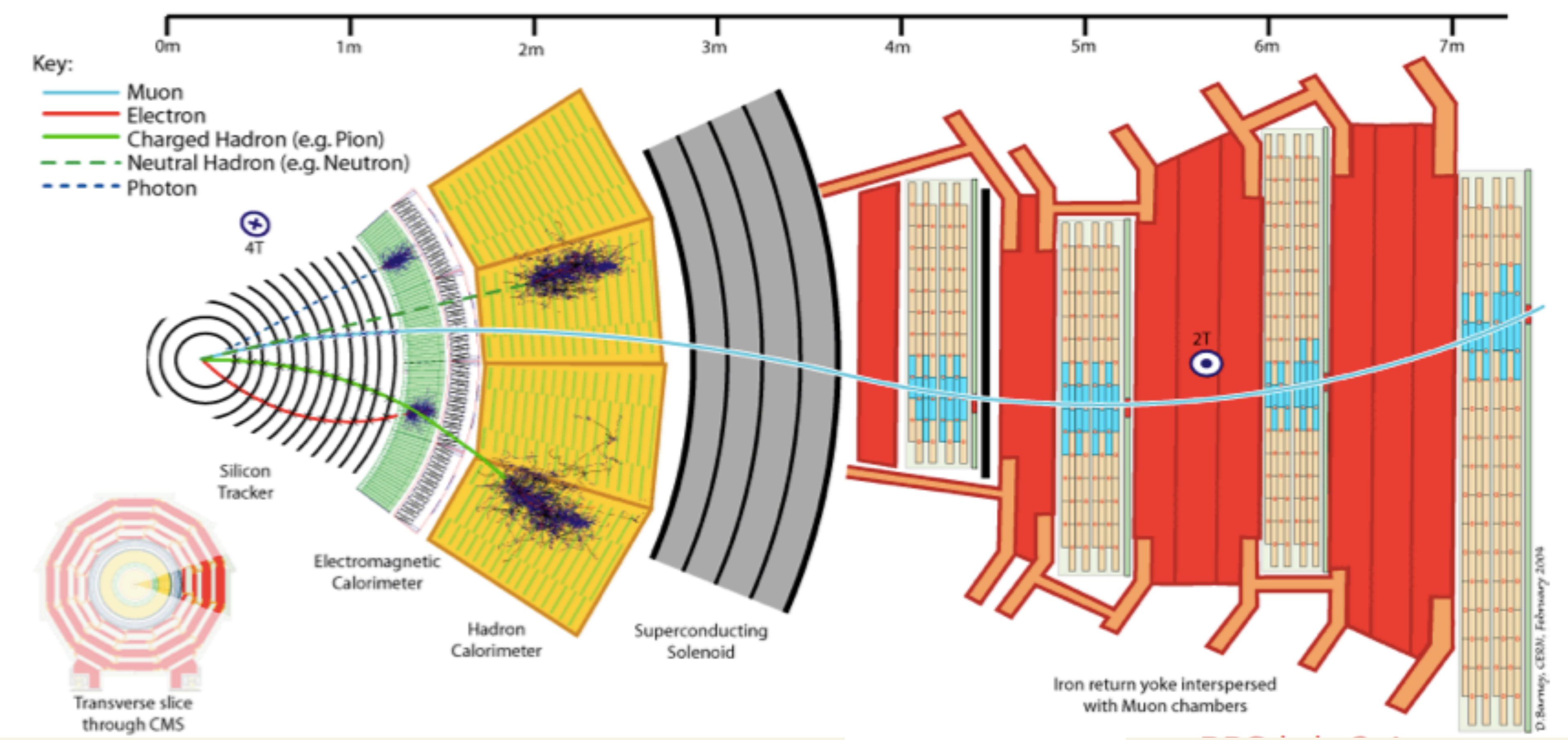
Examples of High Energy Particle Physics Experiments (HEP)

CMS detector at the LHC



§ Composed of several types of detectors §

Particle detection at CMS



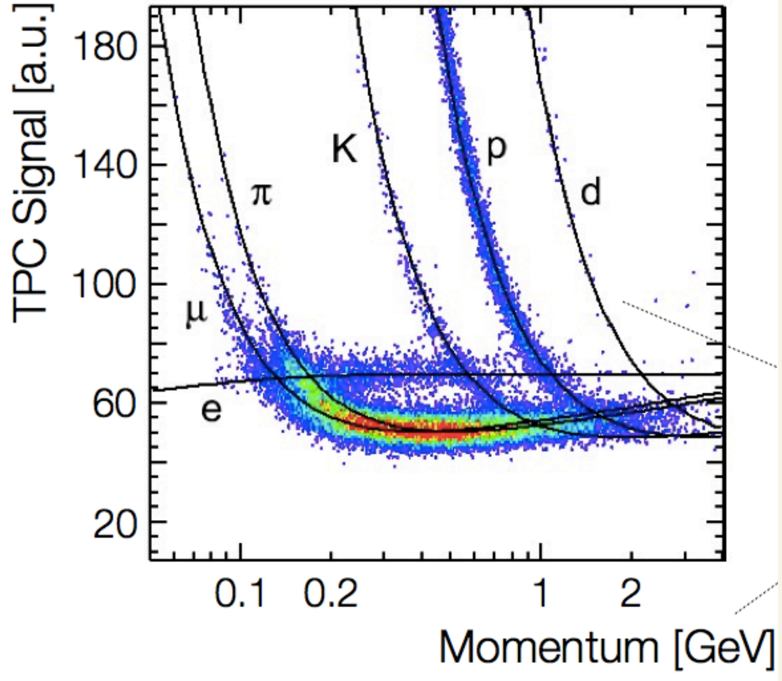
Particle identification

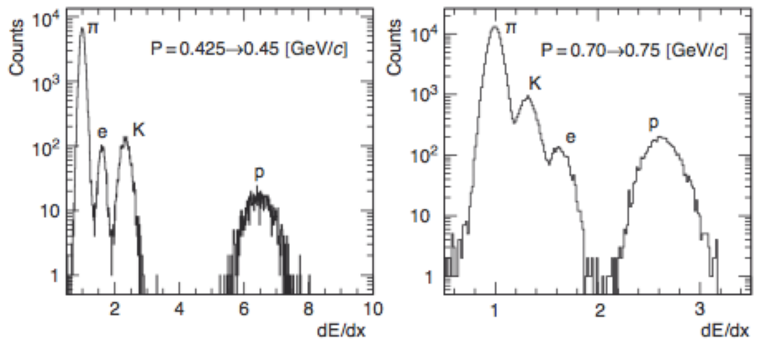
- The **momentum (and charge)** of the particles is measured through the trajectory deflection caused by a **magnetic field**
  - To unveil the particle mass (nature of the particle) it is necessary to add more information

$$p = \gamma m c$$

- **Energy loss**
  - Bethe-Block (dE/dX)
  - Depends on the particle mass

ALICE TPC





ALEPH TPC

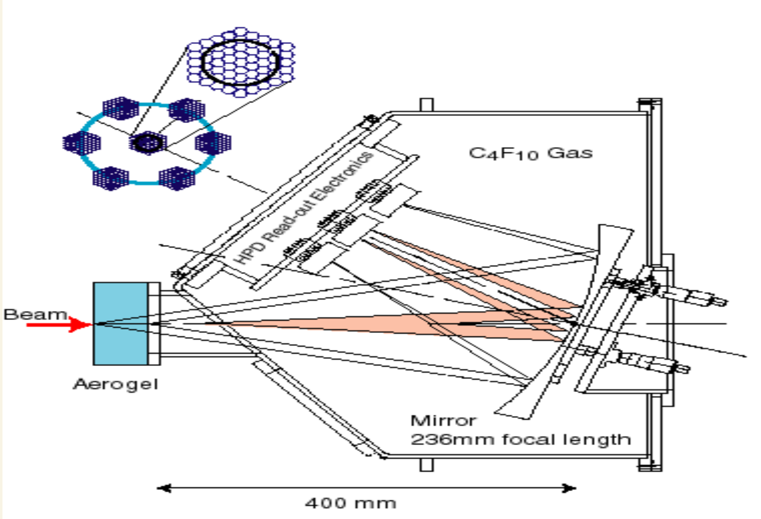
Particle identification

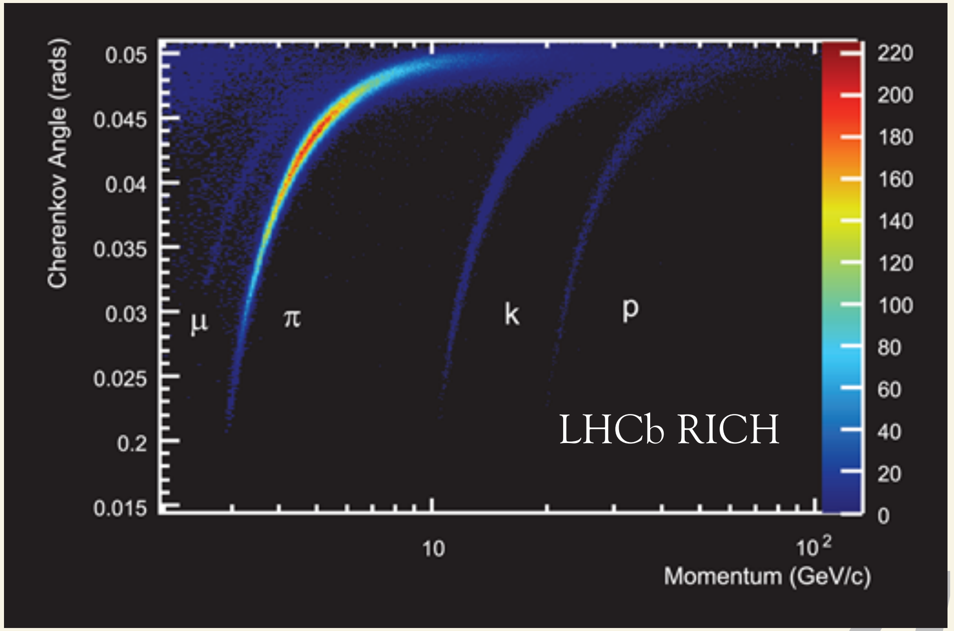
- Measurement of particles **velocity**:
  - **Cerenkov**
    - RICH – Ring Imaging Cerenkov Detector
    - Photons are arranged on a circumference whose radius has a relation with β

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

  - **Time of flight (ToF)**
    - Time that a particle takes to cross two detection planes at a fixed distance (L) is related with its velocity

$$t = \frac{L}{\beta c}$$

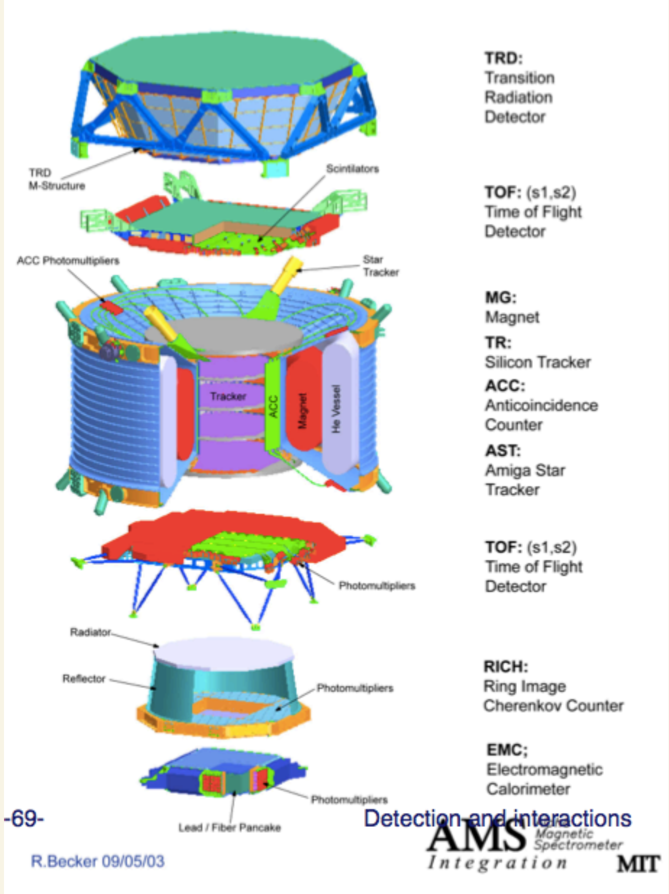




LHCb RICH

Other HEP experiments

AMS-II



TRD:
Transition
Radiation
Detector

TOF: (s1,s2)
Time of Flight
Detector

MG:
Magnet

TR:
Silicon Tracker

ACC:
Anticoincidence
Counter

AST:
Amiga Star
Tracker

TOF: (s1,s2)
Time of Flight
Detector

RICH:
Ring Image
Cherenkov Counter

EMC;
Electromagnetic
Calorimeter

-69-

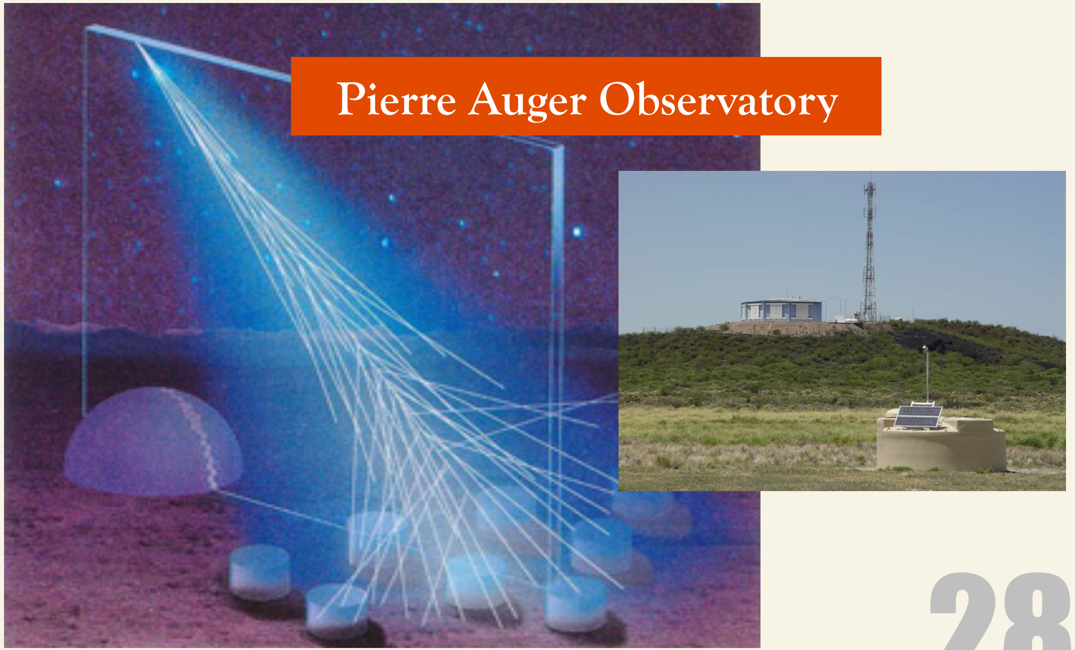
Detection and interactions

R.Becker 09/05/03

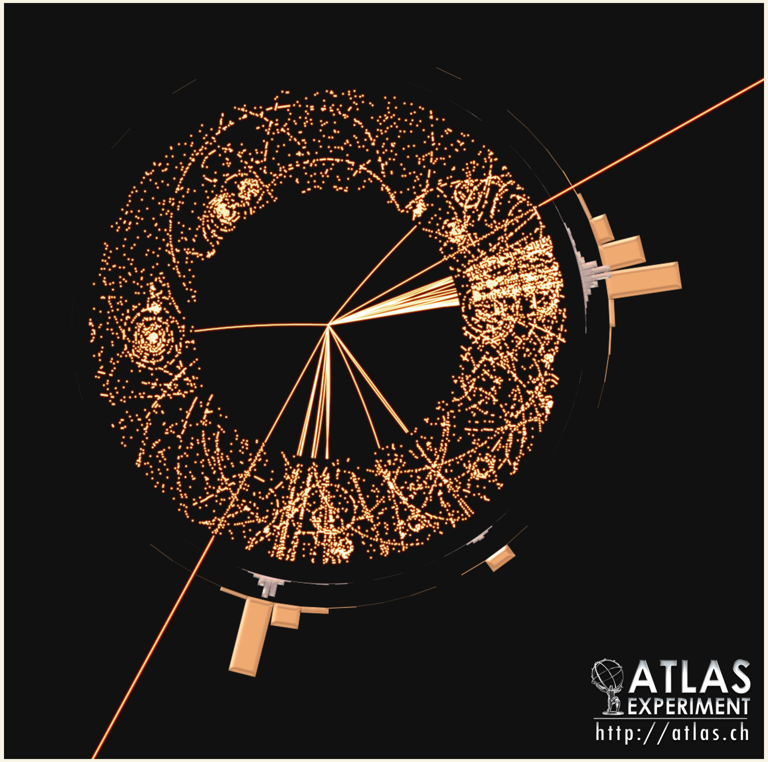
AMS Magnetic Spectrometer
Integration
MIT

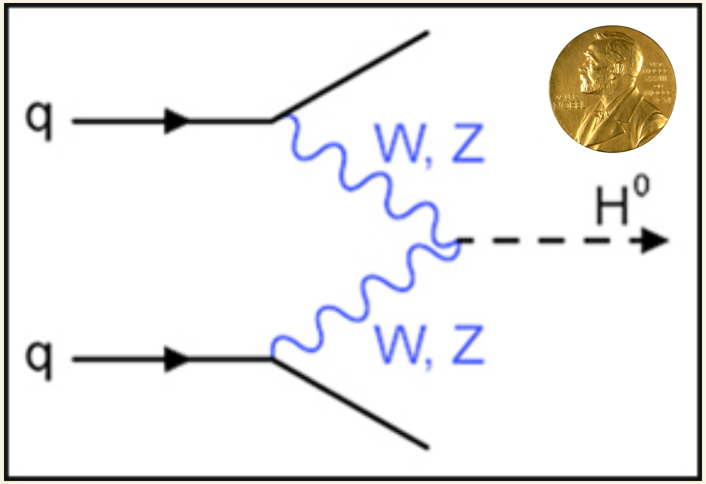
SNO

Pierre Auger Observatory



“Our capability to understand our Universe depends on our ability to experiment it”





Bibliography for this class

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  - Chapter 1, section 1.2 and 1.3
- Particle Data Group
  - Particle detectors for accelerators
    - http://pdg.lbl.gov/2014/reviews/rpp2014-rev-particle-detectors-accel.pdf
  - Particle detectors for non-accelerator physics
    - http://pdg.lbl.gov/2014/reviews/rpp2014-rev-particle-detectors-non-accel.pdf
- A. De Angelis, M. Pimenta, Introduction to particle and astroparticle physics
  - Chapter 4, section 4.2, 4.3, 4.4 and 4.5

Problems

① What gain would be required from a photomultiplier in order to resolve the signal produced by 3 photons from that due to 2 or 4 photons? Assume the fluctuations in the signal are governed by Poisson statistics, and take two peaks to be resolved when their centers are separated by more than the sum of their respective standard deviations.

② What energy must a proton have to circle the earth at the magnetic equator?

- Assume:
  - Earth's magnetic field = 1 G (10^{-4} T);
  - Earth radius = 6.4×10^{6} m;
  - proton charge = 1.6×10^{-19} C;
  - 1 eV = 1.6×10^{-19} J